Transverse Spectra of Hadrons in Central AA Collisions at RHIC and LHC from pQCD+Saturation+Hydrodynamics and from pQCD+Energy Losses

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We study the transverse spectra of hadrons in nearly central AA collisions at RHIC and LHC in a broad transverse momentum range [1]. Low-p_T spectra are calculated by using boost-invariant hydrodynamics with initial energy and net-baryon densities from the EKRT [2] pQCD+saturation model. High-p_T spectra are obtained from pQCD jet calculation [3] including the energy loss of the parton [4] in the matter prior to its fragmentation to final hadrons.

1. Introduction

Transverse momentum spectra of hadrons in ultrarelativistic nuclear collisions provide valuable information of particle production mechanism in the collisions as well as dynamics and properties of the produced QCD matter. Low-p_T features of the single particle spectra are well described by hydrodynamical models and the data is consistent with an ideal fluid behaviour of the matter. The observed azimuthal asymmetry in non-central Au+Au collisions at RHIC has been argued to result from strong collective motion and early thermalization of produced partonic matter. The suppression observed in the high-p_T tail of the spectra relative to the p+p and d+Au collisions is understood as the energy loss of high-p_T partons into the thermalized partonic matter.

Our approach is to calculate initial particle production using the EKRT model which is based on the idea that the low-p_T particle production is controlled by saturation among the final state gluons in contrast to the initial state saturation models, where saturation is the property of colliding nuclei. The EKRT model provides a closed framework to calculate initial transverse energy and net-baryon number in midrapidity in nuclear collisions with sufficiently large $\sqrt{s}$ and A. Final low-p_T hadron spectra are calculated by using hydrodynamics with initial densities from the EKRT model. A good agreement with the measured data in central Au+Au collisions at RHIC is obtained [1,5]. We further predict the hadron spectra in central Pb+Pb collisions at the LHC [1].

High-p_T part of the spectra is calculated using factorized pQCD parton model for high-

p_T parton production and taking into account the parton energy loss before fragmentation.

We compare these two models with the RHIC data and determine the regions where each component is dominant. In particular, we find that the low-p_T hydrodynamical spectrum dominates over the fragmentation spectrum in a much wider p_T region at the LHC than at RHIC. We discuss the independence of the two components and conclude that they are most likely almost independent even in the cross-over region.

2. Models

2.1. pQCD + saturation + hydrodynamics

The EKRT model [2] estimates the final state saturation scale using the following geometric criterion: Saturation becomes important when the produced gluons fill the whole available transverse area of the colliding nuclei. For central collisions this can be written as

$$N_{AA}(q_0, \sqrt{s}, A)\frac{\pi}{q_0^2} = \pi R_A^2, \tag{1}$$

where N_{AA} is the number of gluons above a transverse momentum cut-off, $q_T > q_0$ in the rapidity interval $|y| \leq 0.5$, and R_A is the nuclear radius. This condition provides the saturation scale $p_{sat} = q_0$. If $p_{sat} \gg \Lambda_{QCD}$, pQCD can be used to estimate the number of produced partons and the amount of transverse energy at midrapidity. This approach gives also the net-baryon number at midrapidity. If we assume that the produced matter thermalizes immediately after production at $\tau_0 = 1/p_{sat}$, we obtain the initial energy and net-baryon density at τ_0 for hydrodynamical evolution.

We use ideal fluid hydrodynamics with boost-invariance and azimuthal symmetry. In the bag-model equation of state the hadron gas phase consists of all hadronic states with $m < 2$ GeV and the QGP phase of massless gluons and three flavors of quarks. Critical temperature is chosen to be 165 MeV. After the hydrodynamic expansion and cooling of the matter, the Cooper-Frye decoupling prescription is applied for the calculation of the low-p_T spectra. Below we show the sensitivity of the decoupling procedure on the decoupling condition.

2.2. pQCD + fragmentation + energy loss

High-p_T spectra are calculated using nuclear parton distributions, pQCD parton cross sections, fragmentation functions and quenching weights for energy losses. We use leading order perturbative cross sections with K-factors fixed from p+$p(\bar{p})$ data [3]. The K-factors are extrapolated to the LHC energy by using different parametrizations to estimate the uncertainties in the extrapolation. The magnitude of the energy losses can be expressed with one effective transport coefficient, which is fixed from the RHIC Au+Au data at $\sqrt{s_{NN}} = 200$ GeV [4]. Since the transport coefficient is proportional to energy density, fixing it in one collision predicts it for other collisions. There is quite a large uncertainty associated with the eikonal approximation used in the energy loss calculation; arbitrarily large energy losses are allowed whereas the energy of real jets is limited. There are different ways to deal with this [4], shown here as an uncertainty in our pQCD fragmentation + energy loss results.

3. Results

In Fig 1a we show our results for unidentified charged hadrons at midrapidity for 5 % most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. As mentioned above we show our hydro results with two different decoupling temperatures to show the sensitivity on the decoupling condition. From the figure we observe that both the normalization and slope of the spectra are well reproduced with a single decoupling temperature $T_{dec} = 150$ MeV. The spectra from fragmentation calculation with and without energy loss are plotted in the same figure. It is seen clearly that the measured spectra at high p_T cannot be explained without energy loss. The transport coefficient that determines the energy loss is fixed from this data so that in this case the agreement is obtained by construction. The band in the energy loss results shows the uncertainty of eikonal approximation. For identified particles the spectra can be found from [1].

