PHOTON PRODUCTION IN HIGH-ENERGY HEAVY-ION COLLISIONS: THERMAL PHOTONS AND RADIATIVE RECOMBINATION*

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We present a comprehensive analysis of photon production at RHIC and the LHC, proposing radiative hadronization as an additional photon source in high-energy heavy-ion collisions. For the thermal photon, we perform relativistic viscous hydrodynamic calculation with event-by-event fluctuations.

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1. Introduction

Direct photon is considered an important probe to extract information of quark–gluon plasma (QGP) and hot hadronic matter through space-time evolution of high-energy heavy-ion collisions. Measurements of the photons in relativistic heavy-ion collisions have been performed both at RHIC and the LHC, and large yields of the transverse momentum spectra and strong elliptic flow of photons are reported. Any theoretical model so far seems to be incapable of explaining the photon data adequately. The large yield could be attributed to an early stage of the evolution with higher temperatures, while the strong collective flow prefers large photon emission at a later stage when momentum anisotropy of QGP is well developed. This situation is called the "direct photon puzzle". In this paper, we propose another source of photon production which has been overlooked and is inherent to late stages of the

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QGP time evolution: it is photon radiation at hadronization of QGP, which is, in fact, natural from the viewpoint of ordinary electromagnetic plasmas. In addition, we carry out the numerical computation of thermal photons from the relativistic viscous hydrodynamic model and prompt photons, and show a comprehensive study of direct photons at RHIC and the LHC. However, we should note that there is a reservation about the experimental results because the large yield of photons measured by PHENIX has not been confirmed by STAR. Also, the deviation between thermal photons from a relativistic hydrodynamic model and the experimental data is not so large at the LHC.

2. Photon production in high-energy heavy-ion collisions

2.1. Thermal photons from hydrodynamics

For the computation of thermal photon, we use a relativistic viscous hydrodynamic model which is composed of T$_\mathrm{R}$ENTo for initial condition, hydrodynamic expansion including shear and bulk viscosities, and final-state interactions described by the UrQMD [1]. The temperature dependence of shear and bulk viscosities is included. All the parameters of the model are tuned from rapidity distribution, p_T spectra, and elliptic flow of charged hadrons [1, 2].

Thermal photons are emitted from the QGP and the hadronic phases during hydrodynamic expansion. We combine the contributions from the QGP and the hadronic phase by smooth interpolation formula as

$$\epsilon\frac{\mathrm{d}R^\gamma_\mathrm{th}}{\mathrm{d}^3k} = \frac{1}{2}\left(1-\tanh\frac{T-T_\mathrm{c}}{\Delta T}\right)\epsilon\frac{\mathrm{d}R^\gamma_\mathrm{had}}{\mathrm{d}^3k} + \frac{1}{2}\left(1+\tanh\frac{T-T_\mathrm{c}}{\Delta T}\right)\epsilon\frac{\mathrm{d}R^\gamma_\mathrm{QGP}}{\mathrm{d}^3k}\,, \tag{1}$$

where the interpolation parameters T_c and ΔT are set to $T_\mathrm{c} = 170$ MeV and $\Delta T = 0.1T_\mathrm{c}$ [3]. We use the photon emission rate of QGP which parametrizes the result of the leading-order pQCD calculation in the strong coupling constant g_s [4], and the thermal photon emission rate in hadronic matter given in Refs. [5–7]. Integrating Eq. (1) over the whole volume element of fluid, one can obtain the thermal photon radiation yield from hydrodynamic expansion. Here, for simplicity, we continue hydrodynamic evolution until $T_\mathrm{f} = 116$ MeV which is below the switching temperature $T_\mathrm{SW} = 150$ MeV [2, 8].

2.2. Radiative hadronization

We give a brief explanation of radiative hadronization. For details, refer to Ref. [9]. In the quark recombination picture, a meson formation by radiative hadronization is written as a 2-to-2 process

$$q + \bar{q} \to M + \gamma\,. \tag{2}$$

We model this as a 2-step process, $q+\bar{q} \to M^* \to M+\gamma$, picking up a quark and anti-quark ("preformed") state M^* with the original ReCo model [10, 11], and then letting it decay into a meson M and a photon γ. We call this the radiative ReCo model. Notice that we do not consider this preformed state as any physical resonance but just as an intermediate state in radiative meson production.

