Back-to-Back Correlations of High-p_T Hadrons in Relativistic Heavy-Ion Collisions

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We investigate the suppression factor and the azimuthal correlation function for high p_T hadrons in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV by using a dynamical model in which hydrodynamics is combined with explicitly traveling jets. We study the effects of parton energy loss in a hot medium, intrinsic k_T of partons in a nucleus, and $p_\perp$ broadening of jets on the back-to-back correlations of high p_T hadrons. Parton energy loss is found to be a dominant effect on the reduction of the awayside peaks in the correlation function.

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Recently, from the two-particle azimuthal correlation measurements in central Au + Au collisions at the BNL Relativistic Heavy Ion Collider (RHIC), the magnitude of the awayside jets is found to be significantly suppressed in comparison with the nearside jets at high p_T [1]. In addition to the suppression of the yields for high p_T hadrons already discovered at RHIC [2,3], which was predicted some time ago [4], the high p_T correlation measurement may provide a novel opportunity to study the dense QCD matter produced in high energy nuclear collisions. This phenomenon was first predicted by Bjorken many years ago [5]. Later, the acoplanarity (transverse momentum imbalance) of jets was discussed as a possible diagnostic tool for studying the quark gluon plasma (QGP) [6].

In this Letter, we investigate the effects of (a) parton energy loss during propagation through an expanding hot medium, (b) intrinsic k_T of partons in a nucleus, and (c) $p_\perp$ broadening of jets on back-to-back correlations in Au + Au collisions based on incoherent production of minijets by employing the hydro + jet model [7].

The hydro + jet model is mainly composed of two models. One is a full three dimensional hydrodynamic model which describes the space-time evolution of thermalized partonic/hadronic matter [8]. The other describes the dynamics (production, propagation, and fragmentation) of high p_T partons which interact with thermalized partonic matter through a phenomenological model for parton energy loss. A novel hydrodynamic calculation with the early chemical freezeout shows that the p_T slope for pions is insensitive to thermal freezeout temperature $T^{\rm th}$ [9] and that the p_T spectrum starts to deviate from the data at $p_T = 1.5$–2.0 GeV/c [10]. This result naturally leads us to include minijet components into hydrodynamic results. Thus we simulate the space-time evolution of both a fluid and minijets *simultaneously.*

Initial parameters in the hydrodynamic model are so chosen as to reproduce $dN_{\rm ch}/d\eta$ in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV observed by the BRAHMS Collaboration [11]. The transverse profile of the initial energy density is assumed to scale with the number of binary collisions [12]. For 5% central collisions, we choose the impact parameter as $b = 2.0$ fm and the maximum initial energy density at the initial time $\tau_0 = 0.6$ fm/c as 39.0 GeV/fm^3. For further details on initialization in our hydrodynamic model, see Ref. [9]. We note that contribution from hard components (defined by the particles that have a transverse momentum greater than 2 GeV/c just after initial collisions) becomes the order of unity and can be neglected when we tune initial parameters in the hydrodynamic model.

We include hard partons using the perturbative QCD (pQCD) parton model. The momentum distribution of hard partons per hard collision before traversing hot matter may be written as

$$E\frac{d\sigma_{\rm jet}}{d^3p} = K\sum_{a,b}\int g(k_{T,a})dk_{T,a}^2 g(k_{T,b})dk_{T,b}^2 \times \int f_a(x_1, Q^2)dx_1 f_b(x_2, Q^2)dx_2 E\frac{d\sigma_{ab}}{d^3p}, \quad (1)$$

where f and g are the collinear and transverse parts of parton distribution functions. x is the fraction of the longitudinal momentum, and k_T is the intrinsic transverse momentum of initial partons inside hadron. The parton distribution functions $f_a(x, Q^2)$ are taken to be CTEQ5L [13] with the scale choice $Q^2 = (p_T/2)^2$ for the evaluation of parton distribution. The minimum momentum transfer $p_{T,\rm min} = 2.0$ GeV/c is assumed. The summation runs over all parton species and relevant leading order QCD processes are included. Gaussian intrinsic k_T distribution inside hadron with the width of $\langle k_T^2\rangle = 1$ GeV$^2/c^2$ is assigned to the shower initiator in the QCD hard $2 \to 2$ processes. In the actual calculation, we use PYTHIA 6.2 [14] to simulate each hard scattering and the initial and final states radiation. In order to convert hard partons into hadrons, we use an independent fragmentation model in PYTHIA after hydrodynamic simulations. A factor K is used for the higher order corrections. We have checked that this hadronization model with $K = 2.5$

