Measuring the Collective Flow with Jets

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In nucleus-nucleus collisions, high-p_T partons interact with a dense medium, which possesses strong collective flow components. Here, we demonstrate that the resulting medium-induced gluon radiation does not depend solely on the energy density of the medium, but also on the collective flow. Both components can be disentangled by the measurement of particle production associated with high-p_T trigger particles, jetlike correlations, and jets. In particular, we show that flow effects lead to a characteristic breaking of the rotational symmetry of the average jet energy and jet multiplicity distribution in the $\eta \times \phi$ plane. We argue that data on the medium-induced broadening of jetlike particle correlations in Au + Au collisions at the Relativistic Heavy-Ion Collider may provide evidence for a significant distortion of parton fragmentation due to the longitudinal collective flow.

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Measurements of low-p_T inclusive spectra and azimuthal correlations in nucleus-nucleus collisions at the Relativistic Heavy-Ion Collider (RHIC) indicate that different hadron species emerge from a common medium which has built up a strong collective velocity field [1–4]. They are broadly consistent with calculations based on ideal hydrodynamics [4–8]. Although we still lack a microscopic understanding of why hydrodynamics works so well [9], its success is regarded as strong evidence [10] that the medium produced in nucleus-nucleus collisions has a very small mean free path, shows a very rapid thermalization, and behaves like an almost ideal fluid with vanishing viscosity. For an energy density ϵ, the dynamic behavior of the medium is specified by the energy-momentum tensor

$$T^{\mu\nu}(x) = (\epsilon + p)u^{\mu}u^{\nu} - pg^{\mu\nu}, \tag{1}$$

with the equation of state $p = p(\epsilon, T, \mu_B)$. In hydrodynamic simulations, the collective flow field $u_{\mu}(x)$ emerges dynamically from the pressure gradients in the initial conditions. Thus, the observation of collective flow gives access to the equation of state of dense QCD matter.

At collider energies, the production of high-p_T hadrons and jets provides a novel independent characterization of the medium produced in nucleus-nucleus collisions. This is so since the gluon radiation off parent partons is sensitive to the interaction between the partonic projectile and the medium [11–16]. In particular, quenched high-p_T hadroproduction is sensitive to the transport coefficient $\hat{q}$, which is proportional to the density of scattering centers and characterizes the squared average momentum transfer from the medium to the hard parton per unit path length. This transport coefficient is related to the energy density of the medium [17],

$$\hat{q}[\mathrm{GeV}^2/\mathrm{fm}] = c\epsilon^{3/4}[(\mathrm{GeV}/\mathrm{fm}^3)^{3/4}]. \tag{2}$$

Here, c is a proportionality constant of order unity [17,18].

The main purpose of this Letter is to demonstrate that parton energy loss is sensitive to both the energy density ϵ of the produced matter and the strength and direction of the collective flow $u_{\mu}(x)$. Recent works on parton energy loss account for the rapid decrease of the density of scattering centers caused by collective expansion [19–21]. This effect can be absorbed in a redefinition of the static transport coefficient [21]. Here we go beyond these formulations by taking into account that hard partons are not produced in a rest frame in which the momentum transfer from the medium is isotropic in the plane transverse to the direction of parton propagation (“isotropic rest frame”); see Fig. 1. Rather, they interact with a medium which generically shows collective flow components in this transverse plane. To illustrate the consequences, we consider the medium as a collection of colored Yukawa-type scattering potentials $a(\mathbf{q})$ with Debye screening mass μ. For a colored test particle in an isotropic rest frame, the average momentum transfer per scattering center is μ. In the presence of collective flow, the hard parton interacts with Lorentz-boosted scattering centers. These are modeled by a momentum shift $\mathbf{q}_0$, proportional to the flow component transverse to the direction of parton propagation,

$$|a(\mathbf{q})|^2 = \frac{\mu^2}{\pi[(\mathbf{q} - \mathbf{q}_0)^2 + \mu^2]^2}. \tag{3}$$

We have calculated the medium-induced radiation of gluons with energy ω and transverse momentum $\mathbf{k}$, emitted from a highly energetic parton that propagates over a finite path length L in a medium of density n_0 with collective motion. To first order in opacity, [14,15,22]

