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Book of Abstracts
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The impact of LQCD on transverse momentum parton phenomenology

Semileptonic $b\rightarrow u$ decays and $|V_{ub}|$

A9: P-Wave Two-Body Bound and Scattering States in a Finite Volume including QED

Near Physical Point Lattice Calculation of Isospin-Breaking Corrections to $K_{\ell 2}/\pi_{\ell 2}$

D10: Measuring charged particle polarizabilities on the lattice without background fields

Continuous temperature sampling in a single Monte-Carlo simulation

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Hadron Structure discussion in Gather breakout room #1

QCD at nonzero Temperature and Density discussion in Gather breakout room #2

Group photo on zoom

F10: Lattice Diversity Survey
Welcome (in conference zoom)

Closing

Public lecture: QCD: The Glory and The Power

Physics colloquium-level lecture on QCD, webcast publicly

Title: QCD: The Glory and The Power

Abstract: After a brief oration in praise of the ideal mathematical beauty of QCD and its imposing experimental success, I will describe several of its ongoing and future applications at the frontiers of knowledge. These are the frontier of precision (muon $g - 2$), the frontier of high temperature and density (heavy ion collisions), the frontier of late stellar evolution (supernovae and neutron stars), and the frontier of theoretical adventure (axions and dark matter).

Excitations of isolated static charges in the charge q=2 abelian Higgs model

Author: Kazue Matsuyama

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I present lattice Monte Carlo evidence of localized quantum excitations of the fields surrounding static electric charges in the q=2 abelian Higgs model; such excitations would appear as excited states of isolated fermions. Since the q=2 abelian Higgs model is a relativistic version of the Landau-Ginzburg effective model of superconductivity, these results may have some application in a condensed matter context.

Ruling Out the Massless Up-Quark Solution to the Strong CP Problem by Computing the Topological Mass Contribution with Lattice QCD
Authors: Constantia Alexandrou⁰; Jacob Finkenrath²; Lena Funcke¹; Karl Jansen⁴; Bartosz Kostrzewa⁵; Ferenc Pittler²; Carsten Urbach³

¹ University of Cyprus and The Cyprus Institute
² The Cyprus Institute
³ Perimeter Institute
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⁵ University of Bonn

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The infamous strong CP problem in particle physics can in principle be solved by a massless up quark. In particular, it was hypothesized that topological effects could substantially contribute to the observed nonzero up-quark mass without reintroducing CP violation. Alternatively to previous work using fits to chiral perturbation theory, in this talk we present direct lattice QCD computations of the topological mass contribution, based on examining the dependence of the pion mass on the dynamical strange-quark mass. We find that the size of the topological mass contribution is inconsistent with the massless up-quark solution to the strong CP problem.

Theoretical developments and applications beyond particle physics / 9

Conserving Lattice Gauge Theory for Finite Systems

Author: Alexander Rothkopf⁰

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Corresponding Author: alexander.rothkopf@uis.no

In this talk I present a recent proposal for a novel action for lattice gauge theory for finite systems, which accommodates non-periodic boundary conditions [1]. Drawing on the summation-by-parts formulation of finite differences and finite volume strategies of computational electrodynamics, an action is constructed that implements the proper integral form of Gauss’ law and exhibits an inherently symmetric energy momentum tensor, all while realizing automatic O(a) improvement. Its central ingredients are illustrated using Abelian gauge theory as example.


Standard Model Parameters / 11

Lattice calculation of K→l nu l’ l’ decay width

Authors: Xin-yu Tuo⁰; Xu Feng⁰; Luchang Jin⁰; Teng Wang⁰

¹ Peking University

Corresponding Author: ttxxyy@pku.edu.cn

We develop a methodology for the computation of the $K \rightarrow \ell \nu \ell' \ell''$ decay width using lattice QCD and present an exploratory study. We use a scalar function method to account for the momentum dependence of the decay amplitude. We adopt infinite volume reconstruction (IVR) method to solve temporal truncation effects and general finite-volume effects in a systematic way. To be specifically, general finite-volume effect comes from using arbitrary momentum instead of lattice discrete momentum in phase space integration. Temporal truncation effects can either come from slowly converging exponential factor associated with soft photon region of $K \rightarrow K \ell' \ell'' \rightarrow \ell \nu \ell' \ell''$.
contribution, or from exponentially growing term in $K \to \pi \ell \nu \to \ell \nu \ell^+ \ell^-$ contribution. We then perform a four-body phase-space integral to obtain the decay width. Using the developed methods mentioned above, we calculate the branching ratios for four channels of $K \to \ell \nu \ell^+ \ell^-$ in ensembles at physical pion mass generated by RBC/UKQCD collaborations. The results close to the experimental measurements and ChPT predictions are obtained. Our work demonstrates the capability of lattice QCD to improve Standard Model prediction in $K \to \ell \nu \ell^+ \ell^-$ decay width.

QCD at nonzero Temperature and Density / 12

A Fresh Look at the Chemical Potential on the lattice

Author: Rajiv V Gavai

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Lattice techniques are the most reliable ones to investigate its phase diagram in the temperature-baryon density (chemical potential) plane. They are, however, well-known to be saddled with a variety of problems at nonzero density. I address here the old question of placing the baryonic (quark) chemical potential on the lattice and point out that important consequences for the current and future experimental searches of QCD critical point.

QCD at nonzero Temperature and Density / 13

Semiclassical ensembles of instanton-dyons describe the deconfinement and chiral phase transitions, in the usual and deformed QCD

Author: Edward Shuryak

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Corresponding Author: edward.shuryak@stonybrook.edu

Instanton-dyons are topological solutions of YM equations at finite temperatures. Their semiclassical ensembles were studied by a number of methods, including direct Monte-Carlo simulation, for SU(2) and SU(3) theories, with and without fermions. We present these results and compare them with those from lattice studies. We also consider two types of QCD deformations. One is by adding operators with powers of the Polyakov line, affecting deconfinement. Another is changing quark periodicity condition, affecting the chiral transition. Another paper is using inverse direction, from lattice configurations (with realistic quark masses) looking at zero and near-zero Dirac modes. It turned out that those revealing the shape of the modes, in excellent agreement with analytic instanton-dyon theory. Summarizing both we conclude that QCD phase transitions are well described in terms of such semiclassical objects.

Theoretical developments and applications beyond particle physics / 14

Monopole-like configurations in the O(3) spin model at the upper critical dimension

Authors: Antonio Smecca; Marco Panero
We present a high-precision Monte Carlo study of the $O(3)$ spin theory on the lattice in $D = 4$ dimensions. This model exhibits interesting dynamical features, in particular in the broken-symmetry phase, where suitable boundary conditions can be used to enforce monopole-like topological excitations. We investigate the Euclidean time propagation and the features of these excitations close to the the critical point, where our numerical results show an excellent quantitative agreement with analytic predictions derived from purely quantum-field-theoretical tools by G. Delfino.

We conclude by commenting on the implications of our findings for a conjectured violation of Derrick’s theorem at the quantum level and on the consequences in various areas of physics, ranging from condensed matter to astro-particle physics.

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**Hadron Spectroscopy and Interactions / 16**

**Charmonium-like resonances in coupled $D\bar{D} - D_s\bar{D}_s$ scattering**

**Authors:** Sasa Prelovsek$^1$, Sara Collins$^2$, Daniel Mohler$^2$, M. Padmanath$^3$, Stefano Piemonte$^4$

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The first lattice study of coupled-channel $D\bar{D}$ and $D_s\bar{D}_s$ scattering is presented. The partial waves $l = 0, 2$ are investigated on CLS ensembles. The resulting scattering matrix suggests the existence of three charmonium-like states with $J^{PC} = 0^{++}$ in addition to $\chi_{c0}(1P)$: a $D\bar{D}$ bound state just below threshold, a broader resonance likely related to $\chi_{c0}(3860)$ and a narrow resonance just below $D_s\bar{D}_s$ with a large coupling to this threshold. The partial wave $l = 2$ features a $J^{PC} = 2^{++}$ resonance likely related to $\chi_{c2}(3930)$. We work with several assumptions, such as the omission of $J/\psi\omega$, $\eta c\eta$ and three-particle channels.

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**Vacuum Structure, Confinement, and Chiral Symmetry / 17**

**Confinement from Interacting SU(3) Instanton-dyons**

**Author:** Dallas DeMartini$^5$

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Confinement remains one the most interesting and challenging nonperturbative phenomenon in non-Abelian gauge theories. Recent semiclassical (for $SU(2)$) and lattice (for QCD) studies have suggested that confinement arises from interactions of statistical ensembles of instanton-dyons with the Polyakov loop. In this talk, I will present recent work which has extended the study of semiclassical ensemble of dyons to the $SU(3)$ Yang-Mills theory. It will be shown that such interactions do generate the expected first-order deconfinement phase transition. The properties of the ensemble, including the dyon correlations and densities, and the topological susceptibility, are studied over a
range of temperatures above and below $T_c$. Additionally, the dyon ensemble is studied in the Yang-Mills theory containing an extra trace-deformation term. It will be shown that such a term causes the theory to remain confined even at high temperatures.

QCD in searches for physics beyond the Standard Model / 18

Consistency of lattice and R-ratio determinations of the HVP: Update from RBC/UKQCD

Author: Christoph Lehner

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The Euclidean time windows defined in RBC/UKQCD 2018 provide a means to test the consistency of different lattice results as well as the consistency with the data-driven R-ratio results on a short timescale. This is of particular urgency due to an apparent emerging tension between data-driven results and some lattice results. I will present an update to the 2018 RBC/UKQCD result for Euclidean time windows for the hadronic vacuum polarization (HVP) contribution to the muon $g-2$.

Poster / 19

A3: Grid Python Toolkit (GPT)

Author: Christoph Lehner

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I present GPT (https://github.com/lehner/gpt): a new Python measurement toolkit built on Grid data parallelism (MPI, OpenMP, SIMD, and SIMT). It provides a physics library for lattice QCD and related theories as well as a QIS module including a digital quantum computing simulator.

Hadron Spectroscopy and Interactions / 20

On the three-particle analog of the Lellouch-Lüscher formula

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Back in 2000, Lellouch and Lüscher derived a formula, relating the matrix element of the weak $K \to 2\pi$ decay in a finite volume to its infinite-volume counterpart. In contrast, albeit latest theoretical developments enable the extraction of three-body scattering amplitudes on the lattice, a three-particle analog of the Lellouch-Lüscher equation has not
been available until very recently. In this talk, we report on the first attempt to close this gap.

The interest in the study of three-body decays on the lattice is large. While the most obvious candidates for such a study are provided by the three-pion decays of low-mass light-flavored mesons, like the weak process \( K \to 3\pi \), also the candidates for exotica, \( X(3872) \) and \( X(4260) \), decay largely into three-particle final states as well. Moreover, the proper treatment of the three-particle decay channel of the Roper resonance might improve the extraction of its parameters. Last but not least, the study of the electromagnetic process \( \gamma^* \to 3\pi \), contributing to the anomalous magnetic moment of the muon, is certainly very interesting.

In order to avoid unnecessary technical complications in the derivation of the three-particle analog of the Lellouch-Lüscher formula, we consider the simplest case of a decay into three identical spinless particles, which interact only in the S-wave. The derivation is carried out within the explicitly covariant version of the non-relativistic effective field theory, where relativistic corrections in the internal lines are summed up to all orders. The non-relativistic formalism provides a very transparent and simple framework – especially, the use of the particle-dimer picture drastically reduces the number of relevant diagrams needed to describe the final-state interactions in the three-particle decay. Further developments concerning particles with spin, partial wave mixing, moving frames and so on are already in progress. These modifications will not affect our result at the leading order which, as expected, will be sufficient for the first generation of lattice calculations.

We demonstrate that, similar to the two-particle sector, the relation between the finite- and infinite-volume decay matrix elements is described by an overall multiplicative factor, depending on the size of the cubic box and the parameters of the final-state interactions only. In contrast, at higher orders, the factor will become a matrix with the dimension equal to the number of independent couplings, describing the three-particle decay at this order.

**Theoretical developments and applications beyond particle physics**

**New universality classes of the non-Hermitian Dirac operator in QCD-like theories**

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In non-Hermitian random matrix theory there are three universality classes for local spectral correlations: the Ginibre class and the nonstandard classes AI† and AII†. We show that the continuum Dirac operator in two-color QCD coupled to a chiral U(1) gauge field or an imaginary chiral chemical potential falls in class AI† (AII†) for fermions in pseudoreal (real) representations of SU(2). We introduce the corresponding chiral random matrix theories and verify our predictions in lattice simulations with staggered fermions, for which the correspondence between representation and universality class is reversed. Specifically, we compute the complex eigenvalue spacing ratios introduced recently. We also derive novel spectral sum rules.
Instanton effects on chiral symmetry breaking and hadron spectroscopy

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Monopoles play crucial roles in the color confinement mechanism through condensing in the QCD vacuum, and the instantons induce spontaneous chiral symmetry breaking. Monopoles and instantons are closely related to each other and interact among quarks and gluons in the QCD vacuum. It is very interesting if we can show a clue to observe monopoles and instantons by experiments. Therefore, we perform numerical simulations of lattice gauge theory and investigate the effects of monopoles and instantons on the hadrons.

First, we apply the monopole creation operator to QCD vacua and add one pair of monopole and anti-monopole to the QCD vacua of the quenched SU(3), varying the magnetic charges. Second, we estimate the effects of the monopoles and instantons on observables using the eigenvalues and eigenvectors of the overlap Dirac operator that preserves the exact chiral symmetry. Finally, we compare the numerical results with the predictions and find quantitative relations among the monopoles, instantons, and observables.

In the previous research, we have found that the added monopoles and anti-monopoles create the instantons and anti-instantons without changing the vacuum structure. We have discovered the effects of these instantons and anti-instantons on the observables by increasing the number density of the instantons and anti-instantons as follows: the chiral condensate (defined as a negative value) decreases, masses of the light quarks and mesons become heavy, and decay constants of the light mesons increase. The decay width and lifetime of the charged pion are estimated using these outcomes. The decay width of the charged pion becomes wider than the experiment, and the lifetime of the charged pion becomes shorter than the experiment. Finally, we have obtained quantitative relations among these observables and the number density of the instantons and anti-instantons.

This research investigates the instanton effects on the hadrons: the vector, eta, eta prime mesons, etc. I will show the preliminary results in this presentation.

Lattice N = 4 super Yang-Mills at strong coupling

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In this talk we present results from numerical simulations of $\mathcal{N} = 4$ super Yang-Mills for two color gauge theory over a wide range of ’t Hooft coupling $0 < \lambda \lesssim 30$ using a supersymmetric lattice action. Numerical study of this lattice theory has been stymied until recently by both sign problems and the occurrence of lattice artifact phases at strong coupling. We have recently developed a new action that appears capable of solving both problems. The resulting action possesses just $SU(2)$ rather than $U(2)$ gauge symmetry. By explicit computations of the fermion Pfaffian we present evidence that the theory possesses no sign problem and exists in a single phase out to arbitrarily strong coupling. Furthermore, preliminary work shows that the logarithm of the supersymmetric Wilson loop varies as the square root of the ’t Hooft coupling $\lambda$ for large $\lambda$ in agreement with holographic predictions.
Vacuum Structure, Confinement, and Chiral Symmetry / 24

The dual Meissner effect due to Abelian Dirac-type monopoles in QCD

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Quark confinement mechanism is one of unsolved important problems in QCD. In the dual Meissner picture of color confinement, it is considered that the color flux tube between static quarks is caused by the condensation of color magnetic monopoles in the QCD vacuum. In this talk, we show new results of the dual Meissner effect due to the violation of non-Abelian Bianchi identity corresponding to Abelian Dirac-type monopoles in QCD. In particular, we discuss the vacuum type by evaluating the Ginzburg-Landau parameter through the measurements of Abelian electric field and Abelian squared monopole density in SU(3) gauge theory without gauge fixing.

Hadron Structure / 25

Nucleon isovector form factors from physical-mass 2+1-flavor domain-wall QCD

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Nucleon isovector form factors calculated on 2+1-flavor domain-wall fermion (DWF) numerical lattice-QCD ensemble with physical up-, down- and strange-quark mass and lattice momentum cut off of about 1.730(4) GeV will be reported.

Particle physics beyond the Standard Model / 26

Investigating the conformal behaviour of SU(2) with one adjoint Dirac flavor

Authors: Andreas Athenodorou²; Ed Bennett¹; Georg Bergner²; Biagio Lucini¹

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Motivated by recent scenarios of exotic infrared behaviour and by earlier lattice findings, we present results for the SU(2) gauge theory with one Dirac flavor in the adjoint representation. This provides a major update on our previous investigation of this theory, including data for four values of the gauge coupling β, and for smaller masses and larger volumes than previously considered. Results for the particle spectrum, topological observables, and the anomalous dimension from both hyperscaling and the Dirac mode number are presented. At the finest coupling, we observe a large mass anomalous dimension of γₘ ≈ 0.6. Our findings are analysed in relation to possible infrared
behaviours of the model. In particular, we show that our results are not compatible with a confining scenario in which chiral symmetry is broken.

**Vacuum Structure, Confinement, and Chiral Symmetry / 27**

**Reconstructing QCD Spectral Functions with Gaussian Processes**

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We reconstruct spectral functions from ghost and gluon propagators obtained through lattice QCD calculations with dynamical quarks. To this end, we employ Gaussian process regression (GPR) using kernel parametrizations that explicitly encode the analytically derived asymptotic scaling properties in the infrared and ultraviolet. The proposed ansatz allows us to consistently improve the conditioning of the inverse problem while keeping the additional bias minimal. We largely avoid common problems associated with standard methods, such as unwanted oscillations in the case of linear regression with Tikhonov regularization. Numerical results are promising and motivate the reconstruction of quark spectral functions within the same framework in order to obtain access to real-time properties of QCD.

**Hadron Spectroscopy and Interactions / 28**

**Three-particle quantization condition for nondegenerate particles**

**Author:** Stephen Sharpe\(^1\)  
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We provide the generalization of the formalism needed to relate the three-particle finite-volume spectrum to infinite-volume scattering amplitudes for the case of three nondegenerate scalar particles with arbitrary masses. The results can be expressed in a form similar to those for identical particles, except for the addition of an extra flavor index. We do so using a simplified method in which one first works in time-ordered perturbation theory, and obtains a three-particle quantization condition involving a three-particle kernel whose nine flavor-matrix entries correspond to different subclasses of diagrams. The second stage uses symmetrization identities to rewrite the quantization condition in a form with a single three-particle kernel that sums all diagrams and is Lorentz invariant. The relation of these kernels to the infinite-volume scattering amplitude is also given. A third form of the formalism, which is explicitly Lorentz invariant at every stage, is also derived using Feynman diagrams.
Finite volume corrections to forward Compton scattering off the nucleon

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The study of the Compton amplitude has gained attention in recent years. It plays a central role in the analysis of many fundamental problems such as, for example, the evaluation of the Lamb shift in muonic hydrogen, or the calculation of the proton-neutron mass difference. Hence, the calculation of this amplitude on the lattice would definitely contribute to the solution of the above problems. However, lattice results are always plagued by the finite-volume artifacts which may be sizable in some cases. In order to carry out a precise extraction of the Compton amplitude, these finite-volume corrections should be reliably estimated and removed from the lattice data.

Different approaches have been proposed so far for the extraction of the Compton amplitude on the lattice. In this talk, I shall discuss an approach based on the background field method. The calculations are done in Baryon Chiral Perturbation Theory, up-to-and-including \(O(p^4)\), where \(p\) is a small momentum/mass. Our study will be focused on the calculation of the so-called subtraction function, which is related to the Compton amplitude in a particular kinematics. In the beginning, the forward doubly virtual Compton scattering amplitude off nucleons will be evaluated, and the behavior of the subtraction function at small values of the photon momentum will be discussed. Furthermore, the full set of the finite-volume corrections to the subtraction function will be evaluated up-to-and-including \(O(p^4)\). It will be shown that, despite the poorly known low-energy constants at this order, the finite-volume artifacts can be evaluated quite accurately and do not preclude one from an accurate measurement of the subtraction function on the lattice.

Hadron Structure / 30

Leading order mesonic and baryonic SU(3) low energy constants from \(N_f = 3\) lattice QCD

Authors: Gunnar Bali\(^1\); Sara Collins\(^2\); Wolfgang Söldner\(^3\); Simon Weishäupl\(^1\)

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In the analysis of (lattice) QCD observables very often chiral perturbation theory (ChPT) is heavily used to describe the quark mass dependence or relate different observables via symmetry relations. Within ChPT the low energy constants (LECs) play a crucial role and their precise knowledge is important in lattice QCD as well as in phenomenology. While there are many lattice determinations of the LECs in SU(2) ChPT, the SU(3) LECs are less well determined.

We will present our results for the leading order mesonic \((B_0, F_0)\) and baryonic \((m_0, D, F)\) SU(3) ChPT LECs from \(N_f = 3\) flavour lattice QCD. In our study we employ a subset of the \(N_f = 2 + 1\) flavour Coordinated Lattice Simulations (CLS) gauge ensembles, denoted as the symmetric line which incorporates exact flavour symmetry, i.e., \(m_u = m_d\). The ensembles cover a range of different pion masses as well as 6 different lattice spacings and different volumes. This allows us to perform a controlled extrapolation of all LECs to the chiral, infinite volume and continuum limit.
Hadron Spectroscopy and Interactions / 31

Three-particle finite-volume formalism for $\pi^+\pi^+K^+$ and related systems

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We consider three-particle systems consisting of two identical particles and a third that is different, with all being spinless, e.g. $\pi^+\pi^+K^+$. We generalize the formalism necessary to extract two- and three-particle infinite-volume scattering amplitudes from the spectrum of such systems in finite volume. We use a relativistic formalism based on an all-orders diagrammatic analysis in generic effective field theory, adopting the methodology used recently to study the case of three nondegenerate particles. We present both a direct derivation, and also a cross-check based on an appropriate limit and projection of the fully nondegenerate formalism. Lastly, we work out the threshold expansions for the three-particle K-matrix that will be needed in practical applications, both for systems with two identical particles plus a third, and also for the fully nondegenerate theory.

QCD at nonzero Temperature and Density / 32

Persistent homology analysis for QCD effective models

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We apply the persistent homology analysis to effective models of quantum chromodynamics (QCD) with heavy quarks on a rectangular lattice to investigate the confinement-deconfinement transition. In this talk, I will concentrate on the effective Polyakov-line model and the Potts model with external field as the QCD effective model. The configurations are mapped onto the complex Polyakov-line plane without taking the spatial average and then the $\mathbb{Z}_M$ structure is analyzed. This study may have the relation with previous studies for the center clusters and the percolation properties. The spatial structure of the configurations is analyzed by using the persistent homology to obtain information of the multiscale structure of center clusters. In the confined phase, the data in the three different domains show the same topological tendency characterized by the birth and death times of the holes via the filtration of the alpha complexes, but the deconfined phase show different behavior. By considering the configuration averaged ratio of the birth and death times, we can construct the nonlocal order-parameter of the confinement-deconfinement transition based on the multiscale topological properties of center clusters.

Theoretical developments and applications beyond particle physics / 33

A physicist-friendly reformulation of the mod-two Atiyah-Patodi-Singer index

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Gauge anomaly in 4-dimensions can be viewed as a current inflow into an extra-dimension, where the total phase of the fermion partition function is given in a gauge invariant way by the Atiyah-Patodi-Singer (APS) eta-invariant of a 5-dimensional Dirac operator. However, this formalism requires a non-local boundary condition, which makes the physical roles of edge/bulk modes unclear and the causality of the total theory doubtful. In this talk, we consider a special case where the Dirac operator is in a real representation and its eta invariant becomes the mod-two type APS index. We propose a physicist-friendly reformulation of the mod-two index using domain-wall fermion formalism, which naturally describes how the global anomaly is canceled between edge and bulk.

Highly excited pure gauge SU(3) flux tubes

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Flux tube spectra are expected to have full towers of levels due to the quantization of the string vibrations. We study a spectrum of flux tubes with static quark and antiquark sources with pure gauge SU(3) lattice QCD in 3+1 dimensions up to a significant number of excitations. To go high in the spectrum, we specialize in the most symmetric case $\Sigma_{g}^{++}$, use a large set of operators, solve the generalized eigenvalue and compare different lattice QCD gauge actions and anisotropies.

Lattice QED in external electromagnetic fields

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QED in the presence of strong external fields is relevant to Laser physics, Accelerator physics, Astrophysics and Condensed Matter physics. Standard methods of relativistic quantum mechanics and QED, including perturbation theory, have their limitations. To go beyond this, approximate non-perturbative methods such as the Schwinger-Dyson approach have been applied. We are simulating Lattice QED in external electromagnetic fields, using methods developed for Lattice QCD to study non-perturbative behaviour of QED in this regime. In our first project we simulate Lattice QED in external magnetic fields using the RHMC algorithm. Later we plan to perform simulations with external electric fields and with both electric and magnetic fields. Because QED is not believed to be asymptotically complete we treat it as an effective field theory, i.e. one with a momentum cutoff.
Most charming dibaryon near unitarity

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A pair of triply charmed baryons, \( \Omega_{ccc} \), is studied as an ideal dibaryon system by (2+1)-flavor lattice QCD with nearly physical light-quark masses and the relativistic heavy quark action with the physical charm quark mass. The spatial baryon-baryon correlation is related to their scattering parameters on the basis of the HAL QCD method. The \( \Omega_{ccc} \) in the \( ^1S_0 \) channel taking into account the Coulomb repulsion with the charge form factor of \( \Omega_{ccc} \) leads to the scattering length \( a_C \approx -19 \) fm and the effective range \( r_{eff} \approx 0.45 \) fm. The ratio \( r_{eff} / a_C \approx -0.024 \), whose magnitude is considerably smaller than that of the dineutron \(( -0.149 \)) , indicates that \( \Omega_{ccc} \) is located in the unitary regime.

Machine learning with quantum field theories

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The precise equivalence between discretized Euclidean field theories and a certain class of probabilistic graphical models, namely the mathematical framework of Markov random fields, opens up the opportunity to investigate machine learning from the perspective of quantum field theory. In this talk we will demonstrate, through the Hammersley-Clifford theorem, that the \( \phi^4 \) scalar field theory on a square lattice satisfies the local Markov property and can therefore be recast as a Markov random field. We will then derive from the \( \phi^4 \) theory machine learning algorithms and neural networks which can be viewed as generalizations of conventional neural network architectures. Finally, we will conclude by presenting applications based on the minimization of an asymmetric distance between the probability distribution of the \( \phi^4 \) machine learning algorithms and that of target probability distributions.

Tetraquark channels with \( \bar{b}b \) pair in the static limit

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In 2011, Belle discovered two \( Z_b^+ \) hadrons with quark content \( \bar{b}b\bar{d}u \). Lattice study of hadrons with this quark content is challenging because they can decay to two \( B \)-mesons and also to a bottomonium.
and a light meson, leading to a large number of decay channels. We present a lattice study of the \(b\overline{b}\overline{b}u\overline{d}\) system with the static bottom quarks. Only the channel that couples to \(bb + \pi\) was explored on the lattice before — it features an attractive potential for the \(B\overline{B}^*\) and a bound state below the threshold. Our lattice study incorporates channels with other quantum numbers that have not been investigated before. Eigen-energies of the system are extracted as a function of separation between \(b\) and \(\overline{b}\) in all channels.

**Hadron Structure / 39**

**Recent Progress in Lattice Parton Distributions**

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The large-momentum effective theory (LaMET) framework has been widely used to determine the Bjorken-\(x\) dependence of PDFs in lattice-QCD hadron-structure calculations. In this talk, I will highlight selected recent lattice-QCD results from MSULat.

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**Particle physics beyond the Standard Model / 40**

**Exploring SU(3) + Higgs theories - The adjoint case**

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In GUT-like scenarios it is necessary to break the gauge group to the SM-group. This is usually achieved by adding scalars to the theory, which may introduce one or more possible breaking patterns to the theory. Additionally, a valid description of gauge-symmetry-breaking needs to be manifestly gauge-invariant, which is often neglected in standard phenomenology.

In our work we therefore study the lattice phase diagram of the simplest theory with two breaking patterns: a \(SU(3)\) gauge theory with a Higgs in the adjoint representation. This allows us to analyse possible tensions between perturbative breaking patterns and actual possible ones.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 41**

**Tensor network simulations at nonzero chemical potential and temperature**

**Authors:** Raghav Govind Jha; Maximilian Meister; Jacques Bloch; Jacques Bloch

**Co-author:** Robert Lohmayer

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We present results of tensor network simulations of the three-dimensional O(2) model at nonzero chemical potential and temperature, which were computed using the higher order tensor renormalization group method. This also includes some enhancements to the method which take care of anisotropic tensors. Some special care was also taken to reduce the systematic error on the computation of the observables.

Interpreting machine learning functions as physical observables

Authors: Gert Aarts\textsuperscript{1}; Dimitrios Bachtis\textsuperscript{Note}; Biagio Lucini\textsuperscript{1}

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We interpret machine learning functions as physical observables, opening up the possibility to apply "standard" statistical-mechanics methods to outputs from neural networks. This includes histogram reweighting and finite-size scaling, to analyse phase transitions quantitatively, as well as the incorporation of predictive functions as conjugate variables coupled to an external field within the Hamiltonian of a system, allowing to induce order-disorder phase transitions in a novel manner. A noteworthy feature of this approach is that no knowledge of the symmetries in the Hamiltonian is required.

Nucleon Charges and Sigma Terms from $N_f = 2 + 1$ QCD

Author: Daniel Jenkins\textsuperscript{1}

Co-authors: Sara Collins\textsuperscript{2}; Gunnar Bali\textsuperscript{1}

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We report on the recent progress of our analysis into nucleon sigma terms, as well as the singlet axial and tensor nucleon charges. These are extracted from the CLS gauge configurations, which utilise the Lüscher-Weisz gluon action and the Sheikholeslami-Wohlert fermion action with $N_f = 2 + 1$ fermions, with pion masses ranging from the physical value up to 410 MeV, and lattice spacings covering a range between 0.09 fm and 0.04 fm. We have employed a variety of methods to determine the necessary correlation functions, including the sequential source method for connected contributions, and the truncated solver method for disconnected contributions. Extrapolation to the physical point involves leading order discretisation, chiral, and finite-volume effects.

Toward Simulations of Scalar Quantum Electrodynamics on Quantum Computers
The gauge-invariant formulations of lattice field theories provide a way to study real-time dynamics using a smaller effective Hilbert space. This allows for more information to be encoded for the same quantum resources as a non-gauge invariant formulation which will be important for simulations on Noisy Intermediate Scale Quantum (NISQ) computers. While qubit-based hardware is currently the most widely available, it does not naturally reflect the Hilbert spaces of complicated quantum field theories. Qudits (n-state objects) provide a more natural description of the Hilbert spaces. The purely bosonic nature of Compact Scalar Quantum Electrodynamics (csQED) provides a nice test-bed for qudit based digitizations and truncations of continuous symmetries. We will discuss the methods of digitizing csQED for qudit-based quantum computers, the robustness to different types of noise balanced with accuracy of field truncations.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 45**

**Calculation of the running coupling in non-Abelian gauge theories from Jarzynski’s equality**

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We discuss the theoretical foundations of non-equilibrium Monte Carlo simulations based on Jarzynski’s equality and present, as an example of application, the determination of the running coupling in the Schrödinger-functional scheme.

**QCD at nonzero Temperature and Density / 46**

**QCD viscosity by combining the gradient flow and sparse modeling methods**

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We give a new description to obtain the shear viscosity at finite temperature. Firstly, we obtain the correlation function of the renormalized energy-momentum tensor using the gradient flow method. Secondly, we estimate the spectral function from the smeared correlation functions using the sparse modeling method. The combination of these two methods looks promising to determine the shear viscosity precisely.
QCD in searches for physics beyond the Standard Model / 47

Comparison of lattice QCD+QED predictions for radiative leptonic decays of light mesons with experimental data

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We present a comparison of existing experimental data for the radiative leptonic decays $P \rightarrow \ell\nu\gamma$, where $P = K$ or $\pi$ and $\ell = e$ or $\mu$, from the KLOE, PIBETA, E787, ISTRA+ and OKA collaborations performed in Ref. [1] using the theoretical predictions based on the recent non-perturbative determinations of the structure-dependent vector and axial-vector form factors, $F_V$ and $F_A$ respectively, obtained in Ref. [2]. These were obtained using lattice QCD+QED simulations at order $O(\alpha_{em})$ in the electromagnetic coupling.

We find good agreement with the KLOE data on $K \rightarrow e\nu\gamma$ decays from which the form factor $F^+ = F_V + F_A$ can be determined. For $K \rightarrow \mu\nu\gamma$ decays we observe differences of up to 3 - 4 standard deviations at large photon energies between the theoretical predictions and the data from the E787, ISTRA+ and OKA experiments and similar discrepancies in some kinematical regions with the PIBETA experiment on radiative pion decays.

A global study of all the kaon-decay data within the Standard Model results in a poor fit, largely because at large photon energies the KLOE and E787 data cannot be reproduced simultaneously in terms of the same form factor $F^+$. The discrepancy between the theoretical and experimental values of the form factor $F^- = F_V - F_A$ is even more pronounced. These observations motivate future improvements of both the theoretical and experimental determinations of the structure-dependent form factors $F^+$ and $F^-$, as well as further theoretical investigations of models of "new physics" which might for example, include possible flavor changing interactions beyond $V - A$ and/or non-universal corrections to the lepton couplings.


Theoretical developments and applications beyond particle physics / 49

The Semimetal-Mott Insulator Quantum Phase Transition of the Hubbard Model

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The Hubbard model is an important tool to understand the electrical properties of various materials. More specifically, on the honeycomb lattice it features a quantum phase transition from a semimetal to a Mott insulating state which falls into the Gross-Neveu universality class. In this talk I am going to explain how we confirmed said quantum phase transition by taking advantage of recent improvements in our Hybrid Monte Carlo algorithm. These improvements allowed us to simulate unprecedentedly large lattices and extract critical quantities with very high precision.

Non-perturbative bounds for the semileptonic $B \rightarrow D^{(*)}\ell\nu_\ell$ decays and phenomenological applications

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We apply a novel method to a non-perturbative determination of the hadronic form factors describing the exclusive semileptonic $B \rightarrow D^{(*)}\ell\nu_\ell$ decays. The method is based on the non-perturbative calculation of the dispersive bounds due to unitarity and analyticity, and it allows to determine in a model-independent way the form factors in the full kinematical range of the recoil, starting from existing lattice data which are available only at small recoil (including preliminary ones). We investigate the extraction of the Cabibbo-Kobayashi-Maskawa entry $|V_{cb}|$ from the experimental data on the semileptonic $B \rightarrow D^{(*)}\ell\nu_\ell$ decays, obtaining $|V_{cb}| = (40.7 \pm 1.2) \cdot 10^{-3}$ from $B \rightarrow D$ decays and $|V_{cb}| = (40.6 \pm 1.6) \cdot 10^{-3}$ from $B \rightarrow D^*$ decays. Our exclusive results are consistent within $\sim 1$ standard deviation with the most recent inclusive determination $|V_{cb}|_{incl} = (42.00 \pm 0.65) \cdot 10^{-3}$. We address also the issue of Lepton Flavor Universality thanks to new theoretical estimates of the ratios $R(D^{(*)})$, namely $R(D) = 0.289(8)$ and $R(D^*) = 0.249(21)$. Our findings differ respectively by $\sim 1.6\sigma$ and $\sim 1.8\sigma$ from the latest corresponding experimental determinations.

Flavor decomposition for the proton unpolarized, helicity and transversity parton distribution functions

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We present an ab initio calculation of the individual up, down, and strange quark unpolarized, helicity, and transversity parton distribution functions for the proton. The calculation is performed within the twisted mass clover-improved fermion formulation of lattice QCD. We use a $N_f = 2+1+1$ gauge ensemble simulated with pion mass $M_\pi = 250$ MeV, $M_\pi L \approx 3.8$ and lattice spacing $a = 0.0938$.
Momentum smearing is employed in order to improve the signal-to-noise ratio, allowing for the computation of the matrix elements up to nucleon boost momentum $P_3 = 1.24 \text{ GeV}$. The lattice matrix elements are non-perturbatively renormalized and the final results are presented in the $\overline{\text{MS}}$ scheme at a scale of 2 GeV.

**Vacuum Structure, Confinement, and Chiral Symmetry / 52**

**The flux tube profile in full QCD**

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We measure the spatial distribution of all components of the color fields surrounding a static quark–antiquark pair in QCD with (2+1) HISQ flavors. We isolate the nonperturbative component of the longitudinal chromoelectric color field responsible for the linear term in the confining potential.

**Hadron Structure / 53**

**Precision calculation of the $x$-dependence of PDFs from lattice QCD**

**Authors:** Andrew Hanlon$^1$; Nikhil Karthik$^2$; Peter Petreczky$^3$; Philipp Scior$^4$; Sergey Syritsyn$^5$; Swagato Mukherjee$^2$; Xiang Gao$^6$; Yong Zhao$^7$; Yong Zhao$^8$

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In this talk, we present a model-independent calculation of the $x$-dependence of pion valence PDF with the large-momentum effective theory approach. In this calculation we adopt the most up-to-date theoretical developments on the systematic corrections, which include the hybrid renormalization scheme that rigorously renormalizes the lattice matrix elements at both short and long distances, as well as the two-loop matching kernel that allows for direct calculation of the $x$-dependence of the PDF without any model assumption. Therefore, we are able to make predictions for the PDF at $x \in [x_{\text{min}}, x_{\text{max}}]$ where the systematic uncertainties are under control, which is a firm step towards the stage of precision calculation.
Hadron Structure / 54

Structure-Dependent Electromagnetic Finite-Size Effects

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In this talk we present a relativistic and model-independent method to analytically derive electromagnetic finite-size effects beyond the point-like approximation. Structure-dependence appears in terms of physical form-factors and derivatives thereof. The values of these physical quantities can be taken either from experimental measurements or auxiliary lattice calculations. We apply our method to derive the leading structure-dependence in the meson mass, i.e. at order \(1/L^3\), and compare to that obtained from non-relativistic effective field theory techniques. In addition, we determine the coefficient of the \(1/L^2\)-term in leptonic decays of pions and kaons. The knowledge of the latter allows for improved numerical control in extractions of the relevant CKM-matrix elements from lattice QCD+QED.

Theoretical developments and applications beyond particle physics / 55

Chiral fermion on curved domain-wall

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We consider a massive fermion system having a curved domain-wall embedded in a square lattice. As already reported in condensed matter physics, the massless chiral edge modes appearing at the domain-wall feel ”gravity” through the induced spin connections.

In this work, we embed \(S^1\) and \(S^2\) domain-wall into Euclidean space and show how the gravity is detected from the spectrum of the Dirac operator. We also discuss how we can understand gravitational anomaly inflow and index theorem with nontrivial curvature of the domain-wall.

Poster / 56

A4: Towards the determination of sigma terms for the baryon octet in \(N_f = 2 + 1\) QCD with Wilson quarks

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A lot of progress has been made in the determination of nucleon sigma terms. In this work we consider the sigma terms of the other octet baryons as well. These are determined on CLS gauge field ensembles employing the Lüscher-Weisz gluon action and the Sheikholeslami-Wohlert fermion action with $N_f = 2 + 1$. The ensembles have pion masses ranging from 410 MeV down to the physical value and lattice spacings covering a range between 0.09 fm and 0.04 fm. We present some preliminary results for $a \approx 0.06$ fm along a trajectory where the sum of the sea quark masses is kept constant, focusing on the quark mass dependence. We discuss multi-state fits to tackle the well-known problem of excited state contamination and detail how we analyse connected and disconnected contributions.

Proton decay amplitudes at the physical point with chirally symmetric quarks

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Proton decay is a long-sought manifestation of baryon number violation predicted by Grand Unification and expected due to baryon asymmetry of the Universe. Amplitudes of such decay in various channels depend on proton structure determined by nonperturbative QCD dynamics and have to be determined on a lattice. We report results of a recent calculation of these amplitudes using chirally symmetric quark action at the physical pion mass. While our lattices relatively coarse (a=0.2 and 0.14 fm), we don’t observe any significant lattice spacing dependence.

Imprint of chiral symmetry restoration on the Polyakov loop and the heavy quark free energy

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The Polyakov loop expectation value $\langle P \rangle$ is an order parameter of the deconfinement transition in the heavy quark mass regime, whereas its sensitivity to the deconfinement of light, dynamical quarks is not apparent. From the perspective of an effective Lagrangian in the vicinity of the chiral transition, the Polyakov loop, $P$, is an energy-like observable, and $\langle P \rangle$ should hence scale like the energy density. Using $N_f = 2 + 1$ HISQ configurations at finite lattice spacing, we show that near the chiral transition temperature, the scaling behavior of $\langle P \rangle$ and the heavy quark free energy $F_q$ is
consistent with energy-like observables in the $3d, O(N)$ universality class. We extend this analysis to other energy-like observables, including the response of $F_q$ to the baryon chemical potential, which is expected to scale like a specific heat.

**Poster / 59**

**A10: Precision bottomonium properties and b quark mass from lattice QCD+QED**

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We will discuss the determination of the properties of heavyonium mesons in lattice QCD + quenched QED, using the HISQ action on gluon field configurations that include $2+1+1$ flavours of sea quarks and with lattice spacing values going down to 0.03 fm. Results include values for the bottomonium hyperfine splitting and Upsilon and eta_b decay constants, for comparison to our earlier results for the properties of charmonium from lattice QCD+QED. We also determine the ratio of the masses of b and c quarks in the MSbar scheme at 3 GeV, including QED contributions. Using our earlier result for c quark mass in QCD+QED, this enables a new 0.5\% accurate determination of the b quark mass.

Results have appeared in: 2101.08103 and 2102.09609

**Hadron Spectroscopy and Interactions / 60**

**ππ scattering at large $N_c$**

**Author:** Jorge Baeza-Ballesteros$^1$

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In this work we study the large $N_c$ scaling of pion-pion scattering lengths for $N_f = 4$ degenerate quark flavours. We focus on the standard isospin-2 channel and the adjoint-antisymmetric representation, which is unique for $N_f \geq 4$. We compare the results obtained for two regularisations (Wilson and Twisted-Mass) and three values of the lattice spacing, and observe significant discretisation effects in the AA channel. Finally, we compare our results to NLO SU(4) and NNLO U(4) Chiral Perturbation Theory and study the $N_c$ scaling of the relevant low-energy couplings.

**QCD at nonzero Temperature and Density / 61**

**Symmetries of temporal correlators and the nature of hot QCD.**
The 38th International Symposium on Lattice Field Theory / Book of Abstracts

Authors: Leonid Glozman\textsuperscript{1}\textsuperscript{,} Yasunichi Aoki\textsuperscript{1}; Shoji Hashimoto\textsuperscript{2}; Christian Rohrhofer\textsuperscript{3}

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We report results on symmetries of temporal correlators above $T_c$ obtained within the $N_F = 2$ QCD with the chirally symmetric Dirac operator at physical quark masses. We observe both $U(1)_{A}$ and $SU(2)_L \times SU(2)_R$ chiral symmetries as well as the chiral spin symmetry $SU(2)_{CS}$, which is a symmetry of the color charge and of the electric interaction. Emergence of the latter symmetry suggests that above $T_c$ but below roughly $3T_c$ the color charge is not yet screened and degrees of freedom are the chirally symmetric quarks bound by the electric field into the color singlet objects.

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$V_{cs}$ determination from $D \to K\ell\nu$

Authors: William Parrott\textsuperscript{1}; Christine Davies\textsuperscript{1}; Jonna Koponen\textsuperscript{1}; Peter Lepage\textsuperscript{2}; Bipasha Chakraborty\textsuperscript{3}; Chris Bouchard\textsuperscript{4}

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Semileptonic $D \to K\ell\nu$ decays provide one angle of attack to get at the CKM matrix element $V_{cs}$, complementary to the study of leptonic $D_s$ decays. Here HPQCD present the results of an improved determination of $V_{cs}$, recently released on the arXiv (2104.09883).

We discuss a new, precise determination of $D \to K$ scalar and vector form factors from a lattice calculation on eight different $N_f = 2+1+1$ gluon field ensembles using the HISQ action, including three with physical light quark masses. When combined with experimental results, we are able to extract $|V_{cs}| = 0.9663(80)$ to a sub percent level of precision for the first time. This is achieved using three different methods, which each combine our form factors with different sets of experimental results in different ways, with the results in very good agreement. Our primary method is to use $q^2$ binned data for the differential decay rate, but we also calculate $V_{cs}$ from the total branching fraction and from the value $|V_{cs}| f_+(0)$, which is also measured experimentally.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 65

Improved topological sampling for lattice gauge theories
Standard sampling algorithms for lattice QCD suffer from topology freezing (or critical slowing down) when approaching the continuum limit, thus leading to poor sampling of the distinct topological sectors. I will present a modified Hamiltonian Monte Carlo (HMC) algorithm that triggers topological sector jumps during the assembly of Markov chain of lattice configurations. We study its performance in the 2D Schwinger model and compare it to alternative methods, such as fixing topology or master field. We then discuss the difficulties of the algorithm in a SU(2) gauge model in 4D.

**Determination of the masses of hybrid charmonium mesons**

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There are several unexplained resonances in the charmonium sector. To this end we present a study of the masses and decay constants of the lightest multiplet of charmonium-like hybrid mesons. We obtain precise measurements through the use of a variational basis and a large number of configurations at three lattice spacings. We use staggered fermion operators and our configurations are generated using the HISQ action with 2+1+1 dynamical flavours. The mixing of the vector hybrid with the $J/\Psi$ is examined and bounds on the vector hybrid decay constant are presented.

**Investigating $N \to N\pi$ axial matrix elements**

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Excited state contamination is one of the most challenging sources of systematics to tackle in the determination of nucleon matrix elements and form factors. The signal-to-noise problem prevents one from considering large source-sink time separations. Instead, state-of-the-art analyses consider multi-state fits. Excited state contributions to the correlation functions are particularly significant in the axial channel. In this work, we confront the problem directly. Since the major source of contamination is understood to be related to pion production, we consider 3-point correlators with a $N$ operator at the source and a $N\pi$ interpolating operator at the sink.
which allows studies of $N \rightarrow N\pi$ matrix elements. After discussing the challenges that arise when using a 2-particle interpolating operator, like the projection onto the proper irreducible representation and on the isospin components, we present results of $N \rightarrow N\pi$ processes, mediated by an axial current, on an $m_{\pi} \approx 420\text{MeV}$ ensemble.

**Theoretical developments and applications beyond particle physics / 68**

**Anomalies and symmetric mass generation for staggered fermions**

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I discuss symmetric mass generation (SMG) and its relevance to the problem of constructing lattice chiral fermions. A necessary condition for SMG is the cancellation of certain discrete anomalies which constrain the number of fermions to multiples of sixteen. I give some examples of models based on reduced staggered fermions that are capable of SMG.

**Particle physics beyond the Standard Model / 69**

**Interglueball potential in lattice SU(N) gauge theories**

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The dynamics of the glueballs is important in the context of their experimental search as well as for understanding non-Abelian theories. The glueballs of the dark SU(N) Yang-Mills theory are also good candidates of the dark matter [1,2].

The low energy effective Lagrangian of the $0^{++}$ glueball may be determined from the interglueball potential calculated on lattice. In this talk, we report on the result of the lattice calculations of the interglueball potential of the Yang-Mills theory with the color numbers $N=2,3,4$, with a detailed inspection of the systematics due to the discretization.


**Hadron Structure / 70**

**Nucleon-pion-state contamination in lattice computations of the nucleon electromagnetic form factors**

**Authors:** Oliver Baer; Haris Colic

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The nucleon-pion-state contribution to QCD two-point and three-point functions relevant for lattice calculations of the nucleon electromagnetic form factors are studied in chiral perturbation theory. To leading order the results depend on a few experimentally known low-energy constants only, and the nucleon-pion-state contribution to the form factors can be estimated. The nucleon-pion-state contribution to the electric form factor $G_E(Q^2)$ is at the +5 percent level for a source-sink separation of 2 fm, and it increases with increasing momentum transfer $Q^2$. For the magnetic form factor the nucleon-pion-state contribution leads to an underestimation of $G_M(Q^2)$ by about 5 percent that decreases with increasing $Q^2$. For smaller source-sink separations that are accessible in present-day lattice simulations the impact is larger, although the ChPT results may not be applicable for such small time separations. Still, a comparison with lattice data at $t \approx 1.6$ fm works reasonably well.

Decay amplitudes to three hadrons from finite-volume matrix elements

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In this talk, I will review our recent generalization of the Lellouch-Lüscher to study decays to three particles. First, the result in a simplified theory with three identical particles will be presented, and then the generalizations needed to study phenomenologically relevant three-pion decays will be discussed. Specific processes for which this formalism is applicable are the CP-violating $K \to 3\pi$ weak decay, the isospin-breaking $\eta \to 3\pi$ QCD transition, and the electromagnetic $\gamma^* \to 3\pi$ amplitudes that enter the calculation of the hadronic vacuum polarization contribution to muonic $g - 2$.

PDF in PDFs from Lattice Formulation

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Parton degrees of freedom (PDF) are classified in the Euclidean path-integral formulation of the hadronic tensor in QCD. They include the valence and connected sea partons, the connected sea antipartons, and the disconnected sea partons and antiprotons. These degrees of freedom are shown to be the same as those from the quasi-PDF, pseudo-PDF and lattice cross section approaches on the lattice.

It is advocated that the connected sea and the disconnected sea should be separated in the global analysis of the PDFs. This allows a direct comparison of moments of PDF with the individual lattice matrix elements for the u, d, and s partons in the connected and disconnected insertions respectively.
In view of the above classification in QCD, the separation of the connected and disconnected sea partons is accommodated with the CT18 parametrization of the global analysis of the parton distribution functions (PDFs). This is achieved with the help of the distinct small $x$ behaviors of these two sea partons and the constraint from the lattice calculation of the ratio of the strange momentum fraction to that of the $\bar{u}$ or $\bar{d}$ in the disconnected insertion.

**QCD at nonzero Temperature and Density / 73**

**Quark Density in Lattice QC$_2$D at Imaginary and Real Chemical Potential**

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Two-color QCD (QC$_2$D) with two flavors of staggered fermions is studied at imaginary and real quark chemical potential $\mu_q$ and $T > T_c$. Various methods of analytic continuation of the quark number density from imaginary to real quark chemical potentials $\mu_q$ are considered on the basis of the numerical results for imaginary $\mu_q$. At $T < T_{RW}$ we find that the cluster expansion model provides rather good analytic continuation. Its relation to the canonical formalism is discussed. At $T > T_{RW}$ we see that the analytic continuation to the real values of $\mu_q$ based on trigonometric functions works equally well with the conventional method based on the Taylor expansion in powers of $\mu_q$.

**Particle physics beyond the Standard Model / 74**

**Dilaton chiral perturbation theory and applications**

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We review dilaton chiral perturbation theory (dChPT), the low-energy theory for the light sector of near-conformal, confining theories. dChPT accounts for the pions and the light scalar, and provides a systematic expansion in both the fermion mass and the distance to the conformal window. Unlike ChPT, dChPT predicts a large-mass regime in which the theory exhibits hyperscaling, while the expansion nevertheless remains systematic. We discuss applications to lattice data, presenting successes as well as directions for future work.

**Theoretical developments and applications beyond particle physics / 75**
Tensor renormalization group approach to (1+1)-dimensional Hubbard model

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We investigate the metal-insulator transition of the (1+1)-dimensional Hubbard model in the path-integral formalism with the tensor renormalization group method. The critical chemical potential $\mu_c$ and the critical exponent $\nu$ are determined from the $\mu$ dependence of the electron density in the thermodynamic and zero-temperature limit. Our results for $\mu_c$ and $\nu$ show consistency with the exact solution based on the Bethe ansatz. Our encouraging results indicate the applicability of the tensor renormalization group method to the analysis of higher-dimensional Hubbard models.

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Monopoles of the Dirac type and color confinement in QCD

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When non-Abelian gauge fields in $SU(3)$ QCD have a line-singularity leading to non-commutability with respect to successive partial-derivative operations, the non-Abelian Bianchi identity is violated. The violation as an operator is shown to be equivalent to violation of the Abelian-like Bianchi identities. Then there appear eight Abelian-like conserved magnetic monopoles of the Dirac type in $SU(3)$ QCD. Using lattice Monte-Carlo simulations, perfect Abelian and monopole dominances are shown to exist without introducing additional smoothing techniques like partial gauge fixings when we define lattice Abelian-like monopoles following the DeGrand-Toussaint method adopted in the study of the Dirac monopole in lattice compact QED. As reported separately, the Abelian dual Meissner effect around a pair of static quark and antiquark is caused by the solenoidal Abelian monopole current.

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Results for $\alpha_s$ from the decoupling strategy

**Authors:** Mattia Dallabrida; Roman Höllwieser; Tomasz Korzec; Francesco Knechtli; Alberto Ramos Martinez; Stefan Sint; Rainer Sommer

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5 DESY
We present analysis details and new results for the strong coupling $\alpha_s(m_Z)$, determined by the decoupling strategy detailed in the previous talk. Starting from a line of constant physics (LCP) from previous ALPHA Collaboration work, we simulate $N_f = 3$ massless quarks to measure a set of renormalization and improvement constants which allow us to determine the simulation parameters for the LCP at non-zero mass. Then massive simulations were performed at different $z=LM$ and $L/a$ in order to measure the gradient flow couplings and extrapolate them to the continuum. The massive couplings are matched to effective couplings in pure gauge. Using the running in the pure gauge theory and the perturbative relation of the Lambda parameters, the Lambda parameter of the three flavor theory is obtained by an extrapolation to infinite M. Our final result is compatible both with the FLAG average and with the previous ALPHA result, albeit with a slightly smaller, yet still statistics dominated, error. This constitutes a highly non-trivial check, as the decoupling strategy is conceptually very different from the 3-flavor QCD step-scaling method, and so are most of its systematic errors. These include the uncertainties of the decoupling and continuum limits, which we discuss in some detail. Furthermore, by relying on decoupling once again, we could estimate the small $O(a)$ and $O(1/M)$ contaminations to the massive GF coupling stemming from the SF boundaries by means of pure gauge simulations.

**Poster / 78**

**B1: What is chiral susceptibility probing?**

**Authors:** Hidenori Fukaya$^1$; Sinya Aoki$^2$; Yasumichi Aoki$^3$; Shoji Hashimoto$^4$; Christian Rohrhofer$^5$; Kei Suzuki$^6$

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In the early days of QCD, the axial $U(1)$ anomaly was considered to trigger the breaking of the $SU(2)_L \times SU(2)_R$ symmetry through topological excitations of gluon fields. However, it has been a challenge for lattice QCD to quantify the effect. In this work, we simulate QCD at high temperatures with the overlap Dirac operator. The exact chiral symmetry enables us to separate the axial $U(1)$ breaking effect from others among the susceptibilities in the scalar and pseudoscalar channels. Our result in two-flavor QCD indicates that the chiral susceptibility, which is conventionally used as a probe for $SU(2)_L \times SU(2)_R$ breaking, is actually dominated by the axial $U(1)$ anomaly at temperatures $T \geq 190$ MeV. This talk is based on our recent paper arXiv:2103.05954.

**Plenary / 79**

**A physicist-friendly reformulation of the Atiyah-Patodi-Singer index (on a lattice)**

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The Atiyah-Singer (AS) index theorem on a closed manifold is well understood and appreciated in physics. On the other hand, the Atiyah-Patodi-Singer (APS) index, which is an extension to a manifold with boundary, is physicist-unfriendly, in that it is formulated with a nonlocal boundary condition. Recently we (3 physicists and 3 mathematicians) proved that the same index as APS is obtained from the domain-wall fermion Dirac operator. Our theorem indicates that the index can be expressed without any nonlocal conditions, in such a physicist-friendly way that application to the lattice gauge theory is straightforward. The domain-wall fermion provides a natural mathematical foundation for understanding the bulk-edge correspondence of the anomaly inflow.

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**HAL QCD potentials with non-zero total momentum and an application to the \( I = 2 \pi \pi \) scattering**

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We propose a method to extract the HAL QCD potential from correlation functions with non-zero total momentum (boosted system). After brief explanation of the formulation with non-zero total momentum \((P)\), we apply it to the \( I = 2 \pi \pi \) system. Using 2+1 flavor PACS-CS configurations at \( m_{\pi} = 700 \text{MeV} \) and \( a = 0.09 \text{fm} \) on \( 32^3 \times 64 \) lattice, we calculate the \( I = 2 \pi \pi \) potential with \( P = 2\pi / L \) and \( 4\pi / L \) as well as \( P = 0 \) (center of mass frame). We show that potentials from all 3 cases agree well within statistical errors, which are however larger for larger \( P \).

Not only scattering phase shifts obtained from these potentials agree well but they also agree with scattering phase shifts obtained from finite volume energy spectra through L"uscher’s formula. This shows that the HAL QCD potential method works well even with non-zero total momentum. We briefly discuss future applications of the method to hadron interactions.

Theoretical developments and applications beyond particle physics / 81

**Large \( \mathcal{N} \) simulation of the twisted reduced matrix model with an adjoint Majorana fermion**

**Authors:** Pietro Butti\(^1\); Margarita Garcia Perez\(^2\); Antonio Gonzalez-Arroyo\(^1\); Ken-Ichi Ishikawa\(^3\); Masanori Okawa\(^3\)

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To investigate the properties of the large \( N \) limit of \( \mathcal{N} = 1 \) SUSY Yang-Mills theory, we have started a feasibility study for a reduced matrix model with an adjoint Majorana fermion. The gauge action is based on the Wilson action and the adjoint-fermion is the Wilson-Dirac action on a reduced lattice with twisted gauge boundary condition. We employ the RHMC algorithm in which the absolute value of the Pfaffian is incorporated. The sign of the Pfaffian is involved with the re-weighting method and separately measured as an observable. In this talk, we show the configuration generation status towards the large \( \mathcal{N} \) limit and the behavior of the lowest/lower eigenvalue(s) of the Wilson-Dirac fermion operator.
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Finite temperature QCD with physical $(u/d, s, c)$ domain-wall quarks

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I outline the simulation of lattice QCD with $N_f = 2 + 1 + 1$ optimal domain-wall quarks at the physical point, on the $64^4 \times (6, 8, 10, 12, 16, 20)$ lattices, for three lattice spacings $a \sim 0.064 - 0.075$ fm. The quark masses and lattice spacings are determined at the zero temperature on the $64^4$ lattice. The topological susceptibility of each gauge ensemble is measured by the Wilson flow. In this talk, I present the topological susceptibility $\chi_t(a, T)$ of these gauge ensembles for temperature $T \sim 150 - 520$ MeV, and also obtain $\chi_t(T)$ in the continuum limit.

Particle physics beyond the Standard Model / 83

Isospin breaking for dark matter

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In various theories of strongly-interacting dark matter non-degenerate flavors play an important role to satisfy constraints like relic abundance. To quantify the impact we investigate a candidate theory, Sp(4) gauge theory with two fundamental flavors. At the relevant quark mass scales we find interesting patterns in the pseudoscalar and vector channel, which mix behavior from chiral and non-chiral origins. This paves the way for testing such a scenario quantitatively in a phenomenological setting.

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Nonperturbative excitations in overoccupied gluon plasmas

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Motivated by the early-time dynamics of the quark-gluon plasma in high-energy heavy-ion collisions, we extract gluonic spectral functions of overoccupied gauge theories far from equilibrium using classical-statistical lattice simulations. In 3+1 dimensions we find that the spectral function exhibits quasiparticle excitations at all momenta that are mostly consistent with perturbative hard-thermal loop predictions, while partially showing nonperturbative deviations. In contrast, the structure of excitations in 2+1 dimensions is nontrivial and nonperturbative. These nonperturbative interactions lead to broad excitation peaks in the spectral function, demonstrating the absence of soft quasiparticles in these theories.
Using classical bit-flip correction for error mitigation in quantum computations

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We demonstrate that classical bit-flip correction can be employed to mitigate measurement errors on quantum computers. Importantly, our method can be applied to any operator, any number of qubits, and any realistic bit-flip probability. Starting with the example of the longitudinal Ising model, we then generalize to arbitrary operators and test our method both numerically and experimentally on IBM quantum hardware. As a result, our correction method reduces the measurement error on the quantum hardware by up to one order of magnitude.

