

Wilson loops and quark masses in holographic QCD

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AdS/CFT has been used as a tool to extract qualitative features of QCD. The gravity dual to the gauge theory is thought to capture strong coupling dynamics of the gauge theory. In recent times, a holographic model based on D-branes has been advocated by Sakai and Sugimoto to describe in an elegant geometric manner chiral symmetry breaking in QCD. One of the outstanding problems in this model is the incorporation of quark masses. I will report work in collaboration with Rob Myers on how to extract the related chiral condensate by computing Wilson loop expectation values in the gravity dual.

QCD EQUATION OF STATE FROM IMAGINARY CHEMICAL POTENTIAL WITHIN A QUASIPARTICLE PERSPECTIVE

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We extend our quasiparticle model, which is linked to QCD via the two-loop Φ -functional approach [1], to imaginary chemical potential for which information on the thermodynamics at finite net baryon densities is accessible by standard lattice QCD simulation methods. The model compares impressively well with the available lattice QCD data. This provides a direct test of Peshier's flow equation which is important for transporting information towards larger net baryon densities.

Physical information is obtained by means of analytic continuation. Studying the chemical potential dependence of the chiral condensate, we have access to the quark mass dependence of thermodynamic quantities, thus providing a sensible test of the chiral extrapolation procedure within our quasiparticle model. Both, a reliable chiral extrapolation as well as a self-consistent extrapolation to large baryon densities are important for a firm knowledge of the QCD equation of state (EoS) relevant for the hydrodynamic description of heavy ion collision experiments. For instance, we study the sensitivity of elliptic flow on variations in the softness of the EoS in the confinement region and in the numerical value of the pseudo-critical temperature T_c for RHIC and LHC [2]. Furthermore, we present an unambiguous extrapolation to large baryon densities by Peshiers flow equation (including Landau damping and collective excitations) as needed for SPS and, in particular, for future FAIR experiments.

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Hot QCD equations of state and relativistic heavy ion collisions

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We study hot QCD equations of state which are obtained from the finite temperature quantum chromodynamics. We mainly focus on EOS up to order g^5 and $g^6 \ln(1/g)$ as well as $g^6(\ln(1/g) + \delta)$ and show how they can be utilized to make definite predictions for relativistic heavy ion collisions. Our method involves the extraction of equilibrium distribution functions for partons from the EOS. These distribution functions allow us to compute transport and bulk properties of quark-gluon plasma. We show that the interaction effects may entirely be expressed in terms of the chemical potentials for partons. As an implication, we study the screening lengths as a function of temperature in pure QCD, two-flavour and three-flavour QCD. The screening lengths are shown to be in qualitative agreement with the recent lattice results.

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Angular Momentum Mixing in a Non-spherical Color Superconductor

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Quark matter at high density and low temperature is expected to be a color superconductivity(CSC). we explored the angular dependence of the gap parameter for a non-spherical pairing of CSC. Because of the equal strength of the pairing potential mediated by one-gluon exchange for all partial waves to the leading order of QCD running coupling constant and the nonlinearity of the gap equation, a non-spherical gap parameter cannot be restricted to one angular momentum channel only. Other multipoles are bound to show up, which renders the angular dependence of the gap nontrivial. A non-spherical solution of the gap equation, in general, does not follow the conventional partial wave expansion unless the the pairing is dominated one angular momentum channel. A nonspherical energy gap of QCD at $T < T_c$ is a mixture of all spherical harmonics of odd parity with the same azimuthal

quantum number. At zero temperature, the angle dependent gap function

$$\phi = \phi_{2\text{SC}} f(\hat{p}) \quad (1)$$

where $\phi_{2\text{SC}}$ is the gap function of 2SC ignoring the mismatch, \hat{p} the direction of the relative momentum of the two quarks in a Cooper pair and the angular dependent factor

$$f(\hat{p}) = \sum_{l=1,3,5,\dots} b_l Y_{lm}(\hat{p}) \quad (2)$$

with $b_1 = O(1)$. Carrying the formulation of He^3 over to QCD amounts to drop all higher multipoles, i.e. $b_l = 0$ for all $l \neq 1$, which will not satisfy the gap equation of QCD. It was argued in the literature that $b_l = O(g)$ but this is not the case. Instead, we find that the function $f(\hat{p})$ satisfies a nontrivial integral equation and thus $b_l = O(1)$ for all odd l 's. Therefore the angular momentum mixing does occur in the subleading order of the angular dependence of the gap parameter. On the other hand, the pairing strength to the subleading order decreases with increasing angular momentum l , therefore the mixing effect will not be so big. For the single flavor CSC, we worked out the angular momentum mixing effect explicitly for the gap function with zero azimuthal quantum number at zero temperature. An nonlinear integral equation for the nontrivial angular dependence was derived and its solution was obtained numerically.

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[1] Our paper will be available on arXiv website soon. For reference.

TOWARDS A CONTROLLED STUDY OF THE QCD CRITICAL POINT

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The phase diagram of QCD, as a function of temperature T and baryon chemical potential μ_B , may contain a critical point (μ_E, T_E) whose non-perturbative nature makes it a natural object of lattice studies. However, the sign problem prevents the application of standard Monte Carlo techniques at non-zero baryon density. We have been pursuing an approach free of the sign problem, where the chemical potential is taken as imaginary and the results are Taylor-expanded in μ/T about $\mu = 0$, then analytically continued to real μ [1,2].

Within this approach we have determined the curvature of the pseudo-critical temperature $dT_c/d\mu^2|_{\mu=0}$, which we can compare to the experimentally determined freeze-out curve [3]. We have also determined the sensitivity of the critical chemical potential μ_E to the quark mass, $d(\mu_E)^2/dm_q|_{\mu_E=0}$. Our study indicates that the critical point moves to *smaller* chemical potential as the quark mass *increases* [3,4]. This finding, contrary to common wisdom, implies that the deconfinement crossover, which takes place in QCD at $\mu = 0$ when the temperature is raised, will remain a crossover in the μ -region where our Taylor expansion

can be trusted. If this result, obtained on a coarse lattice, is confirmed by simulations on finer lattices now in progress, then we predict that no *chiral* critical point will be found for $\mu_B \sim 500$ MeV, unless the phase diagram contains additional transitions.

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Thermodynamics of Quasi-Particles

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We present in this work a generalization of the solution of Gorenstein and Yang for a consistent thermodynamics for systems with a temperature dependent Hamiltonian. We show that there is a large class of solutions, work out three particular ones, and discuss their physical relevance. We apply the particular solutions for an ideal gas of quasi-gluons, and compare the calculation to lattice and perturbative QCD results.

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Soft dynamics of the QCD critical point

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We investigate *dynamic* properties of QCD critical point, an endpoint of the first order line in the temperature-chemical potential ($T-\mu$) plane.

