Recent Results from RHIC

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I review recent results from the Relativistic Heavy-Ion Collider with particular emphasis on gluon saturation, elliptic flow and parton energy loss. While studies of gluon saturation are still in an early stage, and as such are not yet conclusive, more results are eagerly awaited, both because of a general interest in saturation physics and because it defines the initial state of high-energy hadronic collisions. Elliptic flow measurements have shown the collective behaviour of the matter produced and are particularly interesting because of the fact that the matter appears to have an extremely low viscosity. The much higher beam energy at RHIC has for the first time given access to jet-related physics in heavy-ion collisions. A strong jet suppression has been observed and is now being studied in detail to unravel the physics mechanisms behind and obtain estimates of the medium density.

1 Introduction

Quantum chromodynamics predicts a phase transition in strongly interacting matter between the confined phase of hadrons at low temperature to a deconfined phase of quarks and gluons at high temperature. The goal of experiments with high-energy nuclear collisions at the Relativistic Heavy-Ion Collider (RHIC) is to study strongly interacting matter at high temperature, and in particular the properties of the partonic phase. The RHIC program, which consisted of four experiments in its initial phase, is now continued with the two major experiments PHENIX and STAR. A wealth of experimental results have been obtained, which go significantly beyond earlier results of the heavy-ion program at the CERN SPS because of the much higher available energy. Due to the huge amount of experimental data, I will in this paper only be able to review a selection of those results, and will in particular concentrate on data related to gluon saturation, elliptic flow, and parton energy loss. For an overview of other results see e.g. [1].

2 The initial state: gluon saturation

Another new state of strongly interacting matter, the *color glass condensate*, has been predicted recently. The number density of quarks and gluons seen in a proton or nucleus is known to increase at large momentum transfer Q^2 (i.e. high spatial resolution), when the momentum fraction x they carry decreases. This linear evolution can successfully be described within perturbative QCD. This increase can however not continue indefinitely. At some point the large number density of gluons would violate fundamental unitarity bounds, and in fact, for large densities non-liner effects become important and compensate the increase with a corresponding decrease due to gluon fusion processes. This balance of creation and annihilation leads to *gluon saturation*. Gluon saturation is a small x phenomenon and is expected to set in below a certain characteristic scale in Q, the *saturation scale*,

$$Q_s \approx \frac{\alpha_s}{\pi R^2} xG(x, Q^2) \propto A^{1/3} \cdot x^{-\lambda},$$

where $\lambda \approx 0.3$.

At this saturated density the occupation number should be large enough that the gluons can be treated as a classical field. The state is often called the *color glass condensate* (CGC): a *color* field, *condensed* in a high density classical state, and slowly varying like a *glass*. In addition to being a fascinating new state of elementary particles in itself, it plays an important role in defining the initial conditions for any high energy hadronic interaction. Knowledge on gluon saturation will therefore have far reaching consequences in high-energy physics. (For a general introduction see e.g. [2].)

Gluon saturation is able to explain the observed particle multiplicities at RHIC, which turned out to be much smaller than previously expected. The behaviour of multiplicities by itself is however not conclusive as a signal of this physics mechanism. In addition, gluon saturation should be observable as a suppression of particle production at forward rapidities in p+A or d+A collisions relative to $p+p$ collisions, in particular via measurements of

- a suppression of inclusive hadron yields in a momentum range where parton scattering is dominant and
- a decrease and/or broadening of the azimuthal correlation related to recoil jets from parton-parton scattering.

Such studies have been performed at RHIC, and first results in particular on the suppression in inclusive hadrons at forward rapidities have been obtained by BRAHMS and STAR (see Fig. 1). The measurements show a significant suppression of the yield in d+Au collisions, qualitatively consistent with gluon saturation. However, no full calculation from a CGC-model has been performed yet. Preliminary studies of azimuthal correlations have been performed by STAR and PHENIX, they do however not yet show results significant for gluon saturation searches. Moreover, questions remain whether the p_T region studied at RHIC allows the use of p+p measurements as a reference for the incoherent limit of perturbative QCD.

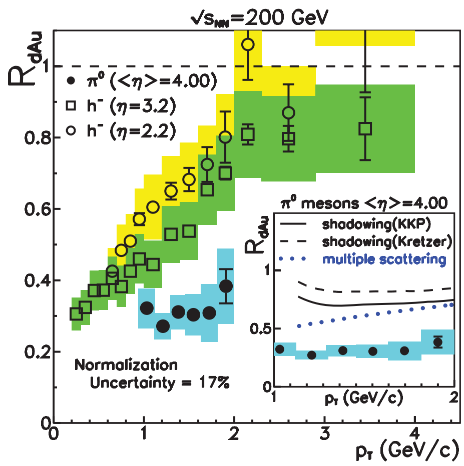

Figure 1: (colour online) Nuclear modification factor R_{dAu} for hadron production in d+Au collisions at forward rapidities as measured by STAR (π^0) and BRAHMS (negative hadrons). The inset illustrates that conventional calculations including shadowing effects are not able to describe the suppression shown in the STAR data (from [3]).

