

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 cannot be disentangled on the basis of leading hadron spectra, but the measurement of particle production associated to high- p_T trigger particles, jet-like correlations and jets, allows for their independent characterization. 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 jet-like particle correlations in Au+Au collisions at RHIC provide a first evidence for a significant distortion of parton fragmentation due to the longitudinal collective flow.

One of the most striking generic features of nucleus–nucleus collisions at the Relativistic Heavy Ion Collider RHIC is the extent to which they support a hydrodynamic interpretation [1, 2, 3, 4]. For transverse momentum up to $p_T \lesssim 2$ GeV, the hadronic transverse momentum spectra, their azimuthal asymmetry and particle species dependence, as well as the shape of rapidity distributions can be accounted for by modelling the medium as an ideal fluid, supplemented by a thermal freeze-out condition [4, 5, 6, 7, 8]. Although we still lack a microscopic understanding of why hydrodynamics is successful [9], this success is regarded as strong evidence [10] that the medium produced in nucleus–nucleus collisions at RHIC equilibrates efficiently and builds up significant position–momentum correlations, i.e. a flow field $u_\mu(x)$. That bulk properties of nucleus-nucleus collisions are calculable from the energy–momentum tensor

$$T^{\mu\nu}(x) = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu} \quad (1)$$

of an ideal fluid also further supports the expectation that nucleus–nucleus collisions give access to the equation of state $p = p(\epsilon, T, \mu_B)$ 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, 12, 13, 14, 15, 16]. In particular, quenched high- p_T hadroproduction is sensitive to the transport coefficient \hat{q} , which is proportional to the density of scattering centres 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],

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

Here, c is a proportionality constant of order unity whose value can be established in model calculations [17] or in comparison with experimental data [18].

The main purpose of this letter is to demonstrate that the sensitivity of parton energy loss is not limited to the energy density ϵ of the produced matter, but extends to the strength and direction of the collective flow field $u_\mu(x)$ in (1). Recent works on parton energy loss account for the rapid decrease of the density of scattering centres caused by collective expansion [19, 20, 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, in heavy-ion collisions, 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 Gyulassy–Wang model [11], which idealizes the medium as a collection of coloured Yukawa-type scattering potentials $a(\mathbf{q})$ with Debye screening mass μ . For a coloured test particle in an isotropic rest frame, the average momentum transfer per scattering centre is μ . In the presence of collective flow, however, the hard partonic projectile interacts with Lorentz-boosted scattering centres which can be modelled by a momentum shift \mathbf{q}_0 . This shift is proportional to the flow field component which points transverse to the direction of parton propagation,

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

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, we find [14, 15, 22]

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

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 $\omega \frac{dI^{\text{tot}}}{d\omega d\mathbf{k}} = \omega \frac{dI^{\text{vac}}}{d\omega d\mathbf{k}} + \omega \frac{dI^{\text{med}}}{d\omega d\mathbf{k}}$. From this, 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 $R = \sqrt{\eta^2 + \phi^2}$,

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

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 $R \rightarrow 0$ 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 . In what follows, we mainly focus on changes of the jet shape due to longitudinal collective flow effects where the directed momentum transfer \mathbf{q}_0 points along the beam direction. The sensitivity of jets and leading hadron spectra to other collective flow components will be discussed elsewhere [25].

To specify input values for the momentum transfer from the medium, we make the following considerations. First, for a given density n_0 of scattering centres, the transport coefficient is given as $\hat{q} \simeq n_0 \mu^2$, 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 $q_0 \gtrsim \mu$.

