School on Continuum Foundations of Lattice Gauge Theories

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CERN

Book of Abstracts

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Proper time path integrals for gravitational waves: an improved wave optics framework

Authors: Alice Garoffolo[1]; Angelo Ricciardone[2]; Ginevra Braga[None]; Nicola Bartolo[3]; Sabino Matarrese[3]

[1] *UPenn*

[2] *Pisa University*

[3] *Padua University*

Corresponding Authors: nicola.bartolo@pd.infn.it, angelo.ricciardone@pd.infn.it, aligaro@sas.upenn.edu, ginevra.braga@gssi.it, sabino.matarrese@pd.infn.it

When gravitational waves travel from their source to an observer, they interact with matter structures along their path, causing distinct deformations in their waveforms. In this study we introduce a novel theoretical framework for wave optics effects in gravitational lensing, addressing the limitations of existing approaches. We achieve this by incorporating the proper time technique, typically used in field theory studies, into gravitational lensing. This approach allows us to extend the standard formalism beyond the eikonal and paraxial approximations, which are traditionally assumed, and to account for polarization effects, which are typically neglected in the literature. We demonstrate that our method provides a robust generalization of conventional approaches, including them as special cases. Our findings enhance our understanding of gravitational wave propagation, which is crucial for accurately interpreting gravitational wave observations and extracting unbiased information about the lenses from the gravitational wave waveforms.

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Semiconductor quantum simulator for lattice gauge theories

Authors: Zohreh Davoudi[1]; Michael Gullans[2]; Vinay Vikramaditya[2]

[1] *University of Maryland*

[2] *University of Maryland, College Park*

Corresponding Authors: mgullans@umd.edu, vvinay@umd.edu, davoudi@umd.edu

Semiconductor spin qubits are ideal for scalable quantum computing due to their long coherence times and compatibility with existing semiconductor fabrication technology. For quantum simulation of lattice gauge theories, the encoding of fermionic d.o.f. into qubits becomes complicated in higher dimensions. Furthermore, encoding with bosonic d.o.f. in a digital scheme introduces additional qubit and gate costs. In a semiconductor platform, the presence of both electrons and (large) nuclear spins provides readily available fermionic and bosonic degrees of freedom, respectively. Moreover, parameters such as tunneling coefficients, chemical potentials, hyperfine couplings, and global magnetic fields are highly tunable. This tunability allows periodic driving of the parameters, which can potentially be used to engineer interactions that simulate gauge dynamics on a lattice.

In this poster, I'll present our ongoing work on implementing an analog simulation scheme for Z2 lattice gauge theory in (1+1)D. The Floquet-Magnus expansion is used to analyze the behavior of the system under high-frequency periodic drives of the parameters involved. Future research will explore the feasibility of implementing an analog or hybrid simulation of gauge theories in (2+1)D on this platform.

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Non-perturbative lattice studies of exotic multiquark systems

Author: Navdeep Singh Dhindsa[1]

[1] *The Institute of Mathematical Sciences, Chennai*

Corresponding Author: navdeep.s.dhindsa@gmail.com

Understanding baryon-baryon interactions is key in nuclear physics because these interactions form the foundation of atomic nuclei. Despite many experiments, the deuteron is still the only confirmed dibaryon bound state, with recent evidence for an unstable light dibaryon, d*(2380). Other dibaryons, if any exist, remain undiscovered. Our study employs state-of-the-art lattice QCD techniques to explore dibaryon systems involving heavy quark baryons, motivated by the significant interest in exotic multi-quark systems and discoveries of quarkonium states in experiments like CMS and LHCb. In this presentation, I will discuss our ongoing work on dibaryon systems involving heavy quark baryons, examining their interactions at the fundamental level of strong interactions. The poster will mainly focus on the dynamics of Ω_{ccc}-Ω_{ccc} and Ω_{sss}-Ω_{sss} systems.