3 Elliptic flow: equilibration, viscosity, and partonic collectivity

One of the most important findings of the RHIC experiments is the strong collectivity, in particular the large values of elliptic flow. The created system in non-central heavy-ion collisions has an azimuthal anisotropy in coordinate space which leads via multiple interactions to an anisotropy in momentum space. Elliptic flow v_2 is defined as the coefficient of the second order Fourier component of this azimuthal anisotropy [4]. Large values of v_2 are generally considered to be signs of hydrodynamic behaviour, which in turn requires local equilibration of the produced matter. v_2 shows a straightforward dependence on the collision geometry, for ideal hydrodynamics it is proportional to the initial spatial eccentricity. Beyond that, its magnitude depends on the equation of state (EoS) of the matter produced. To extract this information from elliptic flow measurements knowledge of the initial distributions, which determine the eccentricity, is important. This makes the studies of gluon saturation significant for the interpretation of elliptic flow.

Figure 2 shows results of elliptic flow measurements as obtained by the STAR experiment [5, 6]. On the left hand side the measurements are compared to the expectation from ideal hydrodynamic calculations for different centralities. While there are discrepancies for the more peripheral reactions, the results have reached the values for the ideal fluid in central collisions. This behaviour has lead to the conclusion that the system created at RHIC behaves like a perfect liquid with very low viscosity [7].

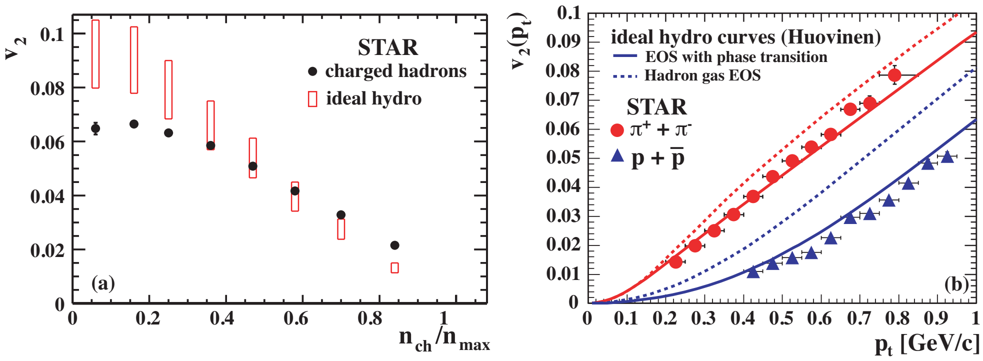

Figure 2: (colour online) (a) Elliptic flow (solid points) as a function of centrality n_{ch}/n_{max}. The open rectangles show a range of values expected for v_2 in the ideal hydrodynamic limit [5]. (b) Elliptic flow of pions and protons as function of transverse momentum [6]. The curves are hydrodynamical model calculations using a hadron gas EoS (dashed curve) and an EoS which incorporates the QCD phase transition (full curve).

These findings have lead to a number of theoretical activities on how to incorporate effects of viscosity in the calculations. The deviations for more peripheral reactions can be understood from the influence of viscous corrections due to the hadronic phase. However, the real behaviour of even the hot and dense phase should show a finite viscosity. It has been shown [8] using the so-called AdS/CFT correspondence that conformal field theories with gravity duals have a shear viscosity normalized to the entropy density of $\eta/s = 1/4\pi$. The authors conjecture that this is a lower bound for any relativistic thermal field theory.

While in early analyses the normalization of v_2 to the initial eccentricity was performed using Glauber calculations, it has now been realized that estimates based on e.g. colour glass condensate model calculations yield significantly different results, which is relevant for the determination of the most likely viscosity of the matter. Different approaches are employed to obtain estimates of η/s, either by performing viscous hydro calculations as e.g. in [9] or to exploit the centrality dependence via a parameterization of v_2 inspired by transport calculations [10, 11]. Both approaches lead to the conclusion that the viscosity is in fact small, but slightly larger than (of the order of a few times) the theoretical bound of 0.08.

The right hand side of Fig. 2 shows v_2 for pions and protons as a function of transverse momentum. In this low momentum region there is a strong mass ordering, where the rise of v_2 with p_T occurs at higher values for the heavier particles. This behaviour can qualitatively be described by hydrodynamic calculations using hadronic degrees of freedom, where the mass ordering is related to the strong collective radial motion in the system, which affects the heavier particles more. A quantitatively satisfactory description is however only obtained in calculations using an EoS incorporating the QCD phase transition (solid lines in the figure).

At higher p_T the mass ordering is reversed, and as a general trend a scaling with the number of constituent quarks in the corresponding hadron has been observed [12]. More recently this has been confirmed with many hadron species. As an example Fig. 3 shows v_2 for pions and protons (left) and for ϕ mesons and Ω baryons (right). The constituent quark scaling works best when using transverse mass instead of transverse momentum and can nicely be demonstrated by comparing flow results for different hadrons when both v_2 and $m_T - m_0$ are normalized to the number of quarks as shown in Fig. 4 for Au+Au and Cu+Cu collisions. Such a behaviour is very naturally obtained if hadron production proceeds via coalescence [13] or recombination [14] from a deconfined phase and the hadron collective motion is determined from the collective motion of the quarks. The phenomenon of constituent quark scaling is thus seen as a strong hint of partonic collectivity.

