Photons from anisotropic Quark-Gluon-Plasma

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ABSTRACT

We calculate medium photons due to Compton and annihilation processes in an anisotropic media. The effects of time-dependent momentum-space anisotropy of Quark-Gluon-Plasma (QGP) on the medium photon production are discussed. Such an anisotropy can results from the initial rapid longitudinal expansion of the matter, created in relativistic heavy ion collisions. A phenomenological model for the time-dependence of the parton hard momentum scale, $p_{\text{hard}}(\tau)$, and anisotropy parameter, $\xi(\tau)$, has been used to describe the plasma space-time evolution. We find significant dependency of photon yield on the isotropization time ($\tau_{\text{iso}}$). It is shown that the introduction of early time momentum-space anisotropy can enhance the photon production by a factor of 10 (1.5) (in the central rapidity region) for free streaming (collisionally-broadened) interpolating model if we assume fixed initial condition. On the other hand, enforcing the fixed final multiplicity significantly reduces the enhancement of medium photon production.

1 Introduction

One of the goals for the ongoing relativistic heavy ion collision experiments at the Relativistic Heavy Ion Collider (RHIC) and the upcoming experiments at CERN Large Hadron Collider (LHC) is to produce and study the properties of QGP. According to the prediction of lattice quantum chromodynamics, QGP is expected to be formed when the temperature of nuclear matter is raised above its critical value, $T_c \approx 170$ MeV, or equivalently the energy density of nuclear matter is raised above 1 GeV/fm$^3$ [1]. The possibility of QGP formation at RHIC experiment, with 5 GeV/fm$^3$ initial density of the created system, is supported by the observation of high $p_T$ hadron suppression (jet-quenching) in the central Au-Au collisions compared to the binary-scaled hadron-hadron collisions [2]. Apart from jet-quenching, several possible probes have been studied in order to characterize the properties of QGP.

However, many properties of QGP are still poorly understood. The most debated question is whether the matter formed in the relativistic heavy ion collisions is in thermal equilibrium or not. The measurement of elliptic flow parameter and its theoretical explanation suggest that the matter quickly comes into thermal equilibrium (with $\tau_{\text{therm}} < 1$ fm/c, where $\tau_{\text{therm}}$ is the time of thermalization) [3]. On the contrary, perturbative estimation suggests

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the slower thermalization of QGP [4]. However, recent hydrodynamical studies [5] have shown that due to the poor knowledge of the initial conditions there is a sizable amount of uncertainty in the estimate of thermalization or isotropization time. It is suggested that (momentum) anisotropy driven plasma instabilities may speed up the process of isotropization [6], in that case one is allowed to use hydrodynamics for the evolution of the matter. However, instability-driven isotropization is not yet proved at RHIC and LHC energies.

In view of the absence of a theoretical proof behind the rapid thermalization and the uncertainties in the hydrodynamical fits of experimental data, it is very hard to assume hydrodynamical behavior of the system from the very beginning. Therefore, one is forced to find out some observables which are sensitive to the early time after the collision. Electromagnetic probes have long been considered as the most effective one to characterize the initial stages of heavy ion collisions. Photons can be one of such observables. Since photons interact only electromagnetically with the plasma, they remains relatively less affected by the later stages of the plasma evolution. Therefore, photons can carry information about the plasma initial conditions [7, 8, 9] only if the observed flow effects from the late stages of the collisions can be understood and modeled properly. The observation of pronounced transverse flow in the photon transverse momentum distribution has been taken into account in model calculations of photon $p_T$ distribution at various beam energies [7, 8, 10, 11, 12]. It is found that because of the transverse kick the low energy photons populate the intermediate regime and consequently, the contribution from hadronic matter becomes comparable with that from the hadronic matter destroying the window where the contribution from QGP was supposed to dominate [12]. Apart from transverse flow effects, the investigation of longitudinal evolution using HBT correlation measurements has been done in Ref. [13]. It is shown that the decrease of $R_{side}$ with $p_T$ ($> 2.5$ GeV) provides a good indication whether transverse flow is significant or not. However, so far as the pre-equilibrium emission is concerned this effect is not important. Moreover, the elliptical flow ($v_2^\gamma$) of photons has recently been calculated in Refs. [14, 15] where it is shown that $v_2^\gamma$ has a rich structure which reflect the interplay between different emission processes. It is argued that the total photon elliptical flow is small at high $p_T$ implying small elliptical flow during the early stages of the collisions.

