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Jet-photon conversion with energy loss in heavy ion collisions*

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Abstract The rate of high energy photons produced from energetic jets during their propagation through the QGP at RHIC and LHC is studied by taking into account the contribution of jet quenching in the medium. It is shown that the jet quenching effect reduces the rate of jet-photon conversion at large transverse momemtum by about 40% at RHIC with $\sqrt{s}=200$ AGeV, and by about 80% at LHC with $\sqrt{s}=5500$ AGeV.

Key words relativistic heavy ion collisions, quark gluon matter, jet-photon conversion, energy loss

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1 Introduction

In ultra-relativistic heavy-ion collisions it is expected that the confined quarks and gluons may be liberated from hadrons and form a new kind of matter (quark-gluon plasma (QGP)) due to the large amount of energy involved and deposited in a small region of space in a very short amount of time. So far, many signatures have been proposed to probe the formation and the properties of QGP. Among them is the production of high energy photons, which has long been considered a clean probe for its special characteristics. The high energy photon may travel a long distance in the nuclear medium since it interacts with the hot and dense medium only through the electromagnetic interaction, which is much weaker compared to the strong interaction between quarks and gluons. Therefore the photon may pass through the medium without rescattering and carry the information of the hot and dense medium. The process is worth investigating in detail, because the photon production rate and the photon momentum distribution depend on the momentum distributions of quarks (anti-quarks) and gluons in the plasma[1—5].

Usually high energy photons or hard photons come from two sources: prompt photons from the initial hard scattering, and fragmentation photons produced by jet fragmentation[6, 7]. Recently in Ref. [8] it was demonstrated that a new source of high energy photon production, jet-photon conversion, should be taken into account. In this process energetic partons travel through the plasma and can produce hard photons via interaction with the hot medium. Later it was pointed out[9, 10] that the original work neglected the effect of jet quenching, that is, a fast parton may lose a large amount of energy when passing through the QGP due to multiple scattering in the hot and dense medium[11], and the contribution of jet-photon conversion to the hard photons should be reduced. A similar conversion mechanism between quark jets and gluon jets has also been found to be important for explaining the p/π ratios observed at RHIC[12].

In this paper we will study the effect of jet quenching on the jet-photon conversion processes by using the parametrization of the parton energy loss by the detailed balance effect obtained in Ref. [13]. This method has been applied to study single hadron production and di-hadron production in heavy-ion colli-

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sions and gave a successful description of the experimental data[14, 15]. With numerical calculations we demonstrate that the rate of jet-photon conversion decreases by about 40% at RHIC and by about 80% at LHC for p_T larger than 8 GeV.

2 Jet-photon conversion: the leading order formulae

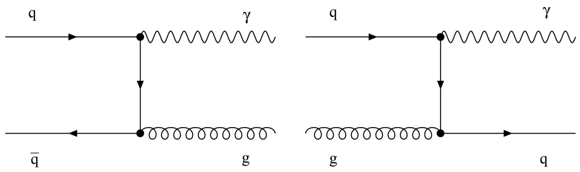

Fig. 1. The Feynman diagram corresponding to annihilation and Compton scattering for photon production in the leading order.

In a hot and dense nuclear medium, the energetic quark jets may produce high energetic photons by interacting with the partons in the hot medium via annihilation processes or Compton processes as shown in Fig. 1. Following the approximation adopted in Refs. [5, 8] and observing that the total cross sections of the annihilation processes or Compton processes are dominated by u-channel or t-channel scattering, we obtain:

$$E_\gamma \frac{d\sigma^{(a)}}{d^3p_\gamma} \approx \sigma^{(a)}(s)\frac{1}{2}E_\gamma[\delta(\boldsymbol{p}_\gamma-\boldsymbol{p}_q)+\delta(\boldsymbol{p}_\gamma-\boldsymbol{p}_{\bar q})], \quad (1)$$

$$E_\gamma \frac{d\sigma^{(C)}}{d^3p_\gamma} \approx \sigma^{(C)}(s)E_\gamma\delta(\boldsymbol{p}_\gamma-\boldsymbol{p}_q). \quad (2)$$

