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Flow excited by full jet shower in QGP fluid and its effect on jet shape

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Abstract

We study the nuclear modification of full jet structure in relativistic heavy-ion collisions, with the inclusion of the effect of the medium response. The evolution of full jet shower is described by a set of transport equations, and the space-time evolution of quark-gluon plasma is simulated by solving relativistic hydrodynamic equations coupled with the energy and momentum depositions by jets as the source terms. We study the effect of medium response to full jet shower and present how jet-induced flow contributes to the full jet structure in PbPb collisions at the LHC.

Keywords: QGP, jet quenching, jet structure, relativistic hydrodynamics

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1. Introduction

Jets are modified in relativistic heavy-ion collisions by elastic and inelastic interactions with the constituents of the quark-gluon plasma (QGP) during their traversing the QGP medium. Such medium modification effects on hard jets is called “jet quenching” [1, 2], which has provided a useful tool to investigate the properties of the QGP medium that jets probe. One important aspect of jet-medium interaction is that some of the lost energy and momentum from the hard jets are deposited into the medium through the collisions with the QGP constituents and excite the medium. Since QGP behaves as a fluid, jet-induced excitation appears as flow in the medium [3, 4, 5, 6, 7]. As a consequence, the particles emitted from the medium around the direction of the jet axis (inside jet cone) are considered as part of jets constructed in the final state [8, 9, 10, 11], and thus contribute to the observed jet modification.

In this work, we study how the medium flow induced by the jet shower contributes to the energy loss and the shape of full jets in heavy-ion collisions. We formulate a model in which the transport equations are used to describe the jet shower evolution and the relativistic hydrodynamic equations with source terms are used to describe the QGP medium evolution. In particular, the medium response to the energy-momentum deposition from the hard jet is taken into account in the description of the QGP fluid evolution. Numerical simulations have been performed for (di-)jet events in PbPb collisions at 2.76A TeV. Our results show that the contribution from jet-induced medium excitation and flow increases the jet-cone size dependence of jet energy loss and suppression, and also modifies the jet shape function at large angles from the jet propagation direction.

2. Jet + Hydrodynamics Model

2.1. Jet Shower Evolution in Medium

To describe the evolution of the jet shower in the QGP medium, we solve the following transport equation [12]:

$$\begin{aligned}\frac{d}{dt}f_j(\omega_j,k_{j\perp}^2,t) &= \left(\hat{e}_j\frac{\partial}{\partial\omega_j}+\frac{1}{4}\hat{q}_j\nabla_{k_\perp}^2\right)f_j(\omega_j,k_{j\perp}^2,t)\\ &+\sum_i\int d\omega_i dk_{i\perp}^2\frac{d\tilde{\Gamma}_{i\to j}(\omega_j,k_{j\perp}^2|\omega_i,k_{i\perp}^2)}{d\omega_j dk_{j\perp}^2 dt}f_i(\omega_i,k_{i\perp}^2,t)\\ &-\sum_i\int d\omega_i dk_{i\perp}^2\frac{d\tilde{\Gamma}_{j\to i}(\omega_i,k_{i\perp}^2|\omega_j,k_{j\perp}^2)}{d\omega_i dk_{i\perp}^2 dt}f_j(\omega_j,k_{j\perp}^2,t),\quad(1)\end{aligned}$$

where $f_i(\omega_i,k_{i\perp}^2,t)=dN_i(\omega_i,k_{i\perp}^2,t)/d\omega_i dk_{i\perp}^2$ denotes the energy and transverse momentum distributions of the

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parton species i within the jet shower, ω_i is the energy, and $k_{i\perp}$ is the transverse momentum with respect to the jet axis. The first and second terms on the right hand side account for the momentum exchanges through the collisions with the medium constituents in the longitudinal direction and in the transverse direction, respectively. The remaining terms account for the contribution of the medium-induced partonic splitting processes. The rates of the medium-induced partonic radiations are taken from the higher-twist formalism [13, 14]. In our current framework, all the partons in the jet shower including the radiated partons experience energy-momentum exchange with the medium via collisions, as well as medium-induced splitting. The sizes of different channels are determined solely by the jet quenching parameter for quarks $\hat{q}_q$ by using the relations $\hat{q}_i = 4T\hat{e}_i$ [15] and $\hat{q}_g/\hat{q}_q = C_\mathrm{A}/C_\mathrm{F}$. In this study, we employ the parametrization, $\hat{q}_q(x) = \hat{q}_{q,0}\,[T(x)/T_0]^3\,[p\cdot u(\tau,\vec{r})/p_0]$, where T_0 is the the initial temperature at the centre of the medium. We set $\hat{q}_{q,0} = 1.7$ GeV^2/fm to fit the experimental data of R_AA from the ATLAS, ALICE, and CMS Collaborations [16, 17, 18]. In the simulations presented below, we generate the initial condition of the jet shower by using Pythia [19] and the Glauber model [20].