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provides good agreement with the transverse spectra of charged hadrons in $p\bar{p}$ collisions [15] and of neutral pions in pp collisions [16] above $p_T = 1$ GeV/c at $\sqrt{s} = 200$ GeV. 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 [2]. The initial transverse coordinate of a parton is specified by the number of binary collision distribution for two Woods-Saxon distributions. We neglect the nuclear shadowing effect because its effect is small at midrapidity at RHIC energies [17,18].

Over the years, much work has been devoted to the study of the propagation of jets through QCD matter [19–22]. Here we employ the first order formula in opacity expansion from the reaction operator approach [22,23]. The opacity expansion is relevant for the realistic heavy ion reactions where the number of jet scatterings is small. The energy loss formula for coherent scatterings in matter has been applied to analyses of heavy ion reactions taking into account the expansion of the system [23,24]. The first order formula in this approach is written as

$$\Delta E = C \int_{\tau_0}^{\infty} d\tau \rho(\tau, \mathbf{x}(\boldsymbol{\tau}))(\tau - \tau_0) \ln\left(\frac{2E}{\mu^2 L}\right). \qquad (2)$$

Here C is an adjustable parameter [25] and $\rho(\tau, \mathbf{r})$ is a thermalized parton density. $\mathbf{x}(\boldsymbol{\tau})$ and E are the position and the initial energy of a jet, respectively. In the hydro + jet approach, ρ is obtained by using hydrodynamic simulations. We take a typical screening scale $\mu = 0.5$ GeV [26] and effective path length $L = 3$ fm. Feedback of the energy to fluid elements in central collisions was found to be about 2% of the total fluid energy. Hence we can safely neglect its effect on hydrodynamic evolution in the case of the appropriate amount of energy loss.

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 $R_{AA} = (d^2N^{A+A}/dp_T d\eta)/(N_{\mathrm{binary}} d^2N^{p+p}/dp_T d\eta)$. The transverse momentum dependence of R_{AA} can provide information about the mechanism of jet quenching [18,27]. In Fig. 1, we represent the results of R_{AA} for neutral pions in Au + Au 10% central collisions at $\sqrt{s_{NN}} = 200$ GeV from the hydro + jet model for parameters of $C = 0.1$, 0.27, and 1.0. Here we choose $b = 2.8$ fm for centrality of 10%. The suppression factor for the model with $C = 0.27$ quantitatively agrees with the PHENIX data.

We now study the dynamical effects of a hot medium on the strength of awayside peaks in the azimuthal correlation function. The azimuthal correlation functions of high p_T charged hadrons in midrapidity region ($|\eta| < 0.7$) are measured by the STAR Collaboration [1]. Charged hadrons in $4 < p_{T,\mathrm{trigger}} < 6$ GeV/c and in $2 < p_{T,\mathrm{associate}} < p_{T,\mathrm{trigger}}$ GeV/c are defined to be trigger particles and associated particles, respectively. The relative