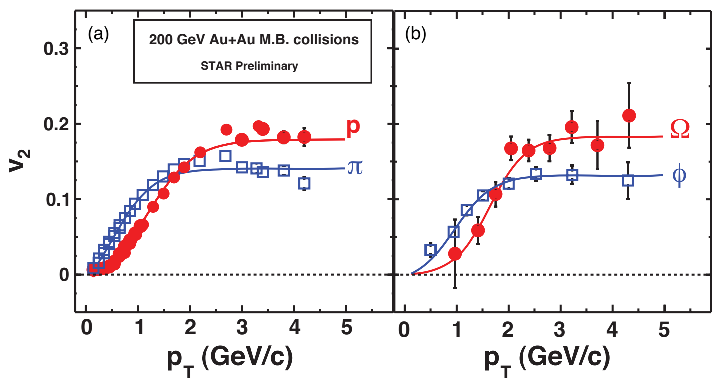

Figure 3: (colour online) Elliptic flow as function of transverse momentum in Au+Au collisions at 200 GeV for pions and protons (a) and ϕ mesons and Ω baryons (b).

There are obvious situations, where this scaling is not expected to work, e.g. at very low momentum, where momentum distributions are strongly modified in the hadronic phase and the hadron mass is thus more important than the number of quarks, or at high momentum, where particles originate from jet fragmentation and azimuthally dependent parton energy loss (see next section) is responsible for the observed anisotropy. In addition, also the details of recombination/coalescence models may lead to differences with respect to how well and in what momentum ranges the constituent quark scaling will be realized. Studies of the details of the scaling properties of v_2 are being performed – they should profit much from further increased statistics and better understanding of non-flow effects.

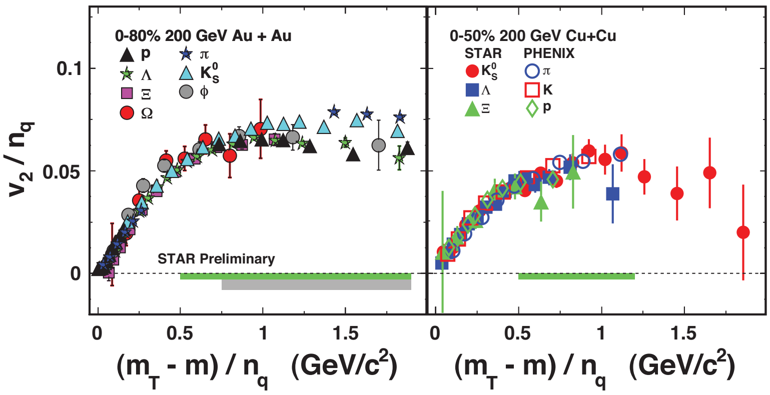

Figure 4: (colour online) Elliptic flow per quark as function of transverse mass per quark for different hadron species in collisions of Au+Au (a) and Cu+Cu (b) at 200 GeV.

4 Parton energy loss: jet quenching and medium response

Jet quenching, which dates back to original ideas from Bjorken in 1982 [15], has been established as a powerful tool to study the early density of the matter produced in heavy-ion collisions and its evolution. It was first observed in the study of inclusive hadron suppression. The inclusive yield of hadrons at high p_T, which are expected to originate from hard parton scattering, is suppressed in central heavy-ion collisions by a factor of ≈ 5 compared to expectations from p+p collisions [16, 17, 18, 19]. This is usually displayed as the nuclear modification factor:

$$R_{AA} = \frac{1/p_T dN_{AA}/dp_T}{\langle N_{coll}\rangle 1/p_T dN_{pp}/dp_T}.$$

The suppression is evident as a deviation from $R_{AA} = 1$.

The PHENIX experiment has now measured the suppression of neutral pions out to transverse momenta as large as $p_T \approx 20\,\mathrm{GeV}/c$, and in more limited ranges for a number of other particle species. A selection of results is displayed in Fig. 5. Neutral pions are suppressed by about a factor of 4-5 in central Au+Au collisions up to very high momenta. η mesons show a similar behaviour albeit with larger statistical errors. Other particles like the ϕ or ω do not show such a strong suppression, they are, however, only measured with much larger errors, or at somewhat lower momenta, where production mechanisms other than jet fragmentation,