The number of the photons emitted in the formation of mesons is given by the product of the number of preformed states $\mathrm{d}N_{M_*}/\mathrm{d}^3P$ and the photon distribution emitted from a preformed state $E_\gamma \mathrm{d}n_\gamma(k; M_*, P)/\mathrm{d}^3k$

$$E_\gamma \frac{\mathrm{d}N_\gamma}{\mathrm{d}^3k} = \kappa \int \mathrm{d}M_*\, \varrho(M_*) \int \mathrm{d}^3P \left(\frac{\mathrm{d}N_{M_*}}{\mathrm{d}^3P}\right) \left(E_\gamma \frac{\mathrm{d}n_\gamma(k; M_*, P)}{\mathrm{d}^3k}\right) . \quad (3)$$

Here, $\varrho(M_*)$ is an invariant mass distribution of the preformed states. In this paper, we use $\varrho(M_*) = \delta(M_* - (m_1 + m_2))$ with m_1 and m_2 being constituent quark masses. In Eq. (3), the overall factor κ is introduced for reflection of other possible effects on radiative hadronization. We will determine κ by comparison with the experimental data.

3. Numerical results

In Fig. 1, we show the p_T spectra of the photons for $b = 5.5$ fm (left panel) and $b = 9.0$ fm (right panel) in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC. The red solid lines stand for total photons which consist of the thermal photons (purple dotted lines), radiative pion production (green dashed lines), and the prompt photons (black dot-dashed lines). Our estimate of the thermal photon contribution is smaller than the PHENIX data [12, 13], which is consistent with other hydrodynamic model studies [8]. Regarding

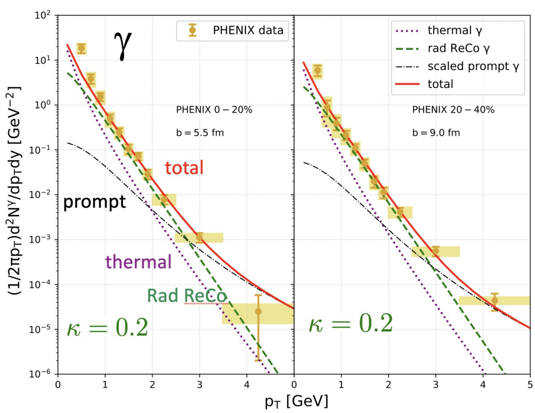

Fig. 1. (Color online) Transverse momentum distributions of direct photons for impact parameter $b = 5.5$ fm (left) and 9.0 fm (right).

prompt photon production in AA collisions, we use the empirical fit of the photon distribution in pp collisions, $a_1(1+p_\mathrm{T}^2/a_2)^{a_3}$ ($a_{1,2,3}$ are constants), as is done by PHENIX [12]. We set the normalization of the radiative ReCo model to $\kappa = 0.2$ so that the sum of the three-photon contributions reproduces the observed photon yield for $p_\mathrm{T} < 3$ GeV. We notice that the photon yield from the radiative ReCo model is estimated to be several times larger than that from the thermal radiation.

In Fig. 2, we show $v_2^\gamma(p_\mathrm{T})$ (red solid) of the total photon as well as those of the thermal photon (purple dotted) and of the radiative ReCo model (green dashed), separately. In addition, we presumed the prompt photons have no collective flow (black dot-dashed). The thermal photons have a nonzero v_2^γ but its value is systematically below the observed values [12]. On the other hand, the photons from the radiative ReCo model have v_2^γ as large as the pion v_2 and its p_T dependence is almost the same as that of the pions. Since the photon yield of the radiative ReCo model is estimated to be several times larger than the thermal photon yield, the resultant $v_2^\gamma(p_\mathrm{T})$ of the total photons is close to that of the radiative ReCo model component and is consistent with the data for $p_\mathrm{T} \lesssim 2$ GeV, albeit with a large uncertainty. At larger p_T, the prompt photons dominate and the flow is suppressed.

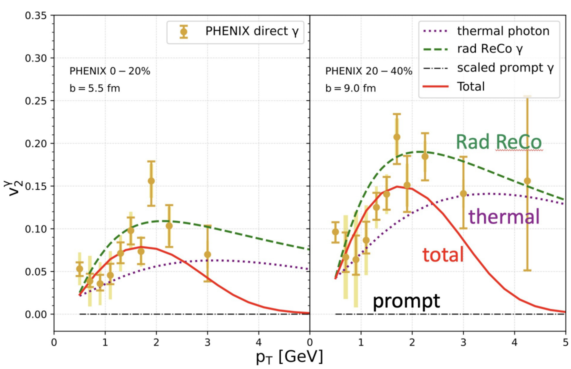

Fig. 2. (Color online) Elliptic flow coefficient v_2^γ of the direct photons for impact parameter $b = 5.5$ fm (left) and 9.0 fm (right).

