The QCD Phase Transition

786. WE-Heraeus-Seminar

03 – 05 April 2023

hybrid

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 786. WE-Heraeus-Seminar:

The QCD phase transition is the transition between matter consisting of quarks and gluons (quark-gluon plasma QGP) and matter consisting of nuclear matter and hadrons. During the expansion of the very early universe the 'big bang' matter crossed this transition approximately 10 microseconds after the origin. Since more than 30 years an international community of several thousands of scientist is studying such matter by the analysis of collisions among heavy nuclei at high energy, the current experimental effort is concentrated at the RHIC collider in the US and the LHC collider at CERN. Research focuses on the determination of the transition temperature, on the possible existence of a critical endpoint in the phase diagram, as well as on the determination of the dynamics and equation of state of the QGP.

For the planned seminar we would like to get together the world's experts on the theoretical and experimental investigation of the QCD phase transition with the aim to summarize the current status and to develop ideas for future studies. We believe this seminar is particularly timely at the start of LHC Run3, and with new data in sight from the RHIC Beam Energy Scan as well as from sPHENIX, NA61, and the future FAIR and NICA facilities.

Scientific Organizers:

Prof. Dr. Peter Braun-Munzinger	GSI Darmstadt, Germany E-mail: p.braun-munzinger@gsi.de
Prof. Dr. Frithjof Karsch	Universität Bielefeld, Germany E-mail: karsch@physik.uni-bielefeld.de
Prof. Dr. Krzysztof Redlich	University of Wroclaw, Poland E-mail: krzysztof.redlich@uwr.edu.pl

Introduction

Administrative Organization:

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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 02 April 2023

17:00 – 20:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Monday, 03 April 2023

08:00	*BREAKFAST*	
09:00	Scientific organizers	**Welcome words**

Session I: QCD phase diagram

09:15 – 10:00	Kenji Fukushima	**QCD phases from academism to pragmatism**
10:00 – 10:30	Christian Schmidt	**Zeros of the QCD partition function and the QCD phase diagram**
10:30 – 11 :00	Owe Philipsen	**The nature of the QCD chiral transition with 2+1 and many flavours**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:00	Maria-Paola Lombardo *(via Zoom)*	**Scaling window and topology in QCD**
12:00 – 12:30	Heng Tong Ding *(via Zoom)*	**Charge fluctuations in strong magnetic fields**
12:30 – 13:00	Nu Xu	**Study of the QCD phase structure in high-energy nuclear collisions**
13:00 – 13:10	**Conference Photo** (in the front of the lecture hall)	

Program

Monday, 03 April 2023

13:15 – 14:30	*LUNCH*	

Session II: Fluctuations

14:30 – 15:15	Toshihiro Nonaka	**Methods and results on conserved charge fluctuations from RHIC-BES and FXT**
15:15 – 15:45	Anar Rustamov	**Probing the QCD matter with fluctuations and correlations of particle multiplicities**
15:45 – 16.15	Jana N. Guenther	**The equation of state from lattice QCD**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 17:30	Volker Koch	**Fluctuations of conserved charges**
17:30 – 18:00	Tom Reichert	**Particle number fluctuations from relativistic transport simulations**
18:00 – 18:30	Pok Man Lo	**Insights of QCD phase structure from hadron spectroscopy and resonance gas model**
18:30 – 18:45	Stefan Jorda	**About the WE-Heraeus-Foundation**
19:00	*DINNER*	

Program

Tuesday, 04 April 2023

08:00	*BREAKFAST*	

Session III: Heavy Quarks

09:00 – 09:45	Johanna Stachel	**Experimental test of quark deconfinement - hadrons with charm quarks**
09:45 – 10:15	Laura Tolos	**Heavy flavor in a hot bath**
10:15 – 10:45	Nora Brambilla	**Regeneration of bottomonia in an open quantum system approach**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 11:45	Sajid Ali	**Quarkonium in the QGP from Nf=2+1 lattice QCD**
11:45 – 12:15	Anton Andronic	**The statistical hadronization model for heavy quarks and the QCD phase boundary**
12:15 – 12:45	Sipaz Sharma	**Charm fluctuations as a probe for deconfinement from lattice QCD**
12:45 – 14:00	*LUNCH*	

Session IV: Transport

14:00 – 14:45	Derek Teaney	**Dynamics of the chiral phase transition**
14:45 – 15:15	Stefan Floerchinger	**Fluid description for high-energy nuclear collisions starting before the collisions**
15:15 – 15:45	Peter Petreczky	**Heavy flavor probes of hot matter and lattice QCD**

Program

Tuesday, 04 April 2023

16:45 – 16:15	*COFFEE BREAK*	

Session V: Equitation of state

16:15 – 16:45	Tetyana Galatyuk	**Electromagnetic probes of QCD matter: experimental overview**
16:45 – 17:15	Jishnu Goswami	**Isentropic Equation of state and speed of sound of (2+1)- flavor QCD**
17:15 – 17:45	Wolfram Weise	**Sound velocity and equation of state in neutron star matter**
17:45 – 18:15	Violetta Sagun	**Constraining the properties of strongly interacting matter with the multi-messenger observations of compact stars**
19:00	*HERAEUS DINNER (social event with cold & warm buffet with complimentary drinks)*	

Program

Wednesday, 05 April 2023

08:00	*BREAKFAST*	

Session VI: Signals for chiral symmetry restoration

09:00 – 09:45	Chihiro Sasaki	**Parity doubling in QCD matter**
09:45 – 10:15	Lijuan Ruan	**Probe chiral symmetry restoration: experimental observables**
10:15 – 10:45	Tobias Fischer	**Astrophysical simulations of compact stellar objects probing the QCD phase transition in dense matter**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 12:45	**Poster session**	
12:45 – 14:00	*LUNCH*	

Session VII: Continued

14:00 – 14:30	Ralf-Arno Tripolt	**Vector and axial-vector mesons in nuclear matter**
14:30 – 15:00	Jon-Ivar Skullerud	**Chiral symmetry signals from the meson and baryon spectrum**
15:00 – 15:30	Michal Marczenko	**Reaching percolation and conformal limits in neutron stars**
15:30	*FAREWELL COFFEE*	

End of the seminar and departure

NO DINNER for participants leaving on Thursday; however, a self-service breakfast will be provided on Thursday morning

Posters

Posters

David Blaschke	**Formation of clusters and the chemical freeze-out in the QCD phase diagram**
Szymon Harabasz	**Thermal model for particle production in heavy-ion collisions at the few-GeV energy**
Oleksii Ivanytskyi	**Early deconfinement of asymptotically conformal color-superconducting quark matter in neutron stars**
Reinhold Kaiser	**The QCD chiral phase transition for various numbers of flavors at imaginary baryon chemical potential**
Győző Kovács	**Finite volume effects in the QCD phase diagram**
Peter Lowdon	**Non-perturbative insights into the spectral properties of QCD at finite temperature**
Adrian Meyer-Ahrens	**Dielectron analysis for the CBM experiment**
Niklas Schild	**Characterising the hot and dense fireball with virtual photons at HADES**
Mahboubeh Shahrbaf	**The role of strangeness in QCD phase transition**
RAVI SHANKER	**Eigenvalue spectrum of 2+1 flavor QCD in the continuum limit**
Udita Shukla	**Speed of sound in dynamical chiral quark models**
Simran Singh	**Extracting Lee Yang and Fisher zeros of the 2D Ising model from multi-point Pade approximants**
Michal Szymanski	**Screening effects at finite chemical potential and magnetic field**

Abstracts of Talks

(in alphabetical order)

Quarkonium in the QGP from N_f=2+1 lattice QCD

Sajid Ali

March 31, 2023

Abstract

We present unquenched correlator data and corresponding reconstructed spectral functions for quarkonium in the pseudoscalar channel. To obtain the correlators, we use clover-improved Wilson fermions on $N_f = 2 + 1$ HISQ lattices, with valence quark masses tuned such that the mass spectrum from lattice QCD is consistent with corresponding experimental values. For the spectral reconstruction, we employ models based on perturbative spectral functions from different frequency regions, such as resummed thermal contributions around the threshold from pNRQCD and vacuum contributions well above the threshold. Our study presents preliminary results of the reconstructed spectral functions for full QCD at two different temperatures.

