Photons from Quark and Hadron Phases in Au + Au Collisions *

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Based on a relativistic hydrodynamic model describing the evolution of the chemically equilibrating quark–gluon plasma system with finite baryon density in a 3+1-dimensional spacetime, we compute photons from the quark phase, hadronic phase and initial non-thermal contributions. It is found that due to the effects of the initial quark chemical potential, chemical equilibration and rapid expansion of the system, the photon yield of the quark–gluon plasma is strongly suppressed, and photons from hadronic matter and initial non-thermal contributions almost reproduce experimental data.

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Many experimental observables have been suggested as possible signatures for the formation of quark–gluon plasma (QGP) in collisions.[1] Among them, photons can provide a direct probe of the plasma. Previously many authors,[2–4] considering that the created QGP in relativistic heavy-ion collisions is a thermodynamic equilibrium system, have studied the photon production. Recently, since the data for photons appear,[5] Turbide and co-workers in Ref. [6] have studied hadronic production of thermal photons on the basis of equation of state above the critical temperature T_c without chemical off-equilibrium to achieve reasonably good consistency with experimental data, and concluded that the QGP appears to be sub-dominant over all the energy range. The authors of Ref. [7] studied energy loss of leading hadrons and direct photon production in evolving QGP. Subsequently, Gale[8] calculated photons from jet-plasma interaction based on the time-evolution of the initial hard gluon, and hard quark plus anti-quark distributions, by solving a set of coupled Fokker–Planck equations, furthermore, the theoretical values have compared with the data for Au+Au at RHIC energies. While authors of Ref. [9] also calculated the production of high energy photons from Compton and annihilation processes as well as fragmentation off quarks in the parton cascade model. As is well known, for a long time with the help of the evolution model of chemically equilibrating QGP established by Shuryak, Biró and co-workers,[10–12] many authors have studied the dilepton and photon production. The authors of Ref. [13] computed the dilepton production, the authors of Refs. [14,15] studied the photon production in a chemically equilibrating and longitudinally expanding baryon-free QGP system, the authors of Ref. [16] discussed the productions of dileptons and photons in a chemically equilibrating baryon-free QGP system with transverse expansion, and the authors of Refs. [17,18] computed photons and strangeness evolution in a chemically equilibrating and longitudinally expanding QGP system at finite baryon density. However, in these calculations the evolutions of the chemically equilibrating QGP system are almost described by a longitudinal expansion model[15–20] or a transverse expansion model.[21] Although the present widespread RHIC data for photons and thermal particles appear, these authors have hardly compared their results with the data. In this work, based on the evolution model of the chemically equilibrating QGP system with finite baryon density in a 3+1-dimensional spacetime, we first study the thermal particle π^- production to determine the initial quark chemical potential and initial temperature in comparison with the data, then compute photons produced in the quark phase, hadronic phase and mixed phase. We also calculate the initial non-thermal contributions.[22]

We should know the evolution of the chemically equilibrating QGP system at finite baryon density firstly. We point out that the particle production of the system necessarily causes the entropy production, accordingly the effect of the entropy increase on the evolution of the system should be considered. Combining the following conservation laws of baryon number and energy-momentum, as well as increase of the entropy with the master equations of reactions $gg \rightleftharpoons ggg$, $gg \rightleftharpoons q\bar{q}$, $gg \rightleftharpoons s\bar{s}$ and $q\bar{q} \rightleftharpoons s\bar{s}$ leading to chemical equilibrium of the system, we obtain a set of relativistic hydrodynamic equations (RHE) of the system in a 3+1-dimensional spacetime on the basis of the thermodynamic relations of the chemically equilibrating QGP system at finite baryon density

$$\partial_t(\gamma n_b) + \frac{1}{r}\partial_r(r\gamma n_b v_r) + \frac{1}{r}\partial_\varphi(n_b\gamma v_\varphi) + \partial_z(n_b\gamma v_z) = 0, \quad (1)$$

