

Direct photon interferometry

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Abstract. We consider recent developments in the theory of the two-photon interferometry in ultrarelativistic heavy ion collisions with emphasis on the difference between photon and hadron interferometry. We review the available experimental results and discuss possibilities of measurement of the photon Bose-Einstein correlations in ongoing and future experiments.

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Direct photon interferometry is the one of the most interesting and informative tools for exploring properties of the hot matter, created in heavy ion collisions. Photons have extremely large free path length in the hot matter and deliver direct information about space-time dimensions of the inner hottest part of the collision. Moreover, the direct photons, emitted at different stages of the collision, dominate in the direct photon spectrum in different ranges of transverse momentum, therefore, measuring correlation radii at different K_T one can extract space-time dimensions of the system at the different stages of the collision and thus access the equation of state of the hot matter.

Direct photons contribute only a small fraction of the total photon yield while the dominant part of inclusive photons comes from decays of final hadrons, mainly π^0 and η mesons. Fortunately, the lifetime of these hadrons is extremely large, and the width of Bose-Einstein correlations between decay photons is of the order of a few eV, so that it can not be observed and it does not obscure the direct photon correlations. So, when one talks about the photon interferometry, one means the correlations of direct photons.

Technically the interferometry of direct photons in most respects is similar to the hadron interferometry, but still it has several specific features, which make it special. These features, which will be discussed in details below, are related to the following properties of a photon:

- The penetrating nature of the direct photons. Since direct photons are emitted from the central zone of the collision and photons with different K_T are emitted at the different stages of the collision, photon interferometric correlation radii do not follow the M_T scaling, usual for hadrons, but have more complicated shape.
- Zero mass of a photon results in specific interpretation of the invariant correlation radius and correlations strength parameter, and requires some special one-dimensional parameterization of the photon correlations.
- Small proportion of direct photons in the total photon yield makes photon correlation strength parameter very small what in turn leads to the importance of background photon correlations.

First predictions of the direct photon intensity correlations in heavy ion collisions have

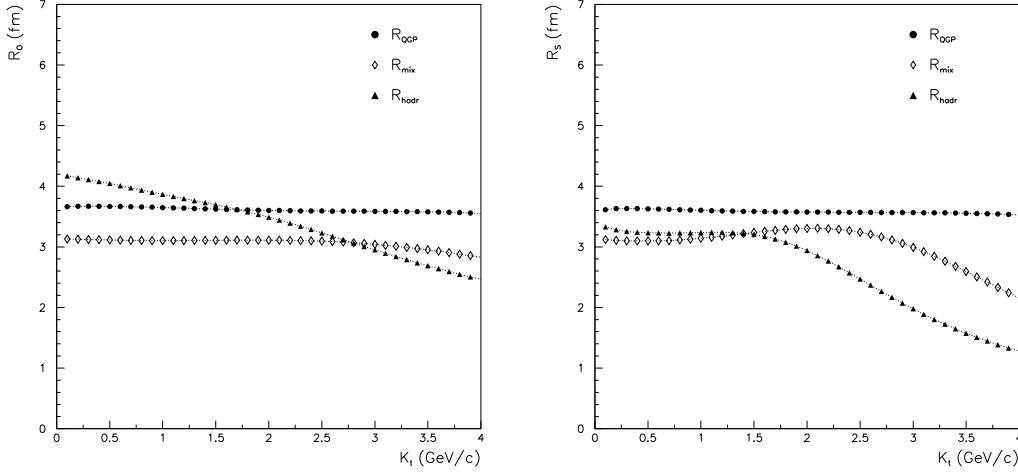


FIGURE 1. Two-photon correlation radii in Au+Au collisions at RHIC energy [4] for "side" (left plot) and "out" (right plot) directions. Contributions of QGP, mixed and hadronic phase are shown separately.

been published long ago [1, 2, 3, 4], while the next bunch of calculations [5, 6, 7] appeared after publishing of the first experimental results on direct photon interferometry by WA98 collaboration [8]. Despite the large number of publications, up to now there is no agreement between predictions not only in the absolute values of the correlation radii of direct photons, but even on the shape of K_T dependence of the correlation radii. For example, in the Fig. 1 we present predictions of the "out" and "side" correlation radii of photons, emitted in Au+Au collisions at RHIC energy [4]. These predictions are made within 2+1 Bjorken hydrodynamics with the first order phase transition. Contributions from the different phases: QGP, mixed and hadronic phase are shown separately. We find no K_T dependence for photons, emitted from the QGP phase (including pQCD photons), radii from the mixed phase is constant up to $K_T \sim 3$ GeV where Doppler-shifted contributions from a few accelerated pieces became important, and photons emitted from the hadronic phase exhibit some K_T dependence in agreement with the large collective flow developed in this phase. We compare two predictions of direct photon correlation radii for central Au+Au collisions at RHIC energy ($\sqrt{s_{NN}} = 200$ GeV), in the Fig.2. In the left plot we present result of the calculations, made within 2+1 Bjorken hydrodynamics [4]. In the right plot we show results obtained using parameterization of the evolution with a constant acceleration [7]. We find the bump and the region with $R_s > R_o$ in the first case and the M_T scaling in the second case. Whether this discrepancy can be attributed to the difference in evolution or it is related to the details of extraction of correlation radii is not clear yet.

