

Effects of hadronic rescattering in mini-jet production and energy loss at the LHC

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We present an extension of hybrid approach, which combines viscous hydrodynamics, particlization, jet energy loss and hadronic cascade, to describe data in the intermediate and high p_T regimes. This enables us to study mini-jet production and energy loss in heavy ion collisions, in conjunction with the bulk dynamics of QGP fireball. This hybrid approach is applied for Pb-Pb collisions at the LHC with $\sqrt{s_{NN}} = 2.76$ TeV, and we demonstrate that hadronic re-scatterings have significant effects on mini-jets with intermediate p_T .

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1. Introduction

Since the first series of heavy ion experiments were carried out, high-energy nucleus-nucleus collisions have been an important tool to study QCD matter at high temperature. One of the most important findings is the existence of quark-gluon plasma (QGP), which behaves like a perfect fluid [1, 2, 3, 4, 5, 6, 7]. The hybrid framework of viscous hydrodynamics and hadronic cascade has been successful in describing a wide range of soft (low- p_T) observables in heavy ion collisions [8, 9, 10, 11]. In addition to the bulk dynamics of QGP, measurements of the nuclear modification factor imply that jet-medium interactions are also useful probes [12, 13]. Even though many sophisticated studies have been done in both the hard and soft regimes, respectively, less attention has been paid to the intermediate p_T ranges involved in heavy ion collision, where the thermal hadrons and mini-jet hadrons have comparable contributions. In this work, we extend a hybrid approach, which provides a reasonable description of the bulk dynamics, toward the higher p_T range by having mini-jet production and energy loss. We also demonstrate that hadronic re-scatterings in the late stage of heavy ion collisions can significantly deform the momentum space distribution of final state hadrons.

2. Model structure

The initial state is determined by the IP-Glasma model [14, 11]. The nucleon positions, from which one can find the positions of participants, spectators, and binary collisions, fluctuate event to event and determine the initial geometry of the collision. The pre-equilibrium dynamics are dominated by low-momentum gluons that are sourced by the hard partons in the colliding nuclei. The large occupation number of the small- x gluons justifies treatment as a classical field. Thus, the gluon field is evolved in time using the classical Yang-Mills equations until $\tau_0 = 0.4$ fm, at which the system is assumed to reach local thermal equilibrium.

The subsequent time evolution of the fireball is handled by means of the second-order viscous hydrodynamics, which is numerically solved by MUSIC [15]. Transport coefficients define how the system reacts to spatial anisotropy and inhomogeneity. In addition to shear and bulk viscosities, there are the second-order transport coefficients specifying contributions of the higher-order gradients [16, 17].

$$\partial_\mu T^{\mu\nu} = 0 \quad (2.1)$$

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta \theta - \delta_{\Pi\Pi} \Pi \theta + \lambda_{\Pi\pi} \pi^{\mu\nu} \sigma_{\mu\nu} \quad (2.2)$$

$$\begin{aligned} \tau_\pi \dot{\pi}^{(\mu\nu)} + \pi^{\mu\nu} &= 2\eta \sigma^{\mu\nu} - \delta_{\pi\pi} \pi^{\mu\nu} \theta + \varphi_\gamma \pi_\alpha^{(\mu} \pi^{\nu)\alpha} \\ &\quad - \tau_{\pi\pi} \pi_\alpha^{(\mu} \sigma^{\nu)\alpha} + \lambda_{\pi\Pi} \Pi \sigma^{\mu\nu} \end{aligned} \quad (2.3)$$

where the temperature-dependent ζ/s has a peak at $T_{\text{peak}} = 180$ MeV and η/s is set to be 0.095 to reproduce the p_T -integrated flow coefficients [8, 11]. The equations of motion for hydrodynamic system can be closed with the equation of state [18], which provides relations among energy density, charge densities, temperature and chemical potentials. In this work, vanishing baryon number density and baryonic chemical potential are assumed, a valid approximation in the mid-rapidity region of heavy ion collisions.

Given that microscopic transport, implemented by means of an N -body simulation of hadrons, is necessary to describe non-equilibrium dynamics in the late stage of heavy ion collisions, the hydrodynamic information must be transformed into particles by a sampling procedure. This is done according to the Cooper-Frye formalism [19], which provides a connection between the momentum-space distribution and the 3-dimensional hypersurface where particles are emerging.

$$\frac{dN}{d^3\mathbf{p}} = g \int_{\Sigma} f(x, \mathbf{p}) \frac{p^\mu d^3\Sigma_\mu}{E_{\mathbf{p}}} \quad (2.4)$$

where the macroscopic information from hydrodynamics comes into the distribution function $f = f_0 + \delta f_{\text{shear}} + \delta f_{\text{bulk}}$. In this work, the leading order contributions to δf_{shear} and δf_{bulk} , which are respectively proportional to $\pi^{\mu\nu}$ [20] and Π [21], are considered. Particles are sampled on the isothermal hypersurface with switching temperature $T_{\text{sw}} = 145 \text{ MeV}$, such that the proton p_T spectrum is reproduced [8, 9].