For the above mentioned reason photon production from relativistic heavy ion collisions assuming isotropic QGP has been extensively studied [16, 17]. In all these works it is assumed that the plasma thermalizes rapidly with $\tau_{th} = \tau_i$ where $\tau_i$ is the time scale of parton formation. In spite of equating thermalization time to the parton formation time, in this work we will introduce an intermediate time scale (isotropization time, $\tau_{iso}$) to study the effects of early time momentum-space anisotropy on the medium photon production. The parton formation time $\tau_i$ can be estimated from the nuclear saturation scale, i. e. $\tau_i \sim Q_s^{-1}$ [18], where $Q_s \sim 1.5 (2)$ GeV for RHIC (LHC). Recently, it has been shown in Ref. [19] that for fixed initial conditions, the introduction of a pre-equilibrium momentum-space anisotropy enhances high energy dileptons by an order of magnitude. To include the time dependent momentum-space anisotropy, we will use the phenomenological model of Ref. [19, 20]. This model assumes two time scales: the parton formation time, $\tau_i$, and the isotropization time, $\tau_{iso}$, which is the time when the system becomes isotropic in momentum space. Immediately after the formation of QGP the system can be assumed to be isotropic [21]. Subsequent rapid expansion of the matter along the beam direction causes faster cooling in the longitudinal direction than in the transverse direction [4]. As a result, the system becomes anisotropic
with $\langle p_L^2 \rangle < \langle p_T^2 \rangle$ in the local rest frame. At some later time when the effect of parton interaction rate overcomes the plasma expansion rate, the system returns to the isotropic state again and remains isotropic for the rest of the period.

The plan of the paper is the following. We will discuss the medium photon production rate and the space-time evolution of anisotropic QGP in the next section. Section 3 is devoted to describe the results for various evolution scenarios. We summarize in section 4.

### 2 Formalism

#### 2.1 Photon rate

The lowest order processes for photon emission from QGP are the Compton ($q(\bar{q}) g \rightarrow q(\bar{q}) \gamma$) and the annihilation ($q \bar{q} \rightarrow g \gamma$) processes. The total cross-section (for both the processes) diverges in the limit $t/u \rightarrow 0$. These singularities have to be shielded by thermal effects in order to obtain infrared safe calculations. It has been argued in Ref. [22] that the intermediate quark acquires a thermal mass in the medium, whereas the hard thermal loop (HTL) approach of Ref. [23] shows that very soft modes are suppressed in a medium providing the natural cut-off $k_c \sim \sqrt{g} T$.

The rate of photon production ($EdN/d^4xd^3p$) from anisotropic plasma due to Compton and annihilation processes has been calculated in Ref. [24]. The soft contribution is calculated by evaluating the photon polarization tensor for an oblate momentum-space anisotropy of the system where the cut-off scale is fixed at $k_c \sim \sqrt{g} p_{\text{hard}}$. Here $p_{\text{hard}}$ is a hard-momentum scale that appears in the distribution functions.

In this work we assume that the infrared singularities can be shielded by the introduction
Photon rate as a function of photon propagation angle ($\theta$) for two different values of anisotropy parameter $\xi$ with $\alpha_s = 0.3$ and $p_{\text{hard}} = 0.446$ GeV for $E = 2$ GeV.

of the thermal masses for the participating partons. This is a good approximation at times short compared to the time scale when plasma instabilities start to play an important role. We shall see that as long as the static rate is concerned our results are similar to that of Ref. [24]. The differential photon production rate for $1+2 \rightarrow 3+\gamma$ processes in an anisotropic medium is given by [24]

$$E \frac{dN}{d^4xd^3p} = \frac{N}{2(2\pi)^3} \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} f_1(p_1, p_{\text{hard}}, \xi) f_2(p_2, p_{\text{hard}}, \xi)$$

$$\times (2\pi)^4 \delta(p_1 + p_2 - p_3 - p) |\mathcal{M}|^2 [1 \pm f_3(p_3, p_{\text{hard}}, \xi)]$$

where, $|\mathcal{M}|^2$ represent the spin averaged matrix element squared for one of those processes which contributes in the photon rate and $N$ is the degeneracy factor of the corresponding process. $\xi$ is a parameter controlling the strength of the anisotropy with $\xi > -1$. $f_1$, $f_2$ and $f_3$ are the anisotropic distribution functions of the medium partons and will be discussed in the following.

