CGC, Hydrodynamics, and the Parton Energy Loss

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Abstract. Hadron spectra in Au+Au collisions at RHIC are calculated by hydrodynamics with initial conditions from the Color Glass Condensate (CGC). Minijet components with parton energy loss in medium are also taken into account by using parton density obtained from hydrodynamical simulations. We found that CGC provides a good initial condition for hydrodynamics in Au+Au collisions at RHIC.

High energy heavy ion collisions involve different aspects according to the relevant energy or time scale. There already exist many theoretical approaches to understand numerous RHIC data. In this work, we consider in particular physics of gluon saturation, hydrodynamic evolution, and the energy loss of hard partons in the medium. Our goals are to combine them and to take a step to a unified understanding of the dynamical aspect of high energy heavy ion collisions.

At soft region $p_T < 2$ GeV/c, where bulk dynamics is governed, hydrodynamical description [1] is successful in describing the elliptic flow at low $p_T$, up to semi-central collisions, and mid-rapidity [2] at RHIC. This is one of the strongest indications of an early thermalization of the quark gluon plasma (QGP) at RHIC. Hydrodynamics also predicts that the scaled elliptic flow, which is defined as the second harmonics $v_2$ divided by initial spatial eccentricity $\varepsilon$, becomes almost constant around 0.2 [3]. The experimental data reaches the hydrodynamic limit for the first time in central and semi-central collisions at RHIC energies [4]. On the other hand, minijets go across the expanding matter and lose their energies (jet quenching) in heavy ion collisions [5]. Observed large suppression of hadron spectra [6] and disappearance of the away-side peak in azimuthal correlation functions at mid-rapidity [7] have been interpreted as a consequence of parton energy loss in the medium. Indeed, Cronin enhancement of the hadron spectra and existence of the back-to-back correlation at mid-rapidity in $dA$ collisions at RHIC [8] support the importance of the strong final state interaction in $AA$ collisions. The current RHIC data strongly suggest that the initial parton density is large. What is an origin of the large density in Au+Au collisions at RHIC? The bulk particle production is dominated by the small $x$ modes in the nuclear wave function, where $x$ is a momentum fraction of the incident particles. It is well known that gluon density increases rapidly with decreasing $x$ by the BFKL cascade until gluons begin to overlap in phase space where nonlinear interaction becomes important [9]. These gluons form the Colour Glass Condensate (CGC) [10]. Remarkably, the CGC results
on the global observables such as the centrality, rapidity and the energy dependences of charged hadron multiplicities agree with the RHIC data [11]. It has been shown that the classical wave function in the MV model contains Cronin enhancement and the quantum evolution in $x$ makes the spectrum suppressed [12].

From the above considerations, the CGC, hydrodynamics, and the energy loss of hard partons are key ingredients to describe the RHIC physics and must be closely related with each other. For example, the CGC could be a good initial condition for thermalization because it produces a large number of gluons. Thus these gluons are responsible to the large suppression of jet spectra. In this work we assume that the origin of thermalized partonic matter is the CGC in high energy heavy ion collisions, and use it as an initial condition in the hydro+jet model [13]. With this approach we expect to get deeper understanding of the dynamical aspect of the heavy ion collisions. In addition, some of the problems which are inherent in a particular approach can be removed. We employ the $k_T$ factorized formula along the line of Kharzeev, Levin, and Nardi (KLN) [11] for the computation of the gluon rapidity distribution which is given by

$$\frac{dN_g}{d^2x_1dy} = \frac{4\pi^2N_c}{N_c^2-1}\int \frac{d^2p_T}{p_T^2}\int d^2k_T\alpha_s\phi_A(x_1,k_T^2)\phi_B(x_2,(p_T-k_T)^2),$$  \hspace{1cm} (1)

where $x_{1,2} = p_T\exp(\pm y)/\sqrt{s}$ with $y$ and $p_T$ are a rapidity and a transverse momentum of a produced gluon. We assume that the system of initially produced gluons reaches local thermaлизed state at a short time scale. Although the produced gluons will reach the thermalized state through the dissipative processes in the realistic situations, the description of non-equilibrium phenomena is beyond the scope of the present paper. We also assume that the shape of the rapidity density distribution is not changed during the system is thermalized. Therefore, we take initial conditions from gluon distribution obtained from Eq. (1). Assuming Bjorken’s ansatz $y = \eta_s$ where $\eta_s$ is the space-time rapidity, we obtain the number or the energy density for gluons at each space-time point.

