

## High Energy-Density QCD Matter

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This article highlights topics in High Energy-Density QCD of relevance to the physics of ultra-relativistic heavy-ion collisions.

### §1. Introduction

The first decade of RHIC operations as well as the first two heavy-ion runs at the LHC have yielded a vast amount of interesting and sometimes surprising data. There exists compelling evidence that RHIC and LHC have created a hot and dense state of deconfined quark-gluon matter with properties similar to that of an ideal fluid — this state of matter has been termed the *strongly interacting Quark-Gluon-Plasma* (sQGP). A first summary on our understanding of the RHIC data has been attempted in a series of publications which appeared in two special volumes of *Nuclear Physics A*: the first one outlining the current theoretical views and case for the sQGP<sup>1)</sup> and the second one detailing the experimental results of the first three years of RHIC operations.<sup>2)</sup> Over the past couple of years, and with the advent of additional high-precision data, the emphasis of the RHIC and LHC programs is now shifting from the initial discovery phase to an exploration phase with the goal of precisely characterizing the properties of the Quark-Gluon-Plasma.

### §2. Fundamental questions

While a lot of progress has been achieved over the past decade on charting the properties of the sQGP, there exist still a number of fundamental open questions for our understanding of the sQGP and the full quantification of its properties. The two most important questions I would like to highlight here are:

1. What is the structure of the initial state?
2. How does the system thermalize on a short time-scale?

On the basis of our knowledge of the dominance of low momentum gluons in the partonic substructure of the proton as well as basic properties of QCD one finds that the initial state of a heavy-ion collision at ultra-relativistic energies is composed of a coherent multi-gluon state, most commonly referred to as the *Color Glass Condensate* (CGC).<sup>3)–5)</sup> Calculations on the structure and properties of the CGC have reached a high level of sophistication, even though the most rigorous calculations still require a certain amount of modeling in order to address finite size and time effects of the collisional system (e.g. the KLN model<sup>6)–8)</sup> used for hydrodynamic initial conditions). An important question in the context of the CGC that has received a lot of attention recently is how to unmask the properties of the CGC from the subsequent pre-equilibrium, hydrodynamic and post-equilibrium

evolution of the system — this will be crucial for the experimental confirmation of a CGC initial condition and the confirmation of its properties. For a survey on the current state-of-the-art please see J. L. Albacete’s writeup in these proceedings.<sup>9)</sup>

The second important fundamental question deals with thermalization: the success of (viscous) relativistic fluid dynamics in describing the bulk dynamics and collective flow properties of the reaction hinges on the formation of a (s)QGP at most 1 fm/c after the beginning of the collision.<sup>10)–15)</sup> How the system could decohere and thermalize with this very short timescale remains a puzzle. A variety of possible mechanisms have been put forward, ranging from multi-particle processes in the context of microscopic transport approaches,<sup>16)</sup> turbulent color fields<sup>17),18)</sup> and quantum fluctuations in a system with strong fields<sup>19)</sup> to AdS/CFT studies that may suggest rapid thermalization in the strong coupling limit, but provide only a poor understanding of the underlying mechanisms and the initial state.<sup>20)</sup>

### §3. Quantifying the properties of QCD matter

One of the most important current challenges in QGP research is to quantify the transport coefficients of this novel state of matter. Currently the most sought after transport coefficients are the jet energy-loss coefficient  $\hat{q}$ , which represents a measure of the amount of transverse momentum a hard probe acquires per unit length as it traverses the hot and dense medium and the specific shear viscosity  $\eta/s$  of the medium. However, these are not the only transport coefficients of use for the characterization of the QGP — others include the heavy-quark diffusion coefficient and the specific bulk viscosity  $\zeta/s$ , that may play a role for the dynamics of the medium close to the transition temperature.

