Medium Modification of the Jet Properties

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Abstract. In the case that a dense medium is created in a heavy ions collision, high-$E_t$ jets are expected to be broadened by medium-modified gluon emission. This broadening is directly related, through geometry, to the energy loss measured in inclusive high-$p_t$ particle suppression. We present here the modifications of jet observables due to the presence of a medium for the case of azimuthal jet energy distributions and $k_t$-differential multiplicities inside the jets.

Recent data from RHIC on inclusive particle production at high-$p_t$ are well described in terms of radiative parton energy loss [1]. Associated to this energy loss, theory predicts a broadening of the radiated gluon spectrum when compared with the vacuum case [2, 3]. Indeed, the average transverse momentum of the radiated gluons is given by $\langle k_t^2 \rangle \sim \frac{\omega_c}{L}$, where $\omega_c$ is the critical energy above which the medium-induced gluon radiation is suppressed by formation time effects (see below).

The general expression for the radiation of a gluon with energy $\omega$ and transverse momentum $k_t$ in the limit of large quark energy takes the form [4]

$$\omega \frac{dI}{d\omega \, dk_t} = \frac{\alpha_s \, C_R}{(2\pi)^2 \, \omega^2} \, 2 \text{Re} \int_0^\infty dy_1 \int_0^\infty dy_1 \int d^2 u \, e^{-ik \cdot u} \, e^{-\frac{i}{2} \int_0^\infty d\xi \, n(\xi) \, \sigma(u)} \times$$

$$\times \frac{\partial}{\partial y_1} \, \frac{\partial}{\partial u} \int_{\gamma(y_1)}^{u(r(y_1))} Dr \, \exp \left[ i \int_{y_1}^{y} \frac{\omega}{2} \, \left( r^2 - \frac{n(\xi) \, \sigma(r)}{i \, 2 \, \omega} \right) \right]. \quad (1)$$

We have studied this formula in two approximations. First, in the saddle point approximation, $\sigma(r) = Cr^2$, the path integral of (1) is that of a harmonic oscillator of imaginary frequency. This approximation corresponds to multiple soft scatterings, and neglects the high-$p_t$ tails of single scattering centers. Second, in the opacity expansion, the integrand of (1) is expanded in powers of $(n(\xi) \, \sigma(r))^N$. This corresponds to a fixed number of $N$ scattering centers. In the following, the label single hard scattering denotes the first term ($N = 1$) in this expansion.

The medium-induced gluon radiation spectrum can be written in terms of two scaling variables [3],

$$\kappa^2 = \frac{k_t^2}{qL}, \quad \omega_c = \frac{1}{2} qL^2 \quad \left[ \kappa^2 = \frac{k_t^2}{\mu^2}, \quad \omega_c = \frac{1}{2} \mu^2 L \quad \text{for single hard} \right]. \quad (2)$$

In the multiple soft scattering approximation, the only parameter is the transport coefficient, $\hat{q}$. This quantity parametrizes the average momentum transfer squared and is proportional to the density of the medium. In the single hard scattering, the Debye
screening mass $\mu$ denotes the average momentum transfer per scattering center. In Fig. 1 we present the double differential spectrum \( \text{d}^2 \sigma / \text{d} \omega \text{d} k^2 \) in $\omega$ and $k^2$.

Qualitative properties of the medium-induced gluon radiation spectrum can be understood by coherence arguments \([5, 6]\). The relevant phase for gluon emission is

$$\varphi = \frac{1}{2 \omega} \langle k^2 \Delta z \rangle \quad \Rightarrow \quad \varphi \sim \frac{L}{l_{\text{coh}}} \sim \frac{\kappa^2}{\omega_c} \quad \text{for} \quad \Delta z \sim L. \quad (3)$$

Gluon radiation occurs if the accumulated phase $\varphi \gtrsim 1$. Thus, the radiation is suppressed for $\kappa^2 \lesssim \omega_c/\omega$ and for $\omega \gtrsim \omega_c$ (as $\kappa \lesssim 1$). These features are observed in the numerical calculations presented in Fig. 1. The presence of a limiting energy $\omega_c$ implies that the average energy loss $\Delta E \sim \omega_c \propto L^2$, as first pointed out in \([8]\).