It has been shown that the associated critical mode is not the sigma meson but a certain

mixed fluctuation of quark number and energy densities, in the Landau-Ginzburg approach and in the simple NJL model [1]. See also Ref.[2].

Divergence of a certain static susceptibility is usually connected with emergence of a critical mode in the channel. At the QCD critical point, however, the quark number susceptibility and specific heat as well as the chiral susceptibility all show the same critical behavior. In this case one might imagine massless sigma and omega mesons mediating long-range fluctuations in those channels. Our point is that the right critical mode of this criticality is the hydrodynamic one which is coupled to these three channels linearly. We exclude the masslessness of the sigma and omega mesons near the QCD critical point. The spectral functions of these channels are explicitly calculated in a quark-meson coupled model as a demonstration. Finally, we will compute the transport coefficients in the vicinity of the critical point.

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Pion production enhancement in the PNJL model near the critical temperature

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We investigate the properties of scalar and pseudo-scalar mesons at finite temperature and chemical potential in the framework of the Nambu–Jona-Lasinio (NJL) model complemented with a Polyakov loop term (PNJL model, [1,2]). In this effective model for QCD written in term of quark degrees of freedom, the latter are coupled to a background temporal gauge field in an attempt of accounting both for the chiral symmetry breaking and deconfinement (governed by the Polyakov loop in a pure gauge theory), In such a quark model the mesons (effective degrees of freedom at low temperature) are build via the poles of the scattering matrix.

Then our work is two fold.

In the first part we will introduce mesons as quasi-particles (quasi-poles of the scattering matrix computed via the Schwinger–Dyson equation at the ring approximation). We then compute the effective coupling constant of a meson to two quarks and give a detailed comparison with the NJL model results. We finally discuss the quantitative confinement effect of the Polyakov loop.

In a second part, we will consider in details the calculation of the sigma to two pion decay width and its phenomenological consequences. In particular we will show that compared to the NJL model, the PNJL one exhibits an enhancement of the pion production near the phase transition that could have interesting consequences on the interpretation of the RHIC or ALICE experiment data.

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Falsifying AdS/CFT Drag or pQCD Heavy Quark Energy Loss with A+A at RHIC and LHC

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We propose the novel observable of the double ratio of charm to bottom nuclear modification factors as the only robust experimental measurement that can falsify AdS/CFT, pQCD, or both formalisms as applied to relativistic heavy ion reactions. Previous efforts to connect AdS/CFT calculations with experiment focused on the entropy to viscosity ratio [1] which, due to its sensitivity to the uncontrolled initial conditions [2], is a fragile probe of the “perfection” of the QGP fluid. The nonphotonic electron puzzle poses a challenge to prevailing pQCD prejudices but does not falsify pQCD methods [3]. Imminent detector upgrades in current experiments and the capabilities of near-future colliders will for the first time allow identified heavy quark suppression measurements. We show that current theoretical errors lead to weak predictions for the individual heavy quark nuclear modification factors but that these cancel to an astonishing degree in the ratio of the two, leading to the possibility of experimental falsification. We will discuss the “speed limits” of the classical supergravity approach, beyond which the AdS/CFT techniques may not be applicable, from both field and string theoretic perspectives. The double ratio signal will be most easily observed at LHC, with its large momentum reach and relatively soft heavy quark production spectra, but will also be measurable at RHIC, where the lower medium temperature leads to higher speed limits.

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PARTONIC PICTURE FOR A STRONGLY-COUPLED PLASMA

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Based on the AdS/CFT correspondence, we study [1] the partonic structure of the strongly-coupled, finite-temperature, phase of the $\mathcal{N} = 4$ supersymmetric Yang-Mills (SYM) gauge theory, viewed as a model for the nearly conformal, quark-gluon plasma, phase of QCD at a temperature a few times the critical temperature for deconfinement. To unveil the partons, we consider the deep inelastic scattering of an \mathcal{R} -current off a plasma at temperature T . We compute this process in the dual string theory, as the propagation of the gravitational wave induced by the \mathcal{R} -current in the background metric of a black hole in AdS_5 — the dual counterpart of the gauge plasma. We thus find a rather sharp transition between a low energy regime where the scattering is almost purely elastic, and a high energy regime, where the wave is totally absorbed by the black hole. For a given virtuality Q^2 , with $Q^2 \gg T^2$, of the \mathcal{R} -current, we find that this transition occurs at a critical energy $E_c \propto Q^3/T^2$, i.e., at a critical value $x_c \propto T/Q$ for the Bjorken's x -variable which measures the momentum fraction of the plasma constituents ('partons') in the infinite momentum frame.

These results suggest the following picture for the strongly-coupled plasma: when probed over a distance scale $1/Q$ much shorter than the wavelength $1/T$ of the typical thermal excitations, the plasma appears as a collection of pointlike partons, each of them carrying only a tiny fraction $x \leq x_c \ll 1$ of the energy of the thermal quasiparticles. There are no partons with larger values of $x > x_c$. This picture is natural at strong coupling: via successive radiative processes, all partons drop down to the smallest values of x which are still compatible with energy-momentum conservation.

Equivalently, for a fixed value of x , all the partons have transverse momenta smaller than, or equal to, the plasma saturation momentum $Q_s(x) \sim T/x$, and occupation numbers of order one. This is similar to parton saturation in perturbative QCD.

This picture is consistent with the recently developed [2] partonic description of a single hadron at strong coupling and high energy. Since, in this framework, DIS proceeds through the absorption of the 'electromagnetic' probe, our results may shed further light on the mechanism for energy loss in a strongly-coupled quark-gluon plasma.

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Classical plasma and quark-gluon plasma. Possible common ways in their characterization

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In the last years many new attempts for describing the new state of the nuclear matter evidenced in $Au-Au$ collisions at RHIC-BNL maximum energy [1-4] have been done. Some of these attempts propose notions, phenomena and specific parameters used in Plasma Physics [5,6]. Using this way a few interesting results have been obtained adapting Plasma Physics parameters for describing the behaviour of the *quark - gluon* plasma [7]. The values of a few parameters densities, Coulomb parameters, temperatures are in the specific range for a *quark - gluon* plasma in liquid state. In this work a few new parameters will be considered and some estimations for new experiments will be done. Search for criteria for the nuclear matter phases will be included.

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New results for a “microscopic Hubble constant” from relativistic nuclear collisions

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Based on some similarities between cosmological scenarios on the Universe evolution after “Big Bang” and the behavior of the highly excited nuclear matter formed in relativistic nuclear collisions, immediately after collisions, an estimation of a “microscopic Hubble parameter/constant” for the expansion rate in relativistic nuclear collisions, similar with the cosmological Hubble constant, has been done [1]. Temporal connections between the evolution of the nuclear matter after impact and the scenarios on the Universe evolution after “Big Bang” Have been introduced. Experimental results on participants, fireball sizes (identical particle interferometry), densities, particle spectra and temperatures have been used. A “Hubble scale” for temporal evolution can be obtained. Satisfactory agreement with Buda-Lund model estimations has been obtained. In this work we increase the number of collisions considered in analysis, as well as its energies. Similar results with those reported previously are obtained.