Here $\sigma^{(a)}(s)$ and $\sigma^{(C)}(s)$ are the corresponding total cross sections of annihilation and Compton scattering. Now we consider a process in which an energetic jet travels through a hot medium and interacts with a thermal parton in the medium. A photon can be created during the jet traveling through this medium and the energy of the emitted photon will carry information on the initial energy of the converted quark. Using Eqs. (1), (2), we get the photon production rate of annihilation and Compton scattering:

$$E_\gamma \frac{dN^{(a)}}{d^4x d^3p_\gamma} = \frac{16E_\gamma}{(2\pi)^6}\sum_{q=1}^{N_f} f_q(\boldsymbol{p}_\gamma)\int d^3p f_{\bar q}(\boldsymbol{p})\times [1+f_g(\boldsymbol{p})]\sigma^{(a)}(s)\frac{\sqrt{s(s-4m^2)}}{2E_\gamma E}, \quad (3)$$

$$E_\gamma \frac{dN^{(C)}}{d^4x d^3p_\gamma} = \frac{32E_\gamma}{(2\pi)^6}\sum_{q=1}^{N_f} f_q(\boldsymbol{p}_\gamma)\int d^3p f_g(\boldsymbol{p})\times [1-f_q(\boldsymbol{p})]\sigma^{(C)}(s)\frac{(s-m^2)}{2EE_\gamma}. \quad (4)$$

Here the f_i are the phase-space distribution functions for the quark, antiquark and gluon. In Ref. [8] it was suggested that the distribution functions can be approximated by a sum of two parts $(f(\boldsymbol{p})=f_{th}(\boldsymbol{p})+f_{jet}(\boldsymbol{p}))$, a thermal part f_{th} defined by $1/(e^{E/T}\pm1)$ and a hard part f_{jet} given by the following relation as a Bjorken correlation[16]:

$$f_{jet}(\boldsymbol{r},\boldsymbol{p},\tau)=\frac{(2\pi)^3}{g_q\tau p_\perp}\frac{dN_{jet}}{d^2p_\perp dy}\frac{2}{\pi R_\perp^2}\left(1-\frac{r_\perp^2}{R_\perp^2}\right)\times \delta(\eta-y)\theta(R_\perp-r_\perp)\theta(\tau-\tau_i)\theta(\tau_{max}-\tau), \quad (5)$$

where $g_q=2\times3$ is the spin and color degeneracy of the quarks, η is the space-time rapidity, $\tau_i\sim\frac{1}{p_\perp}$ is the formation time of the jet, τ_{max} is the smaller of the two values τ_f and τ_d. $\tau_d=(-r\cos\phi+\sqrt{R_\perp^2-r^2\sin^2\phi})/c$ is the time needed by the jet to travel from the position of its production $\boldsymbol{r}$ to the surface of the QGP near the velocity of light and $R_\perp=1.2A^{1/3}$ is the radius of the system for a head-on collision. The momentum distributions of the quarks and antiquarks $dN_{jet}/d^2p_\perp dy$ at $y=0$ for Au+Au at $\sqrt{s_{NN}}=200$ AGeV (RHIC) and for Pb+Pb at $\sqrt{s_{NN}}=5500$ AGeV (LHC) can be parameterized as[8]

$$\left.\frac{dN_{jet}}{d^2p_\perp dy}\right|_{y=0}=K\frac{a}{(1+p_\perp/b)^c}, \quad (6)$$

with different parameters a, b and c for the different partons. The values of the parameters a, b and c in Eq. (6) are listed in Table 1. The numbers of the quarks and antiquarks are the mean values of the three lightest flavors: q=(u+d+s)/3, q̄=(ū+d̄+s̄)/3. $K=2.5$ is a correction factor to take into account the Next To Leading Order (NLO) effects. The validity range of the parametrization with $p_\perp$ is given by 2 GeV$<p_\perp<$20 GeV.

Table 1. Parameters for the minijet distribution $dN_{jet}/d^2p_\perp dy$ of Eq. (6)[8].

		$a/(1/\mathrm{GeV}^2)$	b/GeV	c
RHIC	q	5.0×10^2	1.6	7.9
	q̄	1.3×10^2	1.9	8.9
LHC	q	1.4×10^4	0.61	5.3
	q̄	1.4×10^5	0.32	5.2

Following Wong[5] closely, we perform the integrals in Eqs. (3), (4) and get the results for annihilation and Compton scattering. The resulting expression has an identical form but with different constant terms C_a and C_C, respectively. The result is given by:

$$E_\gamma \frac{\mathrm{d}N^{(a)}}{\mathrm{d}^4x\mathrm{d}^3p_\gamma} = E_\gamma \frac{\mathrm{d}N^{(C)}}{\mathrm{d}^4x\mathrm{d}^3p_\gamma} = \frac{\alpha\alpha_\mathrm{s}}{8\pi^2}\sum_{f=1}^{N_\mathrm{f}}\left(\frac{e_{\mathrm{q_f}}}{e}\right)^2 \times$$
$$[f_\mathrm{q}(p_\gamma)+f_{\bar{\mathrm{q}}}(p_\gamma)]T^2\left[\ln\left\{\frac{4E_\gamma T}{m^2}\right\}+C_\mathrm{a}(C_\mathrm{C})\right], \quad (7)$$

where $C_\mathrm{a}=-1.916$ and $C_\mathrm{C}=-0.416$, T is the temperature of the fireball, m^2 is the thermal quark mass given by $2m_\mathrm{th}^2=4\pi\alpha_\mathrm{s}T^2/3$[17, 18].