2.2. Hydrodynamic Equations with Source Terms

We describe the space-time evolution of the QGP by using the hydrodynamic equations with source terms,

$$\partial_\mu T^{\mu\nu}_{\mathrm{QGP}}(x) = J^\nu(x)\,, \tag{2}$$

where $T^{\mu\nu}$ is the energy-momentum tensor of the QGP and J^ν is the source term, namely the four dimensional energy-momentum density deposited from the jet shower via collisions. Assuming that the deposited energy and momentum from jet shower are locally thermalized in the medium instantaneously, we construct the source term as follows:

$$\begin{aligned} J^\nu(x) &= \sum_j \int \frac{d\omega_j dk^2_{j\perp} d\phi_j}{2\pi} k^\nu_j \left.\frac{df(\omega_j,k^2_{j\perp},t)}{dt}\right|_{\mathrm{col.}} \\ &\quad \times\delta^{(3)}\left(\boldsymbol{x}-\boldsymbol{x}\left(k_j,t\right)\right), \end{aligned} \tag{3}$$

where $\boldsymbol{x}(k_j,t) = \boldsymbol{x}^{\mathrm{jet}}_0 + \dfrac{\boldsymbol{k}_j}{\omega_j}t$, and

$$\left.\frac{df_j(\omega_j,k^2_{j\perp},t)}{dt}\right|_{\mathrm{col.}} = \left(\hat{e}_j\frac{\partial}{\partial\omega_j} + \frac{1}{4}\hat{q}_j\nabla^2_{k_\perp}\right)f_j(\omega_j,k^2_{j\perp},t). \tag{4}$$

We numerically solve the hydrodynamic equations with source terms in $(3+1)$ dimensional space-time with the equation of state from the lattice QCD calculation [21].

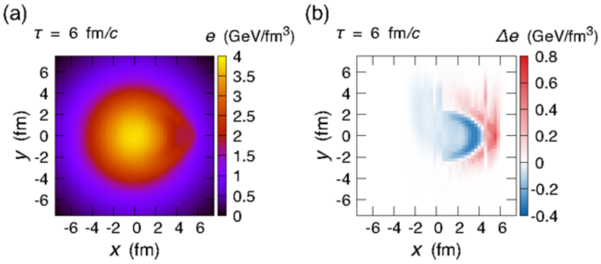

Figure 1: (Colour online) Energy density distribution of the expanding QGP fluid at $\tau = 6$ fm$/c$ in transverse plane at $\eta_s = 0$. The jet with initial $p^{\mathrm{jet}}_T = 150$ GeV$/c$ is created at $(\tau = 0, x = 0\,\mathrm{fm}, y = 0, \eta_s = 0)$ and travels in the x-direction. The left figure (a) shows the whole medium energy density, and the right figure (b) shows the medium energy density subtracted by that in the case without jet propagation.

In this work, we neglect the viscosity of the QGP and treat the medium as an ideal fluid.

The jet-induced flow in the medium enhances the particle emission from the medium. Some of these particles are included in the full jet reconstruction. To see this contribution, we calculate the momentum distribution of the particles form the medium by using Copper-Frye formula [22]. Here we calculate the increase of the particles compared to the case without jet propagation, $\Delta dN/d^3p = dN/d^3p|_{\mathrm{w/\,jet}} - dN/d^3p|_{\mathrm{w/o\,jet}}$, and include it in the jet reconstruction together with the particles from jet shower according to the transport equations (1). Hereafter we refer the contribution of showering particles described by the transport equations as shower part, and that of particles enhanced by medium excitation obtained via Copper-Frye formula as hydro part.

3. Simulations and Results

We perform simulations of (di-)jet events in central PbPb collisions at 2.76A TeV by using our model consisting of the transport equations describing the jet shower evolution and relativistic ideal hydrodynamic equations with source terms simulating the medium evolution. The jets are assumed to be produced in the transverse plane $\eta_\mathrm{s} = 0$ at $\tau = 0$ and freely travel in the transverse plane until $\tau = 0.6$ fm$/c$. Then we turn on the interaction between the jet and the QGP medium with the medium evolution. The initial profile of the QGP medium is generated by employing the optical Glauber model with the impact parameter $b = 0$ [23].

Figure 1 shows the energy density distribution of the QGP medium in the transverse plane at $\eta_\mathrm{s} = 0$ at $\tau = 6$ fm$/c$ in a event with a hard jet produced at the origin. The initial transverse momentum of the jet is 150 GeV$/c$. It can be clearly seen that the propagation