Isoscalar electromagnetic form factors of the nucleon in $N_f = 2+1$ lattice QCD

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We present results for the isoscalar electromagnetic form factors of the nucleon computed on the CLS ensembles with $N_f = 2 + 1$ flavors of $O(a)$-improved Wilson fermions and an $O(a)$-improved conserved vector current. In order to estimate the excited-state contamination, we investigate several source-sink separations and apply the summation method. For the computation of the quark-disconnected diagrams, a stochastic estimation using the one-end trick is employed. By these means, we obtain a clear signal for the form factors including the quark-disconnected contributions, which have a distinguishable effect on our data.
Highly oscillatory path integrals are common in lattice field theory. They crop up as sign problems and as signal to noise problems and prevent Monte Carlo calculations of both lattice QCD at finite chemical potential and real-time dynamics. A general method for treating highly oscillatory path integrals has emerged in which the domain of integration of the path integral is deformed into a complexified field space. In this talk I will review this method, and I will discuss recent progress in machine learning manifolds for lattice QCD.

Lattice QCD calculation of the electroweak box diagrams for the kaon semileptonic decays

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We present a lattice QCD calculation of the axial $\gamma W$-box diagrams relevant for the kaon semileptonic decays. We utilize a recently proposed method, which connects the electroweak radiative corrections in Sirlin’s representation to that in chiral perturbation theory. It allows us to use the axial $\gamma W$-box correction in the SU(3) limit to obtain the low energy constants for chiral perturbation theory. From first principles our results confirm the previously used low energy constants provided by the minimal resonance model with a significant reduction in uncertainties.

Three pion interactions from the lattice

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Much of the resonant spectrum of QCD consists of states which decay strongly into two- and three-body final states. Lattice QCD calculations have matured to the stage where these states can be reliably resolved in first principles numerical calculations. While connecting these finite-volume results to infinite-volume scattering is now commonplace in the two-body sector, three-body physics presents more difficulties.

On the back of the significant progress made in connecting three-body scattering in infinite-volume to finite-volume states, the first determinations of three-body interactions from lattice QCD have recently begun to appear. Building on success in the two-pion sector, I will present our recent lattice QCD calculations of three-pion systems in maximal isospin, with a focus on a recent extraction of the $3\pi^+$ three-body force, and a comparison to other determinations.
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E1: Effective $Z_3$ model for finite density QCD with tensor networks

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The tensor renormalization group is a promising numerical method used to study lattice statistical field theories. However, this approach has been prohibitively expensive in 2+1 and 3+1 dimensions until recently. Here we use relatively new tensor renormalization group methods to study an effective three-dimensional $Z_3$ model for the heavy-quark, high-temperature, strong-coupling limit of single-flavor 3+1 dimensional quantum chromodynamics. Our results are cross-checked using worm Monte Carlo. We present the phase diagram of the model through the measurement of the Polyakov loop, the nearest-neighbor Polyakov loop correlator, and their susceptibilities. The tensor renormalization group results are in good agreement with the literature.

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Computing hybrid static potentials at short quark-antiquark separations from fine lattices in SU(3) Yang-Mills theory

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We compute hybrid static potentials in SU(3) Yang-Mills theory at short quark-antiquark separations using four different small lattice spacings as small as 0.04 fm. The resulting static potentials are important e.g. when computing masses of heavy hybrid mesons in the Born-Oppenheimer approximation. We also discuss and exclude possible systematic errors from topological freezing, the finite lattice volume and glueball decays.

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$\bar{b} \bar{c} q_1 q_2$ tetraquarks from Lattice QCD

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We present the results of a lattice calculation of tetraquark states with quark contents $\bar{b} \bar{c} q_1 q_2$, $q_1, q_2 \subset u, d, s$ in both spin zero ($J = 0$) and spin one ($J = 1$) sectors. For the spin one states, when the light quark ($q_1, q_2$) masses are lighter, we find at least one energy level below the possible thresholds energy levels. These calculations are performed on three dynamical $N_f = 2+1+1$ highly improved...
staggered quark ensembles at lattice spacings of about 0.12, 0.09 and 0.06 fm. We use the overlap action for light to charm quarks while a non-relativistic action with non-perturbatively improved coefficients is employed for the bottom quark.

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\( \mathcal{PT} \) symmetry and patterns in finite-density QCD

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We study the phase structure of effective models of finite-density QCD using analytic and lattice simulation techniques developed for the study of non-Hermitian and \( \mathcal{PT} \)-symmetric QFTs. Finite-density QCD is symmetric under the combined operation of the charge and complex conjugation operators \( \mathcal{C}\mathcal{K} \), which falls into the class of so-called generalized \( \mathcal{PT} \) symmetries. We show that \( \mathcal{PT} \)-symmetric quantum field theories can support patterned ground-state field configurations in the vicinity of a critical endpoint. We apply our methods to a lattice heavy quark model at nonzero chemical potential that displays patterning behavior for a range of parameters. We derive a simple approximate criterion for the formation of these patterns, which can be used with lattice results.

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Towards a Calculation of the Nucleon Axial Form factor with Highly Improved Staggered Quarks

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In this talk, I will report our group’s progress on calculating the nucleon axial form factor with the HISQ action for both valence and sea quarks. Nucleon matrix elements with staggered fermions require careful analysis of the staggered symmetry group. I will report a solution based on the generalized Wigner-Eckart theorem that enables us to extract physical observables from staggered observables. I will present published results for nucleon axial and vector charges and preliminary results on the form factors to demonstrate the feasibility of our methodology.
Search for Efficient Formulations of non-Abelian Lattice Gauge Theories for Hamiltonian Simulation

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Hamiltonian formulation of lattice gauge theories provides the natural framework for the purpose of quantum simulation, an area of research that is growing with advances in quantum-computing algorithms and hardware. It is therefore important to identify the most accurate, while computationally economic, Hamiltonian formulation(s) of lattice gauge theories along with necessary truncation imposed on the Hilbert space of gauge bosons for any finite computing resources. We report a study toward addressing this question in the case of non-Abelian lattice gauge theories that require the imposition of non-Abelian Gauss’s laws on the Hilbert space.

Investigating quark confinement from the viewpoint of lattice gauge scalar models

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Lattice gauge scalar models allow analytical connection between confinement region and Higgs region for gauge invariant operators. Combining the cluster expansion and the duality, we try to understand non-trivial contribution from scalar field in quark confinement mechanism. In order to understand quark confinement further, moreover, we study double-winding Wilson loop averages in the analytical region on the phase diagram.

Emergent phenomena from centre vortices in lattice QCD

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We review some highlights of the centre vortex research programme conducted by the CSSM in SU(3) lattice gauge theory. Starting from the original Monte Carlo gauge fields, a vortex identification procedure yields vortex-removed and vortex-only backgrounds. The original, vortex-removed, and vortex-only ensembles are compared by examining a number of different quantities. The removal of
vortices consistently results in the removal of the corresponding feature associated with confinement or dynamical chiral symmetry breaking. Remarkably, we observe that after some smoothing, the vortex-only degrees of freedom are able to encapsulate the pertinent features of the original gauge fields.

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The ’t Hooft-Veneziano limit of the Polyakov loop models

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The broad class of U(N) and SU(N) Polyakov loop models on the lattice are solved exactly in the combined large N, Nf limit, where N is a number of colors and Nf is a number of quark flavors, and in any dimension. In this ’t Hooft-Veneziano limit the ratio N/Nf is kept fixed. We calculate both the free energy and various correlation functions. The critical behavior of the models is described in details at finite temperatures and non-zero baryon chemical potential. Furthermore, we prove that the calculation of the N-point (baryon) correlation function reduces to the geometric median problem in the confinement phase. In the deconfinement phase we establish an existence of the complex masses and an oscillating decay of correlations in a certain region of parameters.

H-dibaryon away from the $SU(3)_f$ symmetric point

Authors: Padmanath Madanagopalan¹; John Bulava²; Jeremy Green³; Andrew Hanlon⁴; Ben Hoerz⁵; Parikshit Junnarkar⁶; Colin Morningstar⁷; Srijit Paul⁸; Andre Walker-Loud⁹; Hartmut Wittig⁰

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We present the current status of our ongoing efforts in search of the H-dibaryon on $N_f = 2 + 1$ CLS ensembles away from the SU(3) flavor symmetric point. Utilizing the distillation framework (also known as LapH) in its exact and stochastic forms, we calculate two-point correlation matrices using large bases of bi-local two-baryon interpolators to reliably determine the low energy spectra. We report the low lying spectrum on several relevant lattice irreducible representations for multiple
ensembles with different lattice spacing and physical volumes. The status of finite volume analysis to extract the scattering amplitudes will also be discussed.

**Vacuum Structure, Confinement, and Chiral Symmetry / 100**

**Finite temperature and delta-regime in the Schwinger model**

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The Schwinger model is often used as a testbed for conceptual and numerical approaches in lattice field theory. Nevertheless, some of the rich physical properties of the model in anisotropic volumes have not yet been tested. For the multi-flavor finite temperature Schwinger model there is an approximate solution by Hosotani et al. based on bosonization. We perform thorough comparisons with the lattice results and check the validity and limitations of the Hosotani approach. By inverting the physical interpretation of the coordinates we explore the delta-regime and measure the dependence of the pion mass on the spatial size at zero temperature. Our results confirm universal features of theoretical predictions by Leutwyler, Hasenfratz and Niedermayer and enable the computation of the Schwinger model counterpart of pion decay constant. This is further compared with the 2d version of the Witten-Veneziano formula.

**Theoretical developments and applications beyond particle physics / 101**

**Study of a lattice 2-group gauge model**

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In this talk, I discuss a simple model based on the symmetry group \(Z_2\) belonging to the class of 2-group gauge systems. Particular limits of such systems correspond to certain types of topological quantum field theories. In the selected model, independent degrees of freedom are associated to both links and faces of a four-dimensional lattice and are subject to a certain constraint. I present the details of this construction, discuss the expected dynamics in different regions of phase space and show numerical results from Monte Carlo simulations confirming these expectations.

**QCD at nonzero Temperature and Density / 102**

**Charting the scaling region of the Ising universality class in finite temperature QCD**
We discuss the behaviour of a universal combination of susceptibility and correlation length in the Ising model in two and three dimensions, in presence of both magnetic and thermal perturbations, in the neighbourhood of the critical point. In three dimensions we address the problem using a parametric representation of the equation of state. In two dimensions we make use of the exact integrability of the model along the thermal and the magnetic axes. Our results can be used as a sort of “reference frame” to chart the critical region of the model.

While our results can be applied in principle to any possible realization of the Ising universality class, we address in particular, as specific examples, instances of Ising behaviour in finite temperature QCD related in various ways to the deconfinement transition. Most notably, we study the critical ending point in the finite density, finite temperature phase diagram of QCD. In this finite density framework, due to well know sign problem, Montecarlo simulations are not possible and thus a direct comparison of experimental results with QFT/Statmech predictions like the one we discuss may be important. Moreover in this example it is particularly difficult to disentangle “magnetic-like” from “thermal-like” observables and thus an explicit charting of the neighbourhood of the critical point can be particularly useful.

The gradient flow at higher orders in perturbation theory

Author: Robert Valentin Harlander

We describe the systematic treatment of the gradient flow at higher orders in perturbation theory and its application within the small flow-time expansion. The results include the coefficients of the gradient-flow definition of the energy-momentum tensor, the quark and the gluon condensates, as well as the hadronic vacuum polarization at next-to-next-to-leading order in the strong coupling. Combined with suitable lattice calculations, these results allow for independent approaches to various phenomenological problems of low-energy QCD.
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We present a new method aiming at a non-perturbative, model-independent determination of the momentum dependence of the form factors entering hadronic semileptonic decays using unitarity and analyticity constraints. We extend the original proposal of Ref. [1] and, using suitable two-point functions computed non-perturbatively, we determine the form factors at low-momentum transfer $q^2$ from those computed explicitly on the lattice at large $q^2$, without making any assumption about their $q^2$ dependence. As a training ground we apply the new method to the analysis of the lattice data of the semileptonic $D \to K\ell\nu$ decays obtained in Ref. [2] both at finite values of the lattice spacing and at the physical pion point in the continuum limit. We show that, starting from a limited set of data at large $q^2$ it is possible to determine quite precisely the form factors in a model independent way in the full kinematical range, obtaining a remarkable agreement with the direct calculation of the form factors of Ref. [2]. This finding opens the possibility to obtain non-perturbatively the form factors entering the semileptonic $B$ decays in their full kinematical range.

References

Particle physics beyond the Standard Model / 105

Spectral reconstruction in SU(4) gauge theory with fermions in multiple representations

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The naturalness problem in the Higgs sector finds a popular solution in composite Higgs models. In such theories the Higgs boson emerges as the pseudo-Nambu-Goldstone boson associated with the breaking of a global symmetry realised in a new, strongly interacting sector. In this talk we address a model arising in this context and well motivated by phenomenological arguments, a SU(4) gauge theory with fermions in two distinct representations. We present a novel lattice study of this theory, in which we address the non-perturbative reconstruction of spectral densities from lattice correlators.

Vacuum Structure, Confinement, and Chiral Symmetry / 106

On the behaviour of the interquark potential in the vicinity of the deconfinement transition.

Author: Michele Caselle1

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We show that in the vicinity of the deconfinement transition the behaviour of the interquark potential in pure lattice gauge theories can be precisely predicted combining results from Conformal Field Theory, Effective String Theory and Integrable Models. We compare these predictions with simulations of the SU(2) gauge model both in (2+1) and in (3+1) dimensions.

Doubly bottom Tetraquarks

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We investigate doubly heavy tetraquarks with quark structure \(\bar{Q}Q'qq'\) in full lattice QCD using the NRQCD formalism for bottom quarks. We focus mainly on bound states in systems with two heavy antiquarks \(\bar{b}\bar{b}\) and \(\bar{b}c\) in the present of light quarks \(q \in \{u,d,s\}\).

Continuum limit of baryon-baryon scattering with SU(3) flavor symmetry

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A calculation of baryon-baryon scattering via finite-volume spectroscopy using distillation will be reported. Ensembles with SU(3) flavor symmetry and a pion/kaon/eta mass of roughly 420 MeV, covering a wide range of lattice spacings, are employed. For the first time, we take the continuum limit, finding large discretization effects. In the singlet sector, we obtain a weakly bound \(H_{\text{dibaryon}}\).

Validation of the Lüscher method on the lattice

**Author:** Frank Lee\(^1\)

**Co-authors:** Andrei Alexandru\(^2\); Ruairí Brett\(^1\)
The L"{u}sch method for two-particle scattering is a critical tool for connecting finite-volume spectrum to infinite-volume scattering phaseshifts. We numerically validate the quantization conditions up to partial waves \( l=4 \). Various setups used in practice are considered: cubic or elongated lattices, rest or moving frames, unequal or equal masses, and integer or half-integer total angular momentum.

**QCD in searches for physics beyond the Standard Model / 110**

**Leading isospin breaking effects in the HVP contribution to \( \alpha_\mu \) and to the running of \( \alpha \)**

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The anomalous magnetic moment of the muon \( \alpha_\mu \) and the running of the electromagnetic coupling \( \alpha \) play a fundamental role in beyond Standard Model (SM) physics searches. Non-perturbative hadronic contributions to both quantities, which are related to the hadronic vacuum polarization (HVP) function consisting of two electromagnetic currents, are a main source of uncertainty in the SM prediction. We compute the HVP function in lattice QCD+QED applying the time-momentum representation method. We expand the relevant correlation functions around the isosymmetric limit. In particular, we focus on leading isospin breaking effects taking connected contributions into account, which we evaluate on isosymmetric \( N_f = 2 + 1 \) QCD gauge ensembles generated by the CLS initiative with non-perturbatively \( O(\alpha) \)-improved Wilson fermions.

**QCD at nonzero Temperature and Density / 111**

**Lattice QCD in strong magnetic background**

**Authors:** Alfredo Stanzione\(^1\); Francesco Sanfilippo\(^2\); Lorenzo Maio\(^1\); Marco Cardinali\(^3\); Massimo D’Elia\(^1\)

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In this work we study the properties of \( N_f = 2 + 1 \) QCD in the presence of a constant background magnetic field, up to unexplored large values of \( eB \), by means of lattice Monte Carlo simulations. We investigate the string tension and its asymmetry via the study of the static quark-antiquark potential and of the color flux tube. Moreover, we present preliminary results regarding the QCD phase diagram in this regime.

**Hadron Spectroscopy and Interactions / 112**
Parameters of the a1(1260) resonance from lattice QCD

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We present the first determination of the universal parameters of the a1(1260) from QCD. This consists of three steps presented in the talk:

1. Lattice QCD calculation including three-meson operators;
2. Generalization of three-body quantization condition including sub-systems with spin and coupled channels;
3. Analytic continuation of the infinite-volume amplitude and determination of the pole positions and branching ratios. Some comparison to phenomenology will be discussed as well.

QCD at nonzero Temperature and Density / 113

Lattice QCD equation of state at finite chemical potential from an alternative expansion scheme

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Taylor expansion of the equation of state of QCD suffer from shortcomings at chemical potentials \(\mu_B > (2−2.5)T\). First, one faces difficulties inherent in performing such an expansion with a limited number of coefficients; second, higher order coefficients determined from lattice calculations suffer from a poor signal-to-noise ratio.

We present a novel scheme for extrapolating the equation of state of QCD to finite, real chemical potential that can extend its reach further than previous methods.

We show continuum extrapolated lattice results for the new expansion coefficients and for the thermodynamic observables up to \(\mu_B/T \approx 3.5\).

Theoretical developments and applications beyond particle physics / 114

Scale-setting of volume-reduced twisted Eguchi-Kawai model with one adjoint Majorana fermion at large-\(N\)

Authors: Antonio Gonzalez-Arroyo\(^1\); Ken-Ichi Ishikawa\(^4\); Margarita Garcia-Perez\(^1\); Masanori Okawa\(^1\); Pietro Butti\(^3\)

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The 38th International Symposium on Lattice Field Theory / Book of Abstracts

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$\mathcal{N}=1$ SUSY Yang-Mills theory is an appealing theoretical framework that has been studied in the literature using different methods, including standard lattice simulations. Among these, the volume-reduced twisted Eguchi-Kawai model, endowed with one adjoint Majorana fermion, could play an important role in studying its large-$N$ limit via the Curci-Veneziano prescription. In this talk, we present our results on the analysis of the scale of the theory, performed via different methods based on purely gluonic observables as well as (quenched) fundamental mesons in the chiral limit. These lattice results will be used as a scale setting for the analysis of the spectrum of the theory.

Standard Model Parameters / 115

Investigation of the Perturbative Expansion of Heavy Quark Correlators for $N_f = 0$

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The QCD-coupling is a necessary input in the computation of many observables, and the parametric error on input parameters can be a dominant source of uncertainty. The coupling can be extracted by comparing high order perturbative computations and lattice evaluated moments of mesonic two-point functions with heavy quarks, which provide a high energy scale for perturbation theory. The truncation of the perturbative series is an important systematic uncertainty.

We study this issue by measuring pseudo-scalar two-point functions in volumes of $L = 2$ fm with twisted-mass Wilson fermions in the quenched approximation.

We use full twist, the non-perturbative clover term and lattice spacings down to $a = 0.015$ fm to tame the sizable discretization effects. Our preliminary results indicate that higher order perturbative corrections lead to $\sim 10\%$ deviations of the extracted Lambda parameter from its asymptotic value when the quark mass is around $1.5 \, m_{\text{charm}}$.

QCD at nonzero Temperature and Density / 116

An exploration of sphaleron rate in lattice QCD

Authors: Anna-Lena Lorenz; Hai-Tao Shu; Hauke Sandmeyer; Heng-Tong Ding; Hiroshi Ohno; Olaf Kaczmarek; Rasmus Larsen; Swagato Mukherjee

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2 Central China Normal University
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4 University of Bielefeld
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In this talk we show our lattice QCD calculations for the sphaleron rate (the Minkowski rate for topological charge diffusion). It is determined by modeling the spectral function encoded in the Euclidean topological-charge-density two-point function. The Euclidean correlation functions are measured under gradient flow to reduce noise with improved operators which can more accurately measure topology. The calculations are carried out on large, fine lattices in the quenched approximation at $1.5 T_c$. With these data we first perform a continuum extrapolation at fixed physical flow time and then extrapolate the continuum estimates to zero flow time. The extrapolated correlators are then used to study the sphaleron rate by spectral reconstruction based on perturbatively motivated models.

Quirks of QCD: Twist-2 Operators on the Lattice

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When using deep inelastic scattering (DIS) to probe hadronic structure, we can use the operator product expansion to approximate the product of currents, using the operators' twist to suppress higher order effects. On the lattice, these operators experience power divergent mixing, which we aim to control by introducing the gradient flow. We study an example in perturbation theory.

Charged Pion Electric Polarizability from Lattice QCD

Authors: Hossein Niyazi\textsuperscript{1}; Andrei Alexandru\textsuperscript{1}; Frank X. Lee\textsuperscript{2}

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Electric and magnetic polarizabilities are two of the fundamental properties of hadrons which help us understand the distribution of charge and currents inside hadrons and how they respond to external electromagnetic fields. For nucleons, these values are determined experimentally from Compton scattering. For charged pions, the experiments are more challenging since no free pion target is available and the results are less precise, but a number of experiments are planned that will improve the accuracy. Lattice QCD can be used to compute hadron properties as determined by quark and gluon dynamics, providing results that are complementary to other theoretical approaches. In this talk I will review the lattice QCD methods used to compute hadron polarizabilities, focusing on electric polarizability of charged pion, and present our results.
Authors: Zhouyou Fan\textsuperscript{None}; Huey-Wen Lin\textsuperscript{None}

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We present the first determination of the $x$-dependent pion gluon distribution from lattice QCD using the pseudo-PDF approach, on lattice ensembles with 2+1+1 flavors of highly improved staggered quarks (HISQ), generated by MILC Collaboration. We use clover fermions for the valence action and momentum smearing to achieve pion boost momentum up to 2.29~GeV on two lattice spacings $a \approx 0.12$ and 0.15~fm and three pion masses $M_\pi \approx 220, 310$ and 690~MeV. We compare our pion and preliminary nucleon gluon results with the determination by global fits.

Theoretical developments and applications beyond particle physics / 120

Euclidean representation of unconstraint ”Majorana spins”

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The euclidean representation of a newly proposed spin system, which is equivalent to a single Majorana fermion in 2+1 dimensions, is derived. The unconstrained euclidean system reveals a mild sign problem which is quantitatively studied. Implementing constraints without breaking positivity will be shortly outlined.

Theoretical developments and applications beyond particle physics / 121

Vector fields and RG flows in 4 dimensions

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The 1-loop RG flows in the most general local, renormalizable, Euclidean, classically scale invariant and globally SU(N) invariant theory of vector fields is computed. The total number of dimensionless couplings is 7 and several asymptotically free RG flows are found which are not gauge theories but nonetheless perfectly well-defined Euclidean QFT’s. The set of couplings is extended to 9 with the most general globally SU(N) invariant ghost couplings and Yang-Mills theory is shown to emerge on a particular RG flow. Several marginal gauge symmetry breaking deformations of Yang-Mills theory are also found.

QCD at nonzero Temperature and Density / 122

Funny business from the large $N_c$ finite temperature crossover

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It’s well known that the deconfinement transition temperature for $SU(N_c)$ gauge theory is almost independent of $N_c$, and the transition is first order for $N_c \geq 3$. In the real world ($N_c = 3$, light quarks) it is a crossover located far away from the pure gauge value. What happens if you keep the number of fermion flavors fixed ($N_f = 2$) and vary the fermion mass and $N_c$? There are multiple plausible stories, only one of which appears to be true when the systems are simulated on the lattice. There might be consequences for other simple stories people tell about confinement, chiral symmetry breaking, and the quark model.

Theoretical developments and applications beyond particle physics / 123

**Exact gradient flow and saddle points in lattice fermion models**

**Authors:** Savvas Zafeiropoulos$^*$; Christopher Winterowd$^1$; Maksim Ulybyshev$^*$

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We describe new theoretical opportunities arising from the possibility to solve the gradient flow (GF) equations taking into account the fermion determinant exactly employing non-iterative solvers. Using this exact GF we can find real saddle points of the lattice action at zero chemical potential and trace their evolution in complex space at non-zero chemical potential. We show that these saddle points correspond to modified instantons, where the back reaction from the fermion determinant is taken into account already at the level of the Euclidean field equations. We demonstrate how this approach leads to the rigorous numerical procedure for the definition of the inter-instanton interactions and give examples of interaction profiles computed in this way.

We show two possible applications of this technique. First of all, the knowledge of the saddle points can help us to simplify the structure of the Lefschetz thimbles decomposition and to alleviate the sign problem. The second application is the systematic building of a statistical model of interacting instantons from first principles without need of any phenomenological input.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 125

**A novel method to evaluate real-time path integral for scalar phi^4 theory**

**Author:** SHINJI TAKEDA$^1$

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We present a novel method to evaluate the real-time path integral for 1+1 dimensional real scalar phi$^4$ theory. The method can be combined with tensor network coarse-graining schemes. As a demonstration we will show numerical results of two-point correlator in a small lattice.

QCD in searches for physics beyond the Standard Model / 126

**Controlling unwanted exponentials in lattice calculations of radiative leptonic decays**
The 38th International Symposium on Lattice Field Theory / Book of Abstracts

**Authors:** Christopher Kane¹; Davide Giusti²; Christoph Lehner³; Stefan Meinel¹; AMARJIT Soni⁴

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Two important sources of systematic errors in lattice QCD calculations of radiative leptonic decays are unwanted exponentials in the sum over intermediate states and unwanted excited states created by the meson interpolating field. Performing the calculation using a 3d sequential propagator allows for better control over the systematic uncertainties from intermediate states, while using a 4d sequential propagator allows for better control over the systematic uncertainties from excited states. We calculate form factors using both methods and compare how reliably each controls these systematic errors. We also employ a hybrid approach involving global fits to data from both methods. I will present our results comparing these methods for both heavy and light mesons.

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**Hadron Structure / 127**

### Strange and charm contributions to nucleon charges and moments

**Authors:** Rui Zhang¹; Tanmoy Bhattacharya²; Rajan Gupta³; Huey-Wen Lin⁴; Santanu Mondal⁵; Sungwoo Park⁶; Boram Yoon⁷

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We present preliminary lattice calculations of strange and charm contributions to nucleon charges and moments. The scalar charge, axial charge, tensor charge, and unpolarized first moments are calculated on five clover-on-HISQ lattices covering three lattice spacings \( a = \{0.06, 0.09, 0.12\} \text{ fm} \) and three pion masses \( M_\pi = \{310, 220, 130\} \text{ MeV} \). We renormalize the matrix elements with non-perturbative renormalization factors then apply chiral and continuum extrapolation to obtain results in the physical limit.

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**QCD in searches for physics beyond the Standard Model / 128**

### Calculation of kaon semileptonic form factor with the PACS10 configurations

**Authors:** Takeshi Yamazaki⁸; Ken-Ichi Ishikawa¹; Naruhito Ishizuka²; Yoshinobu Kuramashi²; Yoshifumi Nakamura⁹; Yusuke Namekawa¹; Yusuke Taniguchi⁶; Naoya Ukita⁸; Tomoteru Yoshie²

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We present preliminary results for the kaon semileptonic form factors using one of the PACS10 configuration sets, whose physical volume is $(10.2 \text{ fm})^4$ at the physical point with the lattice spacing of 0.064 fm. The configuration was generated using the Iwasaki gauge action and $N_f = 2 + 1$ stout-smeared clover quark action. The value of $|V_{us}|$ is determined using the interpolated result of the form factors to the zero momentum transfer. Our value of $|V_{us}|$ is compared with a prediction of the standard model from the unitarity triangle and recent lattice results. We also show a preliminary result of $|V_{us}|$ in the continuum limit obtained from analysis using the preliminary result of 0.064 fm combined with our previous result at the coarser lattice spacing of 0.085 fm.

Vacuum Structure, Confinement, and Chiral Symmetry / 129

Construction of a non-relativistic quark-diquark model from LQCD

Authors: Kai Watanabe\(^1\); Noriyoshi Ishii\(^2\)

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A novel method is proposed to determine the quark-diquark potential together with quark and diquark masses in the framework of Lattice Quantum Chromo Dynamics (LQCD). Treating a baryon as a quark-diquark bound state, we construct the corresponding two-body potential from the equal-time quark-diquark Nambu-Bethe-Salpeter (NBS) wave function by demanding it to satisfy the Schroedinger equation. In so doing, the quark and diquark masses in the kinetic term of the Schroedinger equation must be determined self-consistently since their direct measurement is hampered by the color confinement. We determine the mass by demanding the p-wave excitation energy obtained from the Schroedinger equation to be equal to that obtained from the two-point correlator. After examining that the formalism gives results consistent with those of the prior works in the $\bar{c}c$ sectors, we consider the $\Lambda_c$ baryon sector to obtain the diquark mass and the quark-diquark potential. Numerical calculations are performed on a $32^3 \times 64$ lattice with a cutoff of $a \approx 0.0907$ [fm] with the pion mass of $m_\pi \approx 700$[MeV] generated by PACS-CS Collaboration. The charm quark mass in this work is $m_c = 1.771(48)$ [GeV] and the diquark mass is $m_D = 1.220(45)$ [GeV]. The latter lies above the naive estimations such as the $\rho$ meson mass $M_\rho = 1.098(5)$ [GeV] and two-third of the nucleon mass $2m_N/3 = 1.049(12)$ [GeV].

QCD at nonzero Temperature and Density / 130

Conjecture about the QCD Phase Diagram

Authors: Wolfgang Bietenholz\(^1\); José Antonio García Hernández\(^2\); Edgar López Contreras\(^2\); Elias Natnael Polanco Eúan\(^2\)

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We present a phase diagram study of the O(4) model as an effective theory for 2-flavor QCD. Both theories perform spontaneous symmetry breaking with isomorphic groups, which suggests that they belong to the same universality class. Since we are interested...
in high temperature, we further assume dimensional reduction
the 3d O(4) model, which implies topological sectors.
As conjectured by Skyrme and others, this topological charge
represents the baryon number. Hence the baryon chemical
potential $\mu_B$ appears as an imaginary vacuum angle, which can
be included in the lattice simulation without any sign problem.
We present numerical results for the critical line in the chiral
limit, and for the cross-over in the presence of light quark masses.
The shapes of these lines are compatible with other predictions, but
up to about $\mu_B = 300$ MeV we did not find a Critical Endpoint,
although there are indications that it could be near-by.

Poster / 131

B2: Latent heat and pressure gap at the first-order deconfining
phase transition of SU(3) Yang–Mills theory using the small flow-
time expansion method

Authors: Kazuyuki Kanaya$^1$; Mizuki Shirogane$^2$; Shinji Ejiri$^1$; Ryo IWAMI$^2$; Masakiyo Kitazawa$^4$; Hiroshi Suzuki$^3$;
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We study latent heat and the pressure gap between the hot and cold phases at the first-order de-
confining phase transition temperature of the SU(3) Yang–Mills theory. Performing simulations on
lattices with various spatial volumes and lattice spacings, we calculate the gaps of the energy density
and pressure using the small flow-time expansion (SFtX) method. We find that the latent heat $\epsilon$ in
the continuum limit is $\epsilon/T^4 = 1.117 \pm 0.040$ for the aspect ratio $N_s/N_t = 8$ and $1.349 \pm 0.038$ for
$N_s/N_t = 6$ at the transition temperature $T = T_c$. We also confirm that the pressure gap is consis-
tent with zero, as expected from the dynamical balance of two phases at $T_c$. From hysteresis curves
of the energy density near $T_c$, we show that the energy density in the (metastable) deconfined phase
is sensitive to the spatial volume, while that in the confined phase is insensitive. Furthermore, we
examine the effect of alternative procedures in the SFtX method—the order of the continuum and the
vanishing flow-time extrapolations, and also the renormalization scale and higher-order corrections
in the matching coefficients. We confirm that the final results are all very consistent with each other
for these alternatives.

Glueballs, localization and thermal monopoles in trace-deformed
Yang-Mills theory.

Authors: Marco Cardinali$^1$; Andreas Athenodorou$^2$; Claudio Bonati$^1$; Massimo D’Elia$^4$; Matteo Giordano$^3$; Fabrizio
Mazziotti$^4$

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In this talk I will present lattice results regarding the glueball spectrum, the localization of Dirac eigenmodes and thermal monopoles properties in trace-deformed YM theory. Trace deformation is an extra piece added to the usual YM action, which stabilizes center symmetry also in the limit of small compactification length. The study of trace-deformation could give a deep insight on the relation between non-perturbative properties and the realization of center symmetry, as well as a theoretical playground to study the properties of YM theory in a space with a compactified dimension. The glueball spectrum is studied in the limit of small compactification length, when center symmetry is recovered due to trace-deformation. The localization of Dirac eigenmodes and the behavior of thermal monopoles, instead, is studied across the re-confinement phase transition, in order to understand if this quantities have a similar behavior of the one observed in the usual deconfinement phase transition.

Particle physics beyond the Standard Model / 133

Testing dilaton potentials for near conformal gauge theories

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In the context of possible dilaton behavior in near conformal gauge theories, it has recently been proposed that a parametrized potential \(V_{\Delta}\), interpolating between two limiting forms, might effectively describe the light particle spectrum. We tested two models, namely SU(3) gauge theory with \(N_f = 8\) fermions in the fundamental rep or \(N_f = 2\) fermions in the sextet rep, against this hypothesis. The data are found to be consistent with the \(V_{\Delta}\) potential across a broad parametrization range, in contrast to claims by other groups that the \(N_f = 8\) model prefers one limit over the other.

Particle physics beyond the Standard Model / 134

SU(2) gauge theory with \(N_f=2\) fundamental fermions - a template for Composite Higgs models

Author: Vincent Drach\(^1\)

Co-authors: Fernando Romero-López; Patrick Fritzsch; Antonio Rago\(^1\)

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We investigate a UV completion of a pseudo-Goldstone Composite Higgs model based on a SU(2) gauge theory with two fundamental flavours of Dirac fermions. The model is based on the SU(4) to Sp(4) chiral symmetry breaking pattern and can be view as a minimal template to explore the phenomenological signatures of Composite Higgs models. To characterize the model, lattice calculations are used to fix some of the low energy parameters that enter into the effective description of
processes at energies explored by current accelerators. The scattering processes of Goldstone bosons are of particular interest, due to their sensitivity to the vector and scalar resonances of the strongly interacting sector. In this talk, we present our latest results concerning the scattering of Goldstone bosons in the scalar channel.

Software development and Machines / 135

Multigrid solver on Fugaku

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We report an implementation of a multigrid solver on supercomputer Fugaku, which uses A64FX cpu with Arm architecture. On Fugaku, a highly optimized BiCGStab solver with domain decomposed preconditionor for Clover fermion, called QCD Wide Simd library (QWS), is available. Multigrid solvers are made from several components so that one can use a part of QWS such as Clover kernel. As the original QWS has a strong constraint on the local lattice volume due to the usage of vector variable, we also use its reimplementation with flexible local volume extension. The code is developed by using Bridge++ code framework and its extension.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 136

Dimensional Expressivity Analysis for Parametric Quantum Circuits

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In this talk, we will be looking at quantum circuits comprising parametric gates and analyze their expressivity in terms of the space of states that can be generated by a given circuit. In particular, we will be considering parametric quantum circuits (PQCs) for use in variational quantum simulations (VQS). In such a setting, the design of PQCs is subject to two competing drivers. On one hand, the set of states, that can be generated by the PQC, has to be large enough to contain the solution state. Otherwise, we may at best find the best approximation of the solution restricted to the states generated by the chosen PQC. On the other hand, the PQC should contain as few parametric quantum gates as possible to minimize noise from the quantum device. In other words, when designing a PQC we want to ensure that there are no redundant parameters.

In order to address these counteracting effects, I will introduce the notion of dimensional expressivity analysis. The main objective here is to identify independent and redundant parameters in the PQC. Using this information, superfluous parameters can be removed and the dimension of the space of states that are generated by the PQC computed. Knowing the dimension of the physical state space as well, allows us to deduce whether or not the PQC can reach all physical states.
In this talk, we will first discuss the mathematical ideas underpinning the parameter identification. Furthermore, we will discuss how to implement the dimensional expressivity analysis using a hybrid quantum-classical algorithm. This implementation has relatively small overhead costs both for the classical and quantum part of the algorithm and could therefore be used in the future for on-the-fly circuit construction, i.e., allowing for optimized circuits to be used in every loop of a VQS rather than the same PQC for the entire VQS.

**Hadron Structure / 137**

**Decomposition of the proton spin from lattice QCD**

**Author:** Kyriakos Hadjiyiannakou

**Co-authors:** Constantia Alexandrou; Simone Bacchio; Martha Constantinou; Jacob Finkenrath; Karl Jansen; Giannis Koutsou; Haris Panagopoulos; Gregoris Spanoudes

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The origin of the proton spin has attracted a lot of attention since the first surprising result from the European Muon Collaboration about 30 years ago. We present a significant step towards solving the proton spin puzzle. The calculation is done using $N_f = 2 + 1 + 1$ twisted mass fermions directly at the physical point. Both gluon and quark contributions to the proton spin are evaluated, where the latter are computed in high precision for both valence and sea quarks. The renormalization is performed non-perturbatively taking into account the mixing between the gluon and quark operators. We will present results for the up, down, strange and charm quark momentum fractions, intrinsic spin, angular momentum, and orbital angular momentum as well as the gluon contributions.

**QCD at nonzero Temperature and Density / 138**

**Heavy quark momentum diffusion from the lattice using gradient flow**

**Author:** Luis Altenkort

**Co-authors:** Lukas Mazur; Hai-Tao Shu; Olaf Kaczmarek; Alexander Maximilian Eller; Guy D. Moore

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Heavy quark transport coefficients calculated from first-principles QCD are a crucial input for transport models. Utilizing the heavy quark limit, we will discuss the results of a novel approach to non-perturbatively estimate the heavy quark diffusion coefficient in a hot gluonic medium from gradient-flowed color-electric correlators on the lattice. Unlike others, this approach can be extended to a medium with dynamical fermions. The correlation functions are computed on fine isotropic lattices at $1.5 T_c$ and are extrapolated to yield continuum data at zero flow time that is fully renormalized. Through theoretically well-established model fits we estimate the corresponding spectral function and in turn the diffusion coefficient, which is consistent with previous studies.
Critical behavior towards the chiral limit at vanishing and non-vanishing chemical potentials

**Author:** Mugdha Sarkar

**Co-authors:** Anirban Lahiri; Christian Schmidt; Frithjof Karsch; Olaf Kaczmarek; Philipp Scior; Sheng-Tai Li

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We study the scaling behavior of the (2+1)-QCD crossover region towards the chiral limit with smaller-than-physical light quark mass gauge ensembles, generated using the HISQ fermion discretisation. We calculate the leading curvature coefficient of the QCD crossover line at smaller light quark masses and compare it with the curvature in the chiral limit obtained using scaling arguments. At zero chemical potential, we study the fluctuations of conserved charges and their correlations with the chiral condensate and chiral susceptibility, towards the chiral limit. We analyse the role of universal and regular contributions to the above quantities.

Charm physics with a tmQCD valence action

**Author:** Alessandro Conigli

**Co-authors:** Carlos Pena Ruano; Gregorio Herdoiza; Andrea Bussone; Jose Angel Romero Jurado; David Preti; Julien Frison; Javier Ugarrio

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We report on our ongoing determination of the charm quark mass and the masses and decay constants of various charmed mesons, obtained within a mixed-action setup. We employ $N_f = 2 + 1$ CLS ensembles combined with a Wilson twisted mass valence action that eliminates the leading $O(a)$ effects from our target observables. Alongside our preliminary results, we will discuss an exploration of GEVP techniques aimed at optimizing the precision in view of the extension of the computation to heavier quark masses.
To facilitate future efficient calculation of the connected and disconnected parts of the vector-vector correlator and other observables in QCD+QED with $C^*$ boundary conditions, dilution and distillation noise reduction techniques were implemented into the OpenQxD program. To find the low-lying eigenmodes of the gauge-covariant Laplacian that form the distillation sub-space, the PRIMME eigensolver was embedded into the package. I will present the dependence of the efficiency of the calculation on the dilution and distillation parameters.

Neutron electric dipole moment using lattice QCD simulations at the physical point

Authors: Andreas Athenodorou$^1$; Antonino Todaro$^1$; Constantia Alexandrou$^1$; Kyriakos Hadjiyiannakou$^2$

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We will present results on the neutron electric dipole moment $|\vec{d}_N|$ using an ensemble of $N_f = 2 + 1 + 1$ twisted mass clover-improved fermions with lattice spacing of $a \simeq 0.08$ fm and physical pion mass $(m_\pi \simeq 139$ MeV). The approach followed in this work is to compute the $CP$-odd electromagnetic form factor $F_3(Q^2 \rightarrow 0)$ by expanding the action to leading order in $\theta$. This gives rise to correlation functions that involve the topological charge, for which we employ a fermionic definition by means of spectral projectors. We include a comparison between the results using the fermionic and the gluonic definition where for the latter we employ the gradient flow. We show that using spectral projectors leads to half the statistical uncertainty on the evaluation of $F_3(0)$. Using the fermionic definition, we find a value of $|\vec{d}_N| = 0.0009(24) \theta e \cdot$ fm.

The torelon spectrum and the world-sheet axion

Authors: Andreas Athenodorou$^1$; Michael Teper$^2$

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We present a major update on the spectrum of the closed flux-tube in $D = 3 + 1$ $SU(N)$ gauge theories. Namely, we calculate the excitation spectrum of a confining flux-tube which winds around a spatial torus as a function of its length $l$, for short as well as long tubes. We do so for $N = 3, 5, 6$ and two different values of the lattice spacing. Our states are characterised by the quantum numbers of spin $J$, transverse parity $P_\perp$, longitudinal parity $P_\parallel$ as well as by the longitudinal momentum $p_\parallel$. Our extended basis of operators used in combination with the generalized eigenvalue method enables us to extract masses for all irreducible representations characterised by $\{J, P_\perp, P_\parallel\}$. 

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We confirm that most of the low-lying states are well described by the spectrum of the Goddard–Goldstone–Rebbi–Thorn string. In addition we provide strong evidence, that in addition to string like states, massive modes exist on the bulk. More precisely the ground state with quantum numbers $J^P_{\perp}P_{\parallel} = 0^{-+}$ exhibits a behaviour which is in agreement with the interpretation of being an axion on the worldsheet of the flux-tube. This state arises from a topological interaction term included in the effective world-sheet action. In addition we observe that the second excited state with $J^P_{\perp}P_{\parallel} = 0^{++}$ behaves as a massive mode with mass twice that of the axion.

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B3: Flux tube profiles in two-color QCD at low temperature and high density

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We investigate the temperature and density dependence of the color flux tube structure of dense two-color QCD with $N_f=2$ Wilson fermions by using a lattice simulation. From Refs. [1] and [2], we have already clarified the rich phase structure in the low temperature region, including the hadronic and superfluid phases. In this study we measure the quark-antiquark potential and color flux tube profiles in such a low temperature region and find that even in the high density superfluid phase, the color electric field is squeezed into a flux tube as in the low density hadronic phase.

Reference

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 146

A variance reduction technique for hadronic correlators with partially twisted boundary conditions

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Partially twisted boundary conditions are widely used for improving the momentum resolution in lattice computations of hadronic correlation functions. The method is however expensive since every additional twist requires computing additional propagators. We propose a novel variance reduction technique that exploits statistical correlations between correlators at different twists to reduce the overall cost for computing correlators with additional twist angles. We explain and demonstrate the method for meson 2pt and 3pt functions.

Hadron Structure / 147

On the axial-vector form factor of the nucleon and chiral symmetry
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We consider the chiral Lagrangian with nucleon, isobar, and pion degrees of freedom. The baryon masses and the axial-vector form factor of the nucleon are derived at the one-loop level. We explore the impact of using on-shell baryon masses in the loop expressions. As compared to results from conventional chiral perturbation theory we find significant differences. An application to QCD lattice data is presented. We perform a global fit to the available lattice data sets for the baryon masses and the nucleon axial-vector form factor, and determine the low-energy constants relevant at N³LO for the baryon masses and at N²LO for the form factor. Partial finite-volume effects are considered. We point out that the use of on-shell masses in the loops results in non-analytic behavior of the baryon masses and the form factor as function of the pion mass, which becomes prominent for larger lattice volumes than presently used.

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**D4: Grid on QPACE 4**

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In 2020 we deployed QPACE 4, which features 64 Fujitsu A64FX model FX700 CPUs interconnected by InfiniBand EDR. QPACE 4 runs an open-source software stack. For LQCD simulations we ported the Grid LQCD framework to support the Arm Scalable Vector Extension (SVE). In this contribution we discuss our SVE port of Grid, the status of SVE compilers and the performance of Grid. We also present the benefits of an alternative data layout of complex numbers for the Domain Wall operator.

**QCD at nonzero Temperature and Density / 149**

**Lattice study of the confinement/deconfinement transition in rotating gluodynamics**

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This report is devoted to the study of the influence of relativistic rotation on the confinement/deconfinement transition in gluodynamics within lattice simulation. We perform the simulation in the reference frame which rotates with the system under investigation, where rotation is reduced to external gravitational field. To investigate the confinement/deconfinement transition the Polyakov loop and its susceptibility are calculated for various lattice parameters and the values of angular velocities which are characteristic for heavy-ion collision experiments. Different types of boundary conditions (open, periodic, Dirichlet) are imposed in directions, orthogonal to rotation axis. Our data for the critical temperature are well described by a simple quadratic function $T_c(\Omega)/T_c(0) = 1 + C_2\Omega^2$ with $C_2 > 0$ for all boundary conditions and all lattice parameters used in the simulations. From this
we conclude that the critical temperature of the confinement/deconfinement transition in gluodynamics increases with increasing angular velocity. This conclusion does not depend on the boundary conditions used in our study and we believe that this is universal property of gluodynamics.

QCD at nonzero Temperature and Density / 150

Flavor number dependence of QCD at finite density by the complex Langevin method

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Co-authors: Yuhma Asano; Yuta Ito; Takashi Kaneko; Hideo Matsufuru; Jun Nishimura; Asato Tsuchiya; Shoichiro Tsutsui; Takeru Yokota

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We discuss the flavor number dependence of QCD at finite density by using the complex Langevin method. In our previous works, the complex Langevin method is confirmed to satisfy the criterion for correct convergence in some regions, such as $\mu/T = 5.2 - 7.2$ on $8^3 \times 16$ and $\mu/T = 1.6 - 9.6$ on $16^3 \times 32$ using $N_f = 4$ staggered quarks at $\beta = 5.7$. We extend this study to more realistic flavor cases, $N_f = 2, 2+1, 3$, using Wilson quarks. $N_f$ dependence of physical observables as well as validity regions of the complex Langevin method is presented.

QCD at nonzero Temperature and Density / 151

Roberge-Weiss transitions at imaginary isospin chemical potential

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At finite imaginary values of the chemical potential, QCD is free of the sign problem. Moreover, at high temperatures the partition function exhibits a new symmetry (the Roberge-Weiss symmetry) connecting phases with different orientations of the Polyakov loop, and the corresponding phase transitions between these. In this contribution we investigate the perturbative one-loop effective potential for the Polyakov loop in the presence of imaginary isospin as well as baryon chemical potentials. This leads to a novel phase diagram, which reveals an interesting insight about the rich phase structure and the center symmetry breaking. We check the perturbative results using direct lattice simulations.
The lower moments of nucleon structure functions in lattice QCD with physical quark masses

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Co-authors: Yasumichi Aoki; Ken-Ichi Ishikawa; Yoshinobu Kuramashi; Shoichi Sasaki; Eigo Shintani; Takeshi Yamazaki

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We will present the current status of nucleon structure studies with physical light quarks ($m_{\pi} = 135$ MeV) in a large spatial extent of about 10 fm. Our calculations are carried out with the PACS10 gauge configurations generated by the PACS Collaboration with the stout-smeared O(a) improved Wilson fermions and Iwasaki gauge action at $\beta = 1.82$ corresponding to the lattice spacing of 0.084 fm. In this talk, we mainly focus on the lower moments of nucleon structure functions that are known as quark momentum and helicity fractions respectively, which are regarded as benchmark on lattice calculations of parton distribution functions. In addition, we will present the preliminary results with another PACS10 ensemble generated at finer lattice spacing.

Zero temperature phase diagram of a 3-D four-fermion model with two flavors of staggered fermions

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We study a strongly interacting lattice field theory model with two massless flavors of staggered fermions in three space-time dimensions. We consider the phase diagram of the model as a function of two couplings: (1) a lattice current-current interaction $U$, and (2) an on-site four-fermion interaction $U'$. While individually both these interactions drive second order phase transitions from the massless fermion phase as the couplings are increased (see Phys. Rev.D 88 (2013) 021701, and Phys. Rev.D 91 (2015) 6, 065035), the coupling $U'$ leads to an exotic strong coupling phase where fermions become massive without bilinear chiral condensates. This suggests a rich phase structure in the $U - U'$ plane. In order to study this phase diagram, we construct an efficient fermion bag algorithm by extending the previous algorithms. We show preliminary results from our study on small lattices.
We provide a first study of Mellin moments of double parton distributions (DPDs) in the nucleon on the lattice, where we consider several combinations of quark flavors and polarizations. These are accessible through two-current correlations, which can be obtained by evaluating four-point functions. In this context we consider all possible Wick contractions, where for almost all of them sufficiently clear signals are obtained. In the present study, we employ an $n_f = 2 + 1$ CLS ensemble on a $96^3$ lattice with lattice spacing $a = 0.0856$ fm and the pseudoscalar masses $m_{\pi} = 355$ MeV and $m_K = 441$ MeV.

Renormalisation of the 3D SU(N) scalar energy-momentum tensor using the Wilson flow

**Author:** Joseph Lee

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In the holographic approach to cosmology, cosmological observables are described in terms of correlators of a three-dimensional boundary quantum field theory. As a concrete model, we study the 3D massless SU(N) scalar matrix field theory with a $\phi^4$ interaction. On the lattice, the energy-momentum tensor (EMT) in this theory can mix with the operator $\phi^2$. We utilise the Wilson Flow to renormalise the EMT on the lattice, and present numerical results for the mixing coefficient for $N=2$. Obtaining the renormalised EMT will allow us to make predictions for the CMB power spectra in the regime where the dual QFT is non-perturbative.

$K\pi$ scattering at physical pion mass using distillation

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Finite-volume scattering at physical pion mass is still an exploratory field in lattice QCD. This generally involves the extraction of excited states through multi-particle correlators on systems with resonances. In that context, distillation has demonstrated to be effective both as a smearing kernel and a computational tool. Motivated by the study of the smearing profile of the distillation operator, we compare stochastic and exact distillation cases for different numbers of Laplacian eigenvectors using a RBC-UKQCD $N_f = 2 + 1$ domain-wall fermion lattice with a physical pion mass.

QCD at nonzero Temperature and Density
Confinement-Deconfinement transition and $Z_2$ symmetry in $Z_2+\text{Higgs}$ theory

Author: Sabiar Shaikh

Co-authors: Sanatan Digal ¹; Minati Biswal ²; Vinod Mamale ¹

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Abstract: we study the confinement-deconfinement transition and $Z_2$ symmetry in lattice $Z_2+\text{Higgs}$ theory in $3 + 1$ dimensional Euclidean space using lattice Monte Carlo simulation methods. In pure $Z_2$ gauge theory the CD transition is first order. Polyakov loop acquires non-zero thermal average value in the deconfined phase and the $Z_2$ symmetry is spontaneously broken. The $Z_2$ symmetry arises from the fact that the allowed gauge transformations are either periodic or anti-periodic in the temporal direction. In the presence of matter fields in the fundamental representation, only the periodic gauge transformations are allowed. Though the action is invariant under anti-periodic gauge transformations, the gauge transformed matter fields do not satisfy required boundary conditions. A configuration of the Polyakov loop and it's $Z_2$ rotated counter part do not have same action, resulting in the explicit breaking of $Z_2$ symmetry. Using numerical Monte Carlo simulations, we compute physical observable sensitive to $Z_2$ symmetry, in order to study the strength of this explicit breaking in the phase diagram of the theory. Our results shows that this $Z_2$ symmetry is realised in the Higgs symmetric phase for large number of temporal lattice sites. Though the action does not have $Z_2$ symmetry but partition function averages exhibit $Z_2$ symmetry for large number of temporal sites. We also observe that the $Z_2$ symmetry is badly broken in the Higgs broken phase and the strength of the explicit symmetry breaking decreases on approach towards the Higgs symmetric phase. To understand the dependence of $Z_2$ symmetry on the number of temporal sites, we consider a simple one dimensional model keeping terms of the original action corresponding to a single spatial site. The partition function and the corresponding free energy for each of the two Polyakov loop sectors are calculated exactly. It is observed that the free energy difference between the two Polyakov loop sectors vanishes in the large temporal lattice sites, which leads to $Z_2$ symmetry. We argue that this is due to the dominance of entropy or the distribution of the density of states corresponding to the action.

Properties of the $\eta$ and $\eta'$ mesons Part I: Masses and decay constants

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We present results for $\eta$ and $\eta'$ masses at the physical point. The two independent decay constants, e.g., for the flavour singlet/non-singlet basis, are also computed for both particles. The chiral and continuum limit extrapolation is performed on 21 CLS $n_f = 2 + 1$ Wilson Clover improved ensembles at four different lattice spacings and along two quark mass trajectories, including one ensemble very close to the physical quark mass point. For the first time the decay constants are determined directly from the axialvector matrix elements without model assumptions. This allows us to study the QCD scale dependence of the decay constants and to determine all low energy constants contributing at NLO in Large-$N_c$ ChPT at a well defined renormalization scale.
Properties of the $\eta$ and $\eta'$ mesons Part II: Gluonic matrix elements

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We present results of gluonic and pseudoscalar matrix elements of the $\eta$ and $\eta'$ mesons at the physical quark mass point, in the continuum limit. The simulations are carried out on $n_f = 2 + 1$ CLS ensembles, with non-perturbatively improved Wilson fermions. We discuss the renormalization of these quantities and check the consistency with the singlet and non-singlet axial Ward identities. Our results are well described in terms of Large-$N_c$ ChPT at NLO. We comment on phenomenological applications.

Heavy quark diffusion in an overoccupied gluon plasma

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We extract the heavy quark diffusion coefficient $\kappa$ and the resulting momentum broadening $\langle p^2 \rangle$ of a heavy quark embedded in a far-from-equilibrium gluon plasma using classical-statistical lattice simulations. We find several features in the time dependence of the momentum broadening: a short initial rapid growth of $\langle p^2 \rangle$, followed by linear growth with time due to Langevin-type dynamics and damped oscillations around this growth at the plasmon frequency. We show that these novel oscillations are not easily explained using perturbative techniques but result from an excess of gluons at low momenta. These oscillations are therefore a gauge invariant confirmation of the infrared enhancement we had previously observed in gauge-fixed correlation functions. We argue that the kinetic theory description of such systems becomes less reliable in the presence of this IR enhancement.

A5: Two-grid overlap solver in lattice QCD

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Co-authors: Rudina Osmanaj\textsuperscript{2}; Niko Hyka\textsuperscript{3}

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In lattice quantum chromodynamics with chiral fermions we want to solve linear systems which are chiral and dense discretizations of the Dirac operator, or the overlap operator. For this purpose, we use the equivalence of the overlap operator with the truncated overlap operator, which is a five dimensional formulation of the same theory. The coarsening is performed along the fifth dimension only. We have tested first this algorithm for small lattice volume $8^4$ and we bring here our results for larger lattice size $16^4$. We have done simulation in the range of coupling constants and quark masses for which the algorithm is fast and saves a factor of 6, even for dense lattice, compared to the standard Krylov subspace methods.

Lattice QCD Equation of State for $\mu_B \neq 0$ by resumming the Taylor expansion

Author: Prasad Hegde

Taylor expansion in powers of baryon chemical potential ($\mu_B$) is an oft-used method in lattice QCD to compute QCD thermodynamics for $\mu_B \neq 0$. We introduce a new way of resumming the contribution of the first $N$ Taylor coefficients to the lattice QCD equation of state to all orders in $\mu_B$. The method reproduces the truncated Taylor expansion when re-expanded in powers of $\mu_B$. We apply the proposed approach to high-statistics lattice QCD calculations using 2+1 flavors of Highly Improved Staggered Quarks with physical quark masses on $32^3 \times 8$ lattices and for temperatures $T \approx 145 - 175$ MeV. We demonstrate that our resummed version leads to a markedly improved convergence compared to the standard Taylor series approach. We also demonstrate the connection between our approach and reweighting. Lastly, our method runs into the Sign Problem which allows us to determine the maximum value of $\mu_B$ beyond which this method breaks down. We connect this maximum value of $\mu_B$ to the zeros of the partition function in the complex-$\mu_B$ plane.

Computation of QCD meson screening masses at high temperature

Authors: Mattia Dalla Brida$^1$, Leonardo Giusti$^1$, Tim Harris$^2$, Davide Laudicina$^3$, Michele Pepe$^4$

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We compute flavor non-singlet meson screening masses in the chiral limit of QCD with $N_f = 3$ quarks. The calculation is carried out at 11 temperatures covering from $T \approx 1$ GeV up to the electroweak scale. For each temperature we simulated 4 different lattice spacings, so as to be able to perform the continuum limit extrapolation with confidence at a few permille-accuracy. The calculation has been performed on large lattices to have finite volume effects under control.
In the entire range of temperatures explored, the meson screening masses deviate from the free theory result $2\pi T$ by at most a few percent. Their values, however, cannot be explained by one-loop perturbation theory up to the electroweak scale, where the pseudoscalar and the vector screening masses are still significantly different within our precision. Chiral symmetry restoration manifests itself through the degeneracy of the pseudoscalar and scalar channels and of the vector and axial ones.

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Localised Dirac eigenmodes and Goldstone’s theorem at finite temperature

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I show that a finite density of near-zero localised Dirac modes can lead to the disappearance of the massless excitations predicted by the finite-temperature version of Goldstone’s theorem in the chirally-broken phase of a gauge theory.