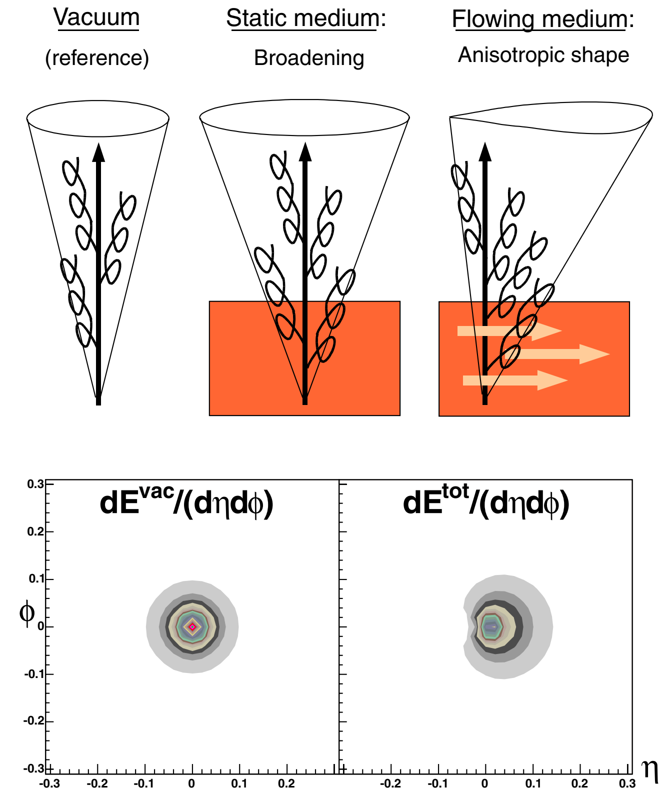

FIG. 1 (color online). Upper part: sketch of the distortion of the jet energy distribution. Lower part: calculated distortion (5) in the $\eta \times \phi$ plane for a 100 GeV jet. The right-hand side is for an average medium-induced radiated energy of 23 GeV and equal contributions from density and flow effects, $\mu = q_0$. Scales of the contour plot are visible from Fig. 2.

$$\omega \frac{dI^{\text{med}}}{d\omega d\mathbf{k}} = \frac{\alpha_s}{(2\pi)^2} \frac{4C_R n_0}{\omega} \int d\mathbf{q} |a(\mathbf{q})|^2 \frac{\mathbf{k} \cdot \mathbf{q}}{\mathbf{k}^2} \times \frac{-L \frac{(\mathbf{k}+\mathbf{q})^2}{2\omega} + \sin(L \frac{(\mathbf{k}+\mathbf{q})^2}{2\omega})}{[(\mathbf{k}+\mathbf{q})^2/2\omega]^2}. \quad (4)$$

In the absence of a medium, the parton fragments according to the vacuum distribution $I^{\text{tot}} = I^{\text{vac}}$. The radiation spectrum (4) characterizes the medium modification of this distribution $\omega \frac{dI^{\text{tot}}}{d\omega d\mathbf{k}} = \omega \frac{dI^{\text{vac}}}{d\omega d\mathbf{k}} + \omega \frac{dI^{\text{med}}}{d\omega d\mathbf{k}}$ in the so-called single hard scattering approximation [14,15,22]. Physically equivalent results are obtained in the multiple soft scattering approximation [12], as explained in [22]. From $\omega \frac{dI^{\text{tot}}}{d\omega d\mathbf{k}}$, we calculate distortions of jet energy and jet multiplicity distributions [23]. Information about I^{vac} is obtained from the energy fraction of the jet contained in a subcone of radius $R = \sqrt{\eta^2 + \phi^2}$,

$$\rho_{\text{vac}}(R) \equiv \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{E_T(R)}{E_T(R=1)} = 1 - \frac{1}{E_T} \int d\omega \int^{\omega} d\mathbf{k} \Theta\left(\frac{k}{\omega} - R\right) \omega \frac{dI^{\text{vac}}}{d\omega d\mathbf{k}}. \quad (5)$$