The statistical hadronization model for heavy quarks and the QCD phase boundary

A. Andronic[1]

[1]*University of Munster, Germany*

We will discuss in the framework of the statistical hadronization model the role of the heavy quarks (charm in beauty) in delineating the QCD (crossover) phase boundary at the LHC energy (vanishing baryochemical potential).
The model is very successful in reproducing the experimental data in Pb-Pb collisions, in particular for charmonium, implying thermalization of charm quarks in QGP and concurrent hadronization with the lighter quarks [1]. The large yield measured for the Λ_c baryon at the LHC can only be explained in the model by assuming a large number of missing charm-quark baryon resonances [2].
For the beauty quarks, the model comparison to data suggests incomplete thermalization, not surprisingly, given the significantly-heavier b quark.

References

[1] A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature **561**, 321 (2018)
[2] A. Andronic et al., JHEP **07**, 035 (2021)

Regeneration of bottomonia in an open quantum system approach

N. Brambilla[1]

[1]*Physik-Department, Technische Universitaet Muenchen, James-Franck-Str. 1, 85748 Garching, Germany*

We demonstrate the importance of quantum jumps in the nonequilibrium evolution of bottomonium states in the quark-gluon plasma. Based on nonrelativistic effective field theory and the open quantum system framework, we evolve the density matrix of color singlet and octet pairs. We show that quantum regeneration of singlet states from octet configurations is necessary to understand experimental results for the suppression of both bottomonium ground and excited states. The values of the heavy-quarkonium transport coefficients used are consistent with recent lattice QCD determinations.

References

1 N. Brambilla et al, TUM-EFT 178/23

Charge fluctuations in strong magnetic fields

Heng-Tong Ding[1]

*[1]Institute of Particle Physics, Central China Normal University,
Wuhan, China*

We present the first lattice QCD results of the second order fluctuations of and correlations among net baryon number, electric charge and strangeness in (2+1)-flavor lattice QCD in the presence of a background magnetic field with physical pion mass $m_{\pi}=135$ MeV. To mimic the magnetic field strength produced in the early stage of heavy-ion collision experiments we use 6 different values of the magnetic field strength up to $\sim 10 m_{\pi}^2$.

We find that the correlation between baryon number and electric charge along the transition line is substantially affected by magnetic fields in the current eB window. This could be useful for probing the existence of a magnetic field in heavy-ion collision experiments.

References

[1] H.-T. Ding, S.-T. Li, J.-H. Liu and X.-D. Wang, arXiv: 2208.07285.
[2] H.-T. Ding, S.-T. Li, Q. Shi and X.-D. Wang, Eur. Phys. J. A 57 (2021) 202.

Astrophysical simulations of compact stellar objects probing the QCD phase transition in dense matter

T. Fischer

Institute of Theoretical Physics, University of Wroclaw, Poland

Motivated from the observations of yet-incompletely understood explosive stellar phenomena, that could be associated with massive supergiant stars of zero-age main sequence (ZAMS) masses around 30–60 solar masses, new light has been shed on an old idea [1], namely, that the appearance of QCD degrees of freedom may account for such cosmic explosions [2]. Obeying nuclear physics constraints and taking yet-another important observation of the very existence of massive pulsars of more than 2 solar masses seriously into account, puts sever constraints on the behaviour of the equation of state at supersaturation density. In particular, sufficient stiffness with increasing density is required, which puts the previously and frequently employed bag models into jeopardy. As a consequence, this excludes the canonical supernova evolution of low- and intermediate mass stars with ZAMS masses of about 10–15 solar masses from the presence of exotic high-density phases. On the other hand, during the supernova evolution of very massive progenitor stars, with ZAMS masses of about 30–75 solar masses, significantly higher core temperatures and densities are reached, where the appearance of the hadron-quark phase transition can potentially triggers not only the supernova explosion but also releases a millisecond neutrino burst, which is absent in canonical neutrino-driven explosions. This observable signature provides unique evidence for the presence of a first–order phase transition at supersaturation density. The future observation of such a feature, from the next galactic event, will allow us to either confirm such scenario or, if not observed, rule out a (strong) first-order phase transition at high densities encountered at the interior of (proto)neutron stars. In my talk I will revisit this scenario with special emphasis on observables, which includes besides neutrinos also gravitational waves [3]. The latter are confirmed to be observable also from the first binary neutron star merger event GW170817, observed on August 17th, 2017 by the LIGO–VIRO collaboration. Furthermore, I will discuss implications of the appearance of QCD degrees of freedom through a first–order phase transition at high density, e.g., the remnants of such supernova explosions are massive neutron stars of 2 solar masses at birth featuring a massive quark-matter core, the presence of *r*-process nucleosynthesis in the ejecta and possible gravitational signatures of such first-order phase transition in the context of binary neutron star mergers [4].

References

1. Sagert, I.; Fischer, T.; Hempel, M.; Pagliara, G.; Schaffner-Bielich, J.; Mezzacappa, A.; Thielemann, F.-K.; Liebendoerfer, M.; "Signals of the QCD phase transition in core-collapse supernovae". Phys. Rev. Lett., 102, 081101 (2009).
2. Fischer, T.; Bastian, N.-U. F.; Wu, M.-R.; Typel, S.; Klähn, T.; Blaschke, D. B.; "Quark deconfinement as a supernova explosion engine for massive blue supergiant stars". Nature Astronomy, 2, 980 (2019).
3. Kuroda, T.; Fischer, T.; Takiwaki, T.; Kotake, K.; "Core-collapse supernova simulations and the formation of neutron stars, hybrid stars and black holes". Astrophys. J., 924, 38 (2021).
4. Bauswein, A.; Bastian, N.-U. F.; Blaschke, D. B.; Chatziinoannou, K.; Clark, J. A.; Fischer, T.; Oertel, M.; "Identifying a first-order phase transition in neutron star mergers through gravitational waves". Phys. Rev. Lett., 122, 061102 (2019).

