Theoretical Highlights of Quark Matter 2004

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Abstract. Selected highlights of the theoretical developments reported at the 2004 Quark Matter conference are discussed, with emphasis on open issues.

1. Introduction

High-energy heavy-ion collisions (HEHIC’s) aim at creating the Quark-Gluon Plasma (QGP), together with a thorough investigation of the phase diagram of strongly interacting matter. The 17th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions constituted another milestone towards these ambitious goals.

From the theory side, the objective is to develop a coherent and consistent description of the relevant processes transforming the incoming nuclei into the finally measured (hadronic and electromagnetic) particle numbers, spectra, and correlations. The combination of different approaches is inevitable; e.g., the evolution of bulk matter might be cast as a succession of color-glass initial state, hydrodynamic expansion of ultradense phases, and transport simulations of moderately dense matter. To interface these building blocks, knowledge on the relevant microscopic degrees of freedom, their interactions and spectral properties is mandatory. The latter also hold the key to relating observables to (pseudo-) order parameters of the phase transition(s) to be identified. A further challenge is posed by the transition regime from bulk matter to perturbative spectra, as emphasized in Wiedemann’s theoretical overview talk [1].

Along these lines, I review below progress that has been reported on theoretical approaches to the QCD phase diagram (Sec. 2), on properties of bulk matter as deduced from RHIC runs 2+3 (Sec. 3) and on microscopic probes expected to be scrutinized in run 4 and the recent SPS run (Sec. 4). Final remarks are made in Sec. 5.

2. QCD Theory at Finite Density and Temperature

2.1. Colorsuperconductivity

The richness of the phase diagram at high densities and small temperatures continues to provide for new phases, especially under conditions relevant for compact stars such

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as color and charge neutrality. The key quantity at moderate quark chemical potential, \( \mu_q \approx 400 \text{ MeV} \), is the (constituent) strange quark mass, \( m_s^*(s) \). Rajagopal elucidated that, reducing \( \mu_q \) from large values, the first transition is probably from the \( u-d-s \) symmetric CFL ground state into a “gapless” CFL phase \([2]\): the asymmetry induced by \( m_s \) trifurcates the gap value and induces “blocking” regions on the \( d \)- and \( s \)-Fermi surfaces where their pairing is inhibited. One of the open questions is whether a 2SC state (\( u-d \) pairing only) exists in nature, which essentially hinges on the condition \( \mu_q < m_s^* \) being met in the quark phase, thus depending on nonperturbative forces responsible for chiral symmetry breaking (\( \chi \text{SB} \)) in the vacuum.

Applications to neutron star phenomenology were discussed by Reddy, who argued that star radii of 8 km or less clearly favor a quark-matter equation of state (EoS). Much like in HEHIC’s, electroweak emission is a promising signal of in-medium effects, probing the low-lying excitations (Goldstone bosons, (di)quark quasiparticles) of the matter in, e.g., supernovae explosions or long-term cooling \([3, 4, 5]\).

2.2. Chiral vs. Deconfinement Transition

A longstanding problem associated with the QCD phase diagram is the relation between chiral and deconfinement transitions. Current lattice calculations indicate that in real QCD the small but finite current quark masses, \( m_q \), lead to a finite-\( T \) transition which is not of first order. However, the peaks in the susceptibilities pertinent to order parameters at \( m_q \rightarrow \infty \) and \( m_q = 0 \) – Polyakov loop \( \langle L \rangle \) and quark condensate \( \langle \bar{q}q \rangle \), respectively – precisely coincide \([6]\). Fukushima suggested \([8]\) this feature to arise through a mixing of the scalar “soft” modes that become massless at the second order endpoints in the \( T-m_q \) plane, cf. left panel of Fig. \([\text{1}]\). For the chiral transition this is the usual “\( \sigma \)”-meson, whereas for deconfinement he argued it to be the electric glueball field. Their mixing ensures the coincidence of the (pseudo-) transitions also in the cross-over region. It is not quite clear, however, why this mechanism is not operative for quarks in the adjoint representation where lattice QCD (LQCD) observes two distinct transition temperatures \([9]\). Similar issues were addressed by Mócsy \([10]\).

