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HOT PROBLEMS OF STRONG INTERACTIONS

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Book of Abstracts

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Contents

Strong-interacting matter at finite temperature

Universal (?) scaling of QCD from Wilson femions

Maria Paola Lombardo
Speaker: M. P. Lombardo (INFN Firenze)

We study the scaling properties of QCD in temperature and mass close to the thermal crossover, and for quark masses ranging from the heavy quark regime to the physical values. The lattice results are obtained in the fixed scale approach, either with anisotropic simulations with $N_f = 2 + 1$ flavours, and with simulations of $N_f = 2 + 1 + 1$ flavours at maximal twist. We note that a simple combination of chiral observables reduces the additive renormalizations and the contribution from the regular terms in the equation of state, thus helping the assessment of the hypothesized universal behaviour.

Universal scaling close to chiral limit of QCD

Anirban Lahiri
Speaker: A. Lahiri (Biefefeld U.)

Chiral phase transition has been a topic of interest over decades and order of the chiral phase transition has an effect on the global phase diagram of QCD. In this talk I will review some of our recent calculations towards the limit of 2 massless flavors. I shall start with the determination of the chiral transition temperature and then show how our calculation is able to throw some light on the long standing debate about the order of the chiral phase transition. I shall also show that the gluonic observables and conserved charge fluctuations towards the chiral limit, can be well described by the scaling behavior of an energy like observable w.r.t. chiral symmetry.

Fluctuations and the QCD phase diagram from functional methods

Christian Fischer
Speaker: C. Fischer (University of Giessen)

We summarise recent theoretical results on the QCD phase diagram and the properties of QCD's critical point based on a combination of lattice QCD and Dyson-Schwinger equations. Using lattice input for the quenched gluon propagator, our approach correctly reproduced and predicted Nf=2+1 flavour lattice results for the quark condensate and the unquenched electric and magnetic gluon propagator at zero chemical potential. At chemical potential up to μ_B/T<3 our approach and extrapolations using lattice QCD both confirm an analytic crossover from the hadronic phase into the QGP. Beyond this region we see a critical end point at (T^c, μ_B^c)=(120,500) MeV, which is neither very sensitive to additional charm quark contributions nor to corrections from virtual baryons. We furthermore present new results for baron number fluctuations. We discuss the changes of ratios of fluctuations up to fourth order along and below the transition line for temperatures and baryon chemical potential up to and beyond the critical end point. Comparing with preliminary STAR data for the skewness and kurtosis ratios, our results are compatible with the scenario of a critical end point at large chemical potential and slightly offset from the freeze-out line. We also discuss the caveats involved in this comparison.

Advances on the QCD phase diagram from Ward Identities and Effective Theories

Angel Gómez Nicola, Jacobo Ruiz de Elvira, Andrea Vioque-Rodríguez
Speaker: A. G. Nicola (Universidad Complutense de Madrid)

I will review recent advances on the QCD phase diagram, regarding mostly the nature of the chiral phase transition and its interplay with $U(1)_A$ restoration. Ward Identities and Effective Theories will be the main theoretical tools. The former allow to establish the thermal behaviour of chiral and $U(1)_A$ partners whereas the latter turns out to be quite fruitful for certain observables of interest such as scalar and topological susceptibilities or to study chiral imbalance. Comparison to recent lattice data will be one of the main guidelines for these approaches.

Correlated Dirac eigenvalues and axial anomaly in chiral symmetric QCD

Yu Zhang, Heng-Tong Ding, Sheng-Tai Li, Swagato Mukherjee, Akio Tomiya, Xiao-Dan Wang
Speaker: Y. Zhang (CCNU)

In this talk I will present our very recent work based on [1]. We introduce novel relations between the derivatives ($\partial^n \rho(\lambda, m_l)/\partial m_l^n$) of the Dirac eigenvalue spectrum ($\rho(\lambda, m_l)$) with respect to the light sea quark mass (m_l) and the ($n+1$)-point correlations among the eigenvalues (λ) of the massless Dirac operator. Using these relations we present lattice QCD results for $\partial^n \rho(\lambda, m_l)/\partial m_l^n$ ($n = 1, 2, 3$) for m_l corresponding to pion masses $m_\pi = 160 - 55$ MeV, and at a temperature of about 1.6 times the chiral phase transition temperature. Calculations were carried out using (2+1)-flavors of highly improved staggered quarks with the physical value of strange quark mass, three lattice spacings $a = 0.12, 0.08, 0.06$ fm, and lattices having aspect ratios $4 - 9$. We find that $\rho(\lambda \to 0, m_l)$ develops a peaked structure. This peaked structure arises due to non-Poisson correlations within the infrared part of the Dirac eigenvalue spectrum, becomes sharper as $a \to 0$, and its amplitude is proportional to m_l^2. We demonstrate that this $\rho(\lambda \to 0, m_l)$ is responsible for the manifestations of axial anomaly in 2-point correlation functions of light scalar and pseudo-scalar mesons. After continuum and chiral extrapolations we find that axial anomaly remains manifested in 2-point correlation functions of scalar and pseudo-scalar mesons in the chiral limit.

[1] H.-T. Ding, S.-T. Li, Swagato Mukherjee, A. Tomiya, X.-D. Wang, Y. Zhang, arXiv:2010.14836.

How can one tell if there is quark matter in neutron stars?

Aleksi Kurkela
Speaker: A. Kurkela (University of Stavanger)

The cores of neutron stars contain the densest stable matter in the universe. Cores of neutron stars reach densities as high as those realized in ultrarelativistic heavy-ion collisions where nuclear matter melts into quark matter. This naturally raises the question: does quark matter also exist inside neutron stars? In my talk, I discuss the analogy of "discovering" quark matter in heavy-ion collisions and in neutron stars. I argue that the fundamental constituents of matter are reflected in the EoS and that the functional behaviour of EoS can be used to determine the phase of matter.

QCD phase diagram under strong external magnetic field

Magnetized QCD phase diagram from the point of view of chiral symmetry restoration

Alejandro Ayala, Luis Hernandez, Renato Zamora, Marcelo Loewe, Dominguez Cesareo
Speaker: L. Hernandez (Instituto de Ciencias Nucleares, UNAM)

In this talk, we present an analysis performed within the Linear Sigma Model coupled to quarks, where the restoration of the chiral symmetry is studied both at finite temperature and baryon chemical potential in the presence of a constant in time and uniform magnetic field. The features of this transition are studied in the QCD phase diagram. We discuss the modification of the transition lines in the phase diagram induced by the field strength.

Neutral meson properties in hot and magnetized quark matter

Ricardo Farias
Speaker: R. Farias (UFSM)

We discuss the properties of neutral mesons using effective models of QCD: Nambu-Jona–Lasinio (NJL) model and Linear Sigma model with quarks (Lsmq). We show that when accounting for the effects of the magnetic field on the model couplings, the neutral pion mass decreases monotonically as a function of the field strength. We find an excellent agreement with recent lattice QCD calculations, reproducing the monotonically decreasing trend with the field strength.