In an isotropic system particles move in all directions with equal probability. However, for an anisotropic system there will be at least one preferred direction. The anisotropic distribution function can be obtained [25] by squeezing or stretching an arbitrary isotropic distribution function along the preferred direction in momentum space,

$$f_i(k, \xi, p_{\text{hard}}) = f_i^{\text{iso}}(\sqrt{k^2 + \xi(k.n)^2}, p_{\text{hard}})$$

where $n$ is the direction of anisotropy. It is important to notice that $\xi > 0$ corresponds to a contraction of the distribution function in the direction of anisotropy and $-1 < \xi < 0$ corresponds to a stretching in the direction of anisotropy. In the context of relativistic heavy ion collisions, one can identify the direction of anisotropy with the beam axis along which the
system expands initially. The hard momentum scale $p_{\text{hard}}$ is directly related to the average momentum of the partons. In the case of an isotropic QGP, $p_{\text{hard}}$ can be identified with the plasma temperature ($T$).

2.2 Space time evolution

The previous discussion on the medium photon rate is not enough to make any phenomenological prediction for the expected medium photon yield in an anisotropic QGP as it gives the static photon rate which is also calculated in Ref. [24]. In other words, the rate is not convoluted with the evolution of the matter. To do this one needs to know the time dependence of $p_{\text{hard}}$ and $\xi$. We shall follow the work of Ref. [19] to evaluate the $p_T$ distribution of photons from the first few Fermi of the plasma evolution. Three scenarios of the space-time evolution (as described in Ref. [19]) are the following: (i) $\tau_{\text{iso}} = \tau_i$, the system evolves hydrodynamically so that $\xi = 0$ and $p_{\text{hard}}$ can be identified with the temperature ($T$) of the system (till date all the calculations have been performed in this scenario), (ii) $\tau_{\text{iso}} \rightarrow \infty$, the system never comes to equilibrium, (iii) $\tau_{\text{iso}} > \tau_i$ and $\tau_{\text{iso}}$ is finite, one should devise a time evolution model for $\xi$ and $p_{\text{hard}}$ which smoothly interpolates between pre-equilibrium anisotropy and hydrodynamics. We shall follow scenario (iii) (see Ref. [19] for details) in which case the time dependence of the anisotropy parameter $\xi$ is given by

$$\xi(\tau, \delta) = \left(\frac{\tau}{\tau_i}\right)^\delta - 1$$

where the exponent $\delta = 2 (2/3)$ corresponds to free-streaming (collisionally-broadened) pre-equilibrium momentum space anisotropy and $\delta = 0$ corresponds to thermal equilibrium. As in Ref. [19], a transition width $\gamma^{-1}$ is introduced to take into account the smooth transition...
from non-zero value of $\delta$ to $\delta = 0$ at $\tau = \tau_{iso}$. The time dependence of various quantities are, therefore, obtained in terms of a smeared step function [20]:

$$\lambda(\tau) = \frac{1}{2}(\tanh[\gamma(\tau - \tau_{iso})/\tau_i] + 1).$$  \hfill (4)

For $\tau \ll \tau_{iso}(\gg \tau_{iso})$ we have $\lambda = 0(1)$ which corresponds to free streaming (hydrodynamics). With this, the time dependence of relevant quantities are as follows [19]:

$$\xi(\tau, \delta) = \left(\frac{\tau}{\tau_i}\right)^{\delta(1-\lambda(\tau))} - 1,$$
$$p\text{hard}(\tau) = T_i \bar{U}^{1/3}(\tau),$$  \hfill (5)

where,

$$U(\tau) \equiv \left[R \left(\frac{\tau_{iso}}{\tau}\right)^{\delta} - 1\right]^{3\lambda(\tau)/4} \left(\frac{\tau_{iso}}{\tau}\right)^{1-\delta(1-\lambda(\tau))/2},$$

