# History of quark-gluon plasma evolution from photon interferometry

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Two-photon intensity interferometry is used to probe the dynamics of quarks and gluons in a high-energy nucleus-nucleus collision. A (1 + 1)-dimensional expansion of the plasma according to Bjorken hydrodynamics as well as a (3 + 1)-dimensional expansion, both with a first-order phase transition, are considered. The correlation of high-transverse-momentum photons is sensitive to the details of the space-time evolution of the high-density QCD plasma. The so-called "longitudinal" and "outward" correlations are found to be dramatically affected by the transverse expansion of the system.

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## I. INTRODUCTION

The primary motivation for colliding large nuclei such as gold or lead at high energies is to study the behavior of quantum chromodynamics (QCD) at high-energy density. By now it is believed that the collision proceeds in the following manner: The two clouds of valence and sea partons pass through each other, and multiple parton collisions and parton production occur, leading to a (generally nonequilibrium) high-density plasma of quarks and gluons [1]. This plasma expands, cools, and becomes more dilute. If QCD admits a first-order deconfinement or chiral symmetry phase transition, it is likely that the system will pass through a phase mixture of quarks and gluons and hadrons [2]. A further expansion causes the hadrons to lose thermal contact and free stream towards the detectors. Probably the most pressing issue is how to obtain useful information experimentally on a system of only ephemeral existence.

Intensity interferometry with electromagnetic waves has been an important tool to learn about the sizes and shapes of distant celestial objects [3]. Intensity interferometry with identical hadrons or light nuclei has also been an important tool to learn about the dynamics of subatomic or nuclear collisions [4]. However, since hadrons only appear in the final state of a very-high-energy nucleus-nucleus collision, their correlations mainly carry information about the late dilute stage of the collision, not about the early dense stage. The interferometric results for hadrons are also affected by final state interactions among the hadrons and contributions from resonance decays. We consider here instead photon interferometry of high-energy collisions [5–7]. In contrast to hadrons, photons are produced throughout the space-time evolution of the reaction, and suffer essentially no interactions with the surrounding medium once they are produced; thus they provide "live coverage" of the collision process. We focus on photons with large transverse momentum. These ought to be created primarily in the quark-gluon plasma because that is when the energy available to produce them is greatest.

In order to use photon interferometry to probe nuclear collision dynamics, we have to first understand the dependence of the $\gamma\gamma$ correlation function on the source size and the time development of the system. Recently, we have obtained [8] preliminary results for the photon interferometry of a quark-gluon plasma undergoing longitudinal expansion according to Bjorken hydrodynamics. We shall see that the correlation is very sensitive to the details of the transverse expansion of the system and to the phase transition. This, we feel, can be effectively utilized to deduce the history of the quark-gluon plasma.

## II. FORMULATION

The correlation between two photons with momenta $\mathbf{k}_1$ and $\mathbf{k}_2$ and the same helicity is

$$C(\mathbf{k}_1,\mathbf{k}_2)=\frac{P(\mathbf{k}_1,\mathbf{k}_2)}{P(\mathbf{k}_1)P(\mathbf{k}_2)}\ , \tag{1}$$

where

$$P(\mathbf{k})=\int d^4x\frac{dN(x,\mathbf{k})}{d^4x d^3k} \tag{2}$$

and

$$P(\mathbf{k}_1,\mathbf{k}_2)=\int d^4x_1 d^4x_2\frac{dN(x_1,\mathbf{k}_1)}{d^4x_1 d^3k_1}\frac{dN(x_2,\mathbf{k}_2)}{d^4x_2 d^3k_2}\times[1+\cos(\Delta k\cdot\Delta x)]\ . \tag{3}$$

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$dN(x, \mathbf{k})/d^4xd^3k$ is the rate per unit volume for producing a photon with momentum $\mathbf{k}$ at the space-time point $x$. This expression assumes an independent production of photons. We shall not consider photon energies so small that coherence effects need be included [5].

We shall represent the correlation function $C(\mathbf{k}_1, \mathbf{k}_2)$ in terms of the longitudinal, outward, and sideward momentum differences (see Fig. 1). Thus we have for the four-momentum $k_i^\mu$ of the $i$th photon,

$$k_i^\mu = (k_{iT} \cosh y_i, \mathbf{k}_i) \ , \tag{4}$$

with

$$\mathbf{k}_i = (k_{iT} \cos\psi_i,\ k_{iT} \sin\psi_i,\ k_{iT} \sinh y_i), \tag{5}$$

where $k_T$ is the transverse momentum, $y$ is the rapidity, and $\psi$ is the azimuthal angle. Now the difference of the transverse momenta $\mathbf{q}_T$ is obtained as

$$\mathbf{q}_T = \mathbf{k}_{1T} - \mathbf{k}_{2T}, \tag{6}$$

and the average transverse momentum is

$$\mathbf{K}_T = (\mathbf{k}_{1T} + \mathbf{k}_{2T})/2. \tag{7}$$

We choose the $x$ axis to be parallel to $\mathbf{q}_T$ and get

$$\begin{aligned} q_L &= k_{1z} - k_{2z} \\ &= k_{1T} \sinh y_1 - k_{2T} \sinh y_2, \end{aligned} \tag{8}$$

$$\begin{aligned} q_{\text{out}} &= \frac{\mathbf{q}_T \cdot \mathbf{K}_T}{K_T} \\ &= \frac{(k_{1T}^2 - k_{2T}^2)}{\sqrt{k_{1T}^2 + k_{2T}^2 + 2k_{1T}\, k_{2T} \cos(\psi_1 - \psi_2)}} \ , \end{aligned} \tag{9}$$

$$\begin{aligned} q_{\text{side}} &= \left| \mathbf{q}_T - q_{\text{out}} \frac{\mathbf{K}_T}{K_T} \right| \\ &= \frac{2k_{1T}\, k_{2T} \sqrt{1 - \cos^2(\psi_1 - \psi_2)}}{\sqrt{k_{1T}^2 + k_{2T}^2 + 2k_{1T}\, k_{2T} \cos(\psi_1 - \psi_2)}} \ . \end{aligned} \tag{10}$$

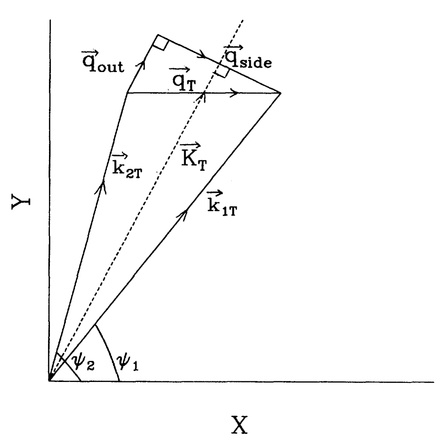


FIG. 1. The difference $\mathbf{q}_T$ of transverse momenta $\mathbf{k}_{1T}$ and $\mathbf{k}_{2T}$ along with the outward momentum $\mathbf{q}_{\text{out}}$ and the sideward momentum $\mathbf{q}_{\text{side}}$.