The initial transverse energy per particle yields $E_T/N_g \sim 1.6$ GeV at $y = 0$ from Eq. (1). This is within a range estimated in a numerical simulation of the classical Yang-Mills equation [14]. It should be noted that the assumption of the thermalization in CGC gluon distribution is to reduce the transverse energy per particle from $E_T/N_g = 1.6$ to $E_T/N_g \approx 1$ within our present parameters. The effect of the hydrodynamic afterburner is to reduce the transverse energy per particles due to $pdV$ work and yields $(dE_T/dy)/(dN/dy)|_{y=0} = 0.54$ GeV. The rapidity distribution becomes slightly wider. Our result supports that KLN calculation [11] which is based on the assumption of parton-hadron duality is a good approximation on the rapidity distributions. In Fig. 1 pseudorapidity distributions of charged hadrons in Au + Au collisions at both $\sqrt{s_{NN}} = 130$ and 200 GeV are compared with the PHOBOS data [15]. $k_T$ factorization approach in the CGC provides very good initial conditions for the hydrodynamical simulations which reproduce rapidity, centrality and energy dependences of multiplicity. It should be emphasized that it is very hard to find such a good initial condition which fits the data with the same quality as the CGC one presented here.
Figure 1. Pseudorapidity distributions of charged hadrons in Au + Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV is compared to the PHOBOS data \[15\]. Impact parameters which correspond to $\langle N_{\text{part}} \rangle$ from PHOBOS are used in the calculations.

Figure 2. Transverse momentum spectra for negative pions (left) and nuclear modification factor $R_{AA}$ (right) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ are compared to the PHENIX data \[16\].

We now turn to the discussion of the high $p_T$ hadron spectrum. In our model, high $p_T$ jets suffer interaction with the local parton density which is governed by hydrodynamic evolution. We only take into account parton energy loss in deconfined matter $T \geq T_c$. In Fig. 2 the result of the centrality dependence of the pion spectrum and the nuclear modification factor $R_{AA}$ integrated over $p_T > 4.5$ GeV/c for $|\eta| < 0.35$ are compared to PHENIX data \[16\]. Our results only account for the data up to midcentral events and fail to reproduce data at peripheral collisions, because neither CGC nor hydrodynamics can be applied in the low density region. The centrality dependence is well described by assuming the number of participants scaling \[17\]. However, note that our density scales as $\rho \sim \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \sim \frac{1}{\alpha_s(Q_T^2)} \rho_{\text{part}}$ at mid-rapidity. By comparison, we also plot the LOpQCD calculations with the same initial condition assuming (1+1)D expansion of the system ($\rho \sim 1/\tau$). LOpQCD calculation without parton energy loss at
$T < T_c = 170$ MeV is consistent with our hydrodynamic result. However, if there is no restriction on the minimum temperature in the calculation of energy loss, we see that agreement with data becomes somewhat better. This may indicate the contribution from hadronic interactions at peripheral collisions.

In summary, CGC, hydrodynamics and the energy loss of hard jets have been integrated into one model and this dynamical approach describes the bulk properties of RHIC data. A systematic study within this dynamical approach is in progress.

