Medium Modification of Jet Shapes and Jet Multiplicities

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Medium-induced parton energy loss is widely considered to underlie the suppression of high-p_t leading hadron spectra in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions at the Relativistic Heavy Ion Collider (RHIC). Its description implies a characteristic k_t broadening of the subleading hadronic fragments associated with the hard parton. However, this latter effect is more difficult to measure and has remained elusive so far. Here, we discuss how it affects genuine jet observables, which are accessible at the Large Hadron Collider and possibly at RHIC. We find that the k_t broadening of jet multiplicity distributions provides a very sensitive probe of the properties of dense QCD matter, whereas the sensitivity of jet energy distributions is much weaker. In particular, the sensitive kinematic range of jet multiplicity distributions is almost unaffected by the high multiplicity background.

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Hard partons produced in dense QCD matter are expected to lose a significant fraction of their energy due to medium-induced gluon radiation prior to hadronization [1]. This follows from calculations of the underlying non-Abelian Landau-Pomeranchuk-Migdal effect and allows one to predict the dependence of parton energy loss on path length and density in a static [2–5] or expanding [6–8] medium. Recent measurements [9] of high-p_t hadroproduction and its centrality dependence in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV provide the first evidence [10] for the occurrence of this jet quenching phenomenon. They allow one to access properties of the dense medium produced in nucleus-nucleus collisions by analyzing the medium modification of high-p_t hadroproduction [8,11,12].

So far, these analyses are limited to the study of leading hadron spectra and leading hadron back-to-back correlations. However, energy loss of the leading parton implies a redistribution of the associated jet energy in transverse phase space or multiplicity. Thus, the observed energy degradation of leading hadrons should be reflected in the modification of genuine jet observables such as jet shapes and jet multiplicity distributions. The main aim of this Letter is to calculate for the first time medium-modified jet observables in the same theoretical framework on which the current jet quenching interpretation of suppressed high-p_t hadroproduction is based.

We start from the k_t-differential medium-induced distribution of gluons of energy ω radiated off an initial hard parton [4,13,14],

$$\omega \frac{dI_{\rm med}}{d\omega\, d\mathbf{k}} = \frac{\alpha_s C_F}{(2\pi)^2\omega^2} 2\,\mathrm{Re} \int_0^\infty dy_l \int_{y_l}^\infty d\bar{y}_l \int d^2\mathbf{u}\, e^{-i\mathbf{k}_t\cdot\mathbf{u}}\, e^{-\frac{1}{2}\int_{\bar{y}_l}^\infty d\xi\, n(\xi)\sigma(\mathbf{u})} \frac{\partial}{\partial \mathbf{y}} \frac{\partial}{\partial \mathbf{u}} \times \int_{\mathbf{y}=\mathbf{r}(y_l)}^{\mathbf{u}=\mathbf{r}(\bar{y}_l)} \mathcal{D}\mathbf{r} \exp\left[i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2}\left(\dot{\mathbf{r}}^2 - \frac{n(\xi)\sigma(\mathbf{r})}{i2\,\omega}\right)\right]. \tag{1}$$

Medium properties enter (1) via the product of the medium density $n(\xi)$ of scattering centers times the dipole cross section $\sigma(\mathbf{r})$, which measures the interaction strength of a single elastic scattering. We first establish that Eq. (1) implies a one-to-one correspondence between the average energy loss of the parent parton and the transverse momentum broadening of the associated gluon radiation, as argued in Ref. [2]. To this end, we evaluate $\omega \frac{dI_{\rm med}}{d\omega\, d\mathbf{k}}$ for $\alpha_s C_F = \frac{4}{9}$ in two approximations.

In the multiple soft scattering limit $n(\xi)\sigma(\mathbf{r}) \approx \frac{1}{2}\hat{q}(\xi)\mathbf{r}^2$, the transport coefficient $\hat{q}$ characterizes the average transverse momentum squared transferred from the medium to the projectile per unit path length. The medium-induced gluon radiation is restricted to gluon energies $\omega < \omega_c = \frac{1}{2}\hat{q}L^2$; see Fig. 1. In medium path length L and transport coefficient $\hat{q}$ determine the average energy loss of the leading parton, $\Delta E = \int d\omega\, \omega \frac{dI_{\rm med}}{d\omega} \sim \alpha_s\omega_c$, and the typical transverse momentum transferred from the medium. This limits medium-induced gluon radiation to $\kappa^2 = \frac{\mathbf{k}^2}{\hat{q}\,L} < 1$.