To extend our hybrid approach toward the intermediate and higher p_T , jet production and energy loss must be involved in our framework. We perform jet production using PYTHIA 8 [22, 23] with a fixed minimum in transverse momentum transfer in $2 \rightarrow 2$ partonic interaction. The probability P_{hard} that we have hard nucleon-nucleon process at each binary collision is given by

$$P_{\text{hard}}(\hat{p}_{T,\text{min}}) = \frac{\sigma_{\text{hard}}(\hat{p}_{T,\text{min}})}{\sigma_{\text{inel}}} \quad (2.5)$$

$$\sigma_{\text{hard}}(\hat{p}_{T,\text{min}}) = \sum_{i,j} \int dx_1 f_i(x_1) \int dx_2 f_j(x_2) \hat{\sigma}_{i,j}(x_1, x_2; \hat{p}_{T,\text{min}}) \quad (2.6)$$

where $\hat{\sigma}_{i,j}$ and $\hat{p}_{T,\text{min}}$ are respectively the partonic cross section and minimum transverse momentum transfer. $\hat{p}_{T,\text{min}}$ is set to be 10 GeV in the presented calculations. Mini-jet partons produced by hard interactions then propagate into thermal QGP medium and experience energy loss. There are two mechanisms that make jet partons lose energy — radiation of gluons [24] and collision with thermal partons [25]. Monte-Carlo implementation of energy loss with given hydrodynamic evolution is performed by MARTINI [26].

Hadronic cascade in the late stage of heavy ion collisions is handled by the UrQMD model [27, 28], which is microscopic transport of hadrons. It provides a solution to the transport equation

$$p^\mu \frac{\partial f}{\partial x^\mu} = \mathcal{C}[f] \quad (2.7)$$

by means of the N -body simulation, where individual particle can propagate and collide.

3. Results

We present the application of our hybrid approach for Pb-Pb collisions at the LHC with $\sqrt{s_{NN}} = 2.76 \text{ TeV}$. The shear and bulk viscosities and switching temperature are fixed such that experimental data for the integrated observables can be reproduced. Figure. 1 shows the identified hadrons p_T spectra and p_T -differential elliptic flow of pions without MARTINI jets. From the functional form of the distribution function $f \sim e^{-p_T/T}$ at high p_T , it can be clearly seen that jet production and energy loss must be incorporated into our hybrid approach. Discrepancy in the

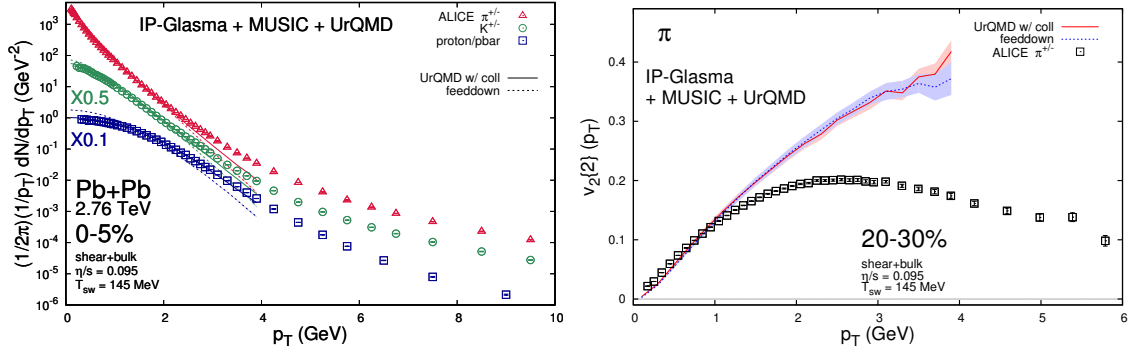


Figure 1: Identified hadrons p_T spectra (left) and p_T -differential elliptic flow of pions (right) in the absence of jet production and energy-loss [9]. ALICE data are respectively from [29] and [30].

