

## Jet Quenching in the Direction Opposite to a Tagged Photon in High-Energy Heavy-Ion Collisions

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We point out that events associated with large  $E_T$  direct photons in high-energy heavy-ion collisions can be used to study jet energy loss in dense matter. In such events, the  $p_T$  spectrum of charged hadrons from jet fragmentation in the direction opposite to the tagged photon is estimated to be well above the background which can be reliably subtracted at moderately large  $p_T$ . We demonstrate that comparison between the extracted fragmentation function in  $AA$  and  $pp$  collisions can be used to determine the jet energy loss and the interaction mean free path in the dense matter produced in high-energy heavy-ion collisions. [S0031-9007(96)00635-7]

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Large transverse momentum jets, among many other hard processes in high-energy heavy-ion collisions, have been proposed as effective probes of the transient dense matter. For example, an enhanced acoplanarity and energy imbalance of two back-to-back jets can be used to study multiple scatterings of a parton inside a dense medium [1]. Study of large  $p_T$  jets can also probe their energy loss due to inelastic scatterings inside a dense matter or a quark-gluon plasma [2]. Because of the enormous background in high-energy heavy-ion collisions, the conventional calorimetric study cannot measure the jet energy to such an accuracy as required to determine the energy loss. Alternately, the single-particle inclusive  $p_T$  spectrum has been shown to be sensitive to the jet energy loss [3]. Since the single-particle spectrum is a convolution of the jet production cross section and the jet fragmentation functions, the suppression of produced hadrons at a fixed  $p_T$  results from jet quenching with a wide range of initial transverse energies, thus making it difficult to measure directly the modification of jet fragmentation for a given transverse energy.

In this Letter, we propose to study the jet quenching in high-energy heavy-ion collisions by measuring the  $p_T$  distribution of charged hadrons in the direction opposite to a tagged direct photon. A direct photon is produced by quark-antiquark annihilation or quark- (antiquark-) gluon Compton scatterings in which a gluon or quark (antiquark) jet is also produced in the opposite direction of the photon. By tagging a direct photon with a given transverse energy  $E_T^\gamma$ , one can avoid the uncertainties associated with the jet production cross section. One can also determine the initial transverse energy of the produced jet,  $E_T \approx E_T^\gamma$ , from momentum conservation, modulo calculable corrections from initial state radiations. At collider energies and sufficiently large  $E_T^\gamma$ , the Cronin effect due to multiple scatterings during the initial interaction stage is also negligible [4]. We shall use perturbative QCD to show that the  $p_T$  spectrum of charged hadrons with moderate  $p_T$  in

the backward direction of a direct photon is a very good approximation of the jet fragmentation function which can thus be reliably extracted. We shall also study the sensitivity of the modification of the jet fragmentation functions in heavy-ion collisions to the energy loss of jets and the jet interaction mean free path inside a dense matter.

Let us consider events with a direct photon in the central rapidity region,  $|y| \leq \Delta y/2$ ,  $\Delta y = 1$ . For sufficiently large  $E_T^\gamma$  of the photon, the rapidity distribution of the associated jet is also centered around zero rapidity with a comparable width. If the azimuthal angle of the photon is  $\phi_\gamma$  and  $\bar{\phi}_\gamma = \phi_\gamma + \pi$ , most of the hadrons from the jet fragmentation will fall into the kinematic region ( $|y| \leq \Delta y/2, |\phi - \bar{\phi}_\gamma| \leq \Delta\phi/2$ ), where one can take  $\Delta\phi = 2$  according to the jet profile as measured in high-energy  $p\bar{p}$  collisions [5]. Given the jet fragmentation functions  $D_{h/a}(z)$ , with  $z$  the fractional momenta of the hadrons, one can calculate the differential  $p_T$  distribution of hadrons from the jet fragmentation in the kinematical region  $(\Delta y, \Delta\phi)$ ,

$$\frac{dN_{ch}^{\text{jet}}}{dyd^2p_T} = \sum_{a,h} r_a(E_T^\gamma) \frac{D_{h/a}(p_T/E_T)}{p_T E_T} \frac{C(\Delta y, \Delta\phi)}{\Delta y \Delta\phi}, \quad (1)$$