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Finite Density in Lattice QCD with the Canonical Approach

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The algorithm for canonical ensemble approach to lattice QCD at finite density will be discussed and the latest numerical simulation to determine the critical point in finite temperature and density will be presented.

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Equation of State and more from lattice regularized QCD

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We present results from a calculation of the equation of state in QCD with two light quark flavors and a heavier strange quark [1]. Calculations with improved staggered fermions have been performed on lattices with temporal extent $N_\tau = 4, 6$ and 8 on a line of constant physics with almost physical quark mass values; the pion mass is about 220 MeV, and the strange quark mass is adjusted to its physical value. High statistics results on large lattices are obtained for bulk thermodynamic observables, *i.e.* pressure, energy and entropy density, in a wide range of temperatures, $140 \text{ MeV} \leq T \leq 800 \text{ MeV}$, that covers the temperature and energy density regime reachable at RHIC and LHC.

We discuss the approach of energy density and pressure to the high temperature perturbative limit, analyze observables sensitive to deconfinement and chiral symmetry restoration in the transition region, $T \simeq (180 - 200) \text{ MeV}$ [1,2], and compare with hadron resonance gas phenomenology at low temperature.

We extract the equation of state, *i.e.* pressure as a function of energy density, present a calculation of the velocity of sound and discuss consequences of the present results for the bulk viscosity of QCD.

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LATTICE QCD THERMODYNAMICS

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We present recent results on QCD thermodynamics obtained by lattice simulations. The nature of the QCD transition is determined and it is found to be an analytic crossover. The transition temperature (T_c) is given in physical units. Different definitions give different values for T_c ranging from 150 MeV to 176 MeV. The QCD phase diagram on the temperature–chemical potential (μ) plane is studied and the curvature of the phase line at $\mu = 0$ is determined. These results were obtained using four sets of lattice spacings (lattices with temporal extensions of $N_t = 4, 6, 8$ and 10) and a continuum extrapolation was carried out. Results on the equation of state (EoS) approaching the continuum limit are presented. A new technique is introduced which makes it possible to determine the EoS for very high temperatures. This provides a link between lattice QCD and perturbation theory.

Microscopic Formula of Causal Viscosity Coefficient

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The effect of dissipations in relativistic hydrodynamics is one of interesting subjects in heavy-ion physics. However, the introduction of dissipation to relativistic hydrodynamics is not trivial. The simple relativistic generalization of the Navier-Stokes equation, which describes Newtonian fluids, is not adequate because the propagation speed of signals exceeds the speed of light and hence causality is broken. To be consistent with causality, the relativistic fluid should be non-Newtonian.

To solve the causal hydrodynamics, we have to know the transport coefficients; the shear viscosity coefficient, the bulk viscosity coefficient, the heat conduction coefficient and the corresponding relaxation times. However, the famous Green-Kubo-Nakano (GKN) formula is not applicable because it is the formula to estimate the transport coefficients of Newtonian fluids.

In this work, we propose a modified GKN formula which is applicable to the causal hydrodynamics [1]. The new formula reproduces the results of the GKN formula under a certain approximation. We further point out that the lower limit of the shear viscosity predicted by using the AdS/CFT correspondence is true only for Newtonian fluids and is not applicable to the causal hydrodynamics. This can explain the inconsistency of the numerical simulations

of causal hydrodynamics and the prediction of the AdS/CFT correspondence [2].

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Magnetic Quasiparticles in sQGP Explain Low Viscosity and Static Potentials

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Although “dual superconductor” nature of confinement was suggested by ’t Hooft and Mandelstam long ago, the importance of magnetic quasiparticles near deconfinement transition and their relation to the “perfect liquid” observed at RHIC were realized only last year [1,2]. In the RHIC region $T=1-2T_c$ both electric and magnetic quasiparticles are important degrees of freedom. They are about equally massive and abundant at $1.4T_c$ and below this T the magnetic ones get lighter, more weakly coupled, and become the dominant component.

One evidence of this phenomenon is magnetic screening mass which exceeds electric one. Another is the persistence of “flux tube”-related linear potential, seen in potential energy and entropy associated with static quarks on the lattice. In a model of electric-magnetic plasma [3,4] we explained its tension — which is few times larger than at $T = 0$ and is seen till about $1.3T_c$ — and fix the magnitude of the magnetic pressure $P_M(T)$ in this region. The condition for electric flux tube’s existence/disappearance is derived: it led to magnetic particle density $n \sim 4.4 - 6.6/fm^3$ at $1.3T_c$, consistent with several lattice results.

We found that a plasma made of electric and magnetic quasiparticles leads to mutual trapping, similar to “magnetic bottle effect”, and explains low viscosity and small diffusion observed at RHIC. We used Molecular Dynamics (MD) for simulation of a strongly coupled plasma consisting of totally ~ 1000 charges of both types with variable density ratio of electric/magnetic components. The measured shear viscosity and diffusion constant are the lowest in the maximally mixed plasma (i.e. 50%-50%) which takes the most advantage of trapping effect, and their values after suitable mapping to sQGP system’s parameter regions fall very close to those suggested by RHIC experiments. The importance of this effect for understanding such short mean free path as indicated by RHIC is further elucidated in [5].

If this mechanism is the only one, and since it is operative only not too far from T_c , then viscosity/diffusion will grow away from “perfect liquid” regime above $2T_c$ and LHC would show significantly different picture than RHIC.

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PROPERTIES OF THE QGP CLOSE TO T_c FROM LATTICE SIMULATIONS AT IMAGINARY μ

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We explore the highly non-perturbative hot region of the QCD phase diagram close to T_c by use of an imaginary chemical potential μ which avoids the sign problem. We compare these results with phenomenological models inspired by a Hadron Resonance Gas parametrization, with a simple modification of a Stefan-Boltzmann law, and with a critical behaviour associated with the transition line in the negative μ^2 half-plane. We discuss at some length the systematic errors associated with analytic continuation. These results complement and extend the information obtained via the analysis of the susceptibilities evaluated at zero μ , yielding a simple description of the candidate strongly interacting QGP phase. As a byproduct of our analysis we investigate the Polyakov loop and its hermitian conjugate. Our data offer a vivid evidence of the importance of the complex nature of the functional integral measure, which results in $L(\mu) \neq \bar{L}(\mu)$ for a real chemical potential μ .