Axion Polariton in Magnetized Dense Quark Matter

Efrain J Ferrer, Vivian de la Incera
Speaker: E. J Ferrer (Univ. of Texas at Rio Grande Valley (UTRGV))

In this talk we review the topological properties and possible astrophysical consequences of a spatially inhomogeneous phase of quark matter, known as the Magnetic Dual Chiral Density Wave (MDCDW) phase, that can exist at intermediate baryon density in the presence of a magnetic field. Going beyond mean-field approximation, we show how linearly polarized electromagnetic waves penetrating the MDCDW medium can mix with the phonon fluctuations to give rise to two hybridized modes of propagation: a rotated photon and a massive axion polariton. The formation of axion polaritons in the MDCDW core of a neutron star can add mass to the star via the Primakoff effect, eventually triggering the star collapse. This mechanism provides a possible solution to the missing pulsar problem in the galactic center.

Magnetic susceptibility of QCD matter

Gergely Endrodi, Gunnar Bali, Stefano Piemonte
Speaker: G. Endrodi (University of Bielefeld)

In this talk I will report on a new method to determine the magnetic susceptibility of thermal QCD matter on the lattice. The method employs current-current correlators evaluated at zero magnetic field, thereby circumventing problems of previous approaches related to magnetic flux quantization. Using the susceptibility, the equation of state at low magnetic fields is reconstructed and parameterized in a manner useful for model approaches. If time allows, a decomposition of the susceptibility into spin- and orbital angular momentum-related contributions will be discussed.

Magnetic field dependence of the NJL coupling from lattice QCD

Gergely Marko, Gergely Endrodi
Speaker: G. Marko (University of Bielefeld)

We address the question of the magnetic phase diagram of strong interactions, where chiral effective model descriptions show a different picture compared to lattice QCD results. We propose a physically motivated improvement scheme for effective models based on continuum extrapolated lattice data. We measured the magnetic field dependence of the baryon spectrum in full QCD simulations, which is fed as an input for the PNJL model to define a magnetic running coupling. This results in a corrected magnetic behaviour for other observables.

Confinement and deconfinement in a magnetic background field

Massimo D'Elia
Speaker: M. D'Elia (University of Pisa and INFN)

I will review recent results on the effects of a magnetic background field on the confining properties of strong interactions and on the deconfinement phase transition

QCD phase diagram in astrophysics

Model-independent approach to the neutron-star-matter equation of state

Aleksi Vuorinen
Speaker: A. Vuorinen (University of Helsinki)

I will discuss recent developments in inferring the equation of state of zero-temperature beta-equilibrated QCD matter using only ab-initio theoretical results at low and high densities together with robust observational data. In particular, I will introduce a novel method for interpolating the equation of state that allows one to accurately keep track of the speed of sound of neutron-star matter, thereby facilitating a more detailed analysis of the properties of matter in the cores of neutron stars of different masses. Using results obtained with the new interpolation scheme, I will argue that the matter located in the centers of massive neutron stars is likely to exhibit properties consistent with those of deconfined quark matter.

Gravitational-Wave Signatures of the Hadron-Quark Phase Transition in Binary Compact Star Mergers

Elias Most, Glòria Montaña, Horst Stöcker, Jens Papenfort, Laura Tolós, Luciano Rezzolla, Lukas Weih, Veronica Dexheimer
Speaker: M. Hanauske (Goethe University Frankfurt, Institute for Theoretical Physics)

With the first detection of gravitational waves from a binary system of neutron stars GW170817, a new window was opened to study the properties of matter at and above nuclear-saturation density. Reaching densities a few times that of nuclear matter and temperatures up to 100 MeV, such mergers also represent potential sites for a phase transition from confined hadronic matter to deconfined quark matter. The gravitational wave signatures of the production of quark matter, both during the inspiral (see [PRD 99 (10), 103009 (2019)][1]), merger and postmerger phase of a compact star merger will be in the focus of this talk. The presented results are based on fully general-relativistic hydrodynamic simulations and employing several suitably constructed equation of states that include a hadron-quark phase transition (see [Phys.Rev.Lett. 122 061101 (2019)][2], [Phys.Rev.Lett. 124, 171103 (2020)][3]).

[1]: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.103009
[2]: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.122.061101
[3]: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.171103

The hadron-quark phase transition and neutron star mergers

Andreas Bauswein
Speaker: A. Bauswein (GSI)

The first unambiguous observation of a neutron star merger in 2017 has highlighted the prospect to learn about incompletely known properties of neutron stars and high-density matter. We will discuss the impact of the hadron-quark phase transition on observables of neutron star mergers. In turn, future observations of neutron star merger events can be employed to understand whether or not the hadron-quark phase transition occurs in neutron stars. In particular, it will be possible to constrain the onset density of the phase transition.

Pasta phase in hybrid hadron-quark stars

Konstantin Maslov
Speaker: K. Maslov (JINR)

We investigate the effect of the formation of the structured mixed phase (pasta phase) on the quark-hadron phase transition. The results of the full numerical solution with pasta phases are compared with those of an interpolating construction used in previous works, for which we demonstrate an adequate description of the numerical results. For each pair of RMF models for quark and hadron matter used in this work, we determined the critical value of the surface tension, above which the phase transition becomes close to the Maxwell construction. This result is applied to demonstrate the effect of pasta phases on the structure of hybrid compact stars and the robustness of a possible third family solution.

Second look to the Polyakov Loop Nambu-Jona-Lasinio model at finite baryonic density

Oleksii Ivanytskyi, Maria Angeles Perez Garcia, Violetta Sagun, Conrado Albertus
Speaker: O. Ivanytskyi (University of Coimbra)

We revisit the Polyakov Loop coupled Nambu-Jona-Lasinio model that maintains the Polyakov loop dynamics at zero temperature, which is the most interesting for astrophysical applications. For this purpose we re-examine potential for the deconfinement order parameter at finite baryonic densities. Secondly, and the most important, we explicitly demonstrate that naive modification of this potential at any temperature is formally equivalent to assigning a baryonic charge to gluons. We develop a general formulation of the present model which is free of the discussed defect and is normalized to asymptotic of the QCD equation of state given by $\mathcal{O}(\alpha_s^2)$ perturbative results. We also demonstrate that incorporation of the Polyakov loop dynamics to the present model sizably stiffens the quark matter equation of state supporting an existence of heavy compact stars with quark cores.

Future Compact star observations that could confirm the existence of a Critical End Point in the QCD phase diagram

David Alvarez Castillo
Speaker: D. Alvarez Castillo (JINR)

The long standing debate on the existence of a critical end point in the QCD phase diagram can be potentially settled down by upcoming compact star observations. The so-called "mass twins stars" scenario demands a strong first order phase transition in dense nuclear matter, therefore it will be the main subject of my talk.

Our understanding of the cold, dense nuclear matter in neutron star interiors has suffered a dramatic revolution during the recent years. On the one hand, laboratory experiments have been able to probe the high densities that comprise the equation of state (EoS) of dense nuclear matter. On the other hand, multi-messenger astronomy observations have brought new physical constraints that narrow the parameter space of the different EoS models. There is however, certain tension between astrophysical and terrestrial measurements, with the mass twins being one possible resolution. One practical way to implement all the available constraints for compact star matter is to perform a Bayesian analysis, useful both for model comparison and statistical inference. Results from this type of analysis that include the mass twins configurations will be presented.