where  $C(\Delta y, \Delta\phi) = \int_{|y| \leq \Delta y/2} dy \int_{|\phi - \bar{\phi}_\gamma| \leq \Delta\phi/2} d\phi f \times (y, \phi - \bar{\phi}_\gamma)$  is an overall factor and  $f(y, \phi)$  is the hadron profile around the jet axis. The summation is over both jet ( $a$ ) and hadron species ( $h$ ), and  $r_a(E_T^\gamma)$  is the fractional production cross section of the  $a$ -type jet associated with the direct photon. We define  $D^\gamma(z) = \sum_{ah} r_a(E_T^\gamma) D_{h/a}(z)$  as the inclusive fragmentation function.  $C(\Delta y, \Delta\phi)$  is the acceptance factor for finding the jet fragments in the given kinematic range. We find  $C(\Delta y, \Delta\phi) \approx 0.5$  at  $\sqrt{s} = 200$  GeV, independent of the photon energy  $E_T^\gamma$ , using HIJING [6] Monte Carlo simulations for the given kinematic cuts. For a fixed  $E_T^\gamma$ , the jet  $E_T$  has a smearing around  $E_T^\gamma$  caused by initial state radiations. One should

therefore average Eq. (1) over such a smearing. The resultant spectrum is very well approximated by Eq. (1) with  $E_T = E_T^y$  [7], as will be shown by comparison with explicit HIJING Monte Carlo simulations.

To calculate the background for the photon-tagged jet fragmentation from particle production in a normal central nucleus-nucleus collision, one convolutes the fragmentation functions with the jet cross sections [8],

$$\begin{aligned} \frac{dN_{ch}^{AA}}{dyd^2p_T} &= K \int d^2r \sum_{abcdh} \int_{x_{a\min}}^1 dx_a \int_{x_{b\min}}^1 dx_b f_{a/A}(x_a, r) f_{b/A}(x_b, r) \\ &\times \frac{D_{h/c}(z_c)}{\pi z_c} \frac{d\sigma}{d\hat{t}}(ab \rightarrow cd), \end{aligned} \quad (2)$$

where  $z_c = x_T(e^y/x_a + e^{-y}/x_b)/2$ ,  $x_{b\min} = x_a x_T e^{-y}/(2x_a - x_T e^y)$ ,  $x_{a\min} = x_T e^y/(2 - x_T e^{-y})$ , and  $x_T = 2p_T/\sqrt{s}$ . The  $K \approx 2$  factor accounts for higher order corrections [9]. The parton distribution density in a nucleus,  $f_{a/A}(x, r) = t_A(r)S_{a/A}(x, r)f_{a/N}(x)$ , is assumed to be factorizable into the nuclear thickness function  $t_A(r)$  [with normalization  $\int d^2r t_A(r) = A$ ], parton distribution in a nucleon  $f_{a/N}(x)$ , and the parton shadowing factor  $S_{a/A}(x, r)$  in which we take the parametrization used in the HIJING model [6]. In our notation, the scale dependences of the parton distributions  $f_{a/N}(x, Q^2)$  and the fragmentation functions  $D_{h/a}(z, Q^2)$  are implicit, which we take to be  $Q = E_T^y$ .

Jet fragmentation functions have been studied extensively in  $p\bar{p}$ ,  $ep$ , and  $e^+e^-$  experiments [10]. We will use the parametrizations of both  $z$  and  $Q^2$  dependence of the most recent analysis [11] for the unmodified fragmentation functions  $D_{h/a}^0(z)$ , in which only pions and kaons are included. We will use the MRS  $D'$  parametrization of the parton distributions [12]. The resultant single-particle  $p_T$  spectra from Eq. (2) for  $pp$  and  $p\bar{p}$  collisions at different energies agree well with the experimental data at moderate  $p_T \geq 2$  GeV/c [7] where particle production from soft processes is expected to be small. Shown in Fig. 1 are the differential  $p_T$  distributions from the fragmentation of a photon-tagged jet with  $E_T^y = 15$  and 20 GeV and the underlying background of normal central Au + Au collisions at  $\sqrt{s} = 200$  GeV. The points are HIJING simulations of 10 K events, and solid lines are numerical results of Eqs. (1) and (2); in both cases no medium effects have been considered in the fragmentation functions. The background in  $pp$  collisions is about 1200 times smaller than Au + Au.

