

Possible non-prompt photons in pp collisions and their effects in AA analyses

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Direct photons are a powerful tool for elucidating the properties of the hot QCD matter in heavy-ion collisions. They are conventionally estimated by taking into account prompt photon contributions in proton-proton collisions and thermal and prompt photon contributions in heavy-ion collisions. However, there could also be other sources of photons such as pre-equilibrium photons. I investigate prompt, pre-equilibrium and thermal photons and their effects on the direct photon p_T spectra at the CERN Large Hadron Collider energies.

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1. Introduction

Relativistic nuclear collisions are a unique tool for investigating hot and dense QCD. One of the important discoveries at the BNL Relativistic Heavy Ion Collider (RHIC) is that the system follows hydrodynamic description in the vicinity of the crossover transition between the hadronic and the quark-gluon plasma (QGP) phases. This is supported by the fact that the observed large azimuthal momentum anisotropy, primarily characterized by the elliptic flow v_2 , is large compared with the geometrical anisotropy of the system in off-central collisions. The fluidity implies that the QCD matter is thermalized and hadronic distributions are mostly determined at thermal and chemical freeze-outs and during subsequent hadronic transport processes.

Contrarily, photons and dileptons are expected to retain information regarding the spacetime evolution of the system since they do not strongly interact with the medium after their production. Those observables, which are called electromagnetic probes, have been extensively studied to elucidate the detailed properties of the QCD matter created in nuclear collisions. A successful example is that of the measurements of direct photon particle spectra for the experimental determination of the average medium temperatures at RHIC and the Large Hadron Collider (LHC). They are shown to be larger than the crossover temperature estimated in lattice QCD, providing evidence that the produced medium is in the QGP phase [1, 2]. Here direct photons are defined as inclusive photons without decay photon contributions. The quantitative description of the photons, however, is still not completely understood. The theoretical estimations of particle spectra and elliptic flow based on hydrodynamic models are known to systematically underestimate the experimental data. The latter is known as “photon v_2 puzzle” [3].

In this study, I estimate non-prompt photon contributions in proton-proton (pp) collisions and their effect in heavy-ion (AA) analyses in order to obtain a more complete picture of direct photon production. The conventional model for photon production expects that direct photons in pp collisions are prompt photons, which are produced in hard processes in the early stage of the collisions, and assumes that thermal photons, which are soft radiation from the medium, and prompt photons are the components of direct photons in AA collisions. This picture, however, may not be complete. Recent hydrodynamic analyses hint at the existence of primordial collective dynamics in small systems [4, 5] which is under debate [6]. There is a possibility of thermal photon radiation in the highest multiplicity pp events [7]. Direct photons should be emitted in the pre-equilibrium stage of both pp and AA collisions since the color glass condensate picture implies that glasma production is likely at high energies when the saturation momentum Q_s is sufficiently large.

2. The model

I consider the contributions of thermal photons, pre-equilibrium photons [8, 9] and prompt photons as sources for direct photon production in nuclear collisions. There can be other sources of photons such as fragmentation photons which shall be discussed elsewhere.

Thermal photons are estimated using a (2+1)-dimensional hydrodynamic model. The equation of state is constructed by matching the one from lattice QCD to the one from the hadron resonance gas model at lower temperatures. The initial condition is based on the Monte-Carlo Glauber model. For demonstrative purposes, I use event-averaged initial conditions at the impact parameter $b =$

4.6 fm for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. This corresponds to the average impact parameter of the 20% most central collisions. The nucleon-nucleon inelastic cross section is $\sigma_{pp}^{\text{in}} = 65$ mb. The thermalization time is chosen as $\tau_{\text{th}} = 0.4$ fm/c.