Hadron Spectroscopy and Interactions / 165

An update on QCD+QED simulations with C* boundary conditions

Authors: Jens Luecke1; Isabel Campos Plasencia2; Madeleine Dale3\textsuperscript{Note}; Patrick Fritzsche\textsuperscript{Note}; Marina Krstic Marinkovic3; Agostino Patella4; Nazario Tantalo5

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This talk is an update on the ongoing effort of the RC\textsuperscript{⋆} collaboration to generate fully dynamical QCD+QED configurations. We present the results of several ensembles with C* boundary conditions that were generated using the openQ\textsuperscript{⋆}D code. The simulations were tuned to the U-symmetric point $(m_d = m_s)$ with pions at $m_{\pi\pm} \approx 400$ MeV and a splitting of $m_{K^0} - m_{K^\pm} \approx 20$ MeV. In order to amplify the isospin breaking effects an artificially large value for the renormalized electromagnetic coupling $\alpha_R \approx 0.04$ was chosen. A novelty in the analysis is the inclusion of the sign of the Pfaffian and a reweighting in the mass. Also, the stability of the algorithm, diagnostic observables and neutral and charged meson masses will be discussed. Furthermore, the line of constant physics and the chosen tuning strategy will be shortly presented.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 166
3+1D Topological $\theta$-Term in the Hamiltonian Formulation of Lattice Gauge Theories for Quantum and Classical Simulations

Author: Angus Kan

Co-authors: Lena Funcke; Stefan Kühn; Karl Jansen; Jan Haase; Luca Dellantonio; Christine Muschik; Jinglei Zhang

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Quantum technologies offer the prospect to efficiently simulate sign-problem afflicted phenomena, such as topological terms, chemical potentials, and out-of-equilibrium dynamics. In this work, we derive the 3+1D topological $\theta$-term for Abelian and non-Abelian lattice gauge theories in the Hamiltonian formulation, paving the way towards Hamiltonian-based simulations of such terms on quantum and classical computers. We further study numerically a 3+1D U(1) lattice gauge theory with the $\theta$-term via exact diagonalization. Our results suggest the occurrence of a phase transition at constant values of $\theta$, as indicated by an avoided level-crossing and abrupt changes in the plaquette expectation value, the electric energy density, and the topological charge density.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 167

Machine Learning for Thermodynamic Observables

Author: Kim Nicoli

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In this talk, I will discuss how thermodynamic observables of lattice field theories can be estimated using machine learning. Specifically, deep generative models are used to estimate the absolute value of the free energy. This is in contrast to MCMC-based methods which are limited to estimating differences of free energies. These methods come with the same asymptotic guarantees as the standard MCMC-based approaches. Application of these methods to two-dimensional $\phi^4$ theory will be presented and compared to existing approaches.

Standard Model Parameters / 168

$B \rightarrow D^*\ell\nu$ at nonzero recoil from lattice QCD

Authors: Alejandro Vaquero Avilés-Casco; Carleton DeTar; Aida El-Khadra; Elvira Gamiz; Zechariah Gelzer; Andreas Kronfeld; John Laiho

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A very rich place to look for phenomena to challenge our current understanding of physics is the flavor sector of the Standard Model (SM). In particular, the $V_{cb}$ matrix element of the CKM matrix is the subject of a long standing tension, depending on whether it is determined using inclusive or exclusive methods. On top of that, the current average of $R(D^*)$ shows a $3\sigma$ tension between experiment and the SM calculations. Theoretical support is urgently needed, and in this work I present the first lattice QCD calculation of the form factors for the decay $B \to D^*\ell\nu$ at non-zero recoil. This analysis includes 15 MILC asqtad ensembles with $N_f = 2+1$ flavors of asqtad sea quarks. The lattice spacing ranges from $a \approx 0.15$ fm down to $0.045$ fm, whereas the ratio between the light and the strange quark mass ranges from 0.05 to 0.4. The valence $b$ and $c$ quarks are treated using the Wilson-Clover action with the Fermilab interpretation, whereas the light sector employs asqtad staggered fermions. After the form factors are extrapolated to the physical point and the continuum limit in the small recoil range, these are extended to the whole kinematic range by using a model-independent parametrization. Comparison with current experimental results coming from Belle and BaBar follows, as well as a joint fit to extract the matrix element $|V_{cb}|$. The lattice prediction for the differential decay rate can be integrated to determine $R(D^*)$ using only lattice data.

Critical behaviour and phase structure of 3d Scalar+Gauge Field Theories in the adjoint representation

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In holographic cosmology, the dual theory may be described by a family of super-renormalisable QFTs in 3 dimensions. In order to obtain cosmological observables, correlators in the massless regime of this QFT are obtained via lattice field theory. Previous work has focused on scalar $\phi^4$ matrix theories in the adjoint representation of SU(N). In this work we present a preliminary exploratory result in the critical behaviour and phase structure of the theory with an SU(N) scalar field coupled to gauge fields by utilising the Heatbath-Overrelaxation (HBOR) algorithm in lattice field theory.

Corrections to the hadron resonance gas from lattice QCD and their effect on fluctuation-ratios at finite density

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The hadron resonance gas (HRG) model is often believed to correctly describe the confined phase of QCD. This assumption is the basis of many phenomenological works on QCD thermodynamics and of the analysis of hadron yields in relativistic heavy ion collisions. We use first-principle lattice simulations to calculate corrections to the ideal HRG. Namely, we determine the sub-leading fugacity expansion coefficients of the grand canonical free energy, receiving contributions from processes like kaon-kaon or baryon-baryon scattering. We achieve this goal by performing a two dimensional scan on the imaginary baryon number chemical potential ($\mu_B$) - strangeness chemical potential ($\mu_S$) plane, where the fugacity expansion coefficients become Fourier coefficients. We carry out a continuum limit estimation of these coefficients by performing lattice simulations with temporal extents of $N_t = 8, 10, 12$ using the 4stout-improved staggered action. We then use the truncated fugacity expansion to extrapolate ratios of baryon number and strangeness fluctuations and correlations to finite chemical potentials. Evaluating the fugacity expansion along the crossover line, we reproduce the trend seen in the experimental data on net-proton fluctuations by the STAR collaboration.

Searching for Yang-Lee zeros in O(N) models

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Near the second order phase transition point, QCD with two flavours of massless quarks can be approximated by an $O(4)$ model, where a symmetry breaking external field $H$ can be added to play the role of quark mass. The Lee-Yang theorem states that the equation of state in this model has a branch cut along the imaginary $H$ axis for $|\text{Im}[H]| > H_c$, where $H_c$ indicates a second order critical point. This point, known as Lee-Yang edge singularity, is of importance to the thermodynamics of the system. We report here on ongoing work to determine the location of $H_c$ via complex Langevin simulations.

Fuzzy sphere regularization of the 1+1 dimensional sigma model

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In order to simulate quantum field theories using quantum computers, a regularization of the target space of the field theory must be obtained which admits a representation in terms of qubits. For the 1+1 dimensional nonlinear sigma model, there have been several proposals for how such a regularization may be achieved. The fuzzy sphere regularization proposes to represent the Hilbert space of the NLSM by a truncation of the noncommutative 2-sphere, a truncation which nonetheless preserves the continuous O(3) symmetry of the theory. In this talk, we discuss an attempt to demonstrate that this regularization reproduces the same physics as the O(3) sigma model using the machinery of matrix product states.
Hadron Structure / 173

Proton momentum and angular momentum decomposition with overlap fermions

Author: Gen Wang

Co-authors: Yibo Yang ; Jian Liang ; Terrence Draper ; Kehfei Liu

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We present a calculation of the proton momentum and angular momentum decomposition using overlap fermions on a 2+1-flavor RBC/UKQCD domain-wall configuration at around 171 MeV which is close to the physical pion mass. A complete determination of the momentum and angular momentum fractions carried by up, down, strange and glue inside proton has been done with valence pion masses varying from 171 to 391 MeV. We have utilized FFT on stochastic sandwich method for connected-insertion parts and the cluster-decomposition error reduction (CDER) technique for disconnected-insertion parts to reduce errors. We carried out the nonperturbative renormalization and mixing for all quantities and final results are reported at the physical pion mass with $\overline{\text{MS}}(\mu = 2 \text{ GeV})$.

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D3: Calculation of the Fermi Velocity renormalization in graphene

Authors: Maksim Ulybyshev

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Application of Hybrid Monte Carlo technique allowed us to perform the simulations of electronic properties of suspended graphene at large enough lattices to directly observe the infrared renormalization of the Fermi Velocity for the first time in non-perturbative Quantum Monte Carlo calculations. We compared the results with experiment, and demonstrated the agreement in the specific case, when short-range electron-electron interactions are taken from cRPA approximation. Comparison of HMC data with perturbative calculations made within the Lattice Perturbation Theory (LPT) and in continuum QED demonstrates the importance of lattice-scale physics for the quantitative description of the Fermi Velocity renormalization. We also discuss the role of the higher-order perturbative corrections beyond RPA level.

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Multi-level computation of the hadronic vacuum polarization contribution to $(g_\mu - 2)$

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The first results from the Fermilab E989 experiment have confirmed the long-standing tension between the experimental determination of the muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$ and its SM determination using the dispersive approach. In order to match the expected final precision from E989, the current uncertainty on ab initio determinations using lattice QCD must be decreased by a factor 5-15, a goal which is hampered by the signal-to-noise ratio problem of the electromagnetic current correlator. Multi-level Monte Carlo integration with fermions is a method which reduces the variance of correlators exponentially in the distance of the fields. Here we demonstrate that the variance reduction in a realistic two-level simulation with a pion mass of 270 MeV, linear size of 3 fm and lattice spacing around 0.065 fm is sufficient to compute the tail of the current correlator with the statistical accuracy required for the hadronic vacuum polarization contribution to $a_\mu$. An efficient estimator is also employed for computing the disconnected contribution.

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HVP contribution to Running Coupling and Electroweak Precision Science

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We investigate the impact of the latest Mainz/CLS collaboration’s result for the hadronic vacuum polarization (HVP) on the electroweak (EW) precision tests. The subject is closely related to the muon g-2 via the HVP. Both precision tests come under scrutiny with respect to physics Beyond the Standard Model. Our HVP calculation is used for the running electromagnetic coupling at low energy and linked at various matching energies to the higher energy running evaluated by phenomenological approaches. We predict the electromagnetic coupling at the Z-pole (alpha(Mz)), providing a lattice-driven input to EW-global fits. Our evaluation of alpha(Mz) is stable for a wide range of matching energies and comes with various systematics taken into account. In light of our alpha(Mz) determination, we discuss a known tension in the EW-global fits.

Hadron Spectroscopy and Interactions / 177

Optimizing distillation for charmonium and glueballs

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We study the charmonium spectrum on an ensemble with two heavy dynamical quarks with a mass at half the physical charm quark mass. Operators for different quantum numbers are used in the
framework of distillation with different smearing profiles to increase the overlap with ground and excited states. The use of exact distillation, large statistics and the absence of light quarks gives robust results for the charmonium spectrum. We also present preliminary results for the glueball spectrum in this theory.

**Particle physics beyond the Standard Model / 178**

**Uses of the gradient-flow beta-function**

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We present various applications of the gradient-flow beta-function, including an extended study of the finite-volume version in the $N_f = 10$ fundamental rep SU(3) model, prompted by claims of possible conformality. We show how the infinite-volume beta-function can be reached through a sequence of stages, handling the correlation across gradient-flow time when taking the continuum limit, and investigate its behavior in the $N_f = 10$ model.

**Theoretical developments and applications beyond particle physics / 179**

**Bosonization of Majorana modes in arbitrary geometries**

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The bosonization procedure for Majorana modes based on Clifford algebra-valued degrees of freedom, valid for arbitrary lattices, will be summarized. In the case of honeycomb geometry the Kitaev model emerges. The role of boundary effects and edge states will be discussed.

**Hadron Spectroscopy and Interactions / 180**

**Emergence of the rho resonance from the HAL QCD potential**

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In this talk, we report the rho resonance study using the HAL QCD method. We calculate the $I = 1 \pi \pi$ potential at $m_\pi \approx 410$ MeV by a combination of the one-end trick, sequential propagator and
covariant approximation averaging (CAA). Thanks to those techniques, we determine the non-local $I = 1 \pi \pi$ potential at the next-to-next-to-leading order (N$^2$LO) of the derivative expansion for the first time and obtain the pole of the S-matrix corresponding to the rho resonance. We also discuss recent applications of the all-to-all techniques to other systems, such as the $N\bar{N}$ interaction and $I = 0 \pi \pi$ interaction.

**Theoretical developments and applications beyond particle physics / 181**

**Symmetric mass generation in lattice gauge theory**

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We construct a four dimensional lattice gauge theory in which fermions acquire mass without breaking symmetries as a result of gauge interactions. We start from a $SU(2)$ lattice Yang-Mills theory with staggered fermions transforming under an additional global $SU(2)$ symmetry. The fermion representations are chosen so that single site bilinear mass terms vanish identically. A symmetric four fermion operator is however allowed and we show numerical results that show that a condensate of this operator develops in the vacuum. The spectrum of the theory contains a triplet of color singlet difermion states whose mass is given by the confinement scale $\Lambda_s$ times a function of the dimensionless ratio $f(\lambda \Lambda_s)$.

**Poster / 182**

**E2: Tensor network formulation of massless lattice Schwinger model**

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We construct a tensor network representation of the partition function for the massless Schwinger model on a two dimensional lattice using staggered fermions. The tensor network representation allows us to include a topological term. Using a particular implementation of the tensor renormalization group (HOTRG) we calculate the phase diagram of the theory. For a range of values of the coupling to the topological term $\theta$ and the gauge coupling $\beta$ we compare with results from hybrid Monte Carlo when possible and find good agreement.
QCD at nonzero Temperature and Density / 183

Single static-quark system above Tc investigated by energy-momentum tensor in SU(3) Yang-Mills theory

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We investigate the distribution of energy-momentum tensor (EMT) around a static quark in the deconfined phase of SU(3) Yang-Mills theory. The EMT defined through the gradient-flow formalism is used for the numerical analysis of the EMT distribution around the Polyakov loop with the continuum extrapolation. Using EMT, one can study the mechanical distortion of the color gauge field induced by the static charge. We find substantial separation in the absolute values of the EMT eigenvalues which is not observed in Maxwell theory. The separation grows as temperature is lowered toward the critical temperature. The lattice data also indicate the thermal screening at long distance and the perturbative behavior at short distance.

Hadron Structure / 184

Pion electric polarizabilities from lattice QCD

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We report a first principle lattice calculation of the pion electric polarizability \(\alpha_\pi\). First, we derive the master formula, which relate the pion polarizabilities with the position space hadronic Compton tensor, \(\langle \pi | J^\mu(x) J^\nu(0) | \pi \rangle\). Then, the hadronic tensor is calculated using Domain Wall fermions directly at physical pion mass. The gauge ensembles are generated by the RBC-UKQCD collaborations. The finite volume effects are exponentially suppressed by the spatial extent of the lattice. We have studied the finite volume and also the discretization effects with different lattice volumes and lattice spacings.

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Generalised Parton Distributions from Feynman-Hellmann Techniques in Lattice QCD

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We report on the use of Feynman-Hellmann techniques to calculate the off-forward Compton amplitude (OFCA) in lattice QCD. At leading-twist, the Euclidean OFCA is parameterised by moments of generalised parton distributions (GPDs). Hence this calculation provides the opportunity to determine GPD-related quantities from first principles.

**Poster / 186**

**E3: Field-Transformation HMC algorithm**

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We report our implementation of the Field-Transformation HMC algorithm following Luescher’s paper “Trivializing maps, the Wilson flow and the HMC algorithm”. This algorithm has similar effects as the Riemannian Manifold HMC (RMHMC) algorithm. Comparing with the original HMC algorithm, improvement on the topology tunneling rate is observed when generating the pure gauge configurations.

**Particle physics beyond the Standard Model / 187**

**S parameter from a prototype composite-Higgs model**

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We calculate the low-energy constant $L_{10}$ in an SU(4) lattice gauge theory with dynamical fermions in two representations. This theory is close to a particular composite-Higgs model. From this, we obtain the contribution of the new strong sector to the S parameter. The resulting upper bound on the vacuum misalignment parameter $\xi$ is similar to current estimates for this bound. We outline future directions for lattice calculations in near-conformal composite-Higgs models.

**Hadron Spectroscopy and Interactions / 188**

**An improvement of glueball mass calculations using gradient flow**
Removing ultraviolet noise from the gauge fields is necessary for glueball spectroscopy in lattice QCD. It is known that the Yang-Mills gradient flow method is an alternative approach instead of smearing or fuzzing of the links in various aspects. In this talk, we study the application of the gradient flow technique to the construction of the extended glueball operators. We find that a simple application of the original gradient flow method has some problems in glueball mass calculations at large flow time. To avoid this problem, only the spatial links are evolved by the “spatial gradient flow”, which is defined by the spatial gradient of the Wilson plaquette action. We examine the new gradient flow approach in calculations of glueball two-point functions and Wilson loops, and then discuss its efficiency in comparison with the original gradient flow method and traditional smearing methods.

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Nuclear force with LapH smearing

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The Laplacian Heaviside (LapH) smearing technique is proved to be useful in precision determination of multi-hadron spectrum. We apply the LapH source smearing to the nuclear force calculation by the HAL QCD method, finding that the 1S0 and 3S1-3D1 potentials are obtained with good precision. The parity-odd sector, including the LS force, are also discussed.

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Compton amplitude and the nucleon structure functions via the Feynman-Hellmann theorem

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We highlight QCDSF/UKQCD Collaboration’s recent developments on computing the Compton amplitude directly via an implementation of the second-order Feynman-Hellmann theorem. As an application, we compute the nucleon Compton tensor across a range of photon momenta at an unphysical quark mass. This enables us to study the $Q^2$ dependence of the low moments of the nucleon structure functions in a lattice calculation for the first time. We present some selected results for the moments of the $F_1$, $F_2$ and $F_L$ structure functions and discuss their implications.

Poster / 191

B4: A new framework to tune an improved relativistic heavy-quark action

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We introduce a new non-perturbative method to tune the parameters of the Columbia formulation of an anisotropic, clover-improved relativistic heavy-quark (RHQ) action. By making use of suitable observables which can be computed at a sequence of heavy-quark mass values, employing an $O(a)$-improved discretized action with domain-wall chiral fermion, and safely interpolated between the accessible heavy-quark mass region and the static point predicted by heavy-quark effective theory, we are able to precisely determine the unknown coefficients of the RHQ action.

In this proof-of-principle study we benefit from the RBC/UKQCD Iwasaki gauge configurations with 2 + 1 flavors of dynamical quarks, at three values of the lattice spacing varying from 0.11 to 0.062 fm. Preliminary results and applications to bottom spectroscopy are also presented.

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Window contributions to the muon hadronic vacuum polarization with twisted-mass fermions

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We present a lattice calculation of the Euclidean position-space windows contributing to the leading-order hadronic vacuum polarization term of the muon anomalous magnetic moment $a_\mu$.

Short-, intermediate- and long-distance windows are considered in order to isolate different scales sensitive to specific integration ranges of experimental time-like data used in the R-ratio.

By adopting the same smooth window function introduced by the RBC and UKQCD Collaborations with width parameter $\Delta = 0.15$ fm, for the isospin-symmetric, light, quark-connected component we get $a_\mu^{SD}(ud, iso) = 48.21 (80) \times 10^{-10}$, $a_\mu^{W}(ud, iso) = 202.2 (2.6) \times 10^{-10}$ and $a_\mu^{LD}(ud, iso) = 382.5 (11.7) \times 10^{-10}$ in the short- (SD), intermediate- (W) and long-distance (LD) time regions, respectively, with $t_0 = 0.4$ fm and $t_1 = 1.0$ fm.

Our results are obtained using the gauge configurations generated by the Extended Twisted Mass Collaboration with $N_f = 2 + 1 + 1$ dynamical quarks, at three values of the lattice spacing varying from 0.11 to 0.062 fm. Preliminary results and applications to bottom spectroscopy are also presented.
Theoretical developments and applications beyond particle physics / 194

Restoration of chiral symmetry in cold and dense Nambu–Jona-Lasinio model with tensor renormalization group

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We analyze the chiral phase transition of the Nambu–Jona-Lasinio model in the cold and dense region on the lattice developing the Grassmann version of the anisotropic tensor renormalization group algorithm. The model is formulated with the Kogut–Susskind fermion action. We use the chiral condensate as an order parameter to investigate the restoration of the chiral symmetry. The first-order chiral phase transition is clearly observed in the dense region at vanishing temperature with μ/Τ≡O(10³³) on a large volume of V=1024×4. We also present the results for the equation of state.

Theoretical developments and applications beyond particle physics / 195

Tensor renormalization group of two-dimensional U(1) lattice gauge theory with a θ term

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We make an analysis of the two-dimensional U(1) lattice gauge theory with a θ term by using the tensor renormalization group. Our numerical result for the free energy shows good consistency with the exact one at finite coupling constant. The topological charge density generates a finite gap at θ=π toward the thermodynamic limit. In addition finite size scaling analysis of the topological susceptibility up to V=1024×1024 allows us to determine the phase transition at θ=π is the first order.

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Decay constants of \( B_{(s)} \) and \( D_{(s)} \) meson on MILC HISQ a12m220 ensemble using the OK action and sequential Bayesian method

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from 0.089 to 0.062 fm, at several lattice volumes and with pion masses in the range \( M_π \simeq 220 – 490 \text{ MeV} \).
We present our current progress on the lattice calculation of decay constants for $B_s$, $D_s$ mesons using sequential Bayesian method and the Oktay-Kronfeld (OK) action for the charm and bottom quarks (valence quarks). Here, the masses of charm and bottom quark are determined non-perturbatively. For the light spectator quarks (up, down and strange), we use HISQ action. Lattice calculation is done on MILC HISQ a12m220 ensemble ($N_f = 2 + 1 + 1$ flavors). $f_{B_s}/f_B$ and $f_{D_s}/f_D$, the flavor SU(3) symmetry breaking ratio, are presented. They are independent of the renormalization constants for the axial current.

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**Neutron Electric Dipole Moment from Overlap Fermions**

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We report our effort on calculating the neutron electric dipole moment (EDM) induced by the theta term using overlap fermions. Three 2+1-flavor RBC/UKQCD domain wall lattices with pion mass ranging from ~300 to ~500 MeV are utilized and on each gauge ensemble we use 3 partially-quenched valence pion masses. Lattice chiral fermions are essential in the calculation, which guarantees a correct chiral limit even at finite lattice spacings, and enables us to reliably extrapolate our result from heavy pion masses to the physical point. Thanks to the cluster decomposition error reduction (CDER) technique and the partially-quenched chiral extrapolation formula, the statistical uncertainties of our calculation are effectively controlled.

**Hadron Structure / 198**

**The contribution of QCD trace anomaly to hadron mass**

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We present the first Lattice QCD calculation of the quark and gluon trace anomaly contributions to the hadron masses, using the overlap fermion on the 2+1 flavor dynamical Domain wall quark ensemble. The result shows that the gluon trace anomaly contributes to most of the nucleon mass, and the contribution in the pion state is smaller than that in others.

**Particle physics beyond the Standard Model / 200**

**Sp(2N) gauge theories on the lattice: status and perspectives**

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Among novel strong interactions beyond the standard being currently investigated, the Sp(4) gauge theory with two fundamental and three antisymmetric fermions is compatible with the pseudo-Nambu-Goldstone-Boson (pNGB) mechanism of electroweak symmetry breaking and the implementation of partial top compositeness. Unlike in QCD, the lack of a manifest experimental counterpart and the scarcity of related works in the lattice literature require a cautious and safe approach to numerical studies of Sp(4) and, more in general, Sp(2N) gauge theories. This has resulted in recent wide explorations of the parameter space of Sp(2N) theories that also include regimes not directly connected with the original motivations related to the pNGB mechanism. In this contribution, I discuss previous calculations of Sp(2N) theories in pure gauge, in the quenched limit and with single-representation dynamical matter. I shall focus on the function of those investigations in connection with studies of the pNGB mechanism of electroweak symmetry breaking and partial top compositeness, highlighting the key milestones in our journey towards current calculations aimed to approach the phenomenologically relevant regime of the system. Potential applications to the SIMP origin of dark matter are also briefly discussed.

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Comparison of the MOM and SMOM renormalization

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The momentum subtraction scheme (MOM) and symmetric momentum subtraction scheme (SMOM) are two of the widely used intermediate schemes for the non-perturbative renormalization of the lattice bare vertices. In principle both the schemes should provide the same MS-bar results with their respective matching, while kinds of the systematic uncertainties can create certain tensions especially at finite lattice spacing. We will show our calculation with the overlap fermion at several quark masses and lattice spacings, to compare the advantage and disadvantage of both the schemes.

Theoretical developments and applications beyond particle physics / 202

Coupling Yang–Mills with Causal Dynamical Triangulations

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In this talk I examine the algorithmic problem of minimal coupling gauge fields of the Yang–Mills type to Quantum Gravity in the approach known as Causal Dynamical Triangulations (CDT) as a step towards studying, ultimately, systems of gravity coupled with bosonic and fermionic matter. I first describe the algorithm for general dimensions and gauge groups and then focus on the results obtained from simulations of 2d CDT coupled to Yang–Mills fields with U(1) and SU(2) gauge groups, where we studied both observables related to gravity and gauge fields, and compared them with analogous simulations in the static flat case.

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**Hadronic contributions to the running of electromagnetic and weak couplings**

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As present and future experiments in both the energy and precision frontiers look to identify new physics beyond the Standard Model, they require increasingly precise determinations of fundamental quantities like the electroweak couplings at various momenta. The latter can be obtained from experimental measurements or a particular reference value and the dependence on the energy. A precise, entirely theoretical determination of the running couplings is highly desirable, even more since the preliminary results of the E989 experiment in Fermilab were published, and non-perturbative techniques at small momentum are necessary.

In our talk, we present the latest results on these quantities of the Mainz group. We analyze a broad set of Coordinated Lattice Simulations ensembles with the time-momentum representation at various lattice spacings and pion masses. We perform an extrapolation to the physical point, we predict the running and compare it with other determinations, both from the lattice and phenomenology.

QCD at nonzero Temperature and Density / 204

**With complex Langevin towards the QCD phase diagram**

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We present an update on our efforts to determine the QCD phase diagram using complex Langevin simulations. In this study, we use two flavours of Wilson fermions with moderate pion masses.
To improve the convergence of the simulations, we employ adaptive step size scaling and dynamic stabilisation. Here we report on our findings at higher temperatures and density. In addition, we also report on the eigenvalue spectrum for increasing chemical potential and smaller temperatures.

Theoretical developments and applications beyond particle physics / 205

A new phase in the Lorentzian type IIB matrix model and the emergence of continuous space-time

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The Lorentzian type IIB matrix model is a promising candidate for a non-perturbative formulation of superstring theory. In previous studies, Monte Carlo calculations provided interesting results indicating the spontaneous breaking of SO(9) to SO(3) and the emergence of (3+1)-dimensional space-time. However, an approximation was used to avoid the sign problem, which seemed to make the space-time structure singular. In this talk, we report our results obtained by using the complex Langevin method to overcome the sign problem instead of using this approximation. In particular, we discuss the emergence of continuous space-time in a new phase, which we discovered recently.

Particle physics beyond the Standard Model / 206

Mixed adjoint-fundamental matter and applications towards SQCD and beyond

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Gauge theories with fermions in adjoint and fundamental representations are relevant for many different applications including composite Higgs models and general aspects of the confinement problem. In this talk, I will present first results from simulations of SU(2) gauge theory with two Dirac fermions in the fundamental representation and one adjoint Majorana flavour. In this context, I will also discuss applications towards simulations of supersymmetric QCD.
A numerical and theoretical study of multilevel performance for two-point correlator calculations

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Multilevel techniques in lattice were introduced twenty years ago by Lüscher and Weisz as a way to overcome exponential signal-to-noise decay in lattice gauge theory. It is known that the algorithm performs well when the correlation length of the system is small, and less favourably when it is large. In this project, the transition between these regimes is studied. The 2D-Ising Model is used as a test system for calculating two-point functions across a range of correlation lengths. We go on to develop a theoretical framework that gives excellent predictions of the numerically observed performance boost.

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Perturbative study of the Gluino-Glue operator in SYM

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We investigate the renormalization of the Gluino-Glue operator, using both Lattice Perturbation Theory (LPT) and a Gauge Invariant Renormalization Scheme (GIRS). The latter scheme involves gauge-invariant Green’s functions of two operators at different space-time points, which can be also computed via numerical simulations. There is no need to fix a gauge and the mixing with gauge noninvariant operators is inconsequential. We calculate perturbatively the conversion factor relating GIRS with the Modified Minimal Subtraction scheme. On the other hand, Gluino-Glue operator being composite, mixes with several gauge noninvariant operators which have the same quantum numbers. The determination of the mixing matrix on the lattice demands the calculation of 2-pt and 3-pt Green’s functions with external gluon, gluino and ghost fields using LPT. We compute at one-loop order the renormalization of the Gluino-Glue operator and all operator mixing coefficients.

Hadron Spectroscopy and Interactions / 209

Scale setting and the light baryon spectrum on CLS ensembles

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We present continuum limit results of the quark mass dependence of octet and decuplet baryon masses obtained from Lattice QCD simulations. This is part of our large-scale programme connected to CLS of simulating \( N_f = 2 + 1 \) flavours of non-perturbatively improved Wilson fermions where ensembles with large volumes together with a wide range of quark masses, including the physical point, are used. The six different lattice spacings reach from 0.1 fm down to below 0.04 fm. In this
analysis we also determine the Wilson flow scale parameter $t_0$ from the masses of the $\Xi$ and $\Omega$ baryons.

**Theoretical developments and applications beyond particle physics / 210**

**Introducing Fermionic Quantum Link Models**

**Authors:** Debasish Banerjee; Emilie Huffman; Lukas Rammelmüller

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Quantum link models (QLMs) are extensions of Wilson-type lattice gauge theories, and show rich physics beyond the phenomena of conventional Wilson gauge theories. Here we explore the physics of $U(1)$ symmetric QLMs, both using a more conventional quantum spin-1/2 representation, as well as a fermionic representation. In 2D, we show that both bosonic and fermionic QLMs have the same physics. We then explore the models in 3D and find different behavior for the two QLMs. For the bosons, we see evidence for a quantum phase transition from a broken phase to a quantum spin liquid, but for the fermions, we identify not one but two distinct phases in addition to the fermionic broken phase. We explore the symmetries of the ground state in the broken phase strong coupling limit, and explain the spectrum for both models. The phase transitions are confirmed through scaling of the gaps as well as the ground state fidelity susceptibilities.

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**Non-perturbative renormalization of the flavour-singlet local vector current with $O(a)$-improved Wilson fermions**

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We determine non-perturbatively the renormalization constant of the flavour-singlet local vector current with $O(a)$-improved Wilson fermions in a moving reference frame. The renormalization constant is fixed by comparing the expectation values (one-point function) of the local vector current and of the conserved one in thermal QCD with a non-zero imaginary chemical potential and in the chiral limit. We implement the method in QCD with $N_f = 3$ flavours discretized by the standard Wilson action for gluons and the non-perturbatively $O(a)$-improved Wilson fermions. By carrying out extensive numerical simulations, the renormalization constant is determined with a precision of a few permille for values of the bare coupling constant in the range $0.52 \leq g_0^2 \leq 1.13$.

**Theoretical developments and applications beyond particle physics / 212**

**Relationship between the Euclidean and Lorentzian versions of type IIB matrix model**
The type IIB matrix model was proposed as a nonperturbative formulation of superstring theory in 1996. We simulate this model by applying the complex Langevin method to overcome the sign problem. Here, we clarify the relationship between the Euclidean and Lorentzian versions of the type IIB matrix model in a new phase we discovered recently.

We present the status of a project to calculate $D \to \pi \ell \nu$, $D \to K \ell \nu$ and $D_s \to K \ell \nu$ semileptonic form factors with 2+1f Domain Wall Fermions for both heavy and light quarks. We plan to cover the full kinematic range and three point functions are being computed on the RBC-UKQCD Iwasaki gauge ensembles. Given the exponential growth of noise, good projection on the ground state is critical for success. We include an analysis of operator diagonalisation within several possible $2 \times 2$ operator bases and find an admixture of gauged fixed wall and $Z(2)$ wall sources to be acceptable at both zero and non-zero momentum. Initial results for semileptonic form factors are presented for first ensembles.

Renormalization constants of the scalar and tensor currents are calculated for overlap fermions on domain-wall fermion configurations. We perform zero, one or two steps of hypercubic smearing in

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**Semileptonic $D \to \pi \ell \nu$, $D \to K \ell \nu$ and $D_s \to K \ell \nu$ decays with 2+1f Domain Wall Fermions**

**Authors:** Peter Boyle, Michael Marshall

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We present the status of a project to calculate $D \to \pi \ell \nu$, $D \to K \ell \nu$ and $D_s \to K \ell \nu$ semileptonic form factors with 2+1f Domain Wall Fermions for both heavy and light quarks. We plan to cover the full kinematic range and three point functions are being computed on the RBC-UKQCD Iwasaki gauge ensembles. Given the exponential growth of noise, good projection on the ground state is critical for success. We include an analysis of operator diagonalisation within several possible $2 \times 2$ operator bases and find an admixture of gauged fixed wall and $Z(2)$ wall sources to be acceptable at both zero and non-zero momentum. Initial results for semileptonic form factors are presented for first ensembles.

**Renormalization of overlap quark bilinear operators with hypercubic smearing**

**Authors:** Zhaofeng Liu, Yujiang Bi, Ying Chen, Ming Gong, Keh-Fei Liu

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Renormalization constants of the scalar and tensor currents are calculated for overlap fermions on domain-wall fermion configurations. We perform zero, one or two steps of hypercubic smearing in
constructing the overlap Dirac operator and examine the discretization effects in the renormalization constants of quark bilinears and check the dependence of those effects on the level of smearing. Both the SMOM and MOM schemes are used and the results are compared.

Particle physics beyond the Standard Model / 215

One Flavour QCD as an analog computer for SUSY

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We numerically study QCD with a single quark flavour on the lattice probing predictions from effective field theories that are equivalent to minimal super-symmetric Yang-Mills theory in the large \(N_c\) limit.

The hadronic spectrum including excited states is analyzed using one gauge coupling and several physical volumes and fermion masses. We use the LapH method and also compute disconnected diagrams. Lattice simulations with an odd number of Wilson fermions give rise to regions of configuration space with a negative fermionic weight entailing a sign problem. We perform a detailed analysis on the spectrum of the Wilson-Dirac operator and report on observed cases of a negative fermion determinant in our ensembles.

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\(Sp(4)\) and \(Sp(6)\) quenched meson spectrum

Author: Jack Holligan\(^1\)

Co-authors: Biagio Lucini \(^1\); C.-J. David Lin; Maurizio Piai \(^1\); Jong-Wan Lee \(^2\); Deog-Ki Hong \(^3\); Ed Bennett \(^1\); Davide Vadacchino \(^3\); Ho Hsiao \(^4\)

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Motivated by studies of Composite Higgs models based on the \(SU(4)/Sp(4)\) coset on the one hand and by large-\(N\) limit investigations on the other, we analyse the quenched meson spectrum of Symplectic – \(Sp(2N)\) – gauge theories on the lattice. We examine fermions in the symmetric representation of \(Sp(4)\); we also study fermions in the fundamental, antisymmetric and symmetric representations of \(Sp(6)\). The previously computed spectrum of \(Sp(4)\) mesons in the fundamental and antisymmetric mesons is also discussed. The \(Sp(6)\) spectrum is explored to supplement the work of \(Sp(4)\) as well as a step along the way to computing the meson spectrum in the large-\(N\) limit of \(Sp(2N)\).
Lattice Gauge Symmetry in Neural Networks

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With increasing interest in machine learning techniques for lattice gauge theory, it becomes important to develop suitable neural network architectures that are compatible with the fundamental symmetries that lie at the heart of lattice QCD. We propose a novel neural network architecture called lattice gauge equivariant convolutional neural networks (L-CNNs) [1] that can be applied to problems in lattice gauge theory while exactly preserving gauge symmetry by construction. This is realized by explicitly accounting for parallel transport in convolutional layers. In combination with bilinear layers, these networks can in principle approximate any gauge covariant function on the lattice. We demonstrate that L-CNNs outperform traditional CNNs when applied to tasks such as computing Wilson loops. Our models can be efficiently trained on small lattices and still generalize well to larger lattice sizes.


Finite volume renormalization schemes and the fermionic gradient flow

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Non-perturbative renormalization of composite operators can be achieved by combining the step-scaling method with an intermediate finite volume renormalization scheme. Matching to low energy physics requires that the finite volume scheme can be accurately evaluated at the bare couplings used in simulations of hadronic physics.

In this regime, the gradient flow for the gauge field has been essential for recent progress with the strong coupling, and one may hope for similar benefits when extending the flow to fermion fields. Here we define finite volume renormalization schemes for fermionic bilinear operators. We use Schrodinger functional (SF) and chirally rotated SF boundary conditions and consider different fermionic flow definitions, with and without spin structure. We present some results at leading order of perturbation theory and identify parameter choices with small discretization effects.

Transverse momentum broadening in real-time lattice simulations of the glasma

Author: Daniel Schuh

QCD at nonzero Temperature and Density
The study of jets in heavy ion collisions provides important information about the interaction of partons with the medium that they traverse. The seeds of jets are highly energetic partons, which are produced from hard scatterings during the collision event. As such, they are affected by all different stages of the medium’s time evolution, including the glasma, which is the pre-equilibrium precursor state of the quark-gluon plasma. I will report on our numerical lattice simulations of partons traversing the boost-invariant, non-perturbative glasma as created at the early stages of collisions at RHIC and LHC [1]. We find that partons quickly accumulate transverse momentum up to the saturation momentum during the glasma stage. Furthermore, we observe an interesting anisotropy in transverse momentum broadening of partons with larger broadening in the rapidity than in the azimuthal direction. Its origin can be related to correlations among the longitudinal color-electric and color-magnetic flux tubes in the initial state of the glasma. I will compare these observations to the semi-analytic results [2] obtained by a weak-field approximation, where we also find such an anisotropy in a parton’s transverse momentum broadening.

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Critical behaviour in the single-flavor Planar Thirring Model

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The Thirring model describes relativistic fermions with a contact interaction between conserved fermion currents. In 2+1 spacetime dimensions its U(2N) global symmetry is broken at strong coupling to U(N)⊗U(N) through generation of a non-vanishing bilinear condensate ⟨ψψ⟩ ≠ 0. I present results of numerical simulations of the single-flavour model using domain wall fermions, which preserve U(2) in the limit wall separation Ls → ∞. The results confirm symmetry breaking takes place implying the critical flavour number Nc ≥ 1. I will also present results for the critical equation of state showing it is consistent with the existence of a quantum critical point with critical exponents distinct from those obtained with staggered fermions.

Spectral reconstruction of an inclusive rate in the two-dimensional O(3) model

Authors: Agostino Patella; John Bulava; Maxwell Hansen; Nazario Tantalo

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We compute a real-time inclusive scattering processes from the spectral function of a Euclidean two-point correlation function in the two-dimensional O(3) model. The intractable inverse problem is overcome using a recently-proposed algorithm to compute the desired spectral function smeared with a variety of finite-width kernels. Systematic errors due to finite volume, continuum limit, and spectral reconstruction are demonstrably controlled, enabling a determination of the smeared spectral functions at energies exceeding the four-particle production threshold. These results are in agreement with the known exact spectral function smeared with the corresponding kernels. Finally, the unsmeared spectral function is computed by extrapolation of the numerical data to the zero-smearing-width limit. Everything discussed here is (in principle) applicable in QCD to determine similar inclusive rates such as the R-ratio.

Chiral phase transition temperature in 3-flavor QCD.

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Establishing whether or not the famous first order corner at small quark masses exists in the Columbia plot is one of the major open issues in studies of the phase diagram of QCD. We delve into this problem and present results from our ongoing study of the chiral limit in three-flavor QCD using the Highly Improved Staggered Quark (HISQ/tree) action.

We investigate four quark masses, which in the continuum correspond to pion masses in the range 80 MeV to 140 MeV. In our simulations, the temporal lattice size, $N_\tau$, is fixed to be equal to 8 and we explore three different aspect ratios $N_\sigma/N_\tau = 3$, 4 and 5.

In the pion mass range explored by us, we do not find any direct evidence of the existence of a first order phase transition. We find the quark mass and volume dependence of the chiral observables to be well-described by the universal finite size scaling functions. We obtain a quite low value for the chiral phase transition temperature that is around 100 MeV.

Localisation of Dirac modes in finite-temperature $\mathbb{Z}_2$ gauge theory on the lattice

Authors: György Baranka; Matteo Giordano

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The low-lying Dirac modes become localised at the finite-temperature transition in QCD and in other
gauge theories, suggesting a general connection between their localisation and deconfinement. The
simplest model where this connection can be tested is $\mathbb{Z}_2$ gauge theory in 2+1 dimensions. We show
that in this model the low modes in the staggered Dirac spectrum are delocalised in the confined
phase and become localised in the deconfined phase. We also show that localised modes correlate
with disorder in the Polyakov loop configuration, in agreement with the "sea/islands picture" of
localisation. These results further support the conjecture that localisation and deconfinement are
closely related.

Vacuum Structure, Confinement, and Chiral Symmetry / 224

Role of inhomogeneities in the flattening of the quantum effec-
tive potential

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We investigate the role of inhomogeneous field configurations in systems with a spontaneously
broken continuous global symmetry. Textbooks tell us that the quantum effective potential of the
system is flat in the thermodynamic limit. At the same time, spontaneous breaking is defined through
the double limit, infinite volume at finite explicit breaking sources, which then approach zero. This
defining procedure leads to a flat potential by construction, however it is incapable of accessing the
flat region itself. We argue that the flatness results from inhomogeneities and demonstrate it by
carrying out constrained lattice simulations in the three dimensional O(2) model.

Particle physics beyond the Standard Model / 225

Sp(4) lattice gauge theory with fermions in multiple representa-
tions

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We study a four-dimensional lattice gauge theory with fermions transforming as the fundamental
and antisymmetric representations of Sp(2N) gauge groups. More specifically, we consider the case
of N=2 with two and three Dirac flavors for the fundamental and antisymmetric fermions, respec-
tively, whose continuum limit serves as the microscopic theory for SU(4)/Sp(4) models of composite
Higgs and top-partial compositeness. The standard Wilson gauge action and Wilson-Dirac fermions
are used for the Euclidean formulation of the theory. We discuss the phase structure of the lattice theory, where we find strong evidence of a first-order bulk transition in the strong coupling regime. We also present a preliminary investigation of the mass spectrum of composite states including the Chimera baryon, a baryonic state composed of valence fermions in the two different representations, in addition to spin 0 and 1 (flavored) mesons.

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Mesonic spectrum of Sp(4) gauge theory with Nf=3 dynamical antisymmetry fermions

Author: Ho Hsiao

Co-authors: Jong-Wan Lee; Maurizio Piai; C.-J. David Lin; Ed Bennett; Deog Ki Hong; Biagio Lucini; Michele Mesiti; Davide Vadacchino; Jack Holligan

We perform dynamical lattice studies for mesonic spectroscopy of Sp(4) gauge theory coupled to three flavours of Dirac fermions in the antisymmetric representation. In addition, mesons composed of valence fundamental Dirac fermions are considered in the partially-quenched setting. We employ the Wuppertal and APE smearing methods to improve the signals of effective masses. By combining the smearing techniques and a variational method, we are able to extract the first excited state of the rho meson. In the lattice calculation, we set the scale using the gradient flow and study continuum extrapolations and finite size effects. Besides, we present our exploratory investigations of chimera baryons.

QCD in searches for physics beyond the Standard Model / 227

Pion Pole Contribution to HLbL from Twisted Mass Lattice QCD at the physical point

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We report on our computation of the pion transition form factor $F_{\pi \to \gamma^* \gamma^*}$ from twisted mass lattice QCD, to determine the numerically dominant light pseudoscalar pole contribution for the analysis of hadronic light-by-light scattering in the muon $g-2$. The pion transition form factor is computed directly at the physical point. We present first results for our estimate of the pion pole contribution to $a_\mu$ with kinematic setup of the pion at rest at a single lattice spacing.
**Approaching the master-field: Hadronic observables in large volumes**

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The master-field approach to lattice QCD envisions performing calculations on a small number of large-volume gauge-field configurations. Substantial progress has been made recently in the generation of such fields, and this must be joined with measurement strategies that take advantage of the large volume.

In this talk, we describe how to compute simple hadronic quantities efficiently and estimate their errors in the master-field approach, i.e. by studying cross-correlations of observables on a single configuration. We discuss the scaling of the uncertainty with the volume and compare extractions based on momentum-projected and position-space two-point functions. The latter show promising results, already at intermediate volumes, but come with additional technical complexities such as a more complicated manifestation of boundary effects, which we also address.

**Improved analysis of nucleon isovector charges and twist-2 matrix elements on CLS \(N_f = 2 + 1\) ensembles**

**Author:** Konstantin Ottnad\(^1\)

**Co-authors:** Dalibor Djukanovic\(^2\); Tim Harris\(^3\); Harvey Meyer\(^4\); Georg von Hippel\(^1\); Hartmut Wittig

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Preliminary results are presented for nucleon isovector charges and twist-2 matrix elements which have been obtained employing an improved analysis strategy to deal with excited state contamination. The set of CLS \(N_f = 2 + 1\) gauge ensembles in this study has been extended compared to our 2018 calculation, including an ensemble at physical quark masses. Besides the addition of new ensembles, the number of gauge configurations and measurements has been increased on several of the existing ensembles and the analysis has been extended to include additional source-sink separations. The ensembles cover a range of the light quark mass corresponding to \(M_\pi \approx 0.130\text{MeV} \ldots 350\text{MeV}\), four values of the lattice spacing \(a \approx 0.05\text{fm} \ldots 0.09\text{fm}\) and a large range of volumes. Results at the physical point are computed for each observable from a combined chiral, continuum and finite size extrapolation.
Vacuum Structure, Confinement, and Chiral Symmetry / 230

The behavior of Topological objects above the chiral crossover transition in QCD

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We compare the behavior of the analytic instanton-dyon solutions to zero and near-zero-modes of the overlap Dirac operator measured on the finite temperature 2+1 flavor lattice QCD configurations, generated with domain wall fermion discretization. By performing numerical fit to the (near) zero-modes from lattice calculations, we extract information about the typical distance between the dyons and the background Polyakov loop they feel in the temperature range 1.0-1.2T_c, T_c being the pseudo-critical temperature. We also show how the density of different species of dyons change as a function of temperature, and how this manifests in the eigenvalue distribution of the overlap Dirac operator.

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**Precision $B^* B\pi$ coupling from three flavor lattice QCD**

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We consider three-flavor QCD and perform a determination of the low energy coupling $\hat{g}$ of SU(2) Heavy Meson Chiral Perturbation Theory. It is the $B^* B\pi$ coupling in the limit of static heavy and chiral light quarks in $N_f = 2 + 1$ flavor QCD and has not been determined with precision thus far. The calculation is performed on the 2 + 1 flavor CLS ensembles using the summed GEVP method. The extrapolation to the limit of chiral light quarks is based on a number of gauge ensembles with pion masses in the range from 420 MeV down to 130 MeV. This allows us to significantly reduce the systematic uncertainty from the extrapolation compared to previous works. Only a weak dependence on the lattice spacing is visible in our results. This work is a first step in the 2 + 1 flavor HQET program of the ALPHA collaboration.

Hadron Spectroscopy and Interactions / 232

**Finite volume analysis on systematics of the derivative expansion in HAL QCD method**

**Authors:** Takumi Doi; Yan LYU; Hui Tong; Takuya Sugiura; Sinya Aoki; Tetsuo Hatsuda; Jie Meng; Takaya Miyamoto

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We study the systematic error associated with the truncation of the derivative expansion for the potential in HAL QCD method. We introduce the Hamiltonian with the leading-order potential determined in the HAL QCD method and study the corresponding eigenmodes in a finite volume. We show that a temporal correlation function of a designated energy eigenstate can be obtained using the finite-volume eigenwavefunction as a projection operator. This enables us to make quantitative comparison between Luscher’s method and HAL QCD method in terms of the energy spectra in a finite volume, avoiding the notorious pseudo-plateau problem in a temporal correlation function [1]. Numerical investigations are performed for the Omega_ccc - Omega_ccc (1S0) system near the physical point [2]. We observe consistency in finite volume spectra, which indicates that the truncation error of derivative expansion is small in this system. This study also gives clear demonstration that the potential (and thus phase shifts/binding energy) can be reliably extracted from the NBS wave function for elastic excited states.


Theoretical developments and applications beyond particle physics / 233

Minimally doubled fermions and topology in 2D

Author: Stephan Durr
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We use the two-dimensional Schwinger model to investigate how lattice fermion operators perceive the global topological charge $q \in \mathbb{Z}$ of the gauge background. After a warm-up part devoted to Wilson and staggered fermions, we consider Karsten-Wilczek and Borici-Creutz fermions, which are in the class of minimally doubled lattice fermion actions. The focus is on the eigenvalue spectrum of the selected operator and on the eigenvalue flow (as a function of the scalar mass $m$) of its hermitean counterpart. Without modification both minimally doubled operators are found to be insensitive to topology, but in either case it is possible to define a suitable taste term to make the operator topology aware.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 234

Algorithms for domain wall Fermions

Author: Peter Boyle
Co-authors: Azusa Yamaguchi ; Kelly Christopher

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I review multigrid algorithms for domain wall fermions and discuss the development status of a domain decomposed hybrid monte carlo appropriate for chiral fermions and tailored for use on GPU accelerated computing nodes.
Excited $J^{--}$ meson resonances at the SU(3) flavor point from lattice QCD

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We present the first calculation within lattice QCD of excited light meson resonances with $J^{PC} = 1^{--}$, $2^{--}$ and $3^{--}$. Working with an exact SU(3) flavor symmetry, for the singlet representation of pseudoscalar-vector scattering, we find two $1^{--}$ resonances, a lighter broad state and a heavier narrow state, a broad $2^{--}$ resonance decaying in both $P$- and $F$-waves, and a narrow $3^{--}$ state. We present connections to experimental $\omega^{\star}, \phi^{\star}$ resonances decaying into $\pi\rho$, $K\bar{K}^{*}$, $\eta\omega$ and other final states.

based upon material appearing in
arXiv:2012.00518

C.T. Johnson, and J.J. Dudek
for the Hadron Spectrum Collaboration

$K\pi$ scattering length at physical quark masses using all-to-all methods

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The scattering length is an important quantity that describes scattering at low energies. We will present our evaluation of the $K\pi$ scattering length in the isospin $I = \frac{1}{2}$ and $I = \frac{3}{2}$ channels. The computation uses the RBC-UKQCD 2+1-flavour ensembles with Domain Wall Fermions at near-physical quark masses. With the help of all-to-all methods, we construct the correlation functions, and we handle excited states and round-the-world effects to obtain a stable result.

QCD in searches for physics beyond the Standard Model

Power divergences of the quark-chromo electric dipole moment operator with the gradient flow

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The quark-chromo electric dipole moment (qCEDM) operator is one of the possible beyond-the-standard-model (BSM) contributions to the electric dipole moment (EDM). Power divergences of
lower dimensional operators are introduced to the qCEDM operator by operator mixing. We compute non-perturbatively the qCEDM power divergence coefficient with the gradient flow, allowing us to control the power divergences and perform the continuum and chiral extrapolation. We present the comparison between non-perturbative computation and perturbation theory as a function of bare and renormalized coupling.

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Semileptonic form factors for $B \to \pi \ell \nu$ decays

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The desire for additional determinations of the CKM matrix element $V_{ub}$ and a long-standing 2-3σ discrepancy between results from inclusive $B \to X_u$ and exclusive $B \to \pi$ processes motivate the study of $B \to \pi$ semileptonic form factors on the lattice. The status of our preliminary $B \to \pi \ell \nu$ results will be discussed by highlighting updates to our analysis. The analysis is carried out on a subset of the RBC/UKQCD 2+1f Iwasaki gauge action ensembles, with $b$ quarks simulated using the Columbia formulation of the relativistic heavy quark action, and the light valence-quarks simulated with domain wall fermions. We predict scalar and vector form factors over the entire range of allowed $q^2$ and use our results to test lepton universality via the R-ratio $\Gamma(B \to \pi \tau \nu)/\Gamma(B \to \pi \ell \nu)$, where $\ell$ in the denominator is either an electron or muon.

Poster / 239

D5: Grid: OneCode and FourAPIs

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We discuss the status, portability and performance of the Grid package for lattice QCD. Accelerated computing nodes are increasingly common and increasingly varied. Programming for all of them is a considerable pain that gets in the way of science. A major update to Grid abstracts the differences and will run well with single source code on SIMD CPUs and on CUDA, HIP and SyCL suitable for Nvidia, AMD and Intel GPUs. Performance results are presented.

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Calculation of neutron electric dipole moment due to the QCD topological term, Weinberg three-gluon operator and the quark chromoelectric moment

Author: Tanmoy Bhattacharya

Co-authors: Vincenzo Cirigliano; Rajan Gupta; emanuele mereghetti; Boram Yoon

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We present results for the neutron electric dipole moment due to the to dimension 4 and dimension 6 gluonic CP violation, and the isovector quark chromoelectric dipole moment using clover valence quarks on HISQ dynamical ensembles. For the gluonic operators, we use the gradient flow scheme to obtain divergence-free continuum results. For the chromoelectric dipole moment operator, we use the unflowed local operator but discuss how the quadratically divergent mixing with the pseudoscalar operator can be controlled non-perturbatively. The connection to the continuum is done using horizontal matching at tadpole-improved tree-level and leading-log running.

The SU(N) running coupling in the twisted gradient flow scheme and volume independence.

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We report on an ongoing study of the running coupling of SU(N) pure Yang-Mills theory in the twisted gradient flow scheme (TGF). The study exploits the idea that twisted boundary conditions reduce finite volume effects, leading to an effective size in the twisted plane that combines the number of colours and the torus period. We test this hypothesis by computing the TGF running coupling and the SU(N) Lambda parameter on asymmetric lattices of size $(NL)^2 \times L^2$ for various gauge groups. Finite volume effects are monitored by analyzing the coupling in different planes and by comparing results at different number of colours.

Stout-smearing and $c_{SW}$ at one loop order

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The one-loop determination of the coefficient $c_{SW}$ of the Wilson quark action has been useful, in conjunction with non-perturbative determinations of $c_{SW}$, to push the leading cut-off effects for on-shell quantities to $O(\alpha^2 a)$, or eventually $O(a^2)$, if no link-smearing is employed. These days it is common practice to include some link-smearing into the definition of the fermion action. Unfortunately, in this situation only the tree-level value $c_{SW}^{(0)} = 1$ is known, and cut-off effects start at $O(\alpha a)$. We present some general techniques for calculating one loop quantities in lattice perturbation theory which continue to be useful for smeared-link fermion actions. Specifically, we discuss the application to the 1-loop improvement coefficient $c_{SW}^{(1)}$ for stout-smeared Wilson fermions.
New approach to lattice QCD at finite density: reweighting without an overlap problem

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All methods currently used to study finite baryon density lattice QCD suffer from uncontrolled systematic uncertainties in addition to the well-known sign problem. We formulate and test a method - sign reweighting - that works directly at finite chemical potential and is yet free from any such uncontrolled systematics: with this approach the only problem is the sign problem itself. In practice the approach involves the generation of configurations with the positive fermionic weights $|\text{Re} \det D(\mu)|$ where $D(\mu)$ is the Dirac matrix and the signs $\text{sign}(\text{Re} \det D(\mu)) = \pm 1$ are handled by a discrete reweighting. Hence there are only two sectors, $+1$ and $-1$ and as long as the average $\langle \pm 1 \rangle \neq 0$ (with respect to the positive weight) this discrete reweighting has no overlap problem - unlike other reweighting methods - and the results are reliable. We will also present results based on this algorithm on the phase diagram of lattice QCD with two different actions: as a first test, we apply the method to calculate the position of the critical endpoint with unimproved staggered fermions at $N_\tau = 4$; as a second application, we study the phase diagram with 2stout improved staggered fermions at $N_\tau = 6$. This second one is already a reasonably fine lattice - relevant for phenomenology.

Lattice QCD calculation of the two-photon exchange contribution to the muonic-hydrogen Lamb shift

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The measurement of muonic-hydrogen spectroscopy provides the most precise determination of the proton charge radius, where the two-photon exchange contribution plays an important role in the understanding of $\mu H$ spectroscopy. We will report a lattice QCD calculation of the two-photon exchange contribution by constructing the proton four-point correlation function.

Estimation of the photon emission rate of the quark-gluon plasma

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We present results for the photon emission rate determined from the transverse channel vector correlator at fixed spatial momentum using two-flavor dynamical Wilson fermions at $T \sim 250$ MeV. We estimate the transverse channel spectral function using the continuum extrapolated correlator by applying various fit ansätze with a smooth matching to the NLO perturbative result. We confront our estimate based on this channel with the latest results of our collaboration based on the difference of the transverse and longitudinal channels.

Poster / 246

D6: Is there gender/race bias in hep-lat publications?

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In this work, we take all the papers since 2000 that are classified as primary hep-lat to study whether there is any race or gender bias in the journal-publication process. We implement machine learning to predict the race and gender of authors based on their names, and look for measurable differences between publication outcomes based on author category. We would like to invite discussion on how journals can make improvements in the near future and how institutions or grant offices should account for these publication differences in gender and race.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 247

Model Independent Error Mitigation in Parametric Quantum Circuits and Depolarizibility of Quantum Noise

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Finding ground states and low-lying excitations of Hamiltonians is one of the most important problems that can be solved with near-term quantum computers. It can be utilized in fields ranging from optimization over chemistry and material science to particle physics. In this work, we propose an efficient error mitigation scheme that is independent of the Hamiltonian and the concrete noise model, applicable to low-depth quantum circuits as they occur in Variational Quantum Eigensolvers (VQE). In principle, our method can eliminate all systematic errors by exploring the depolarizibility of quantum noise up to certain approximations. We carry out both classical simulations and experiments on the IBM’s quantum hardware, to illustrate the performance of the method by computing the mass gap of transversal Ising model and extracting its the zero-temperature critical point.
From tensors to qubits

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We discuss recent progress in Tensor Lattice Field Theory and economical, symmetry preserving, truncations suitable for quantum computations/simulations. We focus on spin and gauge models with continuous Abelian symmetries such as the Abelian Higgs model and emphasize noise-robust implementations of Gauss’s law. We discuss recent progress concerning the comparison between field digitizations and character expansions, symmetry breaking in tensor language, wave-packet preparation and possible new implementations of Abelian models using Rydberg atoms.

QCD at nonzero Temperature and Density

Effect of stout smearing on the phase diagram from multiparameter reweighting in lattice QCD

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The phase diagram and the location of the critical endpoint of lattice QCD was determined earlier with unimproved staggered fermions on a Nt=4 lattice with the multiparameter reweighting method by studying Fisher zeros. In our recent work, as an extension of the old analysis we introduced stout smearing in the fermion action in order to reduce the finite lattice spacing effects. In this talk we will show that increasing the smearing parameter ρ the crossover at μ=0 gets weaker, i.e., the leading Fisher zero gets farther away from the real axis. Furthermore as the chemical potential is increased the overlap problem gets severe sooner than in the unimproved case, therefore shrinking the range of applicability of the method. Nevertheless, even after introducing the smearing certain qualitative features remain, which will be discussed in this talk.

Standard Model Parameters

Determination of the light, strange and charm quark masses using twisted mass fermions

Author: Constantia Alexandrou

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We present recent results on quark masses using $N_f=2+1+1$ clover-improved twisted mass fermion gauge ensembles simulated by the Extended Twisted Mass Collaboration. The renormalized light, strange and charm quark masses are evaluated in isospin-symmetric QCD and different mesonic and baryonic inputs are used to set the scale and define the physical point, thus providing a consistency checks on the results.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 251

The basics and applications of the tempered Lefschetz thimble method for the numerical sign problem

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The numerical sign problem is one of the major obstacles to the first-principles calculations for important physical systems, such as finite-density QCD, strongly-correlated electron systems and frustrated spin systems, as well as for the real-time dynamics of quantum systems. The tempered Lefschetz thimble method (TLTM) [1] was proposed as a versatile algorithm towards solving the numerical sign problem. There, the integration region is deformed into the complex space according to the antiholomorphic gradient flow equation, and the system is tempered using the flow time as a tempering parameter so as to solve both the sign and ergodicity problems simultaneously.

In this talk, I first summarize Monte Carlo approaches to the sign problem, including the methods based on the complex Langevin equation and those on the Lefschetz thimbles. I then focus on the TLTM and explain the basics of the algorithm. I demonstrate the effectiveness and versatility of the algorithm by showing its successful applications to various models, such as the $(0+1)$-dimensional massive Thirring model [1], the Hubbard model away from half filling [2,3], and the Stephanov model (a chiral random matrix model) [4]. I also explain some of the recent improvements in the algorithm [3,4].