2.3. Lattice QCD Results

One can close the gap between the two endpoints \( C \) and \( D \) in Fig. \([\text{1}]\) (left panel) by moving to finite \( \mu_q \). Recent lattice computations have pursued this by an expansion in \( \mu_q/T \), as discussed by Redlich and Karsch \([11, 12]\). Fig. \([\text{1}]\) (right panel) shows results for the quark number susceptibility, which indeed develops a rather sharp maximum (signaling a rapid change in baryon density) at \( \mu_B = 3\mu_q \approx 500 \text{ MeV} \), quite reminiscent to independent determinations of the critical endpoint \([13]\). This puts the latter into the realm of the future GSI facility, the physics of which was reviewed by Friman \([14]\).

Further progress on finite-\( T \) (quenched) LQCD results for charmonium properties was reported by Karsch, Asakawa and Datta. From the color-singlet free energy, \( F_1 = V_1 - TS \), the pertinent \( c\bar{c} \) potential has been extracted which appears to support
bound states for a range of temperatures above $T_c$ [15]. This corroborates the analyses of spectral functions exhibiting resonance/bound states of low-lying charmonia ($\eta_c$, $J/\psi$) surviving up to $\sim 2T_c$ [16, 17], which could have important consequences for charmonium production at RHIC, see Sec. 4.3 below.

3. QCD Bulk Properties at RHIC

In this section, I will essentially follow a chronological order in discussing the properties of matter as evolving in a HEHIC, i.e., from the initial state (Sec. 3.1) via the dense phases through the phase boundary (Secs. 3.2, 3.3) until thermal freezeout (Sec. 3.4).

3.1. Color-Glass Condensate (CGC)

An important experimental finding since the previous Quark Matter conference is the absence of a suppression of (moderately) high transverse-momentum ($p_t$) hadrons in 200 GeV $d$-$Au$ collisions at midrapidity ($\eta=0$), which, however, turns into a suppression at forward $\eta$ [18], cf. left panel of Fig. 2. Whereas the former confirmed strong suppression of high-$p_t$ hadrons in $Au$-$Au$ as an energy loss effect in the produced hot/dense medium (see next section), the latter might have provided first explicit evidence of gluon saturation in the low-$x$ part of the $Au$ nucleus’ wave function, as advocated by Jalilian-Marian, Venugopalan [19] and Kovchegov (see also Ref. [20]). In addition, the increase of suppression with centrality of the $d$-$Au$ collision is qualitatively in line with the CGC [21]. Definite conclusions have to await quantitative comparison with data incorporating also more mundane mechanisms, as stressed by Accardi [22]. E.g., the HIJING event generator [23] satisfactorily describes the rapidity spectra in $d$-$Au$ [24], as well as the $h^+/h^-$ asymmetry in the forward region, indicative for valence-quark fragmentation. The former implies that the low-$p_t$ regime is not an unambiguous signal of CGC. The critical $p_t$-region will thus be around the estimated saturation momentum of $Q_s \approx 2$ GeV (for $\eta=3$ at RHIC). Forward charge asymmetries further
complicate the interpretation of the nuclear modification factor $R_{dAu}$ which uses a $p$-$p$ reference as denominator. Rapidity energy loss of projectile valence quarks can be expected to induce a decreasing centrality dependence of $R_{dAu}$, too.

One should note that if the CGC is indeed operative at moderate $p_t$ in forward $d$-$Au$, it will reflect itself also in bulk hadron production systematics in $Au$-$Au$ at midrapidity. Using pertinent initial conditions for a hydrodynamic evolution leads to a satisfactory description of the observed $dN/dy$ distributions, as shown in Nara’s talk [25].

3.2. Opacity and Thermalization

The main evidence for the production of thermalized matter at RHIC, at energy densities well above the critical one, resides on the quantitative success of parton energy-loss and hydrodynamic calculations.