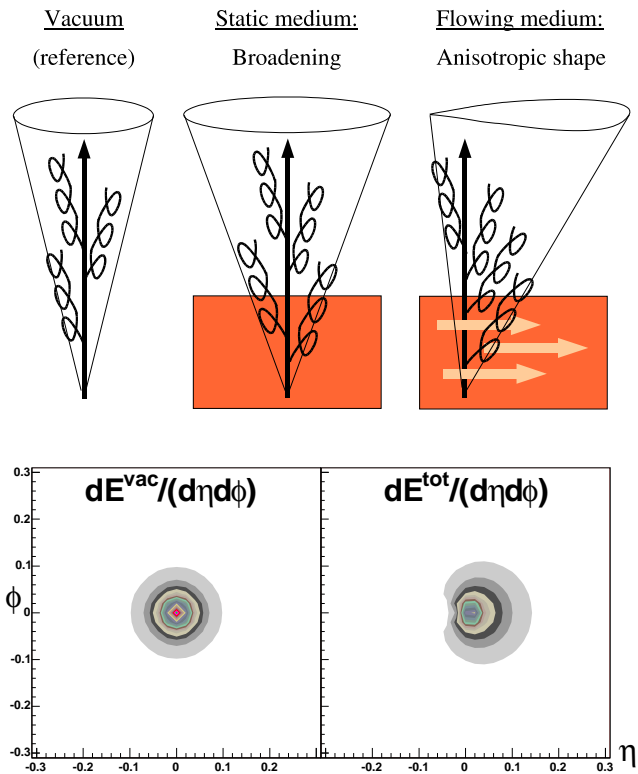


FIG. 1: Upper part: sketch of the distortion of the jet energy distribution in the presence of a medium with or without collective flow. Lower part: calculated distortion of the jet energy distribution (5) in the $\eta \times \phi$ -plane for a 100 GeV jet. The right hand-side is for an average medium-induced 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.

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 (3), $n_0 L \alpha_s C_R = 1$, the momentum transfer per scattering centre $\mu = 1$ GeV, and the length of the medium $L = 6$ fm were adjusted such that an average energy $\Delta E_T = \int d\omega \frac{dI^{\text{med}}}{d\omega} = 23$ 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 even in the absence of a medium. First, any finite multiplicity distribution of a rotationally symmetric sample breaks the symmetry by terms proportional to $1/\sqrt{N}$. In principle, this can be corrected for by the method used to analyze elliptic flow [26]. Second, the k_T -ordering of the final state DGLAP parton shower implies that the first parton splitting in the shower contains significantly more transverse momentum than the following ones, thus leading to a dynamical asymmetry in the $\eta \times \phi$ -plane. Both these effects lead to a symmetry breaking in a *random* direction in the $\eta \times \phi$ -plane; thus rotational symmetry is restored in sufficiently large jet samples. A third source of asymmetry in the $\eta \times \phi$ plane is not random but related to the Jacobian in (6). We have checked that the resulting asymmetry is $< 10\%$ for $R < 0.3$ but can become sizeable for larger jet cones. Most importantly, distributions that are rotationally symmetric in α are elongated by the Jacobian (6) in the ϕ -direction. This choice of coordinates reduces the effect of η -broadening due to longitudinal flow, but can be corrected for analytically.

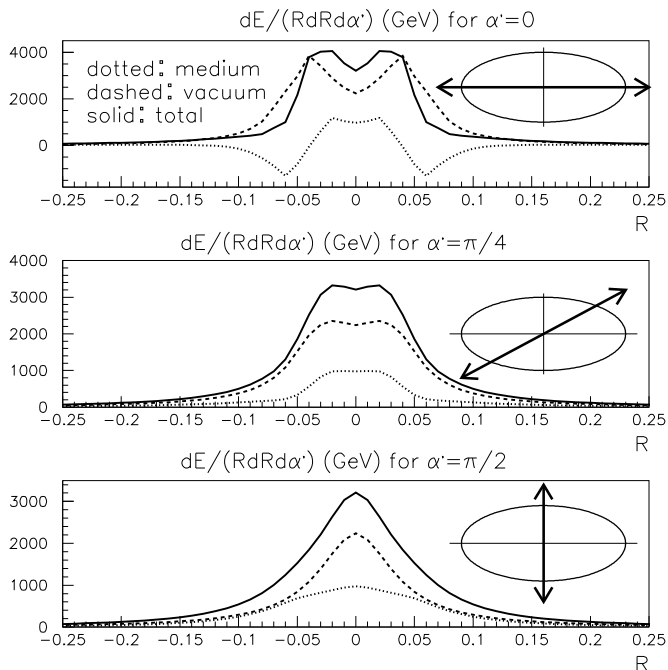


FIG. 2: Jet energy distribution for a sample of jets for which the medium was moving with equal probability in the positive and negative beam direction.