Fig 1b shows our prediction for the 5 % most central Pb+Pb collisions at the LHC. The hydrodynamical results are again shown as a band corresponding to the decoupling temperatures between 120 and 150 MeV. The band for the pQCD fragmentation results without energy loss is from the uncertainty in the extrapolation of the K-factors to the LHC energy. The large uncertainty in the energy loss calculation comes, as before, from the eikonal approximation.

We see in Fig 1a that at RHIC the hydrodynamical and pQCD + energy loss spectra cross at $p_T \sim 3 \ldots 4$ GeV, and that the data starts to deviate from the hydro spectrum in the same p_T region. At the LHC, the crossing region is moved to $p_T \sim 5 \ldots 6$ GeV, suggesting a wider p_T region of applicability of hydrodynamics at the LHC than at RHIC. It is also interesting to note that in the cross-over region the fragmentation and the hydrodynamical components are most likely almost independent: At RHIC 95 % of the thermalized matter comes from mini-jets with partonic transverse momenta $p_{sat} < q_T <$ 3.6 GeV and the higher-q_T partons contribute to the normalizations and the slopes of the hydrodynamic spectra only slightly. On the other hand even without the energy loss the pQCD pions are dominantly from partons with $q_T \sim 1.7 p_T$, which is 5.1 GeV for $p_T \sim 3$ GeV pions. With energy loss included they originate from even higher q_T. Thus the partonic origin of fragmentation pions and pions from thermalized matter is quite different suggesting that the two contributions are quite independent even in the cross-over region and can be added without serious double counting. The same argument holds also at the LHC. Crossing between hydro and fragmentation spectra depends also on particle species as studied at RHIC energies in ref. [6].

4. Conclusions

We have calculated low-p_T spectra of hadrons for central Au+Au collisions at RHIC and Pb+Pb collisions at the LHC using the EKRT model to calculate the initial parton production and hydrodynamics to calculate the expansion of produced matter. High-p_T hadron spectra are calculated by assuming that the high-q_T partons do not thermalize but fragment to hadrons after loosing energy when traversing the thermal matter. Our model is shown to be in a good agreement with the measured data in central collisions at RHIC. We have provided predictions for central Pb+Pb collisions at the LHC, including also the net baryon number, see [1]. The origins of the thermal and the pQCD fragmentation spectra are discussed and it is argued that even in the cross-over region where the two components are comparable, they are essentially independent.

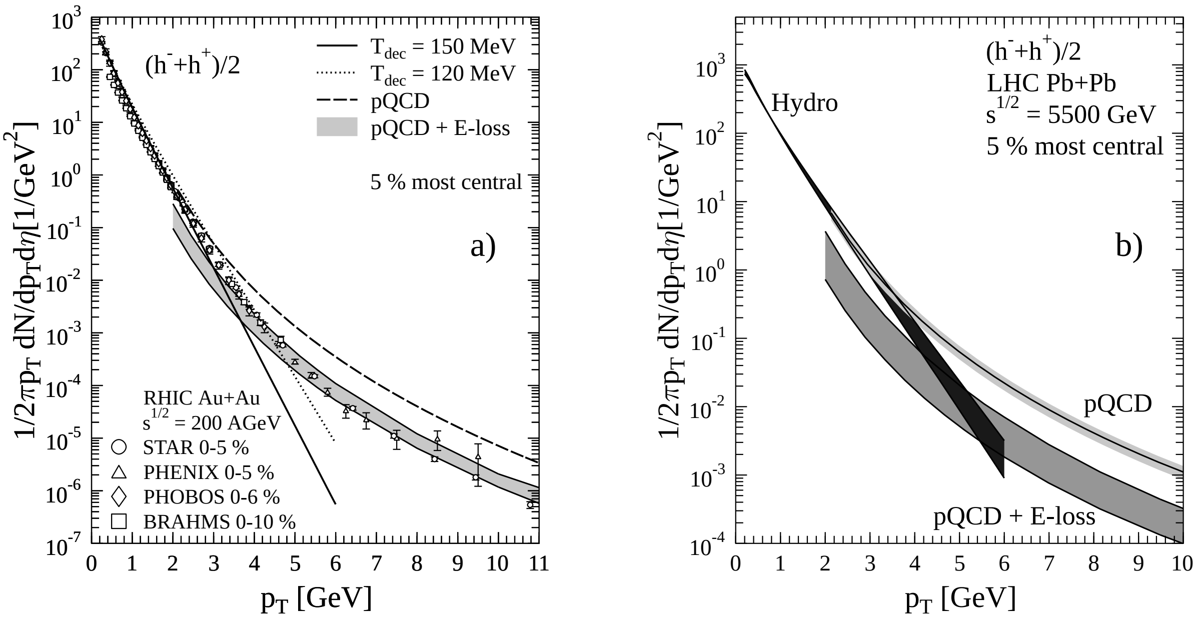

Figure 1. **a)** Transverse momentum spectra of charged hadrons at $y = 0$ in 5 % most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The solid and dotted lines shows our hydrodynamic results with $T_{dec} = 150$ MeV and $T_{dec} = 120$ MeV respectively. The shaded band shows the pQCD fragmentation+energy loss spectrum and dashed line pQCD fragmentation without energy loss. The data is from Refs. [7–10]. **b)** As Fig. 1a but for the 5 % most central Pb+Pb collision at $\sqrt{s_{NN}} = 5500$ GeV.

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