The thermal emission rate of photons has been studied in Ref. [9] (see also Ref. [10]). There it was found that the rates in the hadronic phase and in the plasma phase are the same, within our present ability to calculate them, when compared at the same temperature $T$. We use here the computed rate in the plasma phase, which is

$$E \frac{dN}{d^4xd^3k} = K\, T^2 \ln\left(\frac{2.9}{g^2} \frac{E}{T} + 1\right) \exp(-E/T) \ , \tag{11}$$

where $E$ is the photon energy, $g$ is the QCD coupling constant, and $K$ is a constant which is irrelevant for the correlation function.

In the following we shall first use the Bjorken hydrodynamics [11] relevant for a $(1+1)$-dimensional expansion and then give results for a $(3+1)$-dimensional expansion.

## III. BJORKEN HYDRODYNAMICS

Bjorken hydrodynamics [11] provides a simple description of the dynamic evolution of the plasma. It has been used to estimate both lepton pair [12] and photon production [13,14,10]. Details not given here may be found in those earlier papers.

In Bjorken hydrodynamics the local flow velocity of matter can be expressed in terms of the space-time rapidity $\eta$ as $u^\mu = (\cosh\eta, 0, 0, \sinh\eta)$. The coordinate time and position are $x^\mu = (\tau \cosh\eta, r \cos\phi, r \sin\phi, \tau \sinh\eta)$, where $\tau$ is the proper time and $r$ and $\phi$ are the radial coordinate and angle.

Since the only space-time dependence of the emission rate is through the temperature, and in the Bjorken model $T$ depends only on the proper time $\tau$, it is possible to integrate over all the variables in Eqs. (2) and (3) except for $\tau$. All the integrations are done exactly except the integration over the space-time rapidities for which the Gaussian approximation is made. We find that

$$P(\mathbf{k}_1, \mathbf{k}_2) = P_1 P_2 + P_{c1} P_{c2} + P_{s1} P_{s2} \ , \tag{12}$$

where

$$\begin{aligned} P_i = P(\mathbf{k}_i) = \pi R^2 K \int d\tau\, \tau \sqrt{\frac{2\pi T}{k_{iT}}}\, T^2 \ln\left(\frac{2.9}{g^2} \frac{k_{iT}}{T} + 1\right) \\ \times \exp(-k_{iT}/T) \end{aligned} \tag{13}$$

and

$$\begin{aligned} P_{ci} = \pi R^2 K \int d\tau\, \tau \sqrt{\frac{2\pi T}{k_{iT}}}\, T^2 \ln\left(\frac{2.9}{g^2} \frac{k_{iT}}{T} + 1\right) \\ \times \exp(-k_{iT}/T) \\ \times \left[\frac{2J_1(q_T R)}{q_T R}\right] \cos[(\Delta E \cosh y_i - q_L \sinh y_i)\tau]. \end{aligned} \tag{14}$$

Here $J_1$ is the Bessel function, $R$ is the radius of the identical nuclei undergoing a central collision, and

$$\Delta E = k_{1T} \cosh y_1 - k_{2T} \cosh y_2, \tag{15}$$

$$q_T = |k_{1T} \cos\psi_1 - k_{2T} \cos\psi_2| \ . \tag{16}$$

The $P_{si}$ are the same as the $P_{ci}$ with the substitution of a sine for the cosine. We note that $\Delta E \neq 0$ and/or $q_L \neq 0$ control the time correlation of the emitted photons. The space correlation is decided by $q_T \neq 0$ which is fixed for the "no transverse flow" condition envisaged here if $\Delta E = q_L = 0$.

When combining these expressions to obtain $C(\mathbf{k}_1, \mathbf{k}_2)$ it is apparent that the normalization of the rate $K$ is irrelevant. $K$ *is* important for predicting the total number of photon pairs, but it cancels when computing the normalized correlation function. The correlation function depends on the energies and orientations of the two photons.

The time dependence of the temperature is as follows. For a plasma formed at initial time $\tau_i$ with temperature $T_i$, the temperature falls as $T(\tau) = (\tau_i/\tau)^{1/3} T_i$ until it reaches the critical temperature $T_c$ at time $\tau_Q$. Between $\tau_Q$ and $\tau_H$ the temperature remains at $T_c$ while the latent heat is converted to collective longitudinal expansion energy. The length of time spent in the mixed phase depends on the latent heat. For a plasma of $u$ and $d$ quarks and gluons with a bag constant to simulate confinement, and a hadronic gas consisting of massless pions, $\tau_H/\tau_Q = 37/3$, the ratio of the number of degrees of freedom. In the following we shall treat hadronic matter as consisting of $\pi, \rho, \omega$, and $\eta$ mesons for consistency with the rates (11) and take the effective number of degrees of freedom as 4.56 to account for the masses of these hadrons [14]. Subsequently the temperature falls according to $T(\tau) = (\tau_H/\tau)^{1/3} T_c$ until it reaches some freeze-out temperature $T_f$. After that the pions free stream. We choose $T_c = 160$ MeV, and at the Brookhaven Relativistic Heavy Ion Collider (RHIC), $T_i = 532$ MeV at $\tau_i = 1/3T_i = 0.124$ fm/$c$ [15,1] with $T_f = 140$ MeV for a collision involving two lead nuclei. This model and these numbers are used for illustrative purposes.

In general, the integral over proper time in Eqs. (13) and (14) must be done numerically. There are two exceptions. When the system is in the mixed phase, $T(\tau) = T_c$, and the integral can be done analytically. The other exception is when we choose the configuration of momenta $k_{1T} = k_{2T} = k_T$, $y_1 = y_2$, which is equivalent to $\Delta E = q_L = q_{\text{out}} = 0$ and $q_T = q_{\text{side}}$. The remaining integrals over $\tau$ cancel in the ratio and

$$C(\mathbf{k}_1, \mathbf{k}_2, q_L = 0, q_{\text{out}} = 0) = 1 + \left[\frac{2J_1(q_{\text{side}}R)}{q_{\text{side}}R}\right]^2 , \tag{17}$$

where now $q_{\text{side}} = k_T|\cos\psi_1 - \cos\psi_2|$. This configuration obviously allows one to infer the radius of the emitting system. The typical scale of $q_{\text{side}}$ is seen to be $1/R \approx 20$ MeV for collisions involving lead nuclei. We also note that the correlation function for this configuration depends on $q_{\text{side}}$ alone, and thus its experimental determination can be facilitated by an integration of the rates over a large phase space.

There are obviously many different configurations of the two photons' momenta that can be studied.

