

CPOD2022 - Workshop on Critical Point and Onset of Deconfinement

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Book of Abstracts

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Neutron Stars and very high μ_B - 2 / 3**Reaching percolation and conformal limits in neutron stars****Authors:** Chihiro Sasaki^{None}; Krzysztof Redlich¹; Larry McLerran^{None}; Michał Marczenko²¹ *National Centre for Nuclear Research (PL)*² *University of Wrocław***Corresponding Authors:** michal.marczenko@uwr.edu.pl, mclerran@mac.com, chihiro.sasaki@uwr.edu.pl, krzysztof.redlich@cern.ch

Generating an ensemble of equations of state that fulfill multimessenger constraints, we statistically determine the properties of dense matter found inside neutron stars (NSs). We calculate the speed of sound and trace anomaly and demonstrate that they are driven towards their conformal values at the center of maximally massive NSs. The local peak of the speed of sound is shown to be located at values of the energy and particle densities which are consistent with deconfinement and percolation conditions in QCD matter. We also analyze fluctuations of the net-baryon number density in the context of possible remnants of critical behavior. We find that the global maxima of the variance of these fluctuations emerge at densities beyond those found in the interiors of NSs.

based on arXiv:2207.13059

Fluctuations - 1 / 9**Testing new proxies of 2nd order cumulants of B, Q and S in Au-Au collisions at BES energies with EPOS 4****Author:** Johannès Jahan¹**Co-author:** Klaus WERNER¹ *Subatech (FR)***Corresponding Authors:** johannes.jahan@subatech.in2p3.fr, werner@subatech.in2p3.fr

Within the framework of the exploration of the nuclear matter phase diagram, the susceptibilities of conserved charges are useful tools to probe the existence of a 1st order phase transition, and a possible critical endpoint. They can be related to the cumulants of the considered net-charges, for which STAR collaboration recently published experimental measurements of proxies, in Au-Au collisions at several energies of the Beam Energy Scan. Hence, the measured (co)variances of π^\pm , p/\bar{p} and K^\pm are used to build proxy ratios for the corresponding 2nd order cumulant ratios of electric charge Q, baryonic number B and strangeness S.

It is nevertheless important to disentangle the different effects contributing to these net-multiplicity cumulants of hadronic species, in addition to the fluctuations which they are supposed to probe. For this reason, we studied the impact of hadronic cascades on these observables, thanks to complete simulations of Au-Au collisions performed with EPOS 4. The results are compared with cumulant ratios of exact conserved charges, and proposed enhanced proxy ratios based on a study of the hadronic breakdown contributions to the total susceptibilities with IQCD and HRG model calculations.

We show that using variance of Λ baryons, additionally to σ_π^2 , σ_p^2 and σ_K^2 used by STAR, allow to build proxies that reconstruct quantitatively better the ratios of B, Q and S correlations. Moreover, even if hadronic cascades amplifies the signal for all (co)variances, they have little impact on most of their ratios.

Fluctuations - 3 / 10

Cumulants from global baryon number conservation with short-range correlations

Author: Michał Barej^{None}

Co-author: Adam Bzdak¹

¹ AGH University of Science and Technology

Corresponding Authors: michal.barej@fis.agh.edu.pl, bzdak@agh.edu.pl

The quantum chromodynamics (QCD) phase diagram is not yet well explored. In particular, there is a significant, theoretical and experimental, effort to search for the predicted first-order phase transition and the corresponding critical endpoint between the hadronic matter and quark-gluon plasma. The fluctuations of, e.g., net-baryon number, electric charge, or strangeness are known to be sensitive to the relevant critical phenomena. They are studied in relativistic heavy ion collisions using the cumulants and factorial cumulants. However, these fluctuations can be generated also by the effects not related to the phase transitions, e.g., the global baryon number conservation. This talk will present the baryon multiplicity cumulants in the subsystem generated by the global baryon conservation and short-range correlations. The way to obtain higher-order corrections will be discussed.

Neutron Stars and very high μ_B - 1 / 14

Holographic QCD Equation of State Modeling in the Bayesian Era

Authors: Mauricio Hippert Teixeira¹; Joaquin Grefa^{None}; Jorge Noronha¹; Jacquelyn Noronha-Hostler²; Israel Portillo³; Claudia Ratti^{None}; Romulo Rougemont^{None}

¹ University of Illinois at Urbana-Champaign

² University of Illinois Urbana Champaign

³ University of Houston

Corresponding Authors: joaquinrefa@gmail.com, analysadorcetico@gmail.com, cratti@uh.edu, iportillovazquez@gmail.com, jorgenoronha@gmail.com, mauriciohipperrt@gmail.com, jnorhos@illinois.edu

Predictions for the QCD equation of state across the phase diagram are made using Bayesian inference techniques within the holographic gauge/gravity correspondence. For that, we employ a Einstein-Maxwell-Dilaton (EMD) model capable of reproducing the latest lattice QCD results at zero and finite baryon density, known to predict a high-density critical endpoint. For the first time, we numerically find the posterior probability distribution for holographic model parameters from the lattice data at zero chemical potential, and extract their most likely values. This is possible thanks to new numerical developments which, by boosting the performance of our calculations, allow us to sample a large number of fits to the data via Monte Carlo methods. Thus, we find the maximum a posteriori estimate for the location of the critical point, as well as estimates for the corresponding statistical error bands. We determine the linear combination of model parameters which is the most relevant for these uncertainties and investigate its role for the equation of state at lower densities. Finally, we compare competing parametrizations of the EMD model and discuss systematic uncertainties.

Critical Point - 5 / 15

Characterising the hot and dense fireball with virtual photons at HADES

Author: Niklas Schild^{1None}

Corresponding Author: n.schild@gsi.de

Anisotropic flow serves as a central observable for characterising collectivity in heavy-ion collisions. While all particles experience flow, virtual photons, decaying into lepton pairs, may serve as particularly interesting probes in this context. They can penetrate the strongly interacting medium and deliver information about conditions in the early stages of maximum temperature and density. Thereby, they may give insights about the time evolution of the collectivity in the system.

In this contribution, we present measurements of anisotropic flow coefficients from Ag+Ag collisions, collected at the High-Acceptance-DiElectron-Spectrometer (HADES) at $\sqrt{s_{NN}} = 2.55$ GeV. A particular focus is set on the multidifferential analysis of the directed flow v_1 and elliptic flow v_2 in terms of centrality, rapidity, transverse momentum and invariant mass.

Critical Point - 4 / 18

Adiabatic hydrodynamization in the bottom-up thermalization scenario

Authors: Bruno Sebastian Scheihing Hitschfeld¹; Jasmine Therese Brewer²; Yi Yin³

¹ *Massachusetts Institute of Technology*

² *CERN*

³ *Institute of modern physics, Chinese Academy of Sciences*

Corresponding Authors: yiyin@impcas.ac.cn, jasmine.brewer@cern.ch, bscheihi@mit.edu

In this talk we demonstrate that the early stages of the bottom-up thermalization scenario [1] are well described by the adiabatic hydrodynamization framework. All of the qualitative features exhibited in QCD effective kinetic theory (EKT) simulations at weak coupling [2] are captured by the emergence of an effective low-energy instantaneous ground state for the 1-particle gluon distribution function, which defines the early-time kinetic theory attractor. This ground state may be pulled back to arbitrarily early times, where it represents a free-streaming solution, and at later times it integrally describes the BMSS fixed point, including the recently observed deviations from the original predictions for the scaling exponents [2].

Our discussion is guided by our observations of the deep connections between scaling and adiabaticity in expanding gluon plasmas [3]. To showcase this, we first solve the Boltzmann equation for gluons in the small-angle scattering approximation numerically and find that time-dependent scaling is a feature of this kinetic theory, capturing the QCD EKT scaling of hard gluons [2]. We then proceed to study scaling analytically and semi-analytically in this equation. We find that an appropriate momentum rescaling allows the scaling distribution to be identified as the instantaneous ground state of the operator describing the evolution of the distribution function, and the approach to the scaling function is described by the decay of the excited states. That is to say, there is a frame in which the system evolves adiabatically, and the instantaneous ground state describes the early-time kinetic theory attractor. We obtain this ground state analytically. Corrections to the BMSS fixed point exponents in the small-angle approximation agree quantitatively with those found previously in QCD EKT and arise from the evolution of the ratio between hard and soft scales.