#### 3.1. Jet energy-loss

Experiments at the Relativistic Heavy Ion Collider (RHIC) have established a significant suppression of high- $p_T$  hadrons produced in central A+A collisions compared to those produced in peripheral A+A or binary scaled p+p reactions, indicating a strong nuclear medium effect,<sup>21),22)</sup> commonly referred to as *jet-quenching*. Within the framework of perturbative QCD, the leading process of energy loss of a fast parton is gluon radiation induced by multiple soft collisions of the leading parton or the radiated gluon with color charges in the quasi-thermal medium.<sup>23)–25)</sup>

Over the last few years, a large amount of jet-quenching related experimental data has become available, including but not limited to the nuclear modification factor  $R_{AA}$ , the elliptic flow  $v_2$  at high  $p_T$  (as a measure of the azimuthal anisotropy of the jet cross section) and a whole array of high  $p_T$  hadron-hadron correlations. Computations of such jet modifications have acquired a certain level of sophistication regarding the incorporation of the partonic processes involved.

The recent availability of three-dimensional hydrodynamic evolution codes<sup>13),26)</sup> and related hybrid approaches have allowed for a detailed and quantitative study of jet interactions in a realistic medium. The variation of the gluon density in these approaches is very different from that in a simple Bjorken expansion. The first calculation in this direction<sup>26),27)</sup> estimated the effects of 3-D expansion on the

$R_{AA}$  within a simplified version of the Gyulassy-Levai-Vitev (GLV) approach.<sup>28)</sup> More recently, the Duke group has utilized its 3-D hydrodynamic model to provide the time-evolution of the medium produced at RHIC for jet energy-loss calculations performed in the Baier-Dokshitzer-Mueller-Peigne-Schiff (BDMPS), Armesto-Salgado-Wiedemann (ASW),<sup>29)</sup> Higher Twist<sup>30)</sup> and Arnold-Moore-Yaffe (AMY)<sup>31)</sup> approaches. In each of the three efforts, the inclusive as well as the azimuthally differential nuclear suppression factor  $R_{AA}$  of pions was studied as a function of their transverse momentum  $p_T$ . In addition, the influence of collective flow, variations in rapidity, and energy-loss in the hadronic phase were addressed for the selected approaches. For details regarding the implementation of the energy-loss schemes and their interface to the hydrodynamic medium, we refer the reader to the publications cited above and to 32). The most noteworthy feature of this work was that it allowed for a systematic comparison between the three aforementioned jet energy-loss approaches, utilizing the same hydrodynamic medium evolution as well as the same structure and fragmentation functions for calculating the initial state and final high- $p_T$  hadron distributions.

The analysis revealed that the parameters for all three approaches (initial maximal value for the transport coefficient  $\hat{q}_0$  or coupling constant  $\alpha_s$  in the AMY case) could be adjusted such that the approaches were able to describe the centrality dependence of the nuclear modification factor reasonably well, albeit with very different conclusions on the value of the transport coefficient  $\hat{q}$ . When using the same temperature scaling law to couple to the medium,<sup>32)</sup> the values are  $\hat{q}_0 \approx 2.3$  GeV<sup>2</sup>/fm for the HT approach,  $\hat{q}_0 \approx 10.0$  GeV<sup>2</sup>/fm for the ASW formalism and  $\alpha_s \approx 0.33$  for the AMY approach, which can be converted into a value of  $\hat{q}_0 \approx 4.1$  GeV<sup>2</sup>/fm. Note that the ASW value for  $\hat{q}_0$  at  $\tau = 0.6$  fm/c and  $\epsilon_0 = 55$  GeV/fm<sup>3</sup> lies significantly higher than the Baier estimate for an ideal QGP,  $\hat{q} \approx 2 \cdot \epsilon^{3/4}$ ,<sup>33)</sup> while the HT and AMY values lie significantly below that estimate. The large difference in  $\hat{q}_0$  values between HT and ASW has been pointed out previously, but has been validated here as being inherent to the jet energy-loss calculation and not due to differing choices of the medium or initial state parametrizations. Studying  $R_{AA}$  as a function of azimuthal angle yields some discriminatory power between the different approaches, however, not at the level of precision to conclusively discriminate between any of the schemes or cast a deeper insight on how the differing estimates for  $\hat{q}$  come about.