$$\bar{U} \equiv \frac{U(\tau)}{U(\tau_i)},$$

$$R(x) = \frac{1}{2}[1/(x + 1) + \tan^{-1}\sqrt{x}/\sqrt{x}]$$  \hfill (6)

and $T_i$ is the initial temperature of the plasma. In our calculation, we assume a fast-order phase transition beginning at the time $\tau_f$ and ending at $\tau_H = r_d \tau_f$ where $r_d = g_Q/g_H$ is the ratio of the degrees of freedom in the two (QGP phase and hadronic phase) phases and $\tau_f$ is obtained by the condition $p\text{hard}(\tau_f) = T_c$ which we take as 170 MeV. We also include the
contribution from the mixed phase. Therefore, the total medium photon yield, arising from pure QGP phase and mixed phase is given by,

\[
\frac{dN^\gamma}{dyd^2p_T} = \pi R_\perp^2 \left[ \int_{\tau_i}^{\tau_f} \tau d\tau \int d\eta \frac{dN^\gamma}{d^4xdydp_T} + \int_{\tau_i}^{\tau_f} f_{\text{QGP}}(\tau) \tau d\tau \int d\eta \frac{dN^\gamma}{d^4xdydp_T} \right],
\]

(7)

where, \(f_{\text{QGP}}(\tau) = (r_d - 1)(r_d\tau_f\tau^{-1} - 1)\), is the fraction of the QGP phase in the mixed phase [26], \(R_\perp = 1.2A^{1/3} \text{ fm}\) is the radius of the colliding nucleus in the transverse plane. The energy of the photon in the fluid rest frame is given by \(E_\gamma = p_T \cosh(y - \eta)\) where \(\eta\) and \(y\) are the space-time and photon rapidities respectively.

### 3 Result

To numerically evaluate the medium photon yield in an anisotropic QGP we must have the knowledge of space-time dependence of anisotropy parameter, \(\xi(\tau)\), and hard momentum scale, \(p_{\text{hard}}(\tau)\) as discussed earlier. To include the time dependence of \(\xi\) and \(p_{\text{hard}}\), we will use Eqs. (5) and (6) described in the previous section (see Ref. [19, 20] for details).

We will now discuss contributions to the total photon yield due to medium photon spectrum from anisotropic QGP with initial conditions that might be achieved at RHIC and LHC energies. In what follows we shall consider two interpolating models: (i) free-streaming interpolating model (\(\delta = 2\)) and (ii) collisionally-broadened interpolating model (\(\delta = 2/3\)). To cover the uncertainties in the initial conditions for a given beam energy, we consider two sets of initial conditions, one at a relatively high temperature of \(T_i = 0.446 \text{ GeV}\) and a relatively short initial time of \(\tau_i = 0.147 \text{ fm/c}\) denoted hereafter by Set-I, and another at a lower temperature \(T_i = 0.350 \text{ GeV}\) and somewhat later initial time of \(\tau_i = 0.28 \text{ fm/c}\) denoted hereafter by Set-II. The free-streaming interpolating model with fixed initial conditions (FIC) leads to entropy generation [19] and, therefore, the allowed values of \(\tau_{\text{iso}}\) in this
Figure 6: (Color online) Photon enhancement factor \((\phi_{p_T})\) as a function of photon transverse momentum \((p_T)\) for the free-streaming and collisionally-broadened interpolating models with fixed initial conditions. (a) and (b) correspond to Set-I and Set-II respectively.

case, is much more constrained. On the other hand, for collisionally-broadened interpolation model, the upper bound on \(\tau_{\text{iso}}\) is much larger due to small amount of entropy generation. The estimates of upper bounds on \(\tau_{\text{iso}}\) for both the models are listed in Ref. [19].

We also invoke the conditions of fixed final multiplicity (fixed entropy) to calculate the photon yield from the plasma. In such case, the initial hard momentum scale \((p_{\text{hard}}(\tau_i))\) will be \(\tau_{\text{iso}}\) dependent, i.e. the larger the value of \(\tau_{\text{iso}}\) smaller will be the initial hard momentum scale. Therefore, the enhancement in the yield will be less as compared to the case of fixed initial conditions. Moreover, as we shall see, for a given condition the enhancement will be lower in case of collisionally-broadened model as \(\delta\) is smaller (close to isotropic expansion).