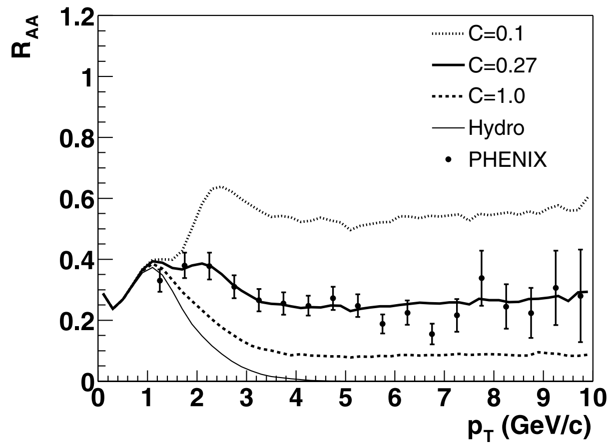

FIG. 1. Comparison of $R_{AA}(p_T)$ for neutral pions in Au + Au 10% central collision at $\sqrt{s_{NN}} = 200$ GeV. A parameter C in Eq. (2) is chosen as 0.1 (dotted), 0.27 (thick solid), and 1.0 (dashed) and $\langle k_T^2 \rangle = 1$ GeV$^2/c^2$ is used. We also show the hydrodynamic component (thin solid). Data are taken from Ref. [28].

azimuthal angle distribution (per trigger particle) of high p_T hadrons is written as

$$C_2(\Delta\phi) = \frac{1}{N_{\mathrm{trigger}}} \int_{-1.4}^{1.4} d\Delta\eta \frac{dN}{d\Delta\phi d\Delta\eta}. \qquad (3)$$

Here $\Delta\phi$ and $\Delta\eta$ are, respectively, the relative azimuthal angle and pseudorapidity between a trigger particle and an associated particle. It is found that, in central Au + Au collisions (0–5%), the nearside peak ($|\Delta\phi| < 0.75$ radians) has the same strength as the one in pp collisions at $\sqrt{s} = 200$ GeV and the awayside peaks ($|\Delta\phi| > 2.24$ radians) disappear clearly [1].

In our theoretical calculations, we take into account only contributions from associated particles which originate from the same hard scattering as a trigger particle. Thus, we compare our results with the STAR data in which elliptic flow components are subtracted assuming $B[1 + 2v_2^2 \cos(2\Delta\phi)]$ with $B = 1.442$ and $v_2 = 0.07$ [1].

As demonstrated in Fig. 2, the awayside peaks gradually decrease with an increase in the amount of parton energy loss. Nevertheless, we cannot obtain the disappearance of the awayside peak by the model with $C = 0.27$ which quantitatively reproduces $R_{AA}(p_T)$ as shown in Fig. 1. Only when we underestimate the suppression factor R_{AA} of the PHENIX data by choosing $C = 1.0$ as depicted in Fig. 1, the awayside peaks almost disappear. This suggests that another mechanism is needed to interpret both the suppression factor $R_{AA} \sim 0.25$ and the disappearance of back-to-back correlation *simultaneously*.

Is a large intrinsic k_T responsible for the disappearance of back-to-back correlation? If colliding partons have only longitudinal momenta directed to the beam axis, produced partons through $2 \to 2$ processes have the same transverse momentum due to kinematics. When partons in

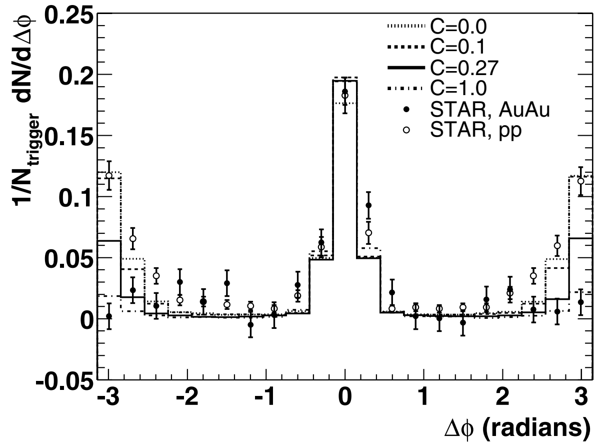

FIG. 2. Energy loss strength dependence on $C_2(\Delta\phi)$ for charged particles in central 0–5% Au + Au collision at $\sqrt{s_{NN}} = 200$ GeV. Parameters C in Eq. (2) are 0 (dotted), 0.1 (dashed), 0.27 (solid), and 1.0 (dash-dotted). $\langle k_T^2 \rangle = 1\ \mathrm{GeV}^2/c^2$ is used. Data are taken from Ref. [1].