Strength of direct photon correlations is usually extremely small, being on the level of tenth of percent, therefore it is difficult to gather sufficient statistics to construct the full three-dimensional correlation function. So one has to deal with averaged one-dimensional distributions. However, for massless particles the averaging from the full three-dimensional correlation function to those, depending on $Q_{inv} = \sqrt{-(k_1 - k_2)^2}$

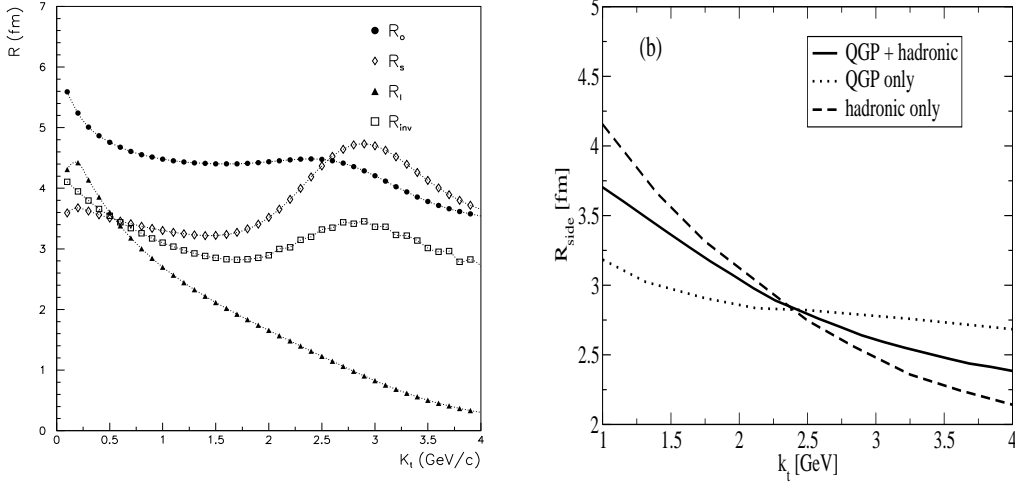


FIGURE 2. K_T dependence of different components of photon correlation radii in Au+Au collisions at RHIC energy, obtained with 2+1 Bjorken hydrodynamics [4] (left plot) and R_{side} dependence within model with parameterization with constant acceleration [7] (right plot).

has some unexpected features. To illustrate this, let us consider a simple toy model: assume, that photons are emitted from the symmetric Gaussian source with the radii $R_x = R_y = R_z = R$ and the emission duration τ so that the full correlation function of photons is

$$C_2(q, K) = 1 + \lambda \exp(-q_x^2 R^2 - q_y^2 R^2 - q_z^2 R^2 - q_e^2 \tau^2),$$

where q and K are relative and average momenta of the pair and λ is the correlations strength parameter. To go from the full three-dimensional to the one-dimensional parameterization, we have to integrate over the components of the relative momentum under the condition $\delta(Q_{inv}^2 + q^2)$. The result can be expressed as follows:

$$\begin{aligned} C_2(Q_{inv}, K) &= \frac{1}{4\pi} \int C_2(\hat{q}, \hat{K}) d\Omega = \frac{1}{4\pi} \int [1 + \lambda \exp(-Q_{inv}^2 R^2 - 4K_T^2 \cos^2 \theta (R^2 + \tau^2))] d\Omega \\ &= 1 + \lambda_{inv} \exp(-Q_{inv}^2 R^2), \end{aligned}$$

where \hat{q} and \hat{K} are the relative and average pair momentum in pair CM frame, the integration $d\Omega$ is done over directions of the relative momentum and K_T is average transverse momentum of the pair. We find that the correlation strength of the one-dimensional correlation function is considerably reduced:

$$\lambda_{inv} = \frac{\lambda}{2} \int d\cos\theta \exp(-4K_T^2 \cos^2 \theta (R^2 + \tau^2)) = \frac{\sqrt{\pi} \operatorname{erf}(2K_T \sqrt{R^2 + \tau^2})}{2K_T \sqrt{R^2 + \tau^2}}.$$

Calculations with the more realistic source demonstrate that the invariant correlation radius of massless particles is (using out-side-long three-dimensional radii) an average of the R_s and R_l correlation radii and almost independent on the R_o component, while the