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$$\partial_t(\gamma s_{qgp}) + \frac{1}{r}\partial_r(r\gamma s_{qgp} v_r) + \frac{1}{r}\partial_\varphi(s_{qgp}\gamma v_\varphi) + \partial_z(s_{qgp}\gamma v_z) = -\sum_i \ln\lambda_i R_i, \tag{2}$$

$$s_{qgp}\Big\{\partial_t(T\gamma v_r) + \partial_r(T\gamma) - v_\varphi\Big[\frac{1}{r}\partial_r(rT\gamma v_\varphi) - \frac{1}{r}\partial_\varphi(T\gamma v_r)\Big] + v_z[\partial_z(T\gamma v_r) - \partial_r(T\gamma v_z)]\Big\} + n_b\Big\{\partial_t(\mu_b\gamma v_r) + \partial_r(\mu_b\gamma) - v_\varphi\Big[\frac{1}{r}\partial_r(r\mu_b\gamma v_\varphi) - \frac{1}{r}\partial_\varphi(\mu_b\gamma v_r)\Big] + v_z[\partial_z(\mu_b\gamma v_r) - \partial_r(\mu_b\gamma v_z)]\Big\} = \gamma v_r T\sum_i \ln\lambda_i R_i, \tag{3}$$

$$s_{qgp}\Big\{\partial_t(T\gamma v_\varphi) + \frac{1}{r}\partial_\varphi(T\gamma) - v_z\Big[\frac{1}{r}\partial_\varphi(T\gamma v_z) - \partial_z(T\gamma v_\varphi)\Big] + v_r\Big[\frac{1}{r}\partial_r(rT\gamma v_\varphi) - \frac{1}{r}\partial_\varphi(T\gamma v_r)\Big]\Big\} + n_b\Big\{\partial_t(\mu_b\gamma v_\varphi) + \frac{1}{r}\partial_\varphi(\mu_b\gamma) - v_z\Big[1r\partial_\varphi(\mu_b\gamma v_z) - \partial_z(\mu_b\gamma v_\varphi)\Big] + v_r\Big[\frac{1}{r}\partial_r(r\mu_b\gamma v_\varphi) - \frac{1}{r}\partial_\varphi(\mu_b\gamma v_r)\Big]\Big\} = \gamma v_\varphi T\sum_i \ln\lambda_i R_i, \tag{4}$$

$$s_{qgp}\Big\{\partial_t(T\gamma v_z) + \partial_z(T\gamma) - v_r[\partial_z(T\gamma v_r) - \partial_r(T\gamma v_z)] + v_\varphi\Big[\frac{1}{r}\partial_\varphi(T\gamma v_z) - \partial_z(T\gamma v_\varphi)\Big]\Big\} + n_b\Big\{\partial_t(\mu_b\gamma v_z) + \partial_z(\mu_b\gamma) - v_r[\partial_z(\mu_b\gamma v_r) - \partial_r(\mu_b\gamma v_z)] + v_\varphi\Big[\frac{1}{r}\partial_\varphi(\mu_b\gamma v_z) - \partial z(\mu_b\gamma v_\varphi)\Big]\Big\} = \gamma v_z T\sum_i \ln\lambda_i R_i, \tag{5}$$

$$\partial_t(n_g\gamma) + \frac{1}{r}\partial_r(r\gamma n_g v_r) + \frac{1}{r}\partial_\varphi(n_g\gamma v_\varphi) + \partial_z(n_g\gamma v_z) = R_3 n_g\Big[1 - \frac{n_g}{\bar n_g}\Big] - 2R_2^{g-q} n_g\Big[1 - \Big(\frac{n_g}{\bar n_g}\Big)^2\frac{n_q n_{\bar q}}{\bar n_q \bar n_{\bar q}}\Big] - 2R_2^{g-s} n_g\Big[1 - \Big(\frac{n_g}{\bar n_g}\Big)^2\frac{n_s n_{\bar s}}{\bar n_s \bar n_{\bar s}}\Big], \tag{6}$$

$$\partial_t(n_q\gamma) + \frac{1}{r}\partial_r(r\gamma n_q v_r) + \frac{1}{r}\partial_\varphi(n_q\gamma v_\varphi) + \partial_z(n_q\gamma v_z) = R_2^{g-q} n_g\Big[1 - \Big(\frac{n_g}{\bar n_g}\Big)^2\frac{n_q n_{\bar q}}{\bar n_q \bar n_{\bar q}}\Big] - 2R_2^{q-s} n_q\Big[1 - \Big(\frac{n_q}{\bar n_q}\Big)^2\frac{n_s n_{\bar s}}{\bar n_s \bar n_{\bar s}}\Big], \tag{7}$$