A promising approach for improving the topographical capabilities of jet energy-loss observables is to extend the scope of the calculations from leading particle energy-loss to full jets. This is usually done via Monte-Carlo techniques and allows for the full accounting of all the radiated quanta as well as the collisional energy-loss contributions. Details on this topic can be found in these proceedings in the article by T. Renk.<sup>34)</sup> A full description of the evolving jet as well as the response of the medium to the deposited energy and momentum will require the development of a full microscopic transport description for jets e.g. via a Parton Cascade approach, including the relevant coherence effects such as the LPM effect.<sup>35)</sup>

### 3.2. Heavy-quark diffusion

Heavy-Quarks, Charmonia and Bottomia are often seen as complimentary probes to jet energy-loss. The large mass of the heavy-quark and its non-relativistic velocity at small transverse momentum suppresses the radiative contributions to its energy-loss<sup>36)</sup> (even though they become substantial for larger heavy-quark momenta), allowing for a heightened sensitivity to the elastic energy-loss contributions.<sup>37)–39), 42)</sup> A number of measurements at RHIC and LHC have shown a significant amount of elliptic flow and a rather small nuclear modification factor  $R_{AA}$  for D-mesons and Charmonia, even though the systematic uncertainties remain large at this point. These measurements seem to indicate that heavy-quarks interact strongly with the deconfined medium, even though a recent analysis showed that they may not thermalize during the evolution of the deconfined system.<sup>43)</sup> For a comprehensive overview of heavy-quark physics at RHIC and LHC we refer to the contributions by P. Gosiaux<sup>40)</sup> and R. Granier de Cassagnac<sup>41)</sup> in this volume.

### 3.3. Shear-viscosity of QCD matter

Recently, attention in the field has been primarily focused on the shear viscosity to entropy density ratio  $\eta/s$ . Calculations utilizing certain strongly coupled supersymmetric gauge theories with gravity duals postulate a lower bound of  $\eta_{\min} = s/4\pi$  for this quantity, often referred to as the KSS bound.<sup>44)</sup> Ideally one would prefer to calculate  $\eta/s$  directly for QCD using Lattice Gauge Theory techniques, however, the extraction of  $\eta/s$  formally requires taking the zero momentum limit in an infinite spatial volume, which is numerically not possible. The extraction of QCD transport coefficients via Lattice QCD will require extreme-scale computing resources which may become available within the next decade. Nevertheless first rough estimates with large systematic errors have been already attempted and point to  $\eta/s$  values compatible with the findings from AdS/CFT calculations.<sup>45)</sup>

Relativistic viscous hydrodynamic calculations (vRFD) require very low values of  $\eta/s$  in order to reproduce the RHIC elliptic flow ( $v_2$ ) data.<sup>14), 15)</sup> However, current purely hydrodynamic calculations assume a fixed value of  $\eta/s$  throughout the entire evolution of the system and neglect its temperature dependence. The exact value of  $\eta/s$  in these calculations can currently only be constrained within a factor of two, due to systematic uncertainties related to the choice of equation of state, pre-equilibrium flow, initial state fluctuations and initial conditions used.

### 3.4. Strong vs weak coupling: anomalous viscosity

The currently prevailing view on the structure of the matter produced at RHIC is anchored by the observation of the strong suppression of the emission of hadrons with a transverse momentum  $p_T$  of several GeV/c or more (i.e. jet-quenching), implying matter of with a very large opacity, and the observed magnitude of the elliptic flow, which requires an early onset of the period during which the expansion is governed by fluid dynamics (earlier than 1 fm/c after first impact) and nearly ideal fluid properties with a viscosity-to-entropy density ratio  $\eta/s \ll 1$ .<sup>10)–15)</sup> The success of the parton recombination model<sup>46)</sup> and a recent analysis of the ratio between the baryon number-strangeness correlation  $\langle \mathcal{BS} \rangle$  and the strangeness fluctuation  $\langle S^2 \rangle$ <sup>47), 48)</sup> are