Fig. 1 shows the medium photon production rate (static) as a function of photon energy, \(E\), for two different values of the anisotropy parameter, \(\xi\), and two different values of photon angle, \(\theta\). We have used \(\alpha_s = 0.3\) and \(p_{\text{hard}} = 0.446\) GeV. It is clear from Fig. 1 that the photon rate is more suppressed in the direction parallel to the direction of anisotropy compared to the transverse direction for an anisotropic QGP. This is due to the fact that for \(\xi > 0\), decreasing value of photon angle \((\theta)\) implies decreasing value of medium parton density and hence decreasing photon rate as can be seen from Eq. (2). This is also clear from Fig. 2, which shows the photon rate as a function of photon angle, \((\theta)\), for \(E = 2\) GeV for two different values of \(\xi\). It is observed that for a given anisotropy parameter, the value of the photon rate is larger in the transverse direction. However, the photon rate in an oblate anisotropic medium \((\xi > 0)\) is always small compared to the photon rate in an isotropic medium. This can be attributed to the fact that an oblate anisotropic distribution (Eq. 2) i.e. +ve value of \(\xi\) corresponds to the suppression of medium parton density. As a result, introduction of anisotropy (with +ve value of anisotropy parameter \((\xi)\)), in general, leads to a suppression of medium photon rate (static).
After the very short discussion of the medium photon rate in an anisotropic QGP, we will now discuss the effects of pre-equilibrium momentum space anisotropy of the QGP on the thermal photon spectrum. To illustrate the effects of pre-equilibrium momentum space anisotropy of QGP on the parton densities, in Fig. 3, we have plotted the ratio \( \frac{f_{\text{aniso}}}{f_{\text{iso}}} \) (for \(|k| = 5 \text{ GeV}\)) as a function of the angle between \(k\) (the momentum of the plasma parton) and \(\hat{n}\) (the direction of anisotropy) for different values of intermediate time with \(\tau_{\text{iso}} = 0.5 \text{ fm}\). Here \(f_{\text{aniso}}(k, p_{\text{hard}})\) is the parton distribution function for a QGP with pre-equilibrium momentum space anisotropy and \(f_{\text{iso}}(k, p_{\text{hard}})\) is the parton distribution function for a QGP without any pre-equilibrium momentum space anisotropy. The anisotropic distribution functions, in Fig. 3, are calculated in the framework of fixed initial condition free-streaming interpolation model with \(\delta = 2\). Fig. 3 clearly shows an enhancement of anisotropic distribution in the transverse direction and suppression in the longitudinal direction for \(\tau < \tau_{\text{iso}}\). The enhancement in the transverse direction is a consequence of the enhancement of the hard momentum scale, \(p_{\text{hard}}\), for \(\tau < \tau_{\text{iso}}\). However, in the longitudinal direction, the suppression due to the nonzero value of the anisotropy parameter does not stand over the enhancement due to the enhanced value of hard momentum scale.

### 3.1 Photon spectrum for fixed initial conditions with \(\delta = 2\) and \(\delta = 2/3\)

In this section we will present the medium photon spectrum assuming fixed initial condition and free streaming (collisionally-broadened) interpolating model with \(\delta = 2\) (2/3). In Fig. 4 we have presented the medium photon yield in the mid rapidity \((\theta = \pi/2)\) as a function of photon transverse momentum at for those two sets of fixed initial conditions. Fig. 4a (4b) corresponds to \(T_i = 0.446\) (0.350) GeV and \(\tau_i = 0.147\) (0.28) \text{ fm}/c. In estimating these results, we have used \(\alpha_s = 0.3\). Different lines in Fig. 4 correspond to different isotropization.
times, \( \tau_{\text{iso}} \). We observe enhancement of photon yield when \( \tau_{\text{iso}} > \tau_i \). The enhancement of photon yield in the transverse directions is due to the fact that momentum-space anisotropy enhances the density of plasma partons moving at the mid rapidity as can be seen from Fig. 3.