Fluid description for high-energy nuclear collisions starting before the collisions

Stefan Floerchinger[1]

[1]*Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, Jena, Germany*

Fluid dynamic models are used successfully to describe many aspects of high-energy nuclear collisions and to relate experimental observables to thermodynamic and transport properties. One difficulty is that initial conditions for fluid fields shortly after the collision are not very well understood. On the other side, one can roughly understand nuclei as droplets of nuclear matter at a first order quantum phase transition, the nuclear liquid-gas transition. In this sense, relativistic fluid dynamics with a realistic thermodynamic equation of state can well describe the state before the collision. In this talk I will report on an attempt to establish a fluid picture for the entire dynamics from before the collision to particle freeze-out. This is based on a thermodynamic equation of state at non-vanishing baryon number.

Based on work together with Federica Capellino, Alaric Erschfeld, Eduardo Grossi and Andreas Kirchner.

QCD phases from academism to pragmatism

Kenji Fukushima

The University of Tokyo, Tokyo, Japan

I will review three approaches to QCD phases that are proposed recently [1,2,3]. The first one based on [1] treats the high-temperature phase where pQCD should be valid. Then, the loop calculation with finite imaginary angular velocity leads to a novel phase that confines color, i.e., perturbative confinement of quarks is realized by a fictitious parameter of imaginary rotation. Then, the topics are shifted toward more pragmatic approaches to real QCD phases. In [2] it has been demonstrated that a smooth crossover from nuclear to quark matter can be detectable from the future gravitational wave signals. Also, this talk emphasizes an extremely nontrivial feature possibly associated with crossover to quark matter; that is, at baryon densities below the crossover, dense matter steeply exhibits approximate conformality [3], which induces a peak structure in the speed of sound. The physical interpretation awaits to be investigated further.

References

[1] S. Chen, K. Fukushima, Y. Shimada, Phys.Rev.Lett. **129**, 242002 (2022)

[2] Y. Fujimoto, K. Fukushima, K. Hotokezaka, K. Kyutoku, Phys.Rev.Lett. in press.

[3] Y. Fujimoto, K. Fukushima, L. McLerran, M. Praszalowicz, Phys.Rev.Lett. **129**, 252702 (2022)

Electromagnetic probes of QCD matter

T. Galatyuk[1,2]

[1]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[2] Technische Universität Darmstadt, Darmstadt, Germany

Matter in thermal equilibrium radiates photons, whose spectrum reflects the temperature as well as possible critical behavior in the vicinity of phase transitions. They are ideal probes for the elementary excitations in a given system. Virtual photons, the generalized form of electromagnetic radiation, materialize after short time by formation of a pair of charged leptons (di-leptons). The spectra of di-leptons have long been recognized as a unique observable to probe the interior of the fireball. Unlike hadrons, di-leptons do not interact strongly. Once produced, they escape the fireball undistorted, thus retain the information imprinted on them at the time of their creation. In this contribution, I will first recall the basic tools and ideas of dilepton spectroscopy in heavy-ion collisions and discuss recent highlights of extracting properties of the QCD medium, as well as diagnosing excitation functions of fireball bulk properties. Special attention will be given to the effects of high baryon densities and the opportunities that arise from these in heavy-ion collisions in the few-GeV energy regime where maximal nuclear compression is expected.

Isentropic Equation of state and speed of sound of *(2+1)*-flavor QCD

***J. Goswami*[1] (HotQCD collaboration)**

[1]Riken Center for Computational Science

The finite temperature and density equation of state (EoS) of quantum chromodynamics (QCD) is crucial for understanding the properties of hot and dense matter created in heavy ion collision experiments. It also finds application in hydrodynamic simulations and studies of the expanding early universe.
Using the high statistics data from the HotQCD Collaboration, we have studied the EoS on trajectories of fixed $\{n_S = 0,\ n_Q/n_B,\ s/n_B\}$ in the (T, μ_B) plane by analyzing the Taylor series of the pressure of (2+1)-favor QCD. Heavy ion collisions closely meet these conditions. We will compare the EoS on these trajectories to high temperature perturbation theory and the hadron resonance gas model at low temperatures. We furthermore show that straightforward Taylor expansion results agree with the Pade resummed series approximants for pressure, net baryon number, energy and entropy densities [1]. We conclude that the Taylor series for bulk thermodynamic observables are reliable up to $\mu_B/T \leq 2.5$ at low temperatures and $\mu_B/T \leq 3$ [2] at high temperatures.

We will also present observables involving higher order T-derivatives such as the specific heat, speed of sound, and adiabatic compressibility of strongly interacting matter. We use these results to discuss bounds on the location of a possible critical point in the QCD phase diagram of strangeness neutral matter at non-vanishing values of the baryon chemical potential.

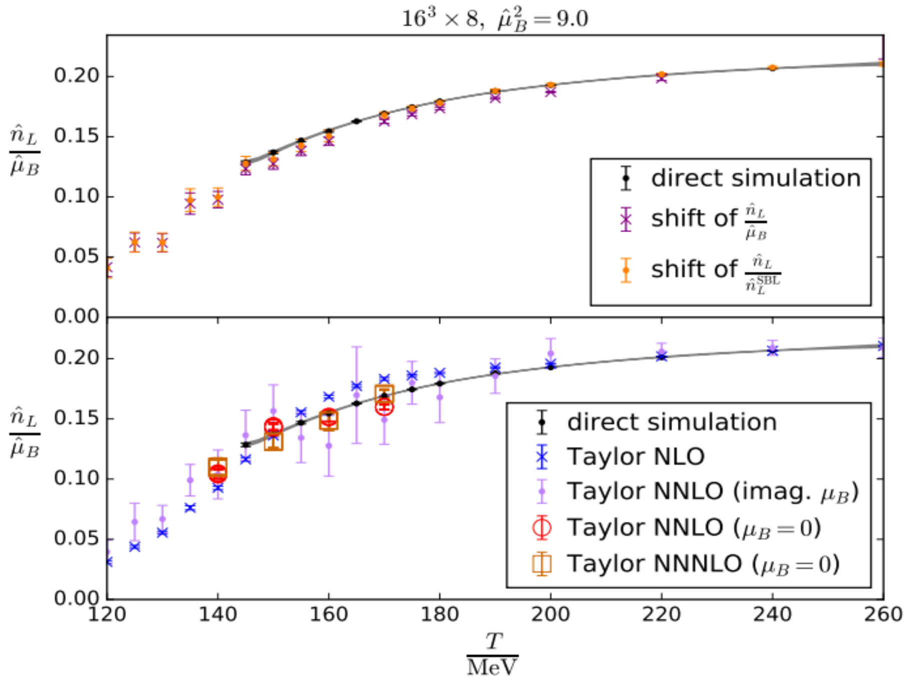
References

1. D. Bollweg et al (HotQCD collaboration), arXiv:2212.09043
2. D. Bollweg et al (HotQCD collaboration), Phys. Rev. D 105, 074511

The Equation of State from Lattice QCD

Jana N. Guenther[1]

[1]*University of Wuppertal, Gaussstrasse 20, 42119 Wuppertal, Germany*



The equation of state is an important quantity both from the purely theoretical point of view as well as input quantity to various models which describe the Quark Gluon plasma. It has been investigated with lattice QCD simulations for a long time, starting out zero chemical potential and, more recently, also at finite baryon chemical potential. The studies at finite chemical potential have to handle the infamous sign problem. Several methods to deal with the sign problem, both for direct simulations and for extrapolation based results, have been explored by my research groups. Some of these techniques are compared in the plot above from reference [1]. In this talk I will summarize recent developments for the equation of state with a focus on results at finite chemical potential from extrapolation based techniques.