The same conclusion is reached in the $N = 1$ opacity expansion of (1) in which the medium is characterized by the average transverse momentum μ per scattering times the average number n_0L of such scatterings. The radiation is restricted to the characteristic gluon energy $\omega_c = \frac{1}{2}\mu^2 L$ and the typical transverse momentum $\kappa^2 = \frac{\mathbf{k}^2}{\mu^2}$. The opacity n_0L can be adjusted such that both approximations give quantitatively comparable results for phase-space averaged quantities as, e.g., the average energy loss [14]. Differences in the shape of the distributions shown in Fig. 1 are indicative of the uncertainties in modeling the detailed structure of the medium.

Next we ask to what extent the k_t broadening of the medium-modified parton shower, established in Fig. 1, shows up in the azimuthal redistribution of jet energy. We start from the fraction $\rho(R)$ of the total jet energy E_t deposited within a given jet subcone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\Phi)^2}$,

$$\rho_{\rm vac}(R) = \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{E_t(R)}{E_t(R=1)}. \qquad (2)$$

In the absence of medium effects, this jet shape is described, e.g., by the parametrization [15] of the Fermilab D0 Collaboration for jets in the range $50 \lesssim E_t \lesssim 150$ GeV and opening cones $0.1 \lesssim R \lesssim 1.0$. In what follows, we work in the frame that is longitudinally comoving with the jet such that pseudorapidity $\Delta\eta$ and azimuth $\Delta\Phi$ is related to the gluon emission angle Θ as $R = \Theta$. Assuming that gluon emission follows an independent Poisson process [16], we calculate the probability $P_{\rm tot}(\epsilon, \Theta)$ that a fraction ϵ of the total jet energy E_t is emitted outside the angle Θ,

$$P_{\rm tot}(\epsilon, \Theta) = \int_C \frac{d\nu}{2\pi i} e^{\nu\epsilon} \exp\left[-\int_0^\infty d\omega \left(\frac{dI_{\rm vac}^{>\Theta}}{d\omega} + \frac{dI_{\rm med}^{>\Theta}}{d\omega}\right)(1 - e^{-\nu\omega})\right]. \qquad (3)$$

Here, the contour C goes along the imaginary axis. The expression (3) takes into account the angular energy distribution of the parton fragmentation process in the vacuum, $\frac{dI_{\rm vac}^{>\Theta}}{d\omega} = \int_\Theta^\pi d\varphi \frac{dI_{\rm vac}}{d\omega\, d\varphi}$, as well as its medium modification $\frac{dI_{\rm med}^{>\Theta}}{d\omega}$ calculated from Eq. (1). Since both contributions are additive, the total probability (3) can be written as a convolution of the vacuum and the medium-induced probability

$$P_{\rm tot}(\epsilon, \Theta) = \int d\epsilon_1 P_{\rm vac}(\epsilon_1, \Theta) P_{\rm med}(\epsilon - \epsilon_1, \Theta). \qquad (4)$$

We have calculated [14] the quenching weight $P_{\rm med}(\epsilon, \Theta)$ from Eq. (1). The vacuum contribution $P_{\rm vac}(\epsilon, \Theta)$ in (4) is determined by the experimentally measured jet shape $\rho_{\rm vac}(R)$, normalized to the vacuum fraction of the total jet energy

$$\int d\epsilon\, \epsilon P_{\rm vac}(\epsilon, \Theta) = \frac{E_t - \Delta E}{E_t}[1 - \rho_{\rm vac}(R = \Theta)]. \qquad (5)$$

In the absence of tabulated experimental data on the width of $P_{\rm vac}(\epsilon, \Theta)$, we choose a sharply peaked distribution $P_{\rm vac}(\epsilon, \Theta) = \delta(\epsilon - \frac{E_t - \Delta E}{E_t}[1 - \rho_{\rm vac}(R)])|_{R=\Theta}$. The medium-modified jet shape $\rho_{\rm med}(R)$ is then defined in terms of the average jet energy fraction $\frac{\Delta E(\Theta)}{E_t}$ radiated outside an angle Θ,

$$\rho_{\rm med}(R) \equiv 1 - \int d\epsilon\, \epsilon P_{\rm tot}(\epsilon, \Theta) = \rho_{\rm vac}(R) - \frac{\Delta E(R)}{E_t} + \frac{\Delta E}{E_t}(1 - \rho_{\rm vac}(R)), \qquad (6)$$