For collisions of identical nuclei, jet samples centered around mid (momentum) rapidity have to be symmetric with respect to $\eta \rightarrow -\eta$. Thus, while each parent parton may experience on average a significant collective flow, the direction of the oriented momentum transfer points with equal probability in the positive or negative

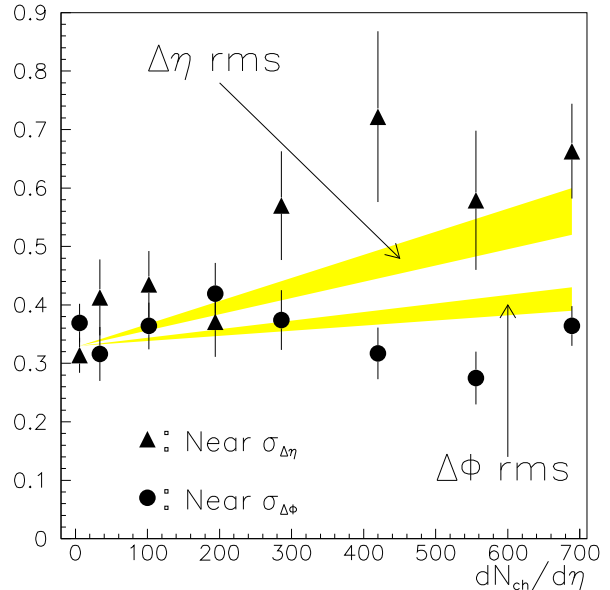


FIG. 3: The width in azimuth and rapidity of the near-side distribution of charged hadrons associated to high- p_T trigger particles of transverse momentum $4 \text{ GeV} < p_T < 6 \text{ GeV}$ in Au+Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$. Black points are preliminary data from the STAR collaboration [27]. The band represents our calculation for longitudinal flow fields in the range $2 < q_0/\mu < 4$, see text for further details.

beam direction, $+\mathbf{q}_0$ or $-\mathbf{q}_0$, respectively. In Fig. 2, we show the average jet energy distribution for the resulting symmetrized jet sample. Jet samples are symmetrized by identifying the calorimetric centres of every jet in the sample, thus mimicking the experimental procedure. Since in the presence of collective flow the energy distribution of each jet is asymmetric with respect to its calorimetric centre, this can result in an energy distribution with a double-hump shape, as seen in Fig. 2. However, details of the shape of the energy distribution may be subject to significant uncertainties in the parametrization of (5) and the calculation of (4) at small angles. In contrast, the asymmetric broadening of the energy distribution in the $\eta \times \phi$ -plane is a generic characteristics of collective flow.

While the calculation of medium-induced gluon radiation is most reliable for calorimetric measurements, 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 and 2 also persist on the level of leading near-side two-particle correlations. This allows us to test our formalism versus preliminary data of the STAR Collaboration [27, 28], which measured the widths of the η - and ϕ -distributions of produced hadrons associated to trigger particles of transverse momentum $4 \text{ GeV} < p_T <$

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. In our calculation of this effect, we have used the width of the jet-like 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 repeatedly [22]. However, the origin of the angular broadening of jet-like 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.

Based on the observation that the ratio $q_0/\mu = 4$ can account for the tendency in the preliminary STAR data of Fig. 3, we conjecture a picture of the space-time distribution of hard processes in nucleus–nucleus collisions. The ratio $q_0/\mu = 4$ corresponds to a boost of the energy–momentum tensor (1) by approximately one unit in rapidity $\Delta\eta$. This indicates that in Au+Au collisions at RHIC the hard parent partons of $4\text{ GeV} < p_T < 6\text{ GeV}$ trigger particles are produced on average distance $\Delta\eta$ away from the part of the medium that is locally longitudinally comoving with their rest frame.

In summary, we have established that jet energy distributions and jet-like particle correlations are sensitive to the density of the medium and its position–momentum correlations such as a collective flow field. Remarkably, comparing a four-fold 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. In our view, this is not the only reason why the flow effect discussed here will play an important role in further comparisons of parton energy loss with data on jet quenching. Other motivations include 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 [29]. Moreover, 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 generated in nucleus–

nucleus collisions. Compared to calculations for a static medium, this enhances the parton energy loss contribution to elliptic flow [25].

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