In heavy-ion collisions, produced partons will experience secondary scatterings and induced radiation which will drive the system toward equilibrium. As a result, large momentum partons will lose part of their energy before they escape and fragment into hadrons. There have been many studies on the energy loss of a propagating parton inside a medium. It is believed that radiative en-

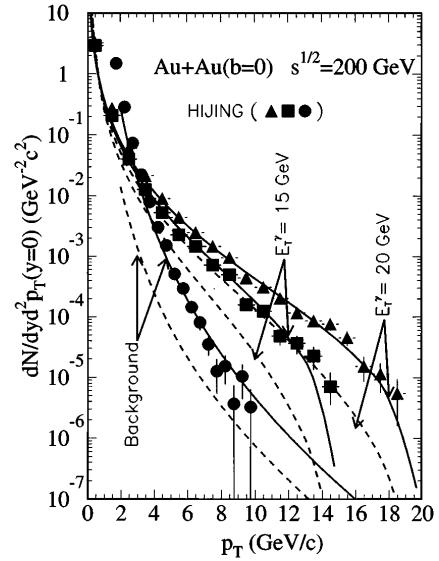


FIG. 1. The differential  $p_T$  spectrum of charged particles from the fragmentation of a photon-tagged jet with  $E_T^y = 15$  and 20 GeV and the underlying background in central Au + Au collisions at  $\sqrt{s} = 200$  GeV. The direct photon is restricted to  $|y| \leq \Delta y/2 = 0.5$ . Charged particles are limited to the same rapidity range and in the opposite direction of the photon,  $|\phi - \phi_\gamma - \pi| \leq \Delta\phi/2 = 1.0$ . Solid lines are perturbative calculations and points are HIJING simulations of 10 K events. The dashed lines are calculations with jet energy loss,  $dE_q/dx = 1$  GeV/fm, and the mean free path  $\lambda_q = 1$  fm.

ergy loss dominates even when the Landau-Pomeranchuk-Migdal suppression is taken into account [13,14]. While a dynamical study of the jet propagation and the modification of the hadronization is more desirable, we will use a phenomenological model here to demonstrate how sensitive our proposed measurement in the photon-tagged events to the interactions and the average energy loss suffered by a parton in a dense medium.

We restrict ourselves to the central rapidity region so that a parton will only propagate in the transverse direction in a cylindrical system. The parton will not hadronize inside a deconfined quark-gluon plasma. In a hadronic medium, we assume that the fragmentation functions can be approximated by their forms in vacuum. We only study the effects of radiative energy loss. Given the inelastic scattering mean free path,  $\lambda_a$ , the probability for a parton to scatter  $n$  times within a distance  $\Delta L$  before it escapes the system is assumed to be

$$P_a(n) = \frac{(\Delta L/\lambda_a)^n}{n!} e^{-\Delta L/\lambda_a}. \quad (3)$$

If we assume the average energy loss per scattering suffered by the parton is  $\epsilon_a$ , the modified fragmentation functions can be approximated as

$$\begin{aligned} D_{h/a}(z, \Delta L, Q^2) &= \frac{1}{C_N^a} \sum_{n=0}^N P_a(n) \frac{z_n^a}{z} D_{h/a}^0(z_n^a, Q^2) \\ &+ \langle n_a \rangle \frac{z'_a}{z} D_{h/g}^0(z'_a, Q_0^2), \end{aligned} \quad (4)$$

where  $z_n^a = z/(1 - n\epsilon_a/E_T)$ ,  $z_a' = zE_T/\epsilon_a$ , and  $C_N^a = \sum_{n=0}^N P_a(n)$ . We limit the number of inelastic scatterings to  $N = E_T/\epsilon_a$  by energy conservation. For large values of  $N$ , the average number of scatterings within a distance  $\Delta L$  is approximately  $\langle n_a \rangle \approx \Delta L/\lambda_a$ . The first term corresponds to the fragmentation of the leading partons with reduced energy  $E_T - n\epsilon_a$ , and the second term comes from the emitted gluons each having energy  $\epsilon_a$  on average. For simplification, we have neglected the fluctuation in the energy carried by each emitted gluon and its possible rescatterings. We also assume that the fragmentation functions can be applied to the hadronization of the emitted gluons. The inelastic scatterings suffered by the leading parton are normally not hard. Therefore, we also assume the scales in the fragmentation functions of the emitted gluons are given by the initial value  $Q_0^2 = 2.0 \text{ GeV}^2$ . Since the emitted gluons will only contribute to hadrons with very small fractional energy, the final modified fragmentation function in the moderately large  $z$  region is not sensitive to the actual radiation spectrum and the scale dependence of the fragmentation.