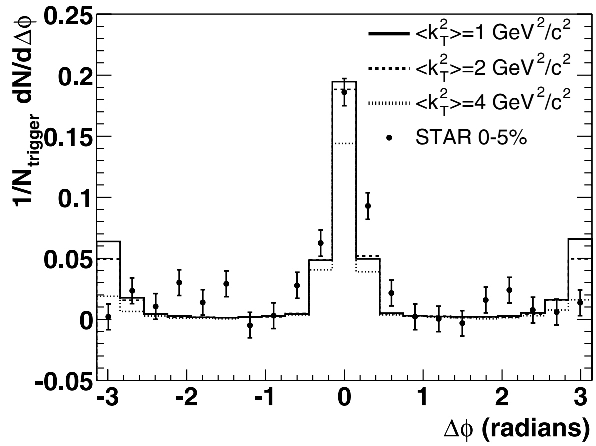

FIG. 3. Intrinsic k_T dependence of azimuthal correlation function $C_2(\Delta\phi)$. Parameter sets are $(\langle k_T^2 \rangle, C) = (1.0, 0.27)$ (solid), $(2.0, 0.35)$ (dashed), and $(4.0, 0.5)$ (dotted). Here the intrinsic transverse momenta $\langle k_T^2 \rangle$ are in the unit of GeV^2/c^2 and the corresponding energy loss parameters C are chosen to fit R_{AA}. Data are taken from Ref. [1].

a nucleon initially have the transverse momentum (intrinsic k_T), this releases the above constraint and, consequently, affects the back-to-back correlation of final high p_T hadrons. Moreover, multiple interactions within the colliding nuclei lead to the so-called Cronin effect [29]. This effect can be parametrized phenomenologically by increasing the average intrinsic transverse momentum $\langle k_T^2 \rangle$ [24,30–32]. We have chosen in the previous analyses $\langle k_T^2 \rangle = 1\ \mathrm{GeV}^2/c^2$ which leads to reproducing the $p\bar{p}$ and pp data at $\sqrt{s} = 200$ GeV. To see the nuclear effect of intrinsic k_T clearly, we calculate the correlation function by choosing $\langle k_T^2 \rangle = 2$ or $4\ \mathrm{GeV}^2/c^2$. Here we readjust a parameter C in Eq. (2) to quantitatively reproduce $R_{AA}(p_T)$ similar quality to $\langle k_T^2 \rangle = 1\ \mathrm{GeV}^2/c^2$ below $5\ \mathrm{GeV}/c$: $C = 0.35$ (0.5) for $\langle k_T^2 \rangle = 2$ (4) GeV^2/c^2. Only when $\langle k_T^2 \rangle = 4\ \mathrm{GeV}^2/c^2$ which is considerably larger than an estimated value of $\sim$2–3 GeV^2/c^2 [24,30–32] at fixed target energies, the height of the awayside peak becomes small (~ 0.02) as shown in Fig. 3. Instead, the nearside peak is also reduced and deviates from data.

Measurements in d + Au collisions should provide important information on the intrinsic k_T at the RHIC energy region. The initial k_T broadening should depend on the transverse position of the hard scattering. We have checked this effect by using the model in Ref. [30] which gives an average $\langle k_T^2 \rangle \sim 2\ \mathrm{GeV}^2/c^2$ for central Au + Au collisions at RHIC. We found that the effect of the transverse position dependence of the intrinsic k_T on the awayside peak is small and the conclusion here remains the same. It is needed to use the impact parameter dependence of the intrinsic k_T for the study of the centrality dependence of the back-to-back correlation. One should fix the intrinsic k_T by pp and $pA(dA)$ data in the systematic study [30,31].