Consider the correlation functions which arise when $y_1 = y_2 = 0$ and $\psi_1 = \psi_2$ and consider $C(\mathbf{k}_1, \mathbf{k}_2)$ as a function of the outward momentum difference $q_{\text{out}}$. This configuration implies $q_L = 0$. In Fig. 2(a) we show the correlation function from the plasma, the mixed phase, and the hadronic phase as if the other two contributions did not exist, for a number of values of $k_{1T}$. Qualitatively they look similar. It is rather intriguing though to see that the correlations vanish most rapidly for the mixed phase contribution, followed by those for the hadronic and the plasma contributions. They are also seen to be independent of $k_{1T}$ for the mixed phase, and nearly so for the plasma.

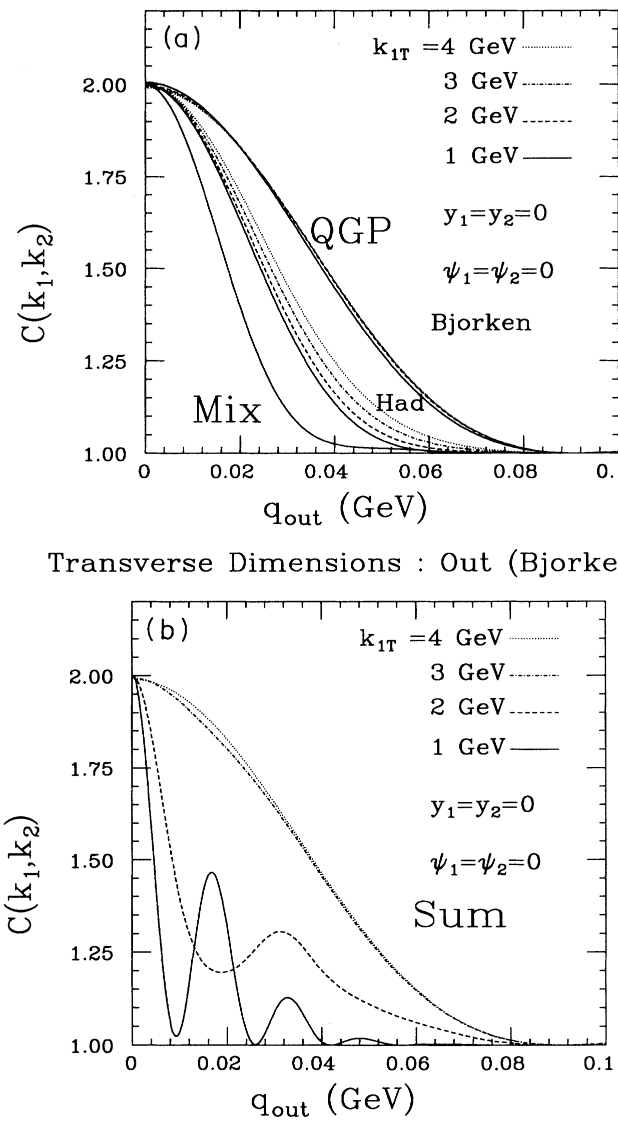


FIG. 2. (a) Outward correlation function at RHIC energy using Bjorken hydrodynamics for the plasma phase only, the mixed phase only, and the hadronic phase only. All the results are for a collision of two lead nuclei. (b) Outward correlation function at RHIC energy when contributions from the plasma, mixed phase, and hadronic phase are added together.

We can understand this as follows: The cosine and the sine terms in the integrals $P_{ci}$ and $P_{si}$ above reduce them in comparision to $P_i$. The moderation implied is largest for the longest living mixed phase and smallest for the shortest living plasma phase. Additionally, the constancy of the temperature during the mixed phase causes the correlation to be independent of $k_{iT}/T$ and it becomes a function of $q_{\rm out}$ alone.

The correlation function for the sum of all the contributions is shown in Fig. 2(b). We see that $C$ is only slightly affected by nonplasma contributions for larger $k_T$. For a smaller $k_T$ the correlation measuring the outward size of the system is seen to imply a decreasing *apparent* radius with increasing $k_T$ which reaches a plateau for larger values of $k_T$. Thus we see that the outward correlator is sensitive to the space as well as the time development of the system, since the physical transverse dimension of the system is constant in the Bjorken scenario. The typical length for the out correlation is seen to be about 20 MeV.

Finally we consider the correlation functions which arise when $k_{1T} = k_{2T}$ and $\psi_1 = \psi_2$, that is, $q_{\rm out} = q_{\rm side} = 0$ and consider $C(\mathbf{k}_1, \mathbf{k}_2)$ as a function of the longitudinal momentum difference $q_L$.