The thermal photon emission rate is estimated by matching the QGP and the hadronic emission rates as

$$E \frac{dR^\gamma}{d^3p} = \frac{1}{2} \left(1 - \tanh \frac{T - T_c}{\Delta T} \right) E \frac{dR_{\text{had}}^\gamma}{d^3p} + \frac{1}{2} \left(1 + \tanh \frac{T - T_c}{\Delta T} \right) E \frac{dR_{\text{QGP}}^\gamma}{d^3p}, \quad (2.1)$$

where $T_c = 0.17$ GeV and $\Delta T = 0.1T_c$. The QGP rate is based on the perturbative QCD result [10] with $N_f = 3$. The QCD coupling is $\alpha_s = 0.2$. The hadronic rate is estimated by taking into account the processes in Refs. [11, 12, 13]. The thermal photon contributions from the medium before the kinetic freeze-out $T_f = 0.14$ GeV are used.

Pre-equilibrium photons are estimated based on the turbulent thermalization approach to glasma. The glasma phase is divided into three stages in the bottom-up scenario [14] as

$$(i) \quad c_0 Q_s^{-1} \ll \tau \ll c_1 Q_s^{-1} \alpha_s^{-3/2}, \quad (2.2)$$

$$(ii) \quad c_1 Q_s^{-1} \alpha_s^{-3/2} \ll \tau \ll c_2 Q_s^{-1} \alpha_s^{-5/2}, \quad (2.3)$$

$$(iii) \quad c_2 Q_s^{-1} \alpha_s^{-5/2} \ll \tau \ll c_3 Q_s^{-1} \alpha_s^{-13/5}. \quad (2.4)$$

Here Q_s is the measure of transverse momentum scale implied from the color glass condensate model mentioned earlier. Since the typical time scale of the bottom-up thermalization would be longer than the actual thermalization time implied by the hydrodynamic modeling of nuclear collisions, the auxiliary coefficients c_0 , c_1 , c_2 and c_3 are introduced to scale the processes into the pre-hydrodynamic phase $1/Q_s < \tau < \tau_{\text{th}}$. The emission rate is based on the Berges-Reygers-Tanji-Venugopalan model [8, 15]. In the stages (i) and (ii), it reads

$$E \frac{dR^\gamma}{d^3p} = \frac{20}{9\pi^2} \alpha_{\text{EM}} \alpha_s \log \left(1 + \frac{2.919}{g^2} \right) f_q(p) \int \frac{d^3p'}{(2\pi)^3} \frac{1}{p'} [f_s(p') + f_q(p')]. \quad (2.5)$$

The quark distribution is parametrized with self-similar scaling as

$$f_q = (Q_s \tau)^{-2/3} f_s(p_T, (Q_s \tau)^{1/3} p_z), \quad (2.6)$$

$$f_s(p_T, p_z) = A p_T^{-1} \exp(-p_z^2 / \sigma_z^2), \quad (2.7)$$

where f_s is exponentially cut off for $p_T > Q_s$ and normalized so that the quark number density matches the phenomenological estimation $n_q = c N_f Q_s^3 / 2\pi^2 Q_s \tau$ where $c = 1.1$. The spatial integral is performed assuming pure longitudinal boost-invariant expansion. In the stage (iii), the emission rate is much closer to the one in equilibrium [16, 17]:

$$E \frac{dR^\gamma}{d^3p} = \frac{5}{9} \frac{\alpha_{\text{EM}} \alpha_s}{2\pi^2} T_{\text{eff}}^2 \exp(-E/T) \log \left(1 + \frac{2.919}{g^2} \right), \quad (2.8)$$

where $T_{\text{eff}} = T_{\text{th}} \tau / \tau_{\text{th}}$. Here T_{th} is the temperature at the time of thermalization. The emission rate is not the same as the QGP emission rate introduced for the thermal photon estimation because only the Compton scattering and the pair-annihilation processes are considered here. Quantitative

discussions should be made carefully because the model is parametrically extended to fit into the pre-hydrodynamic timescales possibly beyond the applicability of the original theory.

Prompt photons are estimated by using the pp direct photon results scaled by the number of collisions N_{coll} [11],

$$E \frac{dR^\gamma}{d^3p} = 6745 \frac{\sqrt{s}}{(p_T)^5} \frac{N_{\text{coll}}}{\sigma_{pp}^{\text{in}}}, \quad (2.9)$$

where σ_{pp}^{in} is in units of pb for the parametrization. The actual prompt photon contributions may be estimated by subtracting non-prompt photon contributions from total direct photons in pp collisions before the scaling. It should be noted that the low-momentum direct photon spectra of pp collisions is not well-known at LHC energies. One may alternatively use perturbative QCD for the estimation of prompt photons, but should also be careful of its applicability at lower p_T .