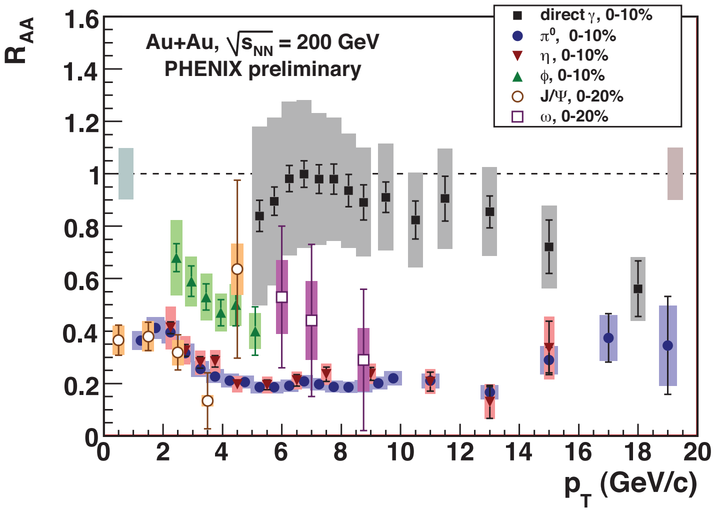

Figure 5: (colour online) Nuclear modification factor for different particle species in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from PHENIX [20].

e.g. the above-mentioned coalescence/recombination, may have a significant influence. It is noteworthy that direct photons do not show a similar suppression. There is a decrease of the photon R_{AA} at very high p_T, but this can be explained e.g. from isospin differences between Au nuclei and protons.

The non-suppression for photons in central Au+Au collisions [21], which do not interact strongly, together with the absence of suppression for hadrons in d+Au collisions [22, 23, 24, 25], where no significant matter in the final state is produced, demonstrates that final state effects involving the strong interaction must be responsible. The most likely interpretation of the suppression is thus medium-induced energy loss of fast partons.

Additional information can be obtained from recent measurements by the STAR experiment. Figure 6 shows the nuclear modification factor R_{AA} for identified pions, kaons, and protons for central Au+Au collisions. There is a similarly strong suppression of the pion yield at high p_T and a distinctly different behavior of protons and kaons over the full momentum range. Kaons show less suppression than pions, and protons in turn again a weaker suppression than kaons. This contradicts a naïve expectation related to the origin of

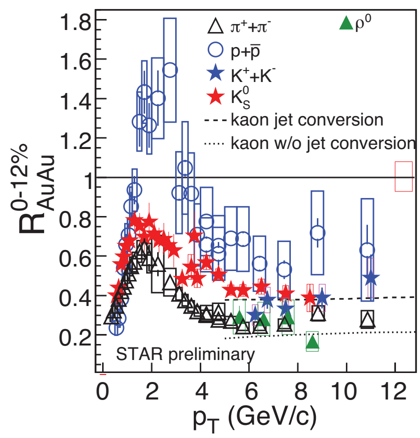

Figure 6: (colour online) Nuclear modification factor (R_{AA}) for pions, kaons, and protons in central collisions of Au+Au at $\sqrt{s_{NN}} = 200$ GeV from STAR [26].

the different particle species. Compared to pions, both kaons and protons should originate for a larger fraction from the fragmentation of gluons relative to quarks. As gluons have a larger colour factor, they should suffer a stronger effect from parton energy loss, which is however not seen in the data. It has been suggested that jet conversion may be able to explain this observation – in any case this demonstrates that the physics of parton energy loss is not completely unravelled.

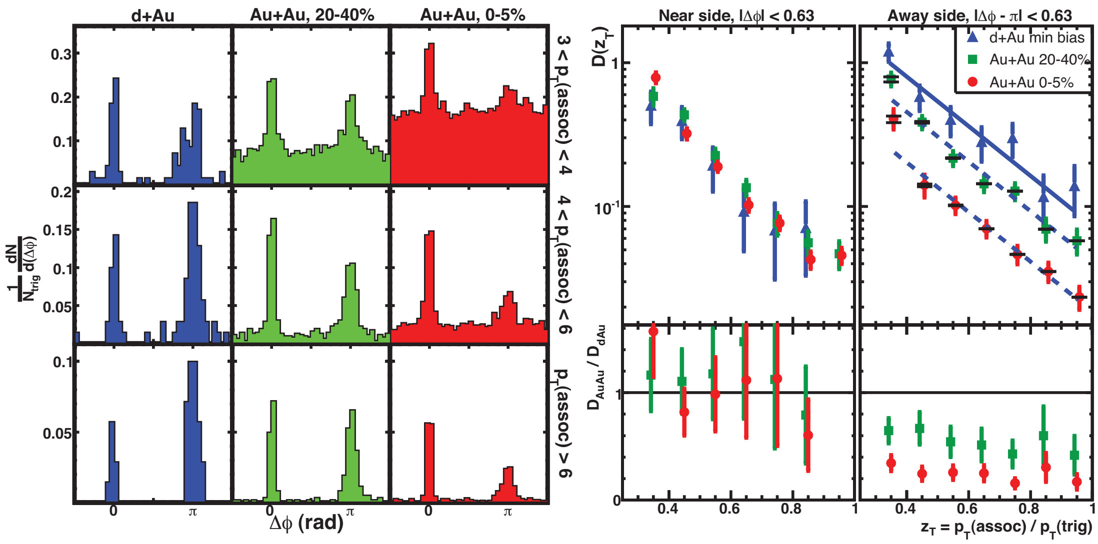

Figure 7: (colour online) left: Per-trigger yields of associated hadrons as a function of relative azimuthal angle for a trigger of $p_T > 8\,\mathrm{GeV}/c$ for d+Au, semi-central Au+Au and central Au+Au at different values of p_T of the associated hadrons. right: Per-trigger yields of correlated hadrons as a function of the momentum fraction z_T (definition see text) for the near side (left) and for the away side)right). The bottom panels show ratios of the upper distributions for Au+Au collisions to those for d+Au. (From[28])