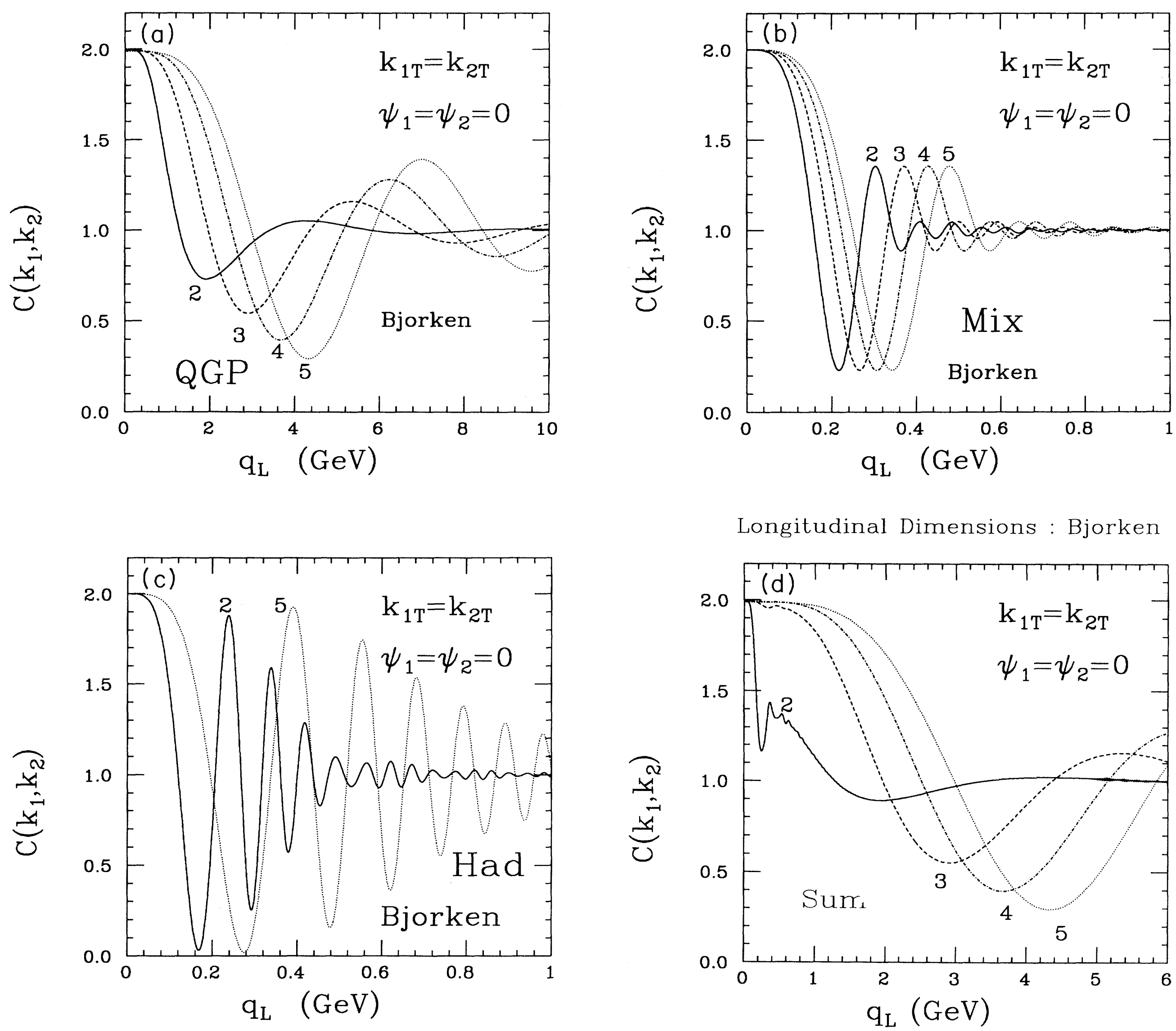


FIG. 3. (a) Longitudinal correlation function at RHIC energy using Bjorken hydrodynamics for the plasma phase only. The numbers 2, 3, 4, 5 indicate the transverse momentum of a single photon in GeV. (b) Same as (a) for the mixed phase only. Note that the horizontal scale here is a factor of 10 smaller than for (a). (c) Same as (a) for the hadronic phase only. Again note that the horizontal scale here is a factor of 10 smaller than for (a). (d) Longitudinal correlation function at RHIC energy when contributions from the plasma, mixed phase, and hadronic phase are added together using Bjorken hydrodynamics.

In Figs. 3(a–c) we show the correlation function from the plasma, mixed, and hadronic phases separately, computed as if the other two contributions did not exist. Qualitatively they look similar: $C \to 2$ as $q_L \to 0$, and $C \to 1$ as $q_L$ becomes large. In between $C$ undergoes damped oscillations due to the intensity interferometric effect. The numbers next to the curves denote the individual photon transverse momentum in GeV. However, it may be noted that the $q_L$ scale is *bigger* by an order of magnitude for the plasma than for the mixed or hadronic phases. This reflects the fact that the time scale in the plasma is much *smaller* than the time scale in the mixed or hadronic phases. Thus, in this configuration, $C$ is probing the temporal scale of the emitting material.

In Fig. 3(d) we combine the contributions from all three sources and recompute $C$. For a photon momentum of 2 GeV the interference between the rapidly oscillating mixed and hadronic contributions and the relatively slowing varying plasma contribution causes $C$ to drop very quickly from its limiting value of 2 at $q_L = 0$ to an average value of 1. At 3 GeV the mixed and hadronic phases influence $C$ only for small values of $q_L$, and for 4 and 5 GeV they have practically no effect at all. The reason is that the rate for producing photons falls exponentially with decreasing temperature, and so the mixed and hadronic phases cannot compete with the plasma phase for the production of high-momentum photons. For these high values of $k_T$ the correlation function is dominated by the high-temperature plasma, and information on it can be obtained.

The most interesting aspect, though, is the fact that the typical scale for the longitudinal correlation is about 2 GeV in comparison to a value of about 20 MeV for the sideward and the outward correlations. This is a consequence of the fact that the photon interferometry is most sensitive to the initial times. In fact for the configuration discussed here and for $k_T \gg T_i$, we can show that the correlation function from the plasma phase for small values of $q_L$ can be approximated as

$$C(\mathbf{k}_1, \mathbf{k}_2, q_{\rm out} = q_{\rm side} = 0) \approx 1 + \cos\left[\,4 k_T\, \tau_i\, \sinh^2(\Delta y/2)\right] . \quad (18)$$

Thus we see that the longitudinal correlator for photons can be used to infer the dimensions of the initial space-time extent of the system [8]. This is in stark contrast to the situation for hadron interferometry where the scales for the three correlators are similar [16] due to their sensitivity to the dimensions of the system at the instant of freeze-out.

This aspect has been demonstrated even more clearly in Ref. [8] where the longitudinal correlation function for two different initial times has been shown to be strikingly different.

## IV. TRANSVERSE FLOW EFFECTS

So far we have assumed that the transverse expansion of matter in the mixed phase and in the final hadronic phase was small enough so that soft photons could not be boosted to high transverse momentum. However, three-dimensional hydrodynamic calculations tend to give rather large collective transverse flow velocities in the late stages of the collision [17,18]. Thus after a time $\tau \approx R/c_s$, where $R$ is the transverse dimension of the system and $c_s$ is the velocity of sound, the rarefaction wave front is likely to reach the center of the expanding system and we cannot ignore the transverse expansion. The most obvious outcome of this flow is to impart an additional transverse (collective) momentum to the particles and their reaction products as noted above. It also leads to a more rapid cooling of the system and a reduced lifetime for the mixed phase and the final hadronic phase.

These aspects have been discussed in some detail [17,18] and we shall apply the techniques [19] used in these references. In brief, cylindrical symmetry along the transverse direction and boost invariance along the longitudinal direction along with appropriate initial boundary conditions [17] are employed. The initial time and the initial temperature are taken as before in Sec. III. The speed of sound during the hadronic phase is taken to be 0.238 [18,10]. In the presence of the transverse expansion of the system, the local flow velocity of the matter becomes

$$u^\mu = \gamma_T(\,\cosh\eta, v_T\,\cos\phi, v_T\,\sin\phi,\,\sinh\eta)\ , \quad (19)$$

where $\gamma_T = 1/\sqrt{1-v_T^2}$ and $v_T$ is the transverse velocity of the matter. This $v_T$ and the temperature of the fluid element are obtained from numerical calculations of the flow [17–19] as functions of $\tau$ and $r$.

Now the functions $P_i$ and $P_{ci}$ of Eqs. (13) and (14) become

$$P_i = K \int d\tau\,\tau\,r\,dr\,d\eta\,d\phi\,T^2\,\ln\left(\frac{2.9}{g^2}\,\frac{\gamma_T\,k_{iT}[\,\cosh(y_i-\eta) - v_T\,\cos(\phi-\psi_i)]}{T} + 1\right) \times \exp\{-\gamma_T\,k_{iT}[\,\cosh(y_i-\eta) - v_T\,\cos(\phi-\psi_i)]/T\} \quad (20)$$

and

$$P_{ci} = K \int d\tau\,\tau\,r\,dr\,d\eta\,d\phi\,T^2\,\ln\left(\frac{2.9}{g^2}\,\frac{\gamma_T\,k_{iT}[\,\cosh(y_i-\eta) - v_T\,\cos(\phi-\psi_i)]}{T} + 1\right) \times \exp\{-\gamma_T\,k_{iT}[\,\cosh(y_i-\eta) - v_T\,\cos(\phi-\psi_i)]/T\} \times \cos[(\Delta E\,\cosh\eta - q_L\,\sinh\eta)\tau - q_T\,r\,\cos\phi]. \quad (21)$$

As before, $P_{si}$ is given by an expression similar to (20) with the cosine replaced by a sine. These integrals have to be evaluated numerically.