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The Charm Quark contribution to the Equation of State of QCD on $N_t = 4$ and $N_t = 6$ lattices

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The equation of state (EoS) of QCD is an important input into the hydrodynamic models that describe the expansion of the Quark-Gluon Plasma (QGP) in the initial moments following

a heavy ion collision. Recently, there have been several detailed calculations of the QCD EoS at vanishing chemical potential ($\mu = 0$) using realistic or nearly realistic masses for the three lightest flavors of quarks and $O(a^2)$ improved lattice actions [1,2]. These studies all neglect the effect of the charm quark. However, a recent paper [3] suggests that the charm quark contribution to the QCD EoS may be visible starting at temperatures as low as $T \sim 350\text{MeV}$, a significant effect for the conditions achieved in the next generation of heavy ion collisions at the LHC. Although the applicability of thermalized charm degrees of freedom to hydrodynamic modelling of heavy ion expansion is a subtle issue, charm quarks certainly play a role in understanding the QGP of the early universe. We present here a calculation of the charm quark contribution to the QCD equation of state on the lattice using the p4fat3 fermion action on $N_t = 4$ and $N_t = 6$ lattices at vanishing chemical potential. In particular, we calculate the energy density, pressure, and entropy density as a function of temperature in the temperature range $0.9T_c < T < 4.2T_c$ [4].

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INVESTIGATION OF THE QCD PHASE TRANSITION USING DOMAIN WALL FERMIONS

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We report on the first lattice QCD study of the QCD phase transition using domain wall fermions with 2+1 flavors. Our calculations are performed on a $16^3 \times 8$ lattice with 32 sites in the fifth dimension. The accurate chiral and flavor symmetries of the domain wall fermion formulation make this approach an important alternative to the more extensive calculations being carried out using staggered fermions. We will present detailed results on the chiral

condensate and Polyakov loop variables and their susceptibilities in the transition region and compare our results to those obtained on $N_t = 8$ lattices with staggered fermions.

Phases of Dense Quarks at Large N_c

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We describe recent work on the phase diagram of QCD in the μ_B - T plane in the limit of a large number of colors N_c . We argue that there are three phases. Two are the familiar confined and deconfined phases, with respective $O(1)$ and $O(N_c^2)$ degrees of freedom. There is a third phase with $O(N_c)$ degrees of freedom which is at high density and intermediate temperature. This phase is confined but has quasi-free quarks, and is called the Quarkyonic phase. In the transition between the confined and Quarkyonic phase, the baryon number expectation value is an order parameter. In the transition between the unconfined and Quarkyonic phase, the order parameter is Polyakov loop.

TRACE ANOMALY AND DIMENSION TWO CONDENSATE ABOVE THE PHASE TRANSITION

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In a series of recent papers it has been shown that the dimension two gluon condensate $\langle A_0^2 \rangle$ can be used to construct a phenomenological model that explain quite well the non-perturbative behaviour observed in lattice data for the heavy quark-antiquark free energy in the deconfined phase of QCD [1] and more specifically in the renormalized Polyakov Loop [2,3]. It is considered in this model a new piece in the gluon propagator driven by a positive mass dimension parameter:

$$D_{00}(\mathbf{k}) = D_{00}^{\text{Pert}}(\mathbf{k}) + D_{00}^{\text{NonPert}}(\mathbf{k}), \quad D_{00}^{\text{NonPert}}(\mathbf{k}) = \frac{m_G^2}{(\mathbf{k}^2 + m_D^2)^2}, \quad m_G^2 > 0.$$

This non-perturbative contribution is the responsible of power-like temperature corrections, in contrast to the flat temperature dependence of the logarithmic running of the QCD coupling constant derived in perturbation theory. The model predicts a interesting duality between the zero temperature potential as a function of the $q\bar{q}$ separation, on the one hand,

and the quark self-energy as a function of the temperature, on the other.

At finite temperature the trace of the energy momentum tensor is related not only to the trace anomaly but also to the difference $\epsilon - 3p$, with ϵ the energy density and p the pressure [4]. Far from the conformal limit, $\epsilon = 3p$, it provides a measure of the interaction. It has been shown recently that unmistakable traces of power temperature corrections also appear in lattice data for the trace anomaly (and pressure) in the region slightly above the phase transition [5,6]. In the present work we extend the previous phenomenological model to derive this non-perturbative behaviour, which may be accommodated by the dimension two gluon condensate. We show under Renormalization Group requirements, explicit expressions of the thermal behaviour for several observables: pressure, energy density, free energy, etc; which reproduces very well lattice data. The value for the gluon condensate predicted from these observables agree quite well with previous works. The mass parameter m_G signals an explicit breaking of the scale invariance.

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How to crossover from hadronic to partonic phase in QCD?

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It is argued that, due to the existence of two vacua in QCD — perturbative and physical, the mechanism for the crossover from hadronic to partonic phase is hard to construct. The hadronization of partons one by one, assumed in current models for crossover, contradict color confinement. The challenge is: how to realize the transition between the two vacua during the gradual crossover of the two phases.

In this talk a possible mechanism for the crossover in QCD compatible with color confinement is proposed, where the way of vacuum-change during the gradual crossover between the two phases is via the following steps:

1) As the increasing of temperature, partons in hadrons start to be delocalized, tunneling between neighboring hadrons, and change the latter to *colored parton-groups* located in *potential wells*, which is referred to as *cells* in percolation calculation.

2) The wells (or cells) connected by *tunnels*, which will be referred to as *bonds* in percolation calculation, form *color singlet clusters*, which grow up in the physical vacuum, and eventually become a big cluster of the system size. Inside this cluster is a *grape-shape per-*

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turbative vacuum, while outside of it is *physical vacuum bubbles*. These bubbles will change to perturbative too as the further increase of temperature, and the colored parton-groups in the wells can then move around, forming a fluid-like matter — sQGP.

3) The potential barriers between neighboring wells will drop to zero at a still higher temperature and all the wells disappear, the sQGP is then turned to wQGP.

A dynamical percolation model is constructed to exhibit this mechanism, which is based on a simple dynamics for quark delocalization. The result of the dynamical calculation is that when two cells are close together the delocalization is large, but when they separate to a certain distance S_0 , the delocalization degree suddenly drops to zero. S_0 is the distance within which quarks are delocalized and bonds are likely to be formed. It is used to construct a percolation procedure. Since there are 3 quarks in a cell and a bond is essentially a tunnel for quark to travel, each cell can connect to 3 bonds at most. Three cells are chosen randomly within the distance S_0 to form bonds with a given cell. Color-singlet clusters are constructed in this way and thus provide a basis for the crossover process described above.

The above-mentioned procedure is a kind of *dynamical-percolation* proposed for the first time, which is superior to the purely geometrical percolation in that, it provides a mechanism for both the crossover of hadronic matter to sQGP and the transition from sQGP to wQGP in the increasing of temperature via a temperature-dependent parameter, while the geometrical percolation models are able to treat only the effect of the increasing of density.

