Enhancement of thermal photon production in event-by-event hydrodynamics

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Thermal photon emission is widely believed to reflect properties of the earliest, hottest evolution stage of the medium created in ultrarelativistic heavy-ion collisions. Previous computations of photon emission have been carried out using a hydrodynamical medium description with smooth, averaged initial conditions. Recently, more sophisticated hydrodynamical models that calculate observables by averaging over many evolutions with event-by-event fluctuating initial conditions (ICs) have been developed. Given their direct connection to the early time dynamics, thermal photon emission appears to be an ideal observable to probe fluctuations in the medium initial state. In this work, we demonstrate that including fluctuations in the ICs may lead to an enhancement of the thermal photon yield of about a factor of 2 in the region $2 < p_T < 4$ GeV/c (where thermal photon production dominates the direct photon yield) compared to a scenario using smooth, averaged ICs. Consequently, a much better agreement with PHENIX data is found. This can be understood in terms of the strong temperature dependence of thermal photon production, translating into a sensitivity to the presence of hotspots in an event and thus establishing thermal photons as a suitable probe to characterize IC fluctuations.

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I. INTRODUCTION

The recent observations of large elliptic flow [1,2] and energy loss of high-energy partons in the medium [3,4] strongly suggest the formation of quark-gluon plasma (QGP), a hot and dense state of quarks and gluons, in ultrarelativistic heavy-ion collisions. The results from the BNL Relativistic Heavy Ion Collider (RHIC) during the last decade, as well as the recent results from the CERN Large Hadron Collider (LHC) [5], are consistent with theoretical calculations that assume early thermalization and a nearly ideal fluid behavior of the system.

The evolution of the system from initial formation to final breakup is reflected in various different observables. Electromagnetic radiation has long been proposed as the most promising and efficient probe to characterize the initial state of the hot and dense matter produced in the collisions [6]. Unlike bulk hadrons, which are emitted from the freeze-out hypersurface, photons come out from every phase of the expanding fireball, suffer negligible final state interactions (since electromagnetic coupling $\alpha \ll$ strong coupling α_s), and carry undistorted information about the medium conditions at their production points. The thermal emission of photons from the evolving system shows a very strong temperature dependence: The high p_T photons are emitted mostly from the hot and dense early stages of matter when the hydrodynamic flow is weak, whereas those at lower p_T are emitted from the relatively cold later parts of the system where a large buildup of radial flow boosts their transverse momentum. Thermal photons with $p_T > 1$ GeV/c are therefore expected to provide a glimpse of the early part of the expansion history when the fireball is in the plasma phase, complementary to the spectra of bulk hadrons that reflect the late conditions close to decoupling.

Initially, direct photon spectra were studied mostly to extract the temperature of the system. Recently, several other photon observables have shown significantly more potential to understand the dynamics of the system, for example, intensity interferometry of photons for space-time information of the evolving system [7,8], momentum anisotropy of the initial partons as well as formation time of QGP from the elliptic flow of thermal photons [9,10], study of jet quenching through photons produced from jet-medium interaction [11–13], etc. In addition, a higher level of sophistication has been reached in the estimation of prompt photons from next-to-leading-order (NLO) perturbative QCD calculations [14], where the result explains the direct photon spectrum from p+p collisions at RHIC quite well for $p_T > 1$ GeV/c [15]. Also, photons from jet-plasma interaction, recently investigated in detail [13], have been suggested as an important contribution to the direct photon yield at $p_T > 2$ GeV/c.

Ideal hydrodynamics with a smooth initial-density profile has been used successfully to model the evolution of the system at RHIC where the experimental data for hadron spectra and elliptic flow are well reproduced up to $p_T \sim 2$ GeV/c (see [16,17]). However, for any given event there are inhomogeneities in the initial-energy-density profile and therefore event-by-event fluctuating density profiles are more realistic than a smooth initial-density distribution. Thus, the important question is whether these event-by-event fluctuating initial conditions (ICs) have any sizable effect on the physical observables if they are computed by averaging over many final states rather than considering an averaged initial-density profile.

It has been shown recently that hydrodynamics with event-by-event fluctuating ICs reproduces the experimental charged particle elliptic flow even for the most central collisions at RHIC [18], which was underestimated by all earlier hydrodynamic calculations using smooth ICs. Several other studies have shown that fluctuating ICs give a better agreement with the experimental charged particle spectra at high p_T by increasing the number of particles there [18,19]. These fluctuations may also help to understand the various structures observed in two-particle correlations [20,21]. Since thermal photons are sensitive to the initial temperature, they are especially suitable for probing fluctuations in the ICs.