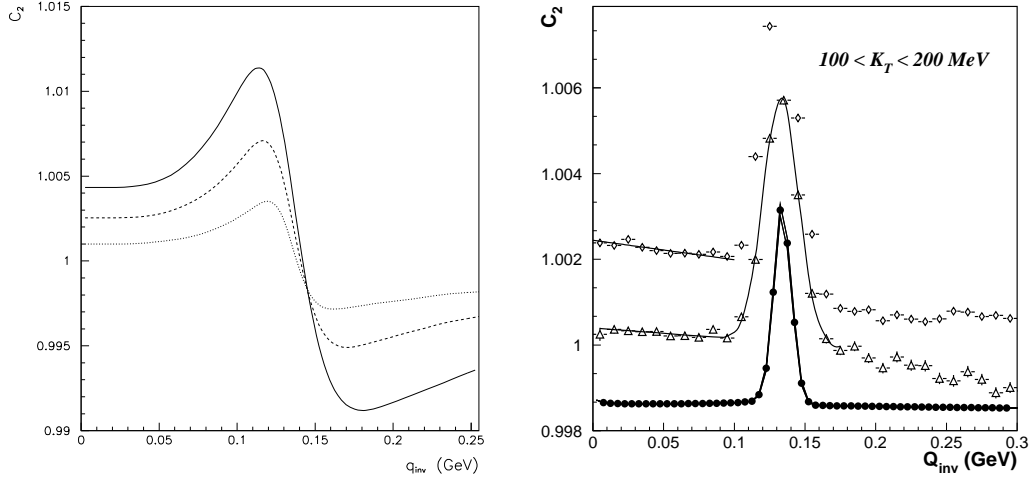


FIGURE 3. Decay photon background correlations. Left plot is residual correlations between products of Bose-Einstein correlated π^0 , calculated for 3 different radii of pion correlations: 4, 5 and 6 fm (solid, dashed and dotted lines correspondingly) [4]. Right plot presents result of Monte-Carlo simulations of different residual correlations within WA98 acceptance and experimental cuts [8] due to π^0 BE correlations (diamonds), elliptic flow (triangles) and kinematic correlations (boxes).

invariant correlation strength parameter depends on the product ($K_T R_o$) and is considerably smaller than the three-dimensional correlation strength parameter. This takes place because Q_{inv} for massless particles depends mainly on the opening angle and is almost independent on the q_o so we average over this component in the range $|q_o| \leq 2K_T$.

The extremely small strength of the direct photon correlations leads to the importance of the photon background correlations: even small correlations between decay photons may completely hide the direct photon correlations. Since the decay photons originate in decays of final hadrons, they may carry some residual correlations. Keeping in mind that the main part of the decay photons comes from π^0 decays, one can classify the background correlations as following: (1) residual correlations between the decay photons originated from Bose-Einstein correlated neutral pions; (2) residual correlations between products of kinematically correlated pions or photons, e.g. photon correlations in the processes $K_S^0 \rightarrow 2\pi^0 \rightarrow 4\gamma$ or $\omega \rightarrow \gamma\pi^0 \rightarrow 3\gamma$; (3) residual correlations due to collective (elliptic) flow of parent pions. The first point (1) is the most dangerous since if the shape of these residual correlations will repeat the shape of Bose-Einstein correlations of the parent pions, this background will completely hide the direct photon correlations. Fortunately, this is not the case. One can analytically demonstrate, that the residual correlations due to pion Bose-Einstein correlations have a characteristic wave-like shape with the plateau at small Q_{inv} (see Fig. 3) and can be disentangled from the direct photon correlations. Monte-Carlo simulations made by WA98 collaboration [8] (fig. 3, right plot) and by Utyuzh et al. [9] support this conclusion. The shape of the background correlations due to the kinematic correlations (case 2) and the elliptic flow (case 3) strongly depends on the apparatus acceptance and the experimental cuts used in analysis, but usually it appears as a long range correlations, as presented in the Fig. 3,