Eight-quark interactions as a chiral thermometer

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The proposal to include eight-quark interactions to stabilize the ground state of the combined three flavor Nambu — Jona-Lasinio Lagrangians has been done in [1], where the most general spin zero combinations have been worked out. They turn out to be also of vital importance in the study of temperature effects in chiral multi-quark interaction lagrangians [2] (SU(3) flavor limit, massless case), and [3] (realistic massive case). The transition temperature can be considerably reduced as compared to the standard approach, in accordance with recent lattice calculations. The mesonic spectra built on the spontaneously broken vacuum induced by the 't Hooft interaction strength, as opposed to the commonly considered case driven by the four-quark coupling, undergo a rapid crossover to the unbroken phase, with a slope and at a temperature which is regulated by the strength of the OZI violating eight-quark interactions. This strength can be adjusted in consonance with the four-quark coupling and leaves the spectra unchanged, except for the sigma meson mass, which decreases. A first order transition behavior is also a possible solution within the present approach. Additional information from lattice calculations and phenomenology is necessary to fix finally the strength of interactions. We expect that the role of eight-quark interactions is of equal importance in studies involving a dense medium and extensions of the model with the Polyakov loop.

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Eightfold way mesons from dynamical first principles in strong coupled lattice QCD

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Abstract

We consider a 3+1 lattice QCD model with three quark flavors, local $SU(3)_c$ gauge symmetry, global $SU(3)_f$ isospin or flavor symmetry, in an imaginary-time formulation and with strong coupling (a small hopping parameter $\kappa > 0$ and a plaquette coupling $\beta > 0$, $0 < \beta \ll \kappa \ll 1$). Associated with the model there is an underlying physical quantum mechanical Hilbert space \mathcal{H} which enables us to introduce spectral representations for correlations and obtain the low-lying energy-momentum spectrum rigorously. Using the decoupling of hyperplane method (Refs. [1,2]) and concentrating on the subspace $\mathcal{H}_e \subset \mathcal{H}$ of vectors with an *even* number of quarks, we obtain the one-particle spectrum showing the existence of 36 meson states from dynamical first principles, i.e. directly from the quark-gluon dynamics. Besides the $SU(3)_f$ quantum numbers (total hypercharge, quadratic Casimir C_2 , total isospin and its 3rd component), the basic excitations also carry spin labels. The total spin operator J and its z -component J_z are defined using $\pi/2$ rotations about the spatial coordinate axes and agree with the infinitesimal generators of the continuum for improper zero-momentum meson states. The eightfold way meson particles are given by linear combinations of these 36 states and can be grouped into three $SU(3)_f$ nonets associated with the vector mesons ($J = 1$, $J_z = 0, \pm 1$) and one nonet associated with the pseudo-scalar mesons ($J = 0$). Each nonet admits a further decomposition into a $SU(3)_f$ singlet ($C_2 = 0$) and octet ($C_2 = 3$). The particles are detected by isolated dispersion curves $w(\vec{p})$ in the energy-momentum spectrum. They are all of the form $w(\vec{p}) = -2 \ln \kappa - 3\kappa^2/2 + (1/4)\kappa^2 \sum_{j=1}^3 2(1 - \cos p^j) + \kappa^4 r(\kappa, \vec{p})$, with $|r(\kappa, \vec{p})| \leq \text{const.}$ For the pseudo-scalar mesons $r(\kappa, \vec{p})$ is jointly analytic in κ and p^j , for $|\kappa|$ and $|\text{Im } p^j|$ small. The meson masses are given by $m(\kappa) = -2 \ln \kappa - 3\kappa^2/2 + \kappa^4 r(\kappa)$, with $r(0) \neq 0$ and $r(\kappa)$ real analytic. For a fixed nonet, the mass of the vector mesons are independent of J_z and are all equal within each octet. All singlet masses are also equal for the vector mesons. For $\beta = 0$, up to and including $\mathcal{O}(\kappa^4)$, for each nonet, the masses of the octet and the singlet are found to be equal. All members of each octet have identical dispersions. Other dispersion curves may differ. Indeed, there is a pseudo-scalar, vector meson mass splitting (between $J = 0$ and $J = 1$) given by $2\kappa^4 + \mathcal{O}(\kappa^6)$. Using

a correlation subtraction method, we show the 36 meson states give the only spectrum in \mathcal{H}_e up to near the two-meson threshold of $\approx -4 \ln \kappa$. Combining our present result with a previous one for baryons (Ref. [1]) shows that the model exhibits confinement up to near the two-meson threshold.

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3D Hydro + UrQMD Model with QCD Critical Point

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Lattice QCD calculations have predicted a critical point for the QCD equation of state where the 1st order phase transition on the phase boundary terminates. However at present its location on the phase diagram is not determined due to the difficulty of performing lattice QCD calculations with finite chemical potential. Therefore experiments and phenomenological quantitative analyses under varying conditions (such as collision energies and system sizes) are indispensable in determining the existence and location of the critical point.

Here, we construct a QCD equation of state with a critical point under the assumption that QCD has the same universality class as the 3d Ising Model. First we determine the singular part of the equation of state in the critical region around the critical point from the 3d Ising Model. Then we map the equation of state of the 3d Ising model onto the QCD phase diagram and match it to the usual QGP (bag model) and hadron (exclude volume model) equations of state [1].

We subsequently utilize a hybrid macro+micro transport model [2] to determine possible experimental signatures of the existence of the critical point in our calculations. This model combines a fully three-dimensional relativistic 3D-hydrodynamics for the QGP phase and phase transition with a microscopic non-equilibrium model for the later hadronic stage. Using an equation of state with a simple 1st order phase transition without a critical point, the hybrid hydro+micro approach has been very successful in describing the dynamics of hot, bulk QCD matter, which has been created in ultra-relativistic heavy ion collisions at RHIC [2]. We will show a detailed comparison between the results of calculations with both equations of state, focusing on reaction dynamics, hadronic freezeout, transverse flow and elliptic flow. In addition we shall explore the location of QCD critical point on the phase diagram via the analyses kinetic freezeout temperature, transverse momentum fluctuation and so on.

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Tests of Fluidity of AdS/CFT Plasma Wakes

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The AdS/CFT correspondence predicts [1] much stronger energy loss of heavy quarks at RHIC and LHC than pQCD. Additionally, it predicts [1-3] a striking Mach-cone plus diffusion jet-wake correlation pattern that resembles the near perfect fluid response of the sQGP. In this work we test the AdS energy-momentum tensor solutions in [3] for collective behavior by matching their form to the expected Navier-Stokes viscous fluid form, assuming the minimal AdS $\eta/s = 1/4\pi$ viscosity. We check to what extent the energy in the wake created by the heavy quark is thermalized and the degree of local isotropization in the plasma's local rest frame (Landau frame). We find that for a reasonably large N t'Hooft coupling $\lambda \sim 10$ and realistic T (~ 300 MeV), the system is well described by relativistic Navier-Stokes equations. This suggests that up to significant differences between strongly coupled QCD and SYM, the energy lost by heavy quarks in the medium created at RHIC should be mostly thermalized. We also perform a comparison between the energy-momentum tensor obtained in [2-3] with a full ideal 3D numerical hydrodynamic solution with the objective of disentangling the viscous and ideal contributions and of ascertaining the form of the energy-momentum source provided by the heavy quark. Unfortunately, contrary to first suggestions and RHIC data, the strong AdS diffusion wake fills the inside of the AdS Mach cone after a Cooper-Frye freeze-out of the sQGP [4]. We discuss how Mach cone like signatures differentiate between pQCD versus AdS/CFT jet energy-momentum loss mechanisms.

