Interference of thermal photons from quark and hadronic phases in relativistic collisions of heavy nuclei

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We explore intensity correlations for thermal photons having $K_T \leqslant 2\,\text{GeV}/c$ for central collisions of heavy nuclei at Relativistic Heavy Ion Collider and Large Hadron Collider energies. These photons get competing contributions from the quark and hadronic phases. This competition gives rise to a unique structure, especially in the outward correlation function, owing to the interference between the photons from the two sources. The temporal separation of the two sources provides the lifetime of the system and their strengths provide the relative contribution of the two phases. The results are found to be quite sensitive to the quark-hadron phase transition temperature and the formation time of the plasma.

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I. INTRODUCTION

The last two decades have witnessed a concerted and well-coordinated theoretical and experimental effort to produce and study quark-gluon plasma—the deconfined strongly interacting matter—in relativistic collisions of heavy nuclei. The eminent commissioning of the Large Hadron Collider (LHC) at CERN and various upgrades, in both the accelerator and the detection systems, at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven will offer further opportunities to advance our understanding of the physics of this novel state of matter that permeated the early universe. We have already been rewarded with the discovery of jet quenching [1,2] and elliptic flow [3,4] and the successful formulation of partonic recombination [5] as a model for hadronization in recent experiments at the RHIC. Thermal photons radiated from such collisions are being studied to determine the high temperatures reached in these collisions [6–9].

The next step in this endeavor involves a critical examination of our concepts about the formation and evolution of the plasma. So that we can use the powerful methods of hydrodynamics to model the evolution of the system, an important question in this connection is how quickly, if at all, does the plasma thermalize? Theoretical estimates of thermalization time (τ_0) vary considerably and experimental observables such as elliptic flow of hadrons only suggest that $\tau_0 \sim 1.0\,\text{fm}/c$. A more quantitative experimental determination of τ_0 would be very valuable. It would also be useful to know the lifetime of the interacting system. Can we determine the temperature at which the phase transition takes place?

The quantum statistical interference between identical particles emitted from these collisions is expected to provide valuable input for the space-time description of the system. The use of photons for these studies introduces several advantages. First, they interact with the system only weakly after their production. Thus, they are not subjected to distorting effects such as rescattering and Coulomb interactions, which affect the results for hadrons. Second, and even more important, photons are emitted from every stage of the collision dynamics. These aspects give us hope of obtaining direct information about the earliest, hot and dense stage of the system by studying photons having higher transverse momenta, K_T. Recently, some additional sources of high-K_T photons have also been proposed [10,11].

The difficulty, of course, arises from the meager emission of direct photons that lie buried in the huge background of decay photons. So far only one measurement involving photons having a very low K_T [12] for the central collision of lead nuclei at the CERN SPS has been reported, by the WA98 Collaboration.

On the other hand, the theory of intensity interferometry of photons from relativistic heavy-ion collisions has been pursued in considerable detail by several authors [13–15]. It is generally felt that the experimental efforts in these studies have a greater likelihood of success at RHIC and LHC energies because of the higher initial temperature of the plasma and the large suppression of pions due to jet quenching. Of late, there have also been tremendous advances in methods for identification of single photons [8].

In the present work, we focus our attention on photons having intermediate $K_T \approx 0.2$–$2\,\text{GeV}/c$. Photons having $K_T \ll 2\,\text{GeV}/c$ will mostly originate from the hadronic phase of the system. They are expected to reveal a source that should be strongly affected by the flow and expansion of the system. Photons having $K_T \gg 2\,\text{GeV}/c$ should unveil a source that is in the infancy of the hot and dense quark-gluon plasma, where the flow has just started to develop. Photons having $K_T \leqslant 2\,\text{GeV}/c$ are unique. They have their origin either in the hot and dense quark phase of the system or in the relatively cooler but rapidly expanding hadronic phase, where a large buildup of the radial flow boosts their transverse momenta.

We shall see that this leads to a rich structure of the correlation function for thermal photons, especially when studied as a function of the outward momentum difference (q_o; see later), owing to the interference of the two sources. The two sources also manifest in the correlation functions for the longitudinal (q_l) and sideward (q_s) momentum differences. This renders the correlation very sensitive to the formation

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time of the plasma. Early formation and thermalization would provide a high initial temperature, whereas late formation and thermalization would lead to a lower initial temperature. This analysis can also help to determine the fractional contributions of the quark and hadronic phases to the single-photon spectrum.

Because the interference mentioned above is controlled by the relative contributions from the quark and hadronic phases, which in turn are decided by the critical temperature used in the model, we find a unique sensitivity of the results to the temperature at which the phase transition takes place.

We discuss the basic formalism in the next section. The results for RHIC and LHC energies are discussed in Secs. III and IV, respectively. In Sec. V we discuss the sensitivity of our results to the initial formation time of the plasma and the transition temperature. Finally, we summarize our findings in Sec. VI.

II. FORMULATION

One can define the spin-averaged intensity correlation between two photons with momenta $\mathbf{k_1}$ and $\mathbf{k_2}$, emitted from a completely chaotic source, as

$$C(\mathbf{q},\mathbf{K}) = 1 + \frac{1}{2}\frac{|\int d^4x\, S(x,\mathbf{K})e^{ix\cdot q}|^2}{\int d^4x\, S(x,\mathbf{k_1})\int d^4x\, S(x,\mathbf{k_2})}, \quad (1)$$

where $S(x,\mathbf{K})$ is the space-time emission function, and

$$\mathbf{q} = \mathbf{k_1} - \mathbf{k_2}, \quad \mathbf{K} = (\mathbf{k_1}+\mathbf{k_2})/2. \quad (2)$$

We shall use hydrodynamics to model the evolution of the system. The space-time emission function S is approximated as the rate of production of photons, EdN/d^4xd^3k, from the quark and hadronic phases.