$$\partial_t(n_s\gamma) + \frac{1}{r}\partial_r(r\gamma n_s v_r) + \frac{1}{r}\partial_\varphi(n_s\gamma v_\varphi) + \partial_z(n_s\gamma v_z) = R_2^{g-s} n_g\Big[1 - \Big(\frac{n_g}{\bar n_g}\Big)^2\frac{n_s n_{\bar s}}{\bar n_s \bar n_{\bar s}}\Big] + R_2^{q-s} n_q\Big[1 - \Big(\frac{n_q}{\bar n_q}\Big)^2\frac{n_s n_{\bar s}}{\bar n_s \bar n_{\bar s}}\Big]. \tag{8}$$

Equation (1) is the conservation equation of the baryon number, Eq. (2) is the equation of the entropy increase,[23] Eqs. (3)–(5) are from energy-momentum conservation, and Eqs. (6)–(8) are the master equations describing the evolutions of quark, gluon and s quark densities. R_i the production rate of the i particle, which is determined by the rate equation $\partial_\mu(n_i u^\mu) = R_i$, where $i = q$, g and s. $v = (v_r^2 + v_\varphi^2 + v_z^2)^{1/2}$ is the fluid velocity, v_r, v_φ and v_z are, respectively, the velocity components in the r, φ and z directions, $\gamma = (1 - v^2)^{1/2}$ the Lorentz contract factor, T the temperature, n_b the baryon density and $\mu_b = 3\mu_q$ the baryon chemical potential, n_i is the i particle density, and $\bar n_{i(\bar i)}$ is the value of $n_{i(\bar i)}$ at $\lambda_{i(\bar i)} = 1$. R_3/T, R_2^{g-q}/T, R_2^{g-s}/T and R_2^{q-s}/T are, respectively, the production rates for processes $gg \to ggg$, $gg \to q\bar q$, $gg \to s\bar s$ and $q\bar q \to s\bar s$.

Before discussing the photon production, we first calculate the thermal particle spectra on the basis of our model, and compare with the data as shown in Ref. [24]. We especially consider the effect of the hydrodynamics of the system on the particle production. The four velocity of the flow and four momentum of the resonance R are, respectively, given by

$$u^\mu = \gamma_t(\mathrm{ch}\eta, \mathrm{sh}\eta, \boldsymbol{v}_t), \tag{9}$$

$$p^\mu = (m_{tr}\mathrm{ch}y_r, m_{tr}\mathrm{sh}y_r, \boldsymbol{p}_{tr}) \tag{10}$$

with Lorentz contract factor

$$\gamma_t = (1 - v_t^2)^{1/2}, \tag{11}$$

where y_r and m_{tr} are, respectively, the rapidity and transverse mass of the resonance, η and v_t are, respectively, the rapidity and transverse velocity of the fluid element. Considering the energy of the resonance $E = p^\mu u_\mu$, the transverse mass distribution of each resonance can be expressed by

$$\frac{dN_r}{dy_r dm_{tr}^2} = \frac{g_r}{8\pi^2}\int d\varphi \cdot \frac{\gamma_t[m_{tr}\mathrm{ch}(y_r-\eta) - p_{tr}v_t\cos\varphi]}{\exp\{\gamma_t[m_{tr}\mathrm{ch}(y_r-\eta) - p_{tr}v_t\cos\varphi] - \mu\}/T \pm 1}, \tag{12}$$

where φ is the angle between the thermal particle momentum and the velocity of the flow. With the help of Ref. [25], considering many body decay we obtain the transverse momentum spectra of particles

$$\frac{dN_1}{dy_1 dp_{t1}^2} = \int_{\left(\sum_{i=2}^n m_i\right)}^{(m_r-m_1)^2} dW^2 Ng(W_2)\int_{y_r^{(-)}}^{y_r^{(+)}} dy_r \int_{m_{tr}^{2(-)}}^{m_{tr}^{2(+)}} \cdot dm_{tr}^2 \frac{m_r}{\sqrt{p_{tr}^2 p_{t1}^2 - [E_1^* m_r - m_{t1}m_{tr}ch(y_1 - y_r + \eta)]^2}} \cdot \frac{dN_r}{dy_r dm_{tr}^2}, \tag{13}$$