As discussed by Vitev and Barnaföldi, using well calibrated perturbative QCD probes in connection with mostly medium-induced (non-abelian) gluon radiation allows to infer energy densities $\epsilon \simeq 20 \text{ GeV/fm}^3$ in the early stages of 200 AGeV central $Au$-$Au$ collisions. In addition to correctly predicting the factor of 4-5 reduction of the nuclear modification factor, $R_{AA}(p_t)$, together with its flatness up to the highest currently measured $p_t \simeq 11 \text{ GeV}$, the calculations reproduce azimuthal correlations, especially for the away-side jet, such as its (slight) broadening in $d$-$Au$ [26], its gradual disappearance with centrality in $Au$-$Au$ [27] (cf. right panel of Fig. 2), as well as its preferably in-plane reappearance in semi-central $Au$-$Au$ (in the short direction of the “almond”).

The relevance of “hadronic” quenching was addressed by Greiner. Whereas Lorentz-dilation precludes noticeable impact on formed hadrons, absorption of colorless “prehadrons” (emerging from hard-scattered valence quarks color-neutralizing on timescales $t \sim E_{jet}/Q^2 \sim 1/p_t$ [29]) on surrounding (pre-) hadrons may be significant. However, the implementation of this approach in a transport model [30] tends to overestimate high-$p_t$
suppression at SPS, while underestimating elliptic flow at RHIC.

Ideal hydrodynamics is remarkably successful in describing the collective evolution of $\sim 99\%$ of all produced particles at RHIC as illustrated in Hirano’s talk (corrections away from midrapidity and due to viscosity were discussed by Heinz and Teaney, respectively). The inherent early thermalization time, $\tau_0 \approx 0.5 \text{ fm}/c$, required especially for second and fourth order azimuthal asymmetries, $v_2(p_t)$ and $v_4(p_t)$, however, cannot be accounted for in terms of perturbative partonic rescattering cross sections, which are much too small. Here, progress could lie in the realization that for moderate temperatures ($1-3 T_c$) the QGP may support $q-\bar{q}$ and/or $g-g$ bound states (resonances), as evidenced by recent LQCD calculations of “hadronic” spectral functions \cite{31}, cf. left panel of Fig. 3. Shuryak and Zahed \cite{32} suggested the color-Coulomb interaction as the underlying force, with the running of $\alpha_s$ only limited at the screening scale $m_{\text{Debye}}$. Brown argued that, close to $T_c$, additional instanton-molecule (IM) induced interactions (augmented by RPA resummations and spatially small Coulomb wave functions) become important to bind thermal quasi-quarks into (almost) massless pions \cite{33}, being continuously connected to the hadronic phase (even though standard estimates of IM coupling strengths are rather small \cite{34}), cf. right panel of Fig. 3.

Resonant rescattering of partons is a promising mechanism to explain the short thermalization times required by hydrodynamics, provided the resonance correlations themselves build up sufficiently fast.

### 3.3. Hydrodynamics vs. Quark Coalescence

Relativistic hydrodynamics, employing an equation of state consistent with predictions from LQCD, provides an excellent description of low-$p_t$ hadron spectra. Implementing jets and their energy loss into a hydrodynamic evolution, Hirano and Nara confirmed that the transition momentum from collective to perturbative production increases with mass ($2, 2.6$ and $3.5 \text{ GeV for } \pi, K$ and $p$ in central $Au-Au$, respectively) \cite{35}. However,
even the hydro protons appear to “run out of steam” too early, in that the \(p/\pi\) ratio in the hydro+jet model underpredicts the experimental data \[36\] above \(p_t\approx3\) GeV (similarly, the experimental \(\Lambda/K\) ratio recovers the perturbative value only close to \(p_t\approx6\) GeV \[37\]). Furthermore, the elliptic flow of all thus far identified hadrons appears to follow a constituent-quark scaling, i.e., a universal “partonic” \(v_2(p_t/n)/n\) with \(n=2\) (3) for mesons (baryons). Both the universal \(v_2\) and the enhanced baryon-to-meson ratios at intermediate \(p_t\) are readily explained within a quark coalescence picture at hadronization, as shown in the talks by Fries, Hwa and Molnar. Whereas the model of Fries et al. \[38\] focuses on coalescence of thermal partons, Greco et al. \[39\] and Hwa et al. \[40\] also allow for recombination with minijet partons. Whether the latter will be able to explain the observed nearside correlations in the 4 GeV regime (recall right panel of Fig. 2) – which appear unmodified from \(p-p\) to central \(Au-Au\) – remains an open question at present. In fact, in the approach of Hwa et al. \[40\], also in \(p-p\) collisions a significant contribution is assigned to coalescence. As for the distinction from hydrodynamic models, the elliptic flow of \(\phi\) mesons (with a mass similar to baryons but only \(n=2\) constituent quarks) is an ideal observable. First data on the ratio of central to peripheral \(\phi\) \(p_t\)-spectra, \(R_{CP}^\phi(p_t)\), seem to follow meson systematics.\[\parallel\]