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Symplectic quantization: a new deterministic approach to the dynamics of quantum fields inspired by statistical mechanics

Authors: Giacomo Gradenigo[1]; Martina Giachello[1]

[1] *Gran Sasso Science Institute*

Corresponding Authors: martina.giachello@gssi.it, giacomo.gradenigo@gssi.it

The present work is about a new method to sample the quantum fluctuations of relativistic fields by means of a pseudo-Hamiltonian dynamics in an enlarge space of variables. The proposed approach promotes the fictitious time of Parisi-Wu stochastic quantisation to a true physical parameter controlling a deterministic dynamics. The sampling of quantum fluctuations is guaranteed by the presence of new additionational conjugated momenta, which reprents the rate of variation of ordinary fields with respect to the newly added time variable. The main goal of this approach is to provide a numerical method to sample quantum fluctuations of fields directly in Minkowski space, whereas all existent methods allowed one so far to do this only in Euclidean space, therefore loosing important physics. From the pseudo-Hamiltonian dynanamics one is then able, assuming ergodicity, to retrieve the Feynman path integral as the Fourier transform of a pseudo-microcanonical partition function. The whole framework proposed is not only the source of a new numerical approach to study quantum fields but also and most importantly reveals important connections between quantum field theory, statistical mechanics and Hamiltonian dynamics. Here we will discuss the main ideas behind the formalism and the first successful results of numerical tests, as well as the difficulties we encountered. (Preprint: https://arxiv.org/abs/2403.17149)

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Localization of Dirac modes in the finite temperature SU(2)-Higgs model

Author: György Baranka[None]

Corresponding Author: barankagy@gmail.com

Low-lying Dirac modes become localized at the finite-temperature transition in QCD and other gauge theories, indicating a connection between localization and deconfinement. This phenomenon can be understood through the "sea/islands" picture: in the deconfined phase, modes become trapped on "islands" of Polyakov loop fluctuations within a "sea" of ordered Polyakov loops.

To test the universality of the "sea/islands" mechanism, we investigate whether changes in the localization properties of low modes occur across other thermal transitions where the Polyakov loop becomes ordered, beyond the usual deconfinement transition. The fixed-length SU(2)-Higgs model serves as an appropriate model for this study. After mapping out the phase diagram, we find that low Dirac modes become localized in the deconfined and Higgs phases, where the Polyakov loop is ordered. However, localization is absent in the confined phase. These findings confirm the "sea/islands" picture.

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Simulating an SO(3) Quantum Link Model with Dynamical Fermions in 2+1 Dimensions

Author: Graham Van Goffrier[None]

Corresponding Author: gwvg1e23@soton.ac.uk

Quantum link models (QLMs) are generalizations of Wilsonian lattice gauge theory which can be formulated with finite-dimensional link Hilbert spaces, and which can be embedded onto local spin Hamiltonians for efficient quantum simulation by exact imposition of the Gauss Law constraint. Previously, SO(3) QLMs have been studied in 1+1d and shown to reflect key properties of QCD and nuclear physics, including distinct confining/deconfining phases and hadronic bound states. We have conducted one of the first simulations of SO(3) QLMs with dynamical fermions in 2+1d, and here report our results. We review the construction of a gauge-invariant state space for 1+1d and

2+1d SO(3) QLMs, and show how knowledge of discrete symmetries facilitates exact diagonalisation of the spin-Hamiltonian. We also comment on how the quantum simulation of the SO(3) QLM in 1+1d and 2+1d may be efficiently performed by variational methods.

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Adjoint Correlators at Finite Temperature with Gradient Flow

Author: Marc Janer[None]

Corresponding Author: m.janer@tum.de

The evolution of a particle in the Quark-Gluon Plasma is determined by transport coefficients. Especially the diffusion of a heavy adjoint quark or quarkonium can be measured from the correlator of two chromoelectric field operators connected by a static Wilson line in the adjoint representation. The first mass correction is then given by using chromomagnetic fields instead. However, the static Wilson line introduces a divergent term in lattice spacing and appears as a renormalon in the continuum. We use gradient flow to renormalize the field components and to regulate this divergence. We present measurements on the relevant correlators on the lattice for the adjoint diffusion and different approaches to extract the divergence.

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Form factors for semi-leptonic $B_{(s)} \to D^*_{(s)} \ell \nu_\ell$ decays

Author: Anastasia Boushmelev[1]

[1] *University of Siegen*

Corresponding Author: ana99bou@gmail.com

Semileptonic $B_{(s)}$ decays are of great phenomenological interest because they allow to extract CKM matrix elements or test lepton flavor universality. Taking advantage of existing data, we explore extracting form factors for vector final states using the narrow width approximation. Based on RBC-UKQCD's set of 2+1 flavor gauge field ensembles with Shamir domain-wall fermion and Iwasaki gauge field action, we study semileptonic $B_{(s)}$ decays using domain-wall fermions for light, strange and charm quarks, whereas bottom quarks are simulated with the relativistic heavy quark (RHQ) action. Exploratory results for $B_s \to D^*_s \ell \nu_\ell$ are presented.