Special session on Anomalous transport phenomena and related issues: CME, CSC CVE, ... + QCD phase structure with chiral imbalance (celebrating the 80th birthday of Valentin Zakharov)

Spin and anomaly

Oleg Teryaev
Speaker: O. Teryaev (JINR)

The manifestations of axial anomaly in the observable spin effects are discussed. The prominent role of dispersive (infrared) approach to anomaly and the anomaly in effective theory with 4-velocity as a gauge field is stressed. The similarity and specifics of hadronic and heavy-ion collisions is addressed. The comparison between anomalous gluon constribution, chiral separation effect and chiral (axial) vortical effect is performed.

Chiral magnetic effect and conductivity of quark-gluon plasma in external magnetic field

Andrey Kotov
Speaker: A. Kotov (Jülich Forschungszentrum)

In this talk we discuss chiral magnetic effect - one of the most actively discussed macroscopic manifestations of the chiral anomaly. One of the consequences of the chiral magnetic effect is the growth of the conductivity in magnetic field. We present results of the lattice measurements of the conductivity of quark-gluon plasma in external magnetic field, both in parallel and perpendicular directions. The results confirm the existence of the chiral magnetic effect. Using these results, relaxation time of the chiral charge is also estimated.

Zilch Vortical Effect, Berry Phase, and Kinetic Theory

Andrey Sadofyev
Speaker: A. Sadofyev (University of Santiago de Compostela)

Rotating photon gas exhibits a chirality separation along the angular velocity which is manifested through a generation of helicity and zilch currents. In my talk I will show how to derive the corresponding Wigner function and construct elements of the covariant chiral kinetic theory for photons from first principles. I will further consider the zilch and helicity currents and show that both manifestations of the chirality transport originate in the Berry phase of photons similarly to other chiral effects. I will also briefly comment on the possible relation between vortical responses in rotating systems of massless particles and the anomalies of underlying quantum field theory.

Topological charge and chiral density production in the early stage of high energy nuclear collisions

Marco Ruggieri
Speaker: M. Ruggieri (Lanzhou University)

We study the topological charge density and the chiral density correlations in the early stage of high energy nuclear collisions. Topological charge is related to the gauge invariant E · B where E and B denote the color-electric and color-magnetic fields, while the chiral density is produced via the chiral anomaly of Quantum Chromodynamics. We discuss how the correlation lengths are related to the collision energy, and how the correlated domains grow up with proper time in the transverse plane for a boost invariant longitudinal expansion. We estimate the correlation lengths of both quantities as well as the proper time for the formation of a steady state in which the production of the chiral density in the transverse plane per unit rapidity slows down, as well as the amount of chiral density that would be produced during the pre-equilibrium stage. Finally, we comment on one possible phenomenological impact of chiral density production in the early stage, namely photons that would be produced via the chiral magnetic effect.

Fermion helicity vs. chirality: transport, thermodynamic, and spin-polarization effects

Maxim Chernodub, Victor Ambruş
Speaker: M. Chernodub (Université de Tours)

Helicity is a classically conserved quantity that can be used, in addition to and independently of the (vector) charge and chirality, to characterize thermodynamic ensembles of Dirac fermions. We demonstrate the existence of new nondissipative transport phenomena, helical vortical effects, that emerge in a helically-imbalanced rotating fermionic system. These phenomena lead to the appearance of a new gapless hydrodynamic excitation, the helical vortical wave. We also show that the presence of the helicity imbalance of quark matter increases the curvature of the QCD chiral pseudocritical line and shifts the critical endpoint towards lower temperatures and higher baryon chemical potentials. We demonstrate the existence of a thermodynamic duality between helical and vector (baryonic) chemical potentials. Finally, we argue that the enhancement in the spin polarization of anti-hyperons compared to the polarization of the hyperons in noncentral relativistic heavy-ion collisions arises as a result of an interplay between the chiral and helical vortical effects: we are able to describe the ratio of the (anti)hyperon spin polarizations, obtained by the STAR group, without fitting parameters.

Heavy-ion physics: Interplay of statistical and field- theoretic approaches

Valentin Zakharov
Speaker: V. Zakharov (ITEP)

Heavy-ion physics: Interplay of statistical and field- theoretic approaches

Inhomogeneous phases in strongly interacting matter

Crystalline chiral condensates in dense quark matter

Stefano Carignano
Speaker: S. Carignano (ICCUB)

I will give a brief review on studies of spatially modulated chiral condensates performed within effective low-energy models of QCD, discussing methods and some recent results on the possible phase structure of quark matter at finite baryon density.

Inhomogeneous chiral condensates within the Functional Renormalisation Group

Martin Jakob Steil, Michael Buballa, Bernd-Jochen Schaefer
Speaker: M. J. Steil (TU Darmstadt)

We investigate the stability of inhomogeneous chiral-symmetry breaking phases at non-vanishing chemical potential and temperature by applying the Functional Renormalization Group (FRG) to the two-flavor quark-meson model (QMM) in the chiral limit. The stability of inhomogeneous phases under quantum and thermal fluctuations beyond the mean-field approximation is an open question in the phase-diagram of low-energy effective models of QCD. We derived FRG flow equations for the QMM in local potential approximation with a specific one-dimensional inhomogeneous chiral condensate, the so called chiral density wave. These flow equations include fermionic and bosonic quantum fluctuations. In this talk we present, numerical results in a renormalization group consistent mean-field approximation, where we have solved the fermionic part of the aforementioned flow equations in a first step towards a complete numerical solution of the full flow equations.

Inhomogeneous phases of the Gross-Neveu model with a finite number of flavors

Andreas Wipf, Marc Wagner, Bjoern Wellegehausen, Julian Lenz, Laurin Panullo
Speaker: A. Wipf (FS-University Jena)

We present some recent results on inhomogeneous phases and baryons in the 1+1-dimensional Gross-Neveu model at finite temperature and finite chemical potential. It is known, that in the large N_f-limit the system shows an inhomogeneous condensate at low temperature and large chemical potential. We address the question whether a breaking of translation invariance is also seen for finite N_f, when quantum fluctuations are not suppressed. Results for $N_f = 8$ and $N_f = 2$ are presented. The simulation results indicate that many qualitative features of the solution for large N_f are rediscovered for finite N_f. The talk is based on two recent works in collaroration with L. Panullo and M. Wagner from Frankfurt and with J. Lenz and B. Wellegehausen from Jena.

Exploring the existence of inhomogeneous phases in the 2+1-dimensional Gross-Neveu model in the limit of infinitely many flavors

Michael Buballa, Lennart Kurth, Marc Wagner, Marc Winstel
Speaker: L. Kurth, M. Wagner (Goethe University Frankfurt)

We explore the existence of inhomogeneous phases in the 2+1-dimensional Gross-Neveu model in the limit of infinitely many flavors using a continuum approach as well as lattice field theory. At finite value of the regulator (momentum cutoff, lattice spacing) we find inhomogeneous phases. These phases disappear, however, when removing the regulator, i.e. when sending the momentum cutoff to infinity or the lattice spacing to zero.