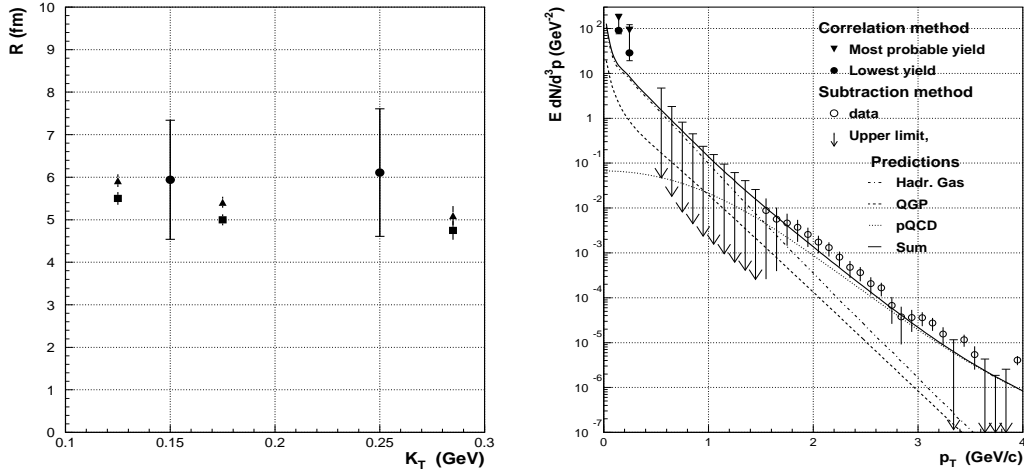


FIGURE 4. Left plot: direct photon invariant correlation radius in Pb+Pb collisions at 158 AGeV (circles), compared to side (triangles) and long (boxes) charged pions correlation radii. Right plot: direct photon yield, extracted from correlation strength parameter, compared to theoretical predictions and yield, obtained with the statistical method [8].

right plot. So, the background photon correlations in nucleus-nucleus collisions can be disentangled from the direct photon correlations but should be accounted in calculation of the correlation parameters.

The first measurement of the direct photon correlations in ultrarelativistic heavy ion collisions was performed by WA98 collaboration [8]. Its unique electromagnetic calorimeter, consisting of $4 \cdot 4 \cdot 40 \text{ cm}^3$ lead glass blocks, was situated at a distance of 21 m from the interaction point. This provided an excellent opportunity to measure photon pairs with very small relative momenta. The main difficulty in this analysis was the separation between the apparatus effects like cluster merging and splitting and the real physical correlations, since the former strongly distort photon correlation function at small q . This separation was done by introducing cuts on a minimal distance between clusters and exploring the dependence of the final result on these cuts. However, at $K_T \geq 0.5 \text{ GeV}$ photons with relative momenta $q < 50 \text{ MeV}$ have so small relative angle that it was not possible to perform such an analysis any more and the invariant correlation radius and the strength parameter were measured only at small K_T , see the Fig. 4. The photon invariant correlation radius was close to the pion "side" and "long" radii and was considerably above than the theoretical predictions [4]. In addition to the photon correlation radius, using the correlation strength parameter, a proportion of the direct photons was extracted and the direct photon yield was measured at a very small p_T , where the other methods can not be applied. Since the relation between the full three-dimensional and the one-dimensional invariant correlation strength parameters involves R_o – radius which can not be estimated using R_{inv} – a lower limit, corresponding to $R_o = 0$ and the most probable yield ($R_o = 6 \text{ fm}$) of direct photons was extracted.

Presently there is a possibility to extract the direct photon correlations in A+A collisions at RHIC energy with the ongoing PHENIX and STAR experiments and at

LHC with building ALICE experiment. Experiment PHENIX has an electromagnetic calorimeter, consisting of two parts, one of them is the same calorimeter used in WA98 installed at a distance of 540 cm from the interaction point while the rest of calorimeter has coarser granularity $5.5 \cdot 5.5 \text{ cm}^2$ and situated at a distance of 510 cm from the interaction point. Although in PHENIX the calorimeter is 4 times closer to the interaction point than one was in the WA98 experiment, this is compensated by smaller energies of photons since PHENIX is a collider experiment so that it is able to access photon pairs at small $q \sim 30 \text{ MeV}$ up to $K_T \sim 1 \text{ GeV}$. Experiment STAR is going to get advantage of their tracking chamber and extract the direct photon correlations between photons, one of which has converted into electron-positron pair on a material of the detector and the second is detected with calorimeter. The ALICE experiment at LHC will be even more suitable for measuring of two-photon correlations. Its highly granulated PHOS calorimeter made of $2 \cdot 2 \cdot 20 \text{ cm}^3 \text{ PbWO}_4$ crystals will be installed at a distance of 460 cm from the interaction point and will have 4 times more channels per solid angle and much better energy and position resolutions than existing calorimeter in PHENIX. Simulations show that PHOS will be able to measure direct photon correlations up to $K_T \sim 2 \text{ GeV}$.

To summarize, the direct photon correlations are very important tool for exploring space-time evolution of the hot matter in ultrarelativistic heavy ion collisions. Although there are plenty of predictions, there is no agreement neither in absolute value of the photon correlation radii nor even in the shape of their K_T dependence. We considered several remarkable differences between photon and hadron interferometry, related to the penetrating nature and zero mass of a photon and the small yield of direct photons. First results from the WA98 experiment demonstrated possibility of measurement of the direct photon correlations in ultrarelativistic heavy ion collisions. Ongoing experiments PHENIX and STAR at RHIC as well as building experiment ALICE at LHC have real possibility to measure the direct photon correlations so one can expect more results soon.

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