For this jet shape, we use the parametrization [24] of the Fermilab D0 Collaboration for jet energies in the range $\approx 50 < E_t < 150$ GeV and opening cones $0.1 < R < 1.0$. We remove the unphysical singularity of this parametrization for $R \to 0$ by smoothly interpolating with a polynomial ansatz for $R < 0.04$ to $\rho(R = 0) = 0$. We then calculate from Eq. (4) the modification [23] of $\rho_{\text{vac}}(R)$ caused by the energy density and collective flow of the medium. To do so, we transform the gluon emission angle $\arcsin(k/\omega)$ in (4) to jet coordinates η, ϕ,

$$k dk d\alpha = \omega^2 \frac{\cos\phi}{\cosh^3 \eta} d\eta d\phi, \quad (6)$$

where α denotes the angle between the transverse gluon momentum $\mathbf{k}$ and the collective flow component $\mathbf{q}_0$.

Here, we focus on changes of the jet shape due to longitudinal collective flow effects. To specify input values for the momentum transfer from the medium, we make the following considerations. First, the linear density n_0 of scattering centers along the path of the hard parton, which enters (4), can be reparametrized in terms of the transport coefficient $\hat{q} \simeq n_0 \mu^2$; see Ref. [22]. Thus, according to (2), the hard parton suffers a momentum transfer that is monotonously increasing with the pressure in the medium, $n_0 \mu^2 \propto p^{3/4}$ and which tests the components $T^{\perp\perp}$ and T^{zz} (z parallel to the beam) of the energy-momentum tensor (1). In the presence of a longitudinal Bjorken-type flow field $u^\mu = (1, \vec{\beta})/\sqrt{1 - \beta^2}$, the longitudinal flow component increases from $T^{zz} = p$ to $T^{zz} = p + \Delta p$, where $\Delta p = (\epsilon + p) u^z u^z = 4p\beta^2/(1 - \beta^2)$ for the equation of state of an ideal gas, $\epsilon = 3p$. For a rapidity difference $\eta = 0.5$, 1.0, 1.5 between the rest frame, which is longitudinally comoving with the jet, and the rest frame of the medium, this corresponds to an increase of the component T^{zz} by a factor 1, 5, 18, respectively. We expect that the collective flow component q_0 rises monotonously with the flow-induced Δp, as μ does with p. This suggests that q_0 lies in the parameter range $q_0 \gtrsim \mu$.

In Fig. 1, we show the medium-modified jet shape for a jet of total energy $E_T = 100$ GeV. To test the sensitivity of this energy distribution to collective flow, we have chosen a rather small directed flow component, $q_0 = \mu$. The effective coupling constant in (4), $n_0 L \alpha_s C_R = 1$, the momentum transfer per scattering center $\mu = 1$ GeV, and the length of the medium $L = 6$ fm were adjusted such that an average energy $\Delta E_T = \int d\omega \omega \frac{dI^{\text{med}}}{d\omega} =$ 23 GeV is redistributed by medium-induced gluon radiation. Previous studies indicate that this value of ΔE_T is a conservative estimate for the modification of jets produced in Pb + Pb collisions at the Large Hadron Collider (LHC) [23]. Despite these conservative estimates, the contour plot of the jet energy distribution in Fig. 1 displays marked medium-induced deviations. First, the jet structure broadens because of the medium-induced Brownian motion of the partonic jet fragments in a dense medium [22]. Second, the jet shape shows a marked rotational asymmetry in the $\eta \times \phi$ plane, which is characteristic of the presence of a collective flow field.

We note that for each single jet, the $\eta \times \phi$ rotation symmetry is broken statistically due to finite multiplicity fluctuations and dynamically due to the k_T ordering of the final state parton shower. Both effects break the symmetry in a *random* direction in the $\eta \times \phi$ plane; thus rotational symmetry is restored in sufficiently large jet samples. Moreover, jet samples that are rotationally symmetric in α are elongated by the Jacobian (6) in the ϕ direction. This asymmetry is $<10\%$ for $R < 0.3$ but can become sizeable for larger jet cones. Thus, a plot of the jet energy distribution in the $\eta \times \phi$ plane reduces the effect of η broadening due to longitudinal flow, but it can be corrected for analytically.