Assuming a 1-d Bjorken expansion, we get the production rate of photons from the jet-medium interaction for midrapidities as $(y=0)$:

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}^2p_\perp\mathrm{d}y} = \int\tau\mathrm{d}\tau\int r\mathrm{d}r\int\mathrm{d}\phi\int\mathrm{d}\eta\frac{\alpha\alpha_\mathrm{s}}{8\pi^2}\sum_{f=1}^{N_\mathrm{f}}\left(\frac{e_{\mathrm{q_f}}}{e}\right)^2[f_\mathrm{q}(p_\gamma)+$$
$$f_{\bar{\mathrm{q}}}(p_\gamma)]T^2(r,\tau)\left[2\ln\left\{\frac{4E_\gamma T}{m^2}\right\}+C_\mathrm{a}+C_\mathrm{C}\right], \quad (8)$$

where $T(r,\tau)=T_0(\tau_0/\tau)^{1/3}[2(1-r_\perp^2/R_\perp^2)]^{1/4}$ is the temperature. For a quark-gluon plasma with u and d quarks, $N_\mathrm{f}=2$ and we have $\sum_{f=1}^{N_\mathrm{f}}(e_{\mathrm{q_f}}/e)^2=5/9$ and if we consider a plasma with u, d and s, the three lightest quark flavors, $\sum_{f=1}^{N_\mathrm{f}}(e_{\mathrm{q_f}}/e)^2=2/3$. In this work we are interested in the produced photons from QGP matter through the jet-medium interactions. We assume that a thermally and chemically equilibrated plasma has been created in the collision at time τ_0 and temperature T_0. Assuming an isentropic expansion[3, 19], we get the following relation:

$$\frac{2\pi^4}{45\xi(3)}\frac{1}{\pi R_\perp^2}\frac{\mathrm{d}N}{\mathrm{d}y}=4aT_0^3\tau_0 , \quad (9)$$

where $\mathrm{d}N/\mathrm{d}y$ is the particle rapidity density in the collision and $a=42.25\pi^2/90$ for a plasma of massless u, d and s quarks as well as gluons. A rapid thermalization limited by $\tau_0\sim 1/3T_0$ is assumed. The particle rapidity density ($\mathrm{d}N/\mathrm{d}y$) is listed in Table 2.

Table 2. Initial condition for the hydrodynamical expansion estimated from multiplicity densities using the Bjorken formula[20].

energies	τ_0/(fm/c)	T_0/GeV	T_c/GeV	$\mathrm{d}N/\mathrm{d}y$[21, 22]
RHIC	0.26	0.370	0.16	1260
LHC	0.13	0.750	0.16	5625

Assuming a Bjorken cooling, $T^3\tau$ is constant, and τ_f is given by

$$\tau_\mathrm{f}=\left[\frac{T_0}{T_\mathrm{c}}\right]^3\tau_0 . \quad (10)$$

Therefore, if we use the values of T_c, T_0, τ_0 given in Table 2, τ_f would be about 3.21 fm/c at RHIC energies and about 13.38 fm/c at LHC energies, respectively. We note here that the transverse flow of the fireball is neglected; including it may give a smaller τ_f at LHC[23].

3 Jet-photon conversion with energy loss

In the previous section we ignored the energy loss of the jet during its propagation through the hot and dense medium. Only then can the phase-space distribution function be written as in Eq. (5). Using Eqs. (5), (8) gives us the high energy photon emission rate without the inclusion of this energy loss.

If the jet passes through a hot and dense medium, its energy E will be reduced by an amount ΔE and the phase-space distribution function should be changed accordingly into[24]:

$$f_\mathrm{jet}(\vec{r},\vec{p},\tau)\longrightarrow f_\mathrm{jet}(\vec{r},\vec{p}+\Delta E,\tau) . \quad (11)$$

It should be emphasized that the jet energy loss ΔE depends on the traveled distance of the jet. According to Ref. [25], the total parton energy loss in a finite and expanding 1d medium can be written as a path integral.