More directly jet suppression is observed in the modification of the characteristic correlation structure in azimuthal angle. For a high-p_T hadron trigger there is a prominent back-to-back correlation peak of associated hadrons with intermediate p_T in elementary reactions. In the earliest studies the same peak is essentially absent in central heavy-ion collisions [27]. Again d+Au collisions do not show a suppression effect. These studies have later been extended to truly high p_T [28]. On the left side of Fig. 7 the yields of hadrons associated with a very high-momentum trigger hadron is shown as a function of azimuthal angle for different systems and different p_T-ranges of the associated particles. In d+Au collision peaks are observed both at $\Delta\phi = 0$ and at $\Delta\phi = \pi$, related to the back-to-back two-jet structure of hard scatterings. In central Au+Au collisions at the lowest p_T the near-side peak is clearly visible, while on the away side there is only an indication of a correlation structure. At the highest p_T both correlation peaks are, however, clearly visible again, but the away-side peak is much smaller in magnitude than for d+Au collisions. This can be studied more quantitatively via the *trigger-normalized* *fragmentation functions*

$$D(z_T) = \frac{1}{N_{trigger}} \frac{dN}{dz_T},$$

where $z_T \equiv p_T(assoc)/p_T(trigger)$, which are displayed in figure 7 on the right. All distributions have an approximately exponential shape with a similar slope parameter. This can best be seen directly from the ratios shown in the lower panels. The ratios are seen to be independent of z_T for both the near and the away side. The near side yield is even compatible with 1, i.e. no modification of these distributions in central Au+Au compared to d+Au, while the away side shows a further suppression by a factor $4-5$. Detailed analysis of the peak structures shows in addition that the peak widths for the higher p_T ranges is similar for all systems.

These findings can most easily be interpreted as follows: The suppression of hadrons at very high p_T is due to energy loss of partons. These partons emerge from the medium with a considerable momentum so that they still fragment in the vacuum as usual into several hadrons. On the near side the trigger requirement selects events which develop an ordinary jet. Energy-independent energy loss would preserve the shape of the distributions. On the away side of the trigger, the other parton suffers additional energy loss, such that the probability to observe a second jet is greatly reduced. Still, if a high-p_T hadron emerges on the away side it is part of a similar jet structure.

In Fig. 8 the measured values of the nuclear modification factor R_{AA} of neutral pions is compared to the expectations for different densities from one energy loss model [29]. The right panel shows the modified χ^2 (which accounts for systematic effects, see [32]) as a function of the medium density which is here given as the mean transport coefficient $\langle \hat{q} \rangle$. The transport coefficient $\hat{q}$ is the squared momentum transfer per unit path length which characterises the energy loss properties of the medium. The mean energy loss $\Delta E \propto \alpha_s \hat{q} L^2$ for a static medium [33]. The extracted value of the mean transport coefficient $\langle \hat{q} \rangle = 13.2^{+2.1}_{-3.2}$ GeV^2/fm, based on this model. A number of other models have also been compared to the data [32, 34] and tend to give lower estimates of the (equivalent) medium density.

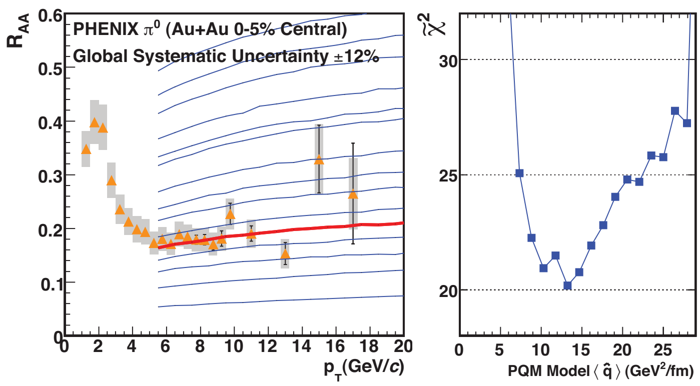

Figure 8: (colour online) Measured nuclear modification factor for π^0, compared to model calculations [29] based on the BDMPS formalism. The right panel shows the modified χ^2 of the comparisons [30].