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Euclidean Monte Carlo informed ground state preparation for quantum simulation

Author: Navya Gupta[None]

Corresponding Author: navyag@umd.edu

Quantum simulators offer great potential for investigating the dynamical properties of quantum field theories. However, a key challenge is the preparation of high-fidelity initial states for these simulations. In this study, we focus on ground states and explore how information about their static properties, which can be efficiently obtained using classical methods such as lattice-based path-integral Monte Carlo performed on classical computers, can help identify suitable initial states. For the scalar field theory in 1+1 dimensions, we demonstrate variational ansatz families that yield comparable ground state energy estimates but exhibit distinct correlations and local non-Gaussianity. The simulation of quantum dynamics is expected to be highly sensitive to such initial state moments beyond the energy. We show that it is possible to optimize the behavior of selected ansatz moments using known ground state moments to address specific simulation needs. Drawing inspiration from the scalar field theory, our ultimate goal is to utilize existing lattice quantum chromodynamics (QCD) data to inform the preparation of the QCD ground state on quantum simulators.

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Using AI for Efficient Statistical Inference of Lattice Correlators Across Mass Parameters

Author: Octavio Vega[None]

Corresponding Author: octavio5@illinois.edu

We study an application of supervised learning to infer two-point lattice correlation functions at one input mass from correlator data computed at a different target mass. Learning across the mass parameters could potentially reduce the cost of expensive calculations involved in light Dirac inversions, which can be a computational bottleneck for performing simulations of quantum chromodynamics on the lattice. Leveraging meson two-point functions computed on an ensemble of gauge configurations generated by the MILC collaboration, we use a simple method for separating the data into training and correction samples that avoids the need for intensive retraining or bootstrapping to quantify uncertainties on our observables of interest. We employ a variety of machine learning models, including decision tree-based models and neural networks, to predict uncomputed correlators at the target mass. Additionally, we apply a simple ratio method which we compare and combine with the machine learning models to benchmark our inference methods. Special attention is given to validating the models we use.

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Lattice determination of the NLO HVP contributions to the muon g-2

Author: Arnau Beltran Martinez[None]

Corresponding Author: abeltran@uni-mainz.de

In this work, we present a full lattice computation for the NLO contribution to the HVP of the muon g-2. First, we study the time-momentum representation (TMR) of the three kernels needed to compute the three different NLO HVP diagrams, following the work of Balzani, Laporta and Passera. For the HO corrections including extra photon or lepton lines, we present an analytical series of expansions for small values of the Euclidian time and numerical series expansions for the large time values. The NLO diagram with two QCD insertions can be analytically solved and then expanded over different regions of the 2D Euclidian time plane. These results are then combined with lattice QCD simulations from 12 different CLS ensembles employing Wilson quarks to obtain a full determination of the sub-leading hadronic contribution to the muon g-2. We apply two different O(a) improvement programmes with two discretizations each to better constrain the continuum limit. On top of that, the Hansen-Patella method has been applied to correct for the finite volume effects. Finally, we perform a chiral and continuum extrapolation to the physical point obtaining a total estimation of the $a_\mu^{\mathrm{hvp}}[\mathrm{NLO}]$.

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Scattering wave packets of hadrons in gauge theories: Preparation on a quantum computer

Author: Hsieh Chung-Chun[None]

Corresponding Author: cchsieh@umd.edu

Quantum simulation holds promise of enabling a complete description of high-energy scattering processes rooted in gauge theories of the Standard Model. A first step in such simulations is preparation of interacting hadronic wave packets. To create the wave packets, one typically resorts to adiabatic evolution to bridge between wave packets in the free theory and those in the interacting theory, rendering the simulation resource intensive. In this work, we construct a wave-packet creation operator directly in the interacting theory to circumvent adiabatic evolution, taking advantage of resource-efficient schemes for ground-state preparation, such as variational quantum eigensolvers. By means of an ansatz for bound mesonic excitations in confining gauge theories, which is subsequently optimized using classical or quantum methods, we show that interacting mesonic wave packets can be created efficiently and accurately using digital quantum algorithms that we develop. Specifically, we obtain high-fidelity mesonic wave packets in the Z2 and U(1) lattice gauge theories coupled to fermionic matter in 1+1 dimensions. Our method is applicable to both perturbative and non-perturbative regimes of couplings. The wave-packet creation circuit for the case of the Z2 lattice gauge theory is built and implemented on the Quantinuum H1-1 trapped-ion quantum computer using 13 qubits and up to 308 entangling gates. The fidelities agree well with classical benchmark calculations after employing a simple symmetry-based noise-mitigation technique. This work serves as a step toward quantum computing scattering processes in quantum chromodynamics.