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Zero mode contribution to quarkonium correlators and heavy quark kinetics

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Heavy quarks play an important role as diagnostic tools of the quark gluon plasma and therefore it is important to learn as much as possible about their in-medium properties from lattice calculations. Recently it has been realized that the dominant source of the temperature dependence of quarkonium correlators is due to the zero mode contribution, i.e. to the contribution coming from the low energy ($\omega \ll T$) part of the corresponding spectral functions [1-2]. Therefore the zero mode contribution contains information on the transport properties of heavy quarks, namely effective masses, thermal velocity and heavy quark diffusion constant. In this contribution I am going to discuss the calculation of the zero mode contribution to quarkonium correlators using lattice data generated on isotropic as well as anisotropic lattices at several lattice spacings which cover the temperature interval $T = 1.06T_c - 3T_c$. From the zero mode contribution to the vector current correlators I extract the thermal velocity of heavy quarks which appears to be significantly smaller than the naive estimate in the entire temperature range. Furthermore, the thermal velocity shows a rapid drop close to the transition temperature. By comparing the obtained zero mode contribution in the scalar and axial-vector correlators to the gas of quasi-free heavy quarks I extract the effective heavy quark masses and possible consequences for the heavy quark dispersion relations. Finally, I plan to discuss to what extent current lattice data can constrain the value of the heavy quark diffusion constant. Preliminary results from these investigations have been reported in Refs. [3,4].

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Heavy Quark Thermodynamics with realistic quark masses

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I am going to present a new and improved study of the heavy quarks in the hot medium using lattice approach. It is based on a large-scale simulation by RBC-Bielefeld collaboration with physical strange quark mass and realistic up/down-quark masses, corresponding to pion masses from 450 down to 150MeV. Monte-Carlo simulations are performed for various lattice sizes, from $16^3 \times 4$ to $32^3 \times 8$. This allows to control approach to the thermodynamic and continuum limits. The entropy contribution to the free energy is separated and I discuss its implications for the heavy quarks bound states dissociation. Running coupling is calculated and dependence of its maximal value on the temperature is shown in a wide temperature range. Renormalized order parameter for the deconfinement transition is extracted using new, improved scheme which is independent of short-distance physics. Implications for perturbation theory-based calculations are also discussed.

Further simulation details can be found in [1,2]

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Relativistic BCS-BEC crossover in a boson-fermion model

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We investigate the crossover from Bardeen-Cooper-Schrieffer (BCS) pairing to a Bose-Einstein condensate (BEC) in a relativistic superfluid within a boson-fermion model. The model includes, besides the fermions, separate bosonic degrees of freedom, accounting for the bosonic nature of the Cooper pairs. The crossover is realized by tuning the difference between the boson mass and boson chemical potential as a free parameter in the mean field approximation. The model yields populations of condensed and uncondensed bosons as well as gapped and ungapped fermions throughout the crossover region for arbitrary temperatures. Moreover, we observe the appearance of antiparticles for sufficiently large values of the crossover parameter. As an application, we study pairing of fermions with imbalanced populations. The model can potentially be applied to color superconductivity in dense quark matter at strong couplings.

The quantum fluctuations of the pairing condensate is provided by bosons in non-zero modes. Using Cornwall-Jackiw-Tomboulis formalism we calculate the condensate and the critical temperature T_c including the contribution from the fluctuations. We also compute the dissociation temperature T^* for bosons, above which they are not stable and start to decay. We find the crossover parameter range for $T^* > T_c$, which indicates the existence of bosons even above T_c but below T^* , or the so-called pseudogap phenomenon in literature.

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The rigidity of crystalline color superconducting quark matter

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Cold three flavor quark matter at large (but not asymptotically large) densities, may exist as a crystalline color superconductor. These phases feature diquark condensates that vary periodically in space, forming crystalline patterns. We present the calculation of the free energies, Ω 's, and gaps, Δ 's, for many different crystalline structures, performed in the Ginzburg-Landau approximation [1,2]. We develop a qualitative understanding of what makes a crystal structure stable, and find two structures with particularly large values of Δ and $-\Omega$. The robustness of these phases results in their being favored over wide ranges of density relevant for neutron star phenomenology, and though it also implies that the Ginzburg-Landau approximation is not quantitatively reliable, it is worthwhile to look at phenomenological implications of their presence in neutron star cores.

The unique feature of the crystalline phases of color superconducting quark matter among all forms of dense matter that may arise within neutron star cores is that they are rigid. We derive the effective action for the phonon fields that describe space- and time-dependent fluctuations of the crystal structure formed by the condensate, and obtain the shear modulus from the coefficients of the spatial derivative terms [3]. Within a Ginzburg-Landau approximation, we find shear moduli which are 20 to 1000 times larger than those of neutron star crusts. This phase of matter is thus more rigid than any known material in the universe, but at the same time the crystalline color superconducting phase is also superfluid — by picking a phase its order parameter breaks the quark-number $U(1)_B$ symmetry spontaneously. These properties raise the possibility that the presence of this phase within neutron stars may have distinct implications for their phenomenology. For example, (some) pulsar glitches may originate in crystalline superconducting neutron star cores.

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On the complete phase diagram of QCD

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The phase diagram of QCD is five dimensional, although only three dimensions are open to experimental probes. Theoretically, only special slices with some symmetries have been considered in the past— for example the mass difference between u and d quarks has been neglected [1].

An investigation of the complete phase diagram of QCD at small chemical potential is reported here. Prior knowledge is extended using basic thermodynamic identities. For QCD with two flavours of quarks, we pay special attention to the u-d quark mass difference, and find that its inclusion has interesting effects on the shape of the phase diagram. The question of stability of the predictions is discussed.

Possible differences between two-flavour and three-flavour QCD [2] are classified, along with their influence on the phase diagram. The importance of locating special points on the phase diagram is dealt with.

Experimental consequences of these results are discussed, with special attention paid to a signal [3] of a critical point in heavy-ion collisions.

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AdS/CFT Gravity Dual for High Energy Collisions

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Holographic description of N=4 SYM theory in strong coupling regime can be achieved via AdS/CFT correspondence. Large number of applications use this tool but most of them are done in a static setting, with either pure AdS (as is for example our calculation [1] of the stress tensor of a static dipole) or at fixed temperature via Witten's AdS black hole metric (as are calculations of Gubser et al and Yaffe et al of the “conical flow”).