References

[1] Sz. Bosanyi et al., e-Print: 2208.05398 [hep-lat] (2022)

Fluctuations of conserved charges

Volker Koch

Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

I will review the present status of fluctuations of conserved charges in heavy ion collisions. I will discuss their utility and limitations to identify a possible critical point and first order transition in the QCD phase diagram. I will further discuss other applications such as the measurement of the speed of sound through fluctuations as well as constraints on baryon annihilation.

Insights of QCD phase structure from hadron spectroscopy and resonance gas model

Pok Man Lo[1]

[1]Univerisity of Wroclaw , Wroclaw, Poland

A very detailed picture of hadronic interactions emerged from an impressive volume of scattering experiment data, and extensive theoretical studies such as chiral perturbation theory and LQCD. We shall discuss how the statistical hadronization model, improved with a scattering matrix (S- matrix) formulation of statistical mechanics, provides the necessary framework to make direct use of this resources for investigating the phenomenology of heavy ion collisions. Some recent progress in analyzing the coupled-channel system of hyperons and the inclusion of $N>2$-body scatterings.

Scaling window and topology in QCD

Maria Paola Lombardo

INFN Sezione di Firenze

The width of the region near the finite temperature chiral phase transition in QCD where a non-trivial scaling sets in is non-universal. Past studies have shown that the width may be suppressed in theories with large number of fermions: the region where mean field scaling holds may grow large at the expenses of the true non-critical scaling. Physical mechanisms controlling the extent of non-trivial scaling include the role of composite fermions at the transition, the interplay of characteristic length scales, and possible influences of critical points in the complex plane. In this talk I discuss results obtained in collaboration with Andrey Kotov and Anton Trunin on non-trivial scaling in QCD, its cross-over to mean field, and the interrelation of these observations with topological features at high temperature.

References

A.Y.Kotov, A.Trunin and M.P.Lombardo, in preparation
A.Y.Kotov, A.Trunin and M.P.Lombardo, PoS LATTICE2021 (2022), 032
A.Y.Kotov, A.Trunin and M.P.Lombardo, *Phys.Lett.B* 823 (2021) 136749

Reaching percolation and conformal limits in neutron stars

M. Marczenko[1], **L. McLerran**[2], **K. Redlich**[3], **C. Sasaki**[3,4]

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[3] *Institute of Theoretical Physics, University of Wrocław, plac Maksa Borna 9, PL-50204 Wrocław, Poland*
[4] *International Institute for Sustainability with Knotted Chiral Meta Matter (SKCM2), Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8511, Japan*

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. The talk is based on Ref. [1].

References

1. M. Marczenko, L. Mclerran, K. Redlich, C. Sasaki, *Phys.Rev.C* 107 (2023) 2, 025802

Methods and Results on Conserved Charge Fluctuations from RHIC-BES and FXT

T. Nonaka

University of Tsukuba, Tennoudai1-1-1, Tsukuba, Ibaraki, Japan

One of the ultimate goals in heavy-ion collision experiments is to understand the QCD phase structure and the nature of the phase transition. At RHIC, cumulants up to the sixth-order of the net-particle multiplicity distributions have been measured for the Beam Energy Scan (BES) and fixed-target (FXT) program (2010-2017), from which some interesting hints on the phase structure have been obtained.
The higher-order cumulants are more sensitive not only to the QCD phase structure but also to the experimental artifacts such as detector efficiencies, initial volume fluctuations, and event pileups. In this talk, we will briefly discuss about the analysis techniques to overcome those issues. We will then present the experimental results from RHIC-BES and FXT [1-4], and current interpretations. We will also discuss about the importance of the p_T acceptance correction [5] and future measurements including hyperons [6].

References

[1] J. Adam et al., Phys. Rev. Lett., 126.092301(2021)
[2] Mohamed Abdallah et al., Phys. Rev. C, 104.024902(2021)
[3] M. S. Abdallah et al., Phys. Rev. Lett., 128.202303(2022)
[4] Mohamed Abdallah et al., Phys. Rev. Lett., 127.262301(2021)
[5] M. Kitazawa et al., Nucl.Phys.A 1030.122591(2023)
[6] T. Nonaka, Nucl.Instrum.Meth.A 1039.167171(2022)

Heavy flavor probes of hot matter and lattice QCD

Peter Petreczky[1]

[1]*Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*

I will discuss recent progress in lattice QCD calculations pertinent to the heavy flavor probes of hot matter produced in relativistic heavy ion collisions, including the heavy quark diffusion coefficient [1,2], in-medium bottomonium width [3], and the complex heavy quark potential [4]. In addition, results on spatial meson correlation function in connection to bottomonium melting will be presented [5].

References

[1] L. Altenkort et al, arXiv:2302.08501, submitted to PRL
[2] N. Brambilla et al, arXiv:2206.02861, to be published in PRD
[3] R. Larsen et al, Phys. Lett. B 800 (2020) 135119
[4] D. Bala et al, Phys. Rev. D 105 (2022) 5, 054513
[5] P. Petreczky, S. Sharma, J.H. Weber, Phys. Rev. D 104 (2021) 5, 054511

The nature of the QCD chiral transition with 2+1 and many flavours

O. Philipsen[1]

[1]*Institute for Theoretical Physics, Goethe University Frankfurt am Main, Germany*

In the limit of massless u,d-quarks, a non-analytic phase transition must separate two distinct phases with spontaneoysly broken and restored chiral symmetry in the QCD phase diagram. Since the physical u,d-quarks are light, the phase diagram at the physical point is intimately connected to, and constrained by, the situation in the chiral limit. The dependence of the zero-density chiral transition on the number of quark flavours, their masses and lattice spacings [1] conclusively demonstrates that previously observed first-order transitions for $N_f \geq 3$ vanish when the continuum and chiral limits are taken in the correct order. As a result, the chiral transition is second-order for Nf=2-7 masseless quarks, and crossover for non-vanishing quark masses.
Preliminary results [2] show the same trend for imaginary chemical potentials. Implications for the physical phase diagram are discussed.

References

[1] F. Cuteri, O. Philipsen, A. Sciarra, JHEP **11**, 141 (2021)
[2] A. D'Ambrosio, R. Kaiser, O. Philipsen, PoS LATTICE2022 **172** (2023)

Particle number fluctuations from relativistic transport simulations

T. Reichert[1,2] and M. Bleicher[1,2]

[1]Institut für Theoretische Physik, Goethe Universität Frankfurt, Max-von-Laue-Strasse 1, D-60438 Frankfurt am Main, Germany
[2] Helmholtz Research Academy Hesse for FAIR (HFHF), GSI Helmholtz Center for Heavy Ion Physics, Campus Frankfurt, Max-von-Laue-Str. 12, 60438 Frankfurt, Germany

The Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model is used to calculate particle number fluctuations in heavy-ion collisions. Especially the proton number fluctuations are often proposed to pose a great tool for the investigation of baryon fluctuations providing insights about the dynamics encountered during the intermediate phase. We investigate how correlations are propagated from the initial state to the final (decoupling) state and also discuss further influences by detector resolution and acceptance cuts.

