Energy loss in high energy heavy ion collisions from the Hydro+Jet model

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We investigate the effect of energy loss of jets in high energy heavy ion collisions by using a three-dimensional space-time evolution of a fluid combined with (mini-)jets that are explicitly evolved in space-time. In order to fit the $p_T^0$ data for the Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV, the space-time averaged energy loss $dE/dx(\tau \leq 3 \text{ fm/c}) = 0.36 \text{ GeV/fm}$ is extracted within the model. It is found that most energy loss occurs at the very early time less than 2 fm/c in the QGP phase and that energy loss in the mixed phase is negligible within our parameterization for jet energy loss. This is a consequence of strong expansion of the system.

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Measurements of high $p_T$ hadrons at the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) may provide insight into the excited partonic matter, often called a quark gluon plasma (QGP), produced in heavy ion collisions. Because jets have to traverse the excited matter, their spectra should be changed compared to the elementary hadron-hadron data. This energy loss of jets has been proposed as a possible signature of the QGP phase. Over the past year, a lot of work have been devoted to study the propagation of jets through QCD matter and also in Bjorken coordinate and in Cartesian coordinate and also in Bjorken coordinate.

Recently, hadronic transverse momentum distribution in Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV has been measured at RHIC and found that these spectra show the depletion at high transverse momentum. Comparison of the data with pQCD parton model based calculations and a transport theoretical study shows the indication of energy loss in central Au + Au collisions at RHIC energies. Phenomenological studies suggest that the space-time averaged energy loss yields small values of $dE/dx \sim 0.25-0.3 \text{ GeV/fm}$. In addition, jet quenching is found to be the main contribution on the elliptic flow parameter in the large transverse momentum region. Jet energy loss is modeled by modifying the fragmentation functions in pQCD parton model and usually neglecting the dynamical effects.

It might be important to consider dynamical effects on the jet interactions. The effects of the expansion of the system on the energy loss and the azimuthal asymmetry have been studied and also in Bjorken coordinate and, moreover, took into account the picture of the early chemical freeze-out in this model. Hydrodynamic model calculations at the RHIC energies suggest that the lifetime of the pure QGP phase is to be about 4 fm/c and that the mixed phase exists up to 9–10 fm/c. The density of the system drops rapidly due to the longitudinal expansion.

In this Letter, we explore the dynamical effects on the energy loss of jets by taking into account the full 3D space-time evolution of a fluid. The hydrodynamic model is combined with the jets (Hydro + Jet model) which are calculated from the pQCD parton model and explicitly propagated in space-time with fluid elements.

We use full 3D hydrodynamics in which initial parameters are fixed for Au+Au collisions at $\sqrt{s_{NN}} = 130 \text{ GeV}$. The transverse profile of the initial energy density is assumed to scale with the number of binary collisions. For 5% central collisions, we choose the impact parameter as $b = 2.4 \text{ fm}$ and the maximum initial energy density at the initial time $\tau_0 = 0.6 \text{ fm/c}$ as 33.7 GeV/fm$^3$. These parameters lead us to reproduce transverse momentum spectra of charged hadrons up to 1.0–1.5 GeV/$c$. It is found that the $p_T$ slope is insensitive to the thermal freeze-out temperature $T$ throughout this Letter. We fix $T = 140 \text{ MeV}$ throughout this Letter.

We include hard partons using pQCD parton model,

$$\frac{d\sigma_{jet}}{dp_T^2 dY_1 dY_2} = K \sum_{a,b} x_1 x_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \frac{d\sigma_{ab}}{dt},$$

(1)

where $Y_1$ and $Y_2$ are the rapidities of the scattered partons and $x_1$ and $x_2$ are the fractions of momentum of the initial partons. The parton distribution functions $f_a(x, Q^2)$ are taken to be CTEQ5 leading order. We use $Q^2 = p_T^2$ for the evaluation of parton distribution. The minimum momentum transfer $p_{T, \text{min}} = 2.0 \text{ GeV/c}$ is assumed. The summation runs over all parton species and relevant leading order QCD processes

$$q + q' \rightarrow q + q', \quad q + q \rightarrow q' + q', \quad q + g \rightarrow g + g, \quad g + g \rightarrow q + g, \quad g + q \rightarrow q + q,$$

(2)

(3)

(4)

are included in addition with the initial and final state radiation to simulate the emission of multiple soft gluons.
Gaussian primordial transverse momentum $k_T$ distribution with the width of $\langle k_T^2 \rangle = 1$ GeV$^2$ is assigned to the shower initiator in the QCD hard $2 \rightarrow 2$ processes. We use PYTHIA 6.2 \cite{25} to simulate each hard scattering in the actual calculation. A factor $K$ is used for the higher order corrections. We chose $K = 2$ to fit the UA1 data of $p\bar{p}$ at $\sqrt{s} = 200$ GeV \cite{26}. In order to convert hard partons into hadrons, we use an independent fragmentation model using PYTHIA after hydro simulations. We have checked that this hadronization model provides good agreement with the transverse spectra of charged hadrons above $p_T = 1$ GeV/c in $p\bar{p}$ data \cite{26}.