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Logarithmic corrections to $\alpha^2$ scaling in lattice QCD with Wilson and GW quarks

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We analyse the leading logarithmic corrections to the $a^2$ scaling of lattice artefacts in QCD, following the seminal work of Balog, Niedermayer and Weisz in the O(n) non-linear sigma model. Limiting to contributions from the action, the leading logarithmic corrections can be determined by the anomalous dimensions of mass-dimension 6 operators. These operators form a minimal on-shell basis of the Symanzik Effective Theory. We present results for non-perturbatively O($a$) improved Wilson and Ginsparg-Wilson quarks.

**Hadron Structure / 253**

**The systematic effects study in lattice calculation of soft function**

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The transverse momentum dependent soft function introduced to describe soft-gluon effects plays an important role in QCD factorization. We present a lattice QCD study on this function by simulating pion matrix element and quasi TMD wave function using the large momentum effective theory. The momenta we adopted are up to 3 GeV. Various systematic effects are examined in our study.

**QCD in searches for physics beyond the Standard Model / 254**

**BSM $B - \bar{B}$ mixing**

**Author:** Felix Erben\(^1\)

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We are presenting our ongoing Lattice QCD study on $B - \bar{B}$ mixing on several RBC/UKQCD and JLQCD ensembles with 2+1 dynamical-flavour domain wall fermions, with a range of inverse lattice spacings from 1.7 to 4.5 GeV and including physical-pion-mass ensembles. We compare various different fitting strategies to extract bag parameters $B_{B_d}$ and $B_{B_s}$ both for the standard-model operator as well as the four BSM operators. On each ensemble, we are simulating a range of heavy-quark masses from below the charm-quark mass towards the bottom-quark mass, with one data point reaching about 75% of $m_{\eta_b}$.

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**The muon g-2 with four flavors of staggered quarks**
The 38th International Symposium on Lattice Field Theory / Book of Abstracts

**Authors:** Christopher Aubin\(^1\), Thomas Blum\(^2\), Maarten Golterman\(^3\), Santiago Peris\(^3\)

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We present updated results for the light-quark connected part of the leading hadronic contribution to the muon g−2 from configurations with 2+1+1 flavors of HISQ quarks using the time-momentum representation of the electromagnetic current correlator. We have added statistics on two ensembles as well as a fourth lattice spacing using configurations that have been generated by the MILC collaboration at the physical pion mass. Additionally we account for the leading finite-volume and taste-breaking effects using Staggered Chiral Perturbation Theory at NNLO.

**Standard Model Parameters / 256**

**Quark mass RG-running for \(N_f = 3\) QCD in a \(\chi\)SF setup**

**Authors:** Isabel Campos Plasencia\(^1\), Mattia Dalla Brida\(^2\), Giulia Maria de Divitiis\(^3\), Andrew Lytle\(^4\), Mauro Papinutto\(^5\), Ludovica Pirelli\(^6\), Tassos Vladikas\(^\text{None}\)

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We perform the complete non-perturbative running of the quark mass from hadronic to electroweak scales in \(N_f = 3\) massless QCD. In the present work we use the same configuration ensembles used for a similar calculation arXiv 1802.05243, subject to Schrödinger Functional (SF) boundary conditions, whereas we use valence quarks with (\(\chi\) SF) boundary conditions, which results in O(a) improvement for observables after tuning of boundary counterterms. We establish the optimal tuning strategy for the critical hopping parameter \(\kappa_{\text{crit}}\) and the \(\chi\)SF boundary counterterm coefficient \(z_f\). Following the recent Alpha strategy, we work in two different energy regimes: at high energies (\(\mu > \sim 2\text{GeV}\)) we use a SF-type coupling, while at low energies (\(\mu < \sim 2\text{GeV}\)) a Gradient Flow (GF)-type coupling.

**Standard Model Parameters / 257**

**Operator renormalization & improvement for \(N_f = 3\) QCD in a \(\chi\)SF setup**

**Authors:** Isabel Campos Plasencia\(^1\), Mattia Dalla Brida\(^2\), Giulia Maria de Divitiis\(^3\), Andrew Lytle\(^4\), Mauro Papinutto\(^5\), Ludovica Pirelli\(^6\), Tassos Vladikas\(^\text{None}\)

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We present our progress in the non-perturbative $O(a)$ improvement and renormalisation of quark operators in three-flavour lattice QCD with Wilson-clover fermions. We employ the chirally rotated Schrödinger functional scheme in finite volumes. Our calculations cover both weak- and strong-coupling regions for the RG-running, where step scaling functions are computed.

**Standard Model Parameters / 258**

$B_c \to J/\psi$ and $B_s \to D_s^*$ Decays with Lattice QCD

**Authors:** Judd Harrison$^1$; Christine Davies$^1$

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We present the results of HPQCD’s recent calculation of the $B_c \to J/\psi$ semileptonic form factors and $R(J/\psi)$ for the first time from lattice QCD using the heavy-HISQ method. We also present results from lattice QCD, using the heavy-HISQ method, for the $B_s \to D_s^*$ semileptonic form factors and $R(D_s^*)$. We give a value for $|V_{cb}|$ computed using our results for the full kinematic range of $B_s \to D_s^*$ decay along with LHCb measurements. We also give a comparison between our results and experimental measurements of the differential shape of the decay rate and related parameters.

**Hadron Spectroscopy and Interactions / 259**

String breaking in $N_f=2+1$ QCD

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We extend our study of the static potential in $N_f=2+1$ QCD to determine its quark mass dependence. We use a set of CLS (Coordinated Lattice Simulations) ensembles at a lattice spacing $a=0.064$ fm along a chiral trajectory of constant sum of the bare quark masses. The pion masses range from $m_\pi = 420$ MeV at the symmetric point down to $m_\pi = 200$ MeV. We use a model to parametrize the lowest three static potentials in the region where string breaking occurs due to formation of a pair of static-light or static-strange mesons. We find that the model works very well at all quark masses analyzed and discuss the dependence of its parameters as the quark mass is varied.
Study of a lattice 2-group gauge model

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Gauge theories admit a generalisation in which the gauge group is replaced by a finer algebraic structure, known as a 2-group. The first model of this type is a Topological Quantum Field Theory introduced by Yetter. I would like to discuss a common generalisation of both the Yetter’s model and Yang-Mills theory. I will focus on the lattice formulation of such model for finite 2-groups. After describing the model I will mention its integrable limits and state some basic expectations about its dynamics.

Hadron Spectroscopy and Interactions / 261

Analytic Expansions of Two- and Three-Particle Excited-State Energies

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The last years have seen significant developments in methods relating two- and three-particle finite-volume energies to scattering observables. These relations hold for both weakly and strongly interacting systems, and studying their predictions in limiting cases can provide important cross checks as well as giving useful insights to the general formulae. In this talk, I present analytic results for finite-volume excited states, including moving frames, recovered by expanding the general relations in powers of the interaction strength. In particular, I highlight the elegant patterns that are predicted, especially for excited three-particle energies, and discuss various applications of the results.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 262

Generalization capabilities of neural networks in lattice applications

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In recent years, the use of machine learning has become increasingly popular in the context of lattice field theories. An essential element of such theories is represented by symmetries, whose inclusion in the neural network properties can lead to high reward in terms of performance and generalizability. A fundamental symmetry that usually characterizes physical systems on a lattice with periodic boundary conditions is equivariance under spacetime translations. In this talk we investigate the
advantages of adopting translationally equivariant neural networks in favor of non-equivariant ones [1]. The system we consider is a complex scalar field with quartic interaction on a two-dimensional lattice in the flux representation, on which the networks carry out various regression and classification tasks. Promising equivariant and non-equivariant architectures are identified with a systematic search. We demonstrate that in most of these tasks our best equivariant architectures can perform and generalize significantly better than their non-equivariant counterparts, which applies not only to physical parameters beyond those represented in the training set, but also to different lattice sizes.


Vacuum Structure, Confinement, and Chiral Symmetry / 263

Complex poles of Landau-gauge QCD propagators and general properties

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We study analytic structures of the gluon, quark, and ghost propagators in the Landau-gauge QCD and general properties from the existence of unusual singularities. First, we investigate analytic structures of the QCD propagators using the massive Yang-Mills model, in which the one-loop gluon and ghost propagators are in good agreement with the numerical lattice results in the Landau gauge. We find that both gluon and quark propagators in this model have complex poles that invalidate the usual spectral representation. Second, we discuss general properties of propagators in the presence of such complex singularities, especially on the positivity and locality. Finally, we consider a possible quantum mechanical interpretation and implications on a confinement mechanism.

Standard Model Parameters / 264

Charm quark mass determination from $N_f = 2+1$ QCD with Wilson fermions

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We have recently performed a determination of the charm quark mass on $N_f = 2+1$ CLS ensembles of non-perturbatively improved Wilson fermions. The extrapolation to the chiral and continuum limits is performed using 5 lattice spacings ranging roughly from 0.09 down to 0.04 fm and pion masses from 420 MeV to 130 MeV. The spatial extent of the ensembles is generally at least $4/M_{\pi}$. We will present the preliminary results of this analysis for the renormalization-group invariant charm quark mass and the ratio $m_c/m_s$. In this talk, we will discuss the various analysis strategies we
considered, including the fitting procedure, corrections for the correlations in the data, and the chiral-continuum extrapolation.

Particle physics beyond the Standard Model / 265

Topology and scale setting for $Sp(2N)$ pure gauge theories

Author: Davide Vadacchino

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$Sp(2N)$ gauge theories are potentially relevant in the context of Composite Higgs Models and provide an alternative sequence to the more widely studied $SU(N)$ and $SO(N)$ groups in the investigation of the large-N limit of Yang-Mills theories.

In this contribution, we report on our study of the scale setting and of the topological features of the vacuum of $Sp(2N)$ lattice (pure) gauge theories using the Wilson Flow. We measure the topological susceptibility and the value of the scales $t_0$ and $w_0$ for a range of inverse couplings at $N = 1, 2, 3, 4$. The continuum and large-N limits of these quantities are discussed and compared to the results obtained in $SU(N)$ lattice gauge theories.

Hadron Spectroscopy and Interactions / 266

Properties and ensembles of Stabilised Wilson Fermions

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In this contribution we announce the formation of a new initiative to study Stabilised Wilson Fermions (SWF). They are an interesting new avenue for QCD calculations with Wilson fermions and we report results on our continued study of this framework: Tuning the clover improvement coefficient we extend the reach of lattice spacings to $\alpha = 0.055, 0.064, 0.080, 0.094, 0.12$ fm. We further tune their flavor symmetric points $m_\pi = m_K = 412$ MeV and define the trajectories to the physical point by fixing $TrM$. Currently our pion mass range extends down to $m_\pi \approx 180 - 200$ MeV. Results on control observables, such as the Dirac eigenvalue distribution, reweighting factors, etc., are shown. An accompanying talk by G. Pederiva will focus on spectroscopic observables. Taken together we
observe the approach enables us to perform stable lattice simulations across a large range of parameters in mass, volume and lattice spacing. Pooling resources our new initiative has made our reported progress possible and through it we will share generated gauge ensembles under an open science philosophy.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 267**

**Benchmarking the performance of readout error mitigation through classical bit-flip correction on IBM and Rigetti devices**

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Readout errors are among the most dominant sources of error on current noisy intermediate-scale quantum devices. Recently an efficient, scaleable method for mitigating such errors has been developed. Here, we benchmark this correction protocol on IBM’s and Rigetti’s quantum devices. Measuring observables in the computational basis, we demonstrate how the mitigation procedure improves the results with only modest overhead cost. In particular, we examine the variances of the noisy original and the mitigated data. Our hardware results show good agreement with the theoretical prediction and that the increase in variance due to the mitigation procedure is only moderate.

**Hadron Structure / 268**

**Valence structure of pion: physical mass, chiral quarks**

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We study pion valence structure from lattice QCD using three mixed action ensembles including a physical pion mass with fine lattice spacings of a = 0.04, 0.06 and 0.076 fm. Our analysis use ratio-based scheme and hybrid scheme to renormalize the equal-time bilocol quark-bilinear matrix elements. We extract first few moments and reconstruct the x-dependent PDF using NNLO leading-twist perturbative matching formula, and investigate the mass dependence as well as approaching continuum limit. Two Domain-Wall ensembles are used to cross check our estimate.
Higher partial wave contamination in finite-volume formulae for 1-to-2 transitions

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It is common practice to truncate the finite-volume formula for K to pi pi, and other one to two transitions, to only include the lowest partial wave, as in the original derivation by Lellouch and Lüscher. However, as the precision of lattice calculations increases, it may become important to assess the systematic effect of this approximation. With this motivation, we compare the S-wave-only ($\ell = 0$) results with those truncated at the next lowest value of angular momentum. Using the general framework for $1+j \rightarrow 2$ transitions we look at the zero-momentum case, with both periodic and twisted boundary conditions (both of which couple to $\ell = 4$) and the moving frame case (which leads to mixing with $\ell = 2$). In addition to general estimates for various scattering parameters, we also give quantitative results for realistic $\pi\pi$ amplitudes.

E4: Performance of several Lanczos eigensolvers with HISQ fermions

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Recent improvements in the numerical lattice simulation have been achieved by making use of the eigenvalue spectrum of the lattice Dirac operator or its variants. The Lanczos algorithm has been employed for that purpose, and the lattice community has studied its improvements with different approaches. We investigate state-of-the-art Lanczos eigensolvers available in the Grid and the QUDA libraries, which include Implicitly Restarted Lanczos, Multi-Grid Lanczos (or Local Coherence Lanczos), Block Lanczos, and Thick Restarted Lanczos. We measure and analyze their performances with the HISQ Dirac operator.

The truncated U(1) Abelian Higgs model and implications for its quantum simulation

Author: Jin Zhang¹

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We have proposed a concrete experimental setup for quantum simulating the \((1 + 1)\)-dimensional Abelian Higgs model in J. Zhang et al. (2018), where the Hamiltonian in the electric field representation can be implemented on a multi-leg ladder with a single atom in each rung. The finite-size scaling of the energy gap can be measured and its universal behavior can be extracted at large enough spin truncations. However, the O(2) limit of this representation is always gapped for any finite spin-\(S\) truncation, and the dynamics of charges cannot be measured directly. We now study the charge representation of the O(2) model in detail with tensor renormalization group applied to the Lagrangian and level spectroscopy applied to the Hamiltonian. We find that there is an infinite-order Gaussian transition for spin-1 truncation, and there are Berezinskii–Kosterlitz–Thouless transitions for \(S \geq 2\) truncations. We find universal functions relating the mass gap, the gauge coupling, and the spatial size in the smallest spin truncations, which do not exist in the field representation. Possible experimental realizations are discussed.

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B-meson semileptonic decays with highly improved staggered quarks

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We present new results on heavy meson semileptonic decays using the highly improved staggered quark (HISQ) action for both valence and 2+1+1 sea quarks. The use of the highly improved action, combined with the MILC collaboration’s gauge ensembles with lattice spacings down to \(-0.042\) fm, allows the b quark to be treated with the same discretization as the lighter quarks. This unified treatment of the valence quarks allows for absolutely normalized currents (in some cases), bypassing the need for perturbative matching, which is a leading source of uncertainty in previous Fermilab/MILC calculations of B-meson decay form factors.

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Truncation effects in dual representations of the O(2) model

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The classical O(2) model is the zero-gauge-coupling limit of compact scalar quantum electrodynamics in Euclidean spacetime. We obtain two dual representations of the O(2) model, where the field quantum numbers on the plaquettes determine the charge quantum numbers on the links according to Gauss’s law. Taking the time continuum limit, we study the Hamiltonians in the two representations with a truncation to "spin $S$", where the quantum numbers have an absolute value less or equal to $S$. In the infinite-$S$ limit the spectra of the two Hamiltonians are identical however for quantum simulations, truncations are needed. The field representation is always gapped for finite spin truncations, while the charge representation preserves the gapped-to-gapless transition even for the smallest spin truncation $S = 1$. We show that the essential singularity in the correlation length for the $S = 1$ truncation is different from that for $S \geq 2$ truncations, where there are real Berezinskii–Kosterlitz–Thouless transitions. Using the ansatz for the scaling of the energy gap, the fidelity susceptibility, and the derivative of the entanglement entropy with respect to the coupling constant, we can extract the location of the infinite-order transitions with high accuracy.

**Standard Model Parameters / 274**

**Charmed semileptonics with twisted-mass valence quarks**

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Our charm program uses a mixed action with twisted-mass valence quarks over non-perturbatively improved Wilson sea quarks, in order to study various quantities in a relativistic and manifestly local framework of full QCD. The sea sector consists of $N_f = 2 + 1$ ensembles generated by the CLS initiative. Thanks to open boundary conditions, this offers access to fine ensembles without topological freezing. In this talk I will more particularly present our current progress on $D \to K\nu l$ and $D \to \pi\nu l$ semileptonics. Those are mainly useful for the computation of the CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$. As we will see, all discretisation effects seem to be reasonably under control with this choice of action, in particular those related to hypercubic lattice artefacts. Eventually, we obtain preliminary results of the form factors as a very smooth curve on the whole range of momentum transfer, and in particular the signal at zero $q^2$ appears to have the potential to be competitive with earlier published results.

**QCD at nonzero Temperature and Density / 275**

**Inhomogeneous phases in 1+1 dimensional Gross-Neveu models at finite number of flavors on the lattice**

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Four-fermion theories are widely appreciated as toy models for QCD and are also used in numerous condensed-matter applications. We investigate such theories, namely the 1+1 dimensional (chiral)
Gross-Neveu models, at finite temperature and density, where mean field studies predict the existence of inhomogeneous phases, i.e., phases where the chiral condensate has a non-trivial spatial dependence. We discuss the fate of these phases when going to a finite number of fermion flavors on the lattice.

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QCD thermodynamics at nonzero isospin asymmetry

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We study the thermodynamic properties of QCD at nonzero isospin chemical potential using improved staggered quarks at physical quark masses. In particular, we will discuss the determination of the equation of state at zero and nonzero temperatures and show results towards the continuum limit. Based on the results for the isospin density $n_I$, the phase diagram in the $(n_I, T)$-plane will also be discussed.

Hadron Spectroscopy and Interactions / 277

First Results of the Hadron Spectrum from Stabilised Wilson Fermions

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We present preliminary results of lattice QCD simulations with dynamical light and strange quarks, all flavors defined using Stabilised Wilson Fermions (SWF). The ensembles are tuned, see the preceding talk by A. Francis, at the flavor symmetric point $m_\pi = m_K = 412$ MeV and the physical point is reached keeping fixed the trace of the quark mass matrix. We show a first determination of the hadron spectrum at 3 different lattice spacings ($\alpha = 0.064, 0.094, 0.12$ fm) and with pion masses ranging in $m_\pi \simeq 200 - 400$ MeV. This allows a first study of cutoff effects with this new lattice action and serves to check the quality of the action for precision measurements. We also investigate other quantities such as flowed gauge observables to study how the continuum limit is approached under basic conditions.
Our collaboration will share the gauge configurations following an open science philosophy so these results will also serve as benchmarks for future determinations.

QCD in searches for physics beyond the Standard Model / 278

Towards determining the short-distance contribution to neutrinoless double-beta decay from lattice QCD.

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Observation of neutrinoless double-beta (0\(\nu\beta\beta\)) decay, a beyond the standard model process that violates lepton number conservation, would imply that neutrinos are Majorana fermions. In order to draw reliable conclusions from the current experimental limits and potential future discoveries, it is important to reduce the uncertainties in the theoretical predictions of its decay rate. A major contribution to these uncertainties comes from the effective field theories (EFT) matched \textit{ab initio} nuclear many-body calculation of its nuclear matrix element. It was pointed out recently that the leading order EFT amplitude of the subprocess \(nn \rightarrow pp(\ell\ell)\) in the simplest scenario of light neutrino exchange remains undetermined due to an unknown contribution from a newly identified short-range operator. Lattice quantum chromodynamics (LQCD) is the only way to directly and reliably determine the associated low-energy constant. We provide here a formalism to obtain the physical \(nn \rightarrow pp(\ell\ell)\) decay amplitude, and hence the missing contribution, from the LQCD calculation of the correlation function for this process. The complications arising from the Euclidean and finite-volume nature of the corresponding correlation functions are fully resolved, and the result of this work, therefore, can be readily employed in the ongoing LQCD studies of this process.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 279

Prediction and compression of lattice QCD data using machine learning algorithms on quantum annealer

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We present regression and compression algorithms for lattice QCD data utilizing the efficient binary optimization ability of quantum annealers. In the regression algorithm, we encode the correlation between the independent and dependent variables into a dictionary optimized for sparse reconstruction. The trained correlation pattern is used to predict lattice QCD observables of unseen lattice configurations from other observables measured on the lattice. In the compression algorithm, we define a mapping from lattice QCD data of floating-point numbers to the binary coefficients that closely reconstruct the input data from a set of basis vectors. Since the reconstruction is not exact, the mapping defines a lossy compression, but, a reasonably small number of binary coefficients are able to reconstruct the input vector of lattice QCD data with the reconstruction error much smaller than the statistical fluctuation. In both applications, we use D-Wave quantum annealers to solve the NP-hard binary optimization problems of the machine learning algorithms.
Open Lattice Field Theory

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The paradigm of effective field theory is one of the most powerful tools available in physics. While most commonly employed in parametrizing renormalization group flow, it is also of great utility in describing dispersive systems such as $K_0 - \bar{K}_0$ states that both oscillate and decay. Of particular interest for the lattice community is the study of field theories off the real axis of coupling constants. This is important for behavior at finite chemical potential as well as in the study of critical phenomena more generally. These models can exhibit a rich phenomenology, such as non-unitary critical points and steady-state attractors. We describe a mapping of an arbitrary dispersive bosonic lattice effective theory onto a class of unitary system + environment models that are amenable to simulation on quantum machinery, and discuss how certain aspects can be studied even on near-term noisy hardware.

Toward Quantum Simulations using Discrete Subgroup Approximations

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The possibility for near-term quantum simulations in lattice field theory depends upon efficiently using the limited resources available. In this talk, we will discuss how approximating lattice gauge theories like SU(3) with discrete subgroups can be theoretically analyzed as a lattice effective field theory. Further, methods for implementation upon quantum hardware will be covered. Numerical results for Euclidean calculations for U(1) and SU(3) subgroups will be presented with modified and improved actions that relate to Hamiltonians other than Kogut-Susskind’s.

Form factors for semileptonic Bs to K and Bs to Ds decays

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Semileptonic Bs to K and Bs to Ds decays provide additional channels to determine the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$ or to investigate lepton flavour universality violation in R-ratios comparing decays with heavy or light final state leptons. We calculate the decay form factors using domain-wall light, strange and charm quarks, with the Columbia formulation of the RHQ action for the b-quark. Form factors $f^+$ and $f_0$ are obtained with full error budgets at q-squared values spanning the range accessible in our simulations. Fits to z-parametrisations extend our results to the entire allowed kinematic range. We compute differential branching fractions and two forms of R-ratios.
Quantum Algorithms for Open Lattice Field Theories

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Some aspects of quantum systems with non-unitary dynamics are well-described by non-Hermitian effective Hamiltonians. Such systems contain a wealth of interesting physics such as their phase structure, e.g., QCD at finite Baryon density, which describes cores of neutron stars. Classical simulation of general non-Hermitian Hamiltonians is rendered difficult, and in some cases, impossible due to the sign problem. Quantum computers offer the promise of solving this issue, but contemporary quantum computers in the Noisy Intermediate Scale Quantum (NISQ) era are not capable of simulating complicated field theories. Simpler, open field theories on small lattices, with the axiom of locality/sparsity, however, are amenable for simulation on near-term devices. We simulate non-unitary dynamics by embedding the system of interest in a larger unital one via ancillary qubits and use measurements on the ancillas to extract the desired dynamics. The price of doing this are the inevitable quantum jumps, which put the system in an error state. In this talk, two measurement-based prescriptions will be presented for simulating general non-Hermitian Hamiltonians. We apply these quantum channels to the well-studied 1-D quantum Ising chain with an imaginary longitudinal magnetic field and show that the channels are sensitive to the exceptional points, which in the thermodynamic limit corresponds to the Lee-Yang Edge singularity, despite quantum jumps.

QCD in searches for physics beyond the Standard Model

Neutron Electric Dipole Moment with Enhanced Low Mode Statistics

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We will present preliminary findings on improving the lattice calculation of the neutron electric dipole moment from the $θ$ term in QCD. The neutron EDM is highly correlated with the lowest lying modes of the Dirac operator. We take advantage of this with a full volume sampling for the low mode part of the quark propagator in order to increase statistics. This augments the all-mode averaging technique using a large number of sources for each configuration. We use the method of measuring the energy shift of the two-point correlation function in a uniform background electric field. Initial results are for a $16^3 × 32$ ensemble of domain-wall fermions at $m_π = 420$ MeV.

QCD at nonzero Temperature and Density

Absence of inhomogeneous phases in the $2 + 1$-dim. Gross-Neveu model with chiral imbalance
In a previous work the regulator dependence of inhomogeneous phases in the $2 + 1$-dimensional Gross-Neveu model has been studied within the mean-field approximation. These are phases, where in addition to chiral symmetry also translational symmetry is broken. Inhomogeneous condensates are a feature shared among various strong-interaction models and not unique to the $2 + 1$-dimensional Gross-Neveu model. In this talk, a chiral chemical potential is introduced to the GN model in addition to finite temperature and chemical potential. The effects on the homogeneous as well as on inhomogeneous phases are studied using two lattice discretizations with naive fermions. The phase diagram is presented and the existence of inhomogeneous phases is ruled out.

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**E5: Pion and Kaon form factors using twisted-mass fermions**

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We present a calculation of the pion and kaon form factors and generalized form factors using matrix elements of local operators. We use an ensemble of two degenerate light, a strange and a charm quark ($N_f=2+1+1$) of maximally twisted mass fermions with clover improvement. The quark masses are chosen so that they reproduce a pion mass of about 260 MeV, and a kaon mass of 530 MeV. The lattice spacing of the ensemble is 0.093 fm and the lattice has a spatial extent of 3 fm. We analyze several values of the source-sink time separation within the range of 1.12 – 2.23 fm to study and eliminate excited-states contributions. We compare the results for the pion and kaon to assess the level of the SU(3) flavor symmetry breaking.

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**E6: x-dependence of twist-3 GPDs from lattice QCD**

**Authors:** Jack Dodson$^1$; Shohini Bhattacharya$^1$; Krzysztof Cichy$^2$; Martha Constantinou$^1$; Andreas Metz$^2$; Aurora Scapellato$^1$; Fernanda Steffens$^3$

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"Calculating the x-dependence of PDFs and GPDs from lattice QCD has become feasible in the last years due to novel approaches. In this work, we employ the quasi-distributions method, which
relies on matrix elements of non-local operators, matched to the light-cone distributions using Large Momentum Effective Theory (LaMET). In this presentation, we focus on results for the first-ever lattice QCD calculation of twist-3 GPDs. The calculation is performed using one ensemble of two degenerate light, a strange and a charm quark ($N_f = 2 + 1 + 1$) of maximally twisted mass fermions with a clover term, reproducing a pion mass of 260 MeV.

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**First study of twist-3 PDFs and GPDs for the proton from Lattice QCD**

**Authors:** Shohini Bhattacharya\(^1\); Krzysztof Cichy\(^{None}\); Martha Constantinou\(^1\); Andreas Metz\(^1\); Aurora Scapellato\(^1\); Fernanda Steffens\(^{None}\)

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The non-perturbative part of the cross-section of high-energy processes may be expanded in terms of the process’s large energy scale. This gives rise to a tower of distribution functions, labeled by their twist (mass dimension minus spin). The leading twist (twist-2) contributions have been at the center of experimental measurements, theoretical investigations, and lattice QCD calculations. It has been recognized that twist-3 contributions to distribution functions can be sizable and should not be neglected. However, it is challenging to disentangle them experimentally from their leading counterparts, posing limitations on the structure of the proton.

In this talk, we will present selected results on the $x$-dependence of the proton twist-3 PDFs $g_T(x)$ and $h_L(x)$. We will also show the first results on the twist-3 helicity GPDs for selected values of the momentum transfer. All calculations have been performed using the quasi-distributions method, and the lattice data are matched to the light-cone distributions using the LaMET framework. We use one ensemble of two degenerate light, a strange and a charm quark ($N_f=2+1+1$) of maximally twisted mass fermions with a clover term, reproducing a pion mass of 260 MeV.

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**E7: Efficiency Study of Overrelaxation and Stochastic Overrelaxation Algorithms for SU(3) Landau Gauge-Fixing**

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As part of our study of two-point functions in SU(3) lattice gauge theory, we have carried out a comparative analysis of Landau Gauge Fixing algorithms, which complements similar existing studies for the SU(2) case. We present the results of our optimization analysis for the Landau Gauge Fixing overrelaxation and stochastic overrelaxation algorithms. By studying the distribution of necessary sweeps for gauge-fixing of a sample of configurations, we obtain the optimal choice of parameters for these algorithms, as well as their dynamical critical exponent. Finally, we also compare the overall time performance and gauge-fixing quality between the considered algorithms.
Improving Schrödinger Equation Implementations with Gray Code for Adiabatic Quantum Computers

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We reformulate the continuous space Schrödinger equation in terms of spin Hamiltonians. For the kinetic energy operator, the critical concept facilitating the reduction in model complexity is the idea of position encoding. Binary encoding of position produces a Heisenberg-like model and yields exponential improvement in space complexity when compared to classical computing. Encoding with a binary reflected Gray code, and a Hamming distance 2 Gray code yields the additional effect of reducing the spin model down to the XZ and transverse Ising model respectively. We also identify the bijective mapping between diagonal unitaries and the Walsh series, producing the mapping of any real potential to a series of k-local Ising models through the fast Walsh transform. Finally, in a finite volume, we provide some numerical evidence to support the claim that the total time needed for adiabatic evolution is protected by the infrared cutoff of the system. As a result, initial state preparation from a free-field wavefunction to an interacting system is expected to exhibit polynomial time complexity with volume and constant scaling with respect to lattice discretization for all encodings. For the Hamming distance 2 Gray code, the evolution starts with the transverse Hamiltonian before introducing penalties such that the low lying spectrum reproduces the energy levels of the Laplacian. The adiabatic evolution of the penalty Hamiltonian is therefore sensitive to the ultraviolet scale. It is expected to exhibit polynomial time complexity with lattice discretization, or exponential time complexity with respect to the number of qubits given a fixed volume.

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Nucleon Axial Form Factor from Domain Wall on HISQ

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The Deep Underground Neutrino Experiment (DUNE) is an upcoming neutrino oscillation experiment that is poised to answer key questions about the nature of the neutrino. Lattice QCD has the ability to make significant impact upon DUNE by computing the interaction of a nucleon to a weak current. Nucleon amplitudes involving the axial form factor are part of the primary signal measurement process for DUNE, and precise calculations from LQCD can significantly reduce the uncertainty for inputs into Monte Carlo generators. Recent calculations of the nucleon axial charge have demonstrated that sub-percent precision is possible on this vital quantity. In this talk, I will discuss preliminary results for the Callat collaboration’s calculation of the axial form factor of the nucleon. These computations are performed with Möbius domain wall valence quarks on HISQ sea quark ensembles generated by the MILC and Callat collaborations. The results use a variety of ensembles including several at physical pion mass.

QCD at nonzero Temperature and Density / 292

Topology in high-T QCD via staggered spectral projectors

**Authors:** Andreas Athenodorou\(^1\); Claudio Bonanno\(^2\); Claudio Bonati\(^3\); Giuseppe Clemente\(^2\); Francesco D’Angelo\(^4\); Massimo D’Elia\(^5\); Lorenzo Maio\(^5\); Guido Martinelli\(^6\); Francesco Sanfilippo\(^7\); Antonino Todaro\(^8\)
We present preliminary lattice results for the topological susceptibility in high-temperature $N_f = 2+1$ QCD obtained discretizing this observable via spectral projectors on eigenmodes of the staggered operator, and we compare them with those obtained with the standard gluonic definition. The adoption of the spectral discretization is motivated by the large lattice artifacts affecting the continuum scaling of the gluonic susceptibility at high temperatures, related to the choice of non-chiral fermions in the action.

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**Electromagnetic conductivity of quark-gluon plasma at non-zero baryon density**

**Authors:** Anton Trunin$^1$; Artem Vasiliev$^{new}$; Francesco Sanfilippo$^3$; Lorenzo Maio$^3$; Marco Cardin$^1$; Massimo D’Elia$^3$; Nikita Astrakhantsev$^{new}$; Victor Braguta$^5$

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We present our results on the study of the electromagnetic conductivity in dense quark-gluon plasma obtained within lattice simulations with $N_f = 2+1$ dynamical quarks. We employ stout improved rooted staggered quarks at the physical point and the tree-level Symanzik improved gauge action. The simulations are performed at imaginary chemical potential and the Backus-Gilbert method is used to extract the conductivity from current-current correlators. Our preliminary results show an increase of conductivity with real baryon density.

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**E8: Short-distance nuclear matrix elements for neutrinoless double beta decay**

**Authors:** David Murphy$^1$; Patrick Oare$^2$; Phiala Shanahan$^1$

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Neutrinoless double beta decay is a long-sought after process which would provide evidence of lepton number violation in our universe. Computing the rate from first principles requires non-perturbative input in the form of a nuclear matrix element which must be computed on the lattice. This poster will discuss the contribution to this matrix element from short-distance, dimension-9 operators. I will present the methods used to perform the computation, and show some preliminary results in which we evaluate this matrix element on an ensemble of domain-wall fermions for the unphysical $\pi^- \rightarrow \pi^+ e^- e^-$ decay.

Patterns of flavour symmetry breaking in hadron matrix elements involving $u$, $d$ and $s$ quarks

Author: Roger Horsley

Using an SU(3) flavour symmetry breaking expansion between the strange and light quark masses, we determine how this constrains the extrapolation of baryon and meson octet matrix elements and form factors. In particular we can construct certain combinations, which fan out from symmetric point (when all the quark masses are degenerate) to the point when the light and strange quarks take their physical values. As an example we consider vector form factors at various momentum.

Clock model interpolation and symmetry breaking in O(2) models

Author: Leon Hostetler

Co-authors: Jin Zhang; Ryo Sakai; Judah Unmuth-Yockey; Alexei Bazavov; Yannick Meurice

The $q$-state clock model is a classical spin model that corresponds to the Ising model (when $q = 2$) and the XY model (when $q \rightarrow \infty$). The integer-$q$ clock model has been studied extensively and has been shown to have a single phase transition when $q = 2, 3, 4$ and two phase transitions when $q > 4$. We define an extended-$q$ clock model that reduces to the ordinary $q$-state clock model when $q$ is an integer and otherwise is a continuous interpolation of the clock model to non-integer $q$. We investigate this class of clock models in 2D using Monte Carlo (MC) and tensor renormalization group (TRG) methods, and we find that the model with non-integer $q$ has a crossover and a second-order phase transition. We also define an extended-O(2) model (with a parameter $\gamma$) that reduces to the XY model when $\gamma = 0$ and to the extended-$q$ clock model when $\gamma \rightarrow \infty$, and we begin to outline the phase diagram of this model. These models with non-integer $q$ serve as a testbed to study symmetry breaking with tensor methods where experimental parameters can be tuned continuously.
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I=1 pi-pi scattering at the physical point and the long-distance behavior of the vector correlator

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We present a finite volume spectroscopy calculation of I=1 pi-pi scattering utilizing the (stochastic) distillation framework on close to physical and physical point N_f = 2 + 1 CLS ensembles. Using the finite volume energy levels, we discuss the long-distance behavior of the vector correlator, which is dominated by the two-pion channel. This part can be accurately constrained using the reconstructions, which has important consequences for lattice calculations of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment.

DK and Dâbar K scattering and the D*0 (2317) from lattice QCD

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I will discuss some recent lattice QCD calculations of DK and Dâbar K scattering, relevant for the enigmatic D*0(2317), with light-quark masses corresponding to m_{\pi} = 239 MeV and m_{\pi} = 391 MeV. The S-waves contain interesting features including a near-threshold J^P = 0^+ bound state in isospin-0 DK, corresponding to the D_{s0}^*(2317), with an effect that is clearly visible above threshold, and suggestions of a 0^+ virtual bound state in isospin-0 Dâbar K. The S-wave isospin-1 DK amplitude is found to be weakly repulsive. There is a deeply bound D* vector resonance, but negligibly small P-wave DK interactions are observed in the energy region considered; the P and D-wave Dâbar K amplitudes are also small.

Based on material in arXiv:2008.06432
G. K. C. Cheung, C. E. Thomas, D. J. Wilson, G. Moir, M. Peardon, S. M. Ryan, for the Hadron Spectrum Collaboration

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Inhomogeneous phases in the chiral Gross-Neveu model on the lattice

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Understanding of the QCD phase diagram is one of important topics in nuclear and hadron physics. In particular, various possible phase structures are proposed from analyses of effective theories in low temperature and high density region. One of them is inhomogeneous chiral condensate which exhibits characteristic space structures. Since there is no general established method for determination of the structure of the chiral condensate, usually some solutions such as chiral spiral and kink solutions are assumed. On the other hand, the Monte Carlo method in lattice QCD does not work in the low temperature and high density region, because of existent of the notorious sing problem. However, the usual lattice calculation is applicable to the 1+1 Gross-Neveu (GN) model and chiral GN model that have similar property of QCD, since they do not have the sign problem at finite density. Recently the interesting phase structure of the inhomogeneous chiral condensate in the 1+1 dimensional GN model on the lattice has been presented [1].

Here we study the phase structure of the 1+1 dimensional chiral GN model, performing the lattice simulation. Advantage of using the Monte Carlo method is that one can investigate the general space structure of the sigma and pion condensates without any assumption of it. We will discuss the phase diagram of the chiral GN model with finite number of flavors, comparing that of the GN model with finite number of flavors.


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**Nuclear Parity Violation from 4-quark Interactions**

**Authors:** Aniket Sen\(^1\); Marcus Petschlies\(^2\); Nikolas Schlage\(^3\); Carsten Urbach\(^3\)

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We investigate the parity odd $\Delta I = 1$ pion-nucleon coupling $h_{\pi}^I$ from lattice QCD. With the PCAC-based use of a parity-conserving effective Hamiltonian, we extract the coupling by determining the nucleon mass splitting arising from effective 4-quark interactions using the Feynman-Hellmann theorem. We present preliminary results of the mass shift for a $32^3 \times 64$ ensemble of $N_f = 2 + 1 + 1$ twisted mass fermions at pion mass 260 MeV and lattice spacing $a = 0.097$ fm.

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**Simulation of Open LFT**

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Open lattice field theories are useful in describing many physical systems. Yet their implementation in traditional quantum computing is hindered by the requirement of Hermiticity. One method used
to overcome this is embedding the non-Hermitian system within a larger Hermitian system by introducing ancillary qubits. We implement the transverse Ising Model with an addition of an imaginary longitudinal magnetic field. We show for two-qubit systems this method works very well. For larger systems in the NISQ era, a robust noise model is needed. We investigate the robustness to noise of this methodology for larger quantum systems using a QISKIT-based noise model.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 302

From lattice QCD to heavy-flavor in-medium potential via deep learning

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In this work, we obtained the finite temperature Bottomonium interaction potential from the first principle lattice-NRQCD calculation of Bottomonium mass and width [Phys.Lett.B 800, 135119 (2020)]. We find that the HTL complex potential is disfavored by the lattice result, which motives us to employ a model-independent parameterization — the Deep Neural Network (DNN) — to represent the Bottomonium potential, extract the potential allowed by the lattice data.

The DNN is a widely used deep-learning method and can be treated as a model-independent parameterization to approximate arbitrary functional relations. In this work, we employ the DNN to represent the temperature-dependent Bottomonium potential and extract both the real and imaginary parts, $V_R(T, r)$ and $V_I(T, r)$. We find that while $V_I(T, r)$ increase with both temperature and distance, the extracted value is significantly greater than the HTL prediction. Also, while the color-screening effect is observed in $V_R(T, r)$, the temperature dependence is qualitatively weaker than other model calculations. Combined with the lattice result, our study suggests a new picture of Bottomonium dissociation. High excitation of bound states, such as 2P and 3S states, are allowed to exist at a temperature as high as $\sim 0.33$ GeV. Their suppression in the Quark-Gluon Plasma is caused by the temperature-dependent decay width. The latter can be as high as $\sim 0.6$-GeV, which corresponds to the lifetime $\sim 0.3$-fm. Such a new dissociation picture can be tested in precise comparison with Bottomonium observables in heavy-ion collisions.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 303

Tensor renormalization group calculation for the phase structure of the CP(1) model in the presence of a topological term

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We calculate the free energy of the CP(1) model with a topological term using the tensor renormalization group (TRG) method. TRG calculations allow to use large volumes and to determine the phase structure in the presence of the topological term. In this talk, we will focus on the systematic errors appearing in the calculations and compare our results to previous work. Our TRG calculations with controlled systematic errors can reach precise results for mapping out the phase diagram.

Standard Model Parameters / 304

Form factors for $B_c^+ \to D^0 \ell^+ \nu_\ell$ and rare $B_c^+ \to D_s^+ \ell^+ \ell^-$ with HISQ

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We present HPQCD’s results of the first lattice QCD calculation of the weak matrix elements for $B_c^+ \to D^0 \ell^+ \nu_\ell$ facilitated by a $b \to u$ transition. Together with observation of this process from LHCb, our form factors will lead to a new determination of $V_{ub}$. In tandem, we also calculate the form factors for rare $B_c^+ \to D_s^+ \ell^+ \ell^-$. Results are derived from correlation functions computed on MILC Collaboration gauge configurations with three different lattice spacings including 2+1+1 flavours of dynamical sea quarks in the Highly Improved Staggered Quark (HISQ) formalism. HISQ is also used for all of the valence quarks. We cover the full range of $q^2$. The uncertainty on the branching fractions $B(B_c^+ \to D^0 \ell^+ \nu_\ell)$ from the error on our form factors is roughly twice as large as the contribution from the uncertainty on the present PDG value for $V_{ub}$. Prospects for reducing errors on our form factors are discussed which will guide future calculations, setting out the path towards highly precise determinations of the form factors.

Theoretical developments and applications beyond particle physics / 305

Chiral and Large $N_c$ limit of QCD

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We present preliminary results for a lattice study of the chiral and continuum limit of pseudoscalar mass and decay constant for $SU(N_c)$ gauge theory with $N_c = 3, 4, 5$ colors and $N_f = 2$ degenerate fermions. Clover fermions are used. We fit these observables to predictions of Wilson chiral perturbation theory. Model-averaging is used to determine an appropriate range of quark masses for the fits. We extrapolate our results to large $N_c$. The goal is to produce continuum numbers for the large $N_c$ limit of QCD, and to compare our results with other approaches to this limit.

Vacuum Structure, Confinement, and Chiral Symmetry / 306

Phases at finite winding number of an Abelian lattice gauge theory
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Pure gauge theories are rather different from theories with pure scalar and fermionic matter, especially in terms of the nature of excitations. For example, in scalar and fermionic theories, one can create ultra-local excitations. For a gauge theory, such excitations need to be closed loops that do not violate gauge invariance. In this talk, we present a study on the condensation phenomenon associated with the stringy excitations of an Abelian lattice gauge theory. These phenomena are studied through numerical simulations of a U(1) quantum link model in 2+1 dimensions in a ladder geometry using matrix product states. We will give a numerical demonstration of the presence of the string excitations in the ground states.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 307**

**Real Time Dynamics At Large N**

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The lattice formulation of finite-temperature field theory is readily extended, via the Schwinger-Keldysh contour, to accomodate the definition of real-time observables. Unfortunately, this extension also induces a maximally severe sign problem, obstructing the computation of, for example, the shear viscosity. In the large-N limit of certain field theories, including $O(N)$-symmetric scalar fields, observables can be computed via a saddle point expansion (closely connected to the Lefschetz thimble programme for alleviating the fermion sign problem). This expansion continues to work for real-time observables. In this talk we present lattice calculations of real-time dynamics in scalar field theory at large N, both near equilibrium (transport coefficients) and far from equilibrium.

**Hadron Spectroscopy and Interactions / 308**

**Scattering from generalised lattice $\phi^4$ theory**

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We numerically investigate different techniques to extract scattering amplitudes from a Euclidean Lattice $\phi^4$ theory with two fields having different masses. We present an exploratory study of a
recently proposed method by Bruno and Hansen for extracting the scattering length from a four-point function (cf. arXiv:2012.11488) and a study of the two and three particle quantization condition.

QCD at nonzero Temperature and Density / 309

The sign problem, $\mathcal{PT}$ symmetry, and exotic phases

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The phase diagram of finite-density QCD is potentially quite complex. Like other lattice models with sign problems and generalized $\mathcal{PT}$ symmetry, equilibrium states of lattice QCD at finite density may be inhomogeneous, with commensurate and incommensurate patterned phases. The phase structures of such models are determined by a set of interwoven concepts: $\mathcal{PT}$ symmetry, Lee-Yang zeros, violation of spectral positivity, Lifshitz instabilities, NP-hard complexity, and lattice duality. $\mathcal{PT}$ symmetry combined with lattice duality leads to models with removable sign problems in broad universality classes with rich phase structures. These models can be simulated on the lattice by standard techniques and analytical methods may be applied as well. These ideas are illustrated using models from the $i\phi^3$, $Z(2)$, $Z(3)$ and $SU(N)$ universality classes.

Hadron Spectroscopy and Interactions / 310

Infinite Volume Reconstruction Method QED Pion Mass Corrections on the Lattice

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We use the Infinite Volume Reconstruction Method to calculate the charged/neutral pion mass difference. The hadronic tensor is calculated on lattice QCD and then combined with an analytic photon propagator, and the mass shift is calculated with exponentially-suppressed finite volume errors. In this talk we discuss the Feynman diagrams relevant to the pion mass difference and we recapitulate the advantages of the Infinite Volume Reconstruction Method. We then discuss finite volume errors and the extrapolation to the continuum limit $a \to 0$.

Software development and Machines / 311

Implementation of the conjugate gradient algorithm for heterogeneous systems

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Lattice QCD calculations require a relevant computational effort and most of the computer time is typically spent in the numerical inversion of the Dirac-Wilson operator. One of the simplest methods to solve large and sparse linear systems is the conjugate gradient (CG). In this work we present an implementation of the CG that can be executed on different devices, including CPUs, GPUs and FPGAs. This is achieved by using SYCL/DPC++ framework, that allows the execution of the same source code on heterogeneous systems.

Poster / 312

B6: Density of states for gravitational waves

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We present the application of a Wang-Landau type algorithm to a pure-gauge SU(4) model on the lattice, with the aim to calculate the gravitational wave signature of the SU(4) pure-gauge content of a composite Dark Matter model. Due to the first order phase transition of the SU(4) model, two phases coexist at the critical temperature and for larger lattice sizes the chances of tunnelling between lattice configurations of these phases becomes less and less likely when using standard algorithms. One way around this problem is calculating the density of states directly, which we do using the Logarithmic Linear Relaxation method.

Hadron Structure / 313

Generalized parton distributions of the proton from lattice QCD

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Generalized parton distributions (GPDs) are among the most fundamental quantities for describing the internal structure of hadrons, providing information about the momentum and spatial distributions of quarks and gluons. Exclusive scattering processes offer a natural framework to extract GPDs from experiments. However, the exclusivity of the process and their indirect relation to the corresponding cross-sections, through Compton form factors, make their determination very challenging.

In this talk, we discuss results on isovector GPDs of the proton obtained within lattice QCD. We
use the quasi-distribution formalism, which relies on computations of correlation functions that, for sufficiently fast-moving hadrons, can be matched to light-cone distributions using Large Momentum Effective Theory (LaMET). The calculation is performed on an ensemble of $\tilde{N}_f = 2 + 1 + 1$ maximally twisted mass fermions, with pion mass $M_\pi = 260$ MeV and lattice spacing $a \simeq 0.093$ fm. The proton is boosted up to 1.67 GeV, which exhibits convergence. Results are presented for unpolarized, helicity, and transversity GPDs at zero and non-zero skewness with controlled statistical uncertainties. Comparisons with their forward limit show qualitative features anticipated from model calculations.

QCD at nonzero Temperature and Density / 314

Coarse Graining in Effective Theories of Lattice QCD in Low Dimensions

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In the strong coupling and heavy quark mass regime, lattice QCD reduces to a 3 dimensional theory of Polyakov loops. We apply coarse graining techniques to such theories in 1 and 2 dimensions at finite temperature and non-zero chemical potential.

In 1 dimension the method is applied to the effective theory up to $O(\kappa^4)$, where $\kappa$ is the hopping parameter of the original Wilson action. Using the transfer matrix, the recursion relations are solved analytically. The thermodynamic limit is taken for some intensive observables. Afterwards, continuum extrapolation is performed numerically and results are discussed.

In 2 dimensions the coarse graining method is applied in the pure gauge and static quark limit. Running couplings are obtained and the fixed points of the transformations are discussed. Finally, the critical coupling of the deconfinement transition is determined in both limits. Agreement to about 15% with Monte Carlo results from the literature is observed.

Hadron Spectroscopy and Interactions / 315

Coulomb corrections to pi-pi scattering

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The relationship between finite volume multi-hadron energy levels and matrix elements and two particle scattering phase shifts and decays is well known, but the inclusion of long range interactions such as QED is non-trivial. Inclusion of QED is an important systematic error correction to K$\to$\pi\pi decays. In this talk, we present a method of including a truncated, finite-range Coulomb interaction in a finite-volume lattice QCD calculation. We show how the omission caused by the truncation can be restored by an infinite-volume analytic calculation so that the final result contains no power-law finite-volume errors beyond those usually present in Luscher’s infinite-volume phase shift determination. This approach allows us to calculate the QED-corrected infinite-volume phase shift for \pi\pi scattering in Coulomb gauge, a necessary ingredient to K$\to$\pi\pi, while neglecting the transverse radiation for now.
Bayesian Model Averaging for Lattice Field Theory

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Statistical modeling plays a key role in lattice field theory calculations. Examples including extracting masses from correlation functions or taking the chiral-continuum limit of a matrix element. We discuss the method of model averaging, a way to account for uncertainty due to model variations, from the perspective of Bayesian statistics. Statistical formulas are derived for model-averaged expectation values and for estimating the required model probability weights. In addition, we reframe the common problem of data subset selection (e.g. choice of minimum time separation for fitting a two-point correlation function) as a model selection problem and study model averaging as a universal alternative to hand tuning of fit ranges.

Critical exponents at the spin-charge flip symmetric fixed point in 2+1d with massless Dirac fermions

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In the Hamiltonian picture, free spin-1/2 Dirac fermions on a bipartite lattice have an O(4) (spin-charge) symmetry. Here we construct an interacting lattice model with an interaction \(V\), which is similar to the Hubbard interaction but preserves the spin-charge flip symmetry. By tuning the coupling \(V\), we show that we can study the phase transition between the massless fermion phase at small \(V\) and a massive fermion phase at large \(V\). We construct a fermion bag algorithm to study this phase transition and find evidence for it to be second order. Perturbative calculations show that the universality class of the transition is different from the one studied earlier involving the Hubbard coupling \(U\). Here we obtain some critical exponents using lattices up to \(L=48\).

K- and D(s)-meson leptonic decay constants with physical light, strange and charm quarks by ETMC

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We will present a lattice QCD computation of the decay constants for the pseudoscalar mesons K and D(s) in the isosymmetric limit by the Extended Twisted Mass Collaboration (ETMC). Simulations of
Nf=2+1+1 dynamical quarks have been performed with the twisted mass fermion action at three values of the lattice spacing, where the masses of the light, strange and charm quarks are all tuned at their physical values.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 319**

**Implementation of Simultaneous Inversion of a Multi-shifted Dirac Matrix for Twisted-Mass Fermions within DDalphaAMG**

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At physical light quark masses, efficient linear solvers are crucial for carrying out the millions of inversions of the Dirac matrix required for obtaining high statistics in quark correlation functions. Adaptive algebraic multi-grid methods have proven to be very efficient in such cases, exhibiting mild critical slowing down towards very light quark masses and outperforming traditional solver methods, such as the conjugate gradient method, at the physical point.

In this talk we will discuss our implementations of simultaneous inversion of a (degenerate) Dirac matrix for twisted-mass fermions for multiple right-hand-sides (rhs) with multi-shifts and block-Krylov solvers. The implementation is carried out within the community library DDalphaAMG, which implements aggregation-based Domain Decomposition adaptive algebraic multi-grid methods. The block-Krylov solvers are provided via the Fast Accurate Block Linear krylov Solver (Fabulous) library and can be used at coarser levels.

Our code inverts Dirac matrices with different twisted-mass terms and for multiple rhs simultaneously and is thus also suitable for components within a typical lattice QCD simulation workflow, such as the rational approximation. We show preliminary results on scalability and compare the performance of our implementation when using different Block-Krylov solver techniques.

**Hadron Spectroscopy and Interactions / 320**

**Light flavor-singlet pseudoscalar in J/ψ radiative decay**

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Experiments show that the flavor-singlet pseudoscalars usually have large production ratios in the radiative decays of J/ψ.

In this work we perform the first lattice investigation on this topic based on a gauge ensemble generated on an anisotropic lattice with two degenerate light dynamical quarks. The mass parameter of the light quarks is tuned to give a pion mass around 300 MeV. The annihilation diagrams of light quarks are calculated using the distillation method.
A new method for a lattice QCD calculation of $\eta_c \rightarrow 2\gamma$

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The two-photon decay process $\eta_c \rightarrow 2\gamma$ can provide an ideal testing ground for the understanding of nonperturbative nature of QCD. In this study, we propose a direct method to calculate the matrix element of a hadron decaying to two-photon. Various systematic effects are examined in this work. The method developed here can also be applied for other processes which involve the leptonic or radiative particles in the final states.

QCD in searches for physics beyond the Standard Model / 322

Tensor Charges and their Impact on Physics Beyond the Standard Model

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The nucleon tensor charge, $g_T$, is an important quantity in the search for beyond the Standard Model tensor interactions in neutron and nuclear $\beta$-decays as well as the contribution of the quark electric dipole moment (EDM) to the neutron EDM. We present results from the QCDSF, UKQCD and the CSSM collaboration for the tensor charge, $g_T$, using lattice QCD methods and the Feynman-Hellmann Theorem. We use a flavour symmetry breaking method to systematically approach the physical quark mass. In this analysis the ensembles span four $\beta$ values, enabling an extrapolation to the continuum limit.

Software development and Machines / 323

Progress on QDP-JIT: Adding support for AMD GPUs

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We report on the progress made on the QDP-JIT library which acts as a drop-in replacement for the QDP++ library which Chroma builds upon. QDP-JIT now targets NVIDIA and AMD GPU machines, like the upcoming Frontier supercomputer, Summit or the new USQCD machine with AMD GPUs at Jefferson Lab. Our new implementation aims to add one missing feature of QDP++: performance.

We use the original type system and operations of QDP++ and have engineered an Just-in-Time (JIT) compiler toolchain based on LLVM for data layout transformations suitable for GPUs. The JIT route
also allows us to beneficially specialize kernels on runtime parameters like, e.g., the machine grid and code path. QDP-JIT is fully-featured, has many optimizations built-in and is production-ready for machines of both GPU types.

QCD at nonzero Temperature and Density / 324

Chromo-electric screening length in 2+1 flavor QCD

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Chromo-electric screening at high temperature is encoded in the large distance behavior of Polyakov loop correlators. In SU(N) gauge theory (quenched QCD) the large distance behavior of the Polyakov loop correlators has been studied and the corresponding chromo-electric screening length has been determined. In QCD with light dynamical quarks this turned out to be very difficult because of the large Monte-Carlo noise. We study the long distance behavior of the correlator of the real and imaginary part of the Polyakov loop in 2+1 flavor QCD with nearly physical quark masses using HISQ action and lattices with temporal extent $N_t = 6, 8, 10$ and $12$. To reduce the noise we apply several levels of HYP smearing to the Polyakov loops and determine the corresponding chromo-electric screening masses. We compare our results to the weak coupling calculations at high temperatures.

Theoretical developments and applications beyond particle physics / 325

A spin-charge flip symmetric fixed point in 2+1d with massless Dirac fermions

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In the Hamiltonian formulation, free spin-1/2 massless Dirac fermions on a bipartite lattice have an $O(4)$ (spin-charge) symmetry. Lattice interaction terms usually break this symmetry down to some subgroups. For example, the Hubbard interaction at half-filling breaks the symmetry down to $SO(4)$ by breaking the spin-charge flip symmetry. In this work, we construct a lattice model with a new interaction $V$, which is similar to the Hubbard interaction, but preserves the spin-charge flip symmetry. Using perturbative calculations in the continuum, we compute the RG flow diagram with both $U$ and $V$ interactions and show the existence of a spin-charge flip symmetric fixed point that can be studied by tuning the coupling $V$ at $U = 0$. In particular we show that this fixed point is different from the one reached by tuning the Hubbard coupling $U$. Monte Carlo calculations using the fermion bag idea can help us compute the critical exponents at the spin-charge flip symmetric fixed point.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 326
Hybrid analog-digital quantum simulations for quantum field theories

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Quantum simulation has the promise of enabling access to Minkowski-time dynamical observables in quantum field theories. Progress in devising and benchmarking quantum-simulation proposals, in form of analog protocols or digital algorithms, is ongoing, and increasingly complex theories are being targeted towards the goal of simulating QCD. In this talk, I will introduce a hybrid analog-digital simulation scheme for studying bosonic field theories coupled to matter, such as the Yukawa theory and the 1+1 dimensional QED, by taking advantage of both bosonic degrees of freedom (phonons) and spin degrees of freedom (internal states of the ions) in a trapped-ion quantum simulator. It will be shown that significant improvement is anticipated in the simulation resource requirement, i.e., the number of qubits and entangling operations, when compared with the fully-digital algorithms, while the flexibility of a digital scheme in engineering a complex Hamiltonian is maintained. This motivates near-term implementations that can supersede both the fully digital and fully analog implementations of the same theories.

QCD at nonzero Temperature and Density / 327

Correlated Dirac Eigenvalues and Axial Anomaly in Chiral Symmetric QCD

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In this talk we present the novel relations between the quark mass derivatives \(\frac{\partial^n \rho(\lambda, m_l)}{\partial m_l^n}\) of the Dirac eigenvalue spectrum and the \((n+1)\)-point correlations among the eigenvalues. Using these relations we present lattice QCD results for \(\frac{\partial^n \rho(\lambda, m_l)}{\partial m_l^n}\) \((n = 1, 2, 3)\) for \(m_l\) corresponding to pion masses \(m_\pi = 160 - 55\) MeV, and at a temperature of about 1.6 times the chiral phase transition temperature. Calculations were carried out using (2+1) flavors of highly improved staggered quarks with the physical value of strange quark mass, three lattice spacings \(a = 0.12, 0.08, 0.06\) fm. We find that \(\rho(\lambda \rightarrow 0, m_l)\) develops a peaked structure. This peaked structure arises due to non-Poisson correlations within the infrared part of the Dirac eigenvalue spectrum, becomes sharper as \(a \rightarrow 0\), and its amplitude is proportional to \(m_l^2\). We demonstrate that this \(\rho(\lambda \rightarrow 0, m_l)\) is responsible for the manifestations of axial anomaly in two-point correlation functions of light scalar and pseudoscalar mesons. After continuum and chiral extrapolations we find that axial anomaly remains manifested in two-point correlation functions of scalar and pseudoscalar mesons in the chiral limit. This talk is based on our recent published paper [PRL 126 (2021) 082001].

Hadron Structure / 328

Composition of the inclusive semi-leptonic decay of B meson
Utilizing the approach recently proposed for the inclusive semi-leptonic decay rate on the lattice, we compute the differential decay rate of a $B_s$ meson for various kinematical channels. The results are compared with the contributions from the ground states ($D$ and $D^*$) as well as from the orbitally excited states ($D^*$'s). The computation so far is carried out with an unphysically light bottom quark and strange spectator quark.