suggestive of a quasi-particle interpretation for the QGP degrees of freedom, at least near the transition temperature  $T_C$ . However, given the experimental evidence for the low viscosity and strong color opacity of the matter, the interpretation of the data in terms of the quasiparticle picture is problematic: in a quasiparticle picture the conjectured lower bound  $\eta/s \geq 1/4\pi$  corresponds to an extremely short mean free path. Using the relation  $\eta \approx n\lambda_f\bar{p}/2$  from standard kinetic theory, where  $n$  denotes the particle density and  $\lambda_f$  is the mean free path, as well as the equations  $\bar{p} = 3T$  and  $s \approx 4n$  holding for massless particle, one finds  $\lambda_f \geq (3\pi T/2)^{-1}$ . This implies that at the lower viscosity bound the mean free path must not be larger than about half the average distance between quasiparticles. This observation is corroborated by simulations of the parton transport within the framework of the Boltzmann equation with binary elastic scattering, which require cross sections up to twenty times larger than expected on the basis of perturbative QCD in order to reproduce the elliptic flow data.<sup>49)</sup>

One possible resolution of the puzzle is to argue<sup>1)</sup> that the quark-gluon plasma near  $T_c$  is actually strongly coupled. It has been argued<sup>50)–52)</sup> that the microscopic structure of such a system is dominated by complex bound states of the elementary constituents. Note, however, that the diagonal and off-diagonal quark flavor susceptibilities calculated on the lattice<sup>53)</sup> strongly constrain — and in many cases rule out — the existence of bound states of the elementary constituents above  $T_C$ . In addition, a recent calculation of the shear viscosity over entropy ratio in weakly coupled  $\mathcal{N} = 4$  supersymmetric Yang-Mills theory yielded a result many times smaller than the corresponding weak-coupling result in QCD.<sup>54)</sup> This finding therefore may actually suggest that the ratio  $\eta/s$  of QCD near the transition point is several times larger than the lower viscosity bound of  $(4\pi)^{-1}$  for this quantity found in  $\mathcal{N} = 4$  supersymmetric Yang-Mills theory.<sup>44)</sup>

The other possible resolution is that the transport properties of the quark-gluon plasma are not governed by collisional processes involving perturbative interactions among elementary excitations, but by collective phenomena. This situation is not uncommon in plasmas, where coherent fields can be spontaneously generated due to instabilities in the field equations in the presence of the medium. The most relevant of these for our purposes is the instability discovered by Weibel, which arises when the momentum distribution of charged particles is anisotropic.<sup>55)</sup>

It has been known for some time<sup>17),56),57)</sup> that similar instabilities exist in quark-gluon plasmas with a parton momentum distribution that is not in thermal equilibrium. As a result of these instabilities long-range color fields can be excited with amplitudes far above the thermal level. The generic nature of such color instabilities has been recognized only in recent years.<sup>58),59)</sup> Most work exploring the consequences of these instabilities<sup>60)–62)</sup> has been focused on the early stage of the collision, when the momentum distribution is highly anisotropic and far from equilibrium. The fields generated by the instabilities drive the parton distribution rapidly toward local isotropy and thus toward the hydrodynamical regime.<sup>63)</sup> However, the expansion of the quark-gluon plasma under its own pressure ensures that the matter never reaches complete equilibrium, and thus the presence of the color instabilities persists even during the period when the matter evolves by viscous hydrodynamical