We note that $q_T \neq 0$ controls the space-correlation and that $\Delta E \neq 0$ and/or $q_L \neq 0$ control the time correlation of the emitted photons.

### A. Sideward correlation

In Fig. 4(a) we show the correlation function for $k_{1T} = k_{2T} = 3$ GeV and $y_1 = y_2 = 0$ as a function of $q_{\rm side}$ for the plasma alone, the mixed phase alone, and the hadronic phase alone, along with the integration over the entire history of the system. This corresponds to the configuration $\Delta E = q_L = q_{\rm out} = 0$ and $q_T = q_{\rm side}$.

We can estimate the effective size of the three sources by parametrizing the corresponding correlation functions using Eq. (17). For the mixed phase and the hadronic phase contributions, $R_{\rm eff} \approx$ 1.5–2 fm. The quark-gluon plasma (QGP) part of the correlation function is found to be nearly identical to (17) with $R$ equal to the radius of the colliding lead nuclei.

This result can be easily understood by realizing that

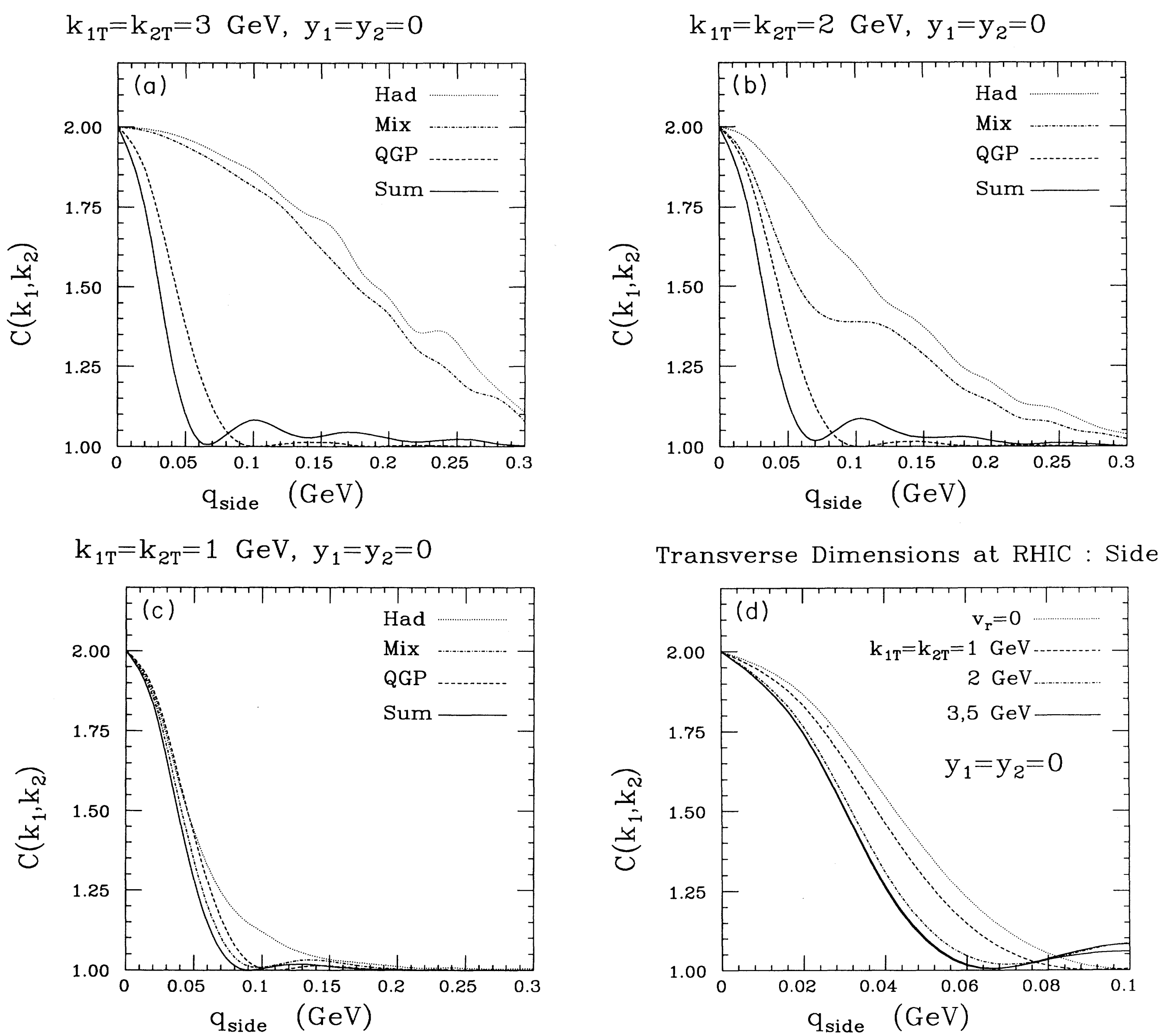


FIG. 4. (a) Sideward correlation function at RHIC energy for a transversely expanding system for photons having $k_T = 3$ GeV for the plasma only, mixed phase only, and hadronic phase only. The correlation for the entire history of the system is also given. (b) Same as (a) for $k_T = 2$ GeV. (c) Same as (a) for $k_T = 1$ GeV. (d) Sideward correlation function for the entire history of the system for $k_T = 1$, 2, 3, and 5 GeV. Results for no transverse flow are also given.

photons having a large $k_T$ can be produced from the colder hadronic matter and the mixed phase in substantial numbers only by taking advantage of the (collective) transverse flow [18] of the fluid. However, now two photons which are produced too far apart will have very different transverse flow velocities, and thus only photons produced near each other will be strongly correlated. We infer, therefore, that the transverse velocity of the QGP phase remains small across the entire original transverse region, whereas for the mixed phase and the hadronic phase it remains uniform only over $r \approx 1.5$–$2$ fm.

Finally, we find from the correlation function for the entire history that the transverse dimension of the system as seen by 3 GeV photons is about 10.5 fm, as compared to about 7.4 fm for the radius of the lead nuclei. This implies a net increase in the transverse dimensions of the system by 40% due to the transverse flow.