Figure 9 (left panel) shows the away-side trigger-normalized fragmentation functions – also called the recoil yield – for trigger particles with $8 < p_{T,trig} < 15$ GeV/c in d+Au and Au+Au

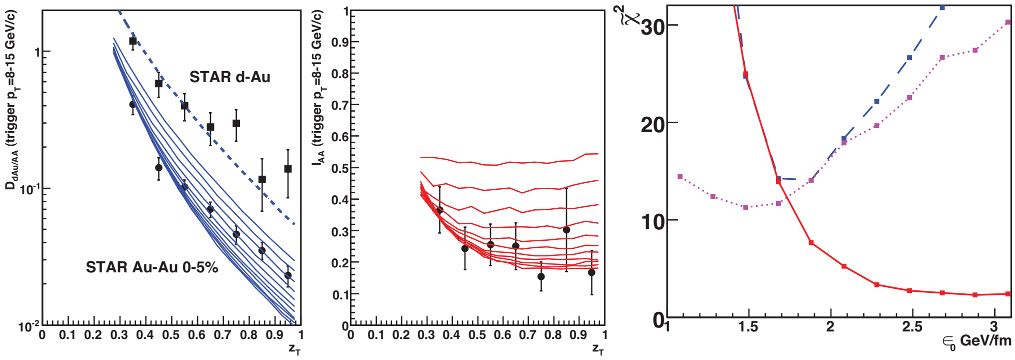

Figure 9: (colour online) Trigger-normalized fragmentation functions $D_{AA}(z_T)$ on the away side for d+Au and Au+Au collisions (left) and the suppression ratio I_{AA} (middle) for trigger particles with $8 < p_{T,trig} < 15$ GeV/c compared to model calculations [31]. The right panel shows the modified χ^2 of the comparisons (see text), including systematic effects [34].

collisions compared to model curves with different medium density. The right panel shows again the modified χ^2 as a function of density. The model used in this case is a higher twist model, because the full set of calculations for the recoil yield has so far only been performed for that model [31]. The parameter describing the medium density in this model is the typical energy loss ϵ_0. Because the d+Au reference measurement for this observable has only limited statistical precision, a few different approaches were taken for the theory fit. Firstly, one can fit the recoil yield using a NLO calculation to describe the p+p result. The resulting χ^2 is shown by the blue dashed curve in Fig. 9. The best-fit value for $\epsilon_0 \approx 1.9$ is compatible with the value extracted using the single-hadron data with this same model $\epsilon_0 = 1.9^{+0.2}_{-0.5}$ GeV/fm [34]. Adding the scale uncertainty on the calculated d+Au reference yield gives the magenta dotted curve. When the d+Au measurement is used to calculate the recoil suppression I_{AA}, the red solid curve is obtained. This last procedure is the least model dependent, but it gives the weakest constraint on ϵ_0. Future high-statistics measurements of di-hadron correlations in p+p and d+Au collisions at RHIC will further constrain the theory in this area.

The energy lost by the hard-scattered parton is expected to be carried by softer particles, and in fact di-hadron correlation studies at lower p_T show large qualitative differences between p+p reference measurements and Au+Au results. Two particularly remarkable feature have emerged. One effect is the observation of a significant associated yield on the near side at larger pseudo-rapidity difference $\Delta\eta \gtrsim 0.7$, which is not expected from jet fragmentation. The other observation is a large broadening of the recoil distribution at low p_T, to the point where the distribution exhibits a double-peak structure.

Figure 10 shows the distribution of associated hadrons with $2 < p_{T,assoc} < 3$ GeV/c in pseudo-rapidity η and azimuthal angle ϕ with respect to a trigger particle with $3 < p_{T,trig} < 4$ GeV/c in central Au+Au collisions at RHIC [35]. At these p_T, the associated hadrons show not only the jet-like peak around ($\Delta\eta$,$\Delta\phi$) = (0,0), but also significant additional associated yield at larger $\Delta\eta$. The additional yield is approximately uniformly in $\Delta\eta$ and the effect is therefore referred to as the *ridge*. The ridge-effect is unique to heavy ion collisions and is found to be present for trigger hadrons over the entire accessible p_T-range (up to 7 GeV/c at present) [35]. The long range of the correlation in $\Delta\eta$ very likely requires a production mechanism at work at very early times. A number of different possible mechanisms have been proposed, such as coupling of radiated gluons to longitudinal flow [36, 37, 38], medium heating by the passage of a hard parton combined with longitudinal flow [39] and a radial flow boost to the underlying p+p event, combined with trigger bias [40, 41]. Further experimental work is going on to distinguish the different scenarios.

Another striking finding from di-hadron correlations at intermediate p_T is that the away-side peak is strongly broadened. This is illustrated in Figure 11, which shows associated hadron distributions with $1 < p_{T,assoc} < 2.5$ GeV/c for three different ranges of $p_{T,trig}$ in central Au+Au collisions [42] (full symbols). The open symbols in the Figure show d+Au results for reference. Clearly, the away-side distribution is strongly broadened in the Au+Au collisions, compared to d+Au collisions. For lower $p_{T,trig}$, there might even be a minimum in the distribution at $\Delta\phi = \pi$. This observation has lead to the suggestion that partons propagating through the strongly interaction medium may give rise to Mach-Cone shock waves [43, 44]. The width of the away-side distribution would then measure the opening angle and thus the velocity of sound in the medium. However, it has also been pointed out that gluon radiation in combination with the kinematic constraint $p_{T,trig} \approx p_{T,assoc}$ may give rise to a broadened away-side as well [45]. It is also important to realize that the raw signal sits on a large background which is not constant, but has a $\cos(2\Delta\phi)$ modulation due to elliptic flow. The background has been subtracted in Fig. 11 and the uncertainty on the extracted signal from the uncertainty in the strength of elliptic flow is indicated by the shaded band. However, possible correlations between elliptic flow and the jet-structure are not taken into account in this estimate. Three-particle correlation measurements are currently being developed to further explore the away-side shapes.

