Effects of running couplings on jet conversion photons

Lusaka Bhattacharya

Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata, Pin-700064, India

Abstract

We calculate photons from jet-plasma interaction considering collisional and radiative energy loss of jet parton. The phase space distribution of the participating jet is dynamically evolved by solving Fokker-Planck equation. We treat the strong coupling constant ($\alpha_s$) as function of momentum and temperature while calculating the drag and diffusion coefficients. It is observed that the quenching factor is substantially modified as compared to the case when $\alpha_s$ is taken as constant. It is shown that the Phenix data is reasonably well reproduced when contributions from all the relevant sources are taken into account.

Key words: energy loss, running coupling, QGP

PACS:

1. Introduction

Heavy ion collisions have received significant attention in recent years. Electromagnetic probes (photons, dileptons etc) have been proposed to be one of the most promising tools to characterize the initial state of the collisions [1]. Because of the very nature of their interactions with the constituents of the system they tend to leave the system almost unscattered. Photons are produced at various stages of the evolution process. The initial hard scatterings (Compton and annihilation) of partons lead to photon production which we call hard photons. If quark gluon plasma (QGP) is produced initially, there are QGP-photon from thermal Compton plus annihilation processes. Photons are also produced from different hadronic reactions from hadronic matter either formed initially (no QGP scenario) or realized as a result of a phase transition from QGP.

These apart, there exits another class of photon emission process via the jet conversion mechanism (jet-plasma interaction) [2] which occurs when a high energy jet interacts with the medium constituents via annihilation and Compton processes.

In current heavy ion collision experiments, the temperature $T$ is not only the important scale, momentum scale, $k$, (of the partons) is also important. Therefore running of the coupling in the high momentum regime ($p \sim T$) has to be taken into account to calculate...
the cross sections and the energy-loss processes. In this work we calculate photons from jet-plasma interaction taking into account running of QCD coupling and both collisional and radiative energy losses.

The plan of the article is as follows. We discuss the formalism in the next section. Results will be discussed in the section 3. Finally we will conclude.

2. Formalism

2.1. Jet-Photon Rate

The lowest order processes for photon emission from QGP are the Compton scattering \((q \bar{q}) g \rightarrow q(\bar{q}) \gamma\) and annihilation \((q \bar{q} \rightarrow g \gamma)\) process. The differential photon production rate for this process is given by [3]:

\[
E \frac{dR}{d^3p} = \frac{N}{2(2\pi)^8} \int \Pi \frac{d^3p_1}{2E_1} f_{jet}(p_1) f_2(E_2) \delta(p_1 + p_2 - p_3 - p) |M|^2 (1 \pm f_3(E_3)) \quad (1)
\]

where, \(|M|^2\) represents the spin averaged matrix element squared for one of these processes which contributes in the photon rate and \(N\) is the degeneracy factor of the corresponding process. \(f_{jet}, f_2\) and \(f_3\) are the initial state and final state partons. \(f_2\) and \(f_3\) are the Bose-Einstein or Fermi-Dirac distribution functions.

2.2. Fokker - Planck Equation: Parton transverse momentum spectra

In the photon production rate (from jet-plasma interaction) one of the collision partners is assumed to be in equilibrium and the other (the jet) is executing random motion in the heat bath provided by quarks (anti-quarks) and gluons. Furthermore, the interaction of the jet is dominated by small angle scattering. In such scenario the evolution of the jet phase space distribution is governed by Fokker-Planck (FP) equation where the collision integral is approximated by appropriately defined drag \((\eta)\) and diffusion coefficients [4].

The drag and diffusion coefficients are infrared singular. The infra-red cut-off is fixed by plasma effects, where only the medium part is considered, completely neglecting the vacuum contribution leading to ambiguity in the energy loss calculation. If the latter part is taken into account the strong coupling should be running. Thus for any consistent calculation one has to take into consideration this fact. In that case \(\alpha_s = \alpha_s(k, T)\) \((k = \sqrt{\omega^2 - q^2} \text{ in this case})\), and the above integrals must be evaluated numerically where the infra-red cut-off is fixed by Debye mass to be solved self-consistently: \(m_D(T) = 4\pi \left(1 + \frac{N_c}{6}\right) \alpha_s(m_D(T), T) T^2\) Here the strong coupling which we take as running, i. e. \(\alpha_s = \alpha_s(\sqrt{\omega^2 - q^2}, T)\). We chose the following parametrization of \(\alpha_s\) which respects the perturbative ultra-violet (UV) behavior and the 3D infra-red (IR) point [5]:

\[
\alpha_s(k, T) = \frac{u_1 k}{1 + \exp(u_2 \frac{k}{T} - u_3)} + \frac{v_1}{(1 + \exp(v_2 \frac{k}{T} - v_3))(\ln(e + (\frac{k}{\Lambda_s})^a + (\frac{k}{\Lambda_s})^b))}, \quad (2)
\]

with \(k = \sqrt{\omega^2 - q^2}\) in this case. The parameters \(u, v, a, b\) and \(\Lambda_s\) are given by \(a = 9.07, b = 5.90\) and \(\Lambda_s = 0.263\) GeV. For the limiting behavior \((k << T)\) of the coupling
we choose, $u_1 = \alpha_{3d}^* (1 + \exp(-u_3))$ Here $\alpha_{3d}^*$ and $\alpha_s^*$ denote the values of the IR fixed point of $SU(3)$ Yang-Mills theory in $d = 3$ and $d = 4$ dimensions, respectively. The remaining four parameters ($u_2 = 5.47, u_3 = 6.01, v_2 = 10.13$ and $v_3 = 9.27$) fit the numerical results for pure Yang-Mills theory obtained from the RG equations in Ref. [6].