Thermal radiation is predicted to be the dominant source of direct photons in the range $1 \leqslant p_T \leqslant 3$ GeV/c [15,22]. Photon results using smooth profile and latest rates [23], however, fall well below the experimental data points (see Fig. 4 of Ref. [15]) in this p_T range. In the present work we report a substantial p_T-dependent enhancement in the production of thermal photons for $p_T > 1$ GeV/c with an event-by-event fluctuating IC relative to a smooth initial-state-averaged profile in the ideal hydrodynamic calculation. Consequently, our results with fluctuating density profiles show a better agreement with the PHENIX experimental data for $2 < p_T < 4$ GeV/c. However, it should be noted that the main aim of this paper is to investigate the effect of initial-state fluctuations on the production of thermal photons rather than explaining the experimental direct photon spectrum, which contains significant contributions from other sources apart from thermal radiation. Also, importantly, we find that the enhancement scales with the initial fluctuation size.

II. EVENT-BY-EVENT HYDRODYNAMICS AND INITIAL DENSITY PROFILE

We use the event-by-event hydrodynamical model developed in [18], which has been applied successfully to study the elliptic flow with fluctuating initial states. The standard two-parameter Woods-Saxon nuclear density profile is used to randomly distribute the nucleons in the colliding nuclei. Two nucleons i and j from different nuclei are then assumed to collide whenever they satisfy the relation

$$(x_i - x_j)^2 + (y_i - y_j)^2 \leqslant \frac{\sigma_{\rm NN}}{\pi}, \tag{1}$$

where $\sigma_{\rm NN} = 42$ mb is the inelastic nucleon-nucleon cross section at $\sqrt{s_{\rm NN}} = 200$ GeV, and x_i, y_i denote the positions of the nucleons in the transverse plane.

The initial-density profile is taken to be proportional to the number of wounded nucleons (WNs), where entropy density s (or the energy density ϵ) is distributed in the x-y plane around the wounded nucleons using a two-dimensional (2D) Gaussian as a size function,

$$s[\epsilon](x, y) = \frac{K}{2\pi\sigma^2} \sum_{i=1}^{N_{\rm WN}} \exp\left(-\frac{(x - x_i)^2 + (y - y_i)^2}{2\sigma^2}\right). \tag{2}$$

We refer to this as the sWN (eWN) profile. The parameter K is a fixed overall normalization constant and σ is a free parameter determining the size of the fluctuations.

The effective interaction radius for the colliding nucleons, $\sqrt{\sigma_{\rm NN}/\pi}/2 \sim 0.6$ fm, sets a natural order of magnitude for the size parameter. Similarly to Ref. [18], the default value of σ is taken as 0.4 fm, however, we test the sensitivity of the results to σ by varying σ from 0.4 to 1.0 fm. We consider the 0%–20% most central Au+Au collisions where the value of $N_{\rm WN}$ fluctuates from 391 to 197 according to the Monte Carlo Glauber model. This corresponds to an average impact parameter of about 4.4 fm.

Using this procedure we thus find intraevent fluctuations (i.e., hotspots and holes) in the ICs in a given event, as well as interevent fluctuations in the total entropy between any two events. We call events with larger than average entropy production hot events and those with smaller than average entropy production cold events.

For Au + Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV, the constant K is taken as 102.1 fm^{-1} (37.8 GeV/fm) for the sWN (eWN) profile, which reproduces the initial total entropy of Ref. [17] when averaging over many initial states in central collisions for $\sigma = 0.4$ fm. As in [18], the initial time is fixed at $\tau_0 = 0.17$ fm/c motivated by the Eskola-Kajantie-Ruuskanen-Tuominen (EKRT) minijet saturation model [17,24] for all the events.

Assuming longitudinal boost invariance, we solve the (2 + 1) dimensional ideal hydrodynamic equations using the sharp and smooth transport algorithm (SHASTA) [25,26], which is able to propagate shock waves possible with the irregular ICs. The equation of state (EOS) which shows a sharp crossover transition from plasma phase to hadronic matter is taken from [27]. The temperature for freeze-out is taken as 160 MeV, which reproduces the measured p_T spectrum of pions [28] well for both the profiles eWN and sWN.

