Photons from Jet - Plasma Interaction in collisional energy loss scenario

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We calculate photons from jet plasma interaction in a collisional energy loss scenario. It is shown that the Phenix photon data is well reproduced when photons from initial hard collisions are taken into account.

I. INTRODUCTION

Study of direct photon and dilepton spectra emanating from hot and dense hadronic matter formed in ultra-relativistic heavy ion collisions is a field of considerable current interest. Electromagnetic probes 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 without much change of their energy and momentum. In fact, photons (dilepton as well) can be used to determine the initial temperature, or equivalently the equilibration time. These are related to the final multiplicity of the produced hadrons in relativistic heavy ion collisions. By comparing the initial temperature with the transition temperature from lattice QCD, one can infer whether Quark Gluon Plasma (QGP) is formed or not.

There are various sources of photons from relativistic heavy ion collisions: (i) Thermal photons from QGP and hot hadronic matter (HHM), (ii) hard photons $(A + B \rightarrow \gamma X)$. (iii) photons from decay of $\pi^0(\eta) \rightarrow \gamma \gamma$. Hard photon yield can be reliably calculated using perturbative quantum chromodynamics.

The last class of photon emission processes is the jet conversion mechanism [2] which occurs when a high energy jet interacts with the medium constituents via annihilation and compton processes. It might be noted that this phenomenon (for Compton process) has been illustrated quite some time ago [3] in the context of estimating photons from equilibrating scenario where, because of the larger cross-section, gluons equilibrate among themselves providing a heat bath to the incoming quark-jet. A comparison of the non-equilibrium photons (equivalent to jet-conversion) with the direct photons (thermal) shows that this contribution remains dominant for photons with $p_T$ upto 6 GeV. However, while evaluating jet-photon the assumption made in Ref. [2] that the largest contribution to photons corresponds to $p_\gamma \sim p_q(p_\bar{q})$ which amounts to saying that the annihilating quark (anti-quark) directly converts to a photon. Moreover, before annihilating the quark jet loses energy in the scattering with the particles in the thermal bath.

The partonic energy loss due to collisional processes was revisited in [4] and its importance was demonstrated in the context of RHIC in [5]. The measurements of non-photonic single electron data [6] show larger suppression than expected. These electrons mainly come from heavy quark decay where the radiative energy loss is suppressed due to dead cone effect. This observation has led to re-thinking the importance of collisional energy loss both for heavy as well as light quarks.

In this work we calculate the photon yield from jet-plasma interaction using exact expression for photon rate. We also include the jet energy loss in the jet-plasma interaction. In view of the controversy over the relative importance between $2 \rightarrow 2$ and $2 \rightarrow 3$ processes we restrict ourselves to the collisional energy loss only. In the photon production rate (from jet-plasma interaction) one of the collision partners is in equilibrium and the other (the jet) is assumed to execute Brownian motion in the heat bath consisting of quarks (anti-quarks) and gluons. Furthermore, the collisional energy loss is dominated by small angle scattering. Under 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 and diffusion coefficients.

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II. THEORY

The lowest order processes for photon emission from QGP are the Compton \((q\bar{q}) g \rightarrow q(\bar{q})\gamma\) and annihilation \((q\bar{q} \rightarrow g\gamma)\) processes. The total cross-section diverges since the differential cross-section suffers singularity at \(t\) and/or \(u = 0\). These singularities have to be shielded by thermal effects in order to obtain infrared safe calculations. It has been argued in Ref. \[7\] that the intermediate quark acquires a thermal mass in the medium, whereas the hard thermal loop (HTL) approach of Ref. \[8\] shows that very soft modes are suppressed in a medium leading to a natural cut-off \(k_c \sim gT\).