Anomaly-induced inhomogeneous phase in QCD-like theories

Tomas Brauner
Speaker: T. Brauner (University of Stavanger)

The ground state of QCD at nonzero baryon number chemical potential and in sufficiently strong magnetic fields is the Chiral Soliton Lattice: a topological phase carrying a crystalline condensate of neutral pions. The same is true for other QCD-like theories, including theories free from the sign problem. This disproves the long-standing conjecture that positivity of the determinant of the Dirac operator in a QCD-like theory implies the absence of inhomogeneous phases in its phase diagram.

QCD phase structure at non-zero baryon density

On the phase structure of QCD

Jan M. Pawlowski
Speaker: J. M. Pawlowski (Heidelberg University)

We map out the QCD phase structure with functional approaches. By now the results for the phase structure from these approaches also converge at large densities, including the location of the critical end point. We evaluate the remaining systematic errors and tasks, as well the the prospects.

The high density QCD phase diagram: of heavy ion collisions and neutron star mergers

Jan Steinheimer, Volodymyr Vovchenko, Anton Motornenko, Horst Stöcker
Speaker: J. Steinheimer (Frankfurt Institute for Advanced Studies)

I will discuss the limits of current methods to calculate the equation of state of QCD matter at finite baryon density. All methods based on expanding lattice QCD results show to be limitred to $\mu_B/T < 3$ a region where contributions from the net baryon density are negligible. Therefore I will show how it is possible to use constraints from astrophysical observations of neutron stars and their mergers, as well as observables from heavy ion collisions, to constrain the features of the QCD EoS at densities up to 10 times nuclear saturation density and Temperatures up to 200 MeV.

QCD Phase Diagrams with Charge and Isospin Axes under Heavy-Ion Collision and Stellar Conditions

Veronica Dexheimer
Speaker: V. Dexheimer (Kent State University)

We investigate the phase transition from hadron to quark matter in the general case without the assumption of chemical equilibrium. The effects of net strangeness on charge and isospin fractions, chemical potentials, and temperature are studied in the context of the Chiral Mean Field (CMF) model that incorporates chiral symmetry restoration and deconfinement. The extent to which these quantities are probed during deconfinement in conditions expected to exist in protoneutron stars, binary neutron-star mergers, and heavy-ion collisions is analyzed via the construction of 3- dimensional phase diagrams.

QCD phase diagram at non-zero real and imaginary chemical potential from lattice QCD

Jishnu Goswami
Speaker: J. Goswami (Bielefeld University)

We will show the continuum extrapolated results for all second order and some of the fourth order cumulants of net baryon-number, strangeness and electric charge fluctuations as well as their correlations obtained using the Highly Improved Staggered Quark (HISQ) action in (2+1)-flavour QCD by the HotQCD collaboration. We will show comparisons of our results with hadron resonance gas (HRG) model calculations and argue that the HRG model based description of strongly interacting matter works only upto the pseudo-crtical temperature of QCD. The cumulants of net charge fluctuations and their correlations at vanishing values of the charge chemical potentials ($\mu_{B,Q,S} = 0$) provide the basis for Taylor expansions of various thermodynamic observables at non-zero values of the chemical potentials. We will use the updated results of HotQCD on higher order cumulants to constrain the location of a possible critical point in the QCD phase diagram.

We will also show a calculation of (2+1)-flavor QCD with an imaginary chemical potential with the aim to determine the critical quark mass at which the second order transition in the Roberge-Weiss plane turns into a first order transition. We use the Highly Improved Staggered Quark (HISQ) action and perform calculations in the Roberge-Weiss plane, where the value of the critical mass is expected to be largest. We explore a range of quark masses corresponding to pion mass values, $m_\pi \geq 40$ MeV. Contrary to calculations performed with unimproved actions we find no evidence for the occurrence of first order transitions at the small quark mass values explored so far.

Open Problems/discussions: i) Resummation of Taylor series at small value of the non-zero baryon density? ii) Interplay between RW transition and Chiral transition in the Chiral limit?

Ref: arXiv:2011.02812 [hep-lat]

QCD crossover line at finite chemical potential from the Lattice

Jana Guenther
Speaker: J. Guenther (Aix Marseille University)

QCD crossover line at finite chemical potential from the Lattice An efficient way to study the QCD phase diagram at small finite density is to extrapolate thermodynamical observables from imaginary chemical potential. The phase diagram features a crossover line starting from the transition temperature already determined at zero chemical potential. This talk focuses on the Taylor expansion of this line up to μ^4 contributions. We present the continuum extrapolation of the crossover temperature.

Universality driven analytic structure of QCD crossover

Vladimir Skokov, Gregory Johnson, Swagato Mukherjee
Speaker: V. Skokov (North Carolina State University / RBRC BNL)

Recent lattice QCD calculations show strong indications that the chiral crossover of QCD at zero baryon chemical potential μ_B is a remnant of the second-order chiral phase transition. Furthermore, the non-universal parameters needed to map temperature T and μ_B to the universal properties of the second-order chiral phase transition have been determined recently. Motivated by these observations, first, we determine the analytic structure of the partition function – the so-called Yang-Lee edge singularity – in the QCD crossover regime, solely based on universal properties. Next, utilizing the lattice QCD results for non-universal parameters we map this singularity to the real T and complex μ_B plane, leading to the determination of the radius of convergence in μ_B in the QCD crossover regime. These universality- and QCD-based results provide tight constraints on the range of validity of the lattice QCD calculations at $\mu_B > 0$. The implication of this result on the location of the conjectured QCD critical point is discussed.

Structure of the Lefschetz thimbles decomposition of lattice fermion models

Maksim Ulybyshev
Speaker: M. Ulybyshev (University of Wuerzburg)

We discuss a framework for studying the properties of the Lefschetz thimbles decomposition for lattice fermion models. Non-iterative solver for the inversion of fermion determinants forms the core of the method. It allows us to solve the gradient flow (GF) equations taking into account the fermion determinant exactly. Being able to do so, we can find both real and complex saddle points of the lattice action and describe the structure of the Lefschetz thimbles decomposition for large enough lattices to extrapolate our results to the thermodynamic limit. We show two possible applications of this technique. First of all, the knowledge about the saddle points can help us to simplify the structure of the Lefschetz thimbles decomposition and to alleviate the sign problem. The second application is systematic building of the quasi-classical approximation taking into account Gaussian fluctuations around exact saddle points.

Effects of rotation in QCD phase diagram

Rotating Relativistic Matter and Angular Momenta

Kenji Fukushima
Speaker: K. Fukushima (The University of Tokyo)

We will discuss the interplay between the magnetic field and the rotation. In the presence of the external magnetic field the angular momentum conservation in a highly nontrivial way. As a demonstration we will show the simplest example of magnetic vortices. If the whole frame is rotated, the boundary condition is crucial not to violate the causality bound, and in this sense, vortices are theoretically ideal objects that are regarded as localized vorticity. Then magnetic vortices are classified into (at least) three distinct classes according to the realization of angular momentum conservation. We also discuss a relation between spin conservation law and chiral anomaly, taking the simplest concrete example of U(1) gauge field.