Since the jet production rate is proportional to the number of binary nucleon-nucleon collisions, the averaged inclusive fragmentation function of a photon-tagged jet in a central nucleus-nucleus collision is

$$D_{AA}^\gamma(z) = \int \frac{d^2 r_A^2(r)}{T_{AA}(0)} \sum_{ah} r_a(E_T^\gamma) D_{h/a}(z, \Delta L), \quad (5)$$

where  $T_{AA}(0) = \int d^2 r_A^2(r)$  is the overlap function of AA collisions at zero impact parameter. Neglecting the transverse expansion,  $\Delta L(r, \phi - \bar{\phi}_\gamma)$  only depends on the jet production position  $(r, \phi)$ . Using Eq. (4) in Eq. (2), we can calculate the single-particle inclusive  $p_T$  spectrum of normal central AA collisions taking into account jet quenching.

In principle,  $\epsilon_a$  and  $\lambda_a$  are related to each other in a dynamical model [13,14]. Phenomenologically, we can treat them as independent parameters. Alternatively, we will vary  $\lambda_a$  and  $dE_a/dx = \epsilon_a/\lambda_a$  in our calculations. The dashed lines in Fig. 1 are calculated with the modified fragmentation functions, with  $dE_q/dx = 1 \text{ GeV/fm}$  and  $\lambda_q = 1 \text{ fm}$ . We have assumed that the mean free path of a gluon is half and the energy loss is twice that of a quark. During the parton propagation, multiple scatterings can also change the direction of the parton resulting in a sizable acoplanarity. Such an acoplanarity due to multiple scatterings is probably small as compared to that caused by initial state radiations for a large  $E_T^\gamma$  photon. Thus, we assume the acceptance factor  $C(\Delta y, \Delta \phi)$  to be the same as in  $pp$  collisions. One observes that there is significant suppression of large  $p_T$  particles both from the background and jet fragmentation in the opposite direction of a tagged photon due to jet quenching. Since the number of particles at large  $p_T \geq 4 \text{ GeV}/c$  from the underlying background is substantially smaller than from the tagged jet fragmentation with and

without jet quenching, one can accurately measure the jet fragmentation function from the  $p_T$  distribution of charged particles in the opposite direction of the tagged photons, given enough number of events. Once the background is subtracted, one can push the limit to even smaller  $p_T \geq 2 \text{ GeV}/c$ , which corresponds to  $z \sim 0.1$ . One can then compare the fragmentation functions measured in  $pp$ ,  $pA$ , or peripheral AA with central AA collisions to obtain the modification due to jet quenching.

To study the sensitivity of the modified inclusive fragmentation function to the energy loss, and the interaction mean free path,  $\lambda$ , we plot in Fig. 2 the ratio of the fragmentation functions with and without energy loss for central Au + Au collisions. There is enhancement of soft particle production due to induced emissions, but only at very small values of  $z$ . The fragmentation function is suppressed for a large range of  $z$  due to energy loss. For fixed  $dE_q/dx = 1 \text{ GeV/fm}$ , the suppression is delayed to larger values of  $z$  for larger jet energies. The optimal situation is when the average total energy loss  $\langle \Delta E_T \rangle$  is comparable to the initial jet energy so that substantial suppression happens at moderate values of  $z$ . From Figs. 2 and 1, we can see that there is such a window of opportunity between  $E_T^\gamma = 10$  and  $20 \text{ GeV}$  at  $\sqrt{s} = 200 \text{ GeV}$  where the background is small.