References

[1] C. Herold, Phys.Rev.C **106** (2022) 2, 024901
[2] J. Steinheimer, Phys.Lett.B **776** (2018) 32-37
[3] S. Sombun, J.Phys.G **45** (2018) 2, 025101

Probe chiral symmetry restoration: experimental observables

Lijuan Ruan

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I will present experimental observables to probe chiral symmetry restoration and discuss future perspectives.

Probe chiral symmetry restoration: experimental observables

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Probing the QCD matter with fluctuations and correlations of particle multiplicities

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The results on fluctuations and correlations of particle multiplicities will be addressed in view of ongoing intensive experimental and theoretical studies of the phase diagram of strongly interacting matter created in head-on collisions of heavy nuclei. After introducing measurements as obtained by several experimental collaborations, their comparison to theoretical calculations will be discussed. In this context, a dedicated approach will be presented to quantify event-by-event baryon number conservation effects within sub-ranges of the full phase space. An innovative approach to account for contributions from fluctuations of participating nucleons will form the final part of the presentation.

Constraining the properties of strongly interacting matter with the multi-messenger observations of compact stars

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Compact stars are the most exotic and dense laboratories in the Universe to test the properties of strongly interacting matter. Understanding the complex phenomena observed in neutron and hybrid stars requires profound knowledge in a wide range of scientific disciplines. In addition to the experimental data on nuclear and hadron matter, the realistic equation of state (EoS) should be consistent with the astrophysical, and gravitational wave observations. While details of the phase transitions and properties of quark matter are traditionally investigated in the accelerator experiments on heavy-ion collisions, compact astrophysical objects recently gained a big interest since observational data on their radii, masses, rotational frequencies, etc. significantly constrain the properties of strongly interacting matter. Another source of information comes from the binary neutron star mergers. Thus, the LIGO-Virgo interferometers detection of gravitational waves emitted during the binary neutron stars merger, GW170817, set the major limit on the tidal deformabilities of the stars involved in the collision and, therefore, on the EoS at the super-high baryonic densities.
I will present the astrophysical and gravitational wave constraints on the EoS of strongly interacting matter as well as the smoking gun signals of the deconfinement phase transition in compact stars and their mergers. As regards observations of gravitational waves, it has been recently reported that phase transition from hadron to quark matter is expected to have a dramatic impact on the frequency of gravitational waves emitted during neutron star mergers, which provides a fresh and continuously updating ground for testing the formulated equation of state. Finally, I will briefly mention how the next generation of gravitational wave telescopes will probe the existence of the deconfinement phase transition in compact stars.

Using an example of the recently announced lightest compact star HESS J1731-347 I will demonstrate how the multi-messenger observations could shed light on the interior composition of the star.

Parity doubling in QCD matter

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In this talk, we focus on spontaneous breaking and restoration of chiral symmetry in hot and/or dense QCD matter, and discuss how in-medium modifications of hadronic degrees of freedom associated with the QCD phase transition would emerge in experimental and observational signals. Especially, the following topics will be presented: signatures in dilepton production via chiral mixing, baryon numbers fluctuations at the nuclear liquid-gas transition and at the QCD critical point, equation of state of neutron star matter.

References

[1] C. Sasaki, Phys. Lett. B **801**, 135172 (2020); Phys. Rev. D **106**, no.5, 054034 (2022).
[2] M. Marczenko, K. Redlich and C. Sasaki, Astrophys. J. Lett. **925**, no.2, L23 (2022); Phys. Rev. D **105**, no.10, 103009 (2022).
[3] M. Marczenko, L. McLerran, K. Redlich and C. Sasaki, Phys. Rev. C **107**, no.2, 025802 (2023).
[4] M. Marczenko, K. Redlich and C. Sasaki, arXiv:2301.09866 [nucl-th].

Zeros of the QCD partition function and the QCD phase diagram

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We discuss a new method to study phase transitions, based on the computation of multi-point Padé approximants and their poles in the complex plane of symmetry breaking or temperature like scaling fields [1]. These poles can be identified with the Lee-Yang and Fischer zeros of the partition function and thus exhibit a universal scaling behaviour. After reviewing the universal scaling of the zeros and some methodological aspects of the method, we discuss the potential applications to the QCD phase diagram, using lattice QCD simulations at imaginary chemical potentials. We present preliminary results in the vicinity of the Roberge-Weiss, indicating a temperature scaling in agreement with the expected universal behaviour. For temperatures below T<170 MeV we find an apparent approach of the complex zeros towards the real axis. We show that a similar behaviour is also observed in the poles of the [4,4]-Padé re-summation of the Taylor series of the pressure about zero chemical potential [2]. Based on this observation and a scaling Ansatz for the Lee-Yang zeros, we speculate on the position of the QCD critical point [3].

References

1. P. Dimopoulous *et al.,* Phys. Rev. D **105,** 0204513 (2022)
2. D. Bollweg *et al.*, Phys. Rev D **105**, 074511 (2022)
3. C. Schmidt *et al.*, Acta Phys. Pol. B Proc. Suppl. 16, 1-A52 (2023)

Charm Fluctuations as a Probe for Deconfinement from Lattice QCD

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We aim to establish whether charmed hadrons dissociate at the chiral crossover temperature or a higher temperature value by analyzing the second and fourth-order cumulants of charm fluctuations and their correlations with lighter conserved flavor quantum numbers, calculated on the high statistics datasets of the HotQCD Collaboration, generated with the Highly Improved Staggered Quark (HISQ) (2+1)-flavor action for light and strange quarks whereas treating the charm sector in the quenched approximation. Analyzing correlations of charm fluctuations with baryon number, electric charge and strangeness fluctuations enables us to make predictions about the not-yet-discovered charmed hadrons by projecting onto charmed baryonic and mesonic correlations in different sectors to compare results with Quark Model extended Hadron Resonance Gas model calculations.

Chiral symmetry signals from the meson and baryon spectrum

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Using anisotropic lattice simulations with N_f=2+1 improved Wilson fermions, we calculate temporal correlators of light and strange baryons and mesons. In the hadronic phase we obtain the ground state masses of positive and negative parity baryons as well as pseudoscalar, vector, axial-vector and scalar mesons. We find that parity doubling for baryons sets in close to the chiral transition, and that pseudocritical temperatures determined from this are consistent across all channels and with T_{pc} determined from the chiral condensate and susceptibility. We also find clear evidence that the axial-vector and vector meson chiral partners become degenerate near T_{pc}.

Experimental Test of Quark Deconfinement - Hadrons with Charm Quarks

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Yields of hadrons with light (u,d,s) valence quarks and of atomic nuclei, anti-nuclei, hyper-nuclei are described very successfully treating the fireball at hadronization of the quark-gluon plasma (QGP) as a statistical ensemble. This is done in the so-called statistical hadronization model (SHM). For LHC data this is achieved with essentially one free parameter. This treatment can be extended to hadrons with heavy valence quarks.