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Lecture 1

Corresponding Author: gilberto.colangelo@unibe.ch

Inverse Problems / **18**

Lecture 1

Corresponding Author: luigi.del.debbio@ed.ac.uk

Resurgence / **19**

Lecture 1

Corresponding Author: gerald.dunne@uconn.edu

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Lecture 1

Corresponding Author: davoudi@umd.edu

Inverse Problems / 21

Lecture 2

Corresponding Author: luigi.del.debbio@ed.ac.uk

Resurgence / 22

Lecture 2

Corresponding Author: gerald.dunne@uconn.edu

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Lecture 2

Corresponding Author: gilberto.colangelo@unibe.ch

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Lecture 3

Corresponding Author: luigi.del.debbio@ed.ac.uk

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Lecture 2

Corresponding Author: davoudi@umd.edu

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Lecture 3

Corresponding Author: gerald.dunne@uconn.edu

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Lecture 3

Corresponding Author: davoudi@umd.edu

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Lecture 3

Corresponding Author: gilberto.colangelo@unibe.ch

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Lecture 4

Corresponding Author: luigi.del.debbio@ed.ac.uk

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Lecture 4

Corresponding Author: gerald.dunne@uconn.edu

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Lecture 4

Corresponding Author: gilberto.colangelo@unibe.ch

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Lecture 4

Corresponding Author: davoudi@umd.edu

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Investigating the behavior of the Lattice Model using the Tensor Renormalization technique.

Authors: Abhishek Samlodia[1]; Vamika Longia[2]; Raghav G Jha[3]; Anosh Joseph[4]

[1] *Department of Physics, Syracuse University, Syracuse NY 13244, USA*

[2] *Indian Institute of Science Education and Research, Mohali*

[3] *Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA*

[4] *National Institute for Theoretical and Computational Sciences, School of Physics, and Mandelstam Institute for Theoretical Physics, University of the Witwatersrand, Johannesburg, Wits 2050, South Africa*

Corresponding Authors: raghav.govind.jha@gmail.com, asamlodia@gmail.com, anosh.joseph@wits.ac.za, vamika.longia@gmail.com

Simulating higher-dimensional lattice models remains a significant challenge, spurring interest in advanced renormalization group (RG) methods for tensor-network states. One such model we study here is the two-dimensional XY model. This theory has been understood greatly and undergoes a BKT type of phase transition. Adding an extra spin-nematic interaction term with period, the modified XY model called generalized XY model, now contains both integer vortices and half-integer vortices excitations. These vortices govern the critical behavior and produce rich physics even in two dimensions. We study the transition behavior between the integer vortex binding and half-integer vortex binding phases and how this transition line merges into two BKT transition lines using the higher-order tensor renormalization group method a promising technique to produce improved results.

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Studies on inclusive semileptonic decays from lattice QCD

Author: Ryan Kellermann[1]

Co-authors: Ahmed Elgaziari [2]; Alessandro Barone [3]; Andreas Juettner ; Shoji Hashimoto [4]; Takashi Kaneko ; Zhi Hu

[1] *High Energy Accelerator Research Organization (KEK)*

[2] *University of Southampton*

[3] *Johannes Gutenberg University Mainz*

[4] *KEK*

Corresponding Authors: huzhi@post.kek.jp, a.elgaziari@soton.ac.uk, abarone@uni-mainz.de, kelry@post.kek.jp, takashi.kaneko@kek.jp, shoji.hashimoto@kek.jp, juettner@soton.ac.uk

We report on the nonperturbative calculation of the inclusive decay rate for semileptonic decays of the D_s meson from lattice QCD. We present a short overview on how the Chebyshev approximation can be employed in order to obtain predictions for the total inclusive decay rate from hadronic correlators generated from lattice simulations. We further present first estimates on the systematic effects associated with the analysis. Namely, we focus on the systematic errors introduced by the finite polynomial order in the Chebyshev approximation used in the analysis and the error due to finite-volume effects.