where $\Delta E \equiv \Delta E(R = 0)$. We have calculated (6) as a function of the in-medium path length L, the jet energy E_t, and the transport coefficient $\hat{q}$. Numerical results are shown in Fig. 2 for parameter values ($\omega_c = 62$ GeV, $\omega_c L = 2000$ and $\omega_c = 132$ GeV, $\omega_c L = 2000$), which correspond to an average squared momentum transfer from the medium to the partonic jet components of size $\hat{q}L \approx (2\ {\rm GeV})^2$ and $\hat{q}L \approx (4\ {\rm GeV})^2$, respectively. These values scan a wide parameter range of momentum transfers expected for nucleus-nucleus collisions at the Large Hadron Collider (LHC) on the basis of multiplicity estimates [8,14]. In the eikonal approximation, the quenching weight $P_{\rm med}(\epsilon, \Theta)$ can have support in the unphysical region $\epsilon > 1$ [14]. This introduces an uncertainty that we estimate with the shaded region in Fig. 2 by comparing the result of an unrestricted ϵ integration in (6), $\frac{\Delta E(\Theta)}{E_t}|_1 \equiv \int d\epsilon\, \epsilon P_{\rm med}(\epsilon, \Theta)$, to the properly reweighted restricted integration

$$\left.\frac{\Delta E(\Theta)}{E_t}\right|_2 = \frac{\int_0^1 d\epsilon\, \epsilon P_{\rm med}(\epsilon, \Theta)}{\int_0^1 d\epsilon\, P_{\rm med}(\epsilon, \Theta)}. \qquad (7)$$

In general, the medium-modification (6) grows approximately linear with the transport coefficient (data not shown) in agreement with the $\hat{q}$ dependence of the average energy loss $\Delta E(\Theta)$. It decreases approximately like $1/E_t$ with increasing jet energy. Qualitatively comparable results are obtained in the $N = 1$ opacity approximation (data not shown). The medium-induced broadening of the jet shape results in a moderately reduced average jet energy fraction inside small jet cones $R = 0.3$ by $\sim$5% [$\sim$10%] for $E_t = 50$ GeV and $\sim$3% [$\sim$6%] for $E_t = 100$ GeV in the case of $\hat{q}L \approx (2\ {\rm GeV})^2$ [$\hat{q}L \approx (4\ {\rm GeV})^2$]. For larger jet cones ($R > 0.7$, say), medium

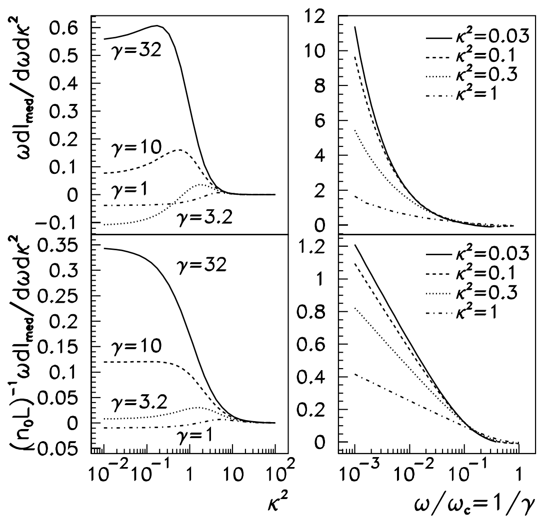

FIG. 1. The gluon energy distribution (1) as a function of the rescaled gluon energy ω/ω_c and the rescaled gluon transverse momentum κ.