Chiral dynamics and gluodynamics under rotation

Mei Huang
Speaker: M. Huang (University of Chinese Academy of Sciences)

We investigate the effect of rotation on chiral dynamics and gluodynamics in the framework of NJL model and holography, respectively. We discuss the effect of rotation on thermodynamical properties and phase structure.

Rotational effect versus finite-size effect on chiral phase transition

Kazuya Mameda
Speaker: K. Mameda (RIKEN)

The rotational (or vortical) effect is one of the central topics in quark-hadron systems, such as heavy-ion collision and neutron stars. For the relativistic rotating matter, the most important fact would be that the thermodynamic limit is ill-defined because of the causality constraint. In this talk, we discuss how the finiteness of system-size affects the low-energy structure of rotating fermions. Taking into account the finite-size effect, we show that while the rotational effect cannot solely become physically visible, other external sources (temperature, density, background fields etc.) enable rotation to affect thermodynamic systems. As an example, we also demonstrate that the interplay between magnetic field and rotation changes the breaking structure of chiral symmetry; due to the rotational effect, chiral symmetry is restored as magnetic field increases, which we call the rotational magnetic inhibition.

Rotation on lattices

Arata Yamamoto
Speaker: A. Yamamoto (University of Tokyo)

I give a introductory talk about rotation in lattice field theory. I overview the formulation and its problem in relativistic and non-relativistic theories.

Lattice study of rotating gluodynamics

Victor Braguta, Andrey Kotov, Denis Kuznedelev, Artem Roenko
Speaker: V. Braguta (MISIS, JINR)

In this report we present the results of lattice study of how rotation influences confinement/deconfinement transition in SU(3) gluodynamics. To conduct this study we pass to the reference frame which rotates with the system under consideration. In this reference frame rotation is accounted for by the external gravitational field. We calculate the Polyakov loop, its susceptibility and determine the critical temperature of the confinement/deconfinement transition for various angular velocities. We find that rotation leads to the rising of the critical temperature.

Non-zero isospin density and meson condensation

Chiral perturbation theory and pion condensation at finite isospin

Jens Oluf Andersen, Prabal Adhikari, Martin Mojahed
Speaker: J. O. Andersen (NTNU)

QCD at finite isospin is interesting for a number of reasons. One of them is that it is free of the sign problem and therefore amenable to lattice simulations. In this talk, I will discuss recent results for two and three flavor chiral perturbation theory at finite isospin. I will present results for the pressure, pion and quark condensates and isospin density. The results will be compared to those of recent lattice simulations.

Meson condensation in chiral perturbation theory

Massimo Mannarelli
Speaker: M. Mannarelli (INFN)

We discuss the properties of homogeneous and inhomogeneous meson condensates in the framework of chiral perturbation theory. We compare the results on the homogeneous pion condensate obtained in chiral perturbation theory with those of lattice QCD showing that there is good agreement for isospin chemical potentials up to about $2m_\pi$. Then, we turn to inhomogeneous phases, presenting the results obtained by a semi-analytical approach on solitonic-like structures.

QCD thermodynamics at nonzero isospin asymmetry

Bastian Brandt, Francesca Cuteri, Gergely Endrodi
Speaker: B. Brandt (University of Bielefeld)

We study the thermodynamic properties of QCD at nonzero isospin chemical potential using improved staggered quarks at physical quark masses. In this talk, we will discuss the extraction of the equation of state and show results at zero and nonzero temperatures. As an application, we briefly discuss its relevance for the trajectory of the early Universe at nonzero lepton asymmetry.

Finite Isospin Chiral Perturbation in a Uniform Magnetic Field

Prabal Adhikari
Speaker: P. Adhikari (St Olaf's College)

In this talk, I will discuss the zero-temperature phase diagram of finite isospin chiral perturbation theory in a uniform, external magnetic field. Since pions enter a superfluid state for chemical potentials larger than the pion mass and are electromagnetically charged, they become superconducting in the presence of a magnetic field. They exhibit type-II superconductivity and support stable magnetic vortices.

QCD phase structure in Polyakov linear-sigma model with non-zero isospin density

Abdel Nasser Tawfik
Speaker: A. N. Tawfik (Nile University)

In mean-field approximation, the Polyakov linear-sigma model (PLSM) with u-, d-, and s-quark flavors is utilized in analyzing the chiral condensates and the deconfinement order parameters, at non-zero isospin density. The results obtained on the bulk thermodynamics including pressure density, interaction measure, susceptibility and second-order correlations with baryon, strange and electric charge quantum numbers shall be confronted to the available lattice quantum chromodynamics (QCD) calculations. The excellent agreement encourage the study of QCD phase structure. We find that the pseudocritical temperatures T decrease with the increase in isospin chemical potential and conclude that the QCD phase structure in (T – I) plane seems to extend the one in (T – B) plane, where B is the baryon chemical potential.

Phase diagram in the context of heavy-ion collisions

Transport properties of the hot and dense QGP

Olga Soloveva, Elena Bratkovskaya, Pierre Moreau, Lucia Oliva, Taesoo Song, Joerg Aichelin
Speaker: O. Soloveva (Goethe University Frankfurt)

We study the influence of the baryon chemical potential μ_B on the dynamical properties of the Quark–Gluon–Plasma (QGP) in and out-of equilibrium. The description of the QGP in equilibrium is based on the effective propagators and couplings from the Dynamical QuasiParticle Model (DQPM)that is matched to reproduce the equation-of-state of the partonic system above the deconfinement temperature Tc from lattice Quantum Chromodynamics (QCD). We study the transport coefficients such as the ratio of the shear and bulk viscosities to the entropy density, i.e. η/s and ζ/s, the electric conductivity σ_0/T as well as the baryon diffusion coefficient κ_B and compare to related approaches from the literature(non-conformal holographic model, lattice QCD, NJL). We find that the ratios η/s and ζ/s as well as σ_0/T are in accord with the results from lattice QCD at $\mu_B = 0$. Furthermore, we have considered the shear viscosity and the electric conductivity of strongly interacting quark matter within the extended Nf= 3 Polyakov Nambu-Jona-Lasinio (PNJL) model along with the crossover transition line for moderate values of baryon chemical potential $0 \leq \mu_B \leq 0.9$ GeV as well as in the vicinity of the critical end point (CEP) and at large baryon chemical potential $\mu_B = 1.2$ GeV, where the first-order phase transition takes place.

We explore how the nature of the degrees-of-freedom affects the transport properties of the QGP. Moreover, we study the possible influence of the presence of a CEP and of a 1st order phase transition at high baryon chemical potential. The out-of equilibrium study of the QGP is performed within the Parton–Hadron–String Dynamics (PHSD) transport approach extended in the partonic sector by explicitly calculating the total and differential partonic scattering cross sections based on the DQPM and the evaluated at actual temperature T and baryon chemical potential μ_B in each individual space-time cell where partonic scattering takes place. The traces of their μ_B dependencies are investigated in different observables for symmetric Au + Au and asymmetric Cu + Au collisions such as rapidity and m_T-distributions and directed and elliptic flow coefficients v1, v2 in the energy range $(s_{NN})^{1/2}$ from 7.7 GeV to 200 GeV.

