Jet energy loss and high $p_T$ photon production in hot quark-gluon plasma

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Abstract

Jet-quenching and photon production at high transverse momentum are studied at RHIC energies, together with the correlation between jets and photons. The energy loss of hard partons traversing the hot QGP is evaluated in the AMY formalism, consistently taking into account both induced gluon emission and elastic collisions. The production of high $p_T$ photons in Au+Au collisions is calculated, incorporating a complete set of photon-production channels. Putting all these ingredients together with a (3+1)-dimensional ideal relativistic hydrodynamical description of the thermal medium, we achieve a good description of the current experimental data. Our results illustrate that the interaction between hard jets and the soft medium is important for a complete understanding of jet quenching, photon production, and photon-hadron correlations in relativistic nuclear collisions.

1. Introduction

Jet-quenching is one of the most important discoveries of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) [1, 2]. Owing to the strong interaction with the hot quark-gluon plasma (QGP) created in these collisions, high transverse momentum ($p_T$) partons produced from early hard scatterings suffer energy loss in the medium, leading to significant suppression of high-$p_T$ hadrons in central A+A collisions in comparison with those from binary-scaled p+p collisions [3]. There has been a lot of effort devoted to understanding the energy loss experienced by hard jets in excited hadronic matter (e. g., see Ref. [4]).

In addition to single-particle observables, more insight may be gained through correlation studies, i.e., measuring high-$p_T$ hadron production associated with a high-$p_T$ trigger. One motivation is that correlation measurements put tighter constraints on the initial momentum distribution of the partons that fragment into the observed hadrons. In this context, high $p_T$ photons have been considered as promising trigger particles [5] as they are mostly produced from early hard binary scatterings. Triggering on such photons should fix the transverse momentum of the away-side parton [6, 7, 8]. However, it should be noted that other photon sources, such as those involving jet-plasma interactions, may contribute to photon-hadron correlations. We present a study [9] of photon-hadron correlations at RHIC which includes relevant high-$p_T$ photon-production channels. The formalism developed in Ref. [10] is employed to account consistently for collisional and radiative energy loss of hard partons in the Arnold-Moore-Yaffe (AMY) approach [11, 12, 13]. The thermalized medium produced in Au+Au collisions is modeled by (3+1)-dimensional hydrodynamics [14].
2. Calculation

The evolution of the jet distributions \( P(E, t) = dN(E, t)/dE \) in the medium is described by a set of coupled Fokker-Planck type equations [13, 16]:

\[
\frac{dP_j(E, t)}{dt} = \sum_{\theta} \int d\omega \left[ P_\theta(E + \omega, t) \frac{d\Gamma_{\theta \to j}(E + \omega, \omega)}{d\omega dt} - P_j(E, t) \frac{d\Gamma_j \to \omega(E, \omega)}{d\omega dt} \right].
\] (1)

Here \( d\Gamma_{\theta \to j}(E, \omega)/d\omega dt \) is the transition rate, with \( E \) the initial jet energy and \( \omega \) the lost energy. The radiative and collisional parts of the transition rates have been discussed in Ref. [17–10].

To obtain high-\( p_T \) hadrons produced in A+A collisions, the medium-modified fragmentation function \( \tilde{D}_{h/j}(z, \vec{r}_\perp, \phi) \) is defined to take into account the energy loss of jets in the medium:

\[
\tilde{D}_{h/j}(z, \vec{r}_\perp, \phi) = \sum_j \int dp_j \frac{z'}{z} \tilde{D}_{h/j}(z')P(p_j|p_j, \vec{r}_\perp, \phi).
\] (2)

Here \( z = p_h/p_j \) and \( z' = p_h'/p_j' \), with \( p_h \) the hadron momentum and \( p_j(p_j) \) the initial (final) jet momentum. \( P(p_j|p_j, \vec{r}_\perp, \phi) \) represents the probability of obtaining a jet \( j' \) with momentum \( p_j \) from a given jet \( j \) with momentum \( p_j \) and is obtained by solving Eq. (1). As the energy loss depends on the local medium profiles along the jet path, one needs to convolve over the distribution of jet production position \( \vec{r}_\perp \) and propagation direction \( \phi \).