The interference between thermal photons from the quark and hadronic phases is best studied by writing the source function S as $S_Q + S_H$ in the numerator, where Q and H stand for the two phases, respectively, and then including either one, or the other, or both.

We shall discuss the results for the correlation function $C(\mathbf{q},\mathbf{K})$ in terms of the outward, sideward, and longitudinal momentum differences, q_o, q_s, and q_ℓ. Thus writing the four-momentum of the ith photon as k_i^μ, we have

$$k_i^\mu = (k_{iT}\cosh y_i, \mathbf{k_i}), \quad (3)$$

with

$$\mathbf{k_i} = (k_{iT}\cos\psi_i, k_{iT}\sin\psi_i, k_T\sinh y_i), \quad (4)$$

where k_T is the transverse momentum, y is the rapidity, and ψ is the azimuthal angle. Defining the difference and the average of the transverse momenta,

$$\mathbf{q_T} = \mathbf{k_{1T}} - \mathbf{k_{2T}}, \quad \mathbf{K_T} = (\mathbf{k_{1T}}+\mathbf{k_{2T}})/2, \quad (5)$$

we can write [13]

$$q_\ell = k_{1z} - k_{2z} = k_{1T}\sinh y_1 - k_{2T}\sinh y_2, \quad (6)$$

$$q_o = \frac{\mathbf{q_T}\cdot\mathbf{K_T}}{K_T} = \frac{\left(k_{1T}^2 - k_{2T}^2\right)}{\sqrt{k_{1T}^2 + k_{2T}^2 + 2k_{1T}k_{2T}\cos(\psi_1-\psi_2)}}, \quad (7)$$

$$q_s = \left|\mathbf{q_T} - q_o\frac{\mathbf{K_T}}{K_T}\right| = \frac{2k_{1T}k_{2T}\sqrt{1-\cos^2(\psi_1-\psi_2)}}{\sqrt{k_{1T}^2 + k_{2T}^2 + 2k_{1T}k_{2T}\cos(\psi_1-\psi_2)}}. \quad (8)$$

The radii corresponding to the above momentum differences are often obtained by approximating the correlation function as

$$C(q_o,q_s,q_\ell) = 1 + \tfrac{1}{2}\exp\left[-\left(q_o^2R_o^2 + q_s^2R_s^2 + q_\ell^2R_\ell^2\right)\right]. \quad (9)$$

We also define the root-mean-square momentum difference $\langle q_i^2\rangle$ as

$$\langle q_i^2\rangle = \frac{\int (C-1)\,q_i^2\,dq_i}{\int (C-1)\,dq_i}, \quad (10)$$

so that for the Gaussian parametrization given in Eq. (9), we have

$$R_i^2 = \frac{1}{2\langle q_i^2\rangle}. \quad (11)$$

Thus, $1/[2\langle q_i^2\rangle]^{1/2}$ becomes a useful measure when the correlation function has a more complex nature, as we shall see later.

We consider central collision of gold and lead nuclei, corresponding to the conditions realized at the RHIC and LHC, respectively. We assume that a thermally and chemically equilibrated quark-gluon plasma is produced at an initial time τ_0. We further assume an isentropic expansion of the system to estimate the initial temperature T_0 in terms of particle rapidity density. Thus,

$$\frac{2\pi^4}{45\zeta(3)}\frac{1}{A_T}\frac{dN}{dy} = 4aT_0^3\tau_0, \quad (12)$$

where A_T is the transverse area of the system, dN/dy is the particle rapidity density, and $a = 42.25\pi^2/90$ for a plasma of massless quarks (u, d, and s) and gluons. The number of flavors for this purpose is taken as $\approx$2.5 to account for the mass of the strange quarks. In the present work we mostly consider $\tau_0 = 0.2$ fm/c and give illustrative results for τ_0 varying from 0.2 to 1.0 fm/c, keeping dN/dy (or the total entropy) fixed. We add that, for study of thermal photons, a value close to 0.2 fm/c may be more appropriate. The initial energy density is taken as a weighted sum of wounded nucleon and binary collision distributions as in earlier studies [16]. The quark-hadron phase transition is assumed to take place at a temperature of 180 MeV, whereas the freeze-out takes place at 100 MeV. The relevant hydrodynamic equations are solved under the assumption of boost-invariant longitudinal and azimuthally symmetric transverse expansion using the procedure discussed earlier [17] and integration performed over the history of evolution. We use the complete leading order results for production of photons from quark matter [18] and the results of Turbide *et al.* [19] for radiation of photons from hadronic matter. A rich equation of state with the inclusion of all the particles in the particle data book, having $M < 2.5\,\mathrm{GeV}/c^2$, describes the hadronic matter. We take dN/dy at $y = 0$ as 1260 [11] for $200A$ GeV Au + Au collisions at the RHIC and 5625 [20] for $5.5A$ TeV Pb + Pb collisions at the LHC. A lower value for the particle rapidity density at the LHC may perhaps be more appropriate, though. This will, however, not change the nature of the findings reported here.

III. RESULTS FOR RELATIVISTIC HEAVY ION COLLIDER ENERGIES

As the first step, in Fig. 1 we show the outward, sideward, and longitudinal correlation functions for thermal photons at RHIC having $K_T \approx 2\,\mathrm{GeV}/c$. The four-momenta of the two photons are chosen so that when we study the outward correlations, q_s and q_ℓ are identically zero and the dependence on q_o is clearly seen, and so on. We first discuss the results when only the hadronic-matter contribution or only the quark-matter contribution is included in the numerator [Eq. (1)]. We find that the correlation functions for the two phases can be approximated as