This has to be done with the constraint that heavy quarks are produced in hard binary collisions of (mostly) gluons very early in the nuclear collision even before the QGP forms. This talk will focus on charm quarks. Since even at full LHC energy thermal charm quark production is negligible, the number of charm quarks in the QGP is fixed and experimentally measured in terms of the charm production cross section. In our current understanding, charm quarks thermalize in the QGP which, according to what we have learned from experiments, is a strongly coupled medium. In the SHMc, we assume that the thermalized, deconfined charm quarks hadronize simultaneously with the other QGP constituents under the constraint of a fixed and known number of charm quarks in the system. Without any additional free parameter, there is then a unique set of predictions concerning their yields and spectra of hadrons with open and hidden charm. This can be tested in the LHC experiments. It will be shown that data gained from the first 10 years of operation of the LHC quantitatively fulfill these expectations, based on thermally equilibrated deconfined charm quarks. There is also a unique set of predictions for the future concerning the formation of many more and even rather exotic states containing charm quarks.

Dynamics of the Chiral Phase Transition

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I review various aspects of the real time dynamics of the chiral phase transition. First, I describe about the appropriate hydrodynamic theories above, below, and during the chiral phase transition. Then I describe a Langevin simulation of the chiral critical point, which lies in the dynamic universality class of "Model G." The axial charge and the order parameter exhibit a rich dynamical interplay, which reflects the qualitative differences in the hydrodynamic effective theories above and below the transition. From the axial charge correlators on the critical line, we extract a dynamical critical exponent of the model which is compatible with the theoretical expectation. Finally, I will discuss ways to look for the chiral phase transition in current and future heavy ion data. If time permits I will discuss the hydrodynamics of partially conserved non-abelian charges based on SU(2) and SU(3) symmetry, which gives predictions for the fluctuations of isospin and strangeness which are different from currently used models.

References

[1] A. Florio, E. Grossi, A. Soloviev and D. Teaney, Phys. Rev. D105 no.5, 054512 (2022).
[2] J. M. Torres-Rincon and D. Teaney, Phys. Rev. D106, no. 5, 056012 (2022).
[3] S. Grieninger, S. Shi, and D. Teaney, in preparation.

Heavy flavor in a hot bath

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We present the properties of open heavy mesons in hot mesonic matter based on a self-consistent theoretical approach that takes into account chiral and heavy-quark spin-flavor symmetries. The heavy-light meson-meson unitarized scattering amplitudes in coupled channels incorporate thermal corrections as well as the dressing of the heavy mesons with the self-energies [1, 2]. As a result, the open heavy-flavor ground-state spectral functions broaden and their peak is shifted towards lower energies with increasing temperatures. This has strong implications for the excited mesonic states generated dynamically in this heavy-light molecular mode. In addition, we discuss several applications of our results. On the one hand, we show the meson Euclidean correlators calculated using the thermal ground-state spectral functions obtained within our approach and compare them with recent calculations of lattice correlators [3]. On the other hand, we discuss the properties of the X(3872), the X(4014) and their bottom counterparts at finite temperature as dynamically generated states via the interaction of two open heavy mesons by incorporating their thermal spectral functions [4]. These results are relevant in relativistic heavy-ion collisions at high energies and can be tested in lattice-QCD calculations exploring the melting of heavy mesons at finite temperature.

References

[1] G. Montaña, A. Ramos, L. Tolos and J. M. Torres-Rincon, Physics Letters **B806**, 135464 (2020)
[2] G. Montaña, A. Ramos, L. Tolos and J. M. Torres-Rincon, Physical Review **D102**, 096020 (2020)
[3] G. Montaña, O. Kaczmarek, L. Tolos and A. Ramos, European Physical Journal **A56,** 294 (2020)
[4] G. Montaña, A. Ramos, L. Tolos and J. M. Torres-Rincon, 2211.01896 [hep-ph]

Vector and Axial-Vector Mesons in Nuclear Matter

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We present recent results on the in-medium spectral function of the rho(770) vector meson and the a1(1260) axial-vector meson in nuclear matter, as well as on the resulting thermal dilepton rate. As an effective description of the thermodynamics and the phase structure of nuclear matter we use a chiral baryon-meson model, taking into account the effects of fluctuations from scalar mesons, nucleons, and vector mesons within the Functional Renormalization Group (FRG) approach. Our results show strong modifications of the spectral functions in particular near the chiral critical endpoint which suggest an enhanced dilepton yield at lower energies. Such an enhancement is also found in GiBUU transport simulations for C+C at 1A GeV when including effects of chiral symmetry restoration in the kinetic equations for baryon propagation. Our results may therefore well be of relevance for electromagnetic rates in heavy-ion collisions and help to identify phase transitions and the critical endpoint.

References

[1] R.-A. Tripolt, C. Jung, L. von Smekal, J. Wambach, Phys. Rev. D **104**, 054005 (2021)

Sound velocity and equation of state in neutron star matter

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Bayesian inference methods are used to constrain the speed of sound in the interior of neutron stars, based on recent multi-messenger data in combination with nuclear theory results at low baryon density. Credibility regions for various neutron star properties are analysed, in particular with reference to the quest for possible phase transitions in cold dense matter. The detailed evaluation of corresponding Bayes factors implies that the occurance of a first-order phase transition in the core of even a two-solar-mass neutron star is extremely unlikely, while a moderate softening of the sound speed, indicating a continuous crossover into a new phase, cannot be ruled out. Implications of a recently explored heavy neutron star with 2.35 +/- 0.17 solar masses are also discussed.

Reference

1. L. Brandes, W. Weise, N. Kaiser, Phys. Rev. **D 107**, 014001 (2023)

Study of the QCD Phase Structure in High-Energy Nuclear Collisions

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In this talk, I will report recent progresses in the RHIC beam energy scan program and the status of the search for the QCD critical point. Physics issues on high-order correlations, hyper-nuclei production at high baryon density and the thermalization in high-energy collisions will be the focus of the discussion. Finally, physics potentials with future facilities will be addressed.

Abstracts of Posters

(in alphabetical order)

Formation of clusters and the chemical freeze-out in the QCD phase diagram

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We discuss medium effects on light cluster production in the QCD phase diagram within a generalized Beth-Uhlenbeck (GBU) approach by relating Mott transition lines to those for chemical freeze-out. We find that in heavy-ion collisions at highest energies provided by the LHC, light cluster abundances should follow the statistical model because of low baryon densities [1]. Chemical freeze-out in this domain is correlated with the QCD crossover transition. At low energies, in the nuclear fragmentation region, where the freeze-out interferes with the liquid-gas phase transition, selfenergy and Pauli blocking effects are important [2, 3]. We demonstrate that at intermediate energies the chemical freeze-out line correlates with the Mott lines for light clusters provided their dependence on the cluster momentum relative to the medium is taken into account [4]. It is important to consider the nonzero thermal momentum because moving clusters are stabilized compared to those at rest in the dense medium. By interpolating between the pseudocritical temperature $T_c(\mu)$ from lattice QCD and the Mott-lines $T_{Mott,c}$ for light clusters, c = d, t, h, α, one can predict the chemical freeze-out line in excellent agreement with the fit formula by Cleymans et al. [5] in its new parametrization by Vovchenko et al. [6].