3. Numerical results

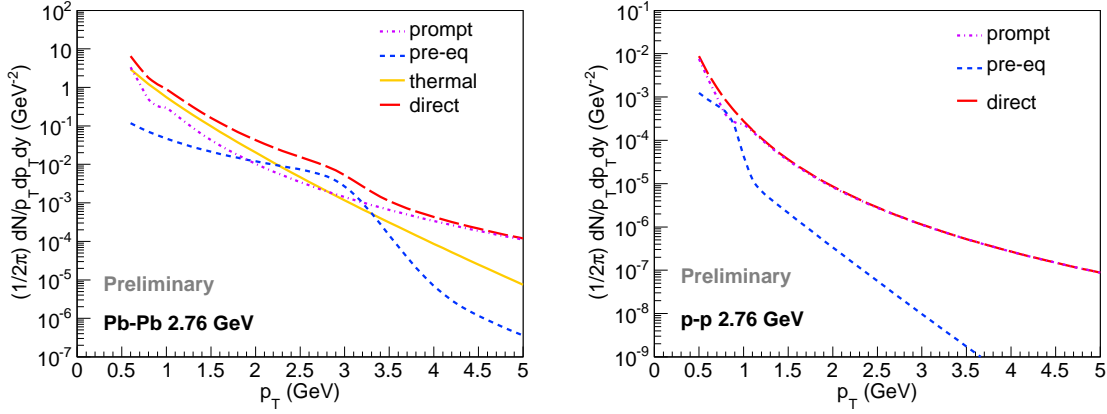


Figure 1: Direct photon transverse momentum spectra by components for (left) Pb-Pb collisions and (right) pp collisions at 2.76 TeV.

The direct photon spectra for the off-central Pb-Pb collisions at $b = 4.6$ fm at 2.76 TeV are shown in Fig. 1 (left). The pre-equilibrium photons are semi-hard reflecting the saturation momentum scale Q_s , which is set to $Q_s = 3$ GeV here. Also the characteristic momentum scale exhibits a time scale ordering from high to low momentum; high p_T regions are dominated by prompt photons, intermediate p_T regions by pre-equilibrium photons and low p_T regions by thermal photons. It should be noted that since pre-equilibrium evolution is not fully understood, the results are still quantitatively dependent on parametrization.

Figure 1 (right) shows the direct photon spectra for pp collisions. Thermal photon results are not shown here but will be discussed elsewhere since it is still controversial whether QGP can be created in proton collisions. Instead, I consider pre-equilibrium photon contributions and find that it could be comparable to the total photon yields near Q_s , which is chosen as $Q_s = 0.9$ GeV. For a given direct photon spectrum, one has to subtract the contribution of non-prompt photons before scaling it with the number of collisions. The spectrum is consequently expected to be reduced near the Q_s of pp collisions and enhanced near that of Pb-Pb collisions.

4. Summary and outlook

Direct photon productions in Pb-Pb and pp collisions are studied. Prompt, pre-equilibrium and thermal photons are considered as the contributions to direct photon production. Numerical estimations indicate that pre-equilibrium photons could provide visible semi-hard contributions to p_T spectra. It is implied that pp direct photons may not be pure prompt photons and thus the baseline for AA analyses may well be modified if experimental data of pp collisions are to be used for the scaling. Since the shape of pre-equilibrium spectra reflect the saturation momentum scale Q_s , one may probe and constrain the pre-equilibrium physics experimentally through direct photon analyses. Modification of prompt photons based on color glass condensate has been discussed recently in Ref. [18].

Future prospects include the analysis of direct photon elliptic flow v_2 to investigate how the pre-equilibrium photons affect the photon puzzle. Full pp thermal photon analyses can be used to test if the QGP is produced in pp collisions experimentally. Implementation of the chemically equilibrating QGP in hydrodynamic models may also be important for understanding pre-equilibrium and thermal photons quantitatively [19, 20].

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