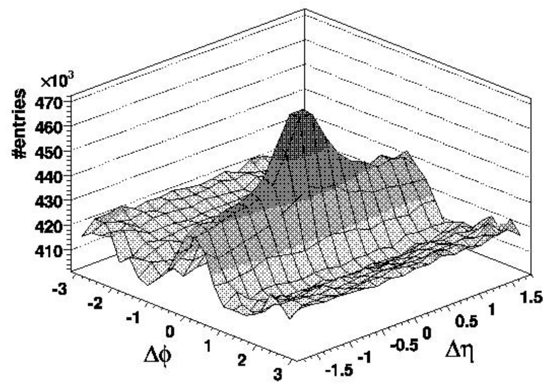

Figure 10: Distribution of associated hadrons with $2 < p_{T,assoc} < 3$ GeV/c in pseudo-rapidity η and azimuthal angle ϕ with respect to a trigger particle with $3 < p_{T,trig} < 4$ GeV/c in central Au+Au collisions at RHIC [35].

The interpretation of the single hadron and di-hadron suppression suffers from the fact, that the initial jet energy is unknown, and that theoretical descriptions thus have to perform averages over initial parton energy distributions in addition to the necessary averages over the spatial distributions of the production points. This significantly limits the discrimination power of the above measurements. Two types of more advanced measurements are currently under study that should provide access to the initial parton energy. One method uses γ-jet events, where the transverse momentum of the direct photon is equal to the initial parton transverse momentum, the other method attempts to perform jet reconstruction in heavy-ion events. First studies using the former method have already been performed [46, 47] but are limited from low statistics due to the small cross section for photon production. The latter has a potentially

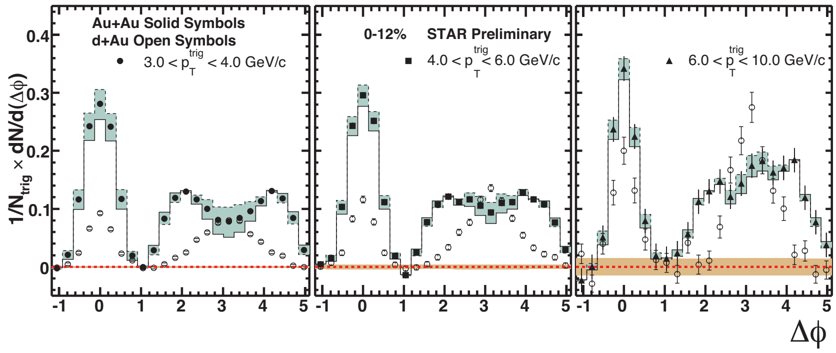

Figure 11: (colour online) Background-subtracted distribution of associated hadrons with $1 < p_{T,assoc} < 2.5$ GeV/c for three different ranges of $p_{T,trig}$, in central Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV (full symbols) and d+Au collisions (open symbols)[42]. The lines indicate the uncertainty on the signal shape due to the uncertainty in the elliptic flow of the background. The shaded bands around 0 indicate the statistical uncertainty on the background level.

large cross section, but suffers from a large background of the high-multiplicity events in heavy ion collisions. Preliminary results of such an analysis have been presented in [48]. In the near future, differential measurements of the suppression as a function of hadron p_T will allow to further constrain parton energy loss in the medium.

5 Summary

The RHIC experimental program has produced a large number of new, interesting results. First dedicated studies of gluon saturation at forward rapidities have been performed. The results are consistent with pictures of gluon saturation, but a full theoretical description and additional data on jet-like correlations are still needed. Elliptic flow analysis shows early equilibration of the system and a preference for an equation of state with a QCD phase transition. Studies of systematic errors and the influence of the initial state distribution are being done to be able to reliably extract values of the viscosity of matter. Current estimates show a small but finite viscosity of about a few times the theoretical lower bound. The analysis has progressed to include many different hadron species, and so far constituent quark scaling has been confirmed in a reasonable momentum range.

Strong jet quenching has been demonstrated in single hadron yields up to transverse momenta of 20 GeV/c. The naïvely expected effects of different energy loss of gluons with respect to quarks have not been observed, pointing to a still not complete understanding of the physics of energy loss. A similar suppression is also observed in the recoil yield opposite to high p_T trigger particles. Both the suppression of single hadrons and of the recoil yield can successfully be described by QCD-based energy loss models, there is however still considerable uncertainty on the exact mechanisms. Strong modifications of the low and intermediate p_T jet-associated hadrons point to significant jet-induced effects on the medium, which are being studied by more advanced analysis methods. γ-jet correlations and full jet reconstruction are the observables of the future which should provide stronger constraints on parton energy loss.

References

[1] Proceedings of Quark Matter 2009, Nucl. Phys. A **830** (2009).

[2] E. Iancu, A. Leonidov, and L. McLerran (2002) `hep-ph/0202270`.

[3] J. Adams *et al.* (STAR collaboration), Phys. Rev. Lett. **97** 152302 (2006).