III. THERMAL PHOTONS

The rate of thermal photon production in the QGP depends on the momentum distribution of the partons which are governed by the thermodynamical conditions of the matter. The quark-gluon Compton scattering and quark-antiquark annihilation are the leading-order processes for photon production in the partonic phase, whereas in next-to-leading order, the bremsstrahlung process contributes significantly to the production [29]. In a hot hadronic gas at a temperature of the order of a pion mass, π and ρ mesons contribute dominantly to the photon production because of the low mass of pions and the large spin-isospin degeneracy of ρ mesons, making them the most easily accessible particles in the medium [30]. The leading photon-producing channels involving π and ρ mesons are $\pi\pi \rightarrow \rho\gamma, \pi\rho \rightarrow \pi\gamma$, and $\rho \rightarrow \pi\pi\gamma$.

We use the rates $R = EdN/d^3pd^4x$ of Ref. [29] for the plasma and those of Ref. [23] for the hadronic matter, which at present can be considered as the state of the art. The transition from the plasma rates to the hadronic rates is assumed to happen at a temperature of 170 MeV in this study. The total thermal emissions from the quark and hadronic-matter phases are obtained by integrating the emission rates over the space-time history of the fireball as

$$E\, dN/d^3p = \int d^4x\, R(E^*(x), T(x)), \tag{3}$$

where $E^*(x) = p^\mu u_\mu(x)$. The four-momentum of the photon is

$$p^\mu = (p_T \cosh Y,\, p_T \cos\phi,\, p_T \sin\phi,\, p_T \sinh Y)$$

and the four-velocity of the flow field is $u^\mu = \gamma_T(\cosh\eta, v_x, v_y, \sinh\eta)$, with $\gamma_T = (1-v_T^2)^{-1/2}$, $v_T^2 = v_x^2+v_y^2$. The volume element is $d^4x = \tau\, d\tau\, dx\, dy\, d\eta$, where $\tau = (t^2-z^2)^{1/2}$

is the longitudinal proper time and $\eta = \tanh^{-1}(z/t)$ is the space-time rapidity. The photon momentum is parametrized by its rapidity Y, transverse momentum p_T, and azimuthal emission angle ϕ.

IV. RESULTS

We compare our results from smooth and fluctuating sWN initial-density profiles with PHENIX data for 0%–20% centrality bin in Fig. 1. The smooth initial-density profile is obtained by taking an average of 1000 fluctuating initial profiles which is enough to remove essentially all fluctuations. To test whether there is a residual dependence on the IC averaging procedure, we vary the value of σ from 0.4 to 1.0 fm. The thermal photon spectrum from the resulting smooth initial-density profiles is almost independent of σ in the low-p_T region. Only at high p_T (>4 GeV/c), a change in the value of σ from 0.4 to 1.0 fm decreases the photon production there by 20%–30%.

Photons from the fluctuating ICs scenario are estimated by averaging photon spectra from a sufficiently large number of random events. We make sure that the addition of another very hot or very cold event does not change the results significantly.

We find that in the entire p_T range, the spectra are dominated by the QGP radiation both for the smooth as well as for the fluctuating ICs. This is not due to our choice of a large freeze-out temperature T_f (160 MeV)—we have checked that a prolonged hydroevolution toward a smaller value like $T_f = 120$ MeV contributes significantly below 1.5 GeV/c but is not substantial for $p_T > 2$ GeV/c, as shown by the brown dash-dotted line in Fig 1. Photons from only the hadronic phase are shown by dotted and short-dashed gray lines for T_f values of 160 and 120 MeV, respectively, for the smooth IC. Both these lines fall well below the plasma and the total contribution. It should be noted that a bag-model EOS produces more hadronic photons near the transition region compared to a lattice-based EOS, however, the contribution from the hadronic phase is not significant for $p_T > 2$ GeV/c even for a bag-model EOS. We also note that the bag-model yield of photons at high p_T is about 50% smaller than the results shown here.

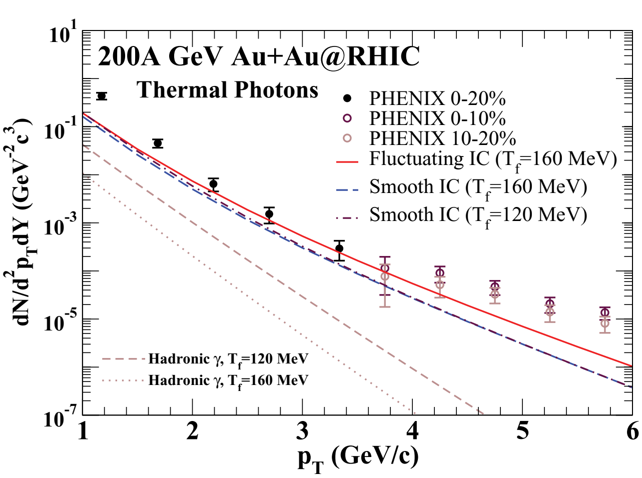

FIG. 1. (Color online) Thermal photons from a smooth (long-dashed blue line) and fluctuating (solid red line) sWN initial-density profile along with experimental direct photon data from PHENIX [15,31] for the 0%–20% centrality bin. The fluctuation size parameter $\sigma = 0.4$ fm here. Also shown are the hadronic contributions for the smooth IC cases.