Hadron Spectroscopy and Interactions / 329

Lattice Study of the Dibaryon System

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We present a lattice QCD calculation of the energy eigenvalues of the dibaryon system using the gauge ensembles generated with the domain wall fermion action. Using the sparsening field method, multiple dibaryon interpolating operators are used to reduce the contamination from excited states. Some relevant results for the weak transition matrix elements of the dibaryon system are also shown.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 330

A universal neural network for learning phases and criticalities

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A universal supervised neural network (NN) relevant to study phase transitions is constructed. The validity of the built NN is examined by applying it to calculate the criticalities of several three-dimensional (3D) and two-dimensional (2D) models including the 3D classical $O(3)$ model, the 3D 5-state ferromagnetic Potts model, a 3D dimerized quantum antiferromagnetic Heisenberg model as well as the 2D $XY$ model. Particularly, while the considered NN is only trained once on a one-dimensional (1D) lattice with 120 sites, it has successfully determined the related critical points of the studied 3D and 2D systems with high accuracy. Moreover, the employed configurations for the prediction are constructed on a 1D lattice of 120 sites as well. As a result, our calculations are ultimately efficient in computation and the applications of the built NN is extremely broaden.
Standard Model Parameters / 331

Calculating $\Delta m_K$ with lattice QCD

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We have completed a lattice QCD calculation of $\Delta m_K$, the mass difference between the long- and short-lived K mesons. The calculation was performed on a $64^3 \times 128$ lattice using 152 configurations with physical quark masses and an inverse lattice spacing of $a^{-1} = 2.36$ GeV. While the statistical error approaches a relatively small size of 9%, several sources of systematic errors may have more significant effects. In this talk we will address studies performed on smaller lattices to estimate the systematic errors in our result.

Vacuum Structure, Confinement, and Chiral Symmetry / 332

Magnetic monopole dominance for the Wilson loops in higher representations

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The dual superconductor picture is one of the most promising scenarios for quark confinement. To investigate this picture in a gauge-invariant manner, we have proposed a new formulation of Yang-Mills theory on the lattice, named the decomposition method, so that the so-called restricted field obtained from the gauge-covariant decomposition plays the dominant role in quark confinement. It was known by preceding works that the restricted field dominance is not observed for the Wilson loop in higher representations if the restricted part of the Wilson loop is extracted by adopting the Abelian projection or the field decomposition naively in the same way as in the fundamental representation.

Recently, by the non-Abelian Stokes theorem (NAST) for the Wilson loop operator, we have proposed suitable gauge-invariant operators constructed from the restricted field to reproduce the correct behavior of the original Wilson loop averages for higher representations. We have demonstrated the numerical evidence for the restricted field dominance in the string tension, which means that the string tension extracted from the restricted part of the Wilson loop reproduces the string tension extracted from the original Wilson loop.

In this talk, we focus on the magnetic monopole. According to this picture, magnetic monopoles causing the dual superconductivity are regarded as the dominant degrees of freedom responsible for confinement. With the help of the NAST, we can define the magnetic monopole and the string tension extracted from the magnetic-monopole part of the Wilson loop in a gauge-invariant manner.

We will further perform lattice simulations to measure the static potential for quarks in higher representations using the proposed operators and examine the magnetic monopole dominance in the string tension, which means that the string tension extracted from the magnetic-monopole part of the Wilson loop reproduces the true string tension from the original Wilson loop.

Hadron Spectroscopy and Interactions / 333

Application of the Misner’s method to the coupled-channel NA-N$\Sigma$ potential in lattice QCD
The baryon-baryon interaction in the strangeness $\Lambda = -1$ channel was recently analysed by using the lattice QCD data near the physical point combined with the HAL QCD method [1]. In the present contribution, we show our first attempt to extract the coupled-channel $N\Lambda - N\Sigma$ potential from the same data by using the Misner’s method which is known to be a reliable way to perform the partial wave decomposition on the lattice [2,3]. The resultant potential is used to calculate scattering phase shifts and the mixing parameter for the low energy scattering in the $1S0$ and $3S1D1$ channels.

At low temperature and high density, quark matter is expected to be a color superconductor (CSC). In a recent study based on lattice perturbation theory, we have found that the CSC occurs even on a lattice with a small spatial length. According to our previous study (JHEP10(2020)144), the complex Langevin method is expected to work on such a lattice without suffering from the excursion and singular drift problems. Here we perform complex Langevin simulation on an $8^3 \times 128$ lattice using 4-flavor staggered fermions. We find, in particular, that the quark number has plateaux with respect to the chemical potential similarly to our previous study, indicating the formation of the Fermi sphere. Furthermore, we found that the Polyakov loop is enhanced when the Fermi surface passes through discrete points in the momentum space, as observed in two-color QCD and QCD on $S^1 \times S^3$ by Hands et. al. We also present some preliminary results on CSC using a diquark-antidiquark operator, which seems to agree with the prediction of lattice perturbation theory.

**Hadron Structure / 336**

**Investigation of the fourth moment of the pion light-cone distribution amplitude**

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The light-cone distribution amplitude (LCDA) is a key object of interest in a range of high-energy, exclusive processes in QCD. In this talk, we describe the application of the heavy quark operator product expansion (HOPE) method to a preliminary study of the fourth Mellin moment of the pion LCDA. We present an exploratory investigation at a pion mass of 560 MeV in the quenched approximation.

**Hadron Spectroscopy and Interactions / 337**

**QED corrections to QCD quantities using massive photons.**

**Author:** J Tobias Tsang\(^1\)

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In recent years many QCD observables have reached (sub-)percent level precision. At this level strong ($m_u \neq m_d$) and weak (charges of up, down and strange) isospin breaking effects have to be
accounted for. Different methods exist to include QED into lattice QCD simulations. In massive QED (QEDm) the photon is given a mass $m_\gamma$, allowing for a local formulation of QED on the lattice. For the example of the meson and baryon spectrum at a pion mass of 310MeV, we present a feasibility study of massive QED, demonstrating that both the extrapolation to infinite volume and to vanishing photon mass limit are under control.

**Hadron Structure / 338**

**Charged and neutral pion magnetic polarisabilities using the background field method**

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The magnetic polarisability of the pion is calculated at a range of quark masses using the background field method. These results are facilitated by the use of the background-field corrected clover fermion action which removes the unphysical quark mass renormalisation due to the Wilson term in a background magnetic field. A magnetic-field dependent quark-propagator projector enables the ground state isolation necessary to construct the relativistic energy differences used to extract the magnetic polarisability. The excellent signal-to-noise properties of pion two-point correlation functions produces precise values for both the charged and neutral pion.

**QCD at nonzero Temperature and Density / 339**

**Perturbative predictions for color superconductivity on the lattice**

**Authors:** Takeru Yokota¹; Yuhma Asano²; Yuta Ito³; Hideo Matsufuru¹; Yusuke Namekawa⁵; Jun Nishimura⁴; Asato Tsuchiya⁶; Shoichiro Tsutsui⁷

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Recent developments in methods to overcome the sign problem in finite density QCD such as the complex Langevin method give us hope to investigate color superconductivity (CSC) in cold dense QCD matter from first principles. In view of this situation, we obtain quantitative predictions for the parameter region for CSC from lattice perturbation theory, which is valid for QCD in a small box. In particular, we use 2-flavor Wilson fermions in addition to 4-flavor staggered fermions reported in APLAT 2020. Based on the Thouless condition, we calculate the coupling constant corresponding to the critical point of CSC as a function of the quark chemical potential without any ansatz for the shape of the Cooper-pair condensates. We find a characteristic behavior that the region of CSC extends towards weak coupling at the chemical potential corresponding to the energy levels of free
quarks in the case of staggered fermions. Similar behavior is observed also in the case of Wilson fermions although the region of CSC slightly shrinks when the chemical potential is very close to the energy levels of free quarks.

Hadron Spectroscopy and Interactions / 340

Topic on pion spectroscopy

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We will present the pion mass and decay constant using the overlap fermion valence on DW fermion sea at several lattice lattice spacings. The mixed action effect in the lattice calculation is also studied, and the result suggests that the mixed action effect with overlap valence on DW sea would be proportional to the fourth power of the lattice spacing. The preliminary determination of the light and strange quark mass \( m_{u,d,s} \), \( F \) and chiral condensate \( \Sigma \) in the \( N_f = 2 \) chiral limit will also be presented.

Hadron Structure / 341

Neutrino-nucleon inclusive scattering cross sections on the lattice

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We compute the inclusive neutrino-nucleon scattering cross sections from the first principles of QCD. This is highly relevant to the recent and future \( \nu - N \) scattering experiments, whose energy regime is excessively low for the perturbative analysis to hold. We use a technique recently proposed to treat the inclusive contributions on the lattice. We compute the forward Compton-scattering amplitude on the lattice where all intermediate states contribute. Total cross section is then constructed by multiplying the phase space factor and integrating over the energy and momentum of final states. By promoting the phase space factor to an operator, the energy integral and the sum over intermediate states is represented by a series of correlators in Chebyshev basis.

In this talk we conduct a series of tests showing the validity of the methodology, tracking the changes in the shape of smeared kernel functions according to the smearing width and to the order of Chebyshev approximation, and check the consistency with phenomenological analyses.

Standard Model Parameters / 342
Spectral sum from Euclidean lattice correlators and determination of renormalization constants

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We construct a method for computing the spectral sum appearing in the Shifman-Vainshtein-Zakharov (SVZ) QCD sum rule. The method gives results consistent with the operator product expansion (OPE) of the $s\bar{s}$ correlation function in the vector channel. The application of this method to other channels is useful for operator renormalization as well as the test of perturbative QCD and OPE.

Vacuum Structure, Confinement, and Chiral Symmetry / 343

Centre Vortex Structure in 2+1 Flavour QCD

Author: James Biddle¹

Co-authors: Derek Leinweber²; Waseem Kamleh¹

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This presentation introduces new insights into the centre-vortex structure of lattice gauge fields, this time exploring the influence of dynamical fermions in the full-QCD vacuum. Calculations of both the Landau-gauge gluon propagator and the static quark potential reveal notable differences in the vortex phenomenology of pure-gauge and full-QCD simulations. Remarkably, configurations composed of centre-vortices alone have the ability to reproduce the static quark potential of full QCD. Moreover, the distribution of vortices in the vacuum is altered significantly with the introduction of dynamical fermions. Together, these results report the substantial influence of dynamical fermions on the centre-vortex structure of QCD-vacuum fields.

Impact of Dynamical Fermions on Centre Vortex Structure

Authors: Derek Leinweber¹; James Biddle²; Waseem Kamleh²

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This presentation examines the centre-vortex structure of Monte-Carlo generated gauge-field configurations using modern visualisation techniques. This time, the manner in which light dynamical fermion degrees of freedom impact the centre-vortex structure is explored. Focusing on the thin vortices identified by plaquettes having a non-trivial centre phase, the vortex structure is illustrated through 3D renderings of oriented spatial plaquettes. Time-oriented plaquettes are illustrated by identifying spatial links associated with these non-trivial plaquettes. The impact of light dynamical fermions is not subtle, changing both the density of vortices and the complexity of the vortex
structures observed. The role of vortex branching points in full QCD is highlighted in the survey of results presented.

Hadron Spectroscopy and Interactions / 345

The mixing of $\eta_c$ and the Pseudoscalar Glueball

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The first lattice QCD study of the mixing of $\eta_c$ and the pseudoscalar glueball is performed. We generate a large gauge configuration ensemble with $N_f = 2$ degenerate charm quarks on an isotropic lattice. The correlation functions of the charm quark bilinear operators, both connected part and disconnected part, are computed via the distillation method. And the correlation functions of glueball operators are also computed on this ensemble and variational analysis method is adopted to obtain optimized operators. By performing a simultaneous two states fit of correlation functions $C_{CC}(t)$, $C_{GG}(t)$ and $C_{GC}(t)$, the mixing angle of $\eta_c$ and pseudoscalar glueball is obtained, which is obviously nonzero but quit small. It would be helpful for understanding the properties of $\eta_c$.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 346

Twisted mass gauge ensembles at physical values of the light, strange and charm quark masses

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Lattice QCD simulations directly at physical masses of dynamical light, strange and charm quarks are highly desirable in order to remove systematic errors due to chiral extrapolations. However such simulations are still challenging. We discuss the adaption of efficient algorithms, like higher order integrators or multi-grid methods, within the molecular dynamics of the Hybrid Monte Carlo algorithm, that are enabling simulations of a new set of gauge ensembles by the Extended Twisted Mass collaboration (ETMC).

We will present the status of the on-going ETMC simulation effort that aim to enable studies of finite size and discretization effects. We work within the twisted mass discretization which is free of odd-discretization effects at maximal twist. We will discuss our tuning procedure and first physical results and give an outlook of future plans.

Particle physics beyond the Standard Model / 347

Exploring a composite Higgs scenario in a model with four light and six heavy flavors
Mass-split models are governed by a nearby conformal infrared fixed point and therefore feature by construction a large separation of scales. This makes them attractive candidates to explore beyond the standard model scenarios describing the Higgs boson as a composite particle. We report updates on our investigation based on an SU(3) gauge theory with four light and six heavy flavors in the fundamental representation. Using ratios of light over heavy flavor masses from 1 down to 0.08, we demonstrate the presence of conformal hyperscaling, explore the validity of dilaton chiral perturbation theory (dChPT) as an effective theory describing our model, and determine the anomalous mass dimension.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 348**

**Smearing is a neural network**

**Authors:** Akio Tomiya\(^1\); Yuki Nagai\(^2\)

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We develop a gauge covariant neural network for four dimensional non-abelian gauge theory, which realizes a map between rank-2 tensor valued vector fields. We also find the conventional smearing procedures for gauge fields can be regarded as this neural network with fixed parameters. We developed a formula to train the network as an extension of the delta rule, which is used in machine learning context. In addition, we perform simulation with self-learning hybrid Monte-Carlo (SLHMC) in 4 dimension for SU(N) with dynamical fermions as a demonstration of the network and the training formula. SLHMC, which is an exact algorithm, uses parametrized force in the molecular dynamics step, and we employed neural network parametrized action and we obtained consistent results with HMC. This talk is based on arXiv:2103.11965 and some additional materials.

**Poster / 349**

**A6: LatticeQCD.jl: Lattice QCD code with Julia**

**Authors:** Akio Tomiya\(^1\); Yuki Nagai\(^2\)

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We developed a new production code for lattice gauge theory in Julia language. Julia language has developed quickly since 2012, and it is used for many of calculations in condensed matter physics. This code has compatible speed with a fortran code, "Lattice Took Kit", and enables us to perform (R)HMC with the staggered and Wilson fermions with stout smearing for SU(N) generic action and measure several observables in four dimension. In addition, we have implemented self-learning Monte-Carlo (SLMC). In this talk we quickly review functionality and performance of our code and discuss future possibilities. The code can be obtained from https://github.com/akio-tomiya/LatticeQCD.jl
B7: Machine Learning Approximated Nucleon Matrix Elements with Domain Wall Fermions

Authors: Akio Tomiya\(^1\); Joseph Carolan\(^2\); Connelly Andrew\(^2\); Taku Izubuchi\(^3\); Luchang Jin\(^{none}\); Chulwoo Jung\(^3\); Christopher Kelly\(^1\); Meifeng Lin\(^1\); Sergey Syritsyn\(^2\)

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Nucleon matrix elements are some of the most expensive quantities to calculate within the framework of lattice QCD simulations, as they involve the computation of nucleon three-point correlation functions. Nucleon three-point correlation functions need additional quark propagators compared to two-point correlation functions, and suffer from exponentially worsening signal-to-noise ratios as quark masses approach the physical limit. Here we discuss the machine learning assisted calculation of nucleon matrix elements following a method by B. Yoon et al., which approximates nucleon three-point correlation functions using nucleon two-point correlation functions as input. We will show results for the machine-learning approximated nucleon three-point correlation functions with 2+1 flavor domain wall fermions, and discuss potential improvements to the machine learning architecture. Furthermore, we will discuss a detailed error analysis to fully represent different sources of uncertainties introduced in the machine learning method.

The \(\pi^0\), \(\eta\) and \(\eta^\prime\) mesons from \(n_f = 1 + 1 + 1\) lattice QCD+QED

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We present the first lattice analysis of the pseudoscalar mesons with consideration for the mixing between the flavour-singlet states \(\pi^0\), \(\eta\) and \(\eta^\prime\). We extract the masses and flavour compositions of the pseudoscalar meson nonet in \(n_f = 1 + 1 + 1\) lattice QCD+QED around an SU(3)-flavour symmetric point, and observe interesting features of the extracted data, along with preliminary extrapolation results at physical pion mass via a novel method. We also resolve the mass splitting in the \(\pi^0\) and \(\eta\) on our ensembles, which is found to exhibit behaviour that is simply related to the corresponding flavour compositions.

Novel Algorithms for Computing Correlation Functions of Large Nuclei

Author: Nabil Humphrey\(^1\)

Co-authors: Ross Young; James Zanotti \(^1\)

\(^1\) University of Adelaide
This work seeks to enable more detailed numerical probes into nuclear structure using the standard model through lattice QCD. The computational cost required to compute nuclear correlations functions grows exponentially in the number of quarks, leaving the study of many large nuclear bound states inaccessible. However, these tensor expressions exhibit a high degree of permutation symmetry that can be exploited either \textit{a priori} or \textit{ad hoc} to reduce computational work. After outlining the novel aspects of two new algorithms, we present a cost comparison and find promising speed-ups for certain choices of interpolating operators. We further present a pathway to apply the new approaches to systems of current and future interest.

\textbf{Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 353}

\textbf{Gauge field compression in SU(N) theories and spatial correlations on the lattice}

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A long standing problem associated with performing lattice gauge theory calculations on GPU hardware is latency for both global memory transfers and MPI data transfers. Mitigating these latencies with data compression techniques can vastly improve the performance of solvers and help to combat strong scaling. In this talk we discuss a new gauge field compression technique in which the SU(N) fields are decomposed into their fundamental representation, and then further compressed using their spatial correlations and the zfp library. Other lattice data types which exhibit spatial correlations can also be compressed in a similar manner with varying efficiency.

\textbf{Hadron Structure / 354}

\textbf{Variations to the z-Expansion of the Form Factor Describing the Decay of B Mesons}

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\textbf{Co-authors:} Yannick Meurice \textsuperscript{1}; Erik Gustafson \textsuperscript{1}

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We studied the decay rate of the particle decay $B^0 \rightarrow D^- \ell^+ \nu_\ell$ using data collected from the Belle Collaboration. In order to analyze this decay rate, we used three parameterizations of the form factor which describes this process, the CLN (Caprini, Lellouch, and Neubert) parametrization, the BGL (Boyd, Grinstein, and Lebed) parametrization, and the BCL (Bourrely, Caprini, and Lellouch) parameterization. This form factor is a function of the hadronic recoil variable $w$ and each parameterization contains unique free parameters which are the interest of this project. One of the goals of this project was to fit these different parameterizations of the form factor to the Belle data in the lattice regime, considering the data points where $w < \sim 1.3$, so that we can predict what the larger $w$ region should look like. We hope to in the future be able to use Monte Carlo simulations to extract values of the form factors, however these simulations are only able to reliably extract these values inside of the lattice regime. By fitting only the low $w$ values, we are able to get an idea of what the larger $w$ region should look like and how many data points are needed in the fit to accurately predict the larger $w$ region.
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Comparison of lattice QCD results for inclusive semi-leptonic decays B mesons with the OPE

Authors: Sandro Maechler\(^1\); Shoji Hashimoto\(^2\); paolo gambino\(^3\); Takashi Kaneko\(^2\)

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A recently proposed approach to inclusive semi-leptonic decay rate on the lattice allows for the calculation of various quantities (differential distributions and moments) in different subchannels. We systematically compare the lattice QCD results for unphysically light bottom and strange quarks with OPE-based predictions, including leading order perturbative and $O(1/m^3)$ power corrections, and explore possible strategies to decrease the systematic uncertainty.

Hadron Spectroscopy and Interactions / 356

Low-lying Odd-parity Nucleon Resonances via Hamiltonian Effective Field Theory

Authors: Anthony Thomas\(^1\); Curtis Abell\(^1\); Derek Leinweber\(^2\); Jiajun Wu\(^3\)

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Recent lattice QCD results for the first two low-lying odd-parity excitations of the nucleon have revealed that they have magnetic moments consistent with constituent-quark-model expectations. Thus, in constructing a basis of states to describe scattering in this channel, one should not represent both odd-parity excitations by a single three-quark basis state. Two single-particle basis states are required to accommodate these two quark-model-like states. This contrasts previous studies where it has been assumed that both low-lying negative-parity states observed on the lattice are part of the finite-volume spectrum associated with the N(1535) resonance. Using Hamiltonian Effective Field Theory (HEFT), we represent these constituent-quark-like states by including two single-particle basis states in the Hamiltonian, mixing through meson-baryon scattering channels. By constraining the parameters of HEFT using S-wave pion-Nucleon scattering data, we perform the first calculation of the finite-volume energy spectrum for this system using multiple single-particle basis states.

Hadron Structure / 357

Lattice QCD calculation of the proton electromagnetic polarizability

Author: Xuan-He Wang\(^\text{None}\)

Co-authors: Xu Feng \(^1\); Luchang Jin
The electromagnetic polarizability is an important property of nucleon. It describes the response of a nucleon when it is placed in an external electric or magnetic field. The polarizability can be extracted from the real or virtual Compton scattering process $\gamma N \rightarrow \gamma N$. We develop a method to calculate the the Compton scattering matrix elements of nucleon from a 4-point correlation function on the lattice. Then we show that the electromagnetic polarizability can be extracted from the lattice data subsequently.

**Nucleon Form Factors from the Feynman-Hellmann Method in Lattice QCD**

Author: Mischa Batelaan

Co-authors: James Zanotti; Ross Young; QCDSF/UKQCD/CSSM Collaboration

Lattice QCD calculations of the nucleon electromagnetic form factors are of interest at the high and low momentum transfer regions. For high momentum transfers especially there are open questions, such as the zero crossing in the proton’s electric form factor, which require more calculations. We will present recent progress from the QCDSF/UKQCD/CSSM collaboration on the calculations of these form factors using the Feynman-Hellmann method in lattice QCD. This method provides an efficient method allowing us to reach high momentum transfers. In this talk we present results of the form factors up to 9 GeV$^2$, using $N_f=2+1$ flavour fermions for three different pion masses in the range 310–470 MeV. The results are extrapolated to the physical point through the use of a flavour breaking expansion at two different values of the lattice spacing, allowing for a study of discretisation effects.

**Direct Measurement and Renormalisation of Quark and Gluon Momentum Fractions in the Quenched Approximation**

Author: Tomas Howson

Co-authors: James Zanotti; Ross Young; QCDSF/UKQCD/CSSM Collaboration

With upcoming Electron-Ion Colliders, such as the eRHIC at Brookhaven National Laboratory and a proposed upgrade to the LHC, the structure of the hadron from both the quark and gluon sectors is quickly becoming a readily accessible frontier in physical investigation. Such experiments are underpinned by a strong theoretical foundation, such as that provided by lattice QCD.

We will show progress in work by the QCDSF/UKQCD/CSSM collaboration to directly measure both quark and gluon momentum fractions in the quenched approximation, and obtain renormalisation factors to match such measurements onto phenomenological quantities in a typical scheme, such
The necessary renormalisation matrix describing the mixing between quark and gluon contributions is constructed non-perturbatively, with the off-diagonal component obtained through mixed amputated vertex functions applied in an RI-MOM scheme. The measurements in the gluon sector make use of the Feynman-Hellmann method, to extract statistically significant signals from typically noisy gluon singlet operators.

QCD at nonzero Temperature and Density / 361

Dual Polyakov loop model at finite density: phase diagram and screening masses

Authors: Alessandro Papa\textsuperscript{1}; Emanuele Mendicelli\textsuperscript{2}; Oleg Borisenko\textsuperscript{3}; Volodymyr Chelnokov\textsuperscript{4}

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We consider a dual representation of an effective three-dimensional Polyakov loop model for the SU(3) theory at nonzero real chemical potential. This representation is free of the sign problem and can be used for numeric Monte-Carlo simulations. These simulations allow us to locate the line of second order phase transitions, that separates the region of first order phase transition from the crossover one. The behavior of local observables in different phases of the model is studied numerically and compared with predictions of the mean-field analysis. Our dual formulation allows us to study also Polyakov loop correlation functions. From these results, we extract the screening masses and compare them with the large-N predictions.

Standard Model Parameters / 362

Static force with and without gradient flow

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Recently a method of measuring static force from the lattice using an insertion of chromoelectric field to an Wilson loop has been proposed to tackle the ambiguities of taking numerical derivative of the static potential. We present the current status of testing the viability of this approach and also expand the calculation for the first time to use gradient flow, which solves the problems with the renormalization of chromoelectric field on the lattice.
Hadron Structure / 363

**Determination of the Collins-Soper Kernel from Lattice QCD**

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We present lattice results for the non-perturbative Collins-Soper (CS) kernel, which describes the energy-dependence of transverse momentum-dependent parton distributions (TMDs). The CS kernel is extracted from the ratios of first Mellin moments of quasi-TMDs evaluated at different nucleon momenta. The analysis is done with dynamical $N_f = 2 + 1$ clover fermions for the CLS ensemble $H101$ ($a = 0.0854$ fm, $m_{\pi} = m_{K} = 422$ MeV). The computed CS kernel is in good agreement with experimental extractions and previous lattice studies.

**Poster / 364**

**B8: Finite temperature phase transition for three flavor QCD with Möbius-domain wall fermions**

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The nature of the finite temperature phase transition in 2+1 flavor QCD depends on the quark mass, and the order and universal class of the phase transition are shown in a diagram called the Columbia plot. The region of light quark masses in this diagram is not yet fully understood. We present preliminary results of a three-flavor QCD study using Möbius-domain wall fermions to search for the critical endpoint in the light quark mass region on the diagonal line of the Columbia plot.

**Vacuum Structure, Confinement, and Chiral Symmetry / 365**

**Peeking into the theta vacuum of 4d Yang-Mills theory**

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We propose a subvolume method to study the $\theta$ dependence of the free energy density of the four-dimensional SU($N$) Yang-Mills theory on the lattice.
As an attempt, the method is first applied to SU(2) Yang-Mills theory at $T = 1.2 T_c$ to understand the systematics of the method. We then proceed to the calculation of the vacuum energy density and obtain the $\theta$ dependence, at least, to $\theta \sim \pi$. The numerical results combined with the theoretical requirements provide the evidence for the spontaneous CP violation at $\theta = \pi$, which is in accordance with the large $N$ prediction and in contrast to the CP\textsuperscript{1} model in two dimensions.

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**B9: Infrared physics of the SU(2) Georgi-Glashow phase transition**

**Authors:** Lauri Niemi\textsuperscript{1}; Kari Rummukainen\textsuperscript{1}; Riikka Seppä\textsuperscript{1}; David Weir\textsuperscript{1}

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We perform a lattice study of the phase transition in the SU(2) Georgi-Glashow model in three dimensions, where the symmetry is broken to U(1) and a photon-like state appears. Motivated by studies of the QCD instanton, we use gradient flow to renormalise the monopole density and study the role of monopoles in the phase transition. We also use modern techniques to measure the mass of the photon-like state in this model. Large volumes are required so that the monopoles are screened from each other. We see evidence for a nonzero photon mass in the broken phase at sufficiently large volumes and confirm its relationship to the monopole density.

The SU(2) Georgi-Glashow model in three dimensions has long been studied as a high-temperature effective field theory for SU(2) QCD-like models. It can also be considered an effective theory of the Standard Model with an additional triplet field where the Higgs field is not dynamical. In both cases, the phase diagram and nature of the phase transition are important for broader questions of phenomenology. Substantial discrepancies exist between perturbative studies and existing lattice results. By studying the role of monopoles in the phase transition, our study seeks to shed light on one likely source of this discrepancy.

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**The qqbar potential from Wilson loop and the qqbar potential from Nambu-Bethe-Salpeter wave function**

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In Phys.Rev.Lett.107,091601, T.Kawanai and S.Sasaki extended HAL QCD method to the ccbar system and showed numerically that the qqbar potential obtained from the Nambu-Bethe-Salpeter wave function agrees with the qqbar potential obtained from Wilson loop in the heavy quark mass limit. However, it is not known how these two potentials can agree. In this talk, the relation between these two qqbar potentials is discussed, and it is shown that they agree in the infinite quark mass limit.

Theoretical developments and applications beyond particle physics / 368
Criticality and related properties of a non-compact 2+1D Thirring Model

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Modelling the behaviour of strongly interacting fermion systems with correct symmetry properties presents significant challenges for lattice field theories. Investigating the suitability of domain wall fermions, we explore the locality and the Ginsparg-Wilson error of the Dirac operator in the context of a dynamical 2+1D non-compact Thirring model. We further investigate the eigenvalues of the Dirac operators and the Banks-Casher relation, as part of a broader search for criticality. Relations between twisted mass domain wall and overlap formulations are reviewed.

QCD in searches for physics beyond the Standard Model / 369

Towards a lattice determination of the form factors of the rare hyperon decay $\Sigma^+ \to p\ell^+\ell^-$

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The rare hyperon decay $\Sigma^+ \to p\ell^+\ell^-$ is an $s \to d$ flavour changing neutral current process that has been recently measured by the LHCb experiment with plans to improve this measurement in the future. This has prompted a need for an improved Standard Model prediction of the branching fraction of this decay. We present our theoretical approach and progress towards an exploratory study of the form factors of this decay on an unphysical RBC-UKQCD lattice using $N_f = 2 + 1$ domain-wall fermions.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 370

A new technique for solving the freezing problem in the complex Langevin simulation of 4D SU(2) gauge theory with a theta term

Author: Akira Matsumoto

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We apply the complex Langevin method (CLM) to overcome the sign problem in 4D SU(2) gauge theory with a theta term extending our previous work on the 2D U(1) case. The topology freezing problem can be solved by using open boundary conditions in all spatial directions, and the criterion for justifying the CLM is satisfied even for large $\theta$ as far as the lattice spacing is sufficiently small. However, we find that the CP symmetry at $\theta = \pi$ remains to be broken explicitly even in the continuum and infinite-volume limits due to the chosen boundary conditions. In particular, this prevents us from investigating the interesting phase structure suggested by the 't Hooft anomaly matching condition. We also try the so-called subvolume method, which turns out to have a similar problem. We therefore discuss a new technique within the CLM, which enables us to circumvent the topology freezing problem without changing the boundary conditions.

Elastic $\pi - N$ scattering in the $I = 3/2$ channel

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We present a lattice QCD study of $\pi - N$ scattering in the iso-spin $I = 3/2$ channel. The calculation is performed using $N_f = 2 + 1 + 1$ flavors of twisted mass fermions including an ensemble with physical pion mass. We compute energy levels for all the moving frames with total momentum up to $\vec{P} = 2\pi L(1,1,1)$, and for all the relevant irreducible representation of the lattice symmetry groups. We perform a phase-shift analysis including $S$ and $P$ wave phase shifts assuming a Breit-Wigner form of the resonance in order to determine the parameters of the $\Delta$ resonance.

E9: Lattice artefacts on the Landau gauge gluon propagator from hypercubic tensor representations

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Lattice tensor representations are used to investigate the lattice Landau gauge gluon propagator for the 4-dimensional, pure SU(3) Yang-Mills gauge theory. Due to the different symmetry structure of hypercubic lattices compared to the continuum spacetime, lattice correlation functions are described by different tensor structures. Therefore, form factors describing lattice correlation functions have, in principle, non-trivial relations with the continuum counterparts. The use of several tensor bases respecting lattice symmetries, and the analysis of...
its completeness allows to quantify the deviations of the lattice results from the continuum theory due to the lattice artefacts, and also estimate the theoretical uncertainty in the propagator. Furthermore, our analysis tests continuum based relations with the lattice data and shows that the lattice Landau gauge gluon propagator is suitably described by a unique form factor, as in the continuum formulation. Additionally, we identified classes of kinematic configurations where these deviations are minimal and the continuum description of lattice tensors is improved.

**The Hubbard model with fermionic Tensor Networks**

**Author:** Manuel Schneider

**Co-authors:** Carsten Urbach; Johann Ostmeyer; Karl Jansen; Laura Zywietz Rolón; Thomas Luu

Graphene can be modeled by the Hubbard model on a honeycomb lattice. However, this system suffers strongly from the sign problem if a chemical potential is included. Tensor network methods are not affected by this problem. We use the imaginary time evolution of a fermionic Projected Entangled Pair State, which allows to simulate both parity sectors independently. Incorporating the fermionic nature on the level of the tensor network allows to fix the particle number to be either even or odd. This way we can access the states at half filling and with one additional electron. We calculate the energy and other observables of both states, which was not possible before with Monte Carlo Methods.

**Lyncs: a Python API for Lattice QCD**

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We present Lyncs, a Python API for Lattice QCD currently under development. Lyncs aims to bring several widely used libraries for Lattice QCD under a common framework. Lyncs flexibly links to libraries for CPUs and GPUs in a way that can accommodate additional computing architectures as these arise, ensuring performance-portability for the calculations while maintaining the same high-level workflow. Lyncs distributes calculations using Dask and mpi4py, with bindings to the libraries performed automatically via cppy. While Lyncs is designed to allow linking to multiple libraries, we focus on a set of targeted packages that include c-lime, DDalphaAMG, tmLQCD and quda. The project is open for contributions as these may arise.
Hadronic light-by-light contribution to \((g-2)_{\mu}\) from lattice QCD: a complete calculation

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The tension between theory and experiment for the anomalous magnetic moment of the muon \((a_{\mu})\) is one of the long-standing puzzles of modern particle physics. After the update by the Fermilab E989 experiment in April 2021, the discrepancy between both sides lies at the 4.2-sigma level, as of the consensus made in the 2020 muon g-2 theory White Paper. The theory error is entirely dominated by the hadronic contributions, which can be calculated using lattice QCD. The order \(\alpha^3_{\text{QED}}\) hadronic light-by-light (hlbl) contribution \(a_{\mu}^{\text{hlbl}}\) admits a large relative uncertainty and represents a non-negligible source of uncertainty for the total error budget. In this talk, the Mainz approach and result for \(a_{\mu}^{\text{hlbl}}\) computed with \(N_f = 2 + 1\) lattice ensembles [arXiv:2104.02632] will be presented. We obtain a value of \(a_{\mu}^{\text{hlbl}} = 106.8(14.7) \times 10^{-11}\) after a chiral, continuum and infinite-volume extrapolation. This result contains all five Wick-contraction topologies needed for a complete lattice determination of \(a_{\mu}^{\text{hlbl}}\).

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**Axial U(1) symmetry at high temperatures in \(N_f = 2 + 1\) lattice QCD with chiral fermions**

**Authors:** Sinya Aoki\(^1\); Yasumichi Aoki\(^2\); Hidenori Fukaya\(^3\); Shoji Hashimoto\(^4\); Issaku Kanamori\(^3\); Takashi Kaneko\(^3\); Yoshifumi Nakamura\(^2\); Christian Rohrhofer\(^6\); Kei Suzuki\(^7\)

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The axial U(1) anomaly in high-temperature QCD plays an important role to understand the phase diagram of QCD. The previous works by JLQCD Collaboration studied high-temperature QCD using 2-flavor dynamical chiral fermions, such as the domain-wall fermion and reweighted overlap fermion. We extend our simulations to QCD with 2+1 flavor dynamical quarks, where the masses of the up, down, and strange quarks are near the physical point, and the temperatures are close to or higher than the pseudocritical temperature. In this talk, we will present the results for the topological susceptibility, axial U(1) susceptibility, and hadronic correlators.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 377

**CP-violating Dashen phase transition in the two-flavor Schwinger model: a study with matrix product states**
We numerically study the Hamiltonian lattice formulation of the Schwinger model with two fermion flavors using matrix product states. Keeping the mass of the first flavor at a fixed positive value, we tune the mass of the second flavor through a range of negative values, thus exploring a regime where conventional Monte Carlo methods suffer from the sign problem. Our results show signatures of a phase transition at the point where the absolute values of both masses are equal. Moreover, we observe the formation of a condensate, thus indicating that the observed transition is the analog of the CP-violating Dashen phase transition in QCD.

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Baryon masses from full QCD+QED_C simulations

We present preliminary results for the masses of the proton, neutron and Omega- baryons obtained from $n_f=1+2+1$ QCD+QED lattice simulations performed using $C^*$ boundary conditions. Spin-1/2 and spin-3/2 baryon two-point correlators are extracted from full QCD+QED lattice simulations through an extension to the OpenQ*D publicly available code. The correlators are computed by smearing, at different levels along the spatial directions, both the gauge configurations and the interpolating operators. Baryon masses are then extracted by applying the Generalised Eigenvalue Problem. These results are part of the ongoing effort of the RC* collaboration (discussed in the companion talk by Jens Lücke) and have been obtained on a single ensemble in which the renormalized electromagnetic coupling is $\alpha_{em}=0.04$, the physical volume is $L=1.7\text{fm}$ and the masses of the four dynamical quarks have been tuned at the U-spin symmetric point $m_d = m_s$.

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Looking at the analytic structure of Landau gauge propagators

We look at the analytic structure of the Landau gauge propagators. The analytic structure is studied using loop calculations and the finite temperature lattice calculations. The results are used to understand the analytic properties of the propagators and the gauge fixing conditions. The study of the analytic structure is important for understanding the behavior of the propagators in different regimes, especially at high energies or temperatures.
Lattice QCD is a first principle tool that allows to solve the theory in the non-perturbative regime. The Landau gauge quark, gluon and ghost propagator have been recently computed using both large physical volumes to access the IR region and large gauge ensembles that reduce the corresponding statistical uncertainties. However, lattice QCD only offers a table of numbers and further treatment is required to understand their meaning. We report a study of the fundamental QCD propagators based on Padé approximants to access their analytical structure. In particular, we try to identify the poles and branch cuts for each of the propagators.

QCD at nonzero Temperature and Density / 380

Lattice QCD with an inhomogeneous magnetic field background

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In non-central heavy-ion collisions, the magnetic fields generated are stronger than any ground-based experiments, reaching magnitudes comparable to the strong scale and being highly non-uniform. To study such extreme conditions, we simulate the theory of strong interactions at finite temperature on the lattice, with staggered fermions and an inhomogeneous magnetic background. Just as in the homogeneous case, the magnetic flux is quantized. We calculate the inhomogeneous chiral condensate, susceptibility, Polyakov loop and estimate the size of lattice artifacts. We assume a $1/\cosh^2$ profile for the field, varying its width and amplitude to study the impact on the computed observables. We find that the condensate follows a similar profile as the magnetic field, being enhanced where the field is peaked and decreased towards the tails. These results might contribute to a better understanding of magnetic field-related effects in non-central heavy-ion collisions, as well as of the QCD phase transition.

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Gauge-invariant renormalization of fermion bilinears and energy-momentum tensor on the lattice

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We study a gauge-invariant renormalization scheme (GIRS) for composite operators, regularized on the lattice, by extending the coordinate space (X-space) scheme proposed some years ago. In this
scheme, Green’s functions of products of gauge-invariant operators located at different spacetime points are considered. Due to the gauge-invariant nature of GIRS, gauge fixing is not needed in the lattice simulations. Also, when operator mixing occurs, the gauge-variant operators (BRST variations and operators which vanish by the equations of motion) can be safely excluded from the renormalization process.

We propose a number of variants of GIRS, including integration over time slices of the operator insertion point in a Green’s function, which may lead to reduced statistical noise in lattice simulations. We employ these variants in the renormalization of fermion bilinear operators and the study of mixing between the gluon and quark energy-momentum tensor operators. We extract the one-loop conversion factors relating the nonperturbative renormalization factors in different versions of GIRS to the reference scheme of $\overline{\text{MS}}$.

QCD at nonzero Temperature and Density / 382

Chromo-electric and chromo-magnetic correlators at high temperature from gradient flow

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The heavy quark diffusion coefficient is encoded in the spectral functions of the chromo-electric and the chromo-magnetic correlators that are calculable on the lattice. We study the chromo-electric and the chromo-magnetic correlator in the deconfined phase of SU(3) gauge theory using Symanzik flow at two temperatures $1.5T_c$ and $10000T_c$, with $T_c$ being the phase transition temperature. To control the lattice discretization errors and perform the continuum limit we use several temporal lattice extents $N_t=16,20,24,28$ and 34. We observe that the flow time dependence of the chromo-magnetic correlator is quite different from chromo-electric correlator most likely due to the anomalous dimension of the former as has been pointed out recently in the literature.

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Worldvolume tempered Lefschetz thimble method and its error estimation

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As a new algorithm towards solving the sign problem, we propose the “worldvolume tempered Lefschetz thimble method” (WV-TLTM) [1]. In this algorithm, we make hybrid Monte Carlo updates on
a continuum set of integration surfaces foliated by the antiholomorphic gradient flow ("the world-volume of the integration surface"). This algorithm is an extension of the tempered Lefschetz thimble method (TLTM) [2]. It tames the sign and multimodal problems simultaneously as the original TLTM. Furthermore, one no longer needs to prepare replicas of configuration space or compute the Jacobian of the flow except for the evaluation of its phase upon measurement, which reduces the computational cost significantly compared to the original TLTM. We apply this algorithm to the Stephanov model (a chiral random matrix model), for which the complex Langevin method is known not to work. We also discuss the effect of choosing a specific flow time region on the estimation of observables, especially by analyzing the autocorrelation times and the statistical errors [3].


QCD at nonzero Temperature and Density / 384

Critical endpoints in (2+1)- and 4-flavor QCD with Wilson-Clover fermions

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We report our study on critical endpoints of finite temperature phase transitions in (2+1)- and 4-flavor QCD with Wilson-Clover fermions. As an extension of our previous calculations on coarser lattices, we performed our simulations on lattices with temporal extents of 8 and 10 for 2+1 and 4 flavors, respectively, to carry out continuum extrapolations more precisely. For the calculation in (2+1)-flavor QCD, as a first step, we fixed \( \beta \) and \( \kappa_s \) values to 1.75 and 0.133000, respectively, and varied \( \kappa_l \), where we found that the phase transition seems to be of first order. In 4 flavor QCD we tried to determine a location of the critical endpoint from calculations at various combinations of \( \beta \) and \( \kappa \) values with three different spatial volumes. The finite size scaling of chiral susceptibility under the assumption of three-dimensional Z(2) universality suggests that the critical endpoint exists around \( \beta = 1.65 \).

QCD in searches for physics beyond the Standard Model / 385

Cutoff effects in short-distance quantities in lattice QCD

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We propose a method to help control cutoff effects in the short-distance contribution to integrated correlation functions, such as the hadronic vacuum polarization, using the corresponding screening correlators computed at finite temperature. The strategy is investigated with Wilson fermions at leading order, which reveals a logarithmically-enhanced lattice artifact in the short-distance contribution, whose coefficient is determined at this order. We also perform a numerical study with \( N_f = 2 \) \( O(a) \)-improved Wilson fermions and a temperature \( T \approx 250 \) MeV, with lattice spacings down to \( a = 0.03 \) fm, which suggests good control can be achieved on the short distance contribution to the hadronic vacuum polarization and the Adler function at large virtuality. Finally, we put forward a scheme to compute the complete hadronic vacuum polarization function at large virtualities using a step-scaling in the temperature.

**Master-field simulations of QCD**

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We report on the first master-field simulations of QCD with 2+1 dynamical quark flavours using non-perturbatively improved stabilised Wilson fermions. Our simulations are performed at a lattice spacing of 0.095 fm with 96 and 192 points in each direction. With \( Lm_\pi = 12.5 \) and 25, both lattices feature a pion and kaon mass of about 270 and 450 MeV. This setup is compatible with a chiral trajectory at fixed trace of the quark mass matrix and allows for comparisons to standard large-scale simulations. In this talk, we present our algorithmic setup and performance measures, and report about our experience in thermalising large master-field lattices with fermions.

**Meson spectroscopy at increasing temperatures using anisotropic ensembles**

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We will show mesonic ground masses at increasing temperatures for different flavour structures and operators. The mass extraction is carried out using a fitting procedure on anisotropic thermal correlation functions. We use FASTSUM collaboration thermal ensembles corresponding to an anisotropy of \( \xi = 3.5 = a_\tau / a_s \).
Using the meson masses as a function of the temperature, we aim to explore the restoration of chiral $SU(2)_A$ and $U(1)_A$ symmetries in QCD.

**Theoretical developments and applications beyond particle physics / 388**

**Real time dynamics of a semiclassical gravitational collapse of a scalar quantum field.**

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We present a new method to numerically investigate the gravitational collapse of a free, massless scalar quantum field in the semiclassical approximation from a spherically symmetric, coherent initial state. Numerical results are presented for a small ($r_s = 3.5 \ell_p$) wave packet in the $l=0$ approximation. We observe evidence for the formation of a horizon and study various systematic effects such as finite volume, time and radial discretization, different waveforms and vacuum subtraction procedures. Within our approximation, we find that the onset of the horizon formation is accelerated by semiclassical effects. Prospects for including higher angular momentum states and observing Hawking radiation are discussed.

**Standard Model Parameters / 389**

**Light meson physics and scale setting from a mixed action with Wilson twisted mass valence quarks**

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We consider a mixed action approach where valence Wilson twisted mass (Wtm) fermions at maximal twist are combined with CLS ensembles consisting of $N_f=2+1$ flavours of $O(a)$-improved Wilson sea quarks. We present an update of the results of the matching of valence and sea quarks, and of the subsequent continuum-limit scaling studies of light-quark observables. A scale setting procedure combining the $O(a)$-improved Wilson and the Wtm regularisations will be discussed.

**Hadron Spectroscopy and Interactions / 390**

**Investigating exotic heavy-light tetraquarks with 2+1 flavour lattice QCD**
There are a number of tetraquark channels for which some phenomenological models – already constrained by the ordinary meson and baryon spectrum – predict deep binding. We present results from our lattice calculations of doubly-charmed and bottom-charm channels where such predictions exist. Finding no evidence of deep binding, we can rule out those models, although this does not preclude the possibility of shallow binding for those states. On the other hand, a consistent picture of deeply-bound, strong-interaction stable $I = 0$, $J^P = 1^+$ $ud\bar{b}\bar{b}$ and $I = 1/2$, $J^P = 1^+$ $\ell s\bar{b}\bar{b}$ (with $\ell = u/d$) tetraquarks has emerged from lattice studies over the last few years. We discuss the current status of our calculations in each channel, outlining improvements that place our results on a firmer quantitative footing. The resulting updated versions of our earlier results for the binding energies of the two doubly-bottom channels are also presented.

**QCD at nonzero Temperature and Density / 391**

**Deconfinement critical point of a heavy quark effective lattice theory**

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Effective 3d Polyakov loop theories derived from QCD by strong coupling and hopping expansions are valid for heavy quarks and can also be applied to finite chemical potential, due to their considerably milder sign problem. We apply the Monte-Carlo method to the $N_f = 1, 2$ effective theories up to $O(\kappa^4)$ in the hopping parameter at zero $\mu$ to determine the critical quark mass, at which the first-order deconfinement phase transition terminates. The critical end point obtained from the effective theory to order $O(\kappa^2)$ agrees well with 4d QCD simulations with a hopping expanded determinant by the WHOT-QCD collaboration. We also compare with full QCD simulations and thus obtain a measure for the validity of both the strong coupling and the hopping expansion in this regime.

**Hadron Spectroscopy and Interactions / 392**

**Bottomonium resonances from lattice QCD static-static-light-light potentials**

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We study $I = 0$ quarkonium resonances decaying into pairs of heavy-light mesons using static-static-light-light potentials from lattice QCD. To this end, we solve a coupled channel Schrödinger equation with a confined quarkonium channel and channels with a heavy-light meson pair to compute phase shifts and t-matrix poles for the lightest decay channel. Additionally, we study the quark composition of the observed states in terms of quarkonium- and meson-meson-composition. We find results for S-, P-, D- and F-wave-states to discuss in the context of corresponding experimental results, in particular for $\Upsilon(10753)$ and $\Upsilon(10860)$.

**Vacuum Structure, Confinement, and Chiral Symmetry** / 393

**Another look at the three-gluon vertex in the minimal Landau gauge**

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The lattice three-gluon vertex in the Landau gauge is revisited using a large physical volume $\sim (8 \text{ fm})^4$ and a large statistical ensemble. The improved calculation explores the symmetries of the hypercubic lattice to reduce the statistical uncertainties and to address the evaluation of the lattice artefacts. In particular we focus on the low energy behaviour of the vertex and look at evidences for (or not for) a change of sign and its relation with ghost dominance.

**Hadron Spectroscopy and Interactions** / 394

**Evidence of glueballs at physical point**

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We perform an exploratory study of glueballs on a RBC/UKQCD gauge ensembles with a large lattice size and with the $N_f = 2 + 1$ dynamical quark masses being tuned at the physical point. The noises of glueball correlation functions are considerably reduced through the cluster-decomposition-error-reduction scheme. The Bethe-Salpeter wave functions are obtained for the sular, the tensor and the pseudoscalar glueballs by using the spatially extended glueball operators defined through the gauge potential $A_\mu(x)$ in the Coulomb gauge. These wave functions show similar features of non-relativistic two-gluon systems, which are used to optimize the signals of the related correlation functions at the early time region, where the ground state masses in each channel can be extracted. By the assumptions that the glueball operators defined in terms gauge potentials couple almost exclusively to pure glueball states, the obtained masses are interpreted to be those of the ground state pure gauge glueballs. For the most interesting scalar channel, the glueball mass is determined to be 1.75(2) GeV, which is in good agreement with the QLQCD predictions and is close to the mass of $f_0(1710)$. Our result shows the existence of glueball states in the presence of dynamical quarks, even though many systematic uncertainties have not yet be well tackled with.
**Fluctuations and correlations of net baryon number, electric charge and strangeness in a background magnetic field**

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We study the second-order fluctuations of and correlations among net baryon number, electric charge and strangeness in (2+1)-flavor QCD at non-zero magnetic field. We perform the lattice simulations using the tree-level improved gauge action and the highly improved staggered quark (HISQ) action with a fixed scale approach \((a \simeq 0.117 \text{ fm})\). The strange quark mass is fixed to its physical quark mass value \(m_{\text{phys}}\) and the light quark mass is set to be \(m_{\text{phys}}/10\) which corresponding to the pion mass is about 220 MeV at vanishing magnetic field. The lattice simulations are performed on \(32^3 \times N_\tau\) lattices with 9 values of \(N_\tau\) varying from 96 to 6 corresponding to temperatures ranging from zero up to 281 MeV. At each nonzero temperature, the magnetic field strength \(eB\) is simulated with 15 different values up to \(\sim 2.5 \text{ GeV}^2\). We find that quadratic fluctuations and correlations do not show any singular behavior at zero temperature in the current window of \(eB\) while they develop peaked structures at nonzero temperatures as \(eB\) grows. By comparing the electric charge-related fluctuations and correlations with hadron resonance gas model calculations and ideal gas limits, we find that the changes in degrees of freedom start at lower temperatures in stronger magnetic fields. Significant effects induced by magnetic fields on the isospin symmetry and ratios of net baryon number and baryon-strangeness correlation to strangeness fluctuation are observed, which could be useful for probing the existence of a magnetic field in heavy-ion collision experiments. This talk is based on arXiv:2104.06843.
The 38th International Symposium on Lattice Field Theory / Book of Abstracts

**Authors:** Kotaro Murakami; Yutaro Akahoshi; Sinya Aoki; Kenji Sasaki

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We study decuplet baryons from meson-baryon interactions. We report the analysis of the $P$-wave $\pi N$ interaction with isospin $I = 3/2$ and the $\bar{K}\Xi$ interaction with $I = 0$, which have channels to a $\Delta$ and $\Omega$ baryon, respectively. The interaction potentials are calculated in the HAL QCD method using 3-quark-type source operators at $m_\pi \approx 410$ MeV. We use the conventional stochastic estimation of all-to-all propagators combined with the all-mode averaging to reduce statistical fluctuation. The scattering phase shifts estimated by using the potentials indicate that the $\Delta$ and $\Omega$ baryon exist as bound states in this setup. The results of the binding energies are consistent with those estimated from the 2-point functions.

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**QCD at nonzero Temperature and Density / 399**

**Searching for the BCS phase at nonzero isospin asymmetry**

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According to perturbation theory predictions, QCD matter in the zero-temperature, high-density limits of QCD at nonzero isospin chemical potential is expected to be in a superfluid Bardeen-Cooper-Schrieffer (BCS) phase of $u$ and $d$ Cooper pairs. It is also expected, on symmetry grounds, that such phase connects via an analytical crossover to the phase with Bose-Einstein condensation (BEC) of charged pions at $\mu_I \gtrsim m_\pi/2$. With lattice results, showing some indications that the deconfinement crossover also smoothly penetrates the BEC phase, the conjecture was made that the former connects continuously to the BEC-BCS crossover.

We compute the spectrum of the Dirac operator, and use generalized Banks-Casher relations, to test this conjecture and identify signatures of the superfluid BCS phase.

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**QCD at nonzero Temperature and Density / 400**

**Chiral properties of (2+1)-flavor QCD in background magnetic fields at zero temperature**

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We show our lattice QCD results for masses and magnetic polarizabilities of light and strange pseudo-scalar mesons, chiral condensates, decay constants of neutral pion and neutral kaon in the presence of background magnetic fields with $eB$ ranging up to around 3.35 GeV$^2$ ($\sim 70 \ M^2_\pi$) in the vacuum. We performed (2+1)-flavor QCD lattice simulations using the Highly Improved Staggered Quarks (HISQ) action with $N_\tau = 96$. In the simulation the strange quark mass is fixed to its physical quark mass $m_{\text{phys}}$ and light quark mass is set to $m_{\text{phys}}/10$ which corresponds to $M_\pi \approx 220 \ MeV$ at zero temperature. We find that as the magnetic field strength grows, the masses of neutral pseudo-scalar mesons monotonously decrease and then saturate at a nonzero value, while there exists a non-monotonous behavior of charged pion and kaon masses as magnetic field grows. We observe a $qB$ scaling of the up and down quark flavor components of neutral pion mass, neutral pion decay constant as well as the up and down quark chiral condensates at 0.05 $eB$ 3.35 GeV$^2$. We show that the correction to the Gell-Mann-Oakes-Renner relation involving neutral pion is less than 6\%, and the correction for the relation involving neutral kaon is less than 30\% at $eB$ 3.35 GeV$^2$.

We further find that the Ward Identity involving the space-time sum of the pseudo-scalar correlation functions and the chiral condensates, together with the GMOR relation, naturally reconciles magnetic catalysis at zero temperature and the reduction of transition temperature in a background magnetic field. This talk is based on arXiv:2008.00493.

Hadron Structure / 401

**Nucleon form factors from $N_f=2+1+1$ twisted mass QCD at the physical point**

Authors: Constantia Alexandrou$^1$; Simone Bacchio$^1$; Martha Constantinou$^2$; Jacob Finkenrath$^1$; Kyriakos Hadjiyiannakou$^1$; Karl Jansen$^3$; Giannis Koutsou$^1$

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We present the nucleon axial and electromagnetic form factors using $N_\tau = 2 + 1 + 1$ twisted mass lattice QCD with clover improvement and with quarks with masses tuned to their physical values. Excited state effects are studied using several sink-source separations in the range 0.8 fm - 1.6 fm, exponentially increasing statistics with the separation such that statistical errors remain approximately constant. In addition, quark disconnected diagrams are included in order to extract the isovector and isoscalar axial form factors and the isospin symmetric proton and neutron electromagnetic form factors, as well as their strange-quark contributions. The radii and moments are extracted by modelling the $Q^2$ dependence, including using the so-called $z$-expansion method. A preliminary assessment of lattice cut-off effects is presented using two lattice spacings directly at the physical point.

Hadron Structure / 402

**Pion and rho structure functions from $N_f = 2+1$ lattice QCD**

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The rho meson is the lightest strongly decaying particle and also the simplest spin-1 meson, which allows for the study of polarisation dependent structure functions that are not present in the spin-1/2 case. Its unstable nature complicates the analysis of its structure, both on the lattice and in
experiment. However, it allows us to study the interplay between hadron polarization and parton densities, and provides us a comparative value for other spin-1 systems. The prominent example here is the $b_1$ structure function of the deuteron measured by HERMES.

So far, only very few lattice studies of the rho meson structure functions exist. Moreover, disconnected contributions where neglected, which we find to be non-negligible. We will present first results for flavor singlet and non-singlet matrix elements of the rho and the pion. Using a large subset of Coordinated Lattice Simulations (CLS) gauge ensembles enables us to perform a controlled quark mass- and continuum extrapolation to the physical limit.

**Vacuum Structure, Confinement, and Chiral Symmetry / 403**

**The static potential in 2+1+1-flavor QCD**

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We report on the status of the analysis of the static potential in 2+1+1-flavor QCD. The static potential is obtained by measuring Wilson loops using the HISQ action, yielding the scales $r_1/a$, $r_2/a$, and the string tension $\sigma$. We put our emphasis on the possible effects due to the dynamic charm quark by comparing the lattice results to continuum results of the static potential with and without a massive flavor at two loops.

**Standard Model Parameters / 404**

**Leptonic decays of charmed mesons with Wilson quarks**

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We present an overview of the RQCD and ALPHA collaboration’s combined effort on charm decay constants. Our calculations are based on the $N_f = 2 + 1$ CLS ensembles including the physical point. We discuss our analysis strategy and present results for the pseudoscalar and vector decay constants $f_{D(s)}$ and $f_{D^*(s)}$, as well as the coupling of the $D^*_s$-mesons to the tensor current.
**SU(3) symmetry breaking in $f_B$ and $f_{B_s}$**

**Authors:** Paul Jackson\(^1\); James Zanotti\(^1\); Ross Young\(^\text{none}\); Shanette De La Motte\(^1\); Sophie Hollitt\(^2\)

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Experimental precision for measurements of $B$ meson decays will continue to improve over the coming years as Belle II collects more data and the LHC returns to operation after its upgrade period. Independent measurements of $V_{ub}$ will soon be possible using rare $B 	o \tau \nu$ decays, for which $B$ meson decay constants $f_B$ are a key input.

We present updates from UKQCD/QCDSF/CSSM on the $SU(3)_f$ breaking in $B$ meson decay constants, using weighted averaging methods during the correlator fitting process. The $b$-quarks are generated with an anisotropic clover-improved action, and are tuned to match properties of the physical $B$ and $B^*$ mesons. Configurations are generated with $m = \frac{1}{2}(2m_l + m_s)$ kept constant to control symmetry breaking effects. Various sources of systematic uncertainty will be discussed, including those from continuum extrapolations and extrapolations to the physical point.

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**Hadron Structure / 406**

**Isovector Axial Vector Form Factors of the Nucleon from Lattice QCD with $N_f = 2 + 1$ $O(\alpha)$-improved Wilson Fermions**

**Author:** Tobias Schulz\(^1\)

**Co-authors:** Dalibor Djukanovic \(^2\); Georg von Hippel \(^1\); Jonna Koponen \(^1\); Harvey B. Meyer \(^4\); Konstantin Ottnad \(^1\); Hartmut Wittig \(^4\)

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We present the analysis of isovector axial vector nucleon form factors for a set of $N_f = 2 + 1$ CLS ensembles with $O(\alpha)$-improved Wilson fermions and Lüscher-Weisz gauge action. The set of ensembles covers a pion mass range of $M_\pi = 130 – 353$ MeV with lattice spacings between $a = 0.05 – 0.09$ fm. In particular, the ensemble list includes a $96^3$ box ensemble at the physical pion mass. For the purpose of the form factor extraction, we employ both the summed operator insertion method (summation method) and explicit two-state fits in order to account for excited-state contributions to the nucleon correlation functions. As for the description of the $Q^2$-behavior of the form factors, we perform $z$-expansion fits. Finally, we present HBChPT-inspired chiral and continuum extrapolations of the data.