References

[1] B. Dönigus, G. Röpke, and D. Blaschke, Phys. Rev. C **106**, 044908 (2022)
[2] G. Röpke, Phys. Rev. C **92**, 054001 (2015)
[3] G. Röpke, D. Blaschke, Y. B. Ivanov, I. Karpenko, O. V. Rogachevsky, and H. H. Wolter, Phys. Part. Nucl. Lett. **15**, 225 (2018)
[4] D. Blaschke, B. Dönigus, S. Liebing, and G. Röpke, in preparation (2023).
[5] J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton, Phys. Rev. C **73**, 034905 (2006)
[6] V. Vovchenko, V.V. Begun, and M.I. Gorenstein, Phys. Rev.C **93**, 064906 (2016)

Thermal model for particle production in heavy-ion collisions at the few-GeV energy.

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In this contribution, I will show that the transverse mass and rapidity spectra of protons and pions produced in Au-Au collisions in the few-GeV energy regime can be well reproduced in a thermal model of particle emission from a spheroid single freeze-out hypersurface. This scenario extends the one used by Siemens and Rasmussen in the original formulation of the blast-wave model by allowing for elongation or contraction of the source. Furthermore, the model calculation incorporates a Hubble-like expansion of QCD matter and the inclusion of resonance decays.
In particular, the Delta(1232) resonance is considered, with a width obtained from the virial expansion.

References

[1] S. Harabasz *et al.*, Phys. Rev. C **201**, 5, 054903 (2020)
[2] S. Harabasz *et al.*, arXiv:2210.07694 [nucl-th] (2022)

Early deconfinement of asymptotically conformal color-superconducting quark matter in neutron stars

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We present a relativistic density functional approach to color superconducting quark matter that mimics quark confinement by a fast growth of the quasiparticle self-energy in the confining region [1]. The approach is shown to be equivalent to a chiral model of quark matter with medium dependent couplings. The approach to the conformal limit at asymptotically high densities is provided by a medium dependence of the vector-isoscalar, vector-isovector and diquark couplings motivated by non-perturbative gluon exchange [2]. While the (pseudo)scalar, vector-isoscalar and vector-isovector sectors of the model are fitted to the mesonic mass spectrum and vacuum phenomenology of QCD, the strength of interaction in the diquark channel is varied in order to obtain the best agreement with the observational constraints from measurements of mass, radius and tidal deformability of neutron stars. These constraints favor an early onset of deconfinement and color superconductivity in neutron stars with masses below one solar mass. We also discuss a new two-zone interpolation scheme for the construction of the hadron-to-quark matter transition [3] that allows to test different structures of the QCD phase diagram with one, two or no critical endpoints in simulations of supernova explosions, neutron star mergers and heavy-ion collisions. We argue that the formation of color-superconducting quark matter drives the trajectories of its evolution in supernovae and neutron star mergers towards the regimes reached in terrestrial experiments with relativistic heavy ion collisions.

References

[1] O. Ivanytskyi and D. Blaschke, Phys. Rev. D **105**, 114042 (2022)
[2] O. Ivanytskyi and D. Blaschke, Particles 5, **514** (2022)
[3] O. Ivanytskyi and D. Blaschke, Eur. Phys. J A. **58**, 152 (2022)

The QCD chiral phase transition for various numbers of flavors at imaginary baryon chemical potential

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The determination of the order of the QCD chiral phase transition in the massless limit is a challenging problem. For $N_f \geq 3$ Pisarski and Wilczek predicted a first-order transition in 1984, based on RG investigations of a linear sigma model in three dimensions [1], which was supported by QCD simulations on coarse lattices. However, recent lattice QCD results from our group refute this picture by providing strong evidence for a second-order chiral phase transition for $N_f = 2 - 6$ massless quark flavors [2]. This is achieved by demonstrating that the first-order chiral transitions observed on coarse lattices terminate at a tricritical lattice spacing, and thus are not connected to the continuum chiral limit. The latter is always approached from a crossover region and thus corresponds to a second-order point. Adopting the same strategy, we now investigate the nature of the chiral transition as a function of the number of flavors and the lattice spacing for a fixed imaginary baryon chemical potential. We observe the same phenomenon as at zero density, i.e. previously observed first-order transitions disappear towards the continuum limit.

References

[1] R. D. Pisarski and F. Wilczek, Phys. Rev. D **29**, 338(R) (1984)
[2] F. Cuteri, O. Philipsen, A. Sciarra, J. High Energ. Phys. **2021**, 141 (2021)

Finite volume effects in the QCD phase diagram

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While in field theoretical calculations, being performed in the thermodynamic limit, the volume is infinite the heavy-ion collisions always carry the effects of the finite system size. It is expected that a sufficiently small volume can affect the thermodynamics and the phase diagram of the strongly interacting matter. These effects can be studied in effective models by taking into account the finite spatial extent of the system via the restriction of the momentum integrals using discretization or with a simplified case using a low momentum cutoff. We investigated the finite-size effects in a vector meson extended Polyakov quark-meson model [1] with both scenarios and found that the resulting modification of the phase diagram, being also influenced by the treatment of the vacuum term, can be different depending on the boundary conditions. Our results also explain certain differences between previous calculations on finite-volume effects.

References

[1] P. Kovács, Z. Szép, and G. Wolf, Phys. Rev. D **93**, 114014 (2016)

Non-perturbative insights into the spectral properties of QCD at finite temperature

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For quantum field theories at finite temperature spectral functions describe how particle systems behave in the presence of a thermal medium. Although data from lattice simulations can in principle be used to determine spectral function characteristics, existing methods rely on the extraction of these quantities from temporal correlators, which requires one to circumvent an ill-posed inverse problem. Here we report on a recent approach that instead utilises the non-perturbative constraints imposed by field locality [1] to extract spectral function information directly from spatial correlators. In particular, we focus on the application of this approach to lattice QCD data of the spatial pseudo-scalar meson correlator in the temperature range 220-960 MeV, and outline why this data supports the conclusion that there exists a distinct pion state above the chiral pseudo-critical temperature [2].

References

[1] P. Lowdon, "Euclidean thermal correlation functions in local QFT," *Phys. Rev. D* **106**, 045028 (2022) [arXiv:2201.12180]

[2] P. Lowdon and O. Philipsen, "Pion spectral properties above the chiral crossover of QCD," *JHEP* **10**, 161 (2022) [arXiv:2207.14718]

Dielectron Analysis for the CBM Experiment

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The Compressed Baryonic Matter (CBM) experiment is a fixed-target heavy-ion experiment currently under construction at FAIR in Darmstadt which will explore the QCD phase diagram at high net-baryon densities. Dielectrons serve as versatile probes for the properties of the hot and dense medium created in the collisions since they do not interact strongly and escape the fireball undisturbed. Dielectron physics relies on the efficient reduction of combinatorial background, dominated by misidentified hadrons as well as electrons from photon conversions in the target or detector material. On this poster, simulation results concerning dielectron invariant mass spectra at CBM will be presented, focusing on background rejection using conventional cut-based selections as well as machine learning methods.