[4] S. Voloshin and Y. Zhang, Z. Phys. C **70**, 665 (1996).

[5] K. H. Ackermann *et al.* [STAR Collaboration], Phys. Rev. Lett. **86**, 402 (2001).

[6] C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **87**, 182301 (2001).

[7] T.D. Lee *et al.*, New Discoveries at RHIC: Case for the Strongly Interacting Quark-Gluon Plasma. Contributions from the RBRC Workshop held May 14-15, 2004. Nucl. Phys. A **750** (2005) 1-171

[8] P. Kovtun, D. T. Son and A. O. Starinets, Phys. Rev. Lett. **94** (2005) 111601

[9] M. Luzum and P. Romatschke, Phys. Rev. C **78**, 034915 (2008).

[10] H. J. Drescher, A. Dumitru, C. Gombeaud and J. Y. Ollitrault, Phys. Rev. C **76** (2007) 024905

[11] R. S. Bhalerao, J. P. Blaizot, N. Borghini and J. Y. Ollitrault, Phys. Lett. B **627** (2005) 49

[12] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **92**, 052302 (2004).

[13] Z.W. Lin and C.M. Ko, Phys. Rev. Lett. **89**, 202302 (2002); D. Molnar and S.A. Voloshin, Phys. Rev. Lett. **91**, 092301 (2003).

[14] R.C. Hwa and C.B. Yang, Phys. Rev. C **67**, 064902 (2003); R.J. Fries, B. Muller, C. Nonaka and S.A. Bass, Phys. Rev. Lett. **90** 202303 (2003).

[15] J.D. Bjorken, Fermilab-Pub-82/59-THY (1982).

[16] K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **88**, 022301 (2002).

[17] C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **89**, 202301 (2002).

[18] S.S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **91**, 072301 (2003).

[19] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **91**, 172302 (2003).

[20] K. Reygers *et al.* [PHENIX Collaboration], J. Phys. G **35** 104045 (2008).

[21] S.S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **94**, 232301 (2005)

[22] B.B. Back *et al.* [PHOBOS Collaboration], Phys. Rev. Lett. **91**, 072302 (2003).

[23] S.S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **91**, 072303 (2003).

[24] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **91**, 072304 (2003).

[25] I. Arsene *et al.* [BRAHMS Collaboration], Phys. Rev. Lett. **91**, 072305 (2003).

[26] J. Putschke *et al.* [STAR Collaboration], Nucl. Phys. A **830** 58c-65c (2009).

[27] C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **90**, 082302 (2003).

[28] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **97**, 162301 (2006).

[29] A. Dainese, C. Loizides, G. Paic, Eur. Phys. J. C **38**, 461 (2005), `hep-ph/0406201`

[30] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **101**, 232301 (2008).

[31] H. Zhang, J.F. Owens, E. Wang, X.N. Wang, Phys. Rev. Lett. **98**, 212301 (2007).

[32] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **77**, 064907 (2008).

[33] C.A. Salgado, U.A. Wiedemann, Phys. Rev. D **68**, 014008 (2003).

[34] J.L. Nagle (2008), `arXiv:0805.0299`

[35] J. Putschke *et al.* [STAR Collaboration], J. Phys. G**34**, S679 (2007).

[36] N. Armesto, C.A. Salgado, U.A. Wiedemann, Phys. Rev. Lett. **93**, 242301 (2004).

[37] A. Majumder, B. Muller, S.A. Bass, Phys. Rev. Lett. **99**, 042301 (2007).

[38] P. Romatschke, Phys. Rev. C **75**, 014901 (2007).

[39] C.B. Chiu, R.C. Hwa, Phys. Rev. C **72**, 034903 (2005).

Discussion

Guido Altarelli (Roma III and CERN): What is the physics programme at RHIC for the next future?

Answer: The upcoming heavy-ion measurements at RHIC will serve to collect significant luminosity for rare probes and should allow e.g. a quantitative characterization of jet quenching. This will profit in particular from the upgrade of the DAQ in STAR. Further detector upgrades already implemented or in progress will enhance the capabilities for particle identification, like the new TOF detector in STAR, the hadron-blind detector (HBD) in PHENIX, or the silicon vertex detector upgrades in both experiments. The latter should allow to obtain crucial information on the production of charm and bottom hadrons, and should help to elucidate the puzzles related to existing heavy flavor measurements at RHIC.

Benni Ward (Baylor University): String theorists have found model violations of the AdSICFT limit you reference as a quantum mechanical limit - quantum mechanics is not a model. Please comment.

Answer: The remark is relevant. In fact in the presentation I have shown a statement on a "quantum mechanical limit" of shear viscosity, which has been used by a number of colleagues in the field but which is strictly speaking not adequate. The limit has been derived from model calculations, which incorporate some aspects of quantum mechanics, but certainly not from first principles. There are some calculations in string theory that you probably refer to, which give a different answer. The purpose of the presentation was, however, to demonstrate that the shear viscosity of the matter produced at RHIC is very low, and possibly close to the AdS/CFT-limit - thus low compared to any other real system, independently of the conceptual status of this limit.