The number of hard partons is assumed to scale with the number of hard scattering which is estimated by using Woods-Saxon nuclear density. This assumption is consistent with the peripheral Au+Au collision at $\sqrt{s_{NN}} = 130$ GeV \cite{3}. The space coordinate of a parton in longitudinal direction is taken to be $\eta_b = Y$, where $\eta_b = (1/2) \log[(t + z)/(t - z)]$, and $Y$ is a momentum rapidity. The transverse coordinate of a parton is specified by the number of binary collision distribution for two Woods-Saxon distributions. Most hard partons are produced with the formation time of $\sim 1/p_T$ assuming the uncertainty relation. Since the initial time of the hydrodynamical simulation is $\tau_0 = 0.6$ fm/c, partons are assumed to travel freely up to $\tau_0$. We neglect the nuclear shadowing effect in the present work for simplicity, because it is small at high transverse momentum \cite{5} \cite{12}.

We assume that the form of energy loss is simply

$$\frac{dE}{dx} = \epsilon \sigma \rho(\tau, r),$$  \hspace{1cm} (5)

where $\epsilon$ is an energy loss per scattering and $\sigma$ is a parton-parton cross section. From a hydrodynamic simulation, we obtain the space-time evolution of temperature $T(\tau, r)$. A parton density $\rho(\tau, r)$ in the QGP phase is calculated from $T(\tau, r)$. For the mixed phase at $T = T_c (=170$ MeV), we put $\rho(\tau, r) = f_{QGP}(\tau, r)\rho(T_c)$ where the fraction of the QGP phase in the mixed phase $f_{QGP}(\tau, r)$ is calculated from energy density $\epsilon(\tau, r)$ and the maximum and minimum energy densities in the mixed phase $\epsilon_{QGP}$ and $\epsilon_{had}$ as

$$f_{QGP}(\tau, r) = \frac{\epsilon(\tau, r) - \epsilon_{had}}{\epsilon_{QGP} - \epsilon_{had}}.$$  \hspace{1cm} (6)

We assume that the energy loss for a quark jet is half of the energy loss of a gluon \cite{27}. In the present work, we neglect the possible space-time variation of parton-parton cross section and regard the product $\epsilon \sigma$ as an adjustable free parameter in the model. Feedback of the energy to fluid elements is ignored, because we use the relatively small values of energy loss parameter used in the work.

In Fig. 1, the transverse momentum distributions of neutral pions for central 10% Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV from PHENIX experiment \cite{7} are compared to the results of the hydro + jet model with different energy loss parameters $\sigma = 0, 0.06$ and 0.3 GeV fm$^2$ together with the hydro result dotted line. In the calculation, we choose the impact parameter $b = 3.35$ fm for 0–10% central events. The corresponding number of binary collisions is $N_{binary} = 906$. In order to connect the contribution from jets and a fluid smoothly, low $p_T$ pions from jets are cut by a switch function $\{1 + \tanh[3(p_T - 1.5 GeV)]\}/2$ \cite{13}. We reproduce $p_T$ spectrum for $\pi^0$ by choosing $\sigma = 0.06$ GeV fm$^2$, while the result which is not taken into account a energy loss overestimates the neutral pion spectrum. The hydro + jet result for $dE/dx = 0.2$ GeV/fm which is obtained

![Fig. 1: Comparison of $\pi^0$ spectra from hydro + jet (solid line) and hydro only (dotted line) with the energy loss parameter $\sigma = 0.06$ GeV fm$^2$ (solid line), hydro + jet with $\sigma = 0.3$ GeV fm$^2$ (dashed line), and hydro only (dotted line) for centrality of 10%. The result of hydro + jet for $dE/dx = 0.2$ GeV/fm calculation is shown in open squares.](image1.png)

![Fig. 2: Comparison of $\pi^0$ spectra from hydro + jet (solid line) and hydro only (dotted line) with the energy loss parameter $\sigma = 0.06$ GeV fm$^2$ and $b = 12.1$ fm to the PHENIX data \cite{7} for peripheral collision (60-80%).](image2.png)
by neglecting the density dependence in Eq. (6) is also shown in Fig. 3. We note that the hydro + jet result for $\epsilon \sigma = 0.3 \text{ GeV fm}^2$ is reproduced by the constant energy loss of $dE/dx = 1.0 \text{ GeV/fm}$. As shown in Fig. 2, $\pi^0$ spectra for peripheral (60-80%) Au + Au collisions can be reproduced only by changing the impact parameter to $b = 12.1 \text{ fm}$ ($N_{\text{binary}} = 20$) and leaving the other parameters. The hydro + jet result in peripheral collisions does not change when energy loss is not included, because the parton density and the volume of the QGP phase are small. On the other hand, the hydro + jet model overpredicts the data without energy loss in the central collisions. The deviation from data in the transverse momentum range below 1.5 GeV/$c$ in the peripheral collisions might be reasonable, because we do not expect that local thermalization is achieved in such a peripheral collision and that hydrodynamics is reliable.