In view of the LQCD spectral functions (Fig. 3), a logical extension of coalescence models could include hadron formation even above \(T_c\), e.g., by solving suitable rate equations, reminiscent to recent calculations in the charmonium context \[41\] (see Sec. 4.3).

3.4. HBT “Puzzle”

New suggestions have been presented at this meeting for the problem of the HBT data, especially the smallness of the “out”-radius, \(R_{out}^2 = D(x_{out},x_{out}) - 2D(x_{out},\beta t) + D(\beta t,\beta t)\) (\(D\): variance). Kapusta \[42\] and Wong \[43\] argued that keeping track of quantum phases in the hadronic rescattering could preserve memory on the initial source size, thereby also addressing the approximate constancy of the radii with collision energy.

We recall that the AMPT transport model \[44\] can account for the measured radii, with a positive \(x_{out}-t\) correlation, (partially) related to decays of long-lived resonances (especially \(\omega\)’s), as a key ingredient to reduce \(R_{out}\). The question remains where the discrepancy to other transport models \[45\] resides, which should be rather similar in the treatment of the late stages, thus pointing to differences in earlier stages.

4. Microscopic Probes of QCD Matter

With the bulk properties of the produced matter at RHIC being reasonably well assessed, the next challenge is to determine its microscopic properties. In this section, I will focus on 3 complexes of observables that are expected to serve this goal, proceeding from the relatively dilute freezeout to the hot and dense phases.

\[\parallel\] One should note that hydrodynamics ceases to be applicable in peripheral collisions.
4.1. Resonance Spectroscopy

Short-lived resonances are a promising tool to deduce in-medium modifications of their spectral shape close to thermal freezeout through invariant-mass spectra of their decay products, e.g., $\rho^0 \rightarrow \pi^+\pi^-$ or $\Delta^{++} \rightarrow p\pi^+$ \[46\]. For $(\mu_N, \mu_\pi, T)_{fo}=(370, 90, 110)$ MeV, the pion (anti-/baryon) density is, in fact, still appreciable, $\rho_\pi=0.65\rho_0$ ($\rho_B=0.25\rho_0$), with $\rho_0=0.16$ fm$^{-3}$. The left panel of Fig. 4 shows a model fit to STAR data \[47\] from 40-80% central Au-Au collisions employing empirical $\pi\pi$ phase shifts in a sudden breakup scenario as discussed by Florkowski \[48\]. He inferred a $\rho$-mass drop of about 50 MeV, similar to previous findings \[49, 50\]. Broadening effects, Bose-Einstein correlations and nonresonant background contributions may reduce this value significantly \[51, 52\]. Also, a comprehensive understanding of appreciable mass shifts as extracted from high-multiplicity $p$-$p$ or $e^+e^-$ reactions is pending. Preliminary data for the $\Delta^{++}$ resonance show a slight increase of its mass, together with a significant broadening, when going from peripheral to central 200 AGeV Au-Au collisions \[46\].