High energy collisions in QCD are very difficult problems. They include non-equilibrium physics and involve different scales and different coupling regimes. Arguments suggested recently put forward a view that QCD has certain “strong coupling window”. In particular, Brodsky and Teramond and Shuryak [2] have argued that the power scaling observed for large number of exclusive processes is not due to perturbative QCD but to a strong coupling regime in which the running is absent and quasi-conformal regime.

The picture we study is similar to well known Lund model, with QCD strings stretched by departing partons. The difference is that now strings are “gravity dual” ones and they fall

into the IR direction of AdS_5 , departing from our world rather than being broken. The details of their motion was studied in our paper [3].

In more recent paper [4] we calculated the stress tensor of excited matter, created by gravity perturbations calculated from linearized Einstein eqns. We found that closed strings (“stones”) falling into AdS center produce *no* stress tensor at all. The falling open strings, connected to receding charges, do produce a nonzero stress tensor which we found analytically from time-dependent linearized Einstein equations in the bulk. It corresponds to exploding non-equilibrium matter: we discuss its behavior in detail, including its internal energy density in a co-moving frame and the “freezeout surfaces”. We then calculate what happens for the ensemble of multiple strings, e.g. for a colliding walls of color charges (so to say, a strongly coupled Color Glass).

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Towards QCD thermodynamics using exact chiral symmetry on lattice

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Investigations of QCD with non-zero chemical potential are important for the physics of neutron stars and heavy ion collisions. Staggered fermions, used most commonly in such studies preserve a chiral symmetry but break flavour and spin, epitomised in the famous “rooting of the determinant” problem. Recently proposed Overlap and Domain Wall Fermions have superior chiral properties and do not suffer from the rooting problem. In an effort to study QCD thermodynamics using them, we investigate the ideal Fermi gases of such fermions and obtain relations between them.

Transverse Momentum Broadening of a Fast Quark in a $\mathcal{N} = 4$ Yang Mills Plasma.

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We compute the momentum broadening of a heavy fundamental charge propagating through a $\mathcal{N} = 4$ Yang Mills plasma at large 't Hooft coupling. We do this by expressing the medium modification of the probe's density matrix in terms of a Wilson loop averaged over the plasma. We then use the AdS/CFT correspondence to evaluate this loop, by identifying the dual semi-classical string solution. The calculation introduces the type "1" and type "2" fields of the thermal field theory and associates the corresponding sources with the two boundaries of the AdS space containing a black hole. The transverse fluctuations of the endpoints of the string determine $\kappa_T = \sqrt{\gamma\lambda}T^3\pi$ – the mean squared momentum transfer per unit time. (γ is the Lorentz gamma factor of the quark.) The result reproduces previous results for the diffusion coefficient of a heavy quark. We compare our results with previous AdS/CFT calculations of \hat{q} .

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Measuring the Transition Temperature on $N_\tau=8$ Lattices with 2+1 flavor asqtad and p4fat3 actions

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Just as heavy ion collisions provide the only means to measure the properties of the quark gluon plasma, the techniques of lattice quantum chromodynamics provide the only currently viable means to calculate many of its properties, such as the transition temperature, the type of transition, and the equation of state. We report on a recent set of calculations by the HotQCD Collaboration to calculate the pseudo-critical temperature of the phase transition with nearly 50M cpu-hours of dedicated time on the LLNL BlueGene/L Supercomputer. These calculations extend recent work by the MILC and RBC-Bielefeld collaborations to lattices of dimension $32^3 \times 8$, using both the asqtad and p4fat3 improved staggered fermion actions for lines of constant physics with the light quark mass set to one tenth the value of the strange quark. Results for the Polyakov loop, chiral susceptibility, and quark number susceptibility will be shown. We find the transition temperatures determined from quantities sensitive to chiral symmetry restoration or to deconfinement to be approximately consistent with one another and we also find excellent agreement between both fermion actions. We will report on the latest HotQCD results and discuss implications for hydrodynamic models

that can be directly compared with experimental data.

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Search for QCD Hawking Radiation in Heavy Ion Collisions

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A wide variety of measurements at RHIC, for example v_2 and energy loss, suggest that the partonic matter created in heavy collisions thermalizes very early. One possible mechanism for this is the creation of the QCD analogue to gravitational black holes [1]. Such objects have no memory of their creation and radiate with a characteristic temperature T that can depend only on their energy, charge and angular momentum. This hypothesis is consistent with the growth of multiplicity with \sqrt{s} in e^+e^- collisions and the thermal temperature observed at LEP. For central heavy ion collisions the angular momentum of the system is approximately zero and the model predicts a universal dependence of the chemical freeze-out temperature on the ratios of charge to transverse energy. This prediction can be tested against BRAHMS data since the very wide angular and p_T acceptance of the experiment, combined with excellent particle identification allows both quantities to be measured as a function of rapidity and $\sqrt{s_{NN}}$. We have fitted BRAHMS data on π^\pm, K^\pm, p and \bar{p} from central Au+Au collisions at several rapidities at $\sqrt{s_{NN}} = 62$ and 200GeV using the grand canonical ensemble. This was done using the THERMUS code [2]. The experimental dependence of the temperature on the ratio of charge to transverse energy will be compared to the Hawking radiation predictions. This model also predicts that the temperature of the system should decrease as the angular momentum increases. Estimating the angular momentum of the system is not trivial. By comparing data sets at different energy, centrality and rapidity we can select systems with the same ratio of baryon number to energy but different rapidities. This may allow us to test for any effect of angular momentum on temperature. Finally we will present suggestions for future low energy running at RHIC and higher energy measurements at LHC.

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SEARCH FOR A SIGNAL ON QCD CRITICAL POINT IN CENTRAL NUCLEUS-NUCLEUS COLLISIONS

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Studying the centrality dependence of the characteristics of nucleus-nucleus collisions is an important experimental way for obtaining information on the QCD phases of strongly interacting matter. Some experimental results on the centrality experiments already indicated the points of regime changes. These points appear as a critical phenomena in the wide range of energy. In some cases after point of regime change the saturation is observed.

If the regime change observed in the different experiments takes place unambiguously two times, this would surely be the most direct experimental evidence seen to observe the QCD critical point and phase transition. But the central experiments could not indicate it. It may be connect with the appearance of the critical transparency of the matter near the critical point. Because it is supposed that in high density matter near the critical point the quarks and partons could be bound as a result of the percolation and the matter might behave as a superconductor [1].

Appearance of the critical transparency could change the absorption capability of the medium and could be a reason why anomalous suppression of the J/Ψ production was indeed observed in central Pb-Pb collisions at the CERN SPS [2]. The saturation which accompanies the point of regime change on the behavior of the ratio of the J/Ψ to Drell-Yan cross-sections as a function of centrality may connect with appearance of the critical transparency around the critical point. We therefore speculate that with increasing centrality the ratio has to decrease as a result of increasing the density of medium and accordingly its absorption capability. The appearance of superconducting property of the strongly interacting matter as a result of the formation of percolation cluster could stop decrease of yields of heavy flavors.