$$C(q_i, \alpha) = 1 + 0.5|\rho_{i,\alpha}|^2, \tag{13}$$

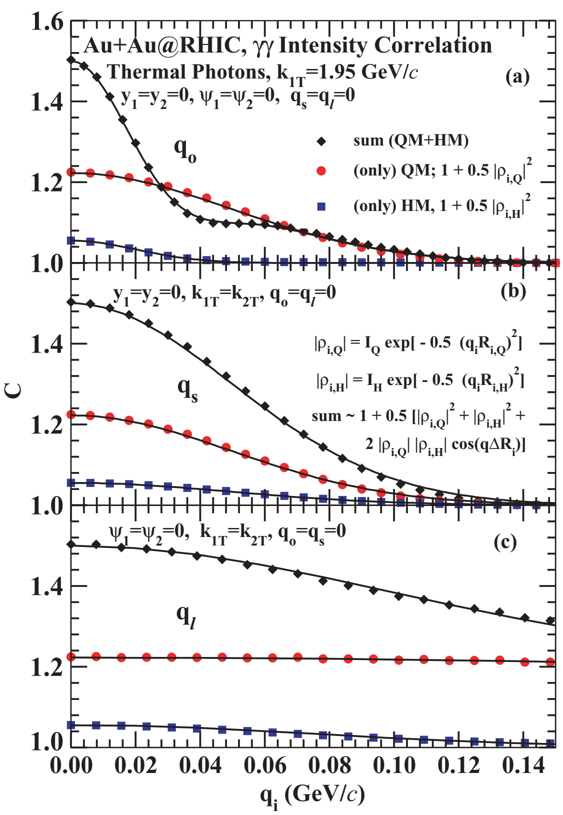

FIG. 1. (Color online) (a) Outward, (b) sideward, and (c) longitudinal correlation functions for thermal photons produced in central collision of gold nuclei at the RHIC taking $\tau_0 = 0.2\,\mathrm{fm}/c$. Symbols denote results of the calculation; curves denote fits.

where $i = o$, s, and ℓ, and α denotes quark matter (Q) and hadronic matter (H) in an obvious notation. The source distribution $|\rho_{i,\alpha}|$ is very well described by

$$|\rho_{i,\alpha}| = I_i \exp\left[-0.5\left(q_i^2 R_{i,\alpha}^2\right)\right], \tag{14}$$

where

$$I_Q = \frac{dN_Q}{(dN_Q + dN_H)}, \tag{15}$$

and

$$I_H = \frac{dN_H}{(dN_Q + dN_H)}. \tag{16}$$

The final correlation function, denoted "sum" in the figures can be approximated as

$$C(q_i) = 1 + 0.5[|\rho_{i,Q}|^2 + |\rho_{i,H}|^2 + 2\,|\rho_{i,Q}||\rho_{i,H}|\cos(q\Delta R_i)] \tag{17}$$

which clearly brings out the interference between the two sources [21]. Here ΔR_i stands for the separation of the two sources in space-time and q is the four-momentum difference. For thermal photons having $K_T \approx 2\,\mathrm{GeV}/c$ at the RHIC, various radii (fm) are obtained as

$$\begin{aligned} &R_{o,Q} = 2.8,\ R_{o,H} = 7.0,\ \Delta R_o = 12.3,\\ &R_{s,Q} \approx R_{s,H} = 2.8,\ \Delta R_s \approx 0,\\ &R_{\ell,Q} = 0.3,\ R_{\ell,H} = 1.8,\ \Delta R_\ell \approx 0. \end{aligned} \tag{18}$$

These results imply [21] that, whereas the spatial separation of the two sources is negligible, their temporal separation is about 12 fm. This gives the lifetime of the system. If the mixed phase is of shorter duration or absent, this will obviously decrease.

This is shown more clearly in Fig. 2, where we have plotted the K_T dependence of ΔR_o and the outward, sideward, and longitudinal radii for the hadronic- and quark-matter sources of photons, obtained using the above procedure. We see that the outward, sideward, and longitudinal radii for the quark contribution depend weakly on the transverse momentum, indicative of only mild development of the flow during that phase. The corresponding radii for the hadronic contribution show a stronger dependence on the transverse momentum, which is indicative of a more robust development of the radial flow during the hadronic phase. The duration of the source reveals a very interesting structure, and in fact it increases slightly at higher transverse momenta as the photons emitted during the hadronic phase benefit from the strong radial flow to greatly increase their transverse momenta. The saturation of ΔR_o toward low K_T has its origin in the competition between radial expansion and decoupling of hadronic matter as it cools down below the freeze-out temperature at the edges.

The inverse root-mean-square momentum, which, as stated earlier, is a measure of the correlation radius, is seen to vary rapidly with K_T for the outward correlation, owing to rapid variation of the competing contributions from the quark- and hadronic-matter phases. For the sideward correlation, it goes smoothly from a value that is close to that for the hadronic matter at lower K_T to that for the quark matter at higher K_T, as one would expect. (The slight difference of $1/[2\,\langle q_s^2\rangle]^{1/2}$