The jet quenching is quantified by the ratio of the particle yield in A+A collisions to the one in p+p collisions scaled up by the number of binary collisions

$$R_{AA} = \frac{d^2N_{A+A}/dp_T dt}{N_{\text{binary}}d^2N_{p+p}/dp_T dt}, \quad (7)$$

The transverse momentum dependence of $R_{AA}$ can provide information about the mechanism of jet quenching. In Fig. 3, the result from the Hydro+Jet model with $\epsilon \sigma = 0.06 \text{ GeV fm}^2$ is compared to the PHENIX data. Our result is almost flat in the range $2 < p_T < 4 \text{ GeV/c}$.

Let us now turn to the study of the dynamical effects on the jet energy loss. The maximum and the average thermalized parton densities at $\eta_k = 0$ from hydrodynamic simulations are plotted as a function of proper time in the collision of impact parameter $b = 3.35 \text{ (12.1)} \text{ fm}$ in upper (lower) panel of Fig. 4. As seen in the figures, thermalized parton density drops rapidly due to the strong longitudinal expansion of the system produced in heavy ion collisions. We expect that jets are likely to lose their energies in the time span of less than $\tau \sim 2 \text{ fm/c}$.

In order to see when jets lose their energies, we plot in Fig. 3, the ratio of the numbers of jets $N(\tau)/N(\tau_0)$ at $p_T = 5 \text{ GeV/c}$. It is found that about 90% of jet quenching occurs up to $\tau \sim 2 \text{ fm/c}$, although the QGP phase exists up to $\tau \sim 4 \text{ fm/c}$ and the mixed phase lasts until $\tau \sim 10 \text{ fm/c}$ within the hydro parameters used in this work. This holds true, even when we take the total density neglecting the existence of the hadrons in the mixed phase in Eq. 6 in order to get the maximum energy loss. Therefore, within our model, only QGP phase is responsible for the jet energy loss.

We showed in Fig. 4 the energy loss $dE/dx = 0.2 \text{ GeV/fm}$ gives the same amount of energy loss as the energy loss parameter $\epsilon \sigma = 0.06 \text{ GeV fm}^2$. Let us estimate a space-time averaged energy loss parameter for central collision ($b = 3.35 \text{ fm}$). If we take a space-time average parton density $\bar{\rho}(\tau)$, $\bar{\rho}(\tau \leq 1.0 \text{ fm/c}) = 11 \text{ fm}^{-3}$, $\bar{\rho}(\tau \leq 2.0 \text{ fm/c}) = 7.7 \text{ fm}^{-3}$, and $\bar{\rho}(\tau \leq 3.0 \text{ fm/c}) = 6.0 \text{ fm}^{-3}$, then the space-time averaged energy loss yields $dE/dx(\tau \leq 1.0 \text{ fm/c}) \sim 0.66 \text{ GeV/fm}$, $dE/dx(\tau \leq
FIG. 5: Jet quenching rate defined as the ratio of the numbers of jets $N(\tau)/N(\tau_0)$ at $p_T = 5$ GeV/c as a function of proper time for $b = 3.35$ fm. The energy loss parameter $\epsilon \sigma = 0.06$ GeV fm$^2$ is used.

2.0 fm/c) \sim 0.46$ GeV/fm, and $dE/dx(\tau \leq 3.0$ fm/c) \sim 0.36$ GeV/fm with the best fit parameter of $\epsilon \sigma = 0.06$ GeV fm$^2$. Those values are close to that of the result calculated by the pQCD parton model [8], in which the effect of expansion is not included. The reason is that the energy loss parameter can be regarded as an average of roughly a short time of $\tau \leq 2$ fm/c.

In summary, we proposed the full 3D hydrodynamical model combined with (mini-) jets, where jets are explicitly propagated in space-time with the hydro simulation. In particular, this model allows us to study the dynamical effects on the jet energy loss. We estimated the energy loss of partons by the fluid elements whose temperature is above the critical value $T_c$. It is found that energy loss of jets occurs in the pure QGP phase of $\tau < 2$ fm/c and that the contribution of energy loss in the mixed phase is negligible under the assumption of the energy loss formula Eq. (5). This indicates that suppression of high $p_T$ spectra contain information about the early stage of partonic matter. However, it has been shown that the formula for the energy loss has non-trivial energy dependence [9] and it is found that energy loss is sensitive to the critical point [9]. It is very important to take into account the coherent (Landau-Pomeranchuk-Migdal) effect in the calculation of radiation spectrum. A result obtained by using a different energy loss formula will be presented elsewhere.

A prediction at higher transverse momentum region is under progress. Elliptic flow parameter should be also studied within the model. It should be studied the charged particle spectra in order to have the unified understanding of the jet quenching mechanism in the medium.

In this study, we do not include the energy loss effects before hydrodynamical evolution. It might be interesting to study to what extent partons lose energy before thermalization using non-equilibrium models [11, 30]. Because parton density is maximum in this stage, energy loss by these partons should be important.

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