Concerning the resonance yields, measured $\rho/\pi$, $f_0/\pi$ and $\Delta/p$ ratios \[46\] are at least a factor of 2 larger than equilibrium values at thermal freezeout \[51\], which could be suggestive for multiple emission necessitating a rate equation approach \[49, 50, 51\], e.g., 2-3 generations of emitted $\rho$, $f_0$ and $\Delta$’s. Such a scenario can simultaneously account for the observed $K^*/(892)/K$ ratio \[46\] — which is reproduced by the equilibrium value at $T_{fo}$ \[51\] — since $\tau_{K^*}\sim\Delta\approx 2-3\tau_{\rho,f_0,\Delta}$.

Towards the phase boundary, chiral symmetry restoration eventually dictates substantial medium modifications in terms of degenerate spectral functions for chiral partners, e.g., $\pi-\sigma$, $\rho-\omega$, $N-N^*$($1535$). The dilepton enhancement found at SPS \[53\] (to be scrutinized by NA60 \[54\], as well as PHENIX at RHIC) may well be a related signal in the $\rho\rightarrow ee$ channel \[55\]. On the one hand, this poses the challenge to be reconciled with chemical-freezeout models \[56, 57\] (usually based on vacuum masses), e.g., using self-consistent thermodynamic potentials \[58\]. On the other hand, resonance spectroscopy may offer direct access to pertinent chiral partners, e.g., via $a_1\rightarrow\pi\gamma$ or $N^*\rightarrow\eta N$. 

Figure 4. Left panel: model fit \[48\] to STAR \[47\] $\pi^+\pi^-$ invariant-mass spectra with a $\rho$-mass shift of -50 MeV. Right panel: direct photon sources at RHIC.
4.2. Electromagnetic (EM) Radiation

The penetrating character of EM emission makes it a versatile probe of all collision stages. It should be emphasized that photons and dileptons are (kinematic) facets of the same object, i.e., the electromagnetic current correlation function (for $M_\gamma=0$ and $M_{ee}>0$, respectively). Gale in his talk advocated that both can be used to tag initial energies of jets [59, 60]; the latter also radiate electromagnetically in their passage through matter, which, in particular for $\gamma$'s, could constitute a major source for $p_T\simeq2$-6 GeV [61], possibly outshining both pQCD and thermal radiation. A characteristic signature of this contribution is its negative elliptic flow. EM radiation off jets is part of what is more generally denoted as “pre-equilibrium” sources, which have recently been evaluated in a parton cascade simulation as presented in Bass’ talk [62]. The pertinent photon spectra for RHIC are confronted with hydrodynamic [63] as well as thermal fireball calculations [64] (right panel), also suggesting that pre-equilibrium yields dominate above $p_T\simeq2$ GeV. The largest component in the parton cascade is due to rescattering of secondary partons (quantum interference (LPM) effects are not included). The two thermal calculations agree rather well, with hadron-gas radiation prevalent up to $p_T\simeq1$ GeV, where QGP radiation takes over. It is also noteworthy that chemical off-equilibrium in a QGP affects the thermal photon yields very little, i.e., undersaturated parton distributions are essentially compensated by higher temperatures [63].

WA98 at SPS reported new data on low-$p_T$ (100-300 MeV) direct photons [65] which exhibit a pronounced excess of a factor of 3 or more over thermal fireball calculations [64]. The latter employed a recently improved assessment of hadronic rates which simultaneously describe CERES low-mass dilepton data. If confirmed, the low-$p_T$ photon enhancement could point to appreciable in-medium effects in the late hadronic stages currently not accounted for, e.g., Bremsstrahlung from $\pi\pi$ scattering via in-medium softened “$\sigma$”-mesons (a possibly related softening might have been observed in low-energy $\pi$-induced $\pi$-production off nuclei, $\pi A\rightarrow\pi\pi A$, see, e.g., Ref. [66]). One should note, however, that the CERES data at very low mass ($M_{ee}\leq100$ MeV) do not leave much room for strong additional sources [53].