[1] R. Baier, A.H. Mueller, D. Schiff and D.T. Son, "Bottom up thermalization in heavy ion collisions," *Phys. Lett. B* 502 (2001) 51

[2] A. Mazeliauskas and J. Berges, "Prescaling and far-from-equilibrium hydrodynamics in the quark-gluon plasma," *Phys. Rev. Lett.* 122 (2019) 122301

[3] J. Brewer, B. Scheihing-Hitschfeld and Y. Yin, "Scaling and adiabaticity in a rapidly expanding gluon plasma," *JHEP* 05 (2022) 145

Hydro Evolution - 3 / 19

Azimuthal anisotropic flow of identified hadrons in Au+Au collisions in BES-II energies

Author: Prabhupada Dixit^{None}

Corresponding Author: prabhupadad@iiserbpr.ac.in

Anisotropic flow of the final state particles produced in heavy-ion collisions is one of the important probes to study the properties of the matter produced in the collisions. Elliptic flow (v_2) and triangular flow (v_3) parameters are the second and third order coefficients in the Fourier expansion of azimuthal distributions of the final state particles in the momentum space. v_2 and v_3 are sensitive to the equation of the state (EoS) and transport properties, such as shear viscosity to entropy density ratio (η/s) of the medium produced in the collisions.

Recently, STAR has completed the data taking for Beam Energy Scan phase-II (BES-II) with improved detector conditions and wider rapidity coverage. In this talk, using BES-II data, we will present the high precision measurements of v_2 and v_3 of identified hadrons, π^+ (π^-), K^+ (K^-), p (\bar{p}), K_S^0 , ϕ , Λ ($\bar{\Lambda}$), Ξ^- ($\bar{\Xi}^+$), and Ω^- ($\bar{\Omega}^+$) in Au+Au collisions at $\sqrt{s_{NN}} = 14.6$ and 19.6 GeV. The centrality and rapidity dependence of v_n and number of constituent quark (NCQ) scaling will be presented. Finally, the physics implications of our measurements in the context of partonic collectivity will be discussed.

Hydro Evolution - 2 / 22

Study of kinematic dependence of azimuthal anisotropies in small collision systems at PHENIX

Author: Sanghoon Lim¹¹ Pusan National University (KR)

Corresponding Author: shlim@bnl.gov

There have been extensive studies to measure long-range correlations among produced particles from small collision systems, and the experimental results clearly indicate collective flow phenomena in these systems. Previously, PHENIX published elliptic and triangular flow results in high multiplicity p +Au, d +Au, and ^3He +Au collisions. The results can be described by hydrodynamics translating initial geometry to final momentum anisotropy. More detailed studies have been performed using the two-particle correlation method, and the new analysis shows consistent elliptic and triangular flow results with the previous results. Another analysis has been done with various detector combinations to understand non-flow effects and longitudinal decorrelations can affect flow measurements. In this presentation, new PHENIX results of long-range particle correlations in $p/d/{}^3\text{He}$ +Au and $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV will be presented.

Fluctuations - 2 / 24

Critical point particle number fluctuations from molecular dynamics

Author: Volodymyr Kuznietsov¹Co-authors: Mark Gorenstein²; Oleh Savchuk³; Volker Koch; Volodymyr Vovchenko⁴¹ Bogolyubov Institute for Theoretical Physics of the National Academy of Sciences of Ukraine

² *Bogolyubov Institute for Theoretical Physics*

³ *Frankfurt Institute for Advanced Studies*

⁴ *Lawrence Berkeley National Laboratory*

Corresponding Author: kuznietsova13@gmail.com

We study fluctuations of particle number in the presence of a critical point by utilizing molecular dynamics simulations of the classical Lennard-Jones fluid in a periodic box. The numerical solution of the N -body problem naturally incorporates all correlations, exact conservation laws, and finite size effects, allowing us to study the fluctuation signatures of the critical point in a dynamical setup. We find that large fluctuations associated with the critical point are observed when measurements are performed in coordinate subspace, but, in the absence of collective flow and expansion, are essentially washed out when momentum cuts are imposed instead. We also analyze phase separation and fluctuations in the coexistence region of the first-order phase transition.

Hydro Evolution - 2 / 25

Diagnosis of the collective flows in p+Au, d+Au and ³He+Au at 200 GeV and d+Au at RHIC energy scan regions by full (3+1)D dynamical model

Authors: Bjoern Schenke¹; Chun Shen²; Sangwook Ryu²; Wenbin Zhao²

¹ *Brookhaven National Lab*

² *Wayne State University*

Corresponding Authors: chunshen@wayne.edu, wenbinzhao237@gmail.com, bschenke@quark.phy.bnl.gov, sangwook.ryu@mail.mcgill.ca

STAR and PHENIX Collaborations have recently reported measurements of the anisotropic flow coefficients in p+Au, d+Au, and ³He+Au collisions at the Relativistic Heavy Ion Collider (RHIC). However, some tension between STAR and PHENIX data has not been fully resolved. Because the STAR and PHENIX Collaborations applied different pseudorapidity ranges to analyze the two-particle correlations, the flow rapidity correlations in these asymmetric systems could play a crucial role in understanding the difference in the data.

This talk will present full (3+1)D dynamical simulations of asymmetric nuclear collisions at RHIC. We explore the rapidity dependence of anisotropic flow in the RHIC small system scan at 200 GeV and d+Au energy scan in the Beam Energy Scan region. By extrapolating from ³He+Au to d+Au and p+Au collisions, we find that the different amounts of longitudinal flow decorrelations result in larger v_3 with the STAR definition than those with the PHENIX definition in p+Au and d+Au collisions at 200 GeV. Furthermore, our calculation demonstrates that a considerable fraction of the $v_3(p_T)$ difference in STAR and PHENIX measurements can be explained using reference flow vectors from different rapidity regions. Therefore, the longitudinal flow decorrelation is crucial to understand the anisotropic flow measurements in asymmetric nuclear collisions. We further extend our model to investigate the energy dependence of the particle productions and collective flow in d+Au collisions at BES energies and compare the results to the PHENIX measurements.

Hydro Evolution - 2 / 26

Elliptic flow of identified particles in Au+Au collisions at $\sqrt{s_{NN}} = 14.6$ GeV in BESII

Corresponding Author: zs155167@mails.ccnu.edu.cn

The main purpose of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), is to create new form of matter call Quark Gluon Plasma (QGP) in the laboratory and study

quantum chromodynamics (QCD) phase structure. The initial anisotropy in the coordinate space is translated into the anisotropy in the momentum space. The elliptic flow (v_2) is defined as the second harmonic coefficient of the Fourier decomposition of azimuthal distribution of produced particles with respect to the reaction plane angle. It is sensitive to the early dynamic evolution of the system and can provide the possible signal of QGP and phase transition.

In this talk, we will present v_2 of π^\pm , K^\pm , p , \bar{p} , K_S^0 , Λ , $\bar{\Lambda}$, Ξ , and $\bar{\Xi}^+$ in Au+Au collisions at $\sqrt{s_{NN}} = 14.6$ GeV in BESII. The v_2 results of pions, kaons, and protons will be compared with those of multi-strange hadrons. The number of constituent quark (NCQ) scaling will be tested as a function of collision centrality. Collision energy dependence of the NCQ scaling will be investigated by comparing v_2 results between 19.6 and 3 GeV. We will also compare our results with transport model calculations. Implications of these measurements in the context of QCD phase structure at high baryon chemical potential region will be discussed.