$$y_r^{\pm} = y_1 \pm \ln\Big[\frac{1}{m_{t1}}\Big(\sqrt{E_1^{\star 2} + p_{t1}^2} + |p_1^\star|\Big)\Big], \tag{14}$$

$$m_{tr}^{\pm} = \frac{m_r[E_1^\star m_{t1}\mathrm{ch}(y_1 - y_r + \eta) \pm p_{t1}Ep]}{m_{t1}^2\mathrm{ch}^2(y_1 - y_r + \eta) - p_{t1}^2}, \tag{15}$$

with

$$Ep = [E_1^{\star 2} + p_{t1}^2 - m_{t1}^2 \mathrm{ch}^2(y_1 - y_r + \eta)]^{1/2}, \quad (16)$$

where $|p_1^\star|$ and $E_1^\star$ are, respectively, the momentum and the energy of particle 1 in the resonance rest frame. For the two body case $Ng(W^2)$ must be a δ-function in m_2^2. For the three body case $Ng(W^2)$ is calculated.[25] Here, the effect of the hydrodynamic behaviour of the nuclear matter on the particle spectra is included. Finally, we obtain the total contribution of the system via integrating the particle yield (13) over spacetime of the system. In this work, we calculate the transverse momentum distributions of the thermal particle π^- and compare with the data given by the PHENIX collaboration. From the agreement between the calculated results and the data, we can determine the initial quark chemical potential of the system.

We now discuss the photon production. The earlier works [2,17] considered the hard photon production due to annihilation $q\bar{q} \to g\gamma$ and QCD Compton ($qg \to q\gamma$ and $\bar{q}g \to \bar{q}\gamma$) scattering processes from a quark matter. Recently, the authors of Refs. [26,27] have found that the near-collinear bremsstrahlung and a new process called inelastic pair annihilation (IPA), fully including the LPM effect, give also significant contribution to photon production. In this work, we also compute the photon production rates from these two processes. Meanwhile we perform a complete calculation including the contributions from the hadronic phase and mixed phase due to reactions $\pi\rho \to \pi\gamma$, $\pi\pi \to \rho\gamma$, $\pi\pi \to \eta\gamma$, $\pi\eta \to \pi\gamma$, $\pi\pi \to \gamma\gamma$, $\pi k^\star \to k\gamma$, $\pi k \to k^\star\gamma$, $\rho k \to k\gamma$, $kk^\star \to \pi\gamma$, $\rho \to \pi\pi\gamma$, $\omega \to \pi^0\gamma$ as well as the axial-vector decay $b_1 \to \pi\pi^0\gamma$. These contributions are quite well understood,[2,6,28,29] and can easily be calculated, too. From Ref. [30], one understands that the initial non-thermal contribution for photons is very important in the range of the larger transverse momenta. In this work, we also include the initial non-thermal contributions.

We consider zero impact parameter cylindrically symmetric collisions only, do not expect significant collective motion and thus take the initial velocity in the radial direction $v_r = 0$. According to Refs. [31,32], we have adopted a non-zero initial velocity in the z direction, $v_z = \tanh(z/t_0)$, where t_0 is a constant which is taken so as to extrapolate the velocity smoothly to unity in the outer parts. Considering the energy density is directly related to the experimental observables, with the help of the SSPC model[13,19,33] we take initial values: $\tau_0 = 0.25\,\mathrm{fm}$, $\lambda_{g0} = 0.34$, $\lambda_{q0} = 0.068$ and $\lambda_{s0} = 0.034$ at initial energy density $\epsilon_0 = 61.4\,\mathrm{GeV/fm^3}$. We note that for these initial values at the ratio $\mu_{q0}/T_0 = 0$ using the thermodynamic relations in the present frame-work we obtain the initial temperature $T_0 = 0.681\,\mathrm{GeV}$ which is near $0.67\,\mathrm{GeV}$ given by the SSPC model calculation.