We, from the very beginning, assume the singularities can be shielded by the introduction of thermal masses for the participating partons. The differential cross-sections for Compton and annihilation processes are taken from Ref. \[9\]. The static photon rate in \(1 + 2 \rightarrow 3 + \gamma\) can be written as \[1\]

\[
\frac{dN}{d^4xd^2p_Tdy} = \frac{N_f}{16(2\pi)^7E_\gamma} \int ds dt |\mathcal{M}|^2 \int dE_1dE_2 \frac{f_1(E_1)f_2(E_2)(1 + f_s(E_3))}{\sqrt{aE_1^2 + 2bE_2 + c}}
\]

where

\[
a = -(s + t - m_2^2 - m_3^2)^2
\]
\[
b = E_1(s + t - m_2^2 - m_3^2)(m_2^2 - t) + E_2(s + t - m_2^2 - m_3^2)
\times (s - m_1^2 - m_2^2) - 2m_1^2(m_2 - t)
\]
\[
c = E_1^2(m_2^2 - t)^2 - 2E_1E_2m_2^2(s + t - m_2^2 - m_3^2)
\times (m_2^2 - t)(s - m_1^2 - m_2^2) - E_2^2[(s - m_1^2 - m_2^2)^2 - 4m_1^2m_2^2]
\times (s + t - m_2^2 - m_3^2)(m_2^2 - t)(s - m_1^2 - m_2^2)
\]
\[
+ m_2^2(s + t - m_2^2 - m_3^2)^2 + m_1^2(m_2^2 - t)^2
\]
\[
E_{1,\text{min}} = \frac{s + t - m_2^2 - m_3^2}{4E} + \frac{E_{m_1}^2}{s + t - m_2^2 - m_3^2}
\]
\[
E_{2,\text{min}} = \frac{E_{m_2}^2}{m_2^2 - t} + \frac{m_2^2 - t}{4E}
\]
\[
E_{2,\text{max}} = \frac{b}{a} + \frac{\sqrt{b^2 - ac}}{a}
\]
\[
E_3 = E_1 + E_2 - E_\gamma
\]

\(f_1(E_1), f_2(E_2)\) and \(f_3(E_3)\) are the distribution functions of parton respectively. \(\mathcal{M}\) represents the amplitude for compton or annihilation process. \(N_f\) is the overall degeneracy factor. For compton process \(N_f = 320/3\) and for annihilation process \(N_f = 20\) when summing over u and d quarks.

As mentioned in the earlier the jet phase space distribution can be obtained by solving FP equation which reads as,

\[
\left(\frac{\partial}{\partial t} - \frac{p_\parallel}{t} \frac{\partial}{\partial p_\parallel}\right)f(p,t) = \frac{\partial}{\partial p_i}[\eta f(p,t)] + \frac{1}{2} \frac{\partial^2}{\partial p_\parallel^2}[B_|| f(p,t)] + \frac{1}{2} \frac{\partial^2}{\partial p_\perp^2}[B_\perp f(p,t)]
\]

where the second term on the left hand side arises due to expansion \[10\]. In Eqn. \[2\] \(f(p,t)\) represents the non-equilibrium distribution of the partons under study, \(\eta = (1/E)dE/dx\) denotes drag coefficient, \(B_\parallel = d((\Delta p_\parallel)^2)/dt\), \(B_\perp = d((\Delta p_\perp)^2)/dt\), represent diffusion constants along parallel and perpendicular directions of the propagating partons.

The transport coefficients, \(\eta\), \(B_\parallel\) and \(B_\perp\) appeared in Eqn.\(\[2\]\) can be calculated from the following expressions:

\[
\frac{dE}{dx} = \frac{\nu}{(2\pi)^5} \int d^3kd^3qd\omega \frac{\delta(\omega - p_\cdot q)(\omega - q_\cdot q)(\mathcal{M})^2}{\sqrt{1 + f(|k|)}}[1 + f(|k + q|)]\omega
\]

\[
B_\perp = \frac{\nu}{(2\pi)^5} \int d^3kd^3qd\omega \frac{\delta(\omega - p_\cdot q)(\omega - q_\cdot q)(\mathcal{M})^2}{\sqrt{1 + f(|k|)}}[1 + f(|k + q|)]q^2_\perp
\]
\[
\equiv 2D_\perp.
\]

\[3\]

\[4\]
in the small angle limit \[4, 5\]. Here \(f(|\mathbf{k}|, t)\) denotes the thermal distributions for the quarks (Fermi-Dirac) or gluons (Bose-Einstein). The matrix elements required to calculate the transports coefficients include diagrams involving exchange of massless gluons which render \(dE/dx\) and \(B_{\parallel, \perp}\) infrared divergent. Such divergences can naturally be cured by using the hard thermal loop (HTL) \[8\] corrected propagator for the gluons, i.e. the divergence is shielded by plasma effects.