Critical Point 3 / 29

Review of intermittency analyses at NA61/SHINE

Author: Tobiasz Czopowicz¹

¹ *Jan Kochanowski University, Warsaw University of Technology*

Corresponding Author: tobiasz.czopowicz@cern.ch

The existence and location of the QCD critical point is an object of both experimental and theoretical studies. The comprehensive data collected by the NA61/SHINE during a two-dimensional scan in beam momentum (13A-150A GeV/c) and system size (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) allows for a systematic search for the critical point – a search for a non-monotonic dependence of various correlation and fluctuation observables on collision energy and size of colliding nuclei. In particular, fluctuations of particle number in transverse momentum space are studied. They are quantified by measuring the scaling behavior of factorial moments of multiplicity distributions.

This contribution reviews ongoing NA61/SHINE studies to search for the critical point of the strongly interacting matter via intermittency analyses.

Hydro Evolution - 3 / 31

Reaction Plane Correlated Triangular Flow in Au+Au Collisions at $\sqrt{s_{NN}} = 3.0$ GeV from STAR

Author: Cameron Racz¹

Co-author: STAR Collaboration

¹ *University of California, Riverside*

Corresponding Author: cracz001@ucr.edu

Directed and elliptic flow have been extensively studied in heavy-ion collisions while triangular flow (v_3) could be further explored. v_3 could prove very useful as a signal for Quark-Gluon Plasma (QGP) formation due to its sensitivity to QGP viscosity and the possibility that it is less affected by transport dynamics at very low energies [1]. In this talk, we will present the current progress of v_3 for π , p , d , and t at the fixed target energy of $\sqrt{s_{NN}} = 3.0$ GeV, which is the lowest in phase-II of the Beam Energy Scan at STAR. The results show a positive correlation between v_3 and the first-order event plane and a significant rapidity-odd v_3 for p. Model comparisons are also made to investigate whether a mean-field potential is required to develop this triangular flow.

[1] J. Auvinen and H. Petersen. Evolution of elliptic and triangular flow as a function of $\sqrt{s_{NN}}$ in a hybrid model. Phys. Rev. C, 88:064908, 2013.

Fluctuations - 4 / 33

Fluctuations of conserved charges in strong magnetic fields from lattice QCD

Author: Junhong Liu¹

Co-authors: Heng-Tong Ding ; Sheng-Tai Li ²; Xiaodan Wang ²

¹ Central China Normal University

² CCNU

Corresponding Authors: xiaodanwang@mails.ccn.edu.cn, junhongliu@ccnu.edu.cn, hengtong.ding@mail.ccn.edu.cn, lishengtai@vip.qq.com

QCD phase structure in the nonzero magnetic fields has attracted intensive interest recently as the strong magnetic field is expected to be present in the early stage of peripheral heavy-ion collisions, early universe and magnetars. In this talk we show that fluctuations of and correlations among net baryon number, strangeness and electrical charge can be useful to probe the imprint of the magnetic field in heavy-ion collisions.\

We will show the first continuum estimated lattice QCD results of the second-order fluctuations of and correlations among net baryon number, electric charge and strangeness in the presence of a background magnetic field. Lattice simulations of (2+1)-flavor QCD are performed on $32^3 \times 8$ and $48^3 \times 12$ lattices using the highly improved staggered fermions with a physical pion mass. We focus on a smaller temperature interval around the pseudo-critical temperature ranging from $0.9 T_{pc}$ to $1.1 T_{pc}$. To mimic the magnetic field strength produced in the early stage of heavy-ion collision experiments we now have 6 different values of the magnetic field strength up to $\sim 10 m_\pi^2$ with $m_\pi = 135$ MeV.\

We discuss the temperature and eB dependences of the second-order fluctuations of and correlations among net baryon number, electric charge and strangeness. We find that these second-order fluctuations and correlations are substantially affected by eB . We also perform a hadron resonance gas model study to show the connection between experimentally measured proxies and the total fluctuations of conserved charges.

We propose to investigate these quantities in experiments in different centrality classes and collision systems where eB could be different.

[1] H.T.Ding, S.T.Li, Q.Shi and X.D.Wang. Fluctuations and correlations of net baryon number, electric charge and strangeness in a background magnetic field

Eur. Phys. J. A \textbf{57} (2021) no.6, 202

[2]Heng-Tong Ding, Sheng-Tai Li, Jun-Hong Liu, Xiao-Dan Wang. Fluctuations of conserved charges in strong magnetic fields from lattice QCD [arXiv:2208.07285]

Fluctuations - 4 / 35

Baryon number fluctuations at large baryon chemical potentials

Author: Shi Yin^{None}

Co-authors: Fabian Rennecke ; Jan M. Pawłowski ; Rui Wen ¹; Wei-jie Fu ¹; Xiaofeng Luo

¹ Dalian University of Technology

Corresponding Authors: wjfu@dlut.edu.cn, yinshi2014@mail.dlut.edu.cn, xfluo@mail.ccnu.edu.cn, fabian.rennicke@theo.physik.uni-giessen.de, j.pawlowski@thphys.uni-heidelberg.de, wvrr09@mail.dlut.edu.cn

Calculations of baryon number fluctuations at finite temperature and density in Ref.[1] have been extended to regime of large baryon chemical potentials with $400 \text{ MeV} \leq \mu_B \leq 650 \text{ MeV}$. A peak structure is found for the dependence of the kurtosis of baryon number distributions, i.e., $R_{42}^B = \chi_4^B / \chi_2^B$, on the collision energy in a range of $3 \text{ GeV} \leq \sqrt{s_{\text{NN}}} \leq 7.7 \text{ GeV}$ [2]. The computation is done within the functional renormalization group approach with a critical end point located at around $(T, \mu_B)_{\text{CEP}} \sim (100, 640) \text{ MeV}$ in the phase diagram, which is in agreement with recent estimates from first-principle QCD calculations. Errors of calculated results arising from, e.g., the chemical freeze-out curves, locations of CEP, effects of baryon number conservation at low collision energy etc., have been evaluated in detail.

Reference:

[1] Wei-jie Fu, Xiaofeng Luo, Jan M. Pawłowski, Fabian Rennecke, Rui Wen, Shi Yin, Phys. Rev. D 104, 094047, 2021, arXiv: 2101.06035 [hep-ph].

[2] Wei-jie Fu, Xiaofeng Luo, Jan M. Pawłowski, Fabian Rennecke, Rui Wen, Shi Yin, in preparation.

Neutron Stars and very high μ_B - 2 / 36

What can heavy neutron stars tell us about the dense matter speed of sound?

Authors: Débora Mroczek¹; Jacquelyn Noronha-Hostler²; Michael Miller³; Nicolas Yunes^{None}

¹ *University of Illinois at Urbana-Champaign*

² *University of Illinois Urbana Champaign*

³ *University of Maryland*

Corresponding Authors: deboramroczek@gmail.com, jnorhos@illinois.edu, nyunes@illinois.edu, mcmiller@umd.edu

Functional forms of the neutron star Equation of State (EoS) are required to extract the viable EoS band from neutron star mergers. Typically, one of three methods are used— spectral functions, piecewise polytropes, or gaussian process. However, realistic nuclear EoS, containing deconfined quarks or hyperons, present nontrivial features in the speed of sound such as bumps, kinks and plateaus. These features in the speed of sound are not captured well by the currently used methods for the functional forms [1]. We modify gaussian processes by introducing spikes and plateaus in the speed of sound and check how those features impact the posterior distribution obtained using constraints from NICER and gravitational-wave observations. We find these new features play a role in understanding ultra-heavy neutron stars that support stellar masses compatible with the $2.5 M_{\odot}$ object detected in GW190814.

[1] Tan et al, Phys.Rev.Lett. 125 (2020) 26, 261104

Critical Point - 4 / 37

Correlation of fluctuation with parametric slow mode: a signature of the QCD critical point?