For large values of  $z > 0.9$ , particles from the leading jets, which have suffered at least one inelastic scattering, are completely suppressed. The remaining contribution comes from only those jets that escape the system without a single scattering. The suppression factor is given by  $\langle \exp(-\Delta L/\lambda_a) \rangle$ , independent of jet energy  $E_T$  and the energy loss  $dE_a/dx$ . Therefore, one can determine the jet interaction mean free path by measuring the suppression factor of the jet fragmentation function at large  $z > 0.9$ . For intermediate values of  $z \sim 0.2-0.5$ , particles from the leading partons with reduced energy dominate as far as  $\epsilon_a \ll E_T$ , a situation we will refer to as

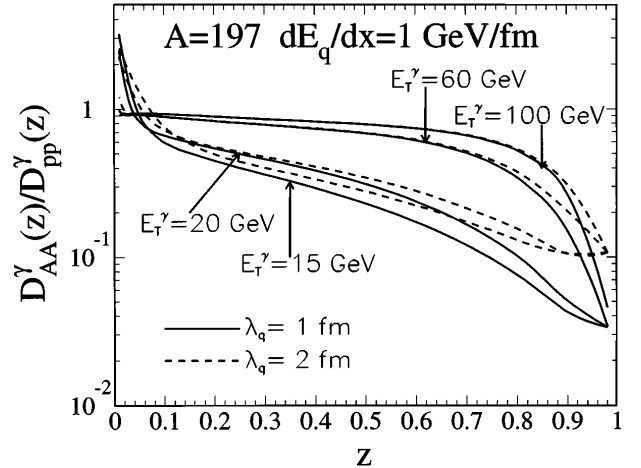


FIG. 2. Ratio of the inclusive fragmentation function of a photon-tagged jet with and without energy loss in central Au + Au collisions for a fixed  $dE_q/dx = 1 \text{ GeV/fm}$ .

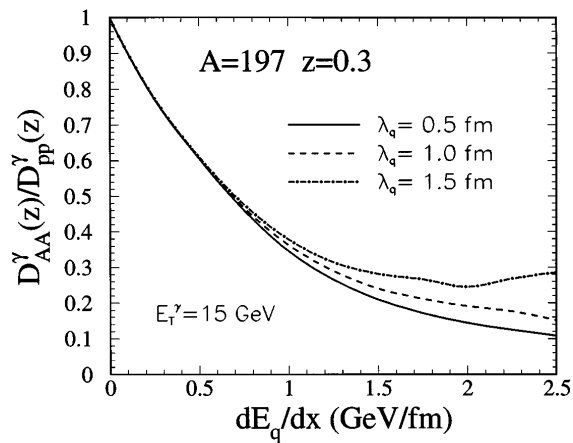


FIG. 3. Ratio of the inclusive fragmentation function of a photon-tagged jet with and without energy loss in central Au + Au collisions at  $z = 0.3$  as a function of  $dE_q/dx$ .

the “soft emission” scenario. Since the average total energy loss by the leading parton is  $\langle \Delta E_{Ta} \rangle = \langle n_a \rangle \epsilon_a = \langle \Delta L \rangle dE_a/dx$ , the suppression factor should scale with  $dE_a/dx$ , depending very weakly on the mean free path. Shown in Fig. 3 is the suppression factor at  $z = 0.3$  as a function of  $dE_q/dx$  for three different values of the mean free path. We see that for the soft emission scenario, the suppression factor scales and decreases almost linearly with  $dE_q/dx$ . At large values of  $dE_q/dx$  and  $\lambda_q$ , the average total energy loss becomes comparable or equal to the initial jet energy  $E_T$ . In this “hard emission” scenario, particle production from the emitted gluons and contributions from those jet partons which escape the system without any induced radiation become important. This is why the suppression factor saturates at larger values of  $dE_q/dx$ , especially for large values of  $\lambda_q$ . Since the mean free path can be determined from the measured suppression factor at large  $z > 0.9$  which is independent of  $dE_q/dx$ , additional measurements of the suppression at intermediate  $z = 0.2-0.4$  will enable one to extract the energy loss.

In summary, we have proposed to study jet energy loss in high-energy heavy-ion collisions by measuring the inclusive jet fragmentation function which can be extracted from the differential  $p_T$  spectrum of charged particles in the opposite direction of a tagged direct photon. The background to the jet fragmentation is estimated to be small for moderately large  $p_T$ . We have also demonstrated that modification of the jet fragmentation function due to jet quenching can be used to obtain the energy loss

and the mean free path of jet interaction inside the dense matter produced in high-energy heavy-ion collisions.

We have not specified the energy dependence of the energy loss in our calculation. In addition, the energy loss,  $dE/dx$ , might also depend on the distance that jet partons have traveled as indicated by a recent study [14]. These dependences can be studied experimentally by varying the energy of the tagged photons in the collisions of different nuclei. These are the subjects of further investigations [7].

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