Finally, we take into account the $p_\perp$ broadening of jets. Both the non-Abelian energy loss and the $p_\perp$ broadening of the propagating jets are manifestations of the strong final state partonic interactions [19–22,33,34]. Partons can obtain a transverse momentum orthogonal to its direction of motion in traversing a dense medium. As a consequence, traversing partons change their direction at each time step and follow zigzag paths in the hot medium. The $p_\perp$ broadening of these partons is quantitatively related to the parton energy loss. We compare two models for the average broadening of partons: $\langle p_\perp^2 \rangle = (\alpha_s N_c/4)^{-1} dE/dx$ (model 1) [33] and $\langle p_\perp^2 \rangle = (\alpha_s N_c/2)^{-1} C \int_{\tau_0} d\tau \rho(\tau, \mathbf{x}(\boldsymbol{\tau}))$ (model 2) [34] where $\alpha_s = 0.3$ is assumed. Although the formula for model 1 is obtained for static plasma, it is accurate except for the factor of logarithm in the case of 1 + 1D Bjorken expansion. Here the distribution of $p_\perp$ is assumed to be a Gaussian function. It should be noted that incorporation of $p_\perp$ broadening does not largely affect the suppression factor R_{AA}. In Fig. 4, the correlation functions $C_2(\Delta\phi)$ with and without $p_\perp$ broadening are shown for $C = 0.35$ and $\langle k_T^2 \rangle = 2\ \mathrm{GeV}^2/c^2$. When model 1 is used, the event average broadening is found to be $\langle\langle p_\perp^2 \rangle\rangle \sim 2.5\ \mathrm{GeV}^2/c^2$ and awayside peaks are suppressed and broadened. On the other hand, $\langle\langle p_\perp^2 \rangle\rangle \sim 0.78\ \mathrm{GeV}^2/c^2$ for model 2 and the reduction of awayside peaks becomes tiny. This is consistent with the recent study based on a pQCD parton model [35].

In summary, we have computed the correlation function $C_2(\Delta\phi)$ for high p_T charged hadrons in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV within the hydro + jet model. We have systematically studied the dependence of the magnitude of parton energy loss on the height of awayside peaks in correlation functions. Moreover, we also investigated the effects of the intrinsic transverse momentum of initial partons and the $p_\perp$ broadening of traversing jets on back-to-back correlations of high p_T

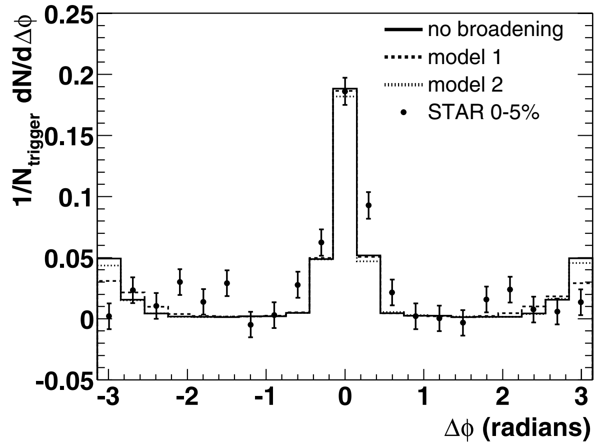

FIG. 4. The effect of $p_\perp$ broadening on azimuthal correlation functions $C_2(\Delta\phi)$. The solid line represents the result for $C = 0.35$ and $\langle k_T^2 \rangle = 2.0\ \mathrm{GeV}^2/c^2$ without $p_\perp$ broadening. The dashed (dotted) line corresponds to the broadening of model 1 (2). See text for details. Data are taken from Ref. [1].

hadrons. About 50% of the reduction of awayside peaks comes from the parton energy loss, but its effect is insufficient to vanish the peaks completely. This indicates that the suppression of the awayside peaks occurs by complex mechanisms. The intrinsic k_T of partons in a nucleus also affects the back-to-back correlation. This is, however, due to the increase of energy loss parameter C in order to reproduce R_{AA} rather than the increase of k_T itself. The $p_\perp$ broadening causes 5–20% reduction of the original height of awayside peaks.

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