The results for photons having a transverse momentum of 2 GeV are given in Fig. 4(b) and those for 1 GeV in Fig. 4(c). The general trend is similar: We find that the transverse dimension determined by 2 GeV photons is about 3.5 fm for the hadronic matter and about 6 fm for the mixed phase, whereas it is between 6 and 8 fm for all the phases for photons having a $k_T$ of 1 GeV.

The correlation function accounting for the entire history of the system in terms of the sideward momentum difference is given in Fig. 4(d). We have also given the result (17) corresponding to no transverse flow discussed in the earlier section. We find that as the transverse momentum of the photons increases the transverse size of the system inferred from these photons increases, until it becomes a constant beyond $k_T \approx 3$ GeV with a value of about 10.5 fm, as discussed above.

At first this may seem to be surprising. However a look at the temperature profiles of the system at different times [Figs. 5(a) and 5(b)] shows that the transverse distance enclosed by a given temperature first increases with a decrease in the temperature (due to the transverse expansion) and then starts decreasing when more and more matter (from the surface) starts decoupling. As a consequence, observables sensitive to higher temperature and hence earlier times see a larger transverse radius. A similar consequence of the transverse expansion has also been seen in connection with freeze-out surface using Landau's hydrodynamics [20].

### B. Outward correlation

Let us now try to understand the dynamics explored by the correlation for the outward momentum difference.

We show the correlation function for $\psi_1 = \psi_2 = 0$ and $y_1 = y_2 = 0$ as a function of $q_{\text{out}}$ for the plasma phase for different values of $k_{1T}$ in Fig. 6(a). This corresponds to the configuration $q_L = 0$. We see that the results are nearly identical to the corresponding findings for Bjorken hydrodynamics in Fig. 2(a). This implies that the space and time development of the QGP phase as sampled by this correlation is not substantially affected by the transverse expansion. However the results for the mixed phase [Fig. 6(b)] and for the hadronic phase [Fig. 6(c)] are dramatically different from the corresponding findings for the case of no transverse flow [Fig. 2(a)]. The transverse expansion of the system forces the high $k_T$ photons from the hadronic and the mixed phases to be strongly correlated only if they are emitted very close to each other. The results for integration over the entire history of the system are given in Fig. 6(d). We see that the correlations for photons having smaller $k_T$ are dramatically affected by the transverse expansion.

It may be noted that both for the sideward and the outward correlations the typical momentum length is of the order of 10–20 MeV.

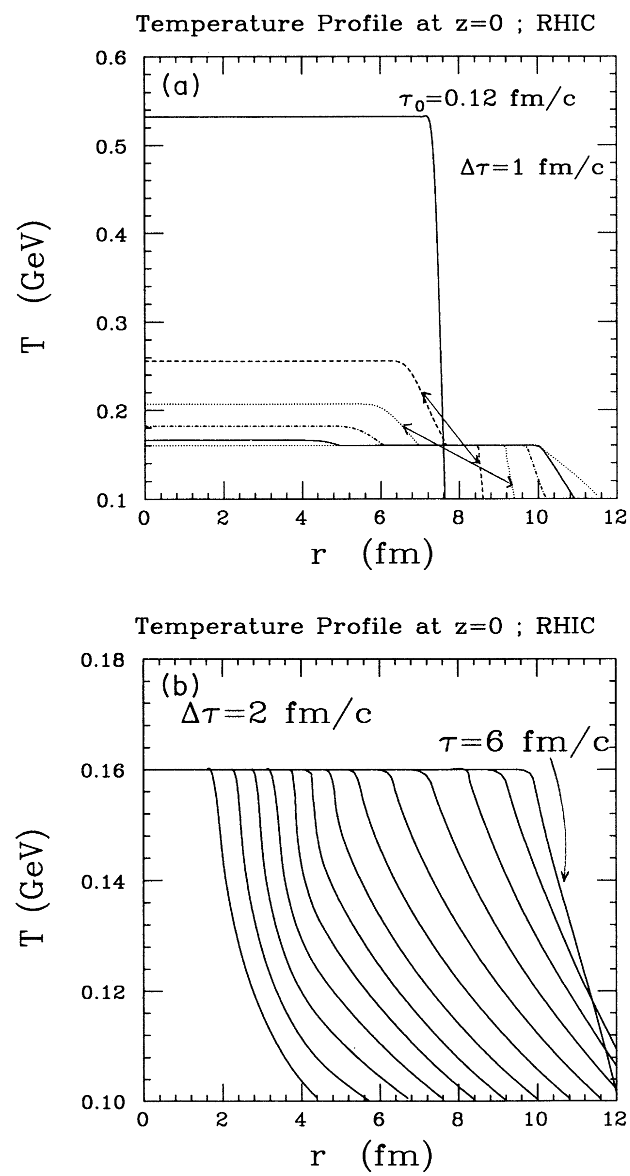


FIG. 5. (a) Temperature profile of the transversely expanding system at early times, when the temperature is still high. (b) Temperature profile of the transversely expanding system at late times, when the temperature is rather low.

### C. Longitudinal correlation

Finally we look at the dynamics explored by the correlation for the longitudinal momentum difference.

We show the correlation function for $\psi_1 = \psi_2 = 0$ and $k_{1T} = k_{2T}$ as a function of $q_L$ for the plasma phase for different values of $k_{1T}$, in Fig. 7(a). This corresponds to the configuration $q_{\rm out} = q_{\rm side} = 0$.

A comparison with Fig. 3(a) reveals that the longitudinal correlation is strongly influenced by the transverse expansion of the system already in the QGP phase even for the large values of the transverse momenta of the photons. The "longitudinal dimension" determined by $1/q_L$ is seen to decrease with the increase of the transverse momentum. The typical scale associated with this length is seen to be of the order of 0.5 GeV, in contrast to about 2 GeV for the case of no transverse flow. This is possibly indicative of the onset of the transverse expansion towards the end of the QGP phase. A similar trend is seen for the correlation of photons emitted from the mixed phase [Fig. 7(b)] and the hadronic phase [Fig. 7(c)] though the associated scale is reduced to 0.1 GeV. Finally the correlation for photons emitted during the entire history of the system is given in Fig. 7(d).

We recall that the inverse length scale for the plasma with no transverse flow was about 100 MeV for photons emitted from the mixed phase and the hadronic phases. These changes are brought about by reduction in lifetimes of the different phases due to transverse expansion.