In general, the strength of the jet asymmetry due to collective flow effects depends on the (momentum) rapidity difference between the jet and that part of the medium through which the jet propagates. Hence, the rapidity distribution of the jet asymmetry may provide a valuable test of, e.g., hydrodynamical model simulations [7] which predict deviations from a longitudinally boost-invariant Bjorken expansion of the medium. For illustrative purposes, we focus here on jet samples centered around midrapidity in the collision of identical nuclei. Such samples are symmetric with respect to $\eta \to -\eta$, since the oriented momentum transfer points with equal probability in the positive or negative beam direction, $+\mathbf{q}_0$ or $-\mathbf{q}_0$, respectively. In Fig. 2, we show the average jet energy distribution for the $\eta \to -\eta$-symmetrized jet sample given in Fig. 1. Jet samples are symmetrized by identifying the calorimetric centers of every jet in the sample, thus mimicking a possible experimental procedure. This may result in an energy distribution with a double-hump shape (see Fig. 2), but details of this shape are subject to significant uncertainties in the parametrization of (5) and in our calculation of (4) at small angles. Thus, Fig. 2 demonstrates that the asymmetry of the jet energy distribution can be characterized by measuring its widths in different directions in the $\eta \times \phi$ plane which are very sensitive to the strength and direction of the collective flow field.

The calculation of medium-induced gluon radiation is most reliable for calorimetric measurements, but it also provides a framework for the discussion of medium-modified multiplicity distributions. In particular, we have checked that the azimuthal asymmetries seen in Figs. 1 also persist on the level of particle distributions. We have compared our calculation to data of the STAR Collaboration [25,26], which measured the widths of the η and ϕ distributions of produced hadrons associated

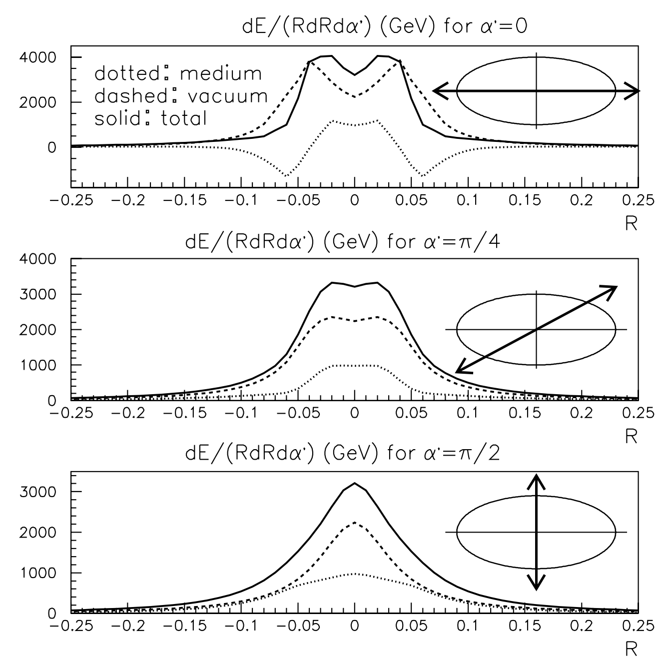

FIG. 2. Jet energy distribution for a sample of jets for which the medium was moving with equal probability in the positive and negative beam direction. The different curves denote the vacuum and medium contributions to the radiation spectrum as well as their sum. The directions of the cuts on the transverse jet profile are defined by α', with $d\eta d\phi = RdRd\alpha'$.