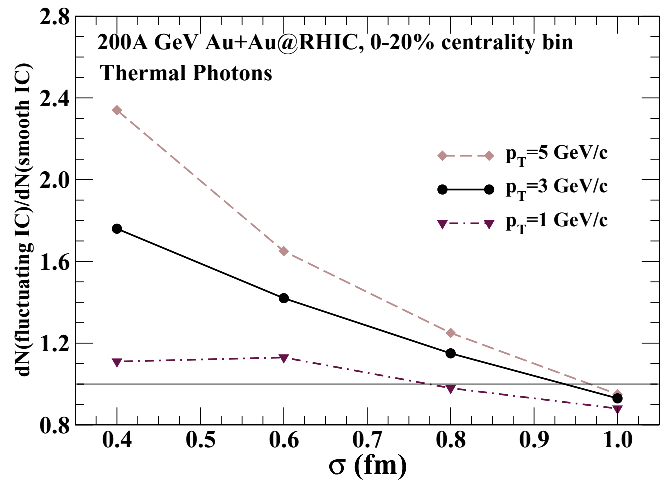

FIG. 2. (Color online) Ratio of photon production from fluctuating and smooth ICs at different p_T as a function of the fluctuation size parameter σ.

The slope of the photon spectrum from the fluctuating IC is about 10% flatter compared to the slope from the smooth IC in the region $2 \leqslant p_T \leqslant 4$ GeV/c and the two results differ by nearly a factor of 2 (see Fig. 2) for $p_T > 2$ GeV/c. In the region $p_T < 2$ GeV/c, the fluctuating case produces 20%–40% more photons than the smooth profile. The thermal emission of photons is exponential in temperature and linear in radiating volume. As a result, the hotspots in the fluctuating events produce more high-p_T photons compared to the smooth profile. On the other hand, the low-p_T part of the spectrum comes from the relatively cold, more volume-dominated later plasma stage, where the emission is not affected significantly due to the change in the ICs. Thus, the difference between the two profiles is small near $p_T \sim 1$ GeV/c and enhanced toward higher p_T.

It may be noted that a similar enhancement of the thermal photon production by a factor ~ 2 in the region $1 < p_T < 4$ GeV/c using the same smooth IC can also be obtained by choosing a smaller initial time τ_0. In this case, one needs to reduce the value of τ_0 to half of its original value [10]. A systematic study of thermal photons at different centrality bins has the potential to distinguish between the effects of fluctuations in the initial state and the formation time.

Similar to the photon results, hardening of the spectra is also observed for hadrons where the fluctuation-driven radial flow makes their spectra harder than the spectra obtained from a smooth IC. This is because the hadrons are emitted from a much later stage of the system expansion (i.e., the surface of freeze-out [18,32]). For photons, the difference between the fluctuating and the smooth ICs is an early time effect (due to the presence of hotspots) when the radial flow is still very small.

Although the photons from the late hadronic phase are affected significantly due to the increased radial flow in the fluctuating IC, the sum spectrum, which is dominated by plasma radiation in the entire p_T range, remains almost unaffected.

Thus, the production of thermal photons shows a very strong dependence on the averaging procedure. We observe that the results for fluctuating ICs show better agreement with the experimental data compared to earlier studies with smooth initial profile, while leaving enough space for the prompt-contribution and jet-conversion photons. This may also affect the photon elliptic flow results [9].

The sensitivity of the results to the fluctuation size parameter σ is shown in Fig. 2, where the ratio of the results from fluctuating and smooth ICs are plotted as a function of σ for different values of p_T. The enhancement is maximal for higher values of p_T and lower values of σ, which clearly shows the dominance of the hotspots in high-p_T photon production. For $\sigma \geqslant 0.8$ fm, profiles with fluctuating ICs do not show pronounced differences from the smooth case as the ratio approaches 1.

We also notice that the photon results are quite sensitive to the initial profiles; the results for sWN are harder than those with the eWN. The entropy initialization leads to more pronounced maxima in the energy density distribution (causing a hotter initial state and harder spectra) than their energy initialization counterparts, which was also observed in some earlier studies [33]. However, the photon spectrum from fluctuating ICs, considering the eWN profile, shows a similar enhancement relative to the smooth profile as observed for sWN in Fig. 1.