Now we move on to $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions at the LHC. In Fig. 3, we compare the photon p_T distribution of our model at $b = 6.0$ (9.2) fm with the experimental data [14] at 0–20 (20–40)% centrality. Unlike in the RHIC case, the thermal photon yield (purple dotted) is not far off the observed data in $1 < p_\mathrm{T} < 2$ GeV, and we can reasonably fit the data in the region $p_\mathrm{T} \lesssim 2$ GeV by adding the photons from the radiative ReCo model (green dashed) with the normalization factor $\kappa = 0.05$. We use the same model of the photon distribution $a_1(1+p_\mathrm{T}^2/a_2)^{a_3}$ in pp collisions as before, setting the infrared cutoff $a_2 = 4$ GeV^2 and tuning the parameter

$a_1 = 1.2 \times 10^{-2}$ GeV^{-2} and $a_3 = -2.7$ to fit the available pp-collision data around $p_T \sim 10$ GeV at $\sqrt{s} = 8$ TeV [15]. We estimate the prompt photons in AA collisions by rescaling this model [12]. Although we obtained a reasonable fit of the data in the low p_T region with $\kappa = 0.05$, we do not have a clear explanation for the decrease of the κ value from the RHIC case.

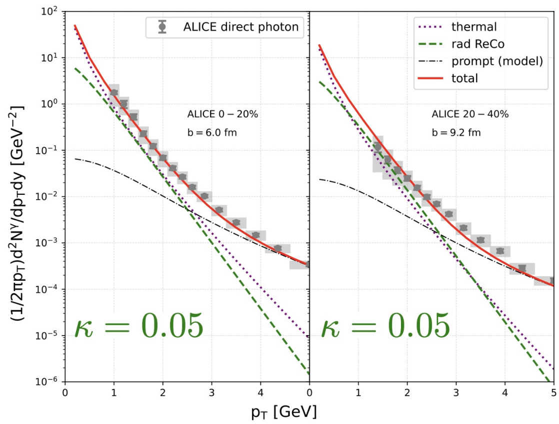

Fig. 3. (Color online) Transverse momentum distributions of direct photons for $b = 6.0$ fm (left) and $b = 9.2$ fm (right).

Figure 4 shows the v_2^γ of photons for $b = 6.0$ fm (left) and 9.2 fm (right). Since in $1 < p_T < 2$ GeV the thermal radiation and radiative hadronization contribute almost equally to the photon yield, the elliptic flow v_2^γ of the total photon yield becomes an average of the two sources and lies just in between v_2^γ of the thermal photon (purple dotted) and v_2^γ of radiative ReCo photons (green dashed) at lower p_T. At higher p_T, it is dominated by prompt photon contribution, which we assume has the zero elliptic flow.

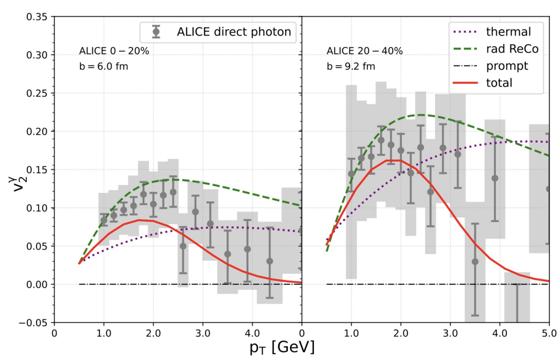

Fig. 4. (Color online) Elliptic flow v_2 of direct photons (red solid) for $b = 6.0$ fm (left) and 9.2 fm (right).

4. Summary and discussion

We have proposed "radiative hadronization" [16] as an additional photon source and performed a comprehensive analysis for photon production at RHIC and the LHC. We embodied the radiative hadronization process with a two-step model, modifying the original ReCo model [10, 11]. For numerical calculations, we considered three kinds of photon sources — prompt photons, thermal photons, and photons from the radiative hadronization.

We have shown that the radiative ReCo model can account for a significant fraction of the total photon yield, while it comes from only a small fraction of total pion yields. At the same time, we succeeded in fitting the strong elliptic flow observed at RHIC, by adding the photons from the radiative ReCo model with the overall factor $\kappa = 0.2$. For the LHC data, we obtained a reasonable fit of the p_{T} distribution and the elliptic flow of photons in $1 < p_{\mathrm{T}} < 4$ GeV, but with the smaller value of $\kappa = 0.05$. The reason for this decrease of κ is the fact that the estimated thermal photon yield is not far off the observed direct photon yield compared to the RHIC case. The origin of this change is unclear and open for future study.

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