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References

[1] P. Huovinen, *nucl-th/0305064*; P. F. Kolb and U. Heinz, *nucl-th/0305084*.
[2] P. F. Kolb, P. Huovinen, U. Heinz, and H. Heiselberg, Phys. Lett. B 500, 232 (2001); P. Huovinen, P. F. Kolb, U. W. Heinz, P. V. Ruuskanen, and S. A. Voloshin, *ibid.* B 503, 58 (2001). T. Hirano, Phys. Rev. C 65, 011901 (2002); T. Hirano and K. Tsuda, Phys. Rev. C 66, 054905 (2002).
[3] P. F. Kolb, J. Sollfrank and U. W. Heinz, Phys. Rev. C 62, 054909 (2000).
[4] C. Adler et al., STAR Collaboration, Phys. Rev. C 66, 034904 (2002).
[5] M. Gyulassy, I. Vitev, X. N. Wang, and B. W. Zhang, *nucl-th/0302077*; A. Kovner and U. A. Wiedemann, *hep-ph/0304151*.
[6] S. S. Adler et al., PHENIX Collaboration, Phys. Rev. Lett. 91, 072301 (2003); K. Adcox et al., STAR Collaboration, Phys. Lett. B 561, 82 (2003).
[7] C. Adler et al., STAR Collaboration, Phys. Rev. Lett. 90, 082302 (2003).
[8] B. B. Back et al., PHOBOS Collaboration, Phys. Rev. Lett. 91, 072302 (2003); S. S. Adler et al., PHENIX Collaboration, *ibid.*, 91, 072303 (2003); J. Adams et al., STAR Collaboration, *ibid.*, 91, 072304 (2003); I. Arsene et al., BRAHMS Collaboration, *ibid.*, 91, 072305 (2003).
[9] L. V. Gribov, E. M. Levin and M. G. Ryskin, Phys. Rept. 100, 1 (1983).
[10] L. D. McLerran and R. Venugopalan, Phys. Rev. D 49, 2233 (1994); *ibid.* 49, 3352 (1994); *ibid.* 50, 2225 (1994); E. Iancu and R. Venugopalan, *hep-ph/0303204*.
[11] D. Kharzeev and M. Nardi, Phys. Lett. B 507, 121 (2001); D. Kharzeev and E. Levin, Phys. Lett. B 523, 79 (2001); D. Kharzeev, E. Levin and M. Nardi, Nucl. Phys. A 730, 448 (2004).
[12] R. Baier, A. Kovner, and U. A. Wiedemann, Phys. Rev. D 68, 054009 (2003); J. L. Albacete, N. Armesto, A. Kovner, C. A. Salgado and U. A. Wiedemann, *hep-ph/0307179*; D. Kharzeev, Y. V. Kovchegov and K. Tuchin, Phys. Rev. D 68, 094013 (2003); J. Jalilian-Marian, Y. Nara and R. Venugopalan, Phys. Lett. B 577, 54 (2003). J. P. Blaizot, F. Gelis and R. Venugopalan, *hep-ph/0402256*; *hep-ph/0402257*; E. Iancu, K. Itakura, D. N. Triantafyllopoulos, *hep-ph/0403103*.
[13] T. Hirano and Y. Nara, Phys. Rev. C 66, 041901(R) (2002); Phys. Rev. Lett. 91, 082301 (2003). Phys. Rev. C 68, 064902 (2003); Phys. Rev. C in press (*nucl-th/0307015*).
[14] A. Krasnitz, Y. Nara, and R. Venugopalan, Phys. Rev. Lett. 87, 192302 (2001); Nucl. Phys. A717, 268 (2003); Nucl. Phys. A 727, 427 (2003). T. Lappi, Phys. Rev. C 67, 054903 (2003).
[15] B. B. Back et al., PHOBOS Collaboration, Phys. Rev. Lett. 91, 052303 (2003)
[16] S. S. Adler et al., PHENIX Collaboration, *nucl-ex/0307022*; *nucl-ex/0308006*.
[17] X. N. Wang, *nucl-th/0305010* Phys. Lett. B 579, 299 (2004).