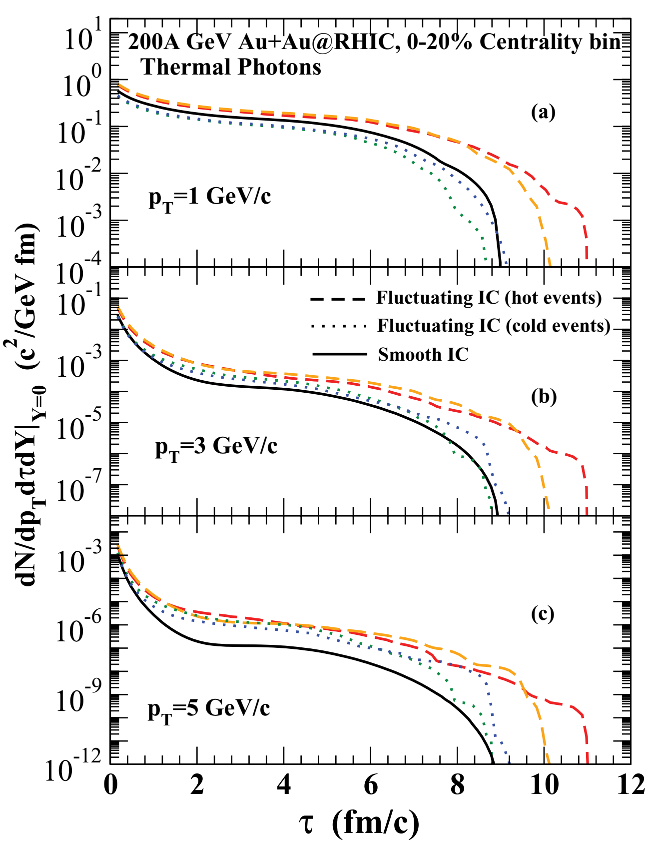

FIG. 3. (Color online) Time evolution of thermal photons for transverse momentum values of (a) 1 GeV/c, (b) 3 GeV/c, and (c) 5 GeV/c. Results are compared with an initial-state-averaged event and four different random events.

In Fig. 3, the time evolution of the photon results for smooth (solid lines) and fluctuating (dashed lines) ICs are shown at p_T values of 1, 3, and 5 GeV/c to illustrate the dynamics leading to the results presented in Fig. 1. For the fluctuating IC, we choose two very hot events (red and orange dashed lines) and two relatively cold events (blue and green dotted lines), whereas the smooth IC event is shown by the solid black lines in the figure. The $dN/dp_Td\tau dY$ results clearly demonstrate that most of the high-p_T photons are emitted quite early where the photon emission rate drops by two orders of magnitude within a time period of about 2 fm/c for $p_T \geqslant 3$ GeV/c. The cold events reflect a relatively smaller system lifetime. The most interesting observation is that the cold events produce more photons at $p_T \geqslant 3$ GeV/c compared to the smooth profile due to the presence of a few hotspots.

V. SUMMARY AND CONCLUSIONS

In conclusion, we find a large enhancement in the production of thermal photons for event-by-event fluctuating ICs compared to a smooth profile in the ideal hydrodynamic calculation. For $p_T < 2$ GeV/c, the production is increased by 20%–40% for the fluctuating initial conditions, whereas for $p_T > 2$ GeV/c, it increases by about a factor of 2, which gives better agreement with PHENIX data in the region $2 < p_T < 4$ GeV/c. A small value of the plasma formation time (0.17 fm/c) ensures that a fraction of the pre-equilibrium photons is accounted for, which is an important source of direct photons at large values of transverse momentum and difficult to estimate separately. The contributions from the initial hard processes and jet-matter interactions are significant for $p_T > 2$ GeV/c, and should be added with the thermal radiation in order to explain the data in the entire p_T range shown in Fig. 1. This enhancement is a result of the strong temperature dependence of the thermal photon emission rates which specifically probe the hotspots. We checked that the photon spectra for the sWN profile are harder than the spectra for the eWN profile, however, the quantitative difference between the fluctuating and smooth ICs remains similar for both cases. A more detailed investigation of the wounded nucleons and binary-collision profiles for both entropy and energy initializations, combined with photon elliptic flow from the fluctuating IC would be very valuable. The difference between the smooth and fluctuating ICs is expected to increase for peripheral collisions as well as for lower collision energies. We postpone these issues for a future study.

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