In Fig. 5, we have shown the predicted photon yields (at the mid rapidity) for a given beam energy (with two different sets of initial conditions) assuming the time dependence of the hard momentum scale and anisotropy parameter as given by Eq. 5 with \( \delta = \frac{2}{3} \). It is important to mention that \( \delta = \frac{2}{3} \) corresponds to collisionally-broadened interpolating model. Fig. 5 shows enhancement of photon yield as we increase the isotropization time. However, compared to the FIC free-streaming interpolating model, discussed in the previous para, here, the enhancement of the photon yield is small. This is due to the fact that in the case of collisionally-broadened interpolating model we have included the possibility of momentum space broadening of the plasma partons due to interactions. Collisionally broadened interpolating model is close to thermal equilibrium. As a result the yield is close to the equilibrium value.

To quantify the effect of isotropization time, we define photon enhancement factor \( \Phi(p_T) \) as [19]:

\[
\Phi(\tau_{\text{iso}}, \theta) = \left( \frac{dN(\tau_{\text{iso}})}{dyd^2p_T} \right)_\theta \left( \frac{dN(\tau_{\text{iso}} = \tau_i)}{dyd^2p_T} \right)_\theta,
\]

which is plotted in Fig. 6 as a function of the photon transverse momentum. Fig. 6a (6b) for \( T_i = 0.446 \text{ GeV} \) and \( \tau_i = 0.147 \text{ fm/c} \) (\( T_i = 0.350 \text{ GeV} \) and \( \tau_i = 0.28 \text{ fm/c} \)) shows that for the fixed initial condition free-streaming interpolating model, the photon yield at \( p_T = 5 \text{ GeV} \) is enhanced by a factor of 13.8 (11.5) at mid rapidity at \( \tau_{\text{iso}} = 2 \text{ fm/c} \). Fig. 6 also includes the photon enhancement factor for FIC collisionally broadened interpolating model. However, in the frame work of FIC collisionally-broadened interpolation model, enhancement of photon yield is marginal at \( \tau_{\text{iso}} = 2 \text{ fm/c} \).
3.2 Photon spectrum for fixed final multiplicity (FMM) with $\delta = 2$ and $\delta = 2/3$

In the previous section we have used the two interpolating models which assumes fixed initial conditions. However, enforcing fixed initial condition results in generation of particle number and enhance the final multiplicity. Starting with a fixed initial condition, the interpolating model (discussed in section 2.2) corresponds to a hard momentum scale (for $\tau >> \tau_{iso}$) which is larger by a factor of $[R((\tau_{iso}/\tau_{i})^{\delta} - 1)]^{0.25}$ compared to the momentum scale results from the free hydrodynamic expansion of a system (with the same initial condition) from the beginning. To ensure fixed final multiplicity in this model one has to redefine $\bar{U}(\tau)$ in Eq. 5 as in [19]:

$$\bar{U}(\tau) = \frac{U(\tau)}{U(\tau_i)} \left[ R((\tau_{iso}/\tau_{i})^{\delta} - 1) \right]^{-3/4} (\tau_i/\tau_{iso})$$

This redefinition corresponds to a lower initial hard momentum scale ($p_{hard}(\tau_i) < T_i$) for $\tau_{iso} > \tau_i$. Larger value of isotropization time corresponds to lower initial hard momentum scale.

The transverse photon yields assuming FMM and free-streaming interpolating model are presented in Fig. 7 as a function of photon transverse momentum for different values of isotropization times with the initial conditions Set I (Fig.7a) and Set II (Fig.7b). In the case of fixed initial condition (free-streaming or collisionally-broadened) interpolating model we have obtained significant enhancement of transverse photon yield due to the pre-equilibrium momentum space anisotropy of QGP. However, fixing the final multiplicity significantly reduce the effect of pre-equilibrium anisotropic phase. Moreover as a result of fixing final multiplicity we obtain a suppression of photon yield in the high $p_T$ region. One more interesting consequence of fixing final multiplicity is that larger isotropization time corresponds to suppression in the high $p_T$ region and less enhancement in the intermediate $p_T$ region.
This is due to the fact that to ensure the fixed final multiplicity in the pre-equilibrium free streaming interpolating model, one has to reduce the initial hard momentum scale or equivalently the initial energy density.

The photon yield for two sets of initial conditions, assuming collisionally-broadened ($\delta = 2/3$) pre-equilibrium phase of QGP with fixed final multiplicity is displayed in Fig. 8. It is observed that fixing final multiplicity significantly reduce the effects of collisionally-broadened pre-equilibrium phase of QGP. As discussed in the previous section, this is again due to the fact that in order to maintain fixed final multiplicity for $\tau_{\text{iso}} > \tau_i$ the initial energy density (or equivalently initial hard momentum scale) has to be reduced.