4.3. Charm(onium)

The intermediate scale of the charm-quark mass renders charmed hadrons another valuable messenger of QGP properties. The first step is to establish a baseline for their primordial spectra. A CGC calculation presented by Tuchin [67] predicts a 40% decrease in $dN/d\eta$ for open-charm when going from $\eta=0$ to 2 in central $Au-Au$, which is essentially a consequence of the saturation scale changing from $Q_s\leq m_c$ at $\eta=0$ (implying $N_{coll}$-scaling) to $Q_s\geq m_c$ at $\eta=2$ (entailing $N_{part}$-scaling). On the other hand, in the color-dipole approach of Raufeisen’s talk [68], a 25% shadowing is found for midrapidity yields which does not significantly vary for $\eta\leq2$.

Recent PHENIX data for “non-photonic” single-electron $p_T$-spectra [69] (ascribed to open heavy-flavor decays) in central $Au-Au$ are consistent with the “null-effect” on
the c-quark energy loss, see Djordjevic’s talk [70]. However, first PHENIX data on the elliptic flow of single-\(e^\pm\) [71] are suggestive for a non-vanishing signal, cf. left panel of Fig. 5. The plot also includes coalescence model predictions [72] for parent \(D\)-mesons formed by recombining thermal light quarks (including (elliptic) flow as determined by pion data [39]) with c-quarks either from PYTHIA (representing no rescattering, dashed line) or being thermalized in, and flowing with, the bulk matter (solid line). No definite conclusions can be drawn yet. Note that, although the two opposite scenarios of no c-quark reinteraction vs. thermalization lead to very similar single-\(e^\pm\) \(p_t\)-spectra up to \(\sim 2\) GeV [73], pertinent \(\Delta l\)-lepton invariant-mass spectra should be quite different, since the back-to-back character of hard production (implying large \(M_{ee}\)) becomes randomized in the thermal case (reducing the average \(M_{ee}\)).

Thermalization of c-quarks has important impact on charmonium production. With 10-20 \(c\bar{c}\) pairs in central 200 AGeV \(Au-Au\), and the realization from LQCD that \(J/\psi\) states possibly persist up to \(2T_c\), their regeneration in the QGP becomes plausible, e.g., via the inverse of gluon dissociation reactions, \(J/\psi+g \rightarrow c+\bar{c}+X\) [4]. In particular, thermalized c-quarks enable the description of these processes in a kinetic theory framework via simplified rate equations of type \(dN_\psi/dt = \Gamma_\psi(N_{\psi}^{eq} - N_\psi)\), where the reaction rate \(\Gamma_\psi\) represents the width of in-medium \(J/\psi\) spectral functions, and thus, in principle, is directly amenable to LQCD calculations. In addition, if, as to be expected, the open-charm number is conserved in the course of an \(A-A\) reaction (i.e., determined by primordial \(N-N\) collisions), the equilibrium level of charmonia is sensitive to open-charm masses [41], which can also be determined in LQCD. Grandchamp in his talk showed solutions to the kinetic equation including essential features of LQCD [41], cf. right panel of Fig. 5. Most of the \(J/\psi\)'s in central \(Au-Au\) at RHIC are indeed regenerated in the QGP, with the band indicating sensitivities to in-medium open-charm masses. The observation of a significant number of \(J/\psi\)'s at RHIC would be another step towards ascertaining the notion of hadronic resonance states in the (nonperturbative) QGP.

¶ This may be viewed as a generalization of statistical production at \(T_c\) [74], see also Refs. 75 76 77.
5. Final Remarks

The search for the QGP has reached a critical phase: the combination of current RHIC data with theoretical analyses shows that the matter created in central $Au-Au$ collisions is (i) very dense, (ii) thermalized, and (iii) probably nonperturbative. Further combining (i)+(ii) with the lattice QCD value for the critical energy density, one is lead to conclude that the QGP has indeed been produced at RHIC. However, to claim such a discovery, one would like to have a deeper understanding of the nature of that phase, as encoded in (iii), i.e., what the relevant (microscopic) degrees of freedom and their interactions are. In this respect, upcoming charm(onium) and electromagnetic probes (photons, dileptons) can be expected to provide valuable insights.

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