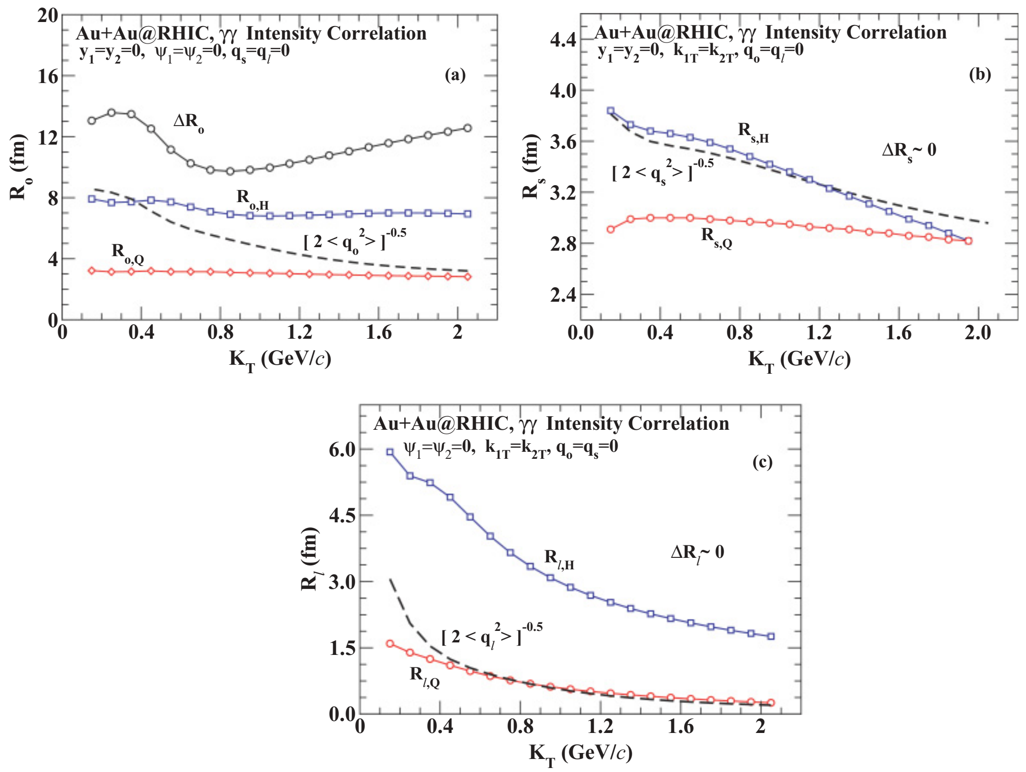

FIG. 2. (Color online) Transverse momentum dependence of (a) outward radii and temporal duration along with (b) sideward and (c) longitudinal radii for hadronic- and quark-matter sources obtained by fitting the final correlation function for thermal photons at RHIC energy. Radii determined from the root-mean-square momentum difference for the correlation function are also given for comparison [13].

from $R_{s,Q} \approx R_{s,H}$ at high K_T is due to the deviation of the calculated correlation function from a perfect Gaussian, to which it is fitted.)

As the fractions of the quark- and the hadronic-matter contributions play such a pivotal role in the momentum dependence of the overall correlation function, we study them next. The fractions I_Q and I_H taken from the calculations for the single-photon spectra are shown in Fig. 3, along with their dependence on the critical temperature. We shall discuss the importance of this dependence a little later.

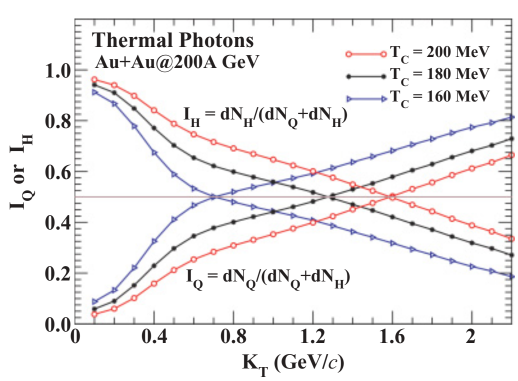

FIG. 3. (Color online) Transverse momentum dependence of the fraction of thermal photons from quark matter (I_Q) and hadronic matter (I_H) at RHIC energy. Solid curves show results for $T_C = 180$ MeV; dashed and dot-dashed curves show results for $T_C = 160$ and 200 MeV, respectively. (see text).

To understand these interesting results more clearly, we have plotted the source functions as a function of the transverse distance and time for thermal photons having $K_T \approx 0.5$, 1.0, and 2.0 GeV/c, in Figs. 4 and 5. In all cases we see that the radial distributions for the QGP as well as for the hadronic phase are centered at r_T near zero and that the source function for the hadronic phase extends considerably beyond the same for the QGP phase. This, of course, is only to be expected, owing to the large transverse expansion of the system. We also note a good yield of thermal photons from the hadronic phase at larger radii. In fact, one can see a slightly enhanced emission at larger radii compared to that from the central region for $K_T = 2\,\text{GeV}/c$. This, as noted earlier, arises due to the large kick received by the photons due to radial expansion, leading to the blue shift of their transverse momenta. The relative importance of the two contributions will depend on K_T and the transition temperature and will lead to a rich structure of the resulting correlation function. However, note that the second term in the source of photons from the hadronic matter becomes important at higher K_T, where the contribution of the hadronic phase to photons is rather small, and thus it could be difficult to detect this effect.

An even more valuable insight is provided by the temporal structure (Fig. 5) of the emission of photons from the QGP and hadronic sources, the latter emerging after a lapse of some time, which the system spends in the QGP phase. The duration during which photons from the hadronic phase are emitted is quite long and essentially controls the parameter ΔR_o. It