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**Standard Model Parameters / 407**

**Scale setting for CLS 2+1 simulations**

**Author:** Ben Strassberger\(^1\)
We present an update of the scale setting for $N_f = 2 + 1$ flavor QCD using gradient flow scales and pseudoscalar decay constants. We analyze the latest ensembles with $2 + 1$ flavors of non-perturbatively improved Wilson fermions generated by CLS for improved precision. Special care is taken to correct for mistuning by measuring directly the mass derivatives of the various observables. We determine $t_0$, $u_0$ and $t_0/u_0^2$ with input taken from $f_\pi$ as well as from $f_K + f_\pi/2$.

Hadron Spectroscopy and Interactions / 408

Mass estimates of the SU(2) scalar glueball from spectral methods

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The estimation of the Källén-Lehmann spectral density from gauge invariant lattice QCD two point correlation functions is proposed, and explored via an inversion strategy based on Tikhonov regularisation. As proof of concept the SU(2) glueball spectrum for the quantum numbers $J^{PC} = 0^{++}$ is investigated, for various values of the lattice spacing, using the published data of arXiv:1910.07756. Our estimates for the ground state mass are in good agreement with the traditional approach, which is based on the large time exponential behaviour of the correlation functions. Furthermore, the spectral density also contains hints of excites states in the spectrum and is able to estimate their mass values. Spectroscopic analysis of glueball two-point functions therefore provides a straightforward and insightful alternative to the traditional method based on the large time exponential behaviour of the correlation functions.

QCD at nonzero Temperature and Density / 409

Deep inelastic scattering off quark-gluon plasma and its photon emissivity

Authors: Arianna Toniato\(^1\); Csaba Török\(^2\); Harvey Meyer\(^3\); Marco Cè\(^4\); Tim Harris\(^5\)

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The photon emissivity of quark-gluon plasma probes the interactions in the medium and differs qualitatively between a weakly coupled and a strongly coupled plasma in the soft-photon regime. The photon emissivity is given by the product of kinematic factors and a spectral function associated with the two-point correlator of the electromagnetic current at lightlike kinematics. A certain Euclidean...
correlator at imaginary spatial momentum can be calculated in lattice QCD and is given by an integral over the relevant spectral function at lightlike kinematics. I will present a first exploratory lattice calculation of this correlator. Secondly, I will show how Euclidean correlators at imaginary spatial momenta can also be used to probe the regime of deep inelastic scattering off quark-gluon plasma, which reveals its parton distribution function.

Hadron Spectroscopy and Interactions / 410

Radiative Transitions in Charmonium from Lattice QCD

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We present calculations of form factors and radiative transitions in the low-lying charmonium sector using Lattice QCD. Results for $J/\psi \rightarrow \eta c \gamma$, $\chi_{c0} \rightarrow J/\psi \gamma$ partial widths are presented alongside other experimentally unobservable form factors. Comparisons are given to previous results in both lattice and experimental studies. Studying radiative transitions provides insights into the structure of charmonia and this study serves as a demonstration of techniques applicable to other more interesting transitions, such as those involving excited and exotic states.

Based on work in preparation by

J. Delaney, C. O’Hara, S.M. Ryan, C.E. Thomas

(for the Hadron Spectrum Collaboration)

QCD at nonzero Temperature and Density / 411

Lattice QCD at imaginary chemical potential in the chiral limit.

Authors: Jishnu Goswami; Frithjof Karsch; Anirban Lahiri; Christian Schmidt; Marius Neumann

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We report on an ongoing study on the interplay between Roberge-Weiss(RW) and chiral transition in simulations of (2+1)-flavor QCD with an imaginary chemical potential. We established that the RW endpoint belongs to the Z(2) universality class when calculations are done with the Highly Improved Staggered Quark (HISQ) action in the Roberge-Weiss plane with physical quark masses. We also have explored a range of quark masses corresponding to pion mass values, $m_\pi \geq 40$ MeV and found that the transition is consistent with Z(2) universality class. We argue that observables, that were usually used to determine the chiral phase transition temperature, e.g. the chiral condensate and chiral susceptibility, are sensitive to the RW transition and are energy like observables for the Z(2) transition, contrary to the magnetic (order parameter) like behavior at vanishing chemical potential. Moreover the calculations performed at $m_\pi \sim 40$ MeV also put an upper bound for a critical pion mass at zero chemical potential for a possible 1st order chiral phase transition. We furthermore determine the curvature of the pseudo-critical line close to the RW point and compare it with that at vanishing chemical potential.
Nonperturbative infrared finiteness in super-renormalisable scalar quantum field theory

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Scalar $\phi^4$ theory in three dimensions with fields in the adjoint of $SU(N)$ is of interest as holographically dual to a model for inflationary cosmology. The theory is perturbatively IR divergent but it was proposed in the past that its dimensionful coupling constant plays the role of the IR regulator nonperturbatively. Using a combination of Markov-Chain-Monte-Carlo simulations of the lattice-regularised theory, both frequentist and Bayesian data analysis, and considerations of a corresponding effective theory we gather evidence that this is indeed the case. We will briefly discuss the implications this potentially has for holographic cosmology.

Calculation of the second moment of the pion light-cone distribution amplitude

**Authors:** Anthony Grebe 1; William Detmold 1; Yong Zhao 3; Robert Perry None; Issaku Kanamori 1; C.-J. David Lin None; Santanu Mondal None

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The light-cone distribution amplitude (LCDA) of the pion carries information about the distribution of its quarks, which is an important input to various experiments. We present our proof-of-concept lattice calculation of the second Mellin moment of the LCDA using the heavy quark operator product expansion (HOPE) method. Our computation shows agreement with complementary methods of computation in the literature.

Precise $I = 3/2$ and $I = 0$ meson-baryon scattering amplitudes from an $N_f = 2 + 1$ CLS ensemble at $m_\pi = 200\text{MeV}$

**Authors:** Colin Morningstar 1; John Bulava 1; Ben Hoerz None; Andrew Hanlon 4; Andre Walker-Loud 5; Amy Nicholson None; Daniel Mohler 5

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A high-statistics computation of meson-baryon scattering amplitudes is presented on a single ensemble from the Coordinated Lattice Simulations (CLS) consortium with $m_\pi = 200 \text{MeV}$ and $N_f = 2 + 1$ dynamical fermions. The finite-volume approach is employed to determine the lowest few partial waves from ground and excited state energies computed by solving the Generalized Eigenvalue Problem. This analysis requires matrices of correlation functions between single- and two-hadron interpolating operators which are projected onto definite spatial momenta and finite-volume irreducible representations using the stochastic LapH approach to quark propagation. Results are presented for the $I = 3/2$ $p$-wave amplitude which includes the $\Delta(1232)$ resonance and the $I = 0$ $s$-wave amplitude with unit strangeness relevant for the $\Lambda(1405)$.

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**QCD in searches for physics beyond the Standard Model / 415**

**Continuum extrapolation of the hadronic vacuum polarization**

**Author:** Kalman Szabo\(^1\)

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In this talk we present in detail the continuum extrapolation procedure of the recent determination of the leading order hadronic vacuum polarization contribution to the muon anomalous magnetic moment from the Budapest-Marseille-Wuppertal collaboration (arxiv:2002.12347).

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**QCD at nonzero Temperature and Density / 416**

**Correlated Dirac eigenvalues around the transition temperature on $N_T = 8$ lattices**

**Authors:** Heng-Tong Ding\(^1\); Min Lin\(^1\); Peter Petreczky\(^2\); Swagato Mukherjee\(^3\); Wei-Ping Huang\(^1\); Yu Zhang\(^1\)

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Dirac Eigenvalue spectrum $\rho$ and its derivatives with respect to quark mass are useful quantities to study the microscopic origin of the chiral symmetry breaking in QCD. It has been proposed in Ref\(^1\) that the n-th order derivative of Dirac eigenvalue spectrum with respect to quark mass $\partial^n \rho / \partial m^n$ is connected to the (n+1)-point correlation function among Dirac eigenvalues, which can be computed directly on the lattice. By investigating on the 1st, 2nd and 3rd derivatives of Dirac eigenvalue spectrum it is found $\rho \propto m^2$ at $T = 205$ MeV. In this talk we extend the computation done in Ref\(^1\) to lower temperatures, i.e. 10 temperature values from 137 MeV to 166 MeV on $N_T = 8$ lattices using Highly Improved Staggered Quarks/Tree-level Improved Symanzik (HISQ/tree) action. We will discuss the temperature and quark mass dependences of the 1st and 2nd order quark mass derivatives of $\rho$ at $T \in (137, 166)$ MeV. We found that $\partial \rho / \partial m / m$ is no longer equal to $\partial^2 \rho / \partial m^2$ as that at $T = 205$ MeV, and $\partial^2 \rho / \partial m^2$ even becomes negative at certain low temperatures. Furthermore, in order to study the magnetic equation of state we also discuss the possibility to get rid of the
UV-divergent contribution in the chiral condensate by putting a UV-cutoff in the Dirac eigenvalue spectrum.

References

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 417

Real-time Quantum Calculations of Phase Shifts On NISQ Hardware Platforms Using Wavepacket Time Delay
Authors: Patrick Dreher¹; Erik Gustafson¹; Yingyue Zhu¹; Norbert Linke¹; Yannick Meurice²

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We introduce a new method to calculate phase shifts on noisy intermediate scale quantum (NISQ) hardware platforms using a wave packet edge time delay. The method uses the early and intermediate stages of the collision because the standard method based on the asymptotic out-state behavior is unreachable using today’s NISQ platforms. The calculation was implemented on a 4-site transverse Ising model in one spatial dimension with and without a potential interaction. A time evolution operator describing the progression of the system was constructed and transmission and reflection coefficients were calculated based on the identified quantum Fourier transformed momentum states. The detailed analysis of the phase shift calculations on both IBM superconducting transmon and University of Maryland ion trap quantum computers shows the platform independence of the methodology. This successful implementation of this wave packet preparation and projection on momentum eigenstates can now be performed with actual quantum computing hardware platforms. This method provides a procedure for calculating phase shifts and opens the possibility of using noisy intermediate scale quantum devices to perform real-time quantum mechanics and quantum field theory scattering calculations.

Theoretical developments and applications beyond particle physics / 418

Search for continuous phase transitions in 5D pure SU(2) lattice gauge theory
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The Renormalization Group (RG) is one of the central and modern techniques in quantum field theory. Indeed, quantum field theories can be understood as flows between fixed points, representing Conformal Field Theories (CFT’s), of the RG. Hence, the search and classification of yet unknown non-trivial CFT’s is a legitimate endeavor. Analytical considerations point to the existence of such
a fixed point in pure SU(2) Yang-Mills fields in 5D. This issue has already been addressed, although inconclusively. We review it, using lattice Monte Carlo methods, and present our results.

**Hadron Spectroscopy and Interactions / 419**

**Lambda-Nucleon and Sigma-Nucleon potentials from space-time correlation function on the lattice**

**Author:** Hidekatsu Nemura¹

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The hyperon-nucleon interaction with the strangeness \( S = -1 \) region is complicated and difficult to investigate because its flavor sector involves all the irreducible representation except the flavor singlet and has the worst signal-to-noise ratio among the Strangeness regions [1-2]. Some efforts to overcome such difficulties will be discussed.

**References:**


**Poster / 420**

**B10: The chiral phase transition from strong to weak coupling**

**Author:** Alfredo D’Ambrosio¹

**Co-authors:** Francesca Cuteri ¹; Owe Philipsen ²; Alessandro Sciarra ¹

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The order of the chiral phase transition of lattice QCD with staggered fermions is known to depend on the quark masses, the number of flavours and the lattice spacing. Studies in the literature show a weakening of the \( N_f = 3, 4 \) first-order transitions with decreasing lattice spacing. Here we investigate what happens when lattices are made coarser, in order to establish contact to the strong coupling region. For \( N_f = 4 \) we find a drastic weakening of the transition when going from \( N_t = 4 \) to \( N_t = 2 \), consistent with a second-order chiral transition expected in the strong coupling limit.

**Hadron Structure / 421**

**Lattice Observables for Parton Distributions**

**Author:** Luigi Del Debbio¹

¹ The University of Edinburgh (GB)
We review recent theoretical developments concerning the definition and the renormalization of equal-time correlators that can be computed on the lattice and related to Parton Distribution Functions (PDFs) through a factorization formula. We focus on the theoretical aspects in the context of a scalar field theory.

**QCD at nonzero Temperature and Density / 422**

**The QCD Deconfinement Critical Point for $N_f = 2$ Flavors of Staggered Fermions**

**Authors:** Alessandro Sciarra¹; Owe Philipsen²; Reinhold Kaiser²

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Quenched QCD at zero baryonic chemical potential undergoes a deconfinement phase transition at a critical temperature $T_c$, which is related to the spontaneous breaking of the global center symmetry. Including heavy but dynamical quarks breaks the center symmetry explicitly and weakens the first order phase transition. For decreasing quark masses the first order phase transition turns into a smooth crossover at a critical $Z_2$ point. The critical quark mass corresponding to this point has been examined with $N_f = 2$ Wilson fermions for several $N_\tau$ in a recent study within our group. For comparison, we also localize the critical $Z_2$ point with $N_f = 2$ staggered fermions on $N_\tau = 8$ lattices. For this purpose we perform Monte Carlo simulations for several quark mass values and various aspect ratios in order to extrapolate to the thermodynamic limit. The critical mass is obtained by fitting to a finite size scaling formula of the kurtosis of the Polyakov loop. Our results indicate large cutoff effects, requiring simulations on lattices with $N_\tau > 8$.

**Poster / 423**

**E10: Machine learning approaches to the QCD transition**

**Authors:** Andrea Palermo¹; Lucio Anderlini²; Maria Paola Lombardo³

**Co-authors:** Andrey Kotov; Anton Trunin ⁴

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We study the high temperature transition in pure $SU(3)$ gauge theory and in full QCD with 3D-convolutional neural networks trained as parts of either unsupervised or semi-supervised learning problems. Pure gauge configurations are obtained with the MILC public code and full QCD are from simulations of $N_f = 2 + 1 + 1$ Wilson fermions at maximal twist. We discuss the capability of...
different approaches to identify different phases using as input the configurations of Polyakov loops. To better expose fluctuations, a standardized version of Polyakov loops is also considered.

QCD at nonzero Temperature and Density / 424

Particle density probability distribution function and center symmetry breaking in finite density lattice gauge theories

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We study the nature of the phase transition at high temperature and high density in lattice gauge theories by focusing on the probability distribution function, which represents the probability of appearance of particle density in a heat bath. The probability distribution function is obtained by constructing a canonical partition function by fixing the number of particles from the grand partition function. However, if the Z(3) center symmetry, which is important for understanding the finite temperature phase transition of SU(3) lattice gauge theory, is strictly maintained on a finite lattice, the probability distribution function is always zero, except when the number of particles is a multiple of 3. For U(1) gauge theory, this problem is more extreme. The center symmetry makes it impossible for a charged state to exist.

In this study, we discuss the solution to this problem, and at the same time, propose a method of avoiding the sign problem, which is an important problem in the finite density lattice gauge theory, by the center symmetry. This problem is essentially the same as the problem that the expectation value of the Polyakov loop is always zero when calculating with finite volume, as long as the center symmetry is not broken. In the U(1) lattice gauge theory, when the fermion mass is heavy, numerical simulations are actually performed, and it is demonstrated that the calculation of the probability distribution function at a finite density is possible using the method proposed in this study. Furthermore, the application of this method to QCD is discussed.

Plenary / 425

Recent work on tessellations of hyperbolic geometries

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I discuss progress in simulating field theories on discrete hyperbolic spaces, with the goal of studying their physics in the bulk, and on the boundary. At tree-level, a free scalar field propagating in the bulk lattice is found to possess power-law two-point correlation functions on the boundary. The power-law behavior excellently matches the expected Klebanov-Witten formula despite being far away from the continuum, as well as matching the expected form due to the explicit breaking of conformal symmetry from the finite-volume boundary. When the field is dynamical—in the case of Ising spins—on a fixed hyperbolic lattice, the boundary physics is separated into two regimes depending on the bulk nearest-neighbor coupling. The conformal behavior of the free field—as well as the strong-coupling limit of the dynamical field—on the boundary can be seen explicitly to be a consequence of the hyperbolic geometry.
Infinite volume, three-body scattering formalisms in the presence of bound states

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Strong interactions produce a rich spectrum of resonances which decay into three or more hadrons. Understanding their phenomenology requires a theoretical framework to extract parameters from experimental data and lattice QCD simulations of hadron scattering. Two classes of relativistic three-body approaches are currently being pursued: the EFT-based and unitarity-based one. We consider a model of relativistic three-body scattering with an S-wave bound state in the two-body sub-channel using both formalisms. We present and discuss numerical solutions for the multi-hadron scattering amplitudes in different kinematical regions, obtained from integral equations of the EFT-based approach. We present the connection of our work to the ongoing program of computing three-body spectrum from the lattice. We also show how to generalize the unitarity-based framework to include all relevant open channels, discuss the nonphysical singularities near the physical region, and show how to eliminate them in a simple case.

Towards determining polarized gluon distribution from lattice QCD

Author: Raza Sufian

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We present a calculation of lattice QCD non-local matrix elements that can be used to determine polarized gluon Ioffe-time distribution and the corresponding parton distribution function using QCD short distance factorization. We construct the nucleon interpolation fields using the distillation technique and flow the gauge fields using the gradient flow. Our calculation is performed on a $32^3 \times 64$ isotropic lattice with a pion mass of 358 MeV.
The decoupling strategy for the determination of $\alpha_s$

**Authors:** Mattia Dalla Brida$^1$; Roman Höllwieser$^2$; Francesco Knechtli$^2$; Tomasz Korzec$^2$; Alessandro Nada$^3$; Alberto Ramos Martínez$^4$; Stefan Sint$^5$; Rainer Paul Sommer$^6$

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The decoupling strategy by the ALPHA collaboration uses simultaneous decoupling of $N_f=3$ heavy quark flavours to obtain a controlled connection between the $\Lambda$-parameters in QCD with $N_f=3$ and $N_f=0$ quark flavours, respectively, in terms of a common decoupling scale. Corrections are either power suppressed in the heavy quark mass, or perturbatively suppressed by powers of $\alpha_s$ at the scale of the heavy quark mass. In this talk I review the theoretical formalism (for results cf.-subsequent talk by R.-Höllwieser).

The Symanzik effective theory and the heavy quark mass expansion are combined and analyzed using recent results by Husung et al. on the leading logarithmic modifications of powers in $\alpha$ or the inverse quark mass. The application to finite volume couplings in a gradient flow scheme, together with perturbative 4-loop results on decoupling from the literature, then yield the basis for the analysis of the continuum and decoupling limits.

QCD at nonzero Temperature and Density / 429

Hamiltonian Lattice QCD from Strong Coupling Expansion

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We present generalizations of Hamiltonian Lattice QCD as derived from the continuous time limit of strong coupling lattice QCD: we discuss the flavor dependence and the effect of gauge corrections. This formalism is applied at finite temperature and baryon density and allows both for analytic and numeric investigations that are sign problem-free.

Hadron Spectroscopy and Interactions / 430

The excited and exotic heavy-light meson spectrum

**Author:** Sinead Ryan$^1$

**Co-authors:** David Wilson$^2$; Luke Gayer

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Preliminary results for the spectra of excited and exotic $B$, $B_s$ and $B_c$ mesons are presented. The calculation on a dynamical anisotropic lattice employs distillation, enabling a large basis of interpolating operators including those proportional to the gluonic field strength which are relevant for hybrid states. A comparison with a similar calculation of $D$ and $D_s$ mesons is made.

**Poster / 431**

**D7: $B_s \rightarrow D_s^{(*)}$ form factors from lattice QCD with $N_f = 2$ Wilson-clover quarks**

**Authors:** Benoit Blossier$^1$; Pierre-Henri Cahue$^3$; Jochen Heitger$^2$; Simone La-Cesa$^3$; Jan Neuendorf$^3$; Savvas Zafeiropoulos$^3$

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We report on a two-flavor lattice QCD determination of the $B_s \rightarrow D_s$ and $B_s \rightarrow D_s^*$ transitions, which in the heavy quark limit can be parameterized by the form factors $c_1G$, and $h_{A_1}, h_{A_2}$ and $h_{A_3}$. In the search of New Physics through tests of lepton-flavour universality, $B_s$ decay channels are complementary to $B$ decays and widely studied at $B$ factories and LHCb. The purpose of our study is to explore a suitable method to extract form factors associated with $b \rightarrow c$ currents from lattice QCD. In particular, we present numerical results for $c_1G$ and $h_{A_1}$.

**Hadron Spectroscopy and Interactions / 432**

**Lattice improvement of nuclear shape calculations using unitary transformations**

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We present a method to improve the lattice effective field theory description of the shape of atomic nuclei by applying unitary transformations to the Hamiltonian. The employed unitary operator is constructed as a reflection transformation from the original and the desired wave function. Similarly to a derivative expansion, it can be improved systematically so that one can tune the $\langle r^n \rangle$ expectation values order by order for the two-particle system. Moreover, the effects of the three-particle operators induced by the unitary transformation have been investigated. The method might be helpful to reduce lattice artifacts in radii and electromagnetic moments.
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**Isospin breaking effects in octet and decuplet baryon masses**

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We present work designed to compute baryon masses on \( N_f = 2 + 1 \) CLS ensembles including isospin breaking effects due to non-degenerate light quark masses and electromagnetic interactions. These effects are determined at leading order via a perturbative expansion around the iso-symmetric theory. We furthermore apply a group theoretical operator construction for the various interpolators describing the different members of the baryon octet and decuplet based on a classification by spin, parity, and flavor content. Finally, we will present first numerical results.

Hadron Structure / 434

**Gravitational Form Factors for Hadrons of Different Spins**

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The gravitational form factors (GFFs) of hadrons are the form factors of the energy momentum tensor of QCD, which quantifies how the energy, spin and mechanical properties are distributed within hadrons and how they split between the quark and gluon degrees of freedom. We use the Belinfante-Rosenfeld prescription in a Lattice QCD calculation with pion mass \( m_\pi = 450 \) MeV to measure the symmetric traceless gluon GFFs for hadrons of spin 0, 1/2, 1 and 3/2 (pion, nucleon, rho meson and delta baryon) for Mandelstam \( t \) in the spacelike region of \( 0 \leq -t < 2 \) GeV². By fitting the normalized GFFs using different functional forms, we extract partial gluonic contributions to the energy, pressure and shear force densities of the hadrons in the 3D and 2D Breit frames as well as in the infinite momentum frame. We also obtain estimates for their partial gluonic mass and mechanical radii.

Vacuum Structure, Confinement, and Chiral Symmetry / 436

**Density of states techniques for lattice field theory with topological terms**

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Topological terms contribute an imaginary part to the action such that for a numerical simulation of such systems the corresponding complex action problem has to be overcome. We address this task
with newly developed density of states techniques combined with open boundary conditions that
lift the integer quantization of the topological charge. We present results for U(1) and SU(2) lattice
gauge theory in 2 and 4 dimensions and demonstrate that the new approach allows for simulations
at finite topological angle.

Standard Model Parameters / 437

Determination of the continuous beta function of SU(3) Yang-Mills
theory

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The interpretation of gradient flow as a Wilsonian renormalization group (RG) transformation allows
one to determine the continuous RG beta function. This approach is alternative to the finite-volume
step-scaling function. Unlike step-scaling methods, where the lattice volume must provide the only
scale, the continuous beta function can be used even in the confining regime. We demonstrate
this technique in SU(3) Yang-Mills theory and explore the determination of the $\Lambda$-parameter. Our
investigation is based on simulations done with the tree-level Symanzik action on volumes up to $48^4$
and bare gauge couplings between 4.5 and 8.5.

Hadron Spectroscopy and Interactions / 438

Variations on the Maiani-Testa approach and the inverse problem

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In their seminal publication of 1990, Maiani and Testa showed that physical amplitudes away from
threshold cannot be directly extracted (i.e. without analytically continuing or solving an inverse
problem), from infinite-volume Euclidean correlators. As a result, in realistic lattice calculations, the
limited knowledge of correlation functions on finite subsets of points allows only for the extraction
of approximate smeared spectral densities (or else amplitudes via finite-volume energies). In this
presentation we discuss the recent results obtained in arXiv:2012.11488, which extend the original
work of Maiani and Testa and relate it to spectral reconstruction methods.

Poster / 439

A7: Evaluation of SU(3) smearing on FPGA accelerator cards

Authors: Grzegorz Korcyl; Piotr Korcyl; Salvatore Cali

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Recent FPGA accelerator cards promise large acceleration factors for some specific computational tasks. In the context of Lattice QCD calculations, we investigate the possible gain of moving the SU(3) gauge field smearing routine to such accelerators. We study Xilinx Alveo U280 cards in conjunction with Vitis high-level synthesis framework. We discuss the possible pros and cons of such solution based on gathered benchmarks.

**Propagator generation with Chroma+QUDA for various fermion actions**

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We will present how to calculate propagators on Chroma+QUDA with overlap, HISQ (highly improved staggered quark) and twisted-mass fermion actions. Those actions are not fully supported before and now most of the actions can be used in Chroma framework efficiently. The multi-grid speed-up for the HISQ and Twisted mass actions using QUDA will also be presented.

**Virtual Photon Emission in Leptonic Decays of Pseudoscalar Mesons**

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We study, with lattice QCD, the leptonic decays of pseudoscalar mesons of the type $P^+ \rightarrow l^+ \nu_l l^+ l^-$. These processes are mediated by the emission of a virtual photon which also interacts with the
The hadronic structure of the pseudoscalar meson $P^+$, giving rise to relevant structure-dependent corrections. They are very suppressed processes, which thus provide an excellent test for the Standard Model and represent an useful ground for the search of New Physics. Particularly interesting is the case of heavy mesons like the $D$ and the $B$, for which Chiral Pertubation Theory (ChPT) does not apply. We present the strategy developed for the lattice calculation of all the relevant structure-dependent form factors and separate their contribution to the amplitude from the point-like structure-independent term. We study the kinematic limitation due to the presence of internal lighter states appearing in the Euclidean correlation function, together with some strategies to overcome this issue. We also present our preliminary results and compare them with experimental data. For processes to which ChPT applies we also compare our results with the ChPT predictions.

QCD in searches for physics beyond the Standard Model / 442

**Hadronic vacuum polarization contribution to the muon $g-2$ from the Mainz collaboration**

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The Fermilab experiment recently published their new measurement of the anomalous magnetic moment of the muon, confirming the Brookhaven’s measurement with a comparable precision. Combining those two results and using the theory estimate published by the “Muon $g-2$ theory initiative”, a discrepancy of about 4 sigmas is observed between experiment and the theory prediction based on the Standard Model of particle physics. However, some lattice QCD calculations tend to produce larger values for the hadronic vacuum polarisation compared to the data-driven approach, bringing the SM prediction closer to the experimental measurement.

In this talk, we present an update of the leading hadronic vacuum polarization contribution from the Mainz group using $N_f = 2 + 1$ O($a$)-improved Wilson quarks. We will focus on the isoscalar channel for the $g-2$ contribution and on the window quantities that can be used as benchmarks between different lattice calculations.

Hadron Structure / 443

**Lattice QCD calculation of the subtraction function**

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**Co-authors:** Ross Young \(^1\); James Zanotti \(^1\); Kadir Utku Can \(^2\); Alec Hannaford Gunn \(^3\)

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The nucleon forward Compton amplitude describes the process of a virtual photon scattering on a nucleon. It is an important object which encodes insights into hadronic structure. The real part of this amplitude contains a component that is unconstrained by a dispersive representation in terms of inelastic scattering data. This component, commonly referred to as the 'subtraction function', contributes significantly to the determination of key physical quantities such as the electromagnetic portion of the proton-neutron mass difference and hence constraining this function has gained renewed interest. Using lattice QCD, the second order Feynman-Hellmann theorem can be utilised to calculate the nucleon forward Compton amplitude. By judiciously choosing the photon and nucleon momenta and direction of the electromagnetic current, the subtraction function $S_1(Q^2)$ can be calculated at fixed photon virtuality, $Q^2$. The subtraction function is calculated for a range of photon momenta up to high $Q^2 \approx 11$ GeV$^2$, using different discretisations of the electromagnetic current. The results indicate an asymptotic behaviour that differs from that anticipated from the operator product expansion. A comparison of results between differing quark masses and lattice volumes and spacings is made to determine whether the behaviour survives the physical limit.

Standard Model Parameters / 444

Renormalization constants of quark bilinear operators in QCD with dynamical up, down, strange and charm quarks

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We present a calculation of the QCD renormalization constants (RCs) for quark bilinear operators, evaluated non-perturbatively on the lattice in the RI'-MOM scheme. The calculation is performed by using dedicated ensembles with $N_f = 4$ degenerate dynamical twisted mass (clover) fermions and the Iwasaki gauge action. A detailed analysis is reported, with emphasis on the control or subtraction of the hadronic contaminations occurring in the lattice estimators of RCs and the check of proper scaling with $a^2$ of the final RC results. Such a careful study of systematic errors is the counterpart of the high statistical precision reached by current calculations of RC’s in the RI’-MOM scheme and is important in order to quote accurate results in phenomenological applications, such as the computation of quark masses.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 445

Bayesian Optimization for Variational Quantum Eigensolvers

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The Variational Quantum Eigensolver (VQE) is a hybrid quantum-classical algorithm used to find the spectrum of a Hamiltonian using the variational method. In particular, this procedure can be used to study LGT in the Hamiltonian formulation. Bayesian Optimization (BO) based on Gaussian Process Regression (GPR) is a powerful algorithm for finding the global minimum of the energy with
a very low number of iterations. This work explores some available methods for BO and GPR, and proposes a setup that is specifically tailored to perform VQE with NISQ devices.

**Hadron Spectroscopy and Interactions / 446**

**Confirmation of the existence of an exotic state in the $\pi D$ system**

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In recent years many candidates for states beyond the most simple realization of the quark model were found in various experiments around the world. However, so far no consensus exists on their structure, although there is strong evidence that at least some of those are dynamically generated from meson-meson interactions.

We provide an important missing piece from the theoretical side to prove that the various structures seen in the $\pi D^{(*)}$, namely the lightest open charm scalars $D^+_s(2317)$ and $D^+_0(2300)$ as well as their axial vector partner states can all be understood as emerging from Goldstone-Boson–$D$-meson scattering.

In a SU(3) flavor-symmetric lattice QCD simulation at large pion masses we establish that there exists a $\pi D$ bound state in the flavor-sextet representation that cannot emerge for quark-antiquark states, but that appears naturally from the multiquark states. Moreover, we find repulsion in the $[15]$ representation, which establishes the pattern predicted for the interactions of Goldstone bosons with $D$ mesons.

**QCD at nonzero Temperature and Density / 447**

**Lee-Yang singularities, series expansions and the critical point**

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Determining the existence and the location of the QCD critical point remains a major open problem, both theoretically and experimentally. In this talk, I present a new way of reconstructing the equation of state in the vicinity of the nearest singularity (the Lee-Yang edge singularity in the crossover region) from a truncated Taylor series expansion for small $\mu$. This is done by using a combination of Padé resummation and conformal/uniformization maps. Then, I show that this information can be used to (i) determine the location of the critical point and (ii) constrain the non-universal mapping parameters between the Ising and QCD equations of state.

I explicitly demonstrate these ideas in the 2d Gross-Neveu model whose phase diagram shares the key aspects of the conjectured QCD phase diagram including the existence of a critical point.
QCD at nonzero Temperature and Density / 448

The QCD chiral phase transition for different numbers of quark flavours

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The Columbia plot specifies the order of the \(N_f = 2 + 1\) QCD thermal transition as a function of the quark masses. Since massless quarks cannot be simulated directly, the nature of the phase transition in the limit of vanishing \(u, d\)-quark masses has remained elusive, with different discretisations showing different orders of the transition in the small mass regime. We propose a modified analysis in the parameter space of degenerate quark masses, variable number of flavours and lattice spacing. Using unimproved staggered fermions with \(N_f \in [2, 7]\) and \(N_\tau = 4, 6, 8\), we map out regions of first-order transitions and crossover transitions, separated by a critical surface, in the bare parameter space of the lattice theory. This constrains the possibilities for an eventual continuum approach.

Hadron Structure / 449

Unpolarized and polarized gluon pseudo-distributions at short distances: Forward case

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We present the results that are necessary in the ongoing lattice calculations of the unpolarized and polarized gluon parton distribution functions (PDFs) within the pseudo-PDF approach. We give a classification of possible two-gluon correlator functions and identify those that contain the invariant amplitude determining the gluon PDF in the light-cone \(z^2 \rightarrow 0\) limit. One-loop calculations have been performed in the coordinate representation and in an explicitly gauge-invariant form. We made an effort to separate ultraviolet (UV) and infrared (IR) sources of the \(\ln(-z^2)\)-dependence at short distances \(z^2\). The UV terms cancel in the reduced Ioffe-time distribution (ITD), and we obtain the matching relation between the reduced ITD and the light-cone ITD. Using a kernel form, we get a direct connection between lattice data for the reduced ITD and the normalized gluon PDF.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 450

Quantum computing for lattice supersymmetry

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Quantum computing allows for the study of real-time dynamics of non-perturbative quantum field theories while avoiding the sign problem in conventional lattice approaches. Current and near-future quantum devices are severely limited by noise, making investigations of simple low-dimensional lattice systems ideal testbeds for algorithm development. Considering simple supersymmetric systems, such as supersymmetric quantum mechanics with different superpotentials, allows for the analysis of phenomena like dynamical supersymmetry breaking. I will present ongoing work applying quantum computing techniques to study such theories, targeting real-time dynamics and supersymmetry breaking effects.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 451

Gauge-Fixed Fourier Acceleration

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For an asymptotically free theory, a promising strategy for eliminating Critical Slowing Down (CSD) is naïve Fourier acceleration. This requires the introduction of gauge-fixing into the action, in order to isolate the asymptotically decoupled Fourier modes. In this talk, we present our approach and results from a gauge-fixed Fourier-accelerated hybrid Monte Carlo algorithm, using an action that softly fixes the gauge links to Landau Gauge. We compare the autocorrelation times with those of the pure hybrid Monte Carlo algorithm. We work on a small-volume lattice at weak coupling. We use fixed, equilibrated boundary links to avoid $Z_3$ and other topological barriers and to anticipate applying a similar acceleration to many small cells in a large, physically-relevant lattice volume.

QCD in searches for physics beyond the Standard Model / 452

All HISQ $B \rightarrow K$ form factors

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We present preliminary HPQCD results for $B \rightarrow K$ form factors $f_{0,+}^{T}(q^2)$ using the HISQ action for all valence quarks on the MILC $N_f = 2 + 1 + 1$ gauge field ensembles. The ensembles used cover five lattice spacings, include the physical pion mass, and span a range of heavy quark masses from $m_c$ to near $m_b$. Our "heavy-HISQ" approach allows us to map form factor heavy-quark dependence, extract results for both $D, B \rightarrow K$, and perform tests of heavy quark effective theory. Using the fully relativistic HISQ action for all quarks allows the weak current to be normalized non-perturbatively, eliminating the previously dominant uncertainty from perturbatively matching NRQCD-HISQ weak currents. In 2104.09883 we determine $D \rightarrow K$ form factors $f_{0,+}^{T}(q^2)$ (and a sub-percent determination of $|V_{cs}|$ - see Will Parrott’s talk at this conference) and report here on $f_{T}(q^2)$. Preliminary phenomenological implications and next steps in our all-HISQ heavy-light form factor campaign will be discussed.
Quantum Algorithms for Simulating the Lattice Schwinger Model

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The Schwinger model is a testbed for the study of quantum gauge field theories. We give scalable, explicit digital quantum algorithms to simulate the lattice Schwinger model in both NISQ and fault-tolerant settings. In particular, we analyze low-order Trotter formula simulations of the Schwinger model, using recently derived commutator bounds, and give upper bounds on the resources needed for simulations. We give scalable measurement schemes and algorithms to estimate observables which we cost in both settings by assuming a simple target observable: the mean pair density. Finally, we bound the root-mean-square error in estimating this observable via simulation as a function of the diamond distance between the ideal and actual CNOT channels. This work provides a rigorous analysis of simulating the Schwinger model, while also providing benchmarks against which subsequent simulation algorithms can be tested.

QCD at nonzero Temperature and Density / 454

The light Roberge-Weiss tricritical endpoint at imaginary isospin chemical potential

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In this talk, we discuss results for the Roberge-Weiss (RW) phase transition at nonzero imaginary baryon and isospin chemical potentials, in the plane of temperature and quark masses. Our study focuses on the light tricritical endpoint which has already been used as a starting point for extrapolations aiming at the chiral limit at vanishing chemical potentials. In particular, we are interested in determining how imaginary isospin chemical potential shifts the tricritical mass with respect to earlier studies at zero imaginary isospin chemical potential. A positive shift might allow one to perform the chiral extrapolations from larger quark mass values, therefore making them less computationally expensive. We also present results for the dynamics of Polyakov loop clusters across the RW phase transition.
D2: Topology of the $O(3)$ non-linear sigma model under the gradient flow

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The $O(3)$ non-linear sigma model (NLSM) is a prototypical field theory for QCD and ferromagnetism, featuring topological qualities. Though the topological susceptibility $\chi_t$ should vanish in physical theories, lattice simulations of the NLSM find that $\chi_t$ diverges in the continuum limit. We study the effect of the gradient flow on this quantity using a Markov chain Monte Carlo method, finding that a logarithmic divergence persists. This result supports a previous study and indicates that either the definition of topological charge is problematic or the NLSM has no well-defined continuum limit. We also introduce a $\theta$-term and analyze the topological charge as a function of $\theta$ under the gradient flow.

Hadron Spectroscopy and Interactions / 456

The lightest $D^*_0$ resonance from QCD

Authors: Nicolas Lang$^1$; Sinead Ryan$^1$; David Wilson$^2$; Christopher Thomas$^2$; Luke Gayer$^3$

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The lightest scalar charm-light $D^*_0$ and charm-strange $D^*_{s0}$ mesons have been puzzling in that experiments have found them at approximately the same mass. This is in contrast with the quark-model prediction. For the first time, we map out the energy dependence of the elastic Isospin-1/2 $D\pi$ scattering amplitude and find a complex $D^*_0$ resonance pole, using Lattice QCD with a pion mass $m_\pi \approx 239$ MeV and the Lüscher finite-volume quantisation condition. The resonance, which is lighter than the $D^*_{s0}$ found on the same lattice, is strongly coupled to the $S$-wave $D\pi$ channel. We find that both $q\bar{q}$-like and $D\pi$-like constructions are necessary to interpolate the corresponding spectrum from the vacuum.

Based on arXiv:2102.04973
L. Gayer, N. Lang, S. Ryan, D. Tims, C. E. Thomas, D. J. Wilson for the Hadron Spectrum Collaboration

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Nucleon isovector momentum fraction, helicity and transversity moment using Lattice QCD

Authors: Santanu Mondal$^4$; Tanmoy Bhattacharya$^1$; Rajan Gupta$^5$; Balint Joo$^3$; Huey-Wen Lin$^6$; Sungwoo Park$^4$; Frank Winter$^7$; Boram Yoon$^8$

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In this talk, I will discuss our recent calculations (Phys. Rev. D102 (2020) no.5, 054512, JHEP 2104 (2021) 044) of the first x-moment of nucleon isovector polarized, unpolarized and transversity distributions (momentum fraction, helicity and transversity moment respectively). We use the standard method for the calculation of these moments (via matrix elements of twist two operators), we carry out a detailed analysis of the sources of systematic uncertainty, in particular of excited state contributions. Our calculations have been performed using two different lattice setups (Clover on HISQ and Clover on Clover), each with several ensembles, which give consistent results that are in agreement with global fit analyses.

Goldstone Scattering with a Light Composite Scalar

Authors: Thomas Appelquist, Richard Brower, George Fleming, Andrew David Gasbarro, Anna Hasenfratz, Joe Kiskis, James C Osborn, Claudio Rebbi, Enrico Rinaldi, David Schaich, Pavlos Vranas, Evan Weinberg, Oliver Witzel, James Ingoldby

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In this talk, we present a lattice study of the scattering of pseudo-Goldstone Bosons in SU(3) gauge theory with $N_f = 8$ light Dirac fermions, a theory which lies close to the boundary of the conformal window. The scattering phase shift is measured in the s-wave, maximal isospin channel for different values of the scattering momentum, as well as for different values of the underlying fermion mass. A light singlet scalar in the spectrum has been reported in earlier studies, and its effect on the scattering of pseudo-Goldstones is examined by comparing the lattice measurements to a dilaton EFT.

Quantization conditions in the finite volume within the plane wave basis expansion

Authors: Lu Meng, Evgeny Epelbaum, Jambul Gegelia

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The quantization of the energy levels of interacting two-particle system in a finite volume has been well considered in which the exponential suppressed finite volume effect was usually omitted. The partial waving mixing effect in the finite volume is also an obstacle to extracting the interacting information in the infinite volume. In this work, we propose a framework to calculate the energy levels of two-particle systems in the box with the plane wave basis expansion rather than the partial wave expansion. We can reduce the interacting matrices of operators into the irreducible representations of the corresponding point groups. We use a nonrelativistic toy model and a relativistic example, $\pi \pi$ scattering, to illustrate the framework for both static and moving systems. In this framework, the exponential suppressed effect and partial wave mixing effect are embedded naturally. Our results show that the exponential suppression effect and the partial wave mixing effect for NN interaction with typical range $1/m_\pi$ are important for the box with size $L<5$ fm. This framework could be used to obtain the two-body finite volume energy spectrum from the effective field theories, unitarization approaches and other theoretical models, which could be related to the lattice QCD raw data.

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**C1: Hybrid stochastic method for the tensor renormalization group**

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We study a hybrid stochastic method for the tensor renormalization group (TRG) approach. The TRG is known as a powerful tool to study the many-body systems and quantum field theory on the lattice. It is based on a low-rank approximation of the tensor using the truncated singular value decomposition (SVD), whose computational cost significantly increases as the bond dimension increases, so that efficient cost reduction techniques are highly demanded. We use a noise vector for the low-rank approximation with combining the truncated SVD, by which the truncation error is replaced with a statistical error due to noise, and an improvement of the error estimation could be expected. We test this method in the classical Ising model in comparison with the original TRG method, and also discuss other applications of the method for further error reductions.

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**Semileptonic decays of heavy baryons to negative-parity baryons**

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The hadronic physics of the simplest semileptonic decays of $\Lambda_b$’s and $\Lambda_c$’s, in which both the initial and final baryons have $J^P = \frac{1}{2}^+$, is by now quite well understood. We have begun exploring more complicated processes with $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$ baryons in the final state, which have a rich
phenomenology but are more challenging for theory and experiment. We present our predictions for these decays and discuss how they compare with quark models, heavy-quark effective theory, zero-recoil sum rules, and experimental measurements.

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**Complex Langevin boundary terms in lattice models and the phase diagram of QCD**

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In complex Langevin simulations, the insufficient decay of the probability density near infinity leads to boundary terms that spoil the formal argument for correctness. We present a formulation of this term that is cheaply measurable in lattice models, and in principle allows also the direct estimation of the systematic error of the CL method. Results for various lattice models from XY model to QCD are presented.

**Pion Distribution Amplitudes in the Continuum Limit**

**Authors:** Nicholas Juliano, Rui Zhang, Carson Honkala, Huey-Wen Lin

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We present a lattice-QCD calculation of the pion distribution amplitudes using large-momentum effective theory (LaMET). Our calculation is carried out using three ensembles with 2+1+1 flavors of highly improved staggered quarks (HISQ), generated by MILC collaboration, at 310 MeV pion mass with 0.06, 0.09, 0.12 and 0.15 fm lattice spacings. We use clover fermion action for the valence quarks and tune the quark mass to match the lightest light and strange masses in the sea. The resulting lattice matrix elements are nonperturbatively renormalized in regularization-independent momentum-subtraction (RI/MOM) scheme and extrapolated to the continuum. We compare different approaches to extract the x-dependence of the pion distribution amplitudes.

**Hadronic vacuum polarization from step scaling in the Schwinger model**

**Author:** Fabian Frech

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We compute the quark-connected component of the hadronic vacuum polarization function at the energy scale of the Z boson mass in the Schwinger model. This is done by computing different representations of the Adler function on different energy scales. The mass parameters for the different scales are set with a step scaling scheme in which the lattice spacing and volume are adjusted to the given momentum. At each step the lattice spacing and volume are halved. We perform the continuum limit and investigate the finite volume behavior.

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**Calculation of the Gluon PDF using Pseudo-PDF technique**

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We present our calculation of the unpolarized gluon parton distribution function (PDF) in the nucleon using the Pseudo-PDF technique on a $32^3 \times 64$ isotropic lattice with a pion mass of 358 MeV. The nucleon interpolating fields are reconstructed using distillation and we apply the sGEVP method to calculate the gluonic matrix elements. We smear the gauge fields using the gradient-flow to compute the flowed matrix elements and using the double ratio, we calculate the flowed reduced Ioffe-time distribution (rITD). We extrapolate the results to the flow-time independent rITD and calculate the light-cone ITD in the $\overline{MS}$ scheme, at the small z-separation limit, using an NLO matching formula. Finally, the gluon PDF is calculated from the light-cone ITD by applying the appropriate kernel form.

**Theoretical developments and applications beyond particle physics / 466**

**Lattice QFT on Curved Spacetime for CFT and BSM**

**Author:** Richard Brower

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Lattices on Spherical Manifolds or on the cylindrical boundary of Anti-de-Sitter space have the potential to explore non-perturbative conformal or near conformal gauge theories for BSM studies for composite Higgs or Dark Matter. We report on progress in the use of Quantum Finite Elements (QFE) to address renormalization on maximally symmetric spherical simplicial manifolds. The simplicial Lagrangians for scalar, Fermionic and gauge fields are found and high precision test of counter term to restore exact isometries for the 2d and 3d Ising CFT are presented. The challenges in extend QFE software to high performance for 4d Gauge theories on $R \times S^3$ are discussed.

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Pseudoscalar transition form factors and the hadronic light-by-light contribution to the muon g-2

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Transition form factors of light pseudoscalar mesons ($\pi^0$, $\eta$ and $\eta'$) play a crucial role in computing the hadronic light-by-light contribution to the muon anomalous magnetic moment.

We present first results toward the extraction of these form factors using lattice QCD with staggered fermions on $N_f = 2 + 1 + 1$ gauge ensembles of the Budapest-Marseille-Wuppertal collaboration. The first part of the talk will focus on the spectroscopy of the three mesons. In the second, we will expound on our strategy to extract the form factors.

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x-dependence reconstruction of pion and kaon PDFs from Mellin moments

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We present a calculation of the connected-diagram contributions to the first three non-trivial Mellin moments for the pion and kaon extracted directly in lattice QCD using local operators with up to 3 covariant derivatives. We reconstruct the $x$-dependence of the pion and kaon PDFs via fits to our results. We find that the reconstruction is feasible and that our lattice data favor a large $x$-dependence that falls as $(1 - x)^2$ for both the pion and kaon PDFs. We integrate the reconstructed PDFs to extract the higher moments with $4 \leq n \leq 6$. Finally, we compare the pion and kaon PDFs, as well as the ratios of their moments, to address the effect of SU(3) flavor symmetry breaking. We use one ensemble of gauge configurations with two
degenerate light, a strange and a charm quark \((N_f = 2 + 1 + 1)\) of maximally twisted mass fermions with clover improvement. The ensemble reproduces a pion mass \(\sim 260\) MeV, and a kaon mass \(\sim 530\) MeV.

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C2: SU(2) gauge theory with \(N_f = 24\) fermions at finite mass

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SU(2) gauge theory with \(N_f = 24\) massless fundamental fermions is trivial: in the UV it has a Landau pole and in the IR it becomes free. At non-zero fermion mass the IR behaviour is expected to change: as the fermions decouple at sufficiently low energies, the theory reduces to pure gauge SU(2) and is therefore confining. We measure the evolution of the coupling constant with the gradient flow method. The decoupling of the fermions is observed clearly: the evolution of the coupling constant smoothly interpolates between the massless \(N_f = 24\) behaviour and pure gauge behaviour as the energy scale \(\mu\) changes from \(\mu \gg m_q\) to \(\mu \ll m_q\). We also measure the mass spectrum and string tension of the theory, and verify that they approach the expected free theory behaviour as \(m_q \rightarrow 0\).

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Determining properties of hyperons

Authors: Grant Bradley\(^{None}\); Malcolm Lazarow\(^1\); Nolan Miller\(^2\); Henry Monge-Camacho\(^3\); Amy Nicholson\(^{None}\); Pavlos Vranas\(^4\); Andre Walker-Loud\(^5\); Others\(^{None}\)

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Hyperon physics is expected to play a role in neutron stars, where the extreme neutron degeneracy pressure could push neutrons into hyperons; indeed, the composition of neutron stars contributes to the "softness" or "stiffness" of the equation of state, therefore setting limits on the possible sizes and masses of neutron stars. In this talk, I will present calculations of hyperonic observables, in particular the axial charges and masses. This work is based on a particular formulation of an SU(2) chiral perturbation theory for hyperons; determining the extent to which this effective field theory converges is instrumental in understanding the limits of its predictive power, especially since some hyperonic observables are difficult to calculate near the physical pion mass (eg, hyperon-to-nucleon form factors) and must be determined via an extrapolation to the physical point instead.

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Finite size effects in the leading hadronic vacuum polarisation contribution to \((g - 2)\_\mu\)

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The leading hadronic vacuum polarisation contribution to \((g - 2)\_\mu\) was recently determined by the Budapest-Marseille-Wuppertal collaboration to sub-percent precision, providing for the first time an ab-initio calculation of this quantity with errors comparable to phenomenological determinations.

To reach this unprecedented level of precision, a number of critical issues needed to be addressed. One such issue was the significant finite-size effects arising from the two-pion physics that dominates the hadronic vacuum polarisation. In this talk we describe how these finite-size effects were addressed through a combination of dedicated lattice simulations, chiral perturbation theory, and phenomenological models.

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**C3: Progress report on computing the disconnected QCD and the QCD plus QED hadronic contributions to the muon’s anomalous magnetic moment.**

**Authors:** Aida El-Khadra\(^1\); Alejandro Vaquero Avilés-Casco\(^2\); Alexei Bazavov\(^3\); Andreas Kronfeld\(^4\); CARLETON DETAR\(^5\); Christine Davies\(^6\); Craig McNeile\(^6\); Daniel Hatton\(^7\); Gaurav Ray\(^7\); Hwancheol Jeong\(^8\); James Simone\(^4\); Peter Lepage\(^9\); Steven Gottlieb\(^10\)

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The recent experimental result for the muon’s anomalous magnetic moment from Fermilab motivates the reduction of the errors on lattice QCD calculations of the leading order hadronic contribution. All of our calculations use the highly-improved staggered quark (HISQ) formulation. The gauge configurations are generated with four flavors of HISQ sea quarks with physical sea-quark masses. The disconnected QCD calculation use configurations at the three lattice spacings: 0.15, 0.12 and 0.09 fm. We report preliminary results for some of the QED+QCD contributions at one lattice spacing, which use either quenched photons or QCD gauge configurations that include the dynamics of QED in the sea.
A1: Investigations of supersymmetric Yang–Mills theories

Author: Angel Sherletov

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I will present new results from investigations of lattice supersymmetric Yang–Mills theories in three and four dimensions. The fermion action of these theories involves a Pfaffian that may be complex. A first analysis of the complex phase of the Pfaffian, \( \langle e^{i\phi} \rangle \), for the 3D theory with maximal supersymmetry (16 supercharges) reveals very small fluctuations around real positive values. This justifies the phase-quenched approximation used in recent work (arXiv:2010.00026). Separately, computing Creutz ratios for both the 3D and 4D theories with 16 supercharges provides information about their running coupling and beta function. Space permitting, I will also present ongoing work on the 3D theory with 8 supercharges.

C4: Algorithms for quantum state preparation in the Schwinger Model

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An important aspect to consider in practical applications of quantum computing is the computational cost of a quantum state preparation. Quantum adiabatic evolution is a possible technique based on the slow time evolution of the Hamiltonian from a simple one to the target one. A different approach is the so-called Rodeo algorithm, where stochastically, and in a recursive manner, all states outside a given energy interval are removed. We discretize the Schwinger model Hamiltonian with a \( \theta \) term, using staggered fermions, and compare the convergence properties of the two algorithms. We also study the impact of increasing the step-size in the Trotter evolution, to assess the feasibility of these type of calculations on a real quantum device.

Thermalization of gauge theories from their entanglement spectra

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If and how gauge theories thermalize is an unanswered question. Partly, this is due to the inability of lattice gauge theory (LGT) simulations to simulate out-of-equilibrium quantum dynamics on classical computers, but also due the difficulty of defining entanglement entropy in lattice gauge theories and finding schemes for its practical computation.

In this work, we study real-time thermalization dynamics of a $Z_2$ LGT in 2+1d using exact diagonalization. We develop a dual formulation for the reduced density operator, which allows us to compute the Entanglement Spectrum (ES) during the time evolution. We show that, in the regime where the system has topological order, it agrees with the low-energy effective Hamiltonian that describes the system in the presence of an open boundary. This finding is analogous to Li & Haldane’s conjecture about the ES of fractional quantum Hall states, which we extend here to lattice gauge theories. Studying quench dynamics, we then extract the entanglement Hamiltonian of non-equilibrium states during time evolution using a variational scheme.

Our formulation can be generalized to more complicated Abelian and non-Abelian lattice gauge theories and may allow future quantum digital computers and analog quantum simulators to uncover the thermalization dynamics e.g. of Quantum Chromodynamics from first principles.

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**Bottomonia screening masses in 2+1 flavor QCD**

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The sequential melting of the bottomonia states is one of the important signals for the existence of a Quark Gluon Plasma. The study of bottomonia spectral functions on the lattice is a difficult task for many reasons. Calculations based on NRQCD, that are commonly used for such purpose, are not applicable at high temperatures. In this work we propose a new method to study this problem by calculating the spatial screening masses of bottomonia states. We calculate the spatial meson correlators and extract the screening masses for mesons in different quantum channels using highly improved staggered quark (HISQ) action for bottom quarks and dynamical 2+1 flavor QCD HISQ gauge configurations. The typical lattice we choose are of size $N_s^3 \times N_t$ where $N_s = 4 N_t$ and $N_t = 8, 10, 12$. We consider the temperature range $T = 300$-$1100$ MeV. We show that for $T > 500$ MeV the temperature dependence of the screening masses of the ground state bottomonia are compatible with the expectations based on uncorrelated quark-antiquark pairs.

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**F1: Neural Network Preconditioning for U(1) Wilson-type Dirac Operators**

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We report progress in preconditioning Wilson-type Dirac operators in 1+1 dimensional U(1) lattice field theory using a neural network. We have developed a convolutional network that produces a preconditioner of comparable sparsity to the input operator. Once the model is trained, applying it to produce preconditioners is computationally cheap; with an optimized implementation, the neural network approach may provide a practical improvement over algebraic multigrid-based preconditioning, since the network is cheaper to apply and tends to produce much sparser preconditioners compared to AMG. So far, we have achieved a consistent reduction in iteration count during the solution of Dirac-operator linear systems using the conjugate gradient algorithm. Furthermore, the purely convolutional network architecture generalizes well across lattice volumes.

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A2: Supercurrent renormalization in $N = 1$ Supersymmetric Yang-Mills Theory

Authors: Apostolos Skouroupathis; Ivan Soler Calero

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In this work we study the renormalization of the SUSY Noether current in Supersymmetric $cal N = 1$ Yang-Mills (SYM) theory on the lattice. In particular, we study the mixing of the current with all other compatible operators of dimension $7/2$ and $5/2$, leading from the lattice-regularized to the $\overline{MS}$-renormalized operator basis. We perform our task in two ways:

(a) We compute, in dimensional regularization, the conversion factors relating the $\overline{MS}$ scheme to an intermediate gauge-invariant coordinate-space scheme. In this second scheme, renormalization can be performed via lattice simulations. This could help to investigate the breaking of SUSY on the lattice and strategies towards simulations of supersymmetric QCD. Here we present some preliminary numerical results.

(b) We use lattice perturbation theory and compute, to one loop, various two- and three-point functions. We consider mixing with all relevant gauge-noninvariant operators, which contain also ghost fields.

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Calculating the $K \rightarrow \pi \ell^+ \ell^-$ Rare Kaon Decay Amplitude at the Physical Point

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The $K \rightarrow \pi \ell^+ \ell^-$ decay is a flavor changing neutral current process which is forbidden at tree level in the Standard Model and thus may be sensitive to potential new physics. This decay is currently being measured at the NA62 experiment in CERN and its form factor is known only through experimental results. I will discuss the ongoing lattice QCD calculation of the $q^2 = 0$ form factor for the $K \rightarrow \pi \gamma^*$ decay at the physical point and present preliminary results.
Quantum simulation of quantum mechanics with a theta-term for a ’t Hooft anomaly

Author: Jiayu Shen

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Dimensionally reducing gauge theories like QED or Yang-Mills theory on small spatial tori often yields simple quantum mechanical models that retain some of the interesting structure of the parent gauge theory. 2D electrodynamics with massive charge-$N$ matter, for example, leads to the quantum mechanics of a particle on a circle with a $Z_N$ potential and a theta-term. This model, despite being simple to solve, exhibits the ’t Hooft anomaly or global inconsistency of the parent theory, and related phenomena of spontaneous symmetry breaking and instanton-anti-instanton interference. We propose a scheme for realizing the real-time quantum simulation of this model on a synthetic dimension. Similar phenomena in more complicated theories are of great interest and may be studied by quantum simulators in the future.

QCD in searches for physics beyond the Standard Model

$B \to D^{(*)}\ell\nu$ semileptonic decays in lattice QCD with domain-wall heavy quarks

Author: Takashi Kaneko

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We calculate the $B \to D^{(*)}\ell\nu$ form factors in 2+1 flavor relativistic lattice QCD by employing the Moebius domain-wall action for all quark flavors. Our simulations are carried out at lattice cut-offs $a^{-1} \approx 2.5, 3.6$ and 4.5 GeV with varying bottom quark masses up to 0.7 $a^{-1}$ to study heavy quark mass dependence and discretization effects. We extrapolate the form factors to the continuum limit and physical quark masses, and make a comparison in the differential decay rate with experiment.

Quark-gluon vertex with 2 flavours of O(a) improved Wilson fermions
**Vacuum Structure, Confinement, and Chiral Symmetry** / 484

**Manifestations of Confinement/Deconfinement in 4D compact QED on the lattice.**

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It has long been known that there is a phase transition between confined and unconfined phases of compact pure gauge QED on the lattice. In this work we report three manifestations of this phase change as seen in the Landau gauge photon propagator, the static potential, and distribution of Dirac Strings in the gauge fixed configurations. Each of these was calculated with large lattices with volumes: $32^4$, $48^4$ and $96^4$. We will show that the confined phase manifests with a Yukawa type propagator with a dynamically generated mass gap, a linearly increasing potential, and a significant concentration of Dirac strings while the unconfined phase appears consistent with the continuum results, a free propagator, a near constant long-distance potential, and a small concentration of Dirac strings trending towards 0. Furthermore, the photon propagator is investigated near the transition between the two phases.

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**C5: QCD topology and axion’s properties from Wilson twisted mass lattice simulations**

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We present the results on topological susceptibility and chiral observables in $N_f = 2 + 1 + 1$ QCD for temperature range $120 < T < 600$ MeV. The lattice simulations are performed with Wilson twisted mass fermions at physical pion, strange and charm masses. In high-$T$ region the chiral observables are shown to follow leading order Griffith analyticity regardless the critical behaviour, and the decay exponent of topological susceptibility agrees with instanton dilute gas models. The
measured topological susceptibility is used to estimate the mass of QCD axion. The resulting axion mass constraints are in agreement with our previous studies at higher pion masses.