In addition to these changes in the typical scales, the

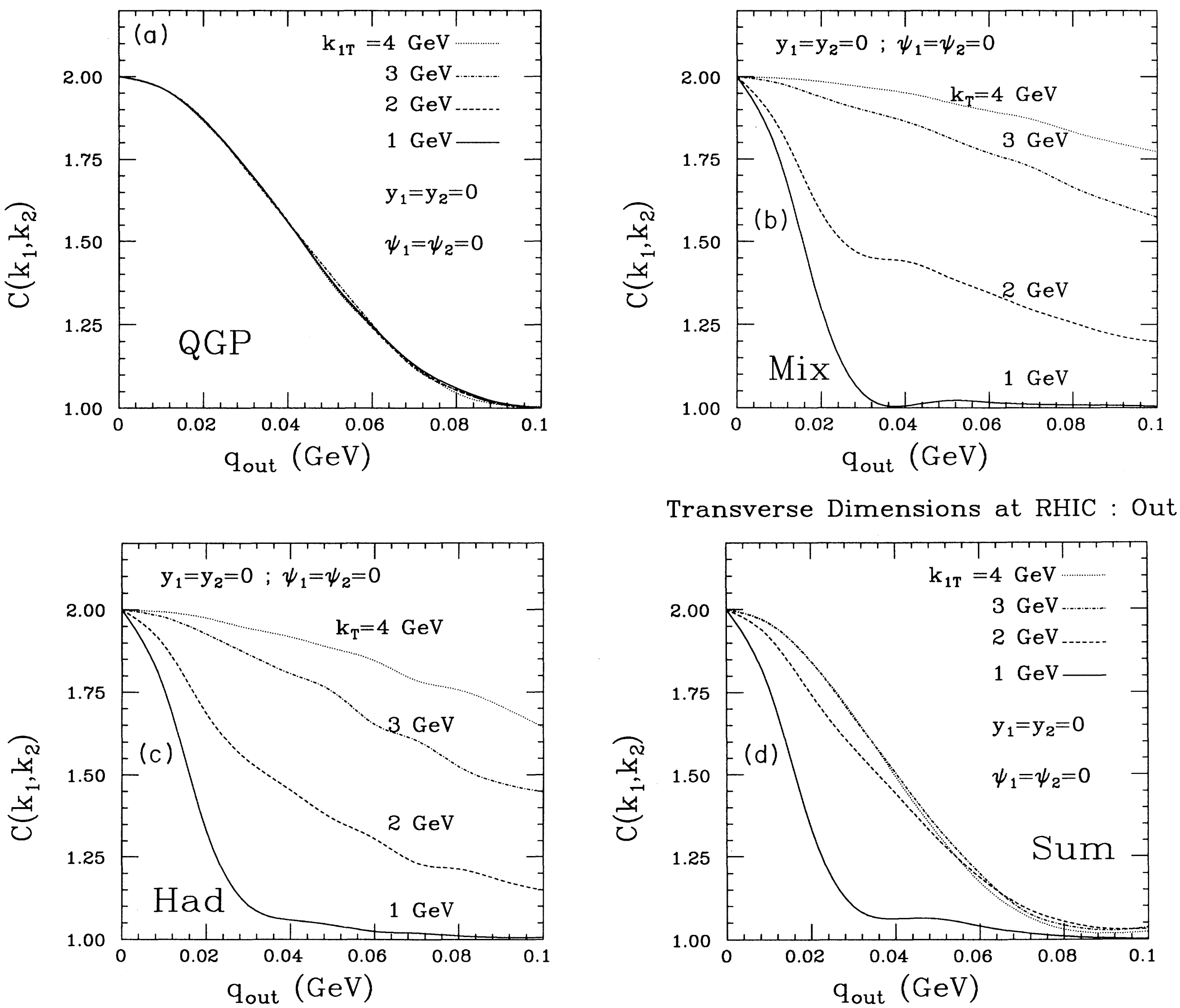


FIG. 6. (a) Outward correlation function at RHIC energy for a transversely expanding system for photons having different $k_T$ for the QGP phase only. (b) Same as (a) for the mixed phase. (c) Same as (a) for the hadronic phase. (d) Outward correlation function for the entire history of the system for $k_T$ = 1, 2, 3, and 4 GeV.

most dramatic difference in the correlation functions with and without the transverse flow is the absence of the oscillations in the former.

## V. SUMMARY AND DISCUSSION

We have studied the interferometry of photons having large transverse momenta emitted from an expanding quark-gluon plasma at RHIC energies with and with-out transverse flow. Results have been presented in terms of sideward, outward, and longitudinal momentum differences for a variety of configurations. The photons having largest tranverse momenta are shown to be least affected by the transverse flow. The correlation function seeks out photons having similar momenta from regions of space and time over which the relative (collective) transverse flow is not large.

The most dramatic consequence of the transverse expansion is in the longitudinal correlation, which is seen to be affected by the transverse expansion of the QGP phase itself, even though this expansion is rather small during the QGP phase.

The outward correlator is also seen to be strongly affected by the transverse expansion. The power of the photon interferometry in probing the history of the system is also seen while studying the sideward correlation, which is sensitive to the transverse dimension of the system. It was found that photons having large momenta exhibit correlation over a large transverse radius seen at