The $k_t$-integrated spectrum (see Refs. \([7, 8]\)) is also suppressed for small values of $\omega$. This fact can also be understood by formation time arguments: the integration limit $k_t < \omega$ cuts the gluon energies $\omega^2 \lesssim k^2$, on the other hand, the spectrum is suppressed for $k_t \lesssim \hat{q}L$ due to formation time effects. This suppresses the spectra for $\omega/\omega_c \lesssim \sqrt{2/\omega_c L}$. In this way, formation time effects make the spectrum stable in the infrared region \([7]\).

Based on this formalism of medium-induced parton energy loss, we have computed the medium-modification of two jet observables, namely the fraction $\rho(R)$ of jet energy inside a cone $R$ and the gluon multiplicity distribution \([5]\).
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The fraction of the jet energy inside a cone of radius \( R = \sqrt{(\Delta \eta)^2 + (\Delta \Phi)^2} \) is

\[
\rho_{\text{vac}}(R) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{E_t(R)}{E_t(R=1)} .
\]  

(4)

In the presence of the medium, this energy is shifted by

\[
\rho_{\text{med}}(R) = \rho_{\text{vac}}(R) - \frac{\Delta E_t(R)}{E_t} + \frac{\Delta E}{E_t} (1 - \rho_{\text{vac}}(R)) .
\]  

(5)

Here, \( \Delta E_t(R) \) is the additional (medium) energy radiated outside a cone \( \Theta = R \), \( \Delta E(\Theta) = \int \epsilon P(\epsilon, \Theta) d\epsilon \). It is determined by the probability \( P(\epsilon, \Theta) \) that an energy fraction \( \epsilon \) is radiated outside \( \Theta \), which can be calculated from eq. (1) [7]. In Fig. 2 we plot the medium-shifted distribution (5). The shaded area corresponds to the uncertainty in finite quark-energy effects: in the eikonal approximation \( P(\epsilon) \) has support in the unphysical region \( \epsilon > 1 \). To estimate this effect we take \( P(\epsilon) \rightarrow P(\epsilon) \int_0^1 d\epsilon P(\epsilon) \).

\[ 
\]

Figure 2. LHS: The jet shape for a 50 GeV and 100 GeV quark-lead jet which fragments in the vacuum (dashed curve) or in a dense QCD medium (solid curve) characterized by \( \omega_c = 62 \text{ GeV} \) and \( \omega_c L = 2000 \). RHS: the corresponding average medium-induced energy loss for \( E_t = 100 \text{ GeV} \) outside a jet cone \( R \) radiated away by gluons of energy larger than \( E_{\text{cut}} \). Shaded regions indicate theoretical uncertainties discussed in the text.

The effect of the medium is very small (at \( R=0.3, \sim 5\% \) for a 50 GeV jet and \( \sim 3\% \) for a 100 GeV jet). The smallness of this effect could allow for a calibration of the total energy of the jet without tagging a recoiling hard photon or Z-boson. It also implies that the jet \( E_t \) cross section scale with the number of binary collisions. In order to check the sensitivity of our results to the small-energy region, we impose low momentum cut-offs which remove gluon emission below 5 GeV. As anticipated, the transverse broadening is very weakly affected by these cuts. This is due to the infrared behavior of the spectrum.
for small values of $\omega$. A proper subtraction of the large background present in heavy ion collisions would benefit from this result.

$k_t$-differential measurements are expected to be more sensitive to medium effects. We studied the intrajet multiplicity of produced gluons as a function of the transverse (with respect to the jet axis) momentum. The medium-induced additional number of gluons with transverse momentum $k_t = |k|$ produced within a subcone of opening angle $\theta_c$ is

$$dN_{\text{med}}/dk_t = \int_{k_t/\sin \theta_c}^{E_t} d\omega \frac{dI_{\text{med}}}{d\omega dk_t}.$$  \(6\)

For the vacuum we simply assume $dN_{\text{vac}}/dk_t \sim 1/k_t \log(E_t \sin \theta_c/k_t)$. The total multiplicity is the sum of the two. Fig. 3 shows that this multiplicity distribution is very sensitive to medium-effects since it broadens significantly. Moreover, the high-$k_t$ tail of the distribution is unaffected by the soft background since only high-$p_t$ particles can have a large $k_t$ inside the jet cone.

The first results on 'jet-like' particle production associated to high-$p_t$ trigger particles have been presented at this conference \footnote{I. Vitev, these proceedings \href{http://arxiv.org/abs/hep-ph/0403089}{hep-ph/0403089} and references therein}. The results are in rough qualitative agreement with the ones shown here for much larger jet energies. A more refined analysis of finite energy corrections is, however, needed for a direct comparison with data.

\begin{itemize}
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