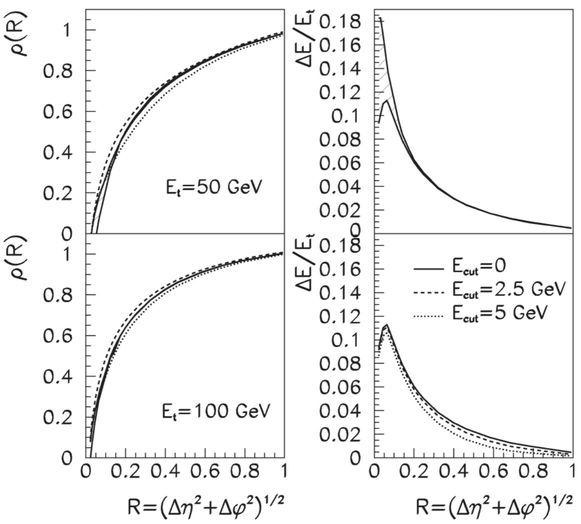

FIG. 2. Left: The jet shape (2) for a 50 and a 100 GeV quark-lead jet that fragments in the vacuum (dashed curve) or in a dense QCD medium characterized by $\omega_c L = 2000$ and $\omega_c = 62$ GeV (solid curve) or $\omega_c = 132$ GeV (dotted curve). Right: The corresponding average medium-induced energy loss for $E_t = 100$ GeV, $\omega_c = 62$ GeV radiated outside a jet cone R by gluons of energy above $E_{\rm cut}$. Shaded regions indicate theoretical uncertainties discussed in the text.

effects become even smaller since the medium-induced energy redistribution occurs mainly inside the jet cone. Thus, jet E_t cross sections in Pb-Pb collisions are expected to scale with the number of binary collisions for sufficiently large jet cones, provided that collisional mechanisms [17] of p_T broadening remain negligible. This may allow one to measure the total jet energy above background without resorting to jet samples "tagged" by a recoiling hard photon or Z boson.

In nucleus-nucleus collisions at LHC, jets up to $E_t > 200$ GeV are produced abundantly [18]. For estimates of the background $E_t^{\rm bg}$ deposited inside the corresponding jet cone, one has to rely on the event multiplicity, which is unknown by a factor of ~ 4 [19], $1500 \lesssim dN^{\rm ch}/dy \lesssim 6000$. For $dN^{\rm ch}/dy = 2500$, we estimate $E_t^{\rm bg} \sim 100$ GeV for $R = 0.3$ and $E_t^{\rm bg} \sim 250$ GeV for $R = 0.5$. Thus, background $E_t^{\rm bg}$ and jet E_t are likely to be of comparable size. This makes it easy to recognize jets above background while the measurement of a 10% modification of the jet shape remains challenging. In particular, such precision may require a better theoretical understanding of how the initial state radiation associated with a high-E_t jet affects the underlying event and its fluctuations (the so-called pedestal effect).

Interestingly, the transverse momentum broadening shown in Fig. 2 changes only weakly with a low momentum cutoff that removes gluon emission below 5 GeV. This can be understood in terms of formation time and phase space limitations in a small-size medium [14]. As a consequence, the transverse momentum broadening of $\rho(R)$ is mainly due to high energy partons, which can be expected to contribute significantly to the hadron yield above background. To illustrate this point, we have calculated the medium-induced additional number of gluons with transverse momentum $k_t = |\mathbf{k}|$, produced within a subcone of opening angle θ_c,

$$\frac{dN_{\rm med}}{dk_t} = \int_{k_t/\sin\theta_c}^{E_t} d\omega \, \frac{dI_{\rm med}}{d\omega \, dk_t}. \tag{8}$$

In Fig. 3, we compare this distribution to the shape of the corresponding vacuum component, $\frac{dN_{\rm vac}}{dk_t} \propto \frac{1}{k_t}\log(E_t \sin\theta_c/k_t)$, calculated from Eq. (1) as well. The total partonic jet multiplicity is the sum of both components. For realistic values of medium density and in-medium path length, medium effects are seen to increase this multiplicity significantly (by a factor >2), in particular, in the high-k_t tails. Also, the shape and width of the distribution (8) changes sensitively with the scattering properties of the medium. Moreover, since gluons must have a minimal energy $\omega > k_t/\sin\Theta_c$ to be emitted inside the jet cone, this high-k_t tail is unaffected by "background" cuts on the soft part of the spectrum, see Fig. 3. These qualitative conclusions are not affected by the uncertainties of our calculation which are illustrated by the significant differences in the angular dependence of the medium-induced gluon radiation (1) in the multiple soft and single hard scattering approximation [14]. In particular, destructive interference effects are known [13] to be more significant in the multiple soft scattering limit and for small angles, which may explain the non-monotonous behavior seen for $\Theta_c = 0.3$ in Fig. 3.