Co-authors: Golam Sarwar¹; Jan-e Alam²

¹ *Physical Research Laboratory, India*

² *Variable Energy Cyclotron Centre, India*

Corresponding Authors: jane@vecc.gov.in, jaman.mdh@gmail.com, golamsarwar1990@gmail.com

The structure factor ($\mathcal{S}_{nn}(k, \omega)$) of dynamical density fluctuation is studied in the presence of the out-of-equilibrium modes (ϕ) within the scope of relativistic viscous hydrodynamics. The $\mathcal{S}_{nn}(k, \omega)$ without the ϕ modes shows three peaks of Lorentzian types, identified as one Rayleigh peak and two Brillouin peaks, symmetrically situated about the Rayleigh peak with even magnitudes. In the presence of the critical point, Brillouin peaks merge with the Rayleigh peak, enhancing the magnitude of the Rayleigh peak. Whereas, the structure factor with the slow mode variable shows four peaks, which are identified as one Rayleigh peak, two Brillouin peaks, and one peak due to the coupling of hydrodynamic modes with the slow mode. The extra peak due to coupling only arises in the second-order theory of hydrodynamics. Contrary to the $\mathcal{S}_{nn}(k, \omega)$ without ϕ mode, the Brillouin peaks are situated asymmetrically about the Rayleigh peak with uneven magnitudes. In the presence of the critical point, the Brillouin peaks get merged with the Rayleigh peak, and the $\mathcal{S}_{nn}(k, \omega)$ shows only the Rayleigh peak and the peak due to coupling of the hydrodynamic modes and the slow mode.

Critical Point 3 / 40

Equilibrium and dynamic lensing effects near a critical point in the QCD phase diagram

Authors: Claudia Ratti^{None}; Débora Mroczek¹; Isaac Long¹; Jacquelyn Noronha-Hostler²; Jamie Karthein³; Paolo Parotto^{None}; Travis Dore¹; Yukari Yamauchi^{None}

¹ *University of Illinois at Urbana-Champaign*

² *University of Illinois Urbana Champaign*

³ *MIT*

Corresponding Authors: jamie@karthein.com, yyukari@terpmail.umd.edu, cratti@central.uh.edu, deboramroczek@gmail.com, jnorhos@illinois.edu, tdore738@gmail.com, paolo.parotto@gmail.com, isaaclong102000@gmail.com

In this work, we study the effects that different critical regions have on hydrodynamic trajectories both with and without viscous effects. Implementing the parametrized BEST collaboration equation of state [1,2], we find that the size and shape of the critical region is an important factor in determining whether the system will experience critical effects for a variety of initial conditions. We argue that isentropic trajectories where s/n_B is constant (i.e. ideal hydrodynamic evolution) are a poor guide for studying more realistic, viscous hydrodynamic trajectories evidenced by large changes in thermal entropy within the system. Although initial viscous effects may push or pull trajectories towards or away from the critical point, the dynamic lensing effect may be able to focus many of these trajectories towards the critical region [3,4]. These effects also introduce a non-trivial distribution of κ_4 at freeze-out.

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Critical Point - 5 / 41

Characteristic momentum of Hydro+ and a bound on the sound speed enhancement near the QCD critical point

Author: Matthias Kaminski¹¹ *The University of Alabama*

Corresponding Authors: abbasi@lzu.edu.cn, mski@ua.edu

Near the critical point in the QCD phase diagram, hydrodynamics breaks down at a momentum where the frequency of the fastest hydrodynamic mode becomes comparable with the decay rate of the slowest non-hydrodynamic mode. Hydro+ was developed as a framework which extends the range of validity of hydrodynamics beyond that momentum. In this talk, we first discuss the analytic structure of the spectrum of linear perturbations in single-mode Hydro+; this contains a single slow mode in addition to the hydro modes. We then show that the slow mode falls out of equilibrium if the momentum of flow is greater than a characteristic momentum value. That characteristic momentum turns out to be set by the branch points of the dispersion relations. Applying these results to the Hydro+ near the critical point, we find a temperature-dependent upper bound for the sound speed enhancement near the critical point in the QCD phase diagram.

Fluctuations - 2 / 42

Baryon annihilation and multiplicity dependence of p/pi and light nuclei ratios

Author: Volodymyr Vovchenko¹

Co-author: Volker Koch

¹ *Institute for Nuclear Theory, University of Washington*

Corresponding Authors: vkoch@lbl.gov, vlvovch@uw.edu

The centrality dependence of the p/π ratio measured by the ALICE Collaboration in 5.02 TeV Pb-Pb collisions indicates a statistically significant suppression with the increase of the charged multiplicity, once the centrality-correlated part of the systematic uncertainty is eliminated from the data. We argue that this behavior can be attributed to the presence of baryon annihilation in the hadronic phase. By implementing the $B\bar{B} \leftrightarrow 5\pi$ reactions in the hadronic phase within a generalized partial chemical equilibrium framework, we estimate the annihilation freeze-out temperature T_{ann} at different centralities. T_{ann} is found to decrease with charged multiplicity to the value of $T_{\text{ann}} = 135 \pm 5$ MeV in 0-5% most central collisions, considerably below the hadronization temperature of $T_{\text{had}} \sim 160$ MeV but above the thermal (kinetic) freeze-out temperature of $T_{\text{kin}} \sim 100$ MeV. One experimentally testable consequence of this picture is the suppression of various light nuclei to proton ratios in central collisions of heavy ions.

Neutron Stars and very high μ_B - 1 / 43

Beam Energy Dependence of Triton Production and Yield Ratio ($N_t \times N_p / N_d^2$) in Au+Au Collisions at RHIC

Corresponding Author: zhangdingwei@mails.cnu.edu.cn

In high-energy nuclear collisions, the light nuclei production is predicted to be sensitive to the local baryon density fluctuations and can be used to probe the QCD phase transition. For example, the

ratio of proton (N_p) and triton (N_t) to deuteron (N_d) yields, which is defined as $N_t \times N_p / N_d^2$, is considered sensitive observable to search for the QCD critical point.

In this talk, we will report the first measurement of triton production in Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 54.4, 62.4,$ and 200 GeV carried out by the STAR experiment at RHIC [1]. We will present collision energy dependence of the particle yield ratios (N_d/N_p and N_t/N_p), and the nuclear compound yield ratio $N_t \times N_p / N_d^2$ as a function of charged-particle multiplicity ($dN_{ch}/d\eta$), collision energy, centrality, and its transverse momentum acceptance dependence. The results are compared with model calculations and their physics implications will be discussed.

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Hydro Evolution - 1 / 44

Probing the hadronic phase via the measurement of resonances in Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV from STAR BES-II

Author: Aswini Kumar Sahoo¹

¹ IISER, Berhampur

Corresponding Author: aswinis19@iiserbpr.ac.in

Resonances of different lifetimes can be used to probe the hadronic stage of the fireball produced in relativistic heavy-ion collisions. For example, the K^{*0} meson, with a lifetime of ~ 4.16 fm/c, decays within the fireball and its decay daughters may experience in-medium effects like re-scattering and regeneration. On the other hand, the ϕ meson, having a long lifetime of ~ 46 fm/c, is expected to decay outside the fireball and its daughter particles may remain immune to these medium effects. Hence simultaneous measurement of these resonances will help us to investigate the interplay of re-scattering and regeneration effects.

Recently, the STAR experiment at RHIC has accumulated a high-statistics data sample of Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV with enhanced detector capabilities and a wider pseudorapidity coverage during the BES-II program. In this talk, we will present measurements of K^{*0} transverse momentum (p_T) spectrum, rapidity distribution, integrated yield and average p_T , using this data sample. The $\langle p_T \rangle$ of K^{*0} will be compared with those of other hadrons. The resonance to non-resonance ratios (K^{*0}/K , ϕ/K) will be shown as a function of centrality to study the rescattering/regeneration effects. An estimate of the lower limit of the hadronic phase lifetime will be shown as a function of centrality, and compared to previous RHIC and LHC results.