Probing the QCD equation of state with fluctuations of conserved charges

Volodymyr Vovchenko
Speaker: V. Vovchenko (Lawrence Berkeley National Laboratory)

Fluctuations of conserved charges carry rich information about the fine details of the QCD equation of state. Recent lattice QCD data on high order baryon number susceptibilities are used here to constrain the excluded volume corrections in the hadron resonance gas model. I will then address the question of comparison between experimental measurements of baryon and proton number fluctuations in heavy-ion collisions and the corresponding grand-canonical thermal fluctuations from lattice QCD/excluded-volume HRG model, with a focus on effects of global conservation laws, thermal smearing and difference between net proton and net baryon cumulants.

Direct photon production in pp, pA and AA collisions

Dmitri Peresunko
Speaker: D. Peresunko (NRC "Kurchatov institute")

We review experimental results on the direct and isolated photon production in pp, pA and AA collisions at different colliding energies and compare them with theoretical calculations. We discuss thermal direct photon production in AA collisions and consider several proposed solutions of "direct photon flow puzzle" - a strong measured collective flow of direct photons, comparable with the one of final hadrons and much stronger than predicted by hydrodynamic models.

Probing chiral symmetry restoration with dileptons

Chihiro Sasaki
Speaker: C. Sasaki (University of Wroclaw)

Finite baryon density induces a mixing between the vector and axial-vector states, and yields multiple bumps and peaks around the vacuum masses of the ρ, ω and ϕ resonances in the spectral function. The modification become significantly pronounced when the mass difference between the parity partners decreases in dense matter. We propose that the emergent enhancement in the dilepton production rates serves as an excellent signature of the partially-restored chiral symmetry to be verified in heavy-ion collisions.

Transport model approach to Λ and Λ^- polarization in heavy-ion collisions

Evgeny Zabrodin, Larisa Bravina
Speaker: E. Zabrodin, L. Bravina ()

Thermal vorticity in non-central Au+Au collisions at energies $7.7 \leq \sqrt{s} \leq 62.4$ GeV is calculated within the microscopic transport model UrQMD. The whole volume of an expanding fireball is subdivided into small cubic cells. Then we trace the final Λ and Λ^- hyperons back to their last interaction point within a certain cell. Extracting the bulk parameters of hot and dense medium in the cell, one can get the temperature and the chemical potentials at the time of the hyperon emission by fitting the extracted characteristics to statistical model of ideal hadron gas. After that the polarization of both hyperons is calculated. We found that the polarization of both Λ and Λ^- increases with decreasing energy of nuclear collisions. The stronger polarization of Λ^- is explained (i) by slightly different freeze-out conditions of both hyperons and (ii) by the different space-time distributions of Λ and Λ^-.

Theoretical ideas and experimental searches of the critical point

Search for the QCD Critical Point in Heavy-ion Collisions at RHIC

Xiaofeng Luo
Speaker: X. Luo (Central China Normal University)

Understanding the properties of quark matter and its phase structure can enhance our knowledge of universe evolution and the structure of visible matters. In the last two decades, many experimental evidences for the strongly interacting quark-gluon plasma (sQGP) have been observed in high energy heavy-ion collisions. Therefore, exploring the QCD phase structure at high baryon density, such as mapping the 1st order phase boundary and finding the QCD critical point, becomes one of the most important goals of the heavy-ion collisions. During 2010-2017, RHIC has finished the first phase of Beam Energy Scan program (BES-I), and STAR experiment has collected the data of Au+Au collisions at various collision energies from 200 to 7.7 GeV. To confirm the intriguing observations at BES-I, RHIC has started the second phase of beam energy scan program (BES-II) since 2018, focusing on the energies below 27 GeV. From 2018 to 2020, STAR experiment has taken the data of high statistics Au+Au collision at 9.2, 11.5, 14.6, 19.6 and 27 GeV (collider mode) and 3.0 - 7.7 GeV (fixed target mode). In this talk, I will discuss the experimental progress for exploring the QCD phase structure at RHIC-STAR experiment, especially focusing on the QCD critical point search. New facilities aiming for high baryon density region and future plan will be also discussed.

Pre-clustering near the QCD critical point: nuclear correlations and light-nuclei production

Juan Torres-Rincon, Edward Shuryak
Speaker: J. Torres-Rincon (Goethe University Frankfurt)

I will discuss some consequences of the proposed modification of the nuclear force due to the QCD critical end point (CEP). A simple model for the internucleon potential close to the CEP suggests that attraction among nucleons is likely to dominate over repulsion. The net effect would result in sizable nuclear correlations, and the possible formation of pre-clusters of nucleons. In this scenario one can expect an eventual overproduction of light nuclei compared to thermal expectations. I will describe how certain light-nuclei yield ratios, in particular those involving Helium 4, can be used to test these effects in heavy-ion collisions, and the presence of the CEP.

Status of the NICA project

Anatoly Sidorin
Speaker: A. Sidorin (JINR)

The global scientific goal of the NICA/MPD (Nuclotron-based Ion Collider fAcility / Multy Purpose Detector) project realizing at JINR is to explore the phase diagram of strongly interacting matter in the region of high compression. The proposed program allows to search for possible signs of the phase transitions and critical phenomena in heavy ion (up to Au) collisions at centre-of-mass energies up to 11 GeV/u. The collider experiment provides optimum conditions for efficient measurements at energy scan. Main accelerator of the NICA complex is the Nuclotron – 251.52 m long superconducting ion synchrotron equipped with two injection chains: for heavy (including small superconducting synchrotron – the Booster) and for light ions. The collider experiments will be provided at two storage rings with two interaction points based on double-aperture (top-to-bottom) superconducting magnets. For the moment, the modernization of the Nuclotron light ion injection chain was provided. New linear accelerator of the heavy ion injection chain was constructed and commissioned in 2016. All superconducting magnets for the Booster were fabricated at JINR, the Booster assembly is completed. Assembly of the MPD has been started in 2020, production of the collider systems is in progress. Completion of the collider assembly is scheduled for 2022.

Experimental study of QCD phase diagram at NICA energy range

Oleg Rogachevsky
Speaker: O. Rogachevsky (JINR)

A short overview is presented on the recent experimental studies of the QCD phase diagram at low collision energy range $\sqrt{s} \leq 11$ GeV, covered in the future by NICA collider. It also considered some physics analyses which are feasible with the first stage of MPD detector and proposed new ones which may give a new way of looking at possible QCD phase transition at NICA energy range.

Phase diagram of strongly interacting matter and how should we study it in heavy ion collisions

Kyrill Bugaev, Oleksii Ivanytskyi
Speaker: K. Bugaev (Bogolyubov Institute for Theoretical Physics)

After almost 40 years of experiments on heavy ion collisions (HIC) the situation with the discovery the new phases of QCD is somewhat paradoxic. On the one hand, we are sure that at highest RHIC energies the partons are created in HIC, but on the other hand, we do not know the answers to three principal questions:
1. At high baryonic charge densities the chiral symmetry restoration and color deconfinement are the same phenomenon or not?
2. At high baryonic charge densities the chiral symmetry restoration and color deconfinement are phase transitions or not?
3. What are the collision energy thresholds for these phenomena?