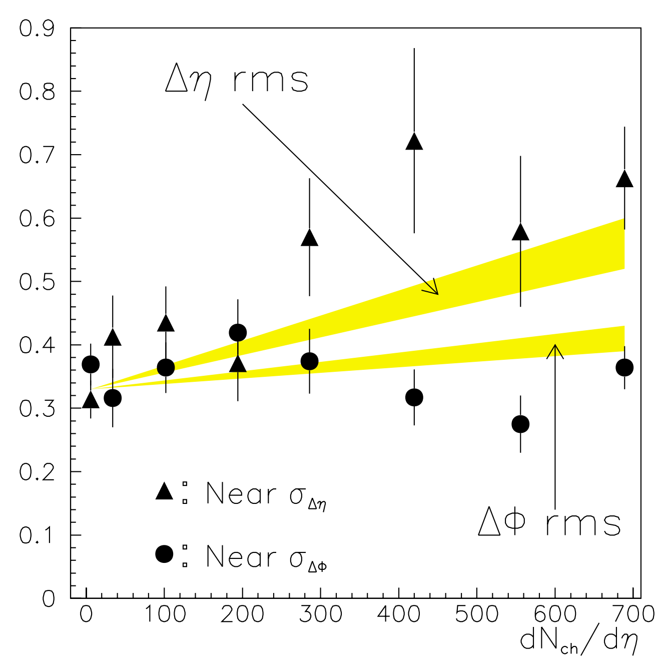

FIG. 3 (color online). The width in azimuth and rapidity of the nearside distribution of charged hadrons associated with high-p_T trigger particles of transverse momentum 4 GeV $< p_T <$ 6 GeV in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Black points are preliminary data from the STAR collaboration [25]. The band represents our calculation for longitudinal flow fields in the range $2 < q_0/\mu < 4$; see text for further details.

with trigger particles of transverse momentum 4 GeV $<$ $p_T < 6$ GeV. As a function of centrality of the collision, the ϕ distribution does not change within errors, while the η distribution shows a significant broadening; see Fig. 3. Although these data are still preliminary, they allow us to illustrate the strategy of determining collective flow effects from jet asymmetries. To this end, we have first used the width of the jetlike correlation in $p + p$ collisions to characterize the vacuum contribution. The energy of the parent parton was fixed to 10 GeV. We have chosen a rather small in-medium path length of $L = 2$ fm to account for the fact that high-p_T trigger particles tend to correspond to parent partons produced near the surface. We then calculated the asymmetry of the broadening in $\Delta\eta$ and $\Delta\phi$ by varying the average momentum transfer between $\mu = 0.7$ and $\mu = 1.4$ GeV, and the size of the collective flow component between $q_0/\mu = 2$ and $q_0/\mu = 4$. The results thus obtained for central Au + Au collisions were extrapolated to peripheral ones by a straight line and are represented by the band in Fig. 3. Numerical uncertainties in applying calculations of parton energy loss to transverse hadron momenta $p_T <$ 10 GeV are significant and have been discussed [22]. However, the origin of the angular broadening of jetlike particle correlations is essentially kinematic, being determined by the ratio between the momentum transfer from the medium and the energy of the escaping particle; hence, the result in Fig. 3 should not depend strongly on the details of our calculation.

We observe that the ratio $q_0/\mu = 4$ can account for the tendency in the preliminary STAR data of Fig. 3. The ratio $q_0/\mu = 4$ corresponds to a boost of the energy-momentum tensor (1) by approximately one unit in rapidity $\Delta\eta$. It is consistent with a space-time picture of Au + Au collisions at RHIC in which the hard parent partons of trigger particles propagate through a medium which is boosted by a rapidity $\Delta\eta$ with respect to the longitudinally comoving frame of the jet.

In summary, we have established that jet energy distributions and jetlike particle correlations are sensitive to the density of the medium as well as to its collective flow field. Remarkably, comparing a fourfold larger flow component $q_0/\mu = 4$ with $q_0/\mu = 0$, we find that the average parton energy loss more than doubles. This indicates that the energy density produced in the medium can be overestimated significantly if flow effects are ignored. Moreover, flow effects on jet energy loss provide the novel possibility to determine the space-time distribution of hard processes in the medium, e.g., by refined studies of the interplay of parton energy loss and hydrodynamic simulations [27]. Furthermore, the formulation of parton energy loss given here implies that partons lose less energy if they escape along trajectories parallel to the transverse flow field. Compared to calculations for a static medium, this enhances the parton energy loss contribution to elliptic flow.

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