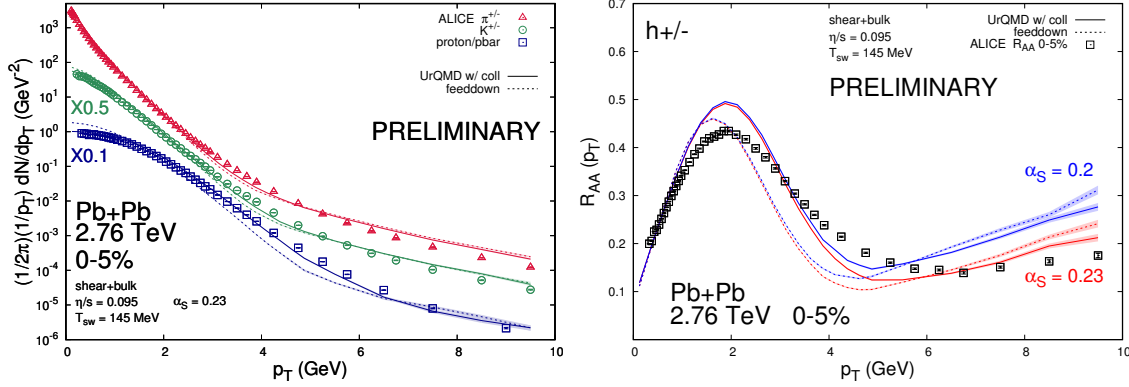


Figure 2: Identified hadrons p_T spectra (left) and inclusive R_{AA} of charged hadrons (right) in the presence of jet production and energy-loss. ALICE data are respectively from [29] and [31].

elliptic flow at intermediate and high p_T is partially due to the fact that contributions of mini-jets with lower anisotropy are not taken into account.

As shown in Figure. 2, inclusion of mini-jet contributions enables us to describe the intermediate and higher p_T observables within the hybrid approach. Hadronic re-scatterings have significant effects on baryonic spectra not only for the low p_T range, but also for higher p_T . The nuclear modification factor R_{AA} indicates that the effects of hadronic re-scatterings in the intermediate p_T range are different from consequence of having different strong coupling α_S in the QGP phase. One can have an interpretation that mini-jet hadrons with high p_T are decelerated while low- p_T hadrons from the fireball are accelerated by re-scatterings.

Anisotropies in the momentum space are also affected by hadronic re-scattering, as depicted in Figure. 3. For pions and protons, re-scatterings result in more anisotropic particle distribution in the intermediate range ($3 \text{ GeV} < p_T < 6 \text{ GeV}$), where thermal and mini-jet hadrons have comparable contributions. Thermal hadrons, emerging from the fireball, are more anisotropic than mini-jet hadrons and shifted toward high- p_T region by collisions with the jet hadrons. In addition, one can see that dependence of the radial and azimuthal distribution on hadronic cascade is stronger than

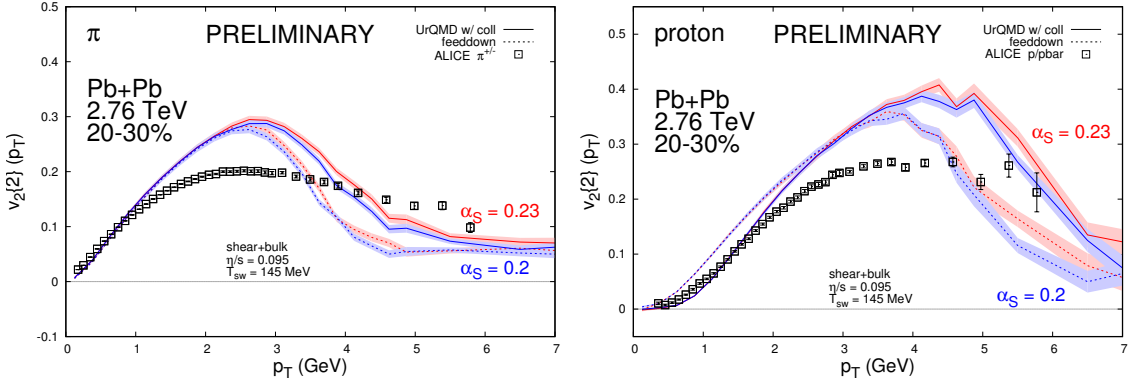


Figure 3: p_T -differential elliptic flow of pions (left) and protons (right) in the presence of jet production and energy-loss. ALICE data are from [30].

that on coupling constant in the QGP phase.

4. Conclusion

We model jet production and energy loss, combined with a hybrid model consisting of viscous hydrodynamics and hadronic afterburner for heavy ion collisions. Inclusion of the mini-jet contributions makes our hybrid approach capable of describing the intermediate and higher p_T observables. We demonstrate that hadronic re-scatterings have distinct effects on the final state particle distribution. Thermal hadrons are accelerated by mini-jets and the p_T spectra and anisotropic flow coefficients are shifted towards higher p_T . Those effects are unique in the sense that they cannot be compensated by different choice of strong coupling in the QGP phase. Given that deviation of the distribution function from the local thermal equilibrium becomes important in the intermediate p_T range ($3 \text{ GeV} < p_T < 6 \text{ GeV}$), we lastly point out that a systematic study on the viscous correction δf to the distribution function will improve the quality of description.

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