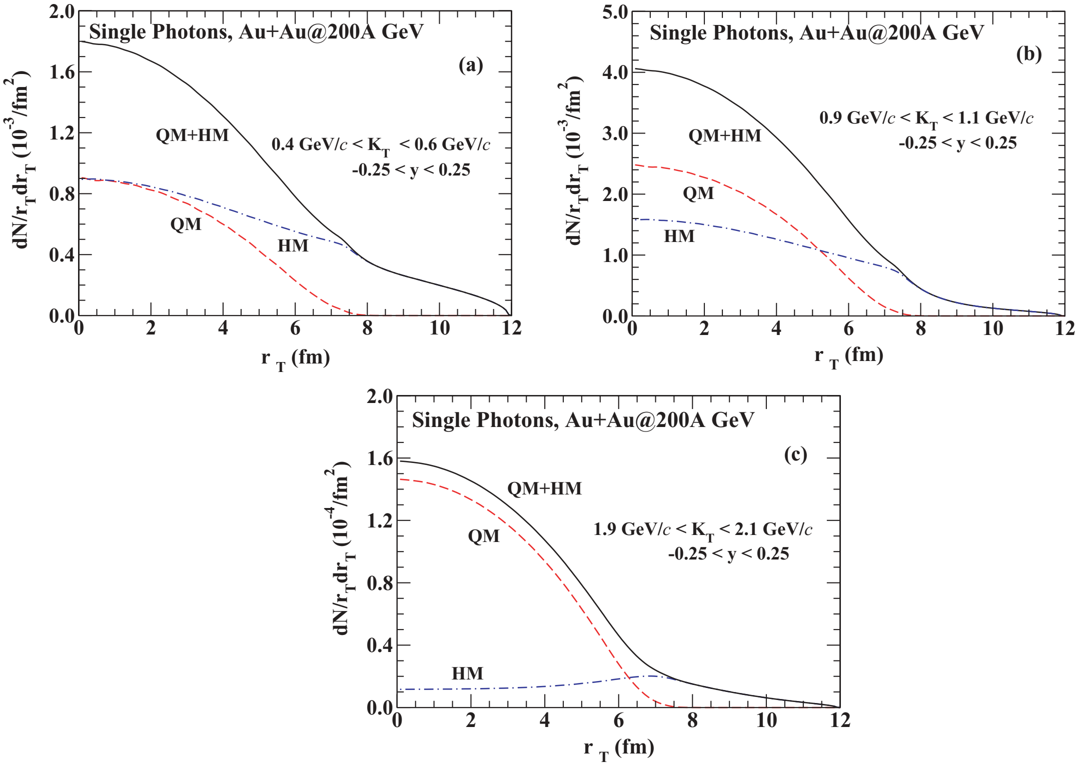

FIG. 4. (Color online) Radial dependence of the source distribution function for emission of photons having transverse momenta of (a) 0.5, (b) 1.0, and (c) 2.0 GeV/c at RHIC energy.

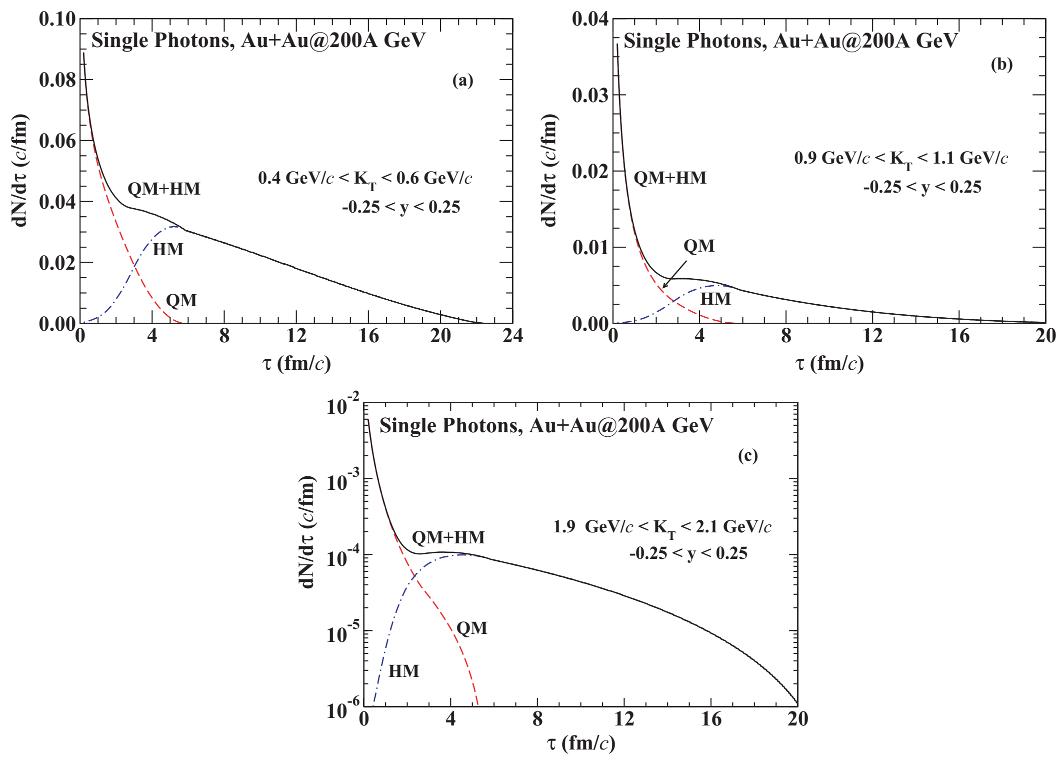

FIG. 5. (Color online) Temporal dependence of the source distribution function for radiation of photons having transverse momenta of (a) 0.5, (b) 1.0, and (c) 2.0 GeV/c at RHIC energy.

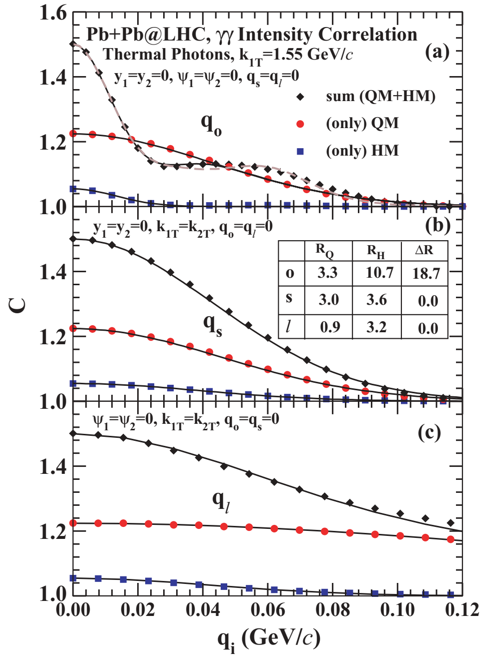

FIG. 6. (Color online) Same as Fig. 1, for Pb + Pb at LHC energy.

is worth recalling that the temporal structure of the source function seen here is qualitatively similar to that of the one seen in nucleus-nucleus collisions at cyclotron energies [21].