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Normalizing flows for the real-time sign problem

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Applications of machine learning techniques to numerical studies of quantum field theories have been explored intensely in recent years. One such application is the use of a neural network for finding a map between the Boltzmann distribution of a lattice field theory and a simpler distribution function (a 'trivializing map' or 'normalizing flow'). Once such a map is found, one expects to improve the Monte-Carlo simulation by sampling field configurations from the simpler distribution function. In this talk, I will discuss the application of normalizing flows to \( \phi^4 \) real scalar field theory in Minkowski space as a first step toward solving its real-time sign problem. The goal is to find a map between the complex-valued Boltzmann distribution via the action of \( \phi^4 \) theory and a real-valued distribution. Firstly I will explain the conjectured existence of such normalizing flows which solve the sign problem completely. Then I will discuss the search for such normalizing flows with the aid of machine learning and the perturbative study of normalizing flows.

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Numerical simulation of self-dual U(1) lattice field theory with electric and magnetic matter

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We study a recently proposed formulation of U(1) lattice field theory with electric and magnetic matter based on the Villain formulation. This discretization allows for a duality that gives rise to relations between weak and strong coupling. We use a worldline version of the model to overcome the complex action problem and discuss suitable algorithms for its simulation. We investigate the self-dual point and study the possibility of a spontaneous breaking of self duality.

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Three-hadron s- and d-wave interactions from lattice QCD

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The past several years have seen significant progress in the theoretical developments for interpreting three-particle finite-volume energies. The successful application of these frameworks using lattice data for three-pion and three-kaon systems with maximal isospin has been demonstrated from several groups using a modest set of energies to constrain the three-particle interactions. Here we present results to push the limits of these finite-volume formalisms by extracting hundreds of energies in frames up to, and including, $L^2/(2\pi)^2 = 9$ on three CLS ensembles with pion masses of 200, 285, and 345 MeV at fixed lattice spacing. To date, only the generic relativistic field theory approach (RFT) has included higher partial waves, and we find the inclusion of d-wave interactions in both the two- and three-particle systems to be necessary to describe our data, thus going beyond s-wave interactions in the three-particle sector for the first time.

**QCD at nonzero Temperature and Density / 489**

**Thermal QCD phase transition and its scaling window from Wilson twisted mass fermions**

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We investigate the thermal QCD phase transition and its scaling properties on the lattice. The simulations are performed with $N_f=2+1+1$ Wilson twisted mass fermions at pion masses from physical up to heavy quark regime. We introduce a new chiral order parameter, which is free from linear mass contributions and turns out to be useful for the study of scaling behaviour. Our results are compatible with $O(4)$ universal scaling for the physical pion mass and the temperature range $[120:300]$ MeV. Violations to scaling at larger masses and other possible scenarios, including mean field behaviour and $Z(2)$ universality class are also discussed. We provide an estimation for the critical temperature in the chiral limit $T_0$.

**Hadron Spectroscopy and Interactions / 491**

**Scrutinizing QED with massive photons for precision physics**

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The current precision reached by lattice QCD calculations of low-energy hadronic observables, requires not only the introduction of electromagnetic corrections, but also a control over all the potential systematic uncertainties introduced by the lattice version of QED. Introducing a massive photon as an infrared regulator in lattice QED, provides a well defined theory, dubbed QED$_M$, amenable to numerical evaluation. An interesting feature of QED$_M$ is to provide a mass gap, ensuring that finite volume corrections decay exponentially with the linear size of the box. The photon mass is removed through extrapolation. In this contribution we scrutinize aspects of QED$_M$ such as the presence and fate of the zero modes contributions and we describe the determination of the photon mass corrections in finite and infinite volume. We test our findings in a numerical feasibility study presented in the talk by J. Tobias Tsang.

Theoretical developments and applications beyond particle physics / 492

Fields in fluctuating hyperbolic space

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We explore holography with geometry fluctuation in the two-dimensional hyperbolic lattice. We present results on the behavior of the boundary-boundary correlation function of scalar fields propagating on discrete 2D random triangulations with the topology of a disk. We use a gravitational action that includes a curvature squared operator which favors a regular tessellation of hyperbolic space for large values of its coupling. An ensemble of such geometries is generated for different values of the coupling using Monte Carlo simulation. We show that the conformal behavior expected for a uniform hyperbolic space survives as this coupling is decreased implying that holographic predictions survive at least weak quantum gravity corrections. We investigated the dependency of the scaling exponent of the correlators on the mass as we vary the coupling of the curvature-squared-operator. Finally, we discuss the extension of this model to allow for the inclusion of matter field interactions and backreaction on the geometry.

Hadron Spectroscopy and Interactions / 493

Comparing meson-meson and diquark-antidiquark creation operators for a bar-b bar-b u d tetraquark

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We compare two frequently discussed competing structures for a stable $\overline{b}b\overline{b}ud$ tetraquark with quantum numbers $I(J^P) = 0(1^+)$ by considering meson-meson as well as diquark-antidiquark creation operators. We treat the heavy antiquarks as static with fixed positions and find diquark-antidiquark dominance for $\overline{b}b$ separations $r < 0.25$ fm, while for $r > 0.50$ fm the system essentially corresponds
to a pair of B mesons. For the meson-meson to diquark-antidiquark ratio of the tetraquark we obtain around 60%/40%.

**Poster / 494**

**D8: Evaluation of OpenMP for Portable CPU and GPU Programming with GridMini**

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OpenMP has been the programming model of choice for shared-memory parallelism on multi-/many-core CPUs for a long time. Recent additions to the OpenMP standard have also enabled the support for offloading certain computations to compute accelerators such as GPUs. This potentially allows us to have a single code written with OpenMP directives that can be executed on both CPU and CPU+GPU platforms. We evaluate the OpenMP offloading features in the context of GridMini, a set of mini-benchmarks based on the Grid C++ lattice QCD library. We will discuss our experience with porting GridMini to NVIDIA, AMD and Intel GPUs using OpenMP. Preliminary benchmark performances will also be presented.

**Poster / 495**

**C6: Using weighted averaging methods in measurements of \( SU(3)_f \) symmetry breaking in \( B \) meson decay constants**

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Measurements of flavour physics anomalies, such as those in the CKM matrix elements, rely on minimising systematic errors from the relevant parameters derived from experiment and theory. One method of determining \( V_{ub} \) requires both \( B \to \ell\nu \) branching fractions from experiment and \( B \) decay constants from lattice QCD calculations, such as \( f_B \) and \( f_{B_s} \).

This work will present the efforts from UKQCD/QCDSF/CSSM in calculating \( f_B \) and \( f_{B_s} \) on controlled \( SU(3)_f \)-breaking ensembles, specifically focusing on the evaluation of \( B \) meson observables as a weighted average across multiple fitting regions. Due to the chosen anisotropic clover-improved action for the heavy \( b \)-quark, the tuning of the free parameters to physical \( B(1) \) and \( B(7) \) properties requires a large number of correlator fits on each ensemble. This increases the effort in choosing optimal fitting ranges, as well as compounding biases in the choice of range. The use of an automated weighted averaging technique over multiple fitting ranges allows for timely tuning of the \( b \)-quark and reduces the impact of systematic errors from fitting range biases in calculations of \( f_B \) and \( f_{B_s} \).

**QCD in searches for physics beyond the Standard Model / 496**
The neutron electric dipole moment revisited

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In QCD there is the possibility of strong CP violation arising from a nonvanishing vacuum angle $\theta$, which would result in an electric dipole moment $d_n$ of the neutron. Recently it has been shown that QCD undergoes a deconfinement phase transition at finite values of $\theta$ due to long-distance vacuum effects, which rules out any CP violation at the hadronic level, thus solving the strong CP problem by itself. To verify this statement we compute the electric dipole moment $d_n$. The calculation is done by rotating the $\theta$ term into the mass matrix and by simulating the action for imaginary values of $\theta$, which allows us to probe a wider range of $\theta$ values.

Hadron Structure / 497

Progress on the extraction of parton distributions from Ioffe time distributions

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The light-cone definition of Parton Distribution Functions (PDFs) does not allow for a direct ab initio determination employing methods of Lattice QCD simulations that naturally take place in Euclidean spacetime. In this presentation we focus on pseudo-PDFs where the starting point is the equal time hadronic matrix element with the quark and anti-quark fields separated by a finite distance. We focus on Ioffe-time distributions, which are functions of the Ioffe-time $\nu$, and can be understood as the Fourier transforms of parton distribution functions with respect to the momentum fraction variable $x$. We present lattice results for the case of the nucleon addressing the physical point and continuum extrapolations. We also incorporate our lattice data in the NNPDF framework treating them on the same footing as experimental data and discuss in detail the different sources of systematics in the determination of the non-singlet PDFs.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 498

Tensor network simulation of strongly coupled U(N)

**Authors:** Pascal Milde1; Jacques BlochNone; Robert Lohmayer1

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We applied tensor network methods to study strongly coupled U(N) in its dimer formulation. We investigated the chiral condensate as a function of the quark mass and the degree of the symmetry group, and find good agreement with Monte Carlo simulations.

**Hadron Structure / 500**

**Relating Euclidean correlators and light-cone correlators beyond leading twist**

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During recent years there has been a tremendous and exciting activity which aims at calculating the full x-dependence of parton distributions (PDFs) and related quantities in lattice QCD. To this end one needs to compute Euclidean correlators which through a perturbative matching procedure can be related to the light-cone correlation functions of interest. While the matching has already been studied in quite some detail for twist-2 light-cone PDFs, the twist-3 case was addressed only very recently for the first time. On the other hand, considering twist-3 PDFs is very important and promising as there exists very little experimental information in this field, mostly due to the kinematical suppression of twist-3 effects. We report on the status of matching calculations for twist-3 PDFs by highlighting the potential role played by singular zero-mode contributions and the need for considering 3-parton correlators. We will also show some pioneering lattice results in this field.

**Hadron Spectroscopy and Interactions / 501**

**Analyzing coupled-channel matrix elements in finite volume**

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Radiative transitions between stable hadrons and hadronic resonances can provide valuable insights into the composition of hadronic resonances. In this talk, we present a toy-model investigation regarding the feasibility of realistic lattice QCD calculations of reactions where a stable hadron undergoes a transition to one of several two-hadron channels. We describe the coupled-channel transition formalism relating the finite-volume matrix elements with the infinite volume transition amplitudes and provide a roadmap for performing the calculation. We demonstrate the efficacy of the approach on a set of synthetic data generated for a non-trivial resonant toy model.

**QCD at nonzero Temperature and Density / 502**
The complex potential from 2+1 flavor QCD from HTL inspired approach

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We have studied finite temperature complex static quark-antiquark potential for 2+1 flavor QCD using highly improved staggered action with pion mass 161 MeV. We extracted the potential using the Wilson line correlator fixed in Coulomb gauge. For the extraction, we have used a newly developed method [1] of splitting the correlator into symmetric and anti-symmetric parts. Using this method we found that the real part of the potential is screened above the crossover temperature, whereas the imaginary part is increasing with both distance and temperature.


Particle physics beyond the Standard Model / 503

The non-perturbative RG $\beta$ function at the sill of the conformal window

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The RG beta function describes the running of the renormalized coupling and connects the ultraviolet and infrared regimes of quantum field theories. We consider both the finite volume step scaling and the continuous beta function of the gradient flow coupling in SU(3) systems with fundamental fermions. Investigating theories with $N_f = 6, 8, 10$ and 12 flavors allows us to study the onset of the conformal phase. Our simulations are based on Moebious domain wall fermions, but we also consider alternate actions in our quest to reveal the universal phase structure of near-conformal systems.

QCD in searches for physics beyond the Standard Model / 504

Renormalization with the Gradient Flow: A Novel Method for Calculating Loop Integrals

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Lattice Quantum Chromodynamics (LQCD) provides the most direct probe into sources of $CP$-violation. These sources assume an effective form in higher-dimensional local operators built from QCD fields. Unfortunately, the operators mix with lower-dimensional operators under renormalization, introducing power divergences in the lattice spacing which inhibit a smooth continuum limit. The gradient flow provides a method to circumvent this problem. By smearing the fields dynamically in a new dimension, the flow time, we reparametrize the operator mixing independently of the lattice spacing.
allowing for a continuum limit at any fixed, nonvanishing flow time. Moreover, the fields are subjected to a Gaussian dampening of high-energy modes, so that ultraviolet divergences are suppressed in the bulk. On the other hand, the nonlinearity of the flow equations and nature of their solutions complicate flowed perturbation theory necessary for the high-energy matching of lattice results. In particular, the damping effect seemingly precludes the use of standard parametrization techniques to calculate loop integrals. We offer a new combinatorial technique for calculating Feynman integrals which is sufficiently general to include diagrams with flowed fields. Further, we present a related renormalization scheme with results and applications of this method to the determination of CP-violating nucleonic matrix elements on the lattice.

Particle physics beyond the Standard Model / 505

Bulk-preventing actions for SU(N) gauge theories

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We introduce a on-parameter family of SU(N) gauge actions which, when used in combination with an HMC update algorithm, prevent the gauge system from entering an artificial bulk-”phase”. We briefly discuss the (presumed) mechanism behind the bulk-prevention and present test results for different SU(N) gauge groups.

Hadron Spectroscopy and Interactions / 506

The neutron-proton mass difference

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We present a Lattice calculation of the mass difference between neutron and proton, obtained at 1st order in the QED coupling $\alpha_{EM}$ and in the mass difference between $u$ and $d$ quarks $m_d - m_u$. We adopt a purely hadronic scheme to renormalize the theory and to separate the QED and strong IB contributions.

The simulation is carried out using the ETMC gauge configurations with $N_f = 2 + 1 + 1$ dynamical quarks. We extrapolate among 3 values of the lattice spacing and pion masses in the range $M_{\pi} \simeq 200 - 450$ MeV.

Hadron Structure / 507

Transverse Momentum Dependent Parton Distribution Functions From Large Momentum Effective Theory

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We show that the transverse momentum dependent parton distribution functions (TMDPDFs), important for understanding 3D hadron structure and describing
high-energy experiments, can be formulated in the framework of the large-momentum effective theory (LaMET). We show that the quasi-TMDPDFs, calculable on lattice, factorize at large momentum limit into physical-TMDPDFs and reduced soft functions. We show that the reduced soft function can be realized as a form-factor and can be extracted by combining lattice calculable quasi-light-front wave functions and light-meson form-factors at large momentum transfer. This paves the wave for first-principle determination of TMDPDFs and Drell-Yan cross sections.

Hadron Structure / 508

Distribution Amplitudes of K* and φ from Lattice QCD

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We present the first lattice QCD calculation of the distribution amplitudes of longitudinally and transversely polarized vector mesons K* and φ using large momentum effective theory. We use the clover fermion action on three ensembles with 2+1+1 flavors of highly improved staggered quarks (HISQ) action, generated by MILC collaboration, at physical pion mass and {0.06, 0.09, 0.12} fm lattice spacings, and choose three different hadron momenta Pz = {1.29, 1.72, 2.15} GeV. The resulting lattice matrix elements are nonperturbatively renormalized in a hybrid scheme proposed recently. Also an extrapolation to the continuum and infinite momentum limit is carried out. We find that while the longitudinal distribution amplitudes tend to be close to the asymptotic form, the transverse ones deviate rather significantly from the asymptotic form. Our final results provide crucial ab initio theory inputs for analyzing pertinent exclusive processes.

Standard Model Parameters / 509

Calculating $K_L \to \gamma\gamma$ using lattice QCD

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Determining the standard model prediction for the decay amplitude of a long-lived neutral kaon into two photons is an important step toward the goal of calculating the two-photon contribution to $K_L \to \mu^+\mu^-$ decay. In this talk we will describe a computational strategy to determine this decay amplitude using lattice QCD. While the lattice QCD calculation is carried out in finite volume, the emitted photons are treated in infinite volume and the resulting finite-volume errors decrease exponentially in the linear size of the lattice volume. Only the CP conserving contribution to the decay is computed and we must subtract unphysical contamination resulting from single pion and eta intermediate states which grows exponentially as the time separation between the initial and final lattice operators is increased. First results from a calculation on a $24^3 \times 64$ lattice volume with $1/a = 1$ GeV and physical quark masses will be presented.

Theoretical developments and applications beyond particle physics / 510
Quantum Counter Terms for Lattice Field Theory on Curved Manifolds

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We present the necessity of counter terms for Quantum Finite Element (QFE) simulations of $\phi^4$ theory on non-trivial simplicial manifolds with semi-regular lattice spacing. In particular, by computing the local cut-off dependence of UV divergent diagrams we found that the symmetries of the continuum theory are restored for $\phi^4$ theory on the manifolds $S^2$ and $\mathbb{R} \times S^2$. Here we consider the construction of non-perturbative local counter terms in an attempt go to larger dimensionless lattice coupling closer to the strong coupling Wilson-Fisher IR fixed point.

Hadron Spectroscopy and Interactions / 511

Lattice determination of the pion mass difference $M_{\pi^+} - M_{\pi^0}$ at order $O(\alpha_{em})$ and $O((m_d - m_u)^2)$ including disconnected diagrams.

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We determine, with Twisted Mass Lattice QCD simulations and adopting the RM123 method, the charged/neutral pion mass difference $M_{\pi^+} - M_{\pi^0}$ at order $O(\alpha_{em})$ in the QED interactions and present preliminary results for $M_{\pi^+} - M_{\pi^0}$ at order $O((m_d - m_u)^2)$ in the strong isospin-breaking term. The latter contribution provides a determination of the SU(2) chiral perturbation theory low-energy constant $\ell_7$, whose present estimate is affected by a rather large uncertainty. The disconnected contributions appearing in the diagrammatic expansion of $M_{\pi^+} - M_{\pi^0}$, being very noisy, are notoriously difficult to evaluate and have been neglected in previous calculations. We will show that making use of the recently proposed Rotated Twisted Mass (RTM) scheme, tailored to improve the signal on mesonic observables, it is possible to evaluate the disconnected diagrams with good precision. For the QED induced pion mass difference, we obtain, after performing the extrapolation towards the continuum and thermodynamic limit and at the physical point, a value that is in nice agreement with the experimental result. For $M_{\pi^+} - M_{\pi^0}$ at order $O((m_d - m_u)^2)$, the results, which are so far limited to a single lattice spacing, are in agreement with phenomenological estimates.

QCD at nonzero Temperature and Density / 512

In-medium static quark potential from spectral functions on realistic HISQ ensembles
We study the static energy between a quark anti-quark pair in a thermal medium based on ensembles with \( N_f = 2 + 1 \) dynamical HISQ flavors. Our dataset spans the phenomenologically relevant temperature range between \( T=140\text{MeV}-2\text{GeV} \) based on lattice sizes \( 48^3 \times 10, 12 \) and 16. The real- and imaginary part of the potential is determined from the spectral function of Wilson-line correlators in Coulomb gauge. We assess the information content in the correlation functions and deploy three complementary strategies to reconstruct spectral information: model fits, Padé approximation and the Bayesian BR method. Limitations of each approach are carefully assessed.

Global symmetry breaking in gauge theories: the case of multi-flavor scalar chromodynamics

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Universal features of second order phase phase transitions can be investigated by studying the phi-to-the-fourth field theory with the corresponding global symmetry breaking pattern. When gauge symmetries are present, the same technique is usually applied to a gauge invariant order parameter field, as in the Pisarski-Wilczek analysis of the QCD chiral phase transition. Gauge fields are thus assumed to be irrelevant in the effective critical model, a fact that is however far from trivial. We will investigate the validity of this approach using three dimensional scalar lattice models with non-abelian global and local symmetries, for which critical exponents and scaling functions can be numerically determined with high accuracy.
Critical slowing down presents a critical obstacle to lattice QCD calculation at the smaller lattice spacings made possible by Exascale computers. Inspired by the concept of Fourier acceleration, we study a version of the Riemannian Manifold HMC (RMHMC) algorithm in which the canonical mass term of the HMC algorithm is replaced by a rational function of the gauge-covariant, QCD Laplace operator. We have developed a suite of tools using Chebyshev filters based on the QCD Laplacian that provides the power spectra of both the gauge and fermion forces and determines the spectral dependence of the resulting RMHMC evolution of long- and short-distance QCD observables. These tools can be used to precisely tune the RMHMC mass term and to anticipate the resulting degree of Fourier acceleration that should be achieved.

**Static potential at non-zero temperature from fine lattices**

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We report on the preliminary studies of static quark anti-quark potential at non-zero temperature in 2+1 flavor QCD using $96^3 \times 32$ lattices with lattice spacing $a=0.03\text{fm}$, physical strange quark mass and light quark masses corresponding to pion mass of about 300 MeV. The static potential is obtained from Wilson line correlator in Coulomb gauge with additional HYP smearing to reduce the noise at large quark anti-quark separations. We apply 0, 5 and 10 steps of HYP smearing to ensure that there is no physical effect from oversmearing. We obtain the complex static potential at non-zero temperature by assuming a single peak plus continuum form of the spectral function. Furthermore, the continuum part of the spectral function is constrained by the $T=0$ calculations at the same lattice spacing. The peak position gives the real part of the potential, while the width of the peak gives the imaginary part.

**Study of the EoS of dense QCD in an external magnetic field**

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In this report, we present our results on the lattice study of the EoS of dense QCD in an external magnetic field. The simulations are performed with $N_f = 2 + 1$ rooted dynamical staggered quarks at the physical point. Finite density is introduced through the imaginary chemical potentials $\mu_u = \mu_d = \mu_I$, $\mu_s = 0$. The EoS is obtained as series with respect to $\mu$ up to $\mu^6$ term. The dependencies of the expansion coefficients on the magnetic field are studied.

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First Lattice QCD determination of semileptonic decays of charmed-strange baryons $\Xi_c$

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While the standard model is the most successfully theory to describe all interactions and constituents in elementary particle physics, it has been constantly examined for over four decades. Weak decays of charm quarks can measure the coupling strength of quarks in different families and serve as an ideal probe for CP violation. As the lowest charm-strange baryons with three different flavors, $\Xi_c$ baryons (made of $csu$ or $csd$) have been extensively studied in experiments at the large hadron collider and in electron-positron collision. However the lack of reliable knowledge in theory becomes the unavoidable obstacle in the way. In this work, we use the state-of-the-art Lattice QCD techniques, and generate 2+1 clover fermion ensembles with two lattice spacings, $a = (0.108\text{fm}, 0.080\text{fm})$. We then present the first ["it ab-initio"] lattice QCD determination of form factors governing $\Xi_c \to \Xi^{\pm} \nu_\ell$, analogous with the notable $\beta$-decay of nuclei. Our theoretical results for decay widths are consistent with and about two times more precise than the latest measurements by ALICE and Belle collaborations. Together with experimental measurements, we independently determine the quark-mixing matrix element $|V_{cs}|$, which is found in good agreement with other determinations.

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D-to-pi semileptonic decays with highly improved staggered quarks

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This talk will report recent results from ongoing calculations of the $D \to \pi$ semileptonic decay by the Fermilab lattice and MILC collaborations. Our calculation employs the HISQ action for both
sea and valence quarks and includes several ensembles with physical-mass up, down, strange, and charm quarks and lattice spacings ranging from 0.15 fm down to 0.06 fm. At each lattice spacing, an ensemble with physical-mass light quarks is included. We present preliminary results for the scalar form factor $f_0$.

Hadron Structure / 519

**Nucleon Form Factors in the Continuum Limit from Clover-on-HISQ Formulation**

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The tension between the lattice calculation, the experimental data and the PCAC relation of the nucleon axial form factors - axial and (induced)-pseudoscalar - has been understood as a systematic resulting from missing multihadron (nucleon and pions) excited states in the analysis. These low-lying excited states are hard to resolve in the conventional analysis. Fits to the temporal component of axial current (A4), with a large excited-state contamination, demonstrate the need for the low-lying excited state, and the resulting axial form factor satisfy the PCAC relation. We will present a full reanalysis of the axial form factors that incorporates the low-energy states. Extensions of this data-driven approach successful for the axial form factor analysis is also applied to the electromagnetic form factors. Continuum results for the nucleon charges and electromagnetic form factors will also be presented. These lattice calculations are performed with Clover valence quarks on the MILC 2+1+1-flavor HISQ ensembles.

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**Lattice-QCD Calculations of TMD Soft Function Through Large-Momentum Effective Theory**

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The transverse-momentum-dependent (TMD) soft function is a key ingredient in QCD factorization of Drell-Yan and other processes with relatively small transverse momentum. We present a lattice QCD study of this function at moderately large rapidity on a 2+1 flavor CLS dynamic ensemble with $a = 0.098$ fm. We extract the rapidity-independent (or intrinsic) part of the soft function through a large-momentum-transfer pseudo-scalar meson form factor and its quasi-TMD wave function using leading-order factorization in large-momentum effective theory. We also investigate the
The rapidity-dependent part of the soft function—the Collins-Soper evolution kernel—based on the large-momentum evolution of the quasi-TMD wave function.

**Theoretical developments and applications beyond particle physics / 521**

**Continuum limit of two-dimensional multiflavor scalar gauge theories**

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We address the interplay between local and global symmetries by analyzing the continuum limit of two-dimensional multicomponent scalar lattice gauge theories, endowed by non-abelian local and global invariance. These theories are asymptotically free. By exploiting Monte Carlo simulations and Finite-Size Scaling techniques, we thus provide numerical results concerning the universal behavior of such models in this critical regime. Our results support the conjecture that two-dimensional multiflavor scalar fields have the same continuum limit as the sigma models associated with symmetric spaces that have the same global symmetry as the lattice model.

**QCD at nonzero Temperature and Density / 522**

**Thimble regularisation of YM fields: crunching a hard problem.**

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Thimble regularisation of Yang Mills theories is still to a very large extent terra incognita. We will discuss a couple of topics related to this big issue. 2d YM theories are in principle good candidates as a working ground. An analytic solution is known, for which one can switch from a solution in terms of a sum over characters to a form which is a sum over critical points. We would be interested in an explicit realisation of this mechanism in the lattice regularisation, which is actually quite hard to work out. A second topic is the inclusion of a topological term in the lattice theory, which is the prototype of a genuine sign problem for pure YM fields. For both these challenging problems we do not have final answers. We will present the current status of our study.

**Hadron Structure / 524**

**Towards High-Precision Nucleon Parton Distributions via Distillation**

**Author:** Colin Egerer¹
The pseudo-distribution formalism is one such methodology capable of illuminating the collinear structure of hadrons from matrix elements of suitably constructed space-like operators calculated using lattice QCD. Looking more closely at the unpolarized nucleon PDF calculation of the Had-Struc collaboration, the improved statistical quality of the computed Ioffe-time pseudo-distributions opens the possibility of rigorously quantifying systematics inherent to this calculation. A method to simultaneously extract the PDFs and capture and remove systematic effects is developed. This bolsters the prospect of a reliable PDF extraction with minimal systematic contamination.

**Hadron Structure / 525**

**The transversity PDF of the nucleon using the pseudo-distribution approach**

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The transversity parton distribution function probes the x-dependent difference between quarks with their spins aligned and anti-aligned with the transverse polarization of the nucleon. The chiral-odd nature of the transversity makes it experimentally harder to extract than unpolarized distributions, thereby making the lattice determination crucial. In this talk, we will present results on the lattice computation of the nucleon transversity PDF using the distillation method and by employing the pseudo-distribution approach on an ensemble with the lattice spacing a=0.094 fm and 358 MeV pion mass.

**Particle physics beyond the Standard Model / 526**

**Estimates for the lightest baryon masses in \(\mathcal{N} = 1\) supersymmetric Yang-Mills theory**

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\(\mathcal{N} = 1\) supersymmetric Yang-Mills theory describes gluons interacting with gluinos, which are spin 1/2 Majorana particles in the adjoint representation of the gauge group. In addition to glueballs and mesonic bound states, the theory contains colour neutral bound states of three gluinos, which are analogous to baryons in QCD. We calculate their correlation functions, involving sunset diagrams” and spectacle diagrams”, numerically for gauge group SU(2), and present an update on the estimates for the lowest masses.
**Excited states and precision results for nucleon charges and form factors**

**Authors:** Rajan Gupta¹; Tanmoy Bhattacharya²; Vincenzo Cirigliano³; Balint Joo⁴; Emanuele Mereghetti⁵; Santanu Mondal⁶; Boram Yoon⁷; Frank Winter⁶; Sungwoo Park³

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Starting with a summary of our studies of the sensitivity of various charges and form factors to the excited state spectrum, including input from PCAC, vector meson dominance and chiral perturbation theory, I will present an update on results for nucleon charges and form factors.

**A novel nonperturbative renormalization scheme for local operators**

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**Co-authors:** Andrea Shindler ²; Anna Hasenfratz ³; Oliver Witzel ⁴; Matthew Rizik ²

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The gradient flow, which exponentially suppresses ultraviolet field fluctuations and removes ultraviolet divergences (up to a multiplicative fermionic wavefunction renormalization), can be used to describe real-space Wilsonian renormalization group transformations and determine the corresponding beta function. We propose a new nonperturbative renormalization scheme for local operators that uses the gradient flow and is amenable to lattice QCD calculations. We present preliminary nonperturbative results for the running of quark bilinear operators in this scheme, the perturbative matching to the MS-bar scheme, and an analysis of tree-level discretization effects in the renormalization parameters.
I will present lattice investigations into the thermal phase structure of the Berenstein–Maldacena–Nastase deformation of maximally supersymmetric Yang–Mills quantum mechanics. The phase diagram of the theory depends on both the temperature $T$ and the deformation parameter $\mu$, through the dimensionless ratios $T/\mu$ and $g = \lambda/\mu^3$ with $\lambda$ the ’t Hooft coupling. We determine the deconfinement $T/\mu$ for couplings $g$ that span three orders of magnitude, to interpolate between the weak-coupling perturbative prediction and large-$N$ dual supergravity calculations in the strong-coupling limit. Analyzing multiple lattice sizes up to $N_\tau = 24$ and numbers of colors up to $N = 16$ allows initial checks of the large-$N$ continuum limit.

The de Sitter Instanton from Euclidean Dynamical Triangulations

Authors: John Laiho$^1$; Judah Unmuth-Yockey$^2$; Marc Schiffer$^3$; Scott Bassler$^4$

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After a brief introduction of Euclidean dynamical triangulations (EDT) as a lattice approach to quantum gravity, I will discuss the emergence of de Sitter space in EDT. Working within the semi-classical approximation, it is possible to relate the lattice parameters entering the simulations to the partition function of Euclidean quantum gravity. This allows to verify that the EDT geometries behave semi-classically, and by making contact with the Hawking-Moss instanton solution for the Euclidean partition function, I discuss how to extract a value of the renormalized Newton’s constant from the simulations. This value is consistent with that of previous determination coming from the interaction of scalar particles. That the same universal constant appears in these two different sectors of the theory is a strong indication that EDT provides a viable formulation of quantum gravity.

Lattice QCD Calculations of Transverse-Momentum-Dependent Wave Function through Large-Momentum Effective Theory

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We’ll present the first lattice QCD calculation of transverse momentum dependence wave function of pion using large momentum effective theory. We use the clover fermion action on three ensembles with $2 + 1 + 1$ flavors of highly improved staggered quarks (HISQ) action, generated by MILC collaboration, at pion mass $670\,MeV$ and $0.12\,fm$ lattice spacing, choose three different hadron momenta $P_z = \{1.72, 2.15, 2.58\}$ GeV. Our calculations includes light-front wave function, form
factor, Collins-Soper kernel, and soft function. For wave function, we use non-perturbative renormalization in MSbar scheme by using Wilson-loop renormalization. We find the curve of wave function with transverse momentum dependence has two turning points, which normal wave function doesn’t.

QCD in searches for physics beyond the Standard Model / 532

Hadronic vacuum polarization of the muon on 2+1+1-flavor HISQ ensembles: an update.

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We present an update, from the Fermilab Lattice, HPQCD, and MILC collaborations, of our results for the light-quark, connected contribution to the hadronic vacuum polarization correction to the muon’s anomalous magnetic moment. The calculation is performed on 2+1+1 highly-improved staggered quark (HISQ) ensembles with physical pion mass at four lattice spacings (0.15fm-0.06fm). We also present preliminary results for a study of the two-pion contributions to the vector-current correlation function performed on the 0.15fm ensemble.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 533

Tensor renormalization group analysis for reduced staggered fermions

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Reduced staggered fermions afford a very economical lattice fermion formulation yielding just two Dirac fermions in the continuum limit. They have also been used to construct models capable of symmetric mass generation. However, generically they suffer from sign problems. We discuss an application of the tensor renormalization group, a sign problem free method, to such models. We make a comparison between tensor renormalization group results and RHMC results in smaller volumes and show behaviors of physical observables in the thermodynamic and the continuum limits.

Particle physics beyond the Standard Model / 534
Large N limit of two-dimensional Yang-Mills theory with four-supercharges

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We study the two-dimensional Yang-Mills theory with four supercharges in the large N limit. By using thermal boundary conditions, the distribution of scalars is studied at large N, in the limit of a vanishing scalar potential. We explore the extent of scalar distribution in this theory and look for behavior identical to its maximally supersymmetric cousin, which is known to admit holographic description. Our lattice results for the scalar distribution as a function of temperature show no visible dependence on N.

Theoretical developments and applications beyond particle physics / 535

Complex Langevin: Boundary Terms at Poles

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The complex Langevin method is a general method to treat systems with complex action, such as QCD at finite density. The formal justification relies on the absence of certain boundary terms, both at infinity and at the unavoidable poles of the drift force. In this talk I focus on the boundary terms at poles for simple models, which so far have not been discussed in detail. The main result is that those boundary terms arise after running the Langevin process for a finite time and vanish again as the Langevin time goes to infinity. This is in contrast to the boundary terms at infinity, which can be found to occur in the long time limit (cf the talk by Dʻenes Sexty).

Hadron Structure / 536

Self-Renormalization of Quasi-Light-Front Correlators on the Lattice

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Large-momentum effective theory provides a way to extract the parton physics from lattice data based on first-principle calculation. In applying large-momentum effective theory, renormalization of the Euclidean correlators in lattice regularization is a challenge due to linear divergences in the self-energy of Wilson lines. Based on lattice QCD matrix elements of the quasi-PDF operator at lattice spacing \( a = 0.03 \text{ fm} \sim 0.12 \ |

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fm with clover and overlap valence quarks on staggered and domain-wall sea, we design a strategy to disentangle the divergent renormalization factors from finite physics matrix elements, which can be matched to a continuum scheme at short distance such as dimensional regularization and minimal subtraction. Our results indicate that the renormalization factors are universal in the hadron state matrix elements. Moreover, the physical matrix elements appear independent of the valence fermion formulations. These conclusions remain valid even with HYP smearing which reduces the statistical errors albeit reducing control of the renormalization procedure. Moreover, we find a large non-perturbative effect in the popular RI/MOM and ratio renormalization scheme, suggesting favor of the hybrid renormalization procedure proposed recently. We show the unpolarized isovector nucleon PDF calculated under hybrid renormalization scheme in comparison with other schemes. The hybrid renormalization scheme can give a better prediction for the negative $x$ region (the antimatter region), which is consistent with the antimatter asymmetry measured by experiments.

Hadron Spectroscopy and Interactions / 537

Connecting Matrix Elements to Multi-Hadron Form-Factors

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We discuss developments in calculating multi-hadron form-factors and transition processes via lattice QCD. Our primary tools are finite-volume scaling relations, which map spectra and matrix elements to the corresponding multi-hadron infinite-volume amplitudes. We focus on two hadron processes probed by an external current, and provide various checks on the finite-volume formalism in the limiting cases of perturbative interactions and systems forming a bound state. By studying model-independent properties of the infinite-volume amplitudes, we are able to rigorously define form-factors of resonances.

Hadron Structure / 539

Flavor diagonal nucleon charges

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We present updates on the calculation of flavor diagonal axial, tensor and scalar nucleon charges $g_{u,d,s}^{A,S,T}$ focusing on understanding the excited state contamination (ESC) including contributions of possible low-lying ($N\pi$ and $N\pi\pi$) excited states to individual nucleon matrix elements.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 540

Comparison of topology changing update algorithms
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In modern lattice simulations, conventional update algorithms do not allow for tunneling between topological sectors at fine lattice spacings. We compare the viability of multiple (less commonly used) algorithms with respect to proper sampling of all topological sectors in the Schwinger model. We briefly comment on the prospects of applying these methods to 4-dimensional SU(3) simulations.

QCD at nonzero Temperature and Density / 541

Thermal QCD with external imaginary electric fields on the lattice

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We study QCD at finite temperature in the presence of imaginary electric fields. In particular, we determine the electric susceptibility, the leading coefficient in the expansion of the QCD pressure in the imaginary field. Unlike for magnetic fields, at nonzero temperature this coefficient requires a non-trivial separation of genuine electric field-related effects and spurious effects related to the chemical potential, which becomes an unphysical gauge parameter in this setting. Our results are based on lattice simulations with stout improved dynamical staggered quarks at several lattice spacings and volumes.

QCD at nonzero Temperature and Density / 542

Spectral Reconstruction in NRQCD using the Backus-Gilbert Method

Author: Ben Page

Co-authors: Gert Aarts; Chris Allton; Benjamin Jaeger; Maria Paola Lombardo; Samuel Offler; Sinead Ryan; Seyong Kim; Thomas Spriggs; Jon-Ivar Skullerud

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We present the Backus-Gilbert method as a means of reconstructing spectral functions from NRQCD meson correlator data at non-zero temperature. We focus in particular on the resolving power of the method, providing a demonstration of how the underlying resolution functions can be probed by exploiting the Laplacian nature of the NRQCD kernel. We conclude with estimates of the bottomonium ground state mass and widths obtained using the method on FASTSUM anisotropic ensembles, comparing the results with several other reconstruction techniques.
Decays of an exotic $1^{-+}$ hybrid meson resonance from QCD

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An exotic hybrid meson resonance appearing in $J^{PC} = 1^{-+}$ is determined for the first time from lattice QCD. Many finite volume energy levels are computed and used with the coupled-channel extension of the Lüscher formalism to determine the scattering amplitudes in the limit where SU(3) flavour symmetry is exact. The scattering amplitude contains a pole that has a large coupling to an axial-vector-pseudoscalar channel, suggestive of a broad $\pi_1$ resonance with a dominant $b_1\pi$ decay mode.


Poster / 544

F2: (2+1+1)-flavor QCD equation of state on coarse lattices

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We present recent results on the QCD equation of state (EoS) with 2+1+1 flavors of highly improved staggered quarks (HISQ). The EoS is calculated with high statistics on lattices with temporal extent $N_T = 6$ and 8. The available temperature range extends up to about 960 MeV. The strange and charm quark masses are tuned to the physical values while the light quark mass corresponds to the pion mass of about 300 MeV in the continuum limit.

QCD at nonzero Temperature and Density / 545

Reconstruction of bottomonium spectral functions in thermal QCD using Kernel Ridge Regression

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We discuss results for bottomonium at nonzero temperature obtained using NRQCD on FASTSUM Generation 2L ensembles. We give an update on results for spectral functions obtained using Kernel Ridge Regression, paying in particular attention to the generation of training data. We compare our findings to estimates of masses of both ground- and the first excited states obtained using multieponential fits.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 546**

**Accessing scattering amplitudes using quantum computers**

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Future quantum computers may serve as a tool to access non-perturbative real-time correlation functions. In this talk, we discuss the prospects of using these to study Compton scattering for arbitrary kinematics. In particular, the need to restrict the size of the spacetime in quantum computers prohibits a naive determination of such amplitudes. However, we present a practical solution to this challenge that may allow for future determinations of deeply virtual Compton scattering amplitudes, as well as many other reactions that are presently outside the scope of standard lattice QCD calculations.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 548**

**Towards sampling complex actions**

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For many physical systems, the computation of observables amounts to solving an integral over a strongly oscillating complex-valued function. This so-called sign problem renders the numerical evaluation of these integrals a hard computational problem. Complex Langevin dynamics is one numerical method for tackling the sign problem. In this talk, I introduce a generalized framework for this method, providing explicit access to problems hindering a general applicability of complex Langevin dynamics.

One of the key problems of complex Langevin dynamics is a potential convergence to unphysical solutions. Starting from first principles, I establish constraints on sampling processes facilitating a sampling of the physically correct solutions. The constraints are built on firm grounds by techniques
of Markov chain Monte Carlo methods which warrant, as opposed to complex Langevin dynamics, explicit control of the underlying sampling process.

The approach opens up a perspective for tackling the sign problem by means of taylor-made sampling schemes.

QCD at nonzero Temperature and Density / 549

Effective Dimensions of Dirac Modes in IR Phase of QCD

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One consequence of the recently developed effective number theory, designed to count objects with probabilities, is that it leads to a well-defined concept of effective dimension. Due to the additivity of effective numbers, the latter is a measure-based construct extending the Hausdorff/Minkowski-like notion of dimension for fixed sets (with metric) to the stochastic domain. Both IR (infrared) and UV properties can be characterized in this way. Here we evaluate the IR effective dimension \( d_{IR} \) of Dirac modes in the IR phase of thermal QCD. Our results support the existence of a non-trivial structure in deep IR of the spectrum, involving integer dimensions. We point out certain similarities of this structure to one that we simultaneously observe in the vicinity of previously identified Anderson-like mobility edge, located above the energy scale set by temperature.

Hadron Structure / 550

Quark spin-orbit correlations in the proton

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Generalized transverse momentum-dependent parton distributions (GTMDs) provide a comprehensive framework for imaging the internal structure of the proton. In particular, by encoding the simultaneous distribution of quark transverse positions and momenta, they allow one to directly access longitudinal quark orbital angular momentum, and, moreover, to correlate it with the quark helicity. The relevant GTMD is evaluated through a lattice calculation of a proton matrix element of
a quark bilocal operator (the separation in which is Fourier conjugate to the quark momentum) fea-
turing a momentum transfer (which is Fourier conjugate to the quark position), as well as the Dirac
structure appropriate for capturing the quark helicity. The weighting by quark transverse position
requires a derivative with respect to momentum transfer, which is obtained in unbiased fashion us-
ing a direct derivative method. The lattice calculation is performed directly at the physical pion mass,
using domain wall fermions to mitigate operator mixing effects. Both the Jaffe-Manohar as well as
the Ji quark spin-orbit correlations are extracted, yielding evidence for a strong quark spin-orbit
coupling in the proton.

Poster / 551

A8: 2021 update of $\varepsilon_K$ with lattice QCD inputs

Authors: Weonjong Lee¹; Jon Bailey²; Yong-Chull Jang³; Jeehun Kim¹; Sunkyu Lee¹; Jaehoon Leem¹; Sungwoo Park⁴

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We report recent progress in determining $\varepsilon_K$, the indirect
CP violation parameter in the neutral kaon system, calculated using
lattice QCD inputs including $\hat{B}_K$, $\xi_0$, $\xi_2$,
$|V_{us}|$, $|V_{cb}|$, and $m_c(m_c)$.

Hadron Structure / 552

Towards precision calculation of partonic structure of hadrons
from lattice QCD

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Calculating the partonic structure of hadrons from lattice QCD has attracted a lot of interest in the
past few years, and now has moved to a stage which calls for precision. In this talk, I’ll discuss some
important steps towards such precision calculations.

Vacuum Structure, Confinement, and Chiral Symmetry / 553

Deep learning study on the Dirac eigenvalue spectrum of staggered quarks

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We study chirality of staggered quarks on the Dirac eigenvalue spectrum using deep learning techniques. The theory expects a characteristic pattern (we call it “leakage pattern”) in the matrix elements of the chirality operator sandwiched between two eigenstates of staggered Dirac operator. Deep learning analysis gives 99.4(24)% accuracy per a single normal gauge configuration and 0.998 AUC (Area Under ROC Curve) for classifying non-zero eigenmode quartets in the Dirac eigenvalue spectrum. It confirms that the leakage pattern is universal on normal gauge configurations. We choose the multi-layer perceptron (MLP) method which is one of the deep learning models. It happens to give the best performance in our study. Numerical study is done using HYP staggered quarks on the $20^4$ lattice in quenched QCD.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 554

**Machine learning Hadron Spectral Functions in Lattice QCD**

**Authors:** Heng-Tong Ding$^1$; Papp Gabor$^2$; Feiyi Liu$^3$; Chen ShiYang$^4$; Chunbin Yang$^4$

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Hadron spectral functions are important quantities as they carry all the information of hadrons. Unfortunately they cannot be computed directly on the lattice, and can only be extracted from Euclidean two-point temporal correlation functions which are directly computable in lattice QCD. The extraction of spectral functions from correlation functions is an inverse problem, and the most commonly used method is the maximum entropy method (MEM). The MEM is an iterative method, and its resulting spectral function depends on the input prior information of the spectral function. On the other hand, the variational autoencoder (VAE) is a type of neural network that learns to reproduce its input mapping it to a latent space. Thus, VAE can naturally be used for solving inverse problems. Here, in this talk we propose a modified version of VAE, in which the Shannon-Jaynes entropy term is added to the loss function fixing the input training spectral function as the prior information. We prove that such a setup of the neural network guarantees the unique solutions of spectral functions with a fixed combination of encoder and decoder. During the training process we use general spectral functions produced from the Gaussian mixture model. As a test, we use both correlators generated from physically motivated spectral functions having the form of one resonance peak with a continuum term, and those computed from the NRQCD. We will discuss the dependence of output spectral functions on the number of data points in temporal correlation functions, and make comparisons with results obtained from the MEM.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 555

**Toward dense QCD in quantum computers**

**Author:** Arata Yamamoto$^1$
Lattice QCD at nonzero baryon density is a big challenge in hadron physics. In this talk, I discuss the quantum computation of lattice gauge theory at nonzero density. I present some results of a benchmark test based on the quantum variational algorithm.

**Vacuum Structure, Confinement, and Chiral Symmetry / 556**

**Impact of center vortex removal on the Landau gauge quark propagator in dynamical QCD**

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The important role of center vortices in dynamical chiral symmetry breaking and corresponding dynamical mass generation has been demonstrated in quenched studies of the Landau gauge quark propagator. We present the results of our investigation into the impact of center vortex removal on the Landau gauge quark propagator computed with overlap fermions on dynamical gauge fields. Upon removal of vortices we find that dynamical mass generation essentially vanishes, and the quark renormalization function remains flat except in the infrared where it exhibits significant suppression.

**Poster / 557**

**C7: Temporal Contact Terms in Lattice Feynman-Hellmann Methods**

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Recently, Feynman-Hellmann methods have been used to calculate four-point functions in lattice QCD, specifically the forward and off-forward Compton amplitudes. However, these calculations are subject to discretisation artifacts from where the two currents are inserted on the same time slice. Here, we discuss the effects of these temporal contact terms, especially their contribution to the "subtraction function", and techniques to remove them.

**Poster / 558**

**C8: Advances in lattice hadron physics calculations using the gradient flow**
Lattice calculations of hadronic observables are aggravated by short-distance fluctuations. The gradient flow, which can be viewed as a particular realisation of the coarse-graining step of momentum space RG transformations, proves a powerful tool for evolving the lattice gauge field to successively longer length scales for any initial coupling. Already at small flow times we find the signal-to-noise ratio of two- and three-point functions significantly enhanced and the projection onto the ground state largely improved, while the physics is left unchanged. A further benefit is that far fewer conjugate gradient iterations are needed for the Wilson-Dirac inverter to converge. The inverter even converges for $\kappa > \kappa_c$, which allows us to explore the Aoki phase. We expect the effect of renormalisation and mixing to be significantly reduced as well.

Breaking the gauge symmetry in lattice gauge-invariant models.

We consider the role that gauge symmetry breaking terms play on the continuum limit of gauge theories in three dimensions. As a paradigmatic example we consider scalar electrodynamics in which $N_f$ complex scalar fields interact with a U(1) gauge field. We discuss under which conditions a mass term destabilizes the critical behavior (continuum limit) of the gauge-invariant theory and the nature of the asymptotic continuum limit observed once the gauge-breaking term is introduced.
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Algebraic multigrid methods have become state of the art at solving discretizations of the Dirac equation in Lattice QCD, in particular, when systems are ill-conditioned. Lattice QCD is bound by the use of supercomputers to speed up their simulations, where algebraic multigrid methods have brought a way of pushing the computational boundaries at large-scale and they open the possibility of scalably simulating at the exascale.

Unfortunately, under certain extreme situations such as the use of many nodes, and/or very high condition of the linear system to be solved which happens when quark masses are small, coarsest-level solves end up representing most of the execution time of the overall multigrid solves. If the solver employed during coarsest-level solves is e.g. GMRES, in which case we see the appearance of many dot products, scalability is at risk. We therefore take on the task of understanding and improving the scalability of coarsest-level solves.

For this, we merge four techniques into a single solver for coarsest-level computations: block Jacobi, polynomial preconditioning, Krylov recycling and pipelining.

All of our implementations and tests are performed within our solver library DD-alphaAMG, tailored in particular for the twisted mass fermion formulation. Recycling has a great interplay with our solver due to changes in the coarser matrices during the setup phase of the AMG employed by DD-alphaAMG, and the matrix-vector multiplications contain nearest-neighbour communications which gives us the opportunity of better scalability.

QCD at nonzero Temperature and Density / 561

Thermal interquark potentials for bottomonium using NRQCD from the HAL QCD method

Author: Thomas Spriggs

Co-authors: Chris Allton; Timothy Burns; Seyong Kim

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We report our calculation of the inter-quark potential of bottomonium at non-zero temperature using the HAL QCD method. This is applied to NRQCD non-local correlation functions generated from anisotropic FASTSUM ensembles. The correlation functions are initially calculated in momentum space for greater efficiency. Results will be presented for the interquark potential of various states as a function of temperature.

Poster / 562

F3: Bottomonium spectral widths at non-zero temperature using maximum likelihood

Author: Thomas Spriggs

Co-authors: Chris Allton; Gert Aarts; Timothy Burns; Benjamin Jaeger; Seyong Kim; Maria Paola Lombardo; Samuel Offler; Ben Page; Sinead Ryan; Jon-Ivar Skullerud

1 Swansea University
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We study the spectrum of the bottomonium system at non-zero temperature using the NRQCD approximation. A maximum likelihood method is used with a Gaussian ansatz for the ground state spectral contribution rather than the traditional delta function. This gives access to the state's width. We apply this approach to the FASTSUM’s anisotropic ensembles and compare results for the ground state masses and widths for S- and P-wave states with those from other methods.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 563

Performance optimizations for porting the openQ*D package to GPUs

Author: Roman Gruber

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OpenQ*D code has been used by the RC* collaboration for the generation of fully dynamical QCD+QED gauge configurations with C* boundary conditions. In this talk, optimization of solvers provided with the openQ*D package relevant for porting the code on GPU-accelerated supercomputing platforms is discussed. We present the analysis of the current implementations of the GCR solver preconditioned with Schwarz alternating procedure for ill-conditioned Dirac-operators. With the goal of enabling support for GPUs from various vendors, a novel method of adaptive CPU/GPU-hybrid implementation is proposed.

Plenary / 564

Software development and performance of Fugaku and ARM architectures

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The supercomputer “Fugaku” was jointly developed by Fujitsu Limited and RIKEN, and is the latest supercomputer installed at the RIKEN Center for Computational Science in Kobe, Japan. In the recent Top500, HPCG, and HPL-AI benchmark rankings, it has been ranked No. 1 in the world for two consecutive terms (June 2020 and November 2020). The CPU installed in Fugaku is a 48-core + 2 assistant core processor called A64FX, which is an extension of the Arm v8-A instruction set architecture for high-performance computing, and was developed by Fujitsu as the processor for Fugaku. The CPU consists of four “core memory groups” (CMGs) of 12 cores, and the L2 cache is shared by the 12 cores in the CMG. The main memory per node is 32GiB. The interconnect is a Tofu interconnect D. In this talk, we will present an overview of Fugaku, development of LQCD code for A64FX and its performance, and large-scale benchmark results on Fugaku.
QCD at nonzero Temperature and Density / 565

The upper right corner of the Columbia plot with staggered fermions

**Authors:** Szabolcs Borsányi\(^1\); Jana N. Guenther\(^1\); Ruben Kara\(^1\); Paolo Parotto\(^1\); Attila Pásztor\(^2\); Dénes Sexty\(^3\)

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QCD with heavy dynamical quarks exhibits a first order thermal transition which is driven by the spontaneous breaking of the global \(Z_3\) center symmetry. Decreasing the quark masses weakens the transition until the corresponding latent heat vanishes at the critical mass. We explore the heavy mass region with three flavors of staggered quarks. We analyze the Polyakov loop and its moments in a finite volume scaling study and monitor the chiral observables at the same time. Thus we calculate the heavy critical mass in the three flavor theory.

Hadron Spectroscopy and Interactions / 566

I=0 and 2 pion-pion scattering phase shift with physical quark mass

**Authors:** Tianle Wang\(^1\); Christopher Kelly\(^1\)

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We summarize the results of the recent work of calculating the \(\pi\pi\) scattering phase shifts for both the s-wave I=0 and I=2 channels at 4 different energies around the kaon mass with physical quark mass and focus on three new topics presented in that work. (i) A determinant test that can be applied to multi-operator data at a single time separation to detect excited state contamination. (ii) A fitting strategy that exploits theoretical input to estimate the excited state error which improves upon the method used to estimate this error in our 2015 calculation. (iii) A method of presenting the combined error on a scattering phase shift determined from finite-volume studies, giving a phase shift error at fixed energy rather than errors on both the phase shift and the energy at which it is evaluated.

QCD at nonzero Temperature and Density / 568

Taylor expansions and Padé approximations for Lefschetz thimbles and beyond

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Deforming the domain of integration after complexification of the field variables is an intriguing idea to tackle the sign problem. In thimble regularization the domain of integration is deformed into an union of manifolds called Lefschetz thimbles. On each thimble the imaginary part of the action stays constant and the sign problem disappears. A long standing issue of this approach is how to determine the relative weight to assign to each thimble contribution in the (multi)-thimble decomposition. Yet this is an issue one has to face, as previous work has shown that different theories exist for which the contributions coming from thimbles other than the dominant one cannot be neglected. Historically, one of the first examples of such theories is the one-dimensional Thirring model. Here we discuss how Taylor expansions can be used to by-pass the need for multi-thimble simulations. If multiple, disjoint regions can be found in the parameters space of the theory where only one thimble gives a relevant contribution, multiple Taylor expansions can be carried out in those regions to reach other regions by single thimble simulations. Better yet, these Taylor expansions can be bridged by Padé interpolants. Not only does this improve the convergence properties of the series, but it also gives access to information about the analytical structure of the observables. The true singularities of the observables can be recovered. We show that this program can be applied to the one-dimensional Thirring model and to a (simple) version of HDQCD. But the general idea behind our strategy can be helpful beyond thimble regularization itself, i.e. it could be valuable in studying the singularities of QCD in the complex $\hat{\mu}$ plane. Indeed this is a program that is currently being carried out by the Bielefeld-Parma collaboration.

**Hadron Spectroscopy and Interactions / 569**

**Finite volume effects and meson scattering in the 2-flavour Schwinger model**

**Authors:** Patrick Bühlmann; Urs Wenger

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We investigate the two-flavour Schwinger model in the canonical formulation with fixed fermion number. We use Wilson fermions on the lattice and present a formalism which describes the Dirac operator with dimensionally reduced canonical operators. These reduced operators allow the direct examination of arbitrary meson sectors and the determination of the energy spectrum in each of the sectors. Using Lüscher’s finite-volume mass-shift formula we discuss the 1-meson mass as well as the effective 3-meson coupling. From the 2-meson energies we determine the scattering phase shifts and compare the 3-meson energies in the finite volume to predictions based on scattering theory and quantization conditions.

**QCD in searches for physics beyond the Standard Model / 570**

**High precision scale setting on the lattice**

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Recently, the hadronic vacuum polarization contribution to the anomalous magnetic moment of the muon was determined by the BMW collaboration with sub-percent precision. Such a precision requires to control many sources of uncertainty. One of these is the uncertainty in the determination of the lattice spacing.
In this talk, we present the scale setting entering this computation. It relies on the mass of the Omega baryon as input which is directly used to set the scale of our main calculation. It also allows us to calculate the value of the intermediate scale setting quantity $w_0$. Here, we present our calculation of this quantity with a relative precision of about 0.4%.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 571

Solving DWF Dirac Equation Using Multi-splitting Preconditioned Conjugate Gradient with Tensor Cores on NVIDIA GPUs

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We show that using the multi-splitting algorithm as a preconditioner for the domain wall Dirac linear operator, arising in lattice QCD, effectively reduces the inter-node communication cost, at the expense of performing more on-node floating point and memory operations. Correctly including the boundary 'snake' terms, the preconditioner is implemented in the QUDA framework, where it is found that utilizing kernel fusion and the tensor cores on NVIDIA GPUs is necessary to achieve a sufficiently performant preconditioner. A reduced-dimension (reduced-$L_s$) strategy is also proposed and tested for the preconditioner. We find the method achieves lower time to solution than regular CG at high node count despite the additional local computational requirements from the preconditioner. This method could be useful for supercomputers with more on-node flops and memory bandwidth than inter-node communication bandwidth.

Theoretical developments and applications beyond particle physics / 572

Newtonian Binding from Lattice Quantum Gravity

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Quantizing gravity is one big problem of theoretical physics and it’s well-known that general relativity is not renormalizable perturbatively. Yet studies of quantum gravity on lattice have given evidence of the asymptotic safety scenario in which there is a strongly coupled UV fixed point. In this talk, I will talk about our study of the interaction of two scalar particles propagating on Euclidean dynamical triangulations working in the quenched approximation, which involves calculating the binding energy of a two-particle bound state. After taking the infinite-volume, continuum limit of the lattice calculation, our result is compatible with what is expected for the ground state energy by solving the Schrodinger equation for Newton’s potential, providing further evidence for EDT as a
theory of gravity in four dimensions. I will also show how we can determine the lattice spacing of EDT calculation for the first time.

QCD at nonzero Temperature and Density / 573

Lee-Yang edge singularities in lattice QCD : A systematic study of singularities in the complex $\mu B$ plane using rational approximations.

Authors: Christian Schmidt¹; Felix Ziesche²; Francesco Di Renzo¹; Guido Nicotra¹; Jishnu Goswami¹; Kevin Zambello³; Lorenzo Dini³; Petros Dimopoulos⁶; Simran Singh⁷

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A new approach is presented to explore the singularity structure of lattice QCD at imaginary chemical potential. Our method can be seen as a combination of the Taylor expansion and analytic continuation approaches. Its novelty lies in using rational (Padé) approximants for studying the analytic continuation. The motivation for using rational approximants will be exhibited. We will also try to provide some confidence in our approach based on numerical experiments performed on well-motivated "toy models". Our focus lies in identifying singularities of the net-baryon number density in the complex $\mu B$ plane. To this end we have found signatures of the Roberge-Weiss critical point and Chiral singularities. In this talk we will discuss the setup, simulation parameters and results obtained for 2+1 QCD at different temperatures and imaginary chemical potential values.

Hadron Structure / 574

NNLO Corrections to Quark Quasi Distributions

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We present the next-to-next-to-leading order (NNLO) calculation of quark quasiparton distribution functions (PDFs) in the large momentum effective theory. The nontrivial factorization at this order is established explicitly and the full analytic matching coefficients between the quasidistribution and the light-cone distribution are derived. In the end we get the PDFs within our NNLO matching coefficients and the lattice data.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 575
**Effects of Cosine Tapering Window on Quantum Phase Estimation**

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We provide a modification to the textbook’s quantum phase estimation algorithm (QPEA) inspired on classical windowing methods for spectral density estimation. From this modification we obtain an upper bound in the cost that implies a cubic improvement with respect to the algorithm’s error rate. Numerical evaluation of the costs also demonstrate an improvement. Moreover, with similar techniques, we detail an iterative projection method for ground state preparation that gives an exponential improvement over previous bounds using QPEA. Numerical tests that confirm the expected scaling behavior are also obtained. For these numerical tests we have used a Lattice Thirring model as testing ground. The procedures described have the flexibility of allowing product formulas, e.g. Suzuki product expansions, as well as post-Trotter methods for Hamiltonian simulation.