Eigenvalue spectrum of 2+1 flavor QCD in the continuum limit

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The transition from hadron to the quark-gluon plasma phase is a smooth crossover in QCD with physical quark masses, nevertheless, the (almost) chiral nature of the light quarks is believed to drive such a transition. This phenomenon can be studied using lattice QCD techniques and the most popularly used fermion discretization, the staggered fermions only have a remnant of the full chiral symmetry of QCD, which is believed to be recovered in the continuum limit. We for the first time, study the eigenvalue spectrum of the QCD Dirac operator with highly improved staggered quark (HISQ) discretization for three different lattice spacings at 0.9-1.1 T_c (T_c is the pseudo-critical temperature) and perform the continuum extrapolation. From the features of the eigenvalue spectrum, we can conclude that though the flavor non-singlet part of the chiral symmetry is restored at T_c the flavor singlet $U_A(1)$ part of it is effectively restored only above 1.15 T_c. Moreover, we observe a level repulsion between the infrared eigenvalues which has a quadratic dependence on the spacing similar to the Gaussian unitary ensemble (GuE) of random matrix theory, unlike the near-zero modes. The consequences of these findings will be discussed.

References

[1] O. Kaczmarek, R. Shanker and S. Sharma, arxiv: 2301.11610.

Characterising the hot and dense fireball with virtual photons at HADES

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Electromagnetic probes (γ, γ^*) offer a unique opportunity to study the conditions during heavy-ion collisions. Not only are they produced throughout all stages of the colliding system, they also penetrate and escape the otherwise strongly interacting medium. Therefore, they open up the possibility to directly investigate the early stages of maximum temperature and density.

In this contribution, we present measurements of virtual photons from Ag+Ag collisions, collected at the High-Acceptance-DiElectron-Spectrometer (HADES) at $\sqrt{s_{NN}} = 2.55$ GeV.

One major focus is set on the reconstruction of the invariant mass spectrum, which entails information about the temperature and lifetime of the hot and dense fireball. A second part is further devoted on the collective properties via a multi-differential analysis of the anisotropic flow. This allows insights into the time-evolution of the systems collectivity.

The role of strangeness in QCD phase transition

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Reproducing both nuclear saturation properties and the observational constraints from neutron stars around 1.4 solar mass as well as 2 solar mass, we have extended the equation of state (EoS) for the hypernuclear matter within two different many-body approaches which are used to construct a phase transition from hadronic matter to quark matter. The experimental data from hypernuclei has been employed to have realistic hyperonic potentials and to retune the scalar and vector meson-baryon couplings. First-order, as well as the crossover phase transition from hypernuclear matter to deconfined quark matter are constructed to investigate if a hybrid star obtained within different types of phase transition could fulfill the observational data from neutron stars. We find that a crossover transition results in a hybrid star with a quark core which is surrounded by a layer of hypernuclear matter and ordinary nuclear matter.

References

[1] M. Shahrbaf, H. R. Moshfegh and M. Modarres, Phys. Rev. C 100, 044314 (2019).

[2] M. Shahrbaf, D. Blaschke, S. Typel, G. R. Farrar and D. E. Alvarez-Castillo, Phys. Rev. D 105, 103005 (2022).

Eigenvalue spectrum of 2+1 flavor QCD in the continuum limit

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The transition from hadron to the quark-gluon plasma phase is a smooth crossover in QCD with physical quark masses, nevertheless, the (almost) chiral nature of the light quarks is believed to drive such a transition. This phenomenon can be studied using lattice QCD techniques and the most popularly used fermion discretization, the staggered fermions only have a remnant of the full chiral symmetry of QCD, which is believed to be recovered in the continuum limit. We for the first time, study the eigenvalue spectrum of the QCD Dirac operator with highly improved staggered quark (HISQ) discretization for three different lattice spacings at 0.9-1.1 T_c (T_c is the pseudo-critical temperature) and perform the continuum extrapolation. From the features of the eigenvalue spectrum, we can conclude that though the flavor non-singlet part of the chiral symmetry is restored at T_c the flavor singlet $U_A(1)$ part of it is effectively restored only above 1.15 T_c. Moreover, we observe a level repulsion between the infrared eigenvalues which has a quadratic dependence on the spacing similar to the Gaussian unitary ensemble (GuE) of random matrix theory, unlike the near-zero modes. The consequences of these findings will be discussed.

References

[1] O. Kaczmarek, R. Shanker and S. Sharma, arxiv: 2301.11610.

Speed of sound in dynamical chiral quark models

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Gravitational waves offer exciting opportunity to study bulk properties of dense matter and challenge theoretical models of dense equations of state (EoS). The standard NJL model has the known problem that the speed of sound fails to approach the conformal limit. We investigate how a dynamical chiral quark model, which implements non-local interactions among quarks, may resolve the issue.

Extracting Lee Yang and Fisher zeros of the 2D Ising model from multi-point Pade approximants

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Lee Yang zeros are points in the complex plane of the external control parameter, like the chemical potential, where the partition function vanishes. Since thermodynamic variables can be related to the logarithm of the partition function, they display non-analyticities at these points. It was shown by Lee and Yang in 1952 [1] that these zeros can be related to the occurrence of phase transitions when a thermodynamic limit of the theory is considered. In [2], Fisher extended this work to the complex temperature plane analysis of the zeros of the partition function. In [3], we have shown that it is possible to extract Lee Yang zeros relevant to the Roberge-Weiss transition, using multi-point Pade approximations to re-sum the net baryon number density cumulants, when 2+1 flavour lattice QCD is simulated at purely imaginary baryon chemical potentials. In this work we provide support to the claim that we are indeed sensitive to the genuine Lee-Yang (and Fisher) zeros, when we simulate the 2D Ising model with external magnetic field, and approximate the net magnetisation using multi-point Pade approximants. Two types of scaling analysis will be presented [4,5] to show that the zeros of the partition function obtained from the poles of the multi-point Pade approximant, indeed follow the expected scaling of the Z2 2D Ising universality class.

References

1. CN. Yang and T.D. Lee, Phys.Rev. **87**, 410-419 (1952)
2. M.E. Fisher, Phys.Rev.Lett **40**, 1610-1630 (1978)
3. P. Dimopoulos, L. Dini, F. Di Renzo, J. Goswami, G. Nicotra, C. Schmidt, S. Singh, K. Zambello, F. Ziesche, Phys.Rev.D **105** (2022)
4. S. Singh, Parma University (2022)
5. F. Di Renzo, S. Singh, PoS LATTICE2022 (2023) **148**

Screening effects at finite chemical potential and magnetic field

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A proper description of chiral symmetry restoration and its manifestation in a hot and dense medium is important for understanding the QCD phase diagram and pinpointing the location of the critical point. One of the important theoretical tools, complementary to the first principle calculations (lattice QCD), are effective models. The possibility to include or suppress certain types of interactions allows for exploring their role in the description of QCD thermodynamics. As an example, we discuss the consequences of the dressing of four-quark interaction by the ring diagram and its backreaction on the quark gap equation in an effective chiral quark model. This, in a natural way, leads to a medium-dependent coupling. We show that such a modification reduces the chiral transition temperature in the (P)NJL-type models without any fine-tuning of parameters and is capable of generating inverse magnetic catalysis at non-zero magnetic fields [1,2]. We also discuss the effect of the screening on the phase diagram in the temperature and baryon chemical potential plane [3].

References

[1] P. M. Lo, M. Szymański, K. Redlich and C. Sasaki, arXiv:2107.05521

[2] P. M. Lo, M. Szymański, K. Redlich and C. Sasaki, Eur. Phys. J. A **58**, no.9, 172 (2022)

[3] P. M. Lo, M. Szymański, K. Redlich and C. Sasaki, in preparation