In our calculation we have considered both collisional and radiative energy losses in the following manner.

$$\eta = \eta_{\text{coll}} + \eta_{\text{rad}} = \frac{1}{E} \left[ \frac{dE}{dx} \right]_{\text{coll}} + \left[ \frac{dE}{dx} \right]_{\text{rad}}$$

For running $\alpha_s$, the expressions for the collisional and radiative energy losses can be found in [4]. Having known the drag and diffusion, we solve the FP equation using Green’s function techniques (for details see Ref. [7]).

### 2.3. Space time evolution

In order to obtain the space-time integrated rate we first note that the phase space distribution function for the incoming jet in the mid rapidity region is given by (see Ref. [8] for details)

$$f_{\text{jet}}(\vec{r}, \vec{p}, t')_{|y=0} = \frac{(2\pi)^3 \mathcal{P}(|\vec{w}_r|)}{\nu_q \sqrt{t_i^2 - z_0^2}} \frac{1}{p_{\gamma} d^2 p_T dy} dN_{\gamma}(p_T, t') \delta(z_0)$$

With this jet parton phase space distribution function one can easily obtain jet photon yield from eqn. (1):

$$\frac{dN_{\gamma}}{d^2 p_T dy} = \int d^4x \frac{dN_{\gamma}}{d^4xd^2 p_T dy}$$

$$= \frac{(2\pi)^3}{\nu_q} \int_{t_i}^{t'} dt' \int_0^R rdr \int d\phi \mathcal{P}(\vec{w}_r) \frac{N_i}{16(2\pi)^7 E_{\gamma}} \int d\hat{s} |\mathcal{M}_i|^2 \int dE_1 dE_2$$

$$\times \frac{1}{p_{1T} d_1 d^2 p_{1T'} dy(p_{1T}, t')} \frac{f_2(E_2)(1 \pm f_3(E_3))}{\sqrt{aE_2^2 + 2bE_2 + c}}$$

### 3. Results

In order to obtain the photon $p_T$ distribution we numerically integrate Eq. (5). The results for jet-photons for RHIC energies are plotted in Fig. 1 (left) where we have taken $T_i = 446$ MeV and $t_i = 0.147$ fm/c. We find that the yield is decreased with the inclusion of both the energy loss mechanisms as compared to the case when only collisional energy loss is considered. It is to be noted that when one considers collisional energy loss alone the yield with constant $\alpha_s$ is more compared to the situation when running $\alpha_s$ is taken into account (see Fig. 1 left).

In order to compare our results with high $p_T$ photon data measured by the PHENIX collaboration [9], we have to evaluate the contributions to the photons from other sources, that might contribute in this $p_T$ range. In Fig. 1 (right) the results for jet-photons corresponding to the RHIC energies are shown, where we have taken $T_i = 446$ MeV and $t_i =$
0.147 fm/c. The individual contributions from hard and bremsstrahlung processes [10] are also shown for comparison.

![Graph](image_url)

Fig. 1. (color online) Left: $p_T$ distribution of photons at RHIC energy. The violet (magenta) curve denotes the photon yield from jet-plasma interaction with collisional (collisional + radiative) energy loss. The blue curve corresponds to the case without any energy loss and the green curve represents the thermal contribution. Right: Our results (the orange line which represents the total photon yield) is compared with the Phenix measurements of photon data [9].

4. Summary

We have calculated the transverse momentum distribution of photons from jet plasma interaction with running coupling, i.e. with $\alpha_s = \alpha_s(k, T)$ where we have included both collisional and radiative energy losses. Using running coupling we find that the depletion in the photon $p_T$ spectra is by a factor of $2 - 2.5$ more as compared to the case with constant coupling for RHIC energies Phenix photon data have been contrasted with the present calculation and the data seem to have been reproduced well in the low $p_T$ domain. The energy of the jet quark to produce photons in this range ($4 < p_T < 14$) is such that collisional energy loss plays important role here. It is shown that inclusion of radiative energy loss also describes the data reasonable well.

References

[1] J. Alam, S. Sarkar, P. Roy, T. Hatsuda, and B. Sinha, Ann. Phys. 286 159 (2000).
[2] R. J. Fries, B. Muller, and D. K. Srivastava, Phys. Rev. Lett. 90, 132301 (2003).
[3] L. Bhattacharya and P. Roy, Eur. Phys. J. C69 445 (2010).
[4] L. Bhattacharya and P. Roy, arxiv:1101.3869 [hep-ph][Accepted for publication in Journal of Phys. G].
[5] J. Braun and H-J. Pirner, Phys. Rev. D75, 054031 (2007).
[6] J. Braun and H. Gies, J. High energy Phys. 06 024 (2006).
[7] H. V. Hees and R. Rapp, Phys. ReV. C71, 034907 (2005).
[8] S. Turbide, C. Gale, S. Jeon and G. D. Moore, Phys. Rev. C72, 014906 (2005).
[9] S. S. Adler et al., Phys. Rev. Lett. 98 012002 (2007).
[10] J. F. Owens, Reviews of Modern Physics, Vol-59, No. 2, 465 (1987).