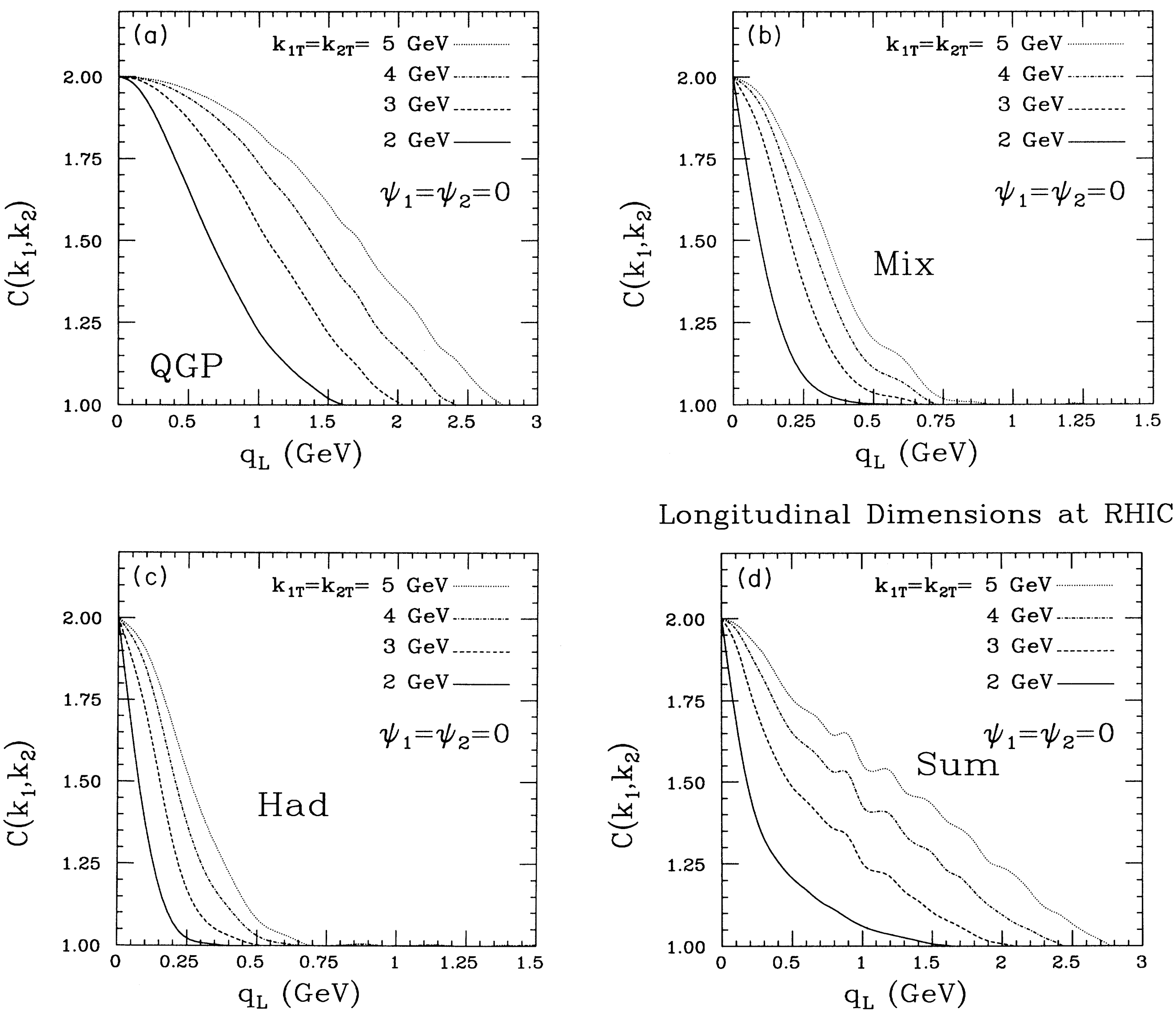


FIG. 7. (a) Longitudinal correlation function at RHIC energy for a transversely expanding system for photons having different $k_T$ for the QGP phase only. (b) Same as (a) for the mixed phase. (c) Same as (a) for the hadronic phase. (d) Longitudinal correlation function for the entire history of the system for $k_T$ = 2, 3, 4, and 5 GeV.

early times when the system was still undergoing expansion. The photons having smaller transverse momenta exhibit correlation over smaller transverse radii, corresponding to later times when the freeze-out surface had started moving in.

From the results presented so far we conclude that photon interferometry can be effectively utilized to probe the history of quark-gluon plasma.

All the results presented so far assume that the polarization of each photon is known. If a polarization average is taken instead, then the factor $1+\cos(\Delta k\cdot\Delta x)$ in Eq. (3) gets replaced by $1+\frac{1}{2}\cos(\Delta k\cdot\Delta x)$. This means that $C\to\frac{3}{2}$ at zero relative momentum rather than 2. Otherwise the behavior of the correlation function would remain unchanged.

The question of background (which, if too large, would destroy the beautiful tool of photon interferometry) has already been discussed in Ref. [8]. In the following, we repeat the arguments developed there. The main source of background photons would be from $\pi^0$ and $\eta$ decays. (Decays of the $\rho^0$ and $\omega$ are included in the rate calculations [9] because their lifetimes are short.) These decay photons do not contribute to the interference term in $C$ unless the relative momentum under consideration is on the order of the inverse lifetime of the meson or less, which is too small to be of interest to us. Therefore, one can write

$$C(\mathbf{k}_1,\mathbf{k}_2)=1+\frac{P_{c1}P_{c2}+P_{s1}P_{s2}}{(P_1+D_1)(P_2+D_2)}\ , \tag{22}$$

where the $P$'s are as defined earlier and the $D$'s are the contributions from the decay photons. An experiment which makes no attempt to subtract $\gamma$'s coming from $\pi^0$ and $\eta$ decay would result in a certain value of $D(\mathbf{k})$; call it $D_{\rm full}(\mathbf{k})$. An experiment which is 100% efficient in identifying decay photons should give $D(\mathbf{k})=0$. An experiment which makes some attempt at identification would give $D(\mathbf{k})=[1-e(\mathbf{k})]\ D_{\rm full}(\mathbf{k})$, where $e(\mathbf{k})$ is the efficiency of identifying decay photons. The oscillatory signal remains, but its magnitude is diminished due to the decay photons. The question then is, how large is $D/P$? At the ISR (the disassembled intersecting storage rings at CERN) it was possible to measure photons, to reconstruct $\pi^0$'s and $\eta$'s, and to subtract their contributions from the total photon spectrum [21]. This procedure left a signal for "direct" photons for $k_T>2$ GeV/$c$. The signal increased with $k_T$. The ratio of direct photons to $\pi^0$'s was found to be about 2% at 2 GeV/$c$ and increased to about 12% at 5 GeV/$c$. It is estimated that if $\gamma_{\rm direct}/\pi^0>5\%$ for $k_T>1$ GeV/$c$ at a relativistic heavy ion collider like RHIC or the CERN Large Hadron Collider, a similar experiment could be successfully designed and built [22]. Then the decay photons could be subtracted out and we would be left with a contamination $D/P$ negligibly small.

One can argue that the situation might even be better in a central collision of heavy nuclei than in a *pp* collision. High $k_T$ pions in a *pp* collision come primarily from hard parton-parton scattering. In a nucleus-nucleus collision, such pions could only be emitted from the surface because partons in the interior would continue to interact and their momentum would be degraded [1]. Another way to phrase this is to recognize that the yield of interesting photons coming from direct QCD processes in the plasma is proportional to the square of the charged particle multiplicity $(dN_{\rm ch}/dy)^2$ whereas the decay photons are proportional to $dN_{\rm ch}/dy$ [23]; thus direct photons become increasingly important with increasing multiplicity. Estimates for $\gamma_{\rm direct}/\pi^0$ in central collision of gold nuclei at RHIC vary from about 20% [14] to 100% [24] for $k_T\approx$ 3 GeV.

In order to simulate a detector, integration of the one- and two-photon distribution functions over some range of momentum space must be done. In this paper, as in Ref. [8], we have fixed all the components of the difference of momenta but one, and plotted the correlation function versus the remaining variable. Of course, the greater the range of momentum space integration, the greater the observable yield of photon pairs will be. However, information is lost with every increase in the range of integration. So there is a tradeoff between yield and information. The experiment will not be easy. If $\gamma_{\rm direct}/\pi^0$ is on the order of 20%, then an experiment would need to run about 25 times longer than if two-hadron interferometry was done and if the same cuts on momenta [25] were applied.

The unique sensitivity of the photon interferometry seen in the present work could also to used to check the validity of hydrodynamic expansion employed here. One may use it to check the other alternative, a cascade model of the mixed and final hadronic phases, which makes no assumptions about the maintenance of local equilibrium, and which yields rather small transverse velocities [26].

It is worthwhile to mention a suggestion [27] that the ease of a near $4\pi$ coverage and much larger luminosities implicit in fixed target experiments might prove to be of enhanced importance for photon interferometry.

In conclusion, we have demonstrated that information about the space-time dynamics of quarks and gluons in high-energy nuclear collisions can be obtained with photon intensity interferometry.

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