$$\Delta E(\tau,b,\vec{r},\phi)\approx\left\langle\frac{\mathrm{d}E}{\mathrm{d}L}\right\rangle_{1\mathrm{d}}\int_{\tau_0}^{\tau}\mathrm{d}\tau'\frac{\tau'-\tau_0}{\tau_0\rho_0}\rho_\mathrm{g}(\tau',b,\vec{r}+\vec{n}\tau), \quad (12)$$

where the upper limit τ is the proper time as in Eq. (8), ρ_0 is the averaged initial gluon density at τ_0 in a central collision, $\rho_\mathrm{g}(\tau',b,\vec{r})=\frac{\tau_0\rho_0}{\tau'}\frac{\pi R^2}{2A}[t(\vec{r})+t(|b-\vec{r}|)]$ is the gluon density, $t(\vec{r})=\frac{3A}{2\pi R^2}\sqrt{1-r^2/R^2}$ is the nuclear thickness function and we set $b=0$ in the calculations. $\langle\mathrm{d}E/\mathrm{d}L\rangle_{1\mathrm{d}}$ is the average parton energy loss over a distance L in a 1d expanding medium with an initial uniform gluon density ρ_0. Here, we use an effective quark energy loss

$$\left\langle\frac{\mathrm{d}E}{\mathrm{d}L}\right\rangle_{1\mathrm{d}}=\epsilon_0(E/\mu_0-1.6)^{1.2}/(7.5+E/\mu_0). \quad (13)$$

The parameter ϵ_0 is proportional to ρ_0; we have chosen $\epsilon_0=1.6$ GeV/fm for the RHIC, $\epsilon_0=4.8$ GeV/fm for the LHC[15] and $\mu_0=1.5$ GeV. The Eqs. (5), (8), (11—13) now give us the rate of high energy photon emission from jet-medium interactions with the jet energy loss ΔE taken into account.

In Fig. 2 we show our theoretical predictions of the direct production of photons by jets in the plasma for Au-Au at RHIC and Pb-Pb at LHC. The solid lines denote the results with the jet energy loss included, while the dashed lines stand for the results without the inclusion of the jet energy loss. From Fig. 2 we can see that the high energy photon production rate is highly sensitive to the jet energy loss. For example, the photon production rate at 3 GeV is suppressed by a factor 1.1 at RHIC, whereas at 20 GeV it is suppressed by a factor 1.6. At LHC we find a large suppression due to a much longer evolution time of the fireball.

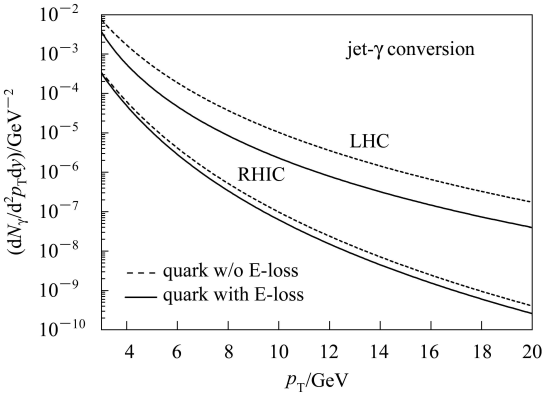

Fig. 2. Direct production of photons by jets in the plasma for Au-Au (RHIC) and Pb-Pb (LHC). Sold line: with jet energy loss; dash line: without jet energy loss.

To demonstrate more clearly the relative contribution of the jet quenching of jet-photon conversion at RHIC and LHC we have plotted the ratios of the conversion rates with energy loss to that without energy loss as a function of p_T in Fig. 3. It is shown that the jet quenching effect reduces the jet-photon conversion rate by about 40% at RHIC energies and by about 80% at LHC energies. This demonstrates that jet quenching has a significant impact on the jet-photon conversion and should never be neglected in any realistic calculation.

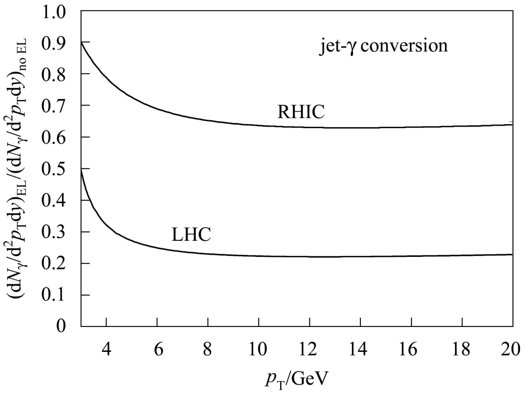

Fig. 3. Ratios of the jet-photon conversion rates with energy loss (EL) and without energy loss (No EL) at RHIC and LHC.

4 Summary

When an energetic jet propagates in the hot and dense nuclear medium, it may interact with the thermal parton and be converted into a high energy photon, which provides another important source of direct photon production in heavy-ion collisions. In this paper we studied this kind of jet-photon conversion process in heavy ion collisions including the jet quenching effect. Numerical calculations for central Au-Au collisions at RHIC energy of $\sqrt{s} = 200$ AGeV, and for Pb-Pb collisions at LHC energy of $\sqrt{s} = 5500$ AGeV show that jet quenching significantly suppresses the jet-photon conversion at high p_T: the rate of jet-photon conversion at $p_T > 8$ GeV is reduced by 40% in central Au-Au collisions at RHIC, and by about 80% in Pb-Pb collisions at LHC, though this effect is moderate at small and intermediate p_T.

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