The new experiments on RHIC and the ones planned on the NICA and FAIR will provide us with a lot of experimental data, but, unfortunately, there are strong arguments that with the existing theoretical knowhow it will be impossible to convince ourselves and the colleagues from the other communities that we have clear answers on these principal questions. The problem is not only that we are dealing with small and short living systems in which there are no phase transitions or (tri)critical endpoint in a strict sense of statistical mechanics. The main problem, in my mind, is that our best theoretical tools to model phase transitions, namely the equations of state and the hydrodynamic codes, are not suited to model those small and short living systems. Based on the morphological thermodynamics [1] and its quantum version [2] I argue that it is absolutely necessary to develop the finite volume statistical models for the phase of chiral hadrons, for quark gluon plasma and phase transformations between them. The best starting point would be exactly solvable models similar to the quark gluon bags with surface tension [3] which, besides the surface tension coefficient, should also include the curvature tension coefficient (a kind of Tolman correction) and large width of quark gluon plasma bags in spirit of Ref. [4]. Such modifications are necessary, but to develop the realistic equations of state of all QCD phases the input from the lattice formulation of QCD, from the Nambu-Jona-Lasinio model (surface tension) and from the generalized functional renormalization group approach (in-medium width) [5] is of high demand. In addition, it seems that without developing the hydro-kinetic approach for the imaginary values of free energy to treat the metastable states in finite systems. Finally, I will argue that to resolve those principal problems we need to create a theoretical collaboration whose members will concentrate their efforts not on the current fashion(s), but on solving those principal problems.

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Heavy quarks

Properties of doubly heavy baryons

Zalak Shah, Ajay Kumar Rai
Speaker: Z. Shah (SVNIT, SURAT)

The two heavy quark combinations cc, bb and bc unifies with s quark in case of three doubly heavy Ω baryons, while for six doubly heavy Ξ baryons light quarks u or d are combined. The ground, radial, and orbital states are calculated in the framework of the hypercentral constituent quark model with Coulomb plus linear potential. The different approaches and their predicted masses of these heavy baryons are mentioned and compared, thus, the average possible range of excited states masses of these baryons can be determined. Recently, the LHCb collaboration reported the mass of Ξ_{cc}^{++} as a ground state. The Regge trajectory is constructed in both the (n, M^2) and the (J, M^2) planes for all doubly heavy baryons and their slopes and intercepts are also determined. Magnetic moments and decay properties of doubly heavy baryons are also discussed.

The doubly heavy particles: baryons, tetraquarks and pentaquarks

Kazem Azizi
Speaker: K. Azizi (University of Tehran & Dogus University)

In this talk, I will review some new theoretical and experimental developments on doubly heavy baryons as well as tetraquarks and pentaquarks made of double heavy quarks, by insisting on our recent studies. I will compare the predictions of the phenomenological models with the experimental data on some parameters of the hadronic states under discussion. I will also discuss different assignments on the structure and quantum numbers of the recently discovered doubly heavy particles at hadron colliders.

Towards the understanding of quarkonium production through global-fit analyses of LHC data

Mariana Araújo, Pietro Faccioli, Carlos Lourenço
Speaker: M. Araújo (LIP-CMS)

Hadron formation is one of the most interesting open problems within the context of QCD. Understanding how the quarks bind with each other implies combining complex analytical perturbative calculations with not-yet-understood non-perturbative aspects. Quarkonia are the simplest quark-antiquark bound states and provide an ideal window to probe hadron formation. The high quality quarkonium production (cross sections and polarizations) measurements reported by the LHC experiments, when studied with state-of-the-art data-driven analysis methods, allow us to perform a significant step forward in our understanding of the mechanisms at the basis of quarkonium formation. In this talk we will present results from a series of global-fit analyses of cross section and polarization measurements performed by the ATLAS and CMS experiments using large samples of pp collisions at 7, 8 and 13 TeV, including comparisons between model-independent phenomenological scenarios and the more complex NRQCD approach.

The fate of quarkonia in heavy-ion collisions at LHC energies: a unified description of the sequential suppression patterns

Carlos Lourenço, Pietro Faccioli
Speaker: C. Lourenço (CERN)

Measurements made at the LHC have shown that the production of the J/psi, psi(2S), Upsilon(1S) and Upsilon(2S) quarkonia is suppressed in Pb–Pb collisions, with respect to the extrapolation of the pp production yields. The psi(2S) and Upsilon(2S) states are more strongly suppressed than the ground states and the level of the suppression changes with the centrality of the collision.

We show that the measured patterns can be reproduced by a simple model, where all quarkonia are treated in a unified way, starting from the recent realisation that, in pp collisions, the probability of quarkonium formation has a universal dependence on the binding-energy of the bound state. The hot-medium suppression effect is parametrized by a penalty factor in the binding energy, identical for all (S- and P-wave) charmonium and bottomonium states, including those that indirectly contribute to the measured results through feed-down decays. This single parameter, computed through a global fit of all available suppression patterns, fully determines the hierarchy of nuclear effects, for all states and centrality bins.

The resulting faithful description of the data provides convincing evidence in favour of the conjecture of sequential quarkonium suppression induced by QGP formation.

Heavy Quarkonium Production in pNRQCD

Hee Sok Chung, Nora Brambilla, Antonio Vairo
Speaker: H. S. Chung (Technical University of Munich)

We compute the color singlet and color octet NRQCD long-distance matrix elements for inclusive production of P-wave quarkonia in the framework of potential nonrelativistic QCD. In this way, the color octet NRQCD long-distance matrix element can be determined without relying on measured cross section data, which has not been possible so far. We obtain inclusive cross sections of χcJ and χbJ at the LHC, which are in good agreement with data. In principle, the formalism developed in this work can be applied to all inclusive production processes of heavy quarkonia.

Fully-heavy tetraquark states and their strong decays into di-charmonia

Wei Chen, Hua-Xing Chen, Xiang Liu, Shi-Lin Zhu, T. G. Steele
Speaker: W. Chen (Sun Yat-Sen University)

In this talk, I will introduce our investigations on the fully-heavy tetraquark states, including the calculations of their mass spectra and their strong decays into di-charmonia. Our calculations of the masses for the fully-heavy tetra quarks have been done several years before the recent LHCb's observation in the di-J/ψ structure. However, our results suggest that the broad structure around 6.2-6.8 GeV in LHCb's observation can be interpreted as an S-wave $cc\bar{c}\bar{c}$ tetraquark with $J^{PC} = 0^{++}$ or 2^{++}, and the narrow structure around 6.9 GeV can be interpreted as a P-wave one with $J^{PC} = 0^{-+}$ or 1^{-+}. These conclusions are also confirmed by our recent study of the strong decays of the fully-charm tetraquarks into di-charmonia, in which we consider all possible two-body strong decays for these tetrequarks and calculate their relative branching ratios through the Fierz rearrangement.