Since the π^- spectrum data have small experimental errors as compared to the photon spectrum data, as seen in Refs. [24,34], we easily find the reasonable initial value μ_{q0}/T_0 of the system via comparing calculated π^- spectra for given μ_{q0} and T_0 with the data. Here, using Eqs. (12) and (13) we have first calculated the π^- spectra from thermal π^-, many body decay processes $\eta \to \pi^-\pi^+\pi^0$, $\rho^{0,-} \to \pi^-\pi^{+,0}$, $\omega \to \pi^-\pi^+\pi^0$, $k^{*,-,0} \to \pi^- k^{0,+}$, $\Delta \to \pi^- n$, $\Sigma^* \to \pi^- y$ and so on for $\mu_{q0}/T_0 = 0.085$ based on the evolution of the system given by the present model, and the results are shown in Fig. 1. We find that the calculated values are better agreement with the data at $\mu_{q0}/T_0 = 0.08$, it shows that the initial quark chemical potential $\mu_{q0} \simeq 54.65\,\mathrm{MeV}$ and initial temperature $T_0 \simeq 683.10\,\mathrm{MeV}$ are reasonable. Therefore, in the work we only compare the calculated results at the $\mu_{q0}/T_0 = 0.08$ with the data.

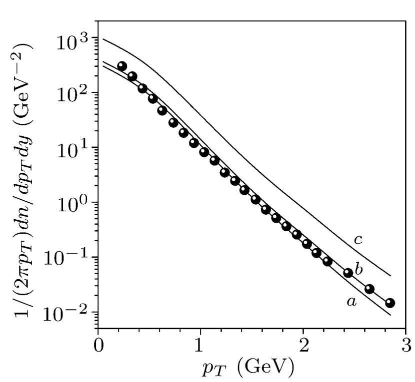

Fig. 1. Calculated π^- spectra of the system, where curves a to c are, respectively, the calculated spectra for μ_{q0}/T_0=0.085, 0.5 and 1. The data are taken from Ref. [24].

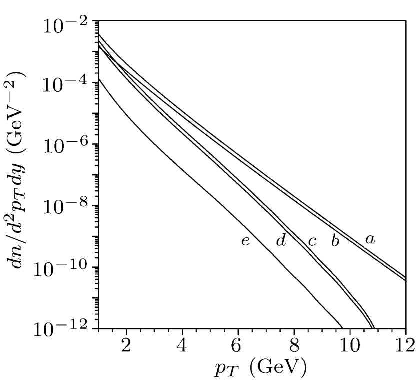

Fig. 2. Calculated photon spectra from the quark matter in the quark phase and mixed phase based on the present evolution model, where curves a to e stand, in turn, for the spectra due to bremsstrahlung, $qg \to q\gamma$, IPA, $\bar{q}g \to \bar{q}\gamma$ and $q\bar{q} \to g\gamma$ at $\mu_{q0}/T_0 = 0.08$.

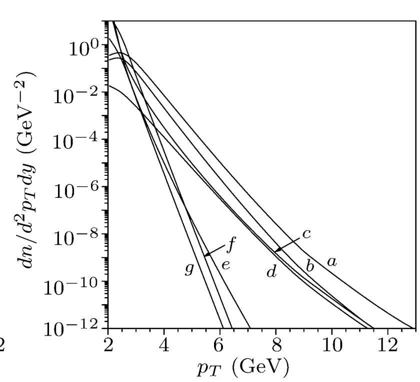

Fig. 3. Calculated photon spectra from the hadronic matter in the hadronic phase and mixed phase based on the present evolution model. Curves a to g stand, respectively, for the spectra due to reactions $\pi\rho \to \pi\gamma$, $\pi\pi \to \rho\gamma$, $\pi K^\star \to K\gamma$, $\pi K \to K^\star\gamma$, $\rho \to \pi\pi\gamma$, $b_1 \to \pi\pi^0\gamma$, and $\omega \to \pi^0\gamma$ at $\mu_{q0}/T_0 = 0.08$.

The calculated photon spectra from the quark matter in the quark phase and mixed phase for $\mu_{q0}/T_0 = 0.08$ are shown in Fig. 2, where curves a to e stand, in turn, for spectra due to the $q\bar{q} \rightarrow g\gamma$, $qg \rightarrow q\gamma$, $\bar{q}g \rightarrow \bar{q}\gamma$, bremsstrahlung and IPA processes and their total. Here, we compare results with those given by previous authors. Mustafa and co-workers[35] have studied the photon production from a chemically equilibrating baryon-free QGP at RHIC energies. Compared with the total contribution shown in the lower panel of Fig. 1 of Ref. [35], we see that our yield is lower than theirs by about 0.4 order of magnitude at the transverse momentum $p_T = 1\,\text{GeV}$ because authors of Ref. [35] only consider the transverse expansion of the system and also neglect the suppression effect of the chemical potential on the yield. In addition, the results given in the left panel of Fig. 3 of Ref. [7] and right panel of Fig. 4 of Ref. [8] show that the contribution of the QGP is not too important. Since we consider the chemical equilibration, include the effect of the chemical potential on the yield, as well as adopt the 3+1-dimensional evolution model of the system, obviously, the calculated photon yield of the QGP by the present model is also not too important.