Hydro Evolution - 1 / 48

Probing initial baryon stopping and equation of state with rapidity-dependent directed flow of identified particles

Authors: Lipei Du¹; Chun Shen²; Sangyong Jeon^{None}; Charles Gale^{None}

¹ McGill University

² Wayne State University

Corresponding Authors: gale@physics.mcgill.ca, jeon@physics.mcgill.ca, lipei.du@mail.mcgill.ca, chunshen@wayne.edu

Using a (3+1)D hybrid hydrodynamic + hadronic transport framework with parametric initial conditions, we study the rapidity-dependent directed flow $v_1(y)$ of identified particles, including pions, kaons, protons, and lambdas, from 7.7 GeV to 200 GeV. The dynamics in the beam direction is first constrained using the measured pseudo-rapidity distribution of charged particles and the net proton

rapidity distribution. Within this framework, the directed flow of mesons is driven by the sideward pressure gradient from the tilted source, and that of baryons mainly by the asymmetric baryon distribution with respect to the beam axis on top of the transverse expansion. Our framework successfully explains the rapidity and beam energy dependences of v_1 for both mesons and baryons. We find that the $v_1(y)$ of baryons has strong constraining power on the initial baryon stopping, and together with that of mesons, the directed flow probes the equation of state for the dense nuclear matter at finite chemical potentials. We also provide predictions for the upcoming STAR Beam Energy Scan II measurements of the pseudo-rapidity dependent v_1 for charged particles at 27 GeV.

Hydro Evolution - 3 / 49

Next-Generation Multi-Fluid Hydrodynamics for RHIC BES

Authors: Boris Tomasik¹; Iurii Karpenko²; Jakub Cimerman³

¹ *Univerzita Mateja Bela (SK)*

² *FNSPE CTU in Prague*

³ *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University*

Corresponding Authors: jakub.cimerman@gmail.com, boris.tomasik@cern.ch, yu.karpenko@gmail.com

The hydrodynamic modelling of heavy-ion collisions at energies from few to tens of GeV per NN pair brings new challenges as compared to simulations at top RHIC or LHC energies. The contraction of the incoming nuclei is much weaker resulting in a long inter-penetration phase and a more complex initial-state geometry. Conventional hydrodynamic models, where the fluid phase starts at a fixed proper time τ_0 , therefore miss the compression stage of collision and may be therefore less sensitive to the EoS of the medium. Multi-fluid dynamics treats the incoming nuclei as two baryon-rich droplets of cold nuclear fluid creating a third baryon-free fluid from the friction between the two colliding fluids.

We present a multi-fluid dynamic approach 3FH to simulate heavy-ion collisions at RHIC BES, newly reimplemented with the use of 3+1 dimensional relativistic viscous hydrodynamic code vHLL. We discuss the challenges in constructing the approach and present benchmark calculations for Au-Au collisions at different RHIC BES energies.

Critical Point - 2 / 51

Exploring the criticality of QCD matter with effective field theory for fluctuating hydrodynamics

Author: Yi Yin¹

¹ *Institute of modern physics, Chinese Academy of Sciences*

Corresponding Authors: nori.sogabe@gmail.com, yiyin@impcas.ac.cn

Recently, a non-equilibrium effective field theory framework has been formulated for fluctuating hydrodynamics [1]. In this talk, we present an example of applying this novel formalism to study the critical properties of QCD. In the view that non-Gaussian fluctuations of baryon density are important for the QCD critical point search, we derive evolution equations for the critical non-Gaussian fluctuations of a conserved density and obtain closed-form solutions based on field theory techniques [2]. Those results can be readily implemented for simulations in realistic situations of heavy-ion collisions. In addition, we find that nonlinear interactions among noise fields, which are missing in traditional stochastic hydrodynamics, could potentially contribute to the quartic (fourth-order) fluctuations in the scaling regime in off-equilibrium situations.

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 [2] Noriyuki Sogabe and Yi Yin, “Off-equilibrium non-Gaussian fluctuations near the QCD critical point: an effective field theory perspective,” JHEP **2022**, 124 (2022).

Critical Point 3 / 56

Lattice study of the critical point in heavy-quark QCD

Authors: Masakiyo Kitazawa^{None}; Ashikawa Ryo¹; Shinji Ejiri²; Kazuyuki Kanaya³; Hiroshi Suzuki^{None}; Naoki Wakabayashi²

¹ *Osaka University*

² *Niigata University*

³ *University of Tsukuba*

Corresponding Authors: hsuzuki@phys.kyushu-u.ac.jp, kitazawa@phys.sci.osaka-u.ac.jp, ashikawa@kern.phys.sci.osaka-u.ac.jp, kanaya@ccs.tsukuba.ac.jp, ejiri@muse.sc.niigata-u.ac.jp

We study phase structure and critical point of QCD with heavy quarks at nonzero temperature by lattice QCD Monte Carlo simulations. We perform numerical simulations with large spatial volumes up to the aspect ratio $N_s/N_t = 15$. The large spatial volume allows us to investigate the scaling behavior around the critical point in detail. To realize the large-volume simulations, we employ rather coarse lattices with $N_t = 4, 6$ and adopt the hopping parameter expansion up to the next-to-leading order for the quark determinant. Through the Binder cumulant analysis, we show that the finite-size scaling of the Z(2) universality class around the critical point is confirmed with high precision. We also find that the correct scaling behavior is observed only on large lattices, and larger volumes are needed as the lattice spacing becomes finer.

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Fluctuations - 4 / 58

Dynamical evolution of particle number fluctuations in hadronic transport

Author: Agnieszka Sorensen¹

¹ *University of Washington*

Corresponding Author: amsorens@uw.edu

We study particle number fluctuations in infinite nuclear matter using hadronic transport simulations. We focus on matter initialized at a series of thermodynamically and mechanically stable points in the phase diagram, and in particular on the influence of the critical point on the equilibrated values of the fluctuations. We compare fluctuations from hadronic transport simulations against the values calculated using the underlying density functional equation of state, and we show that the fluctuations obtained from simulations agree with the underlying theory qualitatively everywhere in the phase diagram, while the degree of the quantitative agreement depends on the distance from the critical point.

Hydro Evolution - 1 / 59**Measurements of light hypernuclei production and properties in Au+Au collisions from STAR experiment****Authors:** Xiujun Li¹; Yuanjing Ji²; Yue-Hang Leung³¹ *USTC*² *Lawrence Berkeley National Lab*³ *Lawrence Berkeley National Laboratory***Corresponding Authors:** yhleung@lbl.gov, yuanjingji@lbl.gov, lixiujun@mail.ustc.edu.cn

Hypernuclei are bound states of nucleons and hyperons. The hyperon–nucleon (Y-N) interaction, which is an essential ingredient in the equation of state of high-baryon-density matter, remains poorly constrained. Also, the production mechanisms of hypernuclei are currently not well understood. Precise measurements of hypernuclei properties and production yields can shed light on their production mechanisms and the strength of the Y-N interaction.

In heavy-ion collisions, light hypernuclei are expected to be abundantly produced at low collision energies due to the high baryon density. Thanks to the high statistics data collected by the STAR BES II program which extends the collision energy down to $\sqrt{s_{NN}} = 3$ GeV, a series of measurements on light hypernuclei have been carried out. In particular, the hypernuclei to light nuclei yield ratios, S_3 and S_4 , have been measured to study the medium properties at freeze-out.

In this presentation, we will report production yields of light hypernuclei (${}^3_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{H}$) in Au+Au collisions at $\sqrt{s_{NN}} = 3, 19.6,$ and 27 GeV. Hypernuclei to light nuclei yield ratios, S_3 and S_4 , will also be presented. We will also report precise measurements of ${}^3_{\Lambda}\text{H}$ branching ratio and lifetimes of light hypernuclei (${}^3_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{H}$, and ${}^4_{\Lambda}\text{He}$). The results will be compared with model calculations and physics implications will be discussed.

Hydro Evolution - 1 / 62**Isentropic equation of state and speed of sound of (2+1)-flavor QCD from Taylor expansions and Pade resummation****Author:** Jishnu Goswami¹¹ *RIKEN Center for Computational Science***Corresponding Author:** jishnu@physik.uni-bielefeld.de

The quantum chromodynamics (QCD) equation of state (EoS) at finite temperature and density is of fundamental importance for the characterization of hot and dense, strongly interacting matter created in heavy ion collision experiments. It also has important applications in hydrodynamic simulations and the EoS of the early universe.