Transport and spectral properties of heavy quarks from lattice QCD

Hai-Tao Shu
Speaker: H.-T. Shu (Bielefeld University)

In this talk I will review our recent lattice results on the charmonia & bottomonia spectral functions and heavy-quark transport properties in hot medium. The spectral analyses are performed on the quarkonium correlators measured on the lattice extrapolated to the continuum limit and interpolated to physical J/ψ and Υ masses. Good agreement is observed between our lattice data and the perturbation spectral functions. We also study the transport properties of heavy quarks via color-electric correlators measured under gradient flow. With this newly developed method we achieved good signal in the data and a non-perturbative renormalization for the correlators. Our studies give consistent results with those from other lattice studies. In the end I will give an outlook for the future work that can be done and the possible difficulties that we could meet.

Heavy tetraquarks in the relativistic quark model

Vladimir Galkin, Rudolf Faustov, Elena Savchenko
Speaker: V. Galkin (FRC CSC RAS)

We give a review of the calculations of the masses of tetraquarks with two and four heavy quarks in the framework of the relativistic diquark-antidiquark model based on the quasipotential approach. Quasipotentials of quark-quark and diquark-antidiquark interactions are constructed similarly to previous studies of mesons and baryons. All parameters of the model were fixed by meson and baryon properties. Diquarks are considered in the color triplet state and it is assumed that they interact as a whole. The internal structure of diquarks is taken into account by the calculated form factor of the diquark-gluon interaction. Theoretical predictions are compared with the available experimental data. It is argued that the structures in the di-J/ψ mass spectrum observed recently by the LHCb Collaboration can be interpreted as $cc\bar{c}\bar{c}$ tetraquarks.

Bottomonia production and polarization in the NRQCD with kt-factorization

Nizami Abdulov, Artem Lipatov
Speaker: N. Abdulov (Lomonosov Moscow State University)

The $\Upsilon(nS)$ production and polarization at high energies is studied in the framework of k_T-factorization approach. Our consideration is based on the non-relativistic QCD formalism for bound states formation and off-shell production amplitudes for hard partonic subprocesses. The direct production mechanism and feed-down contributions from radiative $\chi_b(mP)$ decays are taken into account. The transverse momentum dependent gluon densities in a proton were derived from the Ciafaloni–Catani–Fiorani–Marchesini evolution equation and Kimber-Martin-Ryskin prescription. Treating the non-perturbative color octet transitions in terms of the mulitpole radiation theory, we extract the corresponding non-perturbative matrix elements for $\Upsilon(nS)$ and $\chi_b(mP)$ mesons from a combined fit to $\Upsilon(nS)$ transverse momenta distributions measured by the CMS and ATLAS Collaborations at the LHC energies $\sqrt{s} = 7$ and 13 TeV and from the relative production rate $R^{\chi_b(nP)}_{\Upsilon(nS)}$ measured by the LHCb Collaboration at $\sqrt{s} = 7$ and 8 TeV. Then we apply the extracted values to investigate the polarization parameters λ_θ, λ_ϕ and $\lambda_{\theta\phi}$, which determine the $\Upsilon(nS)$ spin density matrix. Our predictions have a good agreement with the currently available data within the theoretical and experimental uncertainties.

Exotic hadrons from functional methods

Christian Fischer
Speaker: C. Fischer (University of Giessen)

I review recent results on exotic hadrons such as glueballs, and four-quark-states obtained in the framework of functional Dyson-Schwinger and Bethe-Salpeter equations. I present new results for the quenched glueballs spectrum and compare with available lattice results. For four-quark states, based on our earlier results on the light scalar mesons we have generalized our approach to include mixing with ordinary mesons as well as heavy-light states with two charm and two light (anti-)quarks. I discuss results in several J^{PC} channels for closed and open charm cases.

Production of X(3872) at High Multiplicity

Eric Braaten
Speaker: E. Braaten (Ohio State University)

The LHCb collaboration has observed a decrease with multiplicity of the ratio of the prompt production rates of $X(3872)$ and $\psi(2S)$ in pp collisions. We show that this observation can be explained by the scattering of comoving pions from $X(3872)$ if it is a weakly bound charm-meson molecule.

Bottomonium suppression and elliptic flow from real-time quantum evolution

Michael Strickland, Ajaharul Islam
Speaker: M. Strickland (Kent State University)

We compute the suppression and elliptic flow of bottomonium using real-time solutions to the Schroedinger equation with a realistic in-medium complex-valued potential. To model the initial production, we assume that, in the limit of heavy quark masses, the wave-function can be described by a lattice-smeared (Gaussian) Dirac delta wave-function. The resulting final-state quantum-mechanical overlaps provide the survival probability of all bottomonium eigenstates. Our results are in good agreement with available data for R_{AA} as a function of $N_{\rm part}$ and p_T collected at $\sqrt{s_{\rm NN}} = 5.02$ TeV. In the case of v_2 for the various states, we find that the path-length dependence of $\Upsilon(1s)$ suppression results in quite small v_2 for $\Upsilon(1s)$. Our prediction for the integrated elliptic flow for $\Upsilon(1s)$ in the $10-90\%$ centrality class is $v_2[\Upsilon(1s)] = 0.0026 \pm 0.0007$. We additionally find that, due to their increased suppression, excited bottomonium states have a larger elliptic flow and we make predictions for $v_2[\Upsilon(2s)]$ and $v_2[\Upsilon(3s)]$ as a function of centrality and transverse momentum. Similar to prior studies, we find that it is possible for bottomonium states to have negative v_2 at low transverse momentum.

Bottomonium properties at high temperatures from lattice NRQCD

Peter Petreczky
Speaker: P. Petreczky (BNL)

I will discuss the properties of $\Upsilon(nS)$ bottomonium states as well as the properties of $\chi_b(nS)$ bottomonium states at non-zero temperature using lattice NRQCD. In this study $48^3 \times 12$ lattices are used with highly improved staggered quark (HISQ) action with physical strange quark and light quark masses corresponding to the pion mass of 160 MeV in the continuum limit. Furthermore, extended quarkonium operators have been used in the analysis ensuring a relatively simple form of the resulting spectral function. We find that bottomonium states have a large thermal width at high temperatures, which is proportional to the temperature. We also observe a sequential pattern of the thermal width, i.e. higher excited states, which are larger in size, have a larger thermal width. We do not see indications for a significant thermal mass shift of bottomonium states. In addition we study the Bethe-Salpeter amplitudes of S-wave bottomonia at zero and finite temperature on the lattice within NRQCD. The above results are based on the following papers:

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Doubly Heavy Baryons: Lifetimes and Branching fractions of the Weak Decays

Alexey Luchinsky, Anatoly Likhoded
Speaker: A. Luchinsky (IHEP)

Experimental discovery of the Ξ_{cc}^{++} baryon opens an opportunity for observation of some other particles from doubly heavy baryons' family, such as Ξ_{cc}^{+}, Ω_{cc}^{+}, Ξ_{bc}, etc. For this reason the update of the theoretical predictions of their lifetimes and decay branching fractions is highly desirable. In the presented report we give new results for the lifetimes of these particles calculated in the framework of OPE approach with the updated values of the input parameters. In addition, the widths of the exclusive decays are calculated. Some branching fractions turn out to be large enough for experimental observation.