expansion. Since the size of the deviation from kinetic equilibrium is proportional to the viscosity itself, color instabilities are especially important when the quark-gluon plasma is weakly coupled and the collisional shear viscosity is large. In 64) and 65) an expression for the anomalous viscosity in an expanding quark-gluon-plasma was derived, which arises from interactions of thermal partons with dynamically generated color fields. It was found that in the weak coupling limit, the anomalous viscosity  $\eta_A$  will be much smaller than the viscosity due to collisions among thermal partons  $\eta_C$ . Given that the total shear viscosity of the system depends on the anomalous and collisional contributions via  $1/\eta_{\text{tot}} = 1/\eta_A + 1/\eta_C$ , the total shear viscosity could very well be dominated by the small value of the anomalous viscosity during the early reaction phase. By reducing the shear viscosity of a weakly coupled, but expanding quark-gluon plasma, this mechanism could therefore possibly explain the observations of the RHIC experiments without the assumption of a strongly coupled plasma state.

### 3.5. *Current state-of-the-art: hybrid viscous RFD plus microscopic transport*

Currently the most accurate method for the extraction of the specific shear viscosity of QCD matter from the data is via a comparison to viscous RFD calculations. (v)RFD usually assumes a simultaneous chemical and thermal freeze-out — this characteristic poses a problem, since statistical models show chemical freeze-out to occur around  $T = 170$  MeV, whereas the shape of the spectra requires a hydrodynamic evolution to  $T = 110$  MeV. This deficiency can be addressed in an ad-hoc fashion by re-normalizing the particle spectra or by employing the partial chemical equilibrium (PCE) approach.<sup>12),67)</sup> While the PCE approach can account for the proper normalization of the spectra, however, in ideal RFD it has failed to reproduce the transverse momentum and mass dependence of the elliptic flow data.<sup>68)</sup>

Hybrid hydro+micro approaches are able to address most of the shortcomings of the (v)RFD approach, such as the separation of chemical and kinetic freeze-out and the lack of dissipative effects in the hadronic phase in ideal RFD or respectively the lack of temperature dependence of  $\eta/s$  in viscous RFD during that phase. Such a hybrid approach (“hydro-plus-micro”) was pioneered in 69) and has been adopted by other groups.<sup>13),70)–72)</sup> Its key advantages are that the freeze-out now occurs naturally as a result of the microscopic evolution and that flavor degrees of freedom are treated explicitly through the hadronic cross sections of the microscopic transport. As the Boltzmann-equation is the basis of the microscopic calculation in the hadronic phase, viscous effects in the hadronic phase, where they are large, are by default included in the approach. Hybrid macro/micro transport calculations are to date the most successful approaches for describing the soft physics at RHIC.

In 72) a hybrid vRFD+UrQMD approach was utilized to conduct a detailed analysis of the specific shear viscosity of a (s)QGP created at RHIC. At the center of this new analysis is the observation that the ratio of the elliptic flow coefficient  $v_2$  over the initial eccentricity of the collision  $\varepsilon$ ,  $v_2/\varepsilon$ , is a universal function of charged multiplicity per unit overlap area,  $(1/S)(dN/dy)$ , that depends only on the viscosity but not on the model used for computing the initial fireball eccentricity  $\varepsilon$ . The results of the analysis can be seen in Fig. 1, which compares  $v_2(\eta/s)/\varepsilon$  vs  $(1/S)(dN_{ch}/dy)$