Strongly interacting dense matter created in experiments expands along trajectories of fixed s/n_B . Based on high statistics data generated by the HotQCD Collaboration we will determine these trajectories in the (T, μ_B) -plane using a Taylor series of the pressure of (2+1)-flavor QCD for several values of s/n_B and for thermal conditions met in heavy ion collisions. We compare these trajectories for fixed s/n_B with high temperature perturbation theory and the hadron resonance gas model(QMHRG2020) at low temperatures. On these trajectories we determine bulk thermodynamic observables, e.g.net baryon number, energy, and entropy densities. Earlier, we had shown that the pressure series is reliable up to $\mu_B/T \leq 2.5$ and Taylor expansion results are consistent with Pade

resummed series approximants. We show that this also is the case for energy and entropy density expansions and their corresponding Pade approximants. We find that the latter seems to be more efficient in smoothening wiggles that arise from the strong T -dependence of higher order expansion coefficients. We therefore use the Pade approximants to calculate also observables involving higher order T -derivatives such as the specific heat, speed of sound and the adiabatic compressibility of strongly interacting matter.

Neutron Stars and very high μ_B - 1 / 63

Spinodal Enhancement of Light Nuclei Yield Ratio in Relativistic Heavy Ion Collisions

Author: 开佳孙^{None}

Co-author: Che-Ming Ko

Corresponding Authors: sunkaijiaxn@gmail.com, ko@comp.tamu.edu

Using a relativistic transport model to describe the evolution of the quantum chromodynamic matter produced in Au+Au collisions at $\sqrt{s_{NN}} = 3 - 200$ GeV, we study the effect of a first-order phase transition in the equation of state of this matter on the yield ratio $N_t N_p / N_d^2$ (tp/d^2) of produced proton (p), deuteron (d), and triton (t). We find that the large density inhomogeneities generated by the spinodal instability during the first-order phase transition can survive the fast expansion of the subsequent hadronic matter and lead to an enhanced tp/d^2 in central collisions at $\sqrt{s_{NN}} = 3 - 5$ GeV as seen in the experiments by the STAR Collaboration and the E864 Collaboration. However, this enhancement subsides with increasing collision centrality, and the resulting almost flat centrality dependence of tp/d^2 at $\sqrt{s_{NN}} = 3$ GeV can also be used as a signal for the first-order phase transition.

Critical Point - 1 / 66

Equilibrium expectations for non-Gaussian fluctuations near a QCD critical point

Authors: Bruno Sebastian Scheiing Hitschfeld¹; Claudia Ratti^{None}; Debora Mroczek²; Isaac Long²; Jacquelyn Noronha-Hostler³; Jamie Karthein⁴; Krishna Rajagopal⁵; Maneesha Sushama Pradeep^{None}; Misha Stephanov⁶; Paolo Parotto⁷; Travis Dore²; Yi Yin⁸; Yukari Yamauchi^{None}

¹ *Massachusetts Institute of Technology*

² *University of Illinois at Urbana-Champaign*

³ *University of Illinois Urbana Champaign*

⁴ *MIT*

⁵ *Massachusetts Inst. of Technology (US)*

⁶ *UIC*

⁷ *University of Wuppertal*

⁸ *Institute of modern physics, Chinese Academy of Sciences*

Corresponding Authors: misha@uic.edu, jmkar@mit.edu, yyukari@terpmail.umd.edu, parotto@uni-wuppertal.de, deboram2@illinois.edu, jnorhos@illinois.edu, mprade2@uic.edu, cratti@uh.edu, yiyin@impcas.ac.cn, tdore738@gmail.com, krishna@mit.edu, isaaclong102000@gmail.com, bscheihi@mit.edu

With the highly anticipated results from the Beam Energy Scan II program at RHIC coming soon, an understanding of particle-number fluctuations and their significance as a potential signature of

a possible QCD critical point is crucial. Early works that embarked on this endeavor sought to estimate the fluctuations due to the presence of a critical point assuming they stay in equilibrium [1,2]. From these results came the proposal to focus efforts on higher, non-Gaussian, moments of the event-by-event distributions, in particular of the number of protons. These non-Gaussian moments are especially sensitive to critical fluctuations, as their magnitudes are proportional to high powers of the critical correlation length. As the equation of state provides crucial input for hydrodynamical simulations of heavy-ion collisions, we estimate equilibrium fluctuations from the BEST equation of state (EoS) that includes critical features from the 3D Ising Model [3,4,5]. In particular, the net-baryon kurtosis and its dependence on non-universal mapping parameters is investigated within the BEST EoS [6]. Furthermore, the correlation length, as a central quantity for the assessment of fluctuations in the vicinity of a critical point, is also calculated in a consistent manner with the scaling equation of state. We propose a new parameterization of the critical correlation length in terms of the same parametric variables (R, θ) used for BEST EoS, consistent with the ϵ -expansion. Additionally, we study how these parametrizations of the correlation length could be used to calculate critical cumulants, updating the early work of [1]. These will be useful for further comparison to estimates of out-of-equilibrium fluctuations in order to determine the magnitude of the observable fluctuations to be expected in heavy-ion collision experiments, in which the time spent near a critical point is short.

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5. D. Mroczek, A.R. Nava Acuna, J. Noronha-Hostler, P. Parotto, C. Ratti et al., "Quartic cumulant of baryon number in the presence of a QCD critical point," *Phys. Rev. C* 103 (2021) 3, 034901.
6. T. Dore, J.M. Karthein, I. Long, D. Mroczek, J. Noronha-Hostler et al., "Critical lensing and kurtosis near a critical point in the QCD phase diagram in and out-of-equilibrium," *arXiv:2207.04086*.

Critical Point - 5 / 68

Towards locating the (real) critical end point

Author: Friederike Ihssen¹

¹ *ITP Heidelberg*

Corresponding Author: friederike.ihssen@googlemail.com

Lattice simulations and functional approaches established that QCD has no phase transition at small baryon chemical potential. However, second order phase transitions are expected at the conjectured critical endpoint at larger chemical potential and in the chiral limit at vanishing chemical potential.

These phase transitions leave an imprint as Lee-Yang edge singularities and can be found at high temperatures $T > T_c$ for complex magnetisation and complex chemical potential. For an increasing real part of the chemical potential, the edge singularity moves towards the real μ_B -axis, potentially allowing for an extrapolation to the critical endpoint.

As a precursor for a quantitative study in QCD we discuss the impact of fluctuations in a simple low energy effective theory, the non-linear

sigma model. We show that in this model the location of the phase transition can accurately be determined by tracking the Lee-Yang singularities in the complex plane. We close by discussing the remaining task of extending this computation to full QCD.

Neutron Stars and very high μ_B - 2 / 70

Effect of color superconductivity on the mass of neutron stars

Authors: Udit Shukla¹; David Blaschke²

Co-author: Siemon Liebing

¹ *Max Planck Institute for the Physics of Complex Systems/University of Wrocław*

² *University of Wrocław*

Corresponding Author: udita.shukla@uwr.edu.pl

Diquark gap calculated within the framework of a micro-physical (non-local Nambu-Jona Lasinio) model coupled to color and electric neutrality constraints and fit to a μ -dependent ansatz, is employed to an algebraic quark EoS (equation of state) [1]. The effect of this μ -dependent diquark gap is investigated against that of a constant (diquark) gap in the same (algebraic) EoS.

Additional parameters of the EoS, namely, gluon-mediated QCD interactions amongst quarks (in the Fermi sea) and the bag constant are constrained further within the framework of the above ansatz.

Within the framework of hybrid equations of state with transitions to stiff or soft equations of state, the averaged μ in context of neutron star properties is found to produce comparable results if all other parameters are fixed.

The averaged μ in context neutron star properties is found to show comparable results if all other parameters are fixed.