IV. RESULTS FOR LARGE HADRON COLLIDER ENERGIES

The LHC will study collisions of lead nuclei at unprecedented energies of 5500 GeV/nucleon. It is expected that the initial temperature likely to be attained in such collisions would be much higher than that at RHIC energies. This would provide a golden opportunity to study the properties of the QGP and the dynamics of its evolution. A higher initial temperature would lead to a longer duration of the interacting system, which in turn would provide ample opportunity for the mechanism of expansion to develop. We can thus expect to put our models of the evolution of the interacting system to a very rigorous test.

Figure 6 shows our results for the intensity correlation of thermal photons having $K_T \approx 1.5\,\mathrm{GeV}/c$ produced at the LHC. We see, as before, an interference from the photons from the hadronic and QGP phases of the system. We add that the fit to the calculated values for the outward correlation function can be improved considerably (see dashed curve in Fig. 6) by adding one more Gaussian term, centered at $q_0 \approx 0.06\,\mathrm{GeV}/c$, in the source term for the hadronic matter or by approximating $\rho_{o,H} \approx \sqrt{2(C_H - 1)}$, where C_H is the corresponding correlation function obtained numerically. We are trying to understand this observation.

The results for $C(q_s)$ and $C(q_\ell)$ are similar in nature to those found at RHIC energy. We note that now the temporal separation of the two sources is about 19 fm/c (see inset in Fig. 6).

Next we discuss the K_T dependence of the correlation radii (Fig. 7). We see behavior that is qualitatively similar

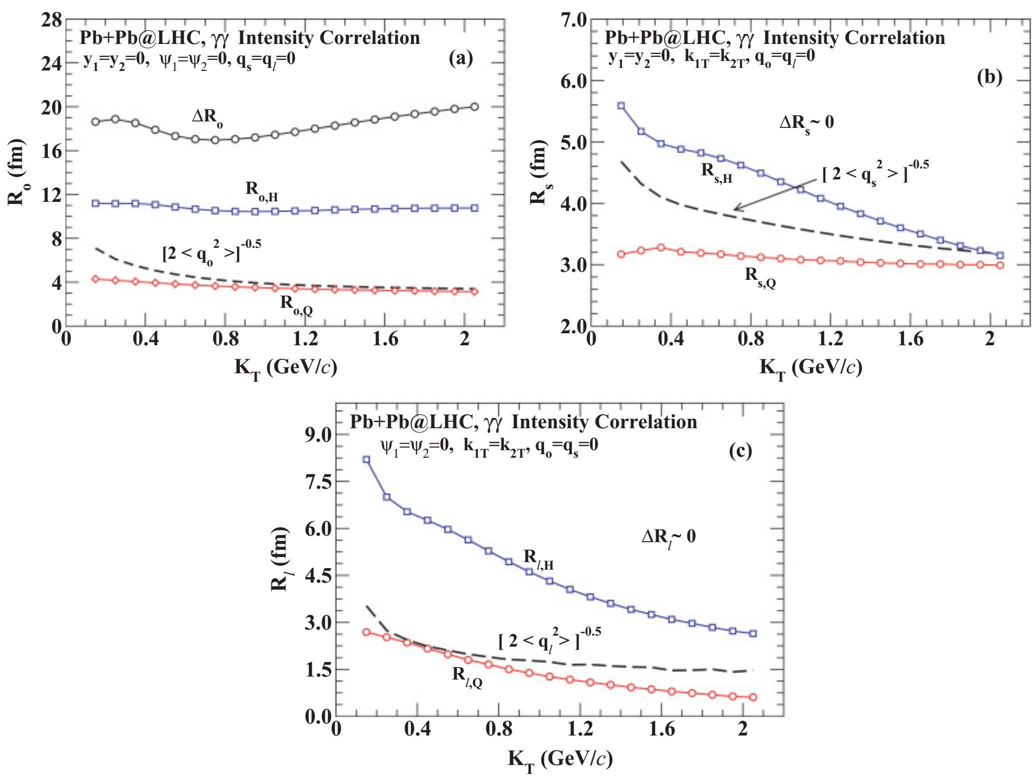

FIG. 7. (Color online) Transverse momentum dependence of (a) outward radii and temporal duration along with (b) sideward and (c) longitudinal radii for hadronic- and quark-matter sources obtained by fitting the final correlation function for thermal photons at LHC energy. Radii determined from the root-mean-square momentum difference for the correlation function are also given for comparison [13].

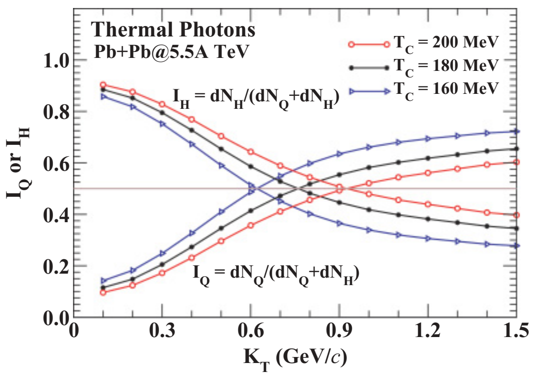

FIG. 8. (Color online) Transverse momentum dependence of the fraction of thermal photons from quark matter (I_Q) and hadronic matter (I_H) at LHC energy. Solid curves show results for $T_C =$ 180 MeV; dashed and dot-dashed curves show results for $T_C = 160$ and 200 MeV, respectively.

to that obtained earlier, though all the correlation radii are larger, especially ΔR_o, which gives the duration of the source. We emphasize here that $1/[2\,\langle q_i^2\rangle]^{1/2}$ is closer to $R_{i,Q}$ at LHC energy due to the dominance of quark matter contribution even at modest K_T.