For jet with energy \(E >> T\) (see \[4\] for details) the energy loss is given by

\[
\frac{dE}{dx} \sim \alpha_s^2 T^2 C_R \ln \frac{E}{g^2 T} \tag{5}
\]

Having known the drag and diffusion, we solve the FP equation using Green’s function techniques with the initial condition

\[
\mathcal{P}(\mathbf{p}, t | p_0, t_i) = \delta^{(3)}(\mathbf{p} - \mathbf{p}_0) \tag{6}
\]

in Bjorken expansion scenario \[11\] along the line of Refs. \[12, 13\].

The solution with an arbitrary initial momentum distribution can now be written as \[12, 13\],

\[
\frac{dN}{d^3p_0} \big|_{y_0=0} = \frac{N_0}{(1 + \frac{p_T}{\beta} Y^\alpha)} \tag{8}
\]

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. \[12\] for details)

\[
f_{\text{jet}}(\mathbf{r}, \mathbf{p}, t')_{|y=0} = \frac{(2\pi)^3 \mathcal{P}(\mathbf{w}_r)}{g q \sqrt{t_i^2 - z_0^2}} \frac{1}{p_T} \int dN \frac{d^2p_{0T}'}{d\eta} (p, t') \delta(z_0) \tag{9}
\]

where \(t_i\) is the jet formation time. \(z_0\) is the jet formation position in the direction of QGP expansion and \(\mathcal{P}(\mathbf{w}_r)\) is the initial jet production probability distribution at the initial radial position \(\mathbf{w}_r\) in the plane \(z_0 = 0\). We assume the plasma expands only longitudinally. Thus using \(d^4x = r dr dt d\eta\) we obtain the transverse momentum distribution as follows:

\[
\frac{dN_T}{d^2p_T dy} = \int d^4x \frac{dN}{d^4xd^2p_T dy} = \frac{(2\pi)^3}{g q} \int_{t_i}^{t_c} dt' d' R \int d\phi \mathcal{P}(\mathbf{w}_r) \times \frac{N}{16(2\pi)^2 E_R} \int d\phi |\mathcal{M}|^2 \\
	imes \int dE_1 dE_2 f_g(E_1, r, t') f_g(E_2) (1 + f_g(E_3)) \frac{a E_2^2 + 2 b E_2 + c}{2 E_2}
\]

\(\phi\) dependence occurs only in \(\mathcal{P}(\mathbf{w}_r)\). So the \(\phi\) integration can be done analytically as in Ref. \[12\].

The temperature profile is taken from Ref. \[12\].

### III. RESULTS

We plot the transverse momentum distribution of quarks in Fig.1 for different times. It is seen that as the time increases the quark stays longer in the medium losing more energy. As a result there is depletion in the distribution. In Fig.2 we show \(p_T\) distribution of photons from various processes which contribute at this high \(p_T\) range. The red (blue) curve denotes the photon yield from jet-plasma interaction with (without) energy loss. The magenta represents the total yield compared with the Phenix measurements of photon data \[15\]. It is observed that due to the
inclusion of energy loss in the jet-plasma interaction the yield is depleted. The total photon yield consists of jet-photon, photons from initial hard collisions, bremsstrahlung photons, and thermal photons. It is seen that Phenix photon data is well reproduced in our model. At high $p_T$ region the data is marginally reproduced. The reason behind this is the following. For high $p_T$ photon the incoming jet must have high energy where the radiative loss starts to dominate. Inclusion of this mechanism will further deplete the photon yield at high $p_T$ reducing the total yield.

IV. SUMMARY

We have calculated the transverse momentum distribution of photons from jet plasma interaction in a collisional energy loss scenario. Our results for jet-plasma interaction is similar to what is obtained in Ref. [2] and [16]. Phenix photon data have been contrasted with the present calculation and it is seen that the data is reproduced quite well. We did not include the radiative energy loss in our calculation as we think that in the measured domain at RHIC collisional energy loss plays a vital role.

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