To calculate the spectrum of high-\( p_T \) non-decay photons produced in relativistic nuclear collisions, one needs to take into account all the important sources: early hard direct photons, fragmentation photons, and jet-medium photons. Prompt direct photons are mostly produced from early hard collisions between partons from two initial nuclei, through quark-anti-quark annihilation and quark-gluon Compton scattering. Fragmentation photons are produced by the surviving high energy jets escaping the medium. As in high-\( p_T \) hadron production, one may define a medium-modified photon fragmentation function \( \tilde{D}_{\gamma/j}(z, \vec{r}_\perp, \phi) \). Jet-medium photons are produced during the passage of high energy jets through the nuclear medium via induced photon bremsstrahlung and jet-photon conversions. This defines an photon evolution equation solved with the jet evolution,

\[
\frac{dP_{\gamma}^{\text{TM}}(E, t)}{dt} = \int d\omega P_{\text{had}}(E + \omega, t) \frac{d\Gamma_{\gamma \to \gamma}(E + \omega, \omega)}{d\omega dt}.
\] (3)

Here \( d\Gamma_{\gamma \to \gamma}(E + \omega, \omega)/d\omega dt \) is the bremsstrahlung processes discussed in Ref. [11, 12, 13], and jet-photon conversion rates \( d\Gamma_{\gamma \to \gamma}(E + \omega, \omega)/d\omega dt \) may be inferred from the photon emission rates for those processes.

For photon-hadron correlations, one defines a yield per-trigger, representing the momentum distribution of away-side hadrons given a trigger photon in the near side with momentum \( p_T^\gamma \):

\[
P(p_T^h|p_T^\gamma) = P(p_T^h, p_T^\gamma)/P(p_T^\gamma).
\] (4)

Note that \( P(p_T^\gamma) \) is the single-particle \( p_T \) distribution and \( P(p_T^\gamma, p_T^h) \) is the \( \gamma-h \) pair \( p_T \) distribution. Often, a photon-triggered fragmentation function is defined,

\[
D_{\gamma A}(z_T, p_T^\gamma) = p_T^\gamma P_{\gamma A}(p_T^h|p_T^\gamma),
\] (5)

with \( z_T = p_T^h/p_T^\gamma \). The effect of the nuclear medium on photon-hadron correlations may be quantified by the nuclear modification factor \( I_{AA} \) defined as,

\[
I_{AA}(z_T, p_T^\gamma) = D_{AA}(z_T, p_T^\gamma)/D_{pp}(z_T, p_T^\gamma).
\] (6)
3. Results

The results for jet-quenching and photon production in Au+Au collisions at RHIC are shown in Fig. 1. The left panel shows neutral pion $R_{AA}$ measured at mid-rapidity for the most central and mid-central collisions [10]. We also compare the relative contributions of induced gluon radiations (dashed) and elastic collisions (dash-dotted) to the final $R_{AA}$ (solid). One finds that the overall magnitude of $R_{AA}$ is sensitive to both radiative and collisional energy loss. The only free parameter, $\alpha_s$, – the strong coupling constant – is chosen such that the experimental measurement of $R_{AA}$ in the most central collisions is described. The same value $\alpha_s = 0.27$ is then used throughout. In the right panel, we show the relative contributions from different channels to high-$p_T$ photon production in central collisions [9], and compare with PHENIX measurements [18]. While photons in the high-$p_T$ regime are predominantly from early hard partonic collisions, the presence of jet-medium interaction is nevertheless important to understand the net photon production in Au+Au collisions at RHIC.

In Fig. 2 we show our results [9] for photon-hadron correlations at high $p_T$ in Au+Au collisions compared to STAR (left) and PHENIX (right) measurements. Figures are taken from Ref. [9].
collisions at RHIC. The left panel shows the photon-triggered fragmentation function $D_{AA}(z_T)$ compared with STAR measurements [19]. The theoretical photon-triggered fragmentation function $D_{AA}(z_T)$ in central Au+Au collisions agrees well with experimental data. Also the STAR measurements for peripheral Au+Au collisions are consistent with p+p calculations. In the right panel, we show the nuclear modification factor $I_{AA}$ for photon-triggered hadron production compared with PHENIX measurements [20]. While the fall of $I_{AA}$ at low but increasing $z_T$ is due to the dominance of direct photons, the flattening $I_{AA}$ predicted at higher values of $z_T$ owes to the increasing influence of jet-medium photons and of fragmentation photons. Also note that several bins of hadron momenta are shown for comparison.

4. Summary

We have presented a study of jet energy loss, photon production and photon-hadron correlations at high $p_T$ within a consistent theoretical framework. Both induced gluon radiation and elastic collisions are incorporated to calculate the energy loss of hard jets traversing the hot and dense medium. A complete set of photon-production channels is included in the computation of high $p_T$ photon spectra. A fully (3+1)-dimensional hydrodynamical evolution is employed to model the thermalized medium created at RHIC. Our results have been shown to provide a good description of the experimental measurements. This implies that jet-medium interaction is important for jet-quenching, photon production, and photon-hadron measurements at RHIC; the study of these correlations will in turn provide insight on the detailed structure of the excited medium created in high-energy nuclear collisions.

Acknowledgments

This work was supported in part by the U.S. Department of Energy under grant DE-FG02-01ER41190, and in part by the Natural Sciences and Engineering Research Council of Canada. G.-Y.Q. acknowledges the support from the organizers of the Quark Matter 2009 conference.

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