Fluctuations - 2 / 71

System size dependence of strangeness production from NA61/SHINE

Author: Piotr Podlaski¹

¹ *University of Warsaw (PL)*

Corresponding Author: piotr.podlaski@cern.ch

NA61/SHINE is a multipurpose fixed-target experiment at the CERN Super Proton Synchrotron. The main goals of the NA61/SHINE strong interactions program are to discover the critical point of strongly interacting matter and study the properties of the onset of deconfinement. To reach these goals, hadron production measurements are performed in the form of a two-dimensional scan by varying collision energy and system size. The Collaboration has recently finished data acquisition for its original program on strong interactions, accumulating broad data samples on hadron production in various systems in the SPS energy range.

In this contribution, the NA61/SHINE results on identified charged kaon and pion production in p+p, Be+Be and Ar+Sc collisions at the SPS energy range ($\sqrt{s_{NN}}=5.1-17.3$ GeV) are presented. The NA61/SHINE measurements of small and intermediate-mass ion collisions establish an interesting system size dependence, showing a rapid change of hadron production properties that starts when

moving from Be+Be to Ar+Sc system. Obtained energy and system size dependence of the measured charged hadron multiplicities are compared with available world data and various theoretical models.

Critical Point - 1 / 74

Dynamics and freeze-out of non-Gaussian fluctuations of hydrodynamic densities

Authors: Jamie Karthein¹; Maneesha Sushama Pradeep²; Krishna Rajagopal³; Misha Stephanov⁴; Bruno Sebastian Scheihing Hitschfeld⁵; Yi Yin⁶

¹ MIT

² University of Illinois at Chicago

³ Massachusetts Inst. of Technology (US)

⁴ UIC

⁵ Massachusetts Institute of Technology

⁶ Institute of modern physics, Chinese Academy of Sciences

Corresponding Authors: jmkar@mit.edu, misha@uic.edu, yiyin@impcas.ac.cn, krishna@mit.edu, bscheihi@mit.edu, mprade2@uic.edu

The traditional Cooper-Frye freeze-out procedure becomes inadequate in heavy ion collisions that pass near a critical point, where fluctuations in the hydrodynamic densities (not just the mean densities) must be passed faithfully from the fluctuating fluid before freeze-out to the fluctuating particles after. Furthermore, the dynamics of the fluctuations must be computed, since because of critical slowing down they will not be able to stay in equilibrium. In recent work [1], some of us introduced an extension to the Cooper-Frye prescription in order to convert not only the averages of the hydrodynamic densities, but also their two-point fluctuations into means and variances, respectively of the particle multiplicities. In this talk, we generalize this prescription for Gaussian cumulants to the more sensitive probes of the critical point, such as the skewness and the kurtosis of particle multiplicities. In an azimuthally symmetric and longitudinally boost invariant scenario [2], we study the evolution of the two, three and four-point fluctuations of the most singular hydrodynamic mode, corresponding to the entropy per baryon as the quark-gluon plasma traverses the phase diagram. We further perform the freeze-out for this numerical simulation of Hydro+ and investigate the dynamical effects of charge conservation and critical slowing down on the cumulants of proton multiplicity. We probe how the strength of critical slowing down, characterized by the proximity of the evolution trajectory to the critical point, and the diffusion rate of the hydrodynamic mode affects the magnitude of the rapidity correlations of proton multiplicity at freeze-out. We conclude by discussing the suppression of the non-Gaussian cumulants of proton multiplicity relative to the equilibrium expectations.

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[2]. Ongoing work

Critical Point - 2 / 78

Fate of critical fluctuations in an interacting hadronic medium

Authors: Hannah Elfner^{None}; Jan Hammelmann^{None}; Marcus Bluhm^{None}; Marlene Nahrgang¹

¹ *Subatech***Corresponding Authors:** marlene.nahrgang@subatech.in2p3.fr, elfner@fias.uni-frankfurt.de, hammelmann@fias.uni-frankfurt.de, bluhm@subatech.in2p3.fr

We study the evolution of critical fluctuations in an expanding system within a hadronic transport approach.

The system is initialized with particle number distributions coupled to the critical mode and the hadron gas then evolves in time with realistic hadronic interactions \cite{Hammelmann:2022yso}.

The initialization of the system with critical fluctuations is achieved by coupling the ideal hadron resonance gas cumulants to the ones from the 3d Ising model \cite{Bluhm:2016byc} and generating the net and total particle numbers from the maximum entropy probability distribution.

We systematically investigate the evolution of the critical fluctuations initialized at various temperatures and chemical potentials along a freeze-out line and the dependency of the final state cumulants as a function of \sqrt{s} is presented. Additionally, the sets of particles which are coupled to the critical mode are modified such that the strength of the propagation of correlations through interactions can be assessed.

We find that in the scaling region of the critical point correlations are propagated through the whole collisional history and are still present after the kinetic freeze-out of the matter.

Critical Point - 1 / 80

Searching for the QCD critical point using Lee-Yang edge singularities

Author: David Clarke^{None}**Co-authors:** Christian Schmidt ¹; Francesco Di Renzo ²; Jishnu Goswami ³; Kevin Zambello ⁴; Petros Dimopoulos ⁵¹ *University of Bielefeld*² *INFN - National Institute for Nuclear Physics*³ *Bielefeld University*⁴ *University of Parma and INFN, Gruppo Collegato di Parma*⁵ *University of Parma***Corresponding Authors:** francesco.direnzo@pr.infn.it, jishnu@physik.uni-bielefeld.de, schmidt@physik.uni-bielefeld.de, clarke.davida@gmail.com, kevin.zambello@studenti.unipr.it, petros.dimopoulos@unipr.it

We present lattice QCD calculations of the position of Lee-Yang edge singularities in the complex chemical potential plane. The singularities have been obtained by the multi-point Pade approach on lattice QCD data of the net baryon number density at imaginary chemical potential. This approach has been used recently to extract the correct scaling of singularities near the Roberge-Weiss transition; we extend this study to the universal scaling of singularities in the vicinity of the QCD critical endpoint. Making use of an appropriate scaling ansatz, we can extrapolate the singularities towards the real axis to determine the position of the QCD critical point. We find an apparent approach toward the real axis with decreasing temperature. Current preliminary results suggest a temperature of approximately 80 MeV for the QCD critical endpoint.

Critical Point - 4 / 82

Impact of mass renormalization on order parameter fluctuations near a phase transition

Authors: Marcus Bluhm^{None}; Marlene Nahrgang^{None}; Masakiyo Kitazawa^{None}; Nadine Attieh¹; Nathan Touroux^{None}

¹ *Subatech***Corresponding Author:** attieh@subatech.in2p3.fr

Heavy ion collisions that aim to probe phase transitions and critical phenomena require robust predictions. In order to scan the QCD phase diagram and gain insight into the exact nature of these transitions and the conjectured critical point, numerical simulations are increasingly used.

Mapping a system onto a finite lattice, with discrete spatial steps, effectively cuts off the theory in the IR (through lattice size) and in the UV (through lattice spacing). The cutoff used to cure UV divergences, inversely proportional to the resolution, creates a lattice spacing dependence, most problematic when considering the behavior at continuum. We are mostly concerned with this sensitivity.

We consider a simplified Ginzburg-Landau effective potential, describing a phase transition. The time evolution of the order parameter from some small out-of-equilibrium condition to its value at the minimum of the potential, is governed by a Ginzburg-Landau-Langevin type equation. The dissipation term and the white additive noise in this relaxation equation, with no conserved charge, lead to the non-physical lattice spacing dependence.

We aim to cure, or at least alleviate, this lattice spacing sensitivity by adding an established counterterm, from a mass renormalization procedure, to our potential. We start by checking the validity of our approach by testing a simple unphysical quantity in the Gaussian limit.

We then choose 2 physical observables: the expectation value and the integrated variance of the order parameter.

In the Gauss approximation, no lattice spacing sensitivity is observed, as expected. Then performing the simulations after including the nonlinear terms, we confirm that the lattice spacing dependence of the mean is eliminated by the counterterm for all tested lattice spacing values, as previously discussed by various authors.