In order to see the difference between FIC and FMM we plot $\Phi_{p_T}$ with FMM condition, in Fig. 9 both for $\delta = 2$ and $\delta = 2/3$. Since the collisionally-broadened interpolating model is always closer to local-isotropic expansion, this results in less photon enhancement compared to the free-streaming pre-equilibrium phase (also see Fig. 6). For the initial condition Set-I (Set-II) we predict an enhancement of the order of $1.6$ ($1.53$) for $p_T = 5$ GeV as a result of collisionally-broadened pre-equilibrium phase with fixed final multiplicity as we vary $\tau_{\text{iso}}$ from $\tau_i$ to $2$ fm/c, whereas free-streaming pre-equilibrium phase with fixed final multiplicity corresponds to a enhancement (for $p_T = 5$ GeV) by a factor of $2.1$ ($1.13$).

### 3.3 Photon yield for fixed initial conditions with higher initial temperature

To demonstrate the effect of higher initial temperature (might be relevant for LHC energies) we proceed to calculate the photon yield with FIC for both the free streaming ($\delta = 2$) and
collisionally broadened ($\delta = 2/3$) interpolating models. The transverse momentum distribution of medium photons in central rapidity region with $T_i = 0.828$ GeV and $\tau_i = 0.1$ fm/c is displayed in Fig. 10. Here also free-streaming pre-equilibrium phase corresponds to more enhancement compared to the collisionally-broadened pre-equilibrium phase. In Fig. 11, we have plotted the photon enhancement factors (for two different values of isotropization time) as a function of photon transverse momentum both for the free-streaming and collisionally-broadened interpolating model with fixed initial condition. Fig. 11 shows an enhancement (for $p_T = 5$ GeV) of transverse photon yield by a factor of 7.3 (1.8) at $\tau_{iso} = 2$ fm/c for fixed initial condition free-streaming (collisionally-broadened) interpolating model.

It should be noted that in order to apply our calculations to explain the experimental data we should add to this the contributions from various other sources of photon productions. The model used for this purpose should properly include the effects of tranverse flow as it affects the photon spectra significantly. Applications of the present work to calculate the photon $p_T$ distribution at RHIC and LHC energies incorporating tranverse flow effects is in progress and will be reported elsewhere [27].

4 Conclusion

To summarize, we have investigated the effects of the pre-equilibrium momentum space anisotropy of the QGP on the medium photon production due to Compton and annihilation processes with various initial conditions. To describe the transition of the plasma from initial non-equilibrium state to an isotropic thermalized state, we have used two phenomenological models for the time dependence of the hard momentum scale ($p_{hard}$) and plasma anisotropy
parameter ($\xi$). The first model is based on the assumption of fixed initial condition. However, enforcing fixed initial condition causes entropy generation. Therefore, we have also considered a second model which assumes fixed final multiplicity. Both the possibilities of free streaming and collisionally broadened pre-equilibrium phase of the QGP are considered. To cover the uncertainties in the initial conditions for a given beam energy, we have used two sets of initial conditions, one at a relatively high temperature and a relatively short initial time and other at a lower temperature and somewhat later initial time.

We estimate the $p_T$ distribution of photons for different isotropization times in the framework of these phenomenological models. It is found that, for fixed initial condition, a free-streaming interpolating model can enhance the thermal photon yield by an order of magnitude at higher $p_T$. However, for collisionally broadened pre-equilibrium phase with fixed initial condition, the enhancement of photon yield is not that much. This is due to the fact that the energy density, hard momentum scale and anisotropy parameter corresponding to the collisionally broadened interpolating model are always closer to the local isotropic expansion. Since fixing the final multiplicity reduce the initial hard momentum scale or equivalently the initial energy density, the enhancement of the photon yield is significantly reduced (both for the free streaming and collisionally broadened interpolating models). Moreover, for fixed final multiplicity, we predict a suppression of thermal photon yield in the low and high transverse momentum region as has been observed in the case of dilepton invariant mass spectrum for anisotropic plasma [19].

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