Jet Quenching in High-Energy Heavy-Ion Collisions

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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, 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.

We proposed that the jet quenching in high-energy heavy-ion collisions can be studied by measuring the p_T distribution of charged hadrons in the opposite direction of a tagged direct photon [4]. 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^γ, 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^γ, the Cronin effect due to multiple scatterings during the initial interaction stage is also negligible [5]. We 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 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^γ 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 ϕ_γ 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 [6]. 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 $(\Delta y, \Delta\phi)$,

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

where $C(\Delta y, \Delta\phi) = \int_{|y|\leq\Delta y/2} dy \int_{|\phi-\bar{\phi}_\gamma|\leq\Delta\phi/2} d\phi f(y, \phi - \bar{\phi}_\gamma)$ 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 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^γ, using HIJING [7] Monte Carlo simulations for the given kinematic cuts.

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],

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

where $z_c = x_T(e^y/x_a + e^{-y}/x_b)/2$, $x_{bmin} = x_a x_T e^{-y}/(2x_a - x_T e^y)$, $x_{amin} = x_T e^y/(2 - x_T e^{-y})$, 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 $S_{a/A}(x, r)$ which we take the parametrization used in HIJING model [7]. 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 $Q = E_T^\gamma$.

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 $D^0_{h/a}(z)$, in which only pions and kaons are included. We use the MRS D$-'$ parametrization of the parton distributions [12]. Shown in Fig. 5 are the differential p_T distributions from the fragmentation of a photon-tagged jet with E_T^γ =15, 20 GeV and the underlying background of normal central $Au + Au$ collisions at $\sqrt{s} = 200$ GeV. The points are HIJING simulations of 10K 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 energy 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, λ_a, the probability for a parton to scatter n times within a distance ΔL before it escapes the system is assumed to be

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

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

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

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 ΔL 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 ϵ_a on the average. For simplification, we have neglected the fluctuation in the energy carried by each emitted gluon and its possible rescattering. 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 $Q_0^2 = 2.0$ 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

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

where $T_{AA}(0) = \int d^2 r t_A^2(r)$ 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, ϕ). 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.

The dashed lines in Fig. 5 are calculated with the modified fragmentation functions, with $dE_q/dx = 1$ GeV/fm and $\lambda_q = 1$ 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^{γ} photon. 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 $p_T \geq 4$ 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

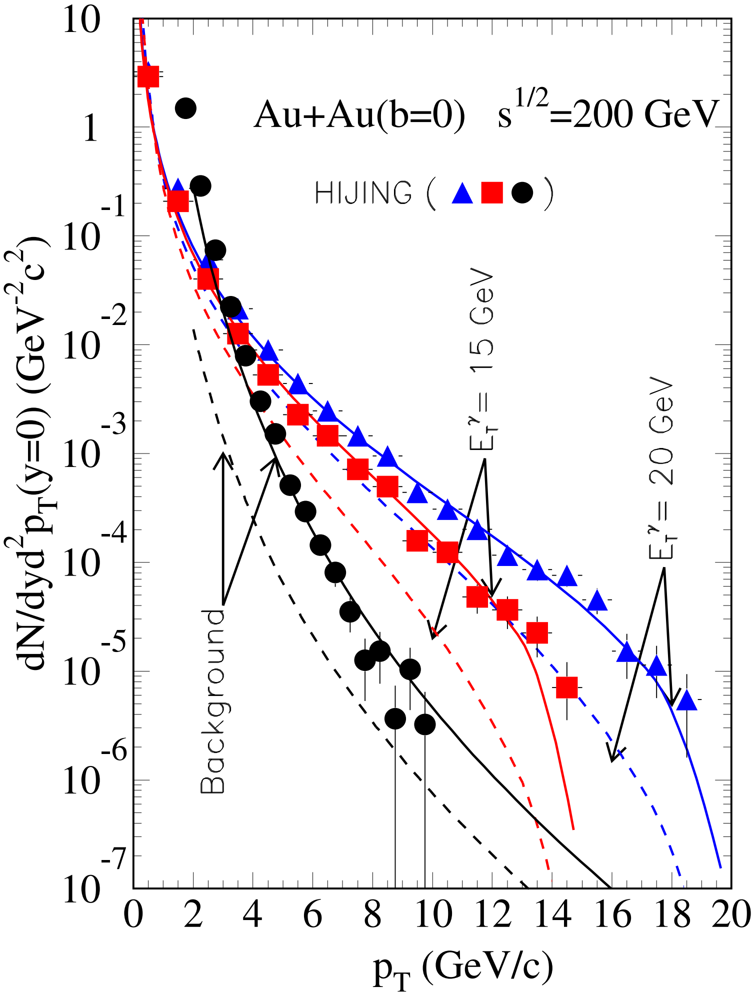

Figure 1: The differential p_T spectrum of charged particles from the fragmentation of a photon-tagged jet with E_T^γ =15, 20 GeV and the underlying background in central $Au + Au$ collisions at $\sqrt{s}$ = 200 GeV [4]. Solid lines are perturbative calculations and points are HIJING simulations. The dashed lines are calculations with jet energy loss, $dE_q/dx = 1$ GeV/fm and the mean-free-path $\lambda_q = 1$ fm. [4].

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 $p_T \geq 2$ 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, λ, we calculate the ratio of the fragmentation functions with and without energy loss for central $Au + Au$ collisions. We find an enhancement of soft particle production due to induced emissions, but only at very small values of z. The fragmentation function is suppressed for large range of z due to energy loss. For fixed $dE_q/dx = 1$ GeV/fm, the suppression is delayed to larger values of z for larger jet energies.

The most 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 3 in Ref. 4 we can see that there is such a window of opportunity between $E_T^\gamma = 10$ and 20 GeV at $\sqrt{s} = 200$ 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 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. In Ref. 4 we show 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 λ_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 λ_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 a way 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.

Our results will be used by the STAR experiment at RHIC to study the effect of jet quenching at RHIC.

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