On the basis of Fig. 3, we argue that the measurement of the transverse momentum distribution of hadrons with

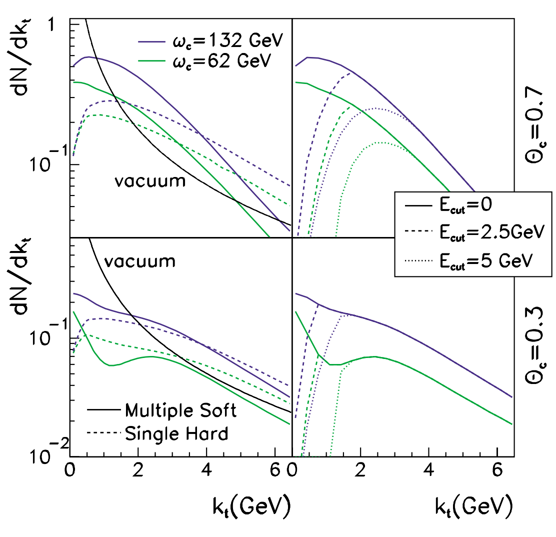

FIG. 3 (color online). Comparison of the vacuum and medium-induced part of the gluon multiplicity distribution (8) inside a cone size $R = \Theta_c$, measured as a function of k_t with respect to the jet axis. Removing gluons with energy smaller than $E_{\rm cut}$ from the distribution (dashed and dotted lines) does not affect the high-k_t tails.

respect to the jet axis is very sensitive to the transverse momentum broadening of the underlying parton shower and should be detectable above background. Despite the expected enhancement in the high-k_t tail, the total multiplicity of a jet will increase and the average energy of the hadronic fragments will soften. Hadronization of the parton shower is known to affect the absolute size and shape of this multiplicity distribution in the vacuum [20] and can be expected to modify the medium-dependent part as well. Also, experimental effects such as an increased uncertainty in determining the jet axis in a high multiplicity environment tend to broaden the distribution and have to be taken into account properly. To become more quantitative on the level of hadronic observables requires a Monte Carlo implementation of the medium-modified parton shower which is not at our disposal yet. However, the effect observed in Fig. 3 can be expected to survive hadronization. In particular, the insensitivity of the high-k_t tail to the low E_t background and its sensitivity to the transverse momentum picked up from the medium are both based on kinematic grounds and should not depend on the details of our calculation.

Other multiplicity distributions may show interesting medium modifications as well. As an example, we mention the modifications of the hump-backed rapidity plateau, i.e., the number of hadrons with jet energy fraction x inside the jet. In the vacuum, it is well-described by the result of the MLLA approximation which depends on the jet energy only via the parameter combination $\frac{E_t \sin\Theta_c}{Q_{\rm eff}}$ with $Q_{\rm eff} \sim 250$ MeV $\sim \Lambda_{\rm QCD}$ the only fit parameter [20]. The medium-modification of the corresponding partonic quantity is

$$\frac{dN_{\rm med}}{d\log x} = \int_0^{\frac{xE_t \sin\Theta_c}{\sqrt{\hat{q}L}}} d\kappa^2 \, \frac{dI_{\rm med}}{d\log x \, d\kappa^2}. \tag{9}$$

Here, we observe only that the medium modification of $\frac{dN_{\rm med}}{d\log x}$ supplements the nonperturbative scale $Q_{\rm eff}$ with a perturbatively large scale $\sqrt{\hat{q}L} \sim Q_s$. A more detailed analysis of (9) and other multiplicity distributions is left to future work.

We finally comment on the implications of our study for the ongoing experiments at the Relativistic Heavy Ion Collider (RHIC). In general, the strategy of triggering on the most energetic hadron biases jet samples significantly and may deplete, in particular, the multiplicity of subleading high-momentum hadrons. Furthermore, if the energy of the leading particle is not sufficiently high, the transverse phase space mapped out in Fig. 3 is simply not available. However, our study points to the possibility that a significant increase in jet multiplicity (and hence a decrease of the average energy of the leading hadron inside the jet) is accompanied by a rather moderate change in the angular distribution of the jet energy flow. This may be tested at RHIC, e.g., by measuring in back-to-back dihadron correlations the total E_t (or multiplicity) in a cone around the triggered hadron as well as the balancing energy in the opposite direction, and subtracting the background energy $E_t^{\rm bg}$.

In summary, the measurements studied here relate k_t broadening quantitatively to parton energy loss. Their measurement would not only further substantiate the picture of a medium-modified parton shower that underlies the current jet quenching interpretation of high-p_t hadroproduction. Compared to leading hadron spectra, the k_t broadening of multiplicity distributions may also provide data of competing accuracy for a better tomographic characterization of dense QCD matter.

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