In order to compare with the data, we have performed a complete calculation including the contributions from the hadronic phase and mixed phase based on the evolution of the present model due to reactions $\pi\rho \rightarrow \pi\gamma$, $\pi\pi \rightarrow \rho\gamma$, $\pi\pi \rightarrow \eta\gamma$, $\pi\eta \rightarrow \pi\gamma$, $\pi\pi \rightarrow \gamma\gamma$, $\pi K^\star \rightarrow K\gamma$, $\pi K \rightarrow K^\star\gamma$, $\rho K \rightarrow K\gamma$, $KK^\star \rightarrow \pi\gamma$, $\rho \rightarrow \pi\pi\gamma$, $\omega \rightarrow \pi^0\gamma$ as well as the axial-vector decay $b_1 \rightarrow \pi\pi^0\gamma$.[2,6,28,29] We have shown the calculated spectra in Fig. 3.

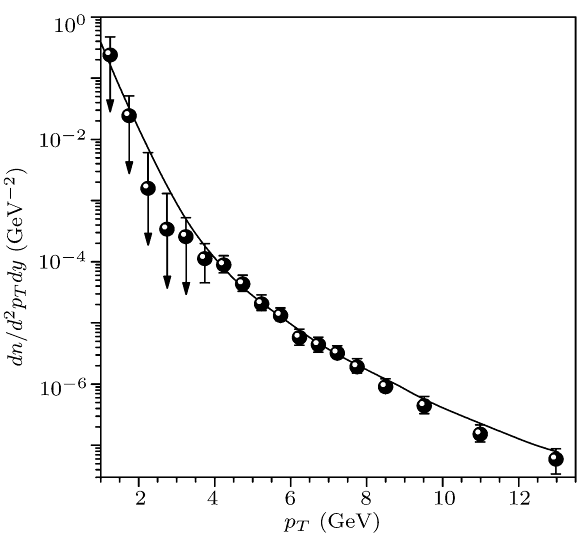

Fig. 4. Calculated photon spectra of the system. The data are taken from Ref. [34].

In Fig. 4, we have shown the total photon spectra from quark matter in the quark phase and mixed phase, hadronic matter in the hadronic phase and mixed phase at $\mu_{q0}/T_0 = 0.08$, as well as initial non-thermal contributions. In order to compare with the data, we have also shown the data from Au+Au central collisions at RHIC energies, taken from Ref. [34]. We find that the calculated values can coincide better with the photon and π^- spectrum data at the initial quark chemical potential $\mu_{q0} \simeq 54.65\,\text{MeV}$ and initial temperature $T_0 \simeq 683.10\,\text{MeV}$. It is shown that the better agreement between the theoretical values and the data.

In conclusion, we have derived a set of coupled RHE of the QGP system, which describes the evolution of the chemically equilibrating QGP system with finite baryon density in a 3+1-dimensional spacetime. Then, for a given energy density we have computed the photon yield from the Compton ($gq \rightarrow q\gamma$ and $g\bar{q} \rightarrow \bar{q}\gamma$), annihilation $q\bar{q} \rightarrow g\gamma$, bremsstrahlung and IPA processes on the basis of evolution of the system produced from Au^{197}+Au^{197} central collisions at RHIC energies. We should emphasize that in the present model the cooling of the system becomes even faster, thus the photon yield is further suppressed. Moreover, for a chemically equilibrating QGP system the photon yield is proportional to the squared fugacity λ_i which is often less than 1. Therefore the photon yield of the quark phase is lower. While we find that in the mixed and hadronic phases the hadronic matter provides an significant contribution to photons since these two phases have the larger evolution time and are reheated during the phase transition due to the releasing of the larger latent heat. In addition, we note that the initial non-thermal contribution is important in the range of larger transverse momenta.

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