In Fig. 8, we have plotted the fractions of momentum dependence of the quark and hadron contributions at LHC energies, at three transition temperatures: $T_C = 160$, 180, and 200 MeV. Comparing these results with those in Fig. 3, we see, once again, that a decreasing T_C increases the fraction of photons coming from the quark matter. We also note that the transverse momentum at which the quark and hadronic contributions become equal is quite sensitive to the transition temperature T_C. Realizing that, in an ideal situation, we would be able to decompose the outward, sideward, and longitudinal correlations into two sources and that their intercepts on the y axis will give I_Q and I_H, this opens up the tantalizing possibility of determination of the transition temperature, the two fractions becoming equal at K_T.

We next discuss the spatial (Fig. 9) and temporal (Fig. 10) distribution of the source function for photons having $K_T = 0.5$, 1.0, and 2.0 GeV/c produced in central collision of Pb nuclei at LHC energy. Although we note that the source distributions at LHC energy are qualitatively similar to those at RHIC energy, the extension of the hadronic sources beyond that of the quark sources (Fig. 9) and enhanced production at higher r_T from hadronic sources are amplified considerably here. A dying-out of the quark source and delayed buildup of the hadronic source in time (Fig. 10) are seen to emerge very clearly.

V. SENSITIVITY TO τ_0 AND T_C

We have seen that the final correlation is decided by the relative contributions from the quark matter, which occupies a smaller volume and is shorter lived, and those from the

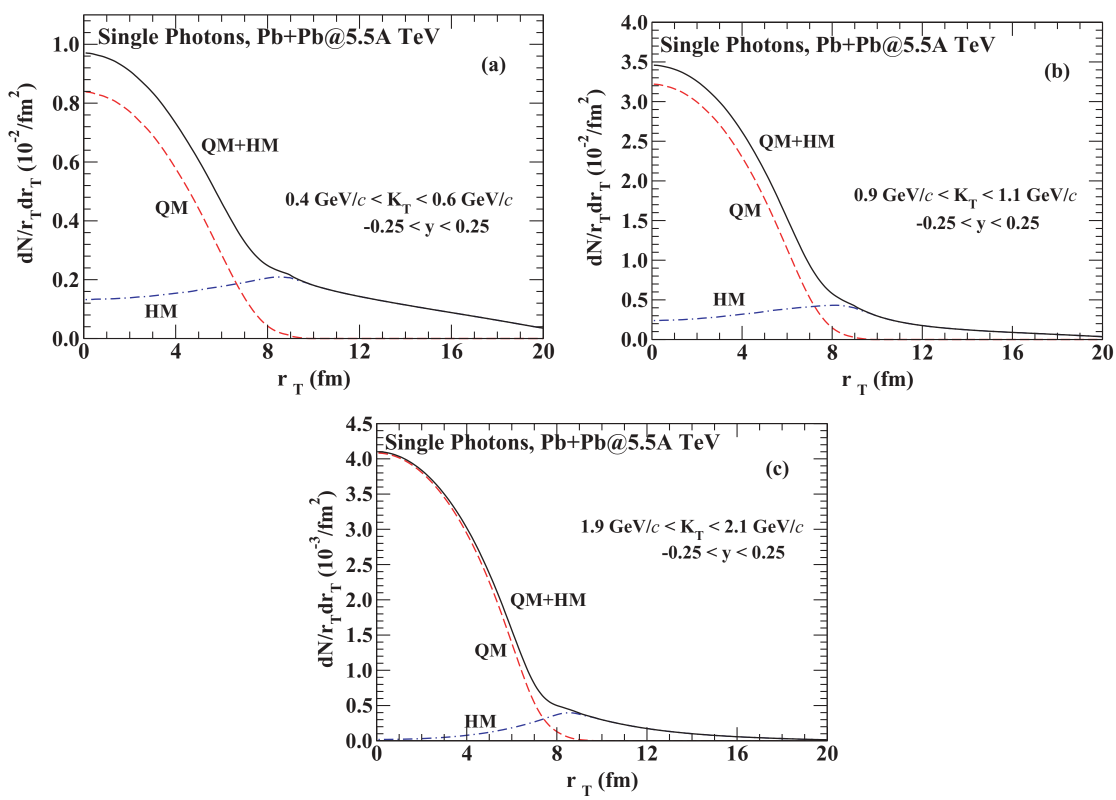

FIG. 9. (Color online) Radial dependence of the source distribution function for emission of photons having transverse momenta of (a) 0.5, (b) 1.0, and (c) 2.0 GeV/c at LHC energy.