**Particle physics beyond the Standard Model / 576**

**Exploring SU(3)+Higgs theories: the fundamental case**

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Many candidate theories for BSM physics involve Yang-Mills gauge fields coupled to scalars. By considering a ‘toy model’ of a GUT — an SU(3) gauge theory with a scalar ‘Higgs’ in the fundamental representation — we give analytical reasons to suspect qualitative discrepancies between the spectrum obtained from the conventional perspective of spontaneous gauge symmetry breaking compared to an approach which explicitly requires nonperturbative gauge invariance. We present lattice spectroscopy results which support this conclusion.

**QCD at nonzero Temperature and Density / 577**

**Lee-Yang edge singularities in 2+1 flavor QCD with imaginary chemical potential.**

**Authors:** Guido Nicotra\(^1\); Francesco Di Renzo\(^2\); Petros Dimopoulos\(^3\); Lorenzo Dini\(^4\); Jishnu Goswami\(^4\); Simran Singh\(^4\); Christian Schmidt\(^4\); Kevin Zambello\(^5\); Felix Ziesche\(^6\)

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Lee-Yang edge singularities have been studied in various spin models to investigate the analytic structure of the ferromagnetic transition. As part of the Bielefeld Parma collaboration we investigate Lee-Yang singularities in lattice QCD. Based on an analytic continuation of the net-baryon number density, we present results of the location of the closest singularities in the complex chemical potential plane, obtained with (2+1)-flavor of highly improved staggered quarks (HISQ) on lattices with temporal extent of $N_{\tau} = 4, 6$. We show that their temperature scaling is in accordance with the expected scaling of the Lee-Yang edge singularities in the vicinity of the Roberge-Weiss transition. The analysis can be used to determine various non-universal parameters that map QCD in the scaling region of the RW transition to the Ising model. We will further discuss how the Lee-Yang edge singularity can be used to probe also the chiral phase transition in QCD. At temperatures close to the chiral phase transition temperature $T_c$ we find again agreement with the expected scaling of the Lee-Yang edge singularity, now expressed in terms of scaling variables that are appropriate for the chiral symmetry breaking. Finally, we discuss the scaling of the Lee-Yang edge singularity in the vicinity of a possible critical end point in QCD, at even lower temperatures. In the future, such a scaling analysis might hint on the existence and location of the critical end point.

**Software development and Machines / 578**

**HotQCD on multi-GPUs**

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We present HotQCD’s software suite for performing lattice QCD calculations on GPUs. Started in late 2017 and intended as a full replacement of the previous single GPU lattice QCD Code used by the HotQCD collaboration, our software suite has been developed into an extensive toolkit for lattice QCD calculations distributed on multiple GPUs over many compute nodes. The code is built on C++, CUDA and MPI and leverages modern C++ language features to provide high level data structures, objects and algorithms that allow users to express lattice QCD calculations in an intuitive way without sacrificing performance. Implemented algorithms range from gradient flow, correlator measurements and mixed precision conjugate gradient solvers all the way to full HISQ gauge field configuration generation using RHMC. After successful deployment in large scale computing projects, we want to share the result of our efforts with the lattice QCD community. In this talk, we will present some of the key features of our code, demonstrate its ease of use and show benchmarks of performance critical kernels on state-of-the-art supercomputers including Summit and JUWELS Booster.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 579**

**LeapFrogLayers: A Trainable Framework for Effective Topological Sampling**

**Authors:** Sam Foreman; Xiao-Yong Jin; James C Osborn

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2 Argonne ALCF
We introduce LeapfrogLayers, an invertible neural network architecture that can be trained to efficiently sample the topology of a 2D U(1) lattice gauge theory. We show an improvement in the integrated autocorrelation time of the topological charge when compared with traditional HMC, and propose methods for scaling our model to larger lattice volumes.

**Poster / 580**

**F4: HMC with Normalizing Flows**

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We propose using Normalizing Flows as a trainable kernel within the molecular dynamics update of Hamiltonian Monte Carlo (HMC). By learning (invertible) transformations that simplify our dynamics, we can outperform traditional methods at generating independent configurations. We show that, using a carefully constructed network architecture, our approach can be easily scaled to large lattice volumes with minimal retraining effort.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 581**

**Sampling lattice gauge theory in four dimensions with normalizing flows**

*Authors*: Daniel Hackett\(^1\); Danilo Jimenez Rezende\(^2\); Denis Boyda\(^3\); Gurtej Kanwar\(^1\); Kyle Stuart Cranmer\(^4\); Michael Albergo\(^5\); Phiala Shanahan\(^6\); Sébastien Racanière\(^6\)

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Flow-based models were previously successfully applied for the generation of configurations in lattice (gauge) field theories in two dimensions. In this work, we discuss further development of this approach for lattice gauge theories in four dimensions. We show several implementations and apply improvements to the approach. We study different masking patterns and choices of frozen loops, as well as improvements to the flow transformations. Also, we investigate different machine learning methods such as different architectures of neural networks and training protocols.
State of the art multi-grid algorithms in QUDA

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Co-authors: Richard Brower; Kate Clark; Jiqun Tu; Mathias Wagner

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The era of exascale computing enables the generation of ever-finer gauge configurations, capturing gauge-fermion physics with unprecedented accuracy. This approach to the continuum comes with a super-linear increase in the cost of the iterative Krylov solve of the Dirac fermion operator, the phenomena of critical slowing down. Multi-grid methods are the optimal approach to addressing this crisis of cost. In this talk we describe the state-of-the-art implementations of multigrid algorithms for Wilson-clover, HISQ, and domain wall fermions in the QUDA library for GPUs. This will include a discussion of the unique approaches to multigrid for each fermion formulation.

Flow-based sampling for fermionic field theories

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Flow models are emerging as a promising approach to sampling complicated probability distributions via machine learning in a way that can be made asymptotically exact. For applications to lattice field theory in particular, success has been demonstrated in proof-of-principle studies of scalar theories, gauge theories, and thermodynamic systems. This work develops approaches which enable flow-based sampling of theories with fermionic degrees of freedom, as is necessary for the technique to be applied to lattice field theory studies of the Standard Model of particle physics, and of many condensed matter systems. The method is demonstrated on Yukawa theory in 1+1 dimensions.

Subleading conformal dimensions using a qubit regularization of the O(4) model

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Computing conformal dimensions $D(j_L, j_R)$ of local fields that transform in an irreducible representation of $SU(2) \times SU(2)$ labeled with $(j_L, j_R)$ at the $O(4)$ Wilson-Fisher fixed point has become interesting recently, especially when $j_L, j_R$ become large. These calculations are challenging in the traditional lattice $O(4)$ model. We can overcome these difficulties by using a qubit regularized $O(4)$ model constructed with a local five dimensional Hilbert space. While previously we computed $D(j, j)$ using this approach, here we design an algorithm to compute $D(j, j - 1)$ for $2 \leq j \leq 20$.

Particle physics beyond the Standard Model / 586

Complex Langevin simulations for PT-symmetric models

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Self-interacting scalar quantum field theories possessing PT-symmetry are physically admissible since their energy spectrum is real and bounded below. However, models with PT-invariant potentials can have complex actions in general. Thus, they cannot be studied using methods based on traditional Monte Carlo due to a sign problem. We use complex Langevin dynamics to study two-dimensional supersymmetric models exhibiting PT invariance. In the literature, using perturbative calculations, SUSY is intact in these models even though parity is broken. In order to answer the question on non-perturbative SUSY breaking, we perform simulations of these models using the complex Langevin method.

QCD in searches for physics beyond the Standard Model / 587

$K \rightarrow \pi \pi$ decay matrix elements at the physical point with periodic boundary conditions

Authors: Masaaki Tomii¹; Thomas Blum²; Daniel Hoying¹; Taku Izubuchi²; Luchang Jin²; Chulwoo Jung²; AMARJIT Soni³

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We calculate $K \rightarrow \pi \pi$ matrix elements using periodic boundary conditions as an independent calculation from our previous calculation with G-parity boundary conditions. We present our preliminary results for physical masses on a $24^3, a^{-1} = 1$ GeV, 2 + 1-flavor Mobius DWF ensemble generated by the RBC and UKQCD collaborations and discuss the prospect for high-precision computation of $\epsilon'$ with periodic boundary conditions.

QCD at nonzero Temperature and Density / 588
Radius of convergence at finite chemical potential with rooted staggered fermions

Authors: Attila Pasztor¹; Daniel Nogradi¹; Kornél Kapás²; Matteo Giordano³; Sandor Katz⁴

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In typical statistical mechanical systems the grand canonical partition function at finite volume is proportional to a polynomial of the fugacity exp(-T/B). The zero of this Lee-Yang polynomial closest to the origin determines the radius of convergence of the Taylor expansion of the pressure around T=0. Rooted staggered fermions, with the usual definition of the rooted determinant, do not admit such a Lee-Yang polynomial. We show that the radius of convergence is then bounded by the spectral gap of the reduced matrix of the unrooted staggered operator. We suggest a new definition of the rooted staggered determinant at finite chemical potential that allows for a definition of a Lee-Yang polynomial. We perform a finite volume scaling study of the leading Lee-Yang zeros and estimate the radius of convergence extrapolated to infinite volume using stout improved staggered fermions on N_t=4 lattices. In the vicinity of the crossover temperature at zero chemical potential, the radius of convergence turns out to be at B/T≈2 and roughly temperature independent.

Software development and Machines / 589

Large scale dynamical Domain-Wall Fermion simulation on GPUs: Techniques and properties

Author: Chulwoo Jung¹

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I will describe the latest dynamical DWF ensemble generation efforts by RBC/UKQCD collaboration, focusing on 96³x192x12, a ≈ 0.07fm, 2+1 flavor ensemble with Iwasaki gauge action at physical point, running on summit machine at Oak Ridge National Laboratory. Basic properties of the ensemble as well as some details of the algorithmic improvements will be given.

Poster / 590

F5: Electromagnetic effects in charged pion decay

Author: Paul Rakow¹

Co-authors: Roger Horsley ²; Gerrit Schierholz ³; James Zanotti ⁴; Ross Young ; Hinnerk Stueben ⁵

¹ University of Liverpool
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Using simulations in QCD+QED we investigate electromagnetic corrections to charged pion decay. We calculate pion-muon three-point functions, and analyze the dependence on time and momentum transfer to investigate the interplay between the strong, weak and electromagnetic effects.

Theoretical developments and applications beyond particle physics / 591

Light Hadron Spectrum from a Yang-Mills Matrix Model

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Abstract: The SU(3) Yang-Mills matrix model coupled to fundamental fermions is an approximation of quantum chromodynamics (QCD) on a 3-sphere of radius \( R \). The spectrum of this matrix model Hamiltonian estimated using standard variational methods, and is analyzed in the strong coupling limit. By employing a renormalization prescription to determine the dependence of the Yang-Mills coupling and the bare quark masses on \( R \), we relate the asymptotic values of the energy eigenvalues in the flat space limit to the masses of light hadrons. We find that the matrix model estimates the light hadron spectrum fairly accurately, with most masses falling within 15\% of their observed values.

Theoretical developments and applications beyond particle physics / 592

Towards the Low-Energy EFT of Euclidean Dynamical Triangulations

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Recent work in Euclidean dynamical triangulations (EDT) has provided compelling evidence for its viability as a formulation of quantum gravity. In particular the lattice value of the renormalized Newton’s constant has been obtained by two distinct methods (the binding energy of scalar particles on the lattice, and comparison with the Hawking-Moss instanton). That these calculations yield mutually compatible results is a nontrivial check which indicates that the low-energy effective action of EDT does include the expected Einstein-Hilbert term, and the lattice value of Newton’s constant fixes the coefficient of this term in lattice units. To make further contact with the low-energy theory
we turn to the two-point function of the scalar curvature, which can be calculated both on the lattice and in the effective theory and which depends straightforwardly on the parameters of the latter. To compare with the lattice predictions we must perform a nontrivial one-loop calculation in the effective theory, which I will discuss in this talk.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 593**

**Lie group integrators and efficient integration of gradient flow**

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It has been recently shown how explicit low-storage Lie group integrators can be built from classical low-storage methods of Williamson’s type. We discuss a one-parameter family of three-stage third-order methods and show how a coefficient scheme can be chosen specifically for optimal integration of the gradient flow. We also illustrate how two low-storage fourth-order integrators can be used as Lie group methods and compare the performance of various integrators. The low-storage schemes of this type can be easily implemented in the existing lattice codes.

**Standard Model Parameters / 594**

**Non-perturbative renormalisation with interpolating momentum schemes**

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We explore various non-perturbative renormalisation schemes in the framework of the Rome-Southampton method. In particular, we implement several non-exceptional interpolating momentum schemes, where the momentum transfer is not restricted to the symmetric point defined in RI/SMOM. Using flavour non-singlet quark bilinears, we compute the renormalisation factors of the quark mass and wave function for \(N_f = 3\) flavours of dynamical quarks. We investigate the perturbative and non-perturbative scale-dependence and give the corresponding one-loop matching factor to \(\overline{MS}\). Our numerical results are obtained from lattice simulations performed with Domain Wall fermions based on ensembles generated by RBC-UKQCD collaborations.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 595**

**Simulating Complex Langevin at short real-times with stable implicit solvers**

**Authors:** Daniel Alvestad\(^1\); Rasmus Larsen\(^1\); Alexander Rothkopf\(^1\)

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We present recent results in which we apply unconditionally stable stochastic partial differential equations solvers [2] to complex Langevin in real-time [3]. This allows us to avoid runaway solutions in principle and enables simulations at relatively large Langevin step size. We show that implicit schemes act as a regulator of the underlying path integral and give a heuristic estimate of the errors introduced by the discrete Langevin evolution. Due to the intrinsic regularization of the implicit scheme, we are able to simulate the quantum anharmonic oscillator on the canonical real-time contour (at short real-times). In turn, for the first time, we gain access to both the forward and backward correlators close to the real-time axis (D>, D<) required for the determination of the system spectral function. Concrete examples in and out-of thermal equilibrium are presented.


Gradient-flow scale setting with $N_f = 2 + 1 + 1$ Wilson-clover twisted-mass fermions

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We present a determination of the gradient flow scales $w_0$, $\sqrt{t_0}$ and $t_0/w_0$ in isosymmetric QCD, making use of the gauge ensembles produced by the Extended Twisted Mass Collaboration (ETMC) with $N_f = 2 + 1 + 1$ flavours of Wilson-clover twisted-mass quarks including configurations close to the physical point for all dynamical flavours. The simulations are carried out at three values of the lattice spacing and the scale is set through the PDG value of the pion decay constant, yielding $w_0 = 0.17383(63)$ fm, $\sqrt{t_0} = 0.14436(61)$ fm and $t_0/w_0 = 0.11969(62)$ fm. Finally, fixing the kaon mass to its isosymmetric value, we determine the ratio of the kaon and pion leptonic decay constants to be equal to $f_K/f_\pi = 1.1995(44)$.

D1: The Evolution of Lattice Field Theory: a Statistical Study

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Researchers working in lattice field theory built an established community since the early 1990s, around the same time when
the arXiv was created. The fact that this field has a specific
arXiv section provides a unique opportunity for a statistical
study of its evolution over the last three decades.
We present data for the annual number of papers and citations,
in total and separated by countries. We compare them to other
arXiv sections (hep-ph, hep-th, cond-mat, nucl-th), and to
socio-economic data for each country involved, like the GDP,
the Education Index and the skilled labor force.

Software development and Machines / 598

Strong scaling RHMC on NVIDIA GPUs

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The ability to strong scale is crucial for Lattice QCD simulations. Therefore Lattice QCD has been
constantly craving for higher network and memory bandwidths. While never enough well-balanced
systems with favorable GPU-to-network ratios are available, e.g. with the Juelich Booster. However,
API overheads and necessary synchronizations between GPU and CPU have become prohibitively
expensive, not keeping up with generational improvements of GPUs and networks. This limits the
ability to strong scale with MPI communication. A shift towards fine-grained GPU-centric communi-
cation provides a way out as it completely removes these bottlenecks by moving the communication
to the GPU kernels. Since version 1.1 QUDA implements GPU-centric communication for NVIDIA
GPUs using NVSHMEM. We will show low-level Dslash results as well as full RHMC scaling results
on modern GPU systems like Selene and the Juelich Booster and discuss further expansions of this
approach to even more latency-limited algorithms as Multigrid.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 599

Quantum algorithm for simulation of an SU(2) lattice gauge theory with fermions

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We present a complete and scalable quantum algorithm for the simulation of SU(2) gauge bosons
coupled to fermionic matter in one spatial dimension. To represent the gauge fields, we find it is more
practical to start from their Schwinger boson formulation, rather than the more conventional Kogut-
Susskind rigid rotor formulation. Within this framework, and taking Trotter-Suzuki decomposition
as the time evolution scheme, we then construct explicit circuits for the simulation of the three types
of terms found in the Hamiltonian: electric energy, fermion mass energy, and the gauge-matter
interaction. We comment on the similarities and differences relative to simulating the U(1) analogue
of this theory, the Schwinger model, which is discussed in another talk by A.F. Shaw.
QCD in searches for physics beyond the Standard Model / 600

QED and strong isospin corrections in the hadronic vacuum polarization contribution to the anomalous magnetic moment of the muon

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Recently, the Budapest-Marseille-Wuppertal collaboration has achieved a sub-percent precision in the evaluation of the HVP contribution to the muon $\mu-2$. At this level of precision, pure isospin-symmetric QCD is not sufficient. In the talk we will review how QED and strong isospin breaking effects have been included in our work. Isospin-breaking is implemented by expanding the relevant correlation functions to second order in electric charge and to first order in $(m_d - m_u)$. The correction terms are then computed using isospin-symmetric configurations. The choice of this approach allows us to better distribute the available computing resources among the various contributions.

Poster / 601


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General-purpose Markov Chain Monte Carlo sampling algorithms suffer from a dramatic reduction in efficiency as the system being studied is driven towards a critical point through, for example, taking the continuum limit. Recently, a series of seminal studies suggested that normalizing flows - a class of deep generative models - can form the basis of a sampling strategy that does not suffer from this ‘critical slowing down’. The central idea is to use machine learning techniques to build (approximate) trivializing maps, i.e. field transformations that map the theory of interest into a ‘simpler’ theory in which the degrees of freedom decouple. These trivializing maps provide a representation of the theory in which all its non-trivial aspects are encoded within an invertible transformation to a set of field variables whose statistical weight in the path integral is given by a distribution from which sampling is easy. No separate process is required to generate ‘training data’ for such models, and convergence to the desired distribution is guaranteed through a reweighting procedure such as a Metropolis test.

From a theoretical perspective, this approach has the potential to become more efficient than traditional sampling, since the statistical efficiency of the sampling algorithm is decoupled from the correlation length of the system. The caveat to all of this is that, somehow, the costs associated with the highly non-trivial task of sampling from the path integral of an interacting field theory are transferred to the training of a model to perform this transformation. We have been investigating various schemes, based on normalizing flows, for building efficient representations of trivializing maps for $\phi^4$ theory, and (more recently) $O(N)$ non-linear $\sigma$ models. The ‘naive’ approach to training such models appears to suffer from an analogue of critical slowing down which unfortunately limits the scalability of this technique, although we are optimistic about the possibility of improving this situation.
Towards robust constraints on nuclear effective field theory from lattice QCD

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In this talk I will discuss several new results from the NPLQCD Collaboration that combine lattice QCD results on (hyper)nuclear systems at unphysical pion masses together with nuclear effective field theories. Two-baryon channels with strangeness $0$ to $-4$ are analyzed, with findings that point to interesting symmetries observed in hypernuclear forces as predicted in the limit of QCD with a large number of colors. Also, several matrix elements of light nuclei are studied. The tritium axial charge, related to the Gamow-Teller matrix element, and the longitudinal momentum fraction of $^3$He that is carried by the isovector combination of $u$ and $d$ are extracted and extrapolated to the physical point. For this latter case, it can be seen how including lattice results to experimental determinations can have imminent potential to enable more precise determinations and to reveal the QCD origins of the EMC effect.

50 ways to build a deuteron: a variational calculation of two-nucleon systems

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Co-authors: Andrew Pochinsky 1; Assumpta Parreño 2; Marc Illa 3; Phiala Shanahan 1; Riyadh Baghdadi; Saman Amarasinghe; William Detmold 1; Zohreh Davoudi 4

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Multi-baryon systems are challenging to study with lattice QCD in particular because of small gaps between the ground state and excited states for large lattice volumes. Variational methods have long been known to be useful for disentangling closely spaced energy levels but require approximations to all-to-all quark propagators that are computationally prohibitive to compute exactly. In this talk, I will discuss a new method for computing multi-nucleon correlation-function matrices using sparsened all-to-all quark propagators and results for a variational calculation of the two-nucleon spectrum at $\mpi \approx 800$ MeV using a large interpolating operator set including local hexaquark operators, nonlocal two-nucleon operators with plane-wave wavefunctions, and exponentially localized two-nucleon operators.

Observifolds: Taming the observable signal-to-noise problem via path integral contour deformations

Authors: Gurtej Kanwar 1; Hank Lamm 2; Michael Wagman 4; Neill Warrington 3; William Detmold 1
Complex contour deformations of the path integral have previously been shown to mitigate extensive sign problems associated with non-zero chemical potential and real-time evolution in lattice field theories. This talk details recent extensions of this method to observables affected by signal-to-noise problems in theories with real actions. Contour deformations are shown to result in redefinitions of observables which do not affect their expectation value and do not modify the Monte Carlo sampling weights. The choice of contour does, however, affect the variance and can be optimized to maximize the signal-to-noise ratio. Families of contour deformations are defined for SU(N) variables and optimized deformations are shown to give exponential improvements in the signal-to-noise ratio of Wilson loops in proof-of-principle applications to U(1) and SU(N) lattice gauge theories.

Hadron Structure / 605

Gravitational form factors of the proton

Authors: Daniel Hackett\(^1\); Dimitra Pefkou\(^2\); Phiala Shanahan\(^2\)

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Hadronic matrix elements of the QCD energy-momentum tensor can be parametrized in terms of gravitational form factors (GFFs) which, through their dependence on momentum transfer and decomposition into quark and glue contributions, encode information about the distributions of energy, angular momentum, pressure, and shear forces within a hadron spatially and amongst its constituents. We report on the progress of an ongoing program to determine the GFFs of the physical proton with full control over uncertainties and including both quark and glue contributions, providing first-principles predictions of the physical energy, spin, pressure, and shear densities. To this end, we present preliminary results of a calculation using Wilson fermions on an ensemble with a close-to-physical pion mass of 170 MeV.

QCD at nonzero Temperature and Density / 606

Heavy-dense QCD at fixed baryon number without a sign problem

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QCD at fixed baryon number can be formulated in terms of transfer matrices explicitly defined in the canonical sectors. In the heavy-dense limit, the fermionic contributions to the canonical partition functions can be calculated analytically in terms of Polyakov loops. It turns out that at low temperatures and infinitely strong coupling the sign problem is exponentially reduced by many orders of magnitude for any baryon number, that is, essentially absent. We show how this can be used for the construction of cluster algorithms which achieve a similar improvement away from the strong coupling limit.
Toward a resolution of the NN controversy

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Lattice QCD calculations of two-nucleon interactions have been underway for about a decade, but still haven’t reached the pion mass regime necessary for matching onto effective field theories and extrapolating to the physical point. Furthermore, results from different methods, including the use of the Luscher formalism with different types of operators, as well as the HALQCD potential method, do not agree even qualitatively at very heavy pion mass. In this talk I will discuss these issues and present steps toward an understanding of the various systematics at play.

Universal Properties of the Vortex in the (2+1)-d O(2) Model through dualization

Author: Joao Barros¹

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Quantizing topological excitations beyond a semiclassical approximation is a nontrivial issue. Examples of relevant topological excitations are vortices in (2+1) dimensions. They are the condensed matter analogs of monopoles in particle physics and arise in Bose-Einstein condensates and superfluids. These systems can be described by the (2+1)-d O(2) model, where vortices are present through nontrivial winding of the field. This model can be dualized into scalar QED and, in the broken phase, the vortex becomes an infraparticle that is surrounded by a cloud of photons spreading out to infinity. As Gauss’s law forbids a single charged particle to be placed in a periodic volume, it equivalently forbids a single vortex to exist by itself. We circumvent this issue, without breaking translation invariance, by imposing C-periodic boundary conditions. By simulating the dual theory, scalar QED, we compute the universal finite-volume vortex mass and charge near the Wilson-Fisher fixed point.
A method to estimate observables with infinite variance in fermionic systems

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Numerical estimation of fermionic observables often requires introduction of auxiliary bosonic fields that have no direct physical relevance through a Hubbard-Stratonovich transformation. The variance of some fermionic observables (for example, appropriately constructed local four-fermion operators in 2d Gross-Neveu model) when they estimated using such auxiliary fields may not correspond to any physical observable and in particular it may diverge. In such cases it is not clear how one can reliably estimate the a physical observable. An important example may be found in the context of exceptional configurations in quenched qcd. We demonstrate other examples in some toy models by appropriately constructing some four-fermion operators. We then propose a suitably chosen discrete Hubbard-Stratonovich transformation that doesn’t suffer from such divergences for these classes of observables.

Poster / 610

D9: Use tensor cores to accelerate math intensive kernels in QUDA

Authors: Jiqun Tu\(^1\); Evan Weinberg\(^{\text{none}}\); Kate Clark\(^2\); Mathias Wagner\(^2\)

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We will present our recent efforts on using tensor cores, which are available on NVIDIA GPUs starting from the Volta architecture, to speed up the math intensive kernels in QUDA. A light-weighted abstraction of the CUDA PTX matrix multiply-add (MMA) instruction is added in order to efficiently stage data through the different layers of GPU memory. Specifically the efforts include:

- Use tensor cores to accelerate the 5th dimension DWF operators in the multi-splitting preconditioned conjugate gradient algorithm, utilizing the HMMA tensor core instruction;
- Use tensor cores to accelerate the dense matrix multiplications in the set up steps in multi-grid;
- Use tensor cores to accelerate the math intensive multi-BLAS kernels;
- Use double precision DMMA instruction to accelerate the contraction workflow.

QCD at nonzero Temperature and Density / 611

Localization at the quenched SU(3) phase transition

Author: G. Tamas Kovaecs\(^1\)

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It is known that the deconfining transition of QCD is accompanied by the appearance of localized eigenmodes at the low end of the Dirac spectrum. In the quenched case localization appears exactly at the critical temperature of deconfinement. In the present work, using quenched simulations exactly at the critical temperature we show that the localization properties of low Dirac modes change abruptly between the confined and deconfined phase. Moreover, in the deconfined phase localization occurs only in the real Polyakov loop sector. We also speculate on the connection between this phenomenon and fluctuations of the topological charge.

Towards a variational calculation of nucleon elastic structure

Authors: Andre Walker-Loud\textsuperscript{1}; Ben Hörz\textsuperscript{2}; John Bulava\textsuperscript{3}; Amy Nicholson\textsuperscript{4}; Chia Cheng Chang\textsuperscript{1}; Aaron Meyer\textsuperscript{4}; Pavlos Vranas\textsuperscript{5}; Kate Clark\textsuperscript{6}; Dean Howarth\textsuperscript{7}; Andrew Hanlon\textsuperscript{8}

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We have implemented and are computing nucleon 3pt functions using the stochastic Laplacian Helwood (sLapH) method. Such a technique enables the use of momentum space creation and annihilation operators providing access to the Breit-Frame as well as full control of the spin of the initial and final operator. It also enables the use of multi-hadron operators, for example the problematic N-pi excited state. We will report on the success (or lack thereof) of using sLapH for such three point function calculations as measured both in terms of the computational cost, the stochastic signal that is achievable as compared to the more standard fixed source-sink separation computations using local creation operators and momentum space sinks.

Neural Network Field Transformation and Its Application in HMC

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We propose a continuous differentiable and invertible gauge field transformation parametrized with neural networks. We apply this technique to 2D U(1) pure gauge system, combine the transformation and HMC, and train the neural network field transformation for improved tunneling of topological sectors during the gauge generation. We present the properties of the trained transformation applied to the gauge fields with different gauge couplings and lattice volumes, and discuss the cost and
benefit of this algorithm in tackling the critical slowing down of generating independent gauge configurations toward the continuum limit.

Poster / 614

F7: Strategies for Quantum-Accelerated Interpolator Construction in Classical Simulations of Lattice Field Theories

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Interpolator constructions are a requisite tool for calculations in lattice quantum field theory. Better interpolating constructions lead to ground state dominance at earlier times, and thus less noise, making computations cheaper computationally. Various classical-computing methods exist to optimize interpolator constructions. In this work, we show that optimal interpolator constructions can be determined in a small-scale quantum simulation. We use a small-scale quantum Hamiltonian simulation of the Schwinger model to variationally optimize an interpolator construction for a vector meson state in the theory, and then employ that construction in a classical path-integral Monte-Carlo calculation, where systematically improvable continuum-limit scaling is possible.

Poster / 615

F8: Algebraic Spectroscopy of Frequency Space Correlation Functions

Authors: Sebastian Tsai¹; Kimmy Cushman¹; George Fleming¹

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Lattice Field Theory correlation functions are usually difficult to model in momentum space. As a result, fitting to a sum of poles in frequency space can be preferable especially when the signal contains an additive constant as this constant is isolated in the zero-frequency mode. To help model the spectroscopy in frequency space, we implemented a black-box method that we call rational approximation, in which we parameterize the function into an over-constrained matrix equation and represent it as a sum of a finite number of poles parametrized by pole energies and their corresponding residues. Using linear least squares, chi-square tests, and information criteria to find optimal fits, we present results for example correlation function data.

Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 616

Machine learning phase transitions in a scalable manner

Author: Marina Krstic Marinkovic¹

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Machine learning is becoming an established area of research in lattice field theories, with prominent applications to phase classification, configuration generation, and noise reduction. When moving beyond the toy models, scalable methods to learn phases of matter are needed. In this talk, we compare two possible avenues to speed up the methods for classifying phase transitions in the 2D Ising model: parallelization of kernel methods, and quantum machine learning. Finally, we discuss the extension of the two approaches to the low-dimensional quantum field theories.

**Poster / 617**

**F9: Finite Volume Study of Flavor Singlet Scalar Meson in SU(3) N_f=8 Gauge Theory**

**Author:** George Fleming

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There are several examples of light flavor-singlet scalar mesons in near-conformal gauge theories, including SU(3) N_f = 8 gauge theory. We present a finite volume study of the scalar mass and scalar decay constant.

**Standard Model Parameters / 618**

**New beta-function and the QCD running coupling at the Z-boson pole mass**

**Author:** Kieran Holland

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With scale changes set by the gradient flow time, a new beta function emerges from infinite volume extrapolations, matching 3-loop predictions from Harlander and Neumann at weak coupling. Non-perturbative lattice methods are used to get the beta-function in the infrared region at strong coupling. The method was tested in multi-flavor QCD with ten and twelve flavors and compared in contrast with the respective step beta-functions where scale changes are set by the physical volume. We are investigating the new beta function for alternate lattice determination of the QCD running coupling at the scale of the Z-boson pole mass.

**Algorithms (including Machine Learning, Quantum Computing, Tensor Networks) / 619**

**Tensor network simulations of a manifestly gauge-invariant SU(2) lattice gauge theory formulation**

**Author:** Aniruddha Bapat

**Co-authors:** Zohreh Davoudi 1; Indrakshi Raychowdhury 2; Niklas Mueller 1

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The tensor network framework is an alternative to traditional lattice-based methods where one can simulate the statics as well as dynamics of lattice gauge theories (LGTs) without encountering the sign problem. So far, however, most tensor network studies of non-abelian LGTs have been restricted in scope to one spatial dimension with open boundary conditions. This restriction is lifted in the loop-string-hadron (LSH) formulation of SU(2) LGT, in which one works with manifestly SU(2)-invariant local operators and states defined at each lattice site that are weaved together by a U(1) constraint along with the links to yield the original Wilson loop and string states of the theory. Here, we construct a tensor network implementation of SU(2) LGT based on the LSH formulation. We recover the bulk and continuum limits of static properties such as the ground state energy and the vector mass gap, accounting for effects of a finite electric field cutoff. Our LSH-based tensor network approach generalizes naturally to higher dimensions, and may provide a path for tensor network-based quantum state preparation of the SU(2) LGTs for quantum simulation.

**Particle physics beyond the Standard Model / 620**

**BB Scattering at N_c=4 for Stealth Dark Matter**

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We study baryon-baryon scattering with Luscher’s method for N_c = 4 gauge theory. To improve signal in our scattering observables, we employ the Laplacian Heaviside or Distillation method to construct low rank interpolating operators with good overlap with low lying energy states. Though of interest for large N_c QCD studies, the LSD collaboration has been investigating a dark matter candidate called stealth dark matter, which would be the neutral composite baryon of an SU(4) gauge theory. In order to place constraints on dark matter self-interactions in this theory, we study BB scattering, and present here our preliminary results.

**Software development and Machines / 621**

**Preparing for QUDA 2.0**

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Adapting QUDA for the Exascale, and beyond, means being prepared for a diversity of architectures, parallel abstractions, and new programming paradigms. We report on the rewrite of QUDA in preparation of the 2.0 release, which will embrace all of the above while also significantly streamlining the design process of new kernels for new use cases. We do so without compromising performance, or hampering the ability to do target specialization.
Pion and kaon distribution amplitude at physical masses

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We will present lattice QCD results for x-dependent distribution amplitudes for pion and kaon. The computations were carried out using valence Wilson Clover fermions on HISQ gauge configurations with 2+1 flavors, all with physical values of pion and kaon masses and at a lattice spacing of 0.076 fm. Computations used hadrons states boosted up to a momentum of 1.7 GeV. To arrive at the results we use improved perturbative QCD matching for the distribution amplitudes that goes beyond the conformal approximation.

Recent progress on nucleon form factors

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The form factors of the nucleon provide key information on nucleon properties and processes. When confronted with precisely measured observables from experiment, they serve as benchmark quantities for lattice calculations. On the other hand lattice determinations may serve as vital theory input for the interpretation of experiments, e.g. in neutrino-nucleus scattering. I will review recent progress in the calculation of nucleon form factors from the lattice and their relevance to future experiments.

The Techni-Pati-Salam Model

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Composite Higgs models can be extended to the Planck scale by means of the partially unified partial compositeness (PUPC) framework. We present in detail the Techni-Pati-Salam model, based on a renormalizable gauge theory SU(8)×SU(2)L×SU(2)R. We demonstrate that masses and mixings for all generations of standard model fermions can be obtained via partial compositeness at low energy, with four-fermion operators mediated by either heavy gauge bosons or scalars. The strong dynamics is predicted to be that of a confining Sp(4)HC gauge group, with hyper-fermions in the fundamental and two-index anti-symmetric representations, with fixed multiplicities. This motivates for Lattice studies of the Infra-Red near-conformal walking phase, with results that may validate or rule out the model. This is the first complete and realistic attempt at providing an Ultra-Violet completion for composite Higgs models with top partial compositeness.
Long-range processes with two-particle intermediate states

Author: Raul Briceno

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A variety of phenomena in the Standard Model and its extensions manifest in long-range processes involving on-shell multi-hadron intermediate states. Given recent algorithmic and conceptual progress, such processes are now realistic targets for lattice QCD. In this talk, I present a recently developed formalism that makes possible the determination of reactions of the form $1 + J \rightarrow 2 \rightarrow 1 + J$ from 2-, 3-, and 4-point functions in a finite-volume Euclidean spacetime. I also give an outlook for the study of more complicated reactions.

Qubit Regularization of Asymptotic Freedom

Author: Hersh Singh

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We provide strong evidence that the asymptotically free (1+1)-dimensional non-linear O(3) sigma model can be regularized using a quantum lattice Hamiltonian, referred to as the “Heisenberg-comb”, that acts on a Hilbert space with only two qubits per spatial lattice site. The Heisenberg-comb consists of a spin-half anti-ferromagnetic Heisenberg-chain coupled anti-ferromagnetically to a second local spin-half particle at every lattice site. Using a world-line Monte Carlo method we show that the model reproduces the universal step-scaling function of the traditional model up to correlation lengths of 200,000 in lattice units and argue how the continuum limit could emerge. We provide a quantum circuit description of time-evolution of the model and argue that near-term quantum computers may suffice to demonstrate asymptotic freedom.

Investigating a Renormalization Group Multigrid Approach for Domain Wall Fermions

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Previous work has shown that renormalization group blocking of a 2+1 flavor DWF ensemble with 1/a = 2 GeV can produce an ensemble with 1/a = 1 GeV, with physical quantities on the blocked 1 GeV ensemble within a few percent of their values on an independently generated 1 GeV ensemble. This has led us to investigate using the blocked ensemble DWF operator as a coarse-grid operator for a multigrid DWF solver. We find that the low-mode space of the coarse-grid operator spans the low-mode space of the original operator quite well. However, in the simplest coarse-grid to fine-grid interpolation step, fine-grid high modes are introduced into a low-mode-accurate, coarse-grid solution. We have studied various filtering schemes to reduce this contamination, with partial success to date. We will review our overall approach and detail our current status.

Hadron Spectroscopy and Interactions / 628

From lattice QCD to predictions of scattering phase shift at the physical point

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The Hadron Spectrum Collaboration (HSC) presented new results on two of their ensembles for s-wave scattering phase shifts in the open-charm sector of QCD. For such ensembles we have made predictions that are based on the chiral Lagrangian that were published two years ago. In this talk we confront our phase shifts with those of HSC. A remarkably consistent picture emerges. In particular there is mounting evidence for the existence of a flavour sextet state in the πD and πD* channels, that show a striking quark-mass dependence.

Plenary / 629

Heavy quarks at finite temperature

Author: Johannes Heinrich Weber4

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New incarnations of heavy-ion collision experiments are turning our attention to hard processes and a more fine-grained resolution of the QGP. In this endeavor quarkonia or open heavy flavors turn out to be versatile probes, which are usually described through models based on perturbative QCD, AdS, and effective field theories. The lattice provides nonperturbative input and constraints to such models.
In-medium bottomonia, the complex static quark-antiquark potential, and the heavy-quark momentum diffusion coefficient are key quantities where lattice gauge theory has recently achieved significant progress with impact for heavy-ion phenomenology. I review these lattice results, relate them to phenomenological applications, and close with a outlook.

Plenary / 630

**Perspectives on the current status of and future prospects for ML in lattice QFT**

**Author:** Sebastien Racaniere

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The lattice community, and more widely the physics community, has a long track record of using and even building advanced Statistical & Machine Learning tools (e.g. HMC). On the other hand, the Machine Learning, and specifically the Deep Learning, community has itself been seeking inspiration from Physics. Geometry and symmetries are inspiring many ML papers and research directions. Those ideas are often designed for applications to images, sounds or 3D data. As such, they are not usually readily applicable to Lattice QFT and need to be adapted.

In this talk, I wish to show examples of such successful interactions, with a particular emphasis on Lattice. I will highlight both difficulties and opportunities that arise from such interactions.

Plenary / 631

**Lattice field theory and BSM phenomenology: The beginning of a beautiful friendship**

**Author:** Giacomo Cacciapaglia

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This talk will offer an overview of the role of lattice field theory in strongly interacting BSM phenomenology.

Plenary / 632

**Recent developments in nuclear lattice effective field theory**

**Author:** Bingnan Lu

**Co-authors:** Dean Lee; Ning Li; Serdar Elhatisari; Ulf Meissner

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In recent years, the lattice effective field theory, a lattice stochastic methods, were successfully applied in solving the nuclear many-body problems. It has shown great advantages in simulating from first principles the atomic nuclei at ground state and excited states, nuclear scattering and reaction, nuclear matter at zero and finite temperature, etc. In this talk, I will give a brief introduction to the method and an overview on recent important progress. Specifically, I will focus on two major breakthroughs in this field. One is the investigation of the hidden spin-isospin exchange symmetry of the nuclear force, which also inspires us to develop new algorithms for implementing the chiral nuclear force as a perturbative expansion around a central force. Another topic will be the new pinhole trace algorithm for simulating the nuclear thermodynamics, which can be as large as one thousand times faster than conventional algorithms based on grand-canonical ensemble.

Tutorial / 633

Intel tutorial: Essentials of Data Parallel C++

Corresponding Author: patrick.steinbrecher@intel.com

Attendees should create a DevCloud account using below link and event code before the session:
https://sforms.intel.com/DevCloud/?eventcode=lattice-07302021

Event Code: lattice-07302021

The session includes a giveaway of 10 Intel GPU developer platforms.

Join our virtual workshop on Essentials of Data Parallel C++ to learn about oneAPI which aims to provide a unified, cross-industry, programming model to program heterogeneous architectures. In this workshop, you will learn oneAPI programming model and how it can solve the challenges of programming in a heterogeneous world. You will also learn the Data Parallel C++ (DPC++) language and familiarize yourself with using Jupyter notebooks on Intel® DevCloud. We will also go in-depth on SYCL fundamental classes and device selection to offload kernel workloads. You will learn new Data Parallel C++ (DPC++) features such as Unified Shared Memory to simplify programming and how to take advantages of using Subgroups and Reductions in DPC++.

Praveen Kundurthy is a Developer Evangelist at Intel with over 15 years of experience in software development and optimization on Intel platforms. In his current role, he works with universities and developers to help them learn and utilize oneAPI for their projects. He has expertise in C++, C#, and Python programming languages. Over the past few years at Intel, he has worked on topics spanning artificial intelligence, storage technologies, gaming, virtual reality and Android. Praveen has a Master's Degree in Computer Engineering from Mississippi State University.

Plenary / 634

Progress in x-dependent partonic distributions from lattice QCD

Author: Krzysztof Cichy

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We review the latest progress in lattice QCD calculations of the partonic structure of hadrons. This structure is, in particular, described in terms of x-dependent distributions, the simplest of which are the standard parton distribution functions (PDFs). The lattice calculations rely on matrix elements probing spatial correlations between partons in a boosted hadron, that can be matched to light-cone correlations defining the relevant distributions. We discuss the recent theoretical and practical refinements of this strategy, as well as new exploratory directions. The latter include generalized parton distributions (GPDs), distributions beyond leading twist, flavor-singlet distributions
and transverse-momentum dependent PDFs (TMDs). We also shortly consider the potential future impact of lattice data on phenomenology.

Plenary / 635

Gender and racial discrimination in STEM: Intersecting oppressions with multifaceted solutions

Author: Asia Eaton

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The underrepresentation of women and BIPOC individuals in STEM in the U.S. is a well-known and long-standing problem. Among the most robust explanations for this underrepresentation is social and structural bias against non-prototypical members of these fields (e.g., Moss-Racusin et al., 2012). In this talk, I extend what we know about unidimensional gender bias or racial bias in STEM and examine how race and gender intersect and interact to create unique barriers and opportunities for STEM scholars and professionals. I first review research on intersectional bias in STEM at the undergraduate (e.g., Milkman et al., 2015), post-doc (e.g., Eaton et al., 2019), and professorial level (e.g., Mitchneck, 2021), focusing heavily on research on physics and the natural sciences. Next, I discuss the consequences of these biases for the advancement of knowledge and practice, and future directions in intersectional research in STEM. On the basis of these findings and conclusions, I offer solutions to transform organizational climate and culture to create diverse, inclusive, and equitable STEM workforces.

Plenary / 636

An overview of the QCD phase diagram at finite $T$ and $\mu$

Author: Jana N. Guenther

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In recent years there has been much progress on the investigation of the QCD phase diagram with lattice QCD. This talk will focus on the developments in the last few years. Especially the addition of external influences and extended ranges of $T$ and $\mu$ yield an increasing number of interesting results, a subset of which will be discussed. Many of these conditions are important for the understanding of both the QCD transition in the early universe and heavy ion collision experiments which are conducted for example at the LHC and RHIC. This offers many exciting opportunities for comparisons between theory and experiment.

Plenary / 637

Direct CP violation and the $\Delta I=1/2$ rule in $K\rightarrow\pi\pi$ decay from the Standard Model

Author: Christopher Kelly

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I will discuss the RBC & UKQCD collaboration’s recent lattice calculation of $\epsilon'$, the measure of direct CP-violation in kaon decays. This result significantly improves on our previous 2015 calculation, with nearly 4x the statistics and more reliable systematic error estimates. I will also discuss how our results demonstrate the Standard Model origin of the $\Delta I = 1/2$ rule, and will present our plans for future calculations.

Plenary / 638

SU(3) gauge theory on quantum hardware

Authors: Natalie Klco¹; Anthony Ciavarella²; Martin Savage³

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A beautiful description of nature’s fundamental forces has been devised through gauge fields introducing local symmetries or conserved charges. While classical techniques continue to provide invaluable information on the emergent properties of gauge field theories relevant to experimental programs throughout the scientific domains, some experimentally relevant parameter regimes (e.g., where coherent dynamics demand exponentially large Hilbert spaces) remain beyond current or foreseeable computational capabilities. Leveraging quantum architectures directly within a computational framework is expected to explore such parameter regimes more naturally. Unfortunately, the inefficient utilization of Hilbert space caused by local symmetries demands careful considerations while devices remain unprotected from quantum noise. In this talk, we will discuss current strategies and progress in representing gauge theories, from Abelian to SU(3) Yang-Mills, on qubit degrees of freedom and performing subsequent dynamical evolutions.

Plenary / 639

QFT Dynamics from CFT Data with Lightcone Conformal Truncation

Author: Liam Fitzpatrick¹

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Using variational methods for QFT at strong coupling is an ancient dream with multiple concrete approaches. We discuss recent work on a particular approach, Lightcone Conformal Truncation, that uses lightcone quantization in infinite volume and a truncated Hilbert space motivated by the conformal symmetry of an ultraviolet fixed point at the upper end of an RG flow containing the QFT of interest.

Plenary / 640

Spectroscopy and Hadron Interactions
Author: Ben Hoerz

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Lattice QCD spectroscopy and subsequent determinations of scattering amplitudes are an active line of research with notable advances. In the two-hadron sector there has been significant progress in constraining more complicated scattering amplitudes as well as in controlling systematic uncertainties. A new frontier is the practical application of finite-volume formalisms to treat three-hadron interactions. I will review some of these recent developments.

Plenary / 641

Muon g-2: BMW calculation of the hadronic vacuum polarization contribution

Author: Balint Toth

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We compute the leading order hadronic vacuum polarization contribution to the anomalous magnetic moment of the muon. The calculations are performed using four flavors of stout smeared staggered quarks, with quark masses at their physical values. The continuum limit is taken using six different lattice spacings ranging from 0.132 fm down to 0.064 fm. All strong isospin breaking and electromagnetic effects are accounted for to leading order. A controlled infinite volume limit is taken thanks to dedicated simulations performed in box sizes up to 11 fm. Putting all these ingredients together, we find \( [(g_{\mu} - 2)/2]_{\text{LO-HVP}} = 707.5 \pm 5.5 \times 10^{-10} \), which has a total uncertainty of 0.8%. Compared to determinations based on the dispersive approach, our result significantly reduces the tension between the standard model prediction for the muon \( g - 2 \) and its experimental value.

Plenary / 642

Lattice Meets Lattice - Application of Lattice Cubature to Models in Lattice Gauge Theory

Author: Frances Kuo

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In this joint venture between mathematicians and physicists, we develop efficient recursive strategies to tackle a class of high dimensional integrals having a special product structure with low order couplings, motivated by models in lattice gauge theory. A novel element of this work is the potential benefit in using a family of numerical integration methods called “lattice cubature rules”. The group structure within lattice rules combined with the special structure in the physics integrands may allow efficient computations based on Fast Fourier Transforms. Applications to the quantum mechanical rotor and compact U(1) lattice gauge theory in two and three dimensions are considered.

Co-authors: Tobias Hartung (The Cyprus Institute), Karl Jansen (DESY Zeuthen), Ian Sloan (UNSW Sydney), Hernan Leovey (AXPO Trading & Sales), Dirk Nuyens (KU leuven)
Effective Field Theories and Lattice QCD for the X Y Z frontier

Author: Nora Brambilla

Exotic states have been predicted before and after the advent of QCD. In the last decades they have been observed at accelerator experiments in the sector with two heavy quarks, at or above the quarkonium strong decay threshold and called X Y Z states. These states offer a unique possibility for investigating the dynamical properties of strongly correlated systems in QCD.

I will show how an alliance of nonrelativistic effective field theories and lattice can allow us to address these states in QCD. In particular I will explain what are the opportunities and challenges of lattice QCD in this respect and which new tools should be developed.
In this talk I will review some of the trends in computing systems including discussing the new and upcoming systems in the U.S. and elsewhere as information allows. I will also discuss some of the programming models to develop software for these systems with an emphasis on portable, and where possible, performance portable approaches.

Recent progress in the tensor renormalisation group

The tensor renormalization group (TRG) is a promising approach to study various models of lattice field theory. In particular, we can easily realize numerical calculations for theories with the sign problem, and on extremely large volume lattices, by the method. In this talk, I will review the recent progress in the TRG method.

The US Electron Ion Collider and Lattice QCD: Physics Opportunities and Experimental Challenges

The US electron ion collider (EIC) was established firmly as a project in the Office Of Science in January 2020. The EIC will be built at Brookhaven National Laboratory (BNL) jointly by BNL and Jefferson Lab working as partners. An EIC Project has been setup and is making progress fast. The EIC Users Group is evolving into proto-collaborations which are expecting to submit preliminary detector design proposals by December 2021 for evaluation. The detector construction will start in ~2024/25 and progress along with the machine, so as to have at least one detector ready when the machine starts providing the 1st beams ~2030. New ideas for measurements at the EIC are continually making the EIC’s science scope broader and stronger. In this talk I will present an overview of the EIC project, potential measurements with emphasis on precision and control, that could be of high interest to the Lattice QCD community.

The impact of LQCD on transverse momentum parton phenomenology

Semileptonic $b \to u$ decays and $|V_{ub}|$
The Cabibbo–Kobayashi–Maskawa (CKM) matrix element $|V_{ub}|$ describes the coupling between $u$ and $b$ quarks in the weak interaction, and is one of the fundamental parameters of the Standard Model. $|V_{ub}|$ is the focus of a longstanding puzzle, as the world-average values derived from inclusive and exclusive $B$-meson decays show a tension of a few standard deviations.

Semileptonic decays can be used to extract CKM elements by combining a lattice QCD calculation of the form factors and the experimental branching fractions. This talk will focus on the recent lattice QCD results and the current status of $V_{ub}$.

**Poster / 655**

**A9: P-Wave Two-Body Bound and Scattering States in a Finite Volume including QED**

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The mass shifts for two-fermion bound and scattering P-wave states subject to the long-range interactions due to QED in the non-relativistic regime in refs. [1, 2] are presented. Introducing a short range force coupling the spinless fermions to one unit of angular momentum in the framework of pionless EFT, we first report the two-body scattering amplitudes with Coulomb corrections in the infinite-volume context [3]. Motivated by the research on particle-antiparticle bound states, we show the T-matrix elements and the leading scattering parameters for fermions of identical mass and opposite charge. Second, we immerse the system into a cubic box with periodic boundary conditions and we display the finite-volume corrections to the energy of the lowest bound and unbound T1-eigenstates. In particular, power law contributions proportional to the finite structure constant and resembling the recent results for S-wave states are found [4]. Higher order terms in $\alpha$ are neglected, since the gapped nature of the momentum operator in the finite-volume environment allows for a perturbative treatment of the QED interactions. Some hints concerning the extension of the analysis to D-wave short-range interactions are eventually given.


**QCD in searches for physics beyond the Standard Model / 656**

**Near Physical Point Lattice Calculation of Isospin-Breaking Corrections to $K_{\ell 2}/\pi_{\ell 2}$**

**Corresponding Author:** andrew.yong@ed.ac.uk

In recent years, lattice determinations of non-perturbative quantities such as $f_K$ and $f_\pi$, which are relevant for $V_{us}$ and $V_{ud}$, have reached an impressive precision of $O(1\%)$ or better. To make further progress, electromagnetic and strong isospin breaking effects must be included in lattice QCD simulations.

We present the status of the RBC&UKQCD lattice calculation of isospin-breaking corrections to light meson leptonic decays. This computation is performed in a (2+1)-flavor QCD+QED using Domain
Wall Fermions with near-physical quark masses. The QED effects are implemented via a perturbative expansion of the action in $\alpha$. In this calculation, we work in the electro-quenched approximation and the photons are implemented in the Feynman gauge and QEDL formulation.

**Poster / 657**

**D10: Measuring charged particle polarizabilities on the lattice without background fields**

**Author:** Frank Lee

**Co-author:** Walter Wilcox

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We show how to compute electromagnetic polarizabilities of charged hadrons on the lattice without using background fields. The low-energy behavior of the Compton scattering amplitude is matched to matrix elements of current-current four point functions. Working in momentum space, formulas for electric polarizability and magnetic polarizability are derived for both charged pion and proton. Lattice four-point correlation functions are constructed from quark and gluon fields to be used in Monte-Carlo simulations. The content of the functions is assessed in detail and specific prescriptions are given to isolate the polarizabilities.

**QCD at nonzero Temperature and Density / 658**

**Continuous temperature sampling in a single Monte-Carlo simulation**

**Corresponding Author:** junnarkar.pm@gmail.com

We present a novel method which enables a continuous temperature sampling in a single Monte-Carlo simulation. The method can be generally used to compute continuous temperature dependence of any observable and we use it to evaluate the temperature dependence of QCD topological susceptibility at very high temperatures. The various advantages and disadvantages of the method will be presented. Work based on Phys.Rev.D 104 (2021) 1, 014502.

**Particle physics beyond the Standard Model / 659**

**AdS/CFT Correspondence for Scalar Field Theory in Lattice AdS$_2$, AdS$_3$**

**Author:** Cameron Cogburn

**Co-authors:** Evan Owen; Richard Brower

1. Boston University
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We use a regular tessellation of AdS$_2$ based on the (2,3,7) triangle group, with an extension to Euclidean AdS$_3$, to study the AdS/CFT correspondence. Perturbative calculations are verified and initial tests of monte carlo calculations for non-perturbative $\phi^4$ theory exhibit critical phenomena on the boundary.

Discussion/social / 660

Hadron Structure discussion in Gather breakout room #1

Discussion/social / 661

QCD at nonzero Temperature and Density discussion in Gather breakout room #2

Group photo on zoom

Poster / 663

F10: Lattice Diversity Survey

Author: Vera Guelpers$^1$

Co-authors: Christopher Aubin$^2$; Gunnar Bali$^3$; Huey-Wen Lin; Liuming Liu$^4$; Luigi Del Debbio$^5$; Sinead Ryan$^6$; Sophie Hollitt$^7$; William Detmold$^8$

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This poster presents the results of the 2021 Lattice Diversity and Inclusion Committee survey.
Tutorial / 664

Intel OneAPI tutorial

**Corresponding Author:** patrick.steinbrecher@intel.com

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Event Code: lattice-07302021

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Discussion/social / 665

Academic careers panel

Panelist Biographies:

Professor Aida El-Khadra received her PhD. in 1989 from the University of California, Los Angeles, after receiving her diploma from Freie Universitat, Berlin, Germany. She held postdoctoral research appointments at Brookhaven National Laboratory, Fermi National Accelerator Laboratory, and the Ohio State University before joining the Illinois faculty in 1995. El-Khadra is a fellow of the American Physical Society, a recipient of the Department of Energy’s Outstanding Junior Investigator Award, and a Sloan Foundation fellow. In addition to a number of other research and teaching awards, she has also been named a Fermilab Distinguished Scholar.

Vera Gülbers is a lecturer at the University in Edinburgh (UK) since July 2020. Vera finished her Ph.D. in September 2015 at the University in Mainz (Germany), where she had already graduated with a Diploma in Physics in 2011. Following her Ph.D., Vera has been a Postdoctoral Researcher at the University of Southampton (UK) from 2015 - 2018 and subsequently at the University of Edinburgh from 2018 - 2020 before taking on the Lecturer position in Edinburgh.

Taku Izubuchi received his Ph.D. at Tokyo University and held a postdoctoral position at Tsukuba University. In 1999 he was appointed as an Assistant Professor at Kanazawa University, and since 2003 he is affiliated with Brookhaven National Laboratory (BNL), as an RBRC Fellow of RIKEN, and later as an Assistant Scientist and RIKEN fellow of RIKEN-BNL Research Center. In 2010 he became an Associate Scientist at BNL, and since 2011 is the group leader of the Computing Group of RIKEN BNL Research Center. He is a recipient of the 2012 Ken Wilson Lattice Award, 2018 APS fellowship, 2019 BNL Science and Technology Award.

Xiangdong Ji received his bachelor’s degree from Tongji University in 1982 and his Ph.D. from Drexel University in 1987. He was a postdoctoral researcher at Caltech and MIT. In 1991, he became Assistant Professor at the MIT, and in 1996 he moved to the University of Maryland, where he was the chair of the Maryland Center for Fundamental Physics from 2007 to 2009. He is also professor and chair of the Institute for Nuclear and Particle Physics at Shanghai Jiao Tong University. Since 2005, he has also been a visiting professor at Peking University. In 2014 he won the Humboldt Prize and in 2015 he won the Outstanding Nuclear Physicists Award from the Jefferson Sciences Associates. In 2000, he became a fellow of the American Physical Society. In 2003, he won the Overseas Outstanding Chinese Scientist Award. In 2016 he won the Herman Feshbach Prize in Theoretical Nuclear Physics
for pioneering work in developing tools to characterize the structure of the nucleon within QCD and for showing how its properties can be probed through experiments; this work not only illuminates the nucleon theoretically but also acts as a driver of experimental programs worldwide. In addition to his focus on nuclear physics, he also works on dark matter physics using liquid xenon detectors (a variety of neutrinos being candidates for dark matter), leptogenesis, neutrino mass, and neutrino oscillation in GUT models.

Jian Liang got his Ph.D. in 2015 from the Institute of High Energy Physics, Chinese Academy of Sciences. Then, he moved to the University of Kentucky as a postdoctoral fellow in the group of Prof. Keh-Fei Liu for 5 years. Since 2020, he is holding a faculty position at the Institute of Quantum Matter in South China Normal University.

Marina Marinkovic, currently an assistant professor at ETH Zurich, earned her Ph.D. in the computational physics group at the Humboldt University of Berlin. After a postdoctoral stay at the University of Southampton, she was awarded a prestigious CERN fellowship, which was followed by a Hitachi Assistant Professorship in High-Performance Computing, and a junior professorship at the Ludwig Maximilian University of Munich. As one of the founding members of RC* collaboration, Marinkovic investigates the inclusion of isospin breaking effects to lattice simulations, while as a member of MUonE collaboration she uses lattice insights to augment results of CERN experiments. Her research on scalable algorithms for strong interaction aims to bring machine learning to the established areas of particle physics in simultaneous preparations for exascale computing and quantum computing era.

Tilo Wettig studied physics at the University of Tübingen and at SUNY Stony Brook, where he got his Ph.D. in 1994. After two postdocs at the Max Planck Institute in Heidelberg and at the Technical University of Munich he moved to Yale University as an assistant professor (1999) and associate professor (2003). In that period he was also a fellow of the RIKEN-BNL Research Center. In 2004 he moved to the University of Regensburg, where he is a full professor.

Savvas Zafeiropoulos is a researcher in the particle physics section of the Centre for Theoretical Physics - CNRS at the Aix-Marseille-Université et Université de Toulon. His research interests include Lattice Quantum Chromodynamics, Random Matrix Theory, Chiral Perturbation Theory, Non-Perturbative Renormalization, Phase Diagram of QCD, Quark-Gluon Plasma, Heavy Ions, Graphene, Parton Distribution Functions.

Discussion/social / 666

Non-academic careers panel

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