Thus it is expected to see the new structure in the behavior of the charmonium yields as a function of the centrality which would connect with the percolation cluster formation around the critical point.

So, the study of behavior of centrality dependence of the ratio (the nuclear modification factor) of heavy flavor particle yield with fixed values of the p_T (or η) in heavy ion collisions to those ones in nucleon-nucleon (or light nuclear) interaction as a function of centrality could give the information on change of absorption properties of medium near the critical point.

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QGP SUSCEPTIBILITIES FROM PNJL MODEL

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We study various thermodynamic variables within the framework of Polyakov-Nambu-Jona-Lasinio (PNJL) model [1,2,3] and its improved version. PNJL model is the synthesis of NJL model [4] with the Polyakov loop model [5]. The advantage of the model is that one can study both the confinement-deconfinement transition and the Chiral phase transition within a single framework. Using the model we study the quark number susceptibility and its higher order derivatives, speed of sound, specific heat and conformal measure. These quantities are related to various fluctuations which can be measured from the heavy ion collision experiments. We compared our results with the Lattice data and find good agreement with the later. Next we extend the PNJL model by including the effect of the SU(3) measure with a Van der Monde term. The most important physical problem with the simpler version of the PNJL model is that Φ becomes greater than 1 at temperatures above $2T_c$ (here Φ is the normalized trace of the Wilson Line \mathbf{L} and should lie between 0 and 1). We cure this problem by adding a Van der Monde term which is nothing but Jacobian of transformation from the matrix valued field \mathbf{L} to the complex valued field Φ . The pressure, energy density, specific heat, speed of sound and conformal measure show small or negligible effects from this term. However various quark number and isospin susceptibilities are all found to approach their respective ideal gas limits around $2T_c$.

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Charmonium dissociation temperatures in lattice QCD with a finite volume technique

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We present a study of charmonium dissociation temperatures in lattice QCD. The dissociation temperatures of J/ψ , ψ' , and χ_c states play key roles in sequential J/ψ suppression scenarios. To distinguish a bound state from the scattering states, charmonium spectral functions have been studied on the lattice using e.g. the Maximum Entropy Method. Recently,

however, we have pointed out that a constant mode in finite temperature meson correlators can lead to misleading conclusions about the stability of charmonium states when the constant mode is not removed in the spectral function [1]. In this study, we adopt a finite volume method [2] taking into account the effects of the constant mode. We investigate the charmonium mass spectra under different spatial boundary conditions. We combine a variational analysis to improve the signals of excited states such as ψ' states. Besides the dissociation temperatures, we discuss the temperature dependence of the wave function (the Bethe-Salpeter amplitude) of the charmonia [3] to see whether the c -quark and \bar{c} -quark stay together with each other or not above T_c .

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RADIAL DISTRIBUTION FUNCTION OF HOT QGP

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In all the recent topics on the relativistic heavy ion physics, the most prominent one is how to understand the mechanism of strong coupling in QGP. Hydrodynamics is merely a description at macroscopic level that cannot directly answer why it is strong coupling. In this work, we try to discuss this problem at microscopic level by investigating its dynamical interaction from the liquid state points of view. As for a liquid, the most basic characteristic is the short-range order, i.e., the radial distribution function possesses the typical shape of damping oscillation instead of monotonic decreasing as in ideal gas.

The radial distribution function is the probability of finding two particles at a distance r from each other, which can be related to the 'potential of mean force' $V(r)$ by the relationship [1] $g(r) = \exp(-V(r)/T)$ where $V(r)$ gives the average static interparticle potential and is so called in-medium interparticle potential. This potential can be evaluated[2] through

$$V(r) = \frac{Q_1 Q_2}{4\pi^2 r} \text{Im} \int_{-\infty}^{\infty} dq \frac{q e^{iqr}}{q^2 + F(0, q)}, \quad (3)$$

where Q_1 and Q_2 are the charges, $q = |\mathbf{q}|$ is the three-momentum transfer, and F is the longitudinal component of boson polarization tensor defined as $F = (Q^2/q^2)\Pi_{00}$. It's clear that the behavior of static in-medium interparticle potential or the radial distribution function is determined by the analytic structure of integrand which depends on the polarization

patterns. In this work, we involved the colored bound state picture in QGP[3] and found out that polarization tensor persists complex poles, which makes an oscillatory interparticle potential like

$$V(r) = \frac{Q_1 Q_2}{\pi(a^2 + b^2)} \frac{e^{-q_i r}}{r} [a \cos(q_r r) + b \sin(q_r r)], \quad (4)$$

where a and b are some constants. This refers to the so-called Yukawa oscillations which produces a liquid-like radial distribution function.

We emphasize that the static mode is determined by the polarization pattern. In case the pattern is well chosen, there might exit a certain mode in sQGP that can produce eligible long-range order serving for a liquid state.

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Free quarks and antiquarks versus hadronic matter

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The form of matter produced in high-energy heavy ion collisions has been widely and intensely explored since 1974. Above T_c this matter was conjectured as weakly interacting quark-gluon plasma, but recently is realized from RHIC Au-Au collisions as strongly interacting quark-gluon plasma [1] and even is theoretically suggested as the coexistence of quark-gluon plasma and bound states of quarks and antiquarks [2]. Below T_c the recognition on the form of matter is embodied in the picture: this matter only consists of hadrons, i.e. pure hadronic matter, and the evolution of this matter is determined by hadron scatterings and hadron flows. Hadron-hadron elastic scatterings establish thermal states of hadronic matter. However, we show that this pure hadronic matter is mixed with free quarks and antiquarks [3]. The reason is that meson-meson scatterings into free quarks and free antiquarks at typical high temperature can cause the ratio of free-quark number density to number density of hadronic matter to be larger than 0.1 in a short time period of 0.5 fm/c. In deconfinement one generally think that quarks and antiquarks automatically move from the small hadron volume toward the large volume of hadronic matter and such a process only relates to individual hadron. However, we show that the meson-meson reactions offer a new way for deconfinement near the critical temperature, and name the deconfinement via the reactions collisional deconfinement [3]. We address the occurrence of deconfinement from variation of number densities of hadrons, free quarks and antiquarks in contrast to the variation of energy density, chiral condensate and the screening mass of a heavy quark-antiquark pair studied in lattice QCD [4]. It is interesting to directly study such collisional

deconfinement in lattice QCD while collision of two $SU(2)$ Yang-Mills wave packets in free space is manageable [5]. We limit our attention to matter below T_c and focus on the reactions of π , ρ , K and K^* because the four hadron species are dominant meson species in hadronic matter at RHIC. In fact, in a method we explicitly raise and solve the two problems: whether matter below T_c is the pure hadronic matter or not and whether color deconfinement relates to low-energy meson-meson collisions in hadronic matter or not.

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