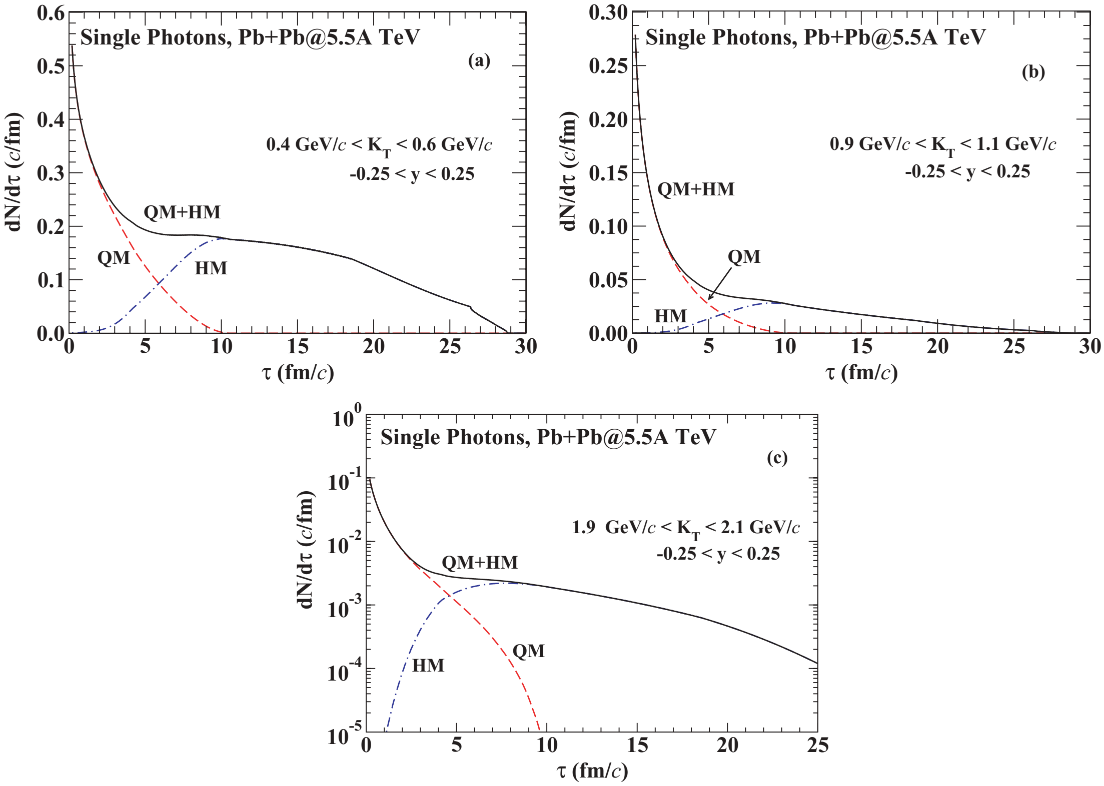

FIG. 10. (Color online) Temporal dependence of the source distribution function for radiation of photons having transverse momenta of (a) 0.5, (b) 1.0, and (c) 2.0 GeV/c at LHC energy.

hadronic matter, which occupies a larger volume and lives longer.

If the system thermalizes quickly, the initial temperature will be high. One can test the sensitivity of the results to the formation time of the plasma by considering systems with identical entropies but varying formation times (τ_0). The fractional contribution of the quark matter (I_Q) will increase with decreasing τ_0. Figure 11 shows the τ_0 dependence of the outward and longitudinal correlations at RHIC energy. The sideward correlation function did not show any perceptible change owing to the variation of τ_0 and is not shown here.

We must add here that choosing a long τ_0 would necessitate inclusion of the pre-equilibrium contribution to photons [10] that must surely be there, at least at higher K_T. The jet-conversion mechanism [11] is also likely to contribute at higher K_T. These contributions per force have their origin in the deconfined matter, and their spatial distribution is not likely to be very different from the early stages of the initial distributions assumed here. Their contributions would increase I_Q in these studies, which in turn could mimic an effectively shorter τ_0. This would still be useful, as it would amount to getting an effective τ_0, after which hydrodynamics can be applied.

However, these discussions open the door to another interesting and potentially powerful observation, perhaps with a far-reaching implication. We have already noted the sensitivity of the fractions of the contributions of the quark matter (I_Q) and the hadronic matter (I_H) to the transition temperature at both RHIC and LHC energies (see Figs. 3 and 8). Figure 12 shows our results for the sensitivity of the outward correlation at RHIC energy to the transition temperature. Recalling that an increase in the transition temperature leads to a decrease in I_Q, and that the quark-matter contribution has a smaller R_o, the change in the interference pattern seen at larger q_o is easily understood.

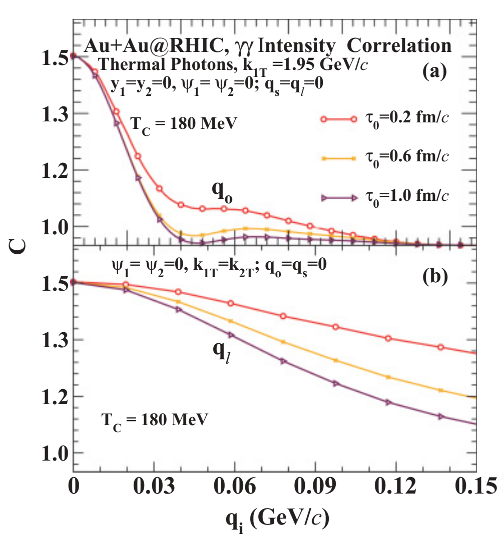

FIG. 11. (Color online) τ_0 dependence of (a) the outward and (b) the longitudinal correlation function at RHIC energy.

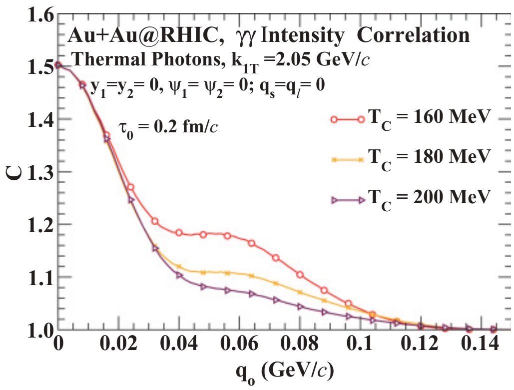

FIG. 12. (Color online) T_C dependence of the outward correlation function at RHIC energy.

It is felt that the results shown here should be valid whenever the correlations arise from contributions from two sources separated in space and time (see, e.g., Ref. [21]). The contribution of the two sources to the correlation function also provides a natural explanation for the failure of earlier studies [13] to find a simple Gaussian parametrization for it.

VI. SUMMARY

To summarize, the rich structure of the sideward, outward, and longitudinal correlation functions for intensity interferometry of thermal photons at RHIC and LHC energies has been calculated. The correlation functions are marked by a very distinctive interference between photons from the quark and those from the hadronic matter, which is most clearly visible in the outward correlation. We have calculated the transverse momentum dependence of the correlation radii and the duration of the emission and tried to understand their behavior by calculating the spatial and temporal distribution of the sources and their contributions. The study has thrown open the interesting possibility of determination of the transition temperature and formation time of the plasma. Finally, we would like to add that, even though several earlier studies have also talked of the two sources of photons (quark and hadronic matter) contributing to the correlation function, the present work, as far as we know, is the first attempt to study their interference in relativistic heavy-ion collisions.

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