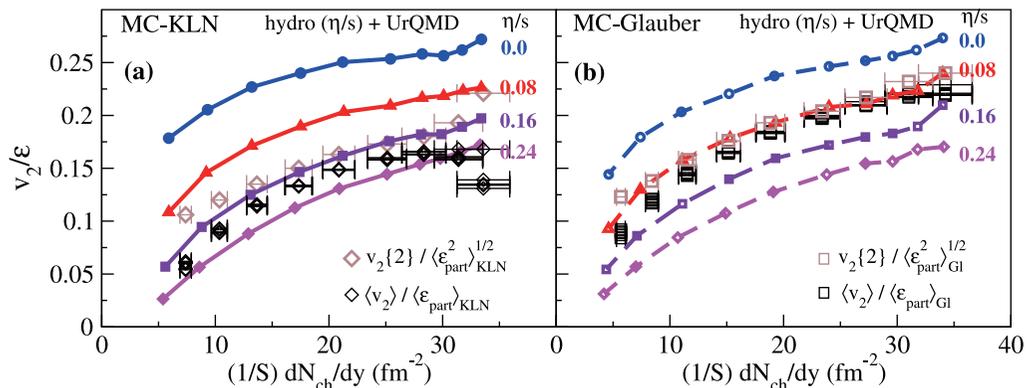


Fig. 1. Hybrid vRFD comparison of  $v_2(\eta/s)/\epsilon$  vs  $(1/S)(dN_{ch}/dy)$  curves with experimental data for  $\langle v_2 \rangle$  from the STAR Collaboration. The data used in (a) and (b) are identical, but the factors  $\langle \epsilon_{\text{part}} \rangle$  and  $S$ , as well as the factor  $\langle \epsilon_{\text{part}}^2 \rangle^{1/2}$  used to normalize the  $v_2\{2\}$  data, are taken from the MC-KLN model in (a) and from the MC-Glauber model in (b). Figure taken from 72).

curves for different values of the specific shear viscosity with experimental data for  $\langle v_2 \rangle$  from the STAR Collaboration for two different models of the initial state: the MC-KLN model in (a) and the MC-Glauber model in (b). The experimental data used in (a) and (b) are identical, but the normalization factors  $\langle \epsilon_{\text{part}} \rangle$  and  $S$  used on the vertical and horizontal axes, as well as the factor  $\langle \epsilon_{\text{part}}^2 \rangle^{1/2}$  used to normalize the  $v_2\{2\}$  data, are taken from the respective initial state models. Likewise, the theoretical curves are from simulations with MC-KLN initial conditions in (a) and with MC-Glauber initial conditions in (b). It is found that the QGP shear viscosity for  $T_c < T < 2T_c$  lies within the range  $1 < 4\pi(\eta/s)_{\text{QGP}} < 2.5$ , with the remaining uncertainty dominated by insufficient theoretical control over the initial source eccentricity  $\epsilon$ . While this range roughly agrees with the one extracted in 73), the width of the uncertainty band has been solidified by using a more sophisticated dynamical evolution model which eliminates most possible sources of error that the earlier analysis<sup>73)</sup> was unable to address. Small bulk viscous effects<sup>74)</sup> and proper event-by-event hydrodynamical evolution of fluctuating initial conditions<sup>75)</sup> may slightly reduce the ideal fluid dynamical baseline, while pre-equilibrium flow may slightly increase it. After cancellations one would expect the quoted uncertainty band for  $(\eta/s)_{\text{QGP}}$  to shift by at most a few percent.

#### §4. Conclusion and outlook

Quark-Gluon-Plasma research has made the transition from its discovery – to its exploratory phase. Our knowledge on the transport coefficients of hot and dense QCD matter (including the QGP) has improved significantly over the past few years. Yet a number of fundamental open questions remain on the characterization of the initial state and the dynamics of thermalization. While the question on whether the QGP is weakly or strongly coupled may rest on determining the (anomalous?) nature of its specific shear viscosity, hybrid viscous hydrodynamic plus microscopic models

are able to place strong constraints on  $\eta/s$  of a QGP in the temperature range of  $T_c < T < 2T_c$ , with  $1 < 4\pi(\eta/s)_{\text{QGP}} < 2.5$ . The main uncertainty in the constraints of  $\eta/s$  has been identified to be related to the initial conditions of the hydrodynamic evolution, which in turn is governed by our current uncertainty regarding the nature of the initial state and exact dynamics of the early pre-equilibrium phase of the heavy-ion collision. The ongoing RHIC program as well as new data from the LHC should lead to significant progress in our understanding of the early-time dynamics of ultra-relativistic heavy-ion collisions which in turn will lead to increased precision for the determination of the transport coefficients of QCD matter.

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