However, for the integrated variance some lattice spacing dependence seems to persist. Preliminary results indicate that satisfactory results are only achieved for certain ranges of lattice spacing.

In the course of our study, we also discuss the possible influence and implications of the system volume and the chosen geometry on the results.

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Dynamics of the conserved charge fluctuations in an expanding medium

Author: Grégoire PIHAN^{None}**Co-authors:** Marcus Bluhm¹; Marlene Nahrgang²; Masakiyo Kitazawa¹ *Subatech. Nantes*² *Subatech***Corresponding Authors:** marlene.nahrgang@subatech.in2p3.fr, kitazawa@phys.sci.osaka-u.ac.jp, gregoire.pihan@subatech.in2p3.fr, marcus.bluhm@subatech.in2p3.fr

A non-monotonic net-proton kurtosis as a function of the collision energy for very central collisions has been suggested and may be confirmed by recent BES-II program results advocating the existence of the QCD critical point. Fluctuations at the origin of this peculiar behavior are produced in the highly dynamic environment of ultra-relativistic collisions. Especially, the violent longitudinal expansion and the associated temperature cooling may have a non-trivial impact on how we interpret the experimental data. The in- or out-of equilibrium nature of the fluctuations during this expansion is a crucial question in discriminating between critical contributions and purely dynamical features.

Here, we inspect the diffusive dynamics of the conserved charges net density fluctuations in a Bjorken-type 1+1D expanding system. Between the initial time of the collision and the chemical freeze-out, the equilibrium thermodynamics is described by a potential derived from a

Ginzburg-Landau free-energy functional parametrized by its second and fourth-order susceptibilities. In the scaling region, the susceptibilities are mapped from the 3D Ising model and at $\mu_B = 0$ MeV, from lattice QCD calculations. Between the chemical freeze-out and the kinetic freeze-out, the thermodynamics is determined by the hadron resonance gas of the 19 lightest species at first order in the chemical potentials. The non-trivial interplay between the diffusive properties of the constituents and the longitudinal expansion of the medium allows us to study the critical fluctuations in the dynamically expanding medium as well as their survival in the hadronic phase until kinetic freeze-out.

We demonstrate the enhancement of the critical fluctuations for trajectories passing near the critical point. The signal is shown to be largely dependent on the diffusive properties of the medium and the chemical freeze-out temperature. After chemical freeze-out, we observe that the diffusion in the hadronic medium has a huge impact on the amplitude of the critical fluctuations. We conclude that the signal survives longer in sectors related to the electric charge.

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Evolving non-Gaussian fluctuations in dynamical relativistic fluid

Authors: Xin An¹; Gokce Basar²; Misha Stephanov³; Ho-Ung Yee⁴

¹ NCBJ

² University of North Carolina, Chapel Hill

³ UIC

⁴ University of Illinois at Chicago

Corresponding Authors: misha@uic.edu, hyee@uic.edu, anxin627@gmail.com, gbasar@unc.edu

First-principle quantitative description of fluctuation dynamics is essential for interpreting the upcoming results of the phase II of the Beam Energy Scan experiment aimed at discovering the QCD critical point. Such a formalism, based on relativistic hydrodynamics, has been developed for *Gaussian* fluctuations previously. Also, in our previous work, the evolution equations for *non-Gaussian* fluctuations of baryon charge density have been derived, but only for *static* and uniform background. Here we shall present an important step towards the general relativistically covariant formalism for non-Gaussian fluctuations of all hydrodynamic variables in a fluid with arbitrary flow. We demonstrate this formalism by focusing on the fluctuations of the hydrodynamic mode dominant near the critical point. This mode involves fluctuations of the baryon charge as well as the energy density. The resulting equations, as expected, differ from those for the baryon diffusion problem and could be now used in a realistic simulation of relativistic hydrodynamics with fluctuations near the critical point.

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Measurements of Local Parton Density Fluctuations via Proton Clustering from STAR Beam Energy Scan

Author: Dylan Neff^{None}

Corresponding Author: dneff@physics.ucla.edu

Quark-Gluon Plasma (QGP), a novel state describing the bulk properties of QCD matter at high energies, can be experimentally probed with relativistic nucleus-nucleus collisions. The nature of the

transition between the QGP phase and the final state hadron gas phase is yet to be established. The Beam Energy Scan (BES) program at RHIC aims at searches for a possible critical point in the QCD phase diagram.

Local density fluctuations are a characteristic signature of a first-order phase transition. Baryons, formed via the coalescence of quarks at hadronization, could be sensitive to these local parton density fluctuations at the phase transition boundary. In order to explore this, the multiplicity distribution of protons is studied in subvolumes obtained by partitioning the azimuthal phase space. Mixed events are constructed to wash out any event-by-event signal but to preserve background effects, and thus serve as a baseline.

Measurements of the standard deviation of proton multiplicity distributions in azimuthal partitions of Au+Au collisions are made as a function of the number of protons in the full azimuth. Deviations of these distribution widths from those of the mixed event baseline are interpreted as a measure of azimuthal correlation between proton tracks. Correlation strengths extracted from these measurements in BES I data at $\sqrt{s_{NN}} = 7.7 - 62$ GeV are presented. These results are compared with those obtained from the non-critical AMPT and MUSIC+FIST model calculations.

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Fluctuations in the mixed phase of the first order phase transition and nucleus-nucleus collisions

Co-authors: Mark Gorenstein ¹; Oleh Savchuk ²; Volodymyr Kuznietsov ³; Volodymyr Vovchenko ⁴

¹ *Bogolyubov Institute for Theoretical Physics*

² *Frankfurt Institute for Advanced Studies*

³ *Bogolyubov Institute for Theoretical Physics of the National Academy of Sciences of Ukraine*

⁴ *Lawrence Berkeley National Laboratory*

Corresponding Author: rpoberezhnyuk@gmail.com

We present the analytic description of particle number (conserved charge) fluctuations within the subvolume of the thermal system in the coexistence region of the first order phase transition. Different approximations are applied for the metastable states, for the region of spinodal decomposition [1] and in the special case of a homogeneous system [2]. The results are checked within non-relativistic molecular dynamics with Lennard-Jones potential. We these results in the context of event-by-event fluctuations in heavy ion collision experiments. Within the UrQMD transport model with interaction potential, we show that the enhancement of fluctuations in the region of a first order phase transition persists to late times of the nucleus-nucleus collision [3].

The presence of the phase transition has a much smaller influence on event-by-event fluctuations in the momentum space, where a notable effect is observed only in high-order cumulants, namely, in kurtosis.

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ALICE

Corresponding Author: igor.altysbeev@cern.ch

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STAR

Corresponding Author: mnasim2008@gmail.com

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HADES

Corresponding Author: s.spies@gsi.de

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SHINE

Corresponding Author: andras.laszlo@cern.ch

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Future

Corresponding Author: herrmann@physi.uni-heidelberg.de

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BEST

Corresponding Author: jnorhos@illinois.edu

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Lattice 1

Corresponding Author: philipsen@itp.uni-frankfurt.de

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Corresponding Author: hengtong.ding@mail.ccnu.edu.cn

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Corresponding Author: ashish.pandav@niser.ac.in

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Corresponding Author: roy.lacey@stonybrook.edu

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Corresponding Author: a.rustamov@cern.ch

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Partonic Critical opalescence & Jet quenching

Corresponding Author: fengli@lzu.edu.cn

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Corresponding Author: tdore738@gmail.com

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Corresponding Author: udit.shukla@uwr.edu.pl

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Corresponding Author: fernando.flor@cern.ch

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Corresponding Author: marek.gazdzicki@cern.ch

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Corresponding Author: maja.katarzyna.mackowiak@cern.ch

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Acceptance - the key experimental challenge - STAR

Corresponding Author: nxu@lbl.gov

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Quo Vadis, CBM

Author: Norbert Herrmann¹

¹ *Univ. Heidelberg*

Corresponding Author: herrmann@physi.uni-heidelberg.de

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Quo Vadis, NA60++

Corresponding Author: enrico.scomparin@cern.ch