Direct Photon Interferometry in Bi-Bi Collisions at $\sqrt{s_{NN}}$ = 9.2 GeV

The 28th International Scientific Conference of Young Scientists and Specialists (AYSS-2024)

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29 October 2024

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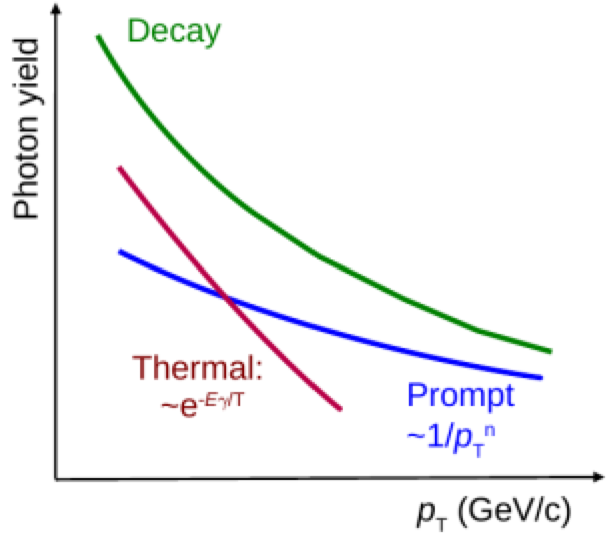
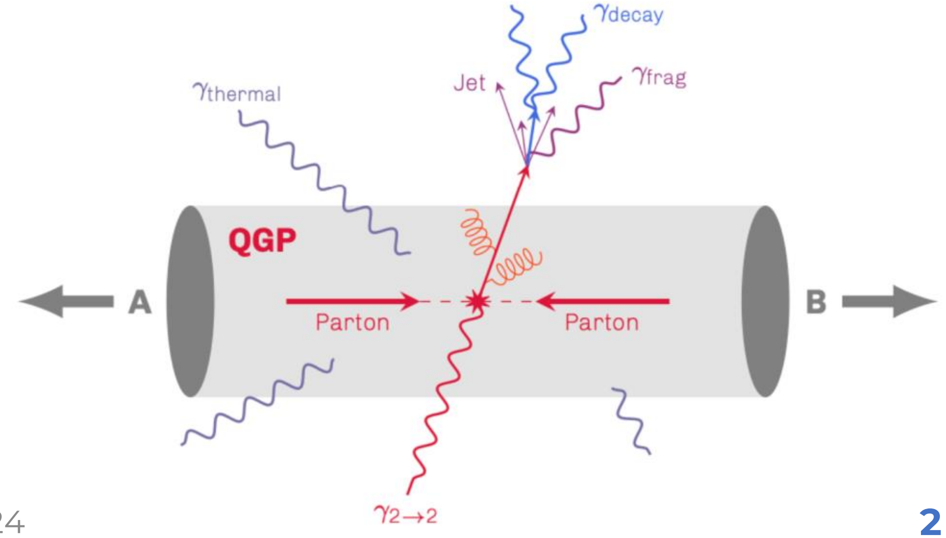
Introduction

- **Direct photons** – photons not originating from hadron decays:
  - **thermal photons** ($\sim e^{-E_\gamma T}$), thermal radiation of QGP, space-time evolution of QGP
  - **prompt photons** ($\sim 1/p_T^n$), initial hard scattering, testing pQCD, PDF (+nPDF modification) and FF constrains:

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = \sum_{i,j,k} f_i(x_i, Q^2) \otimes f_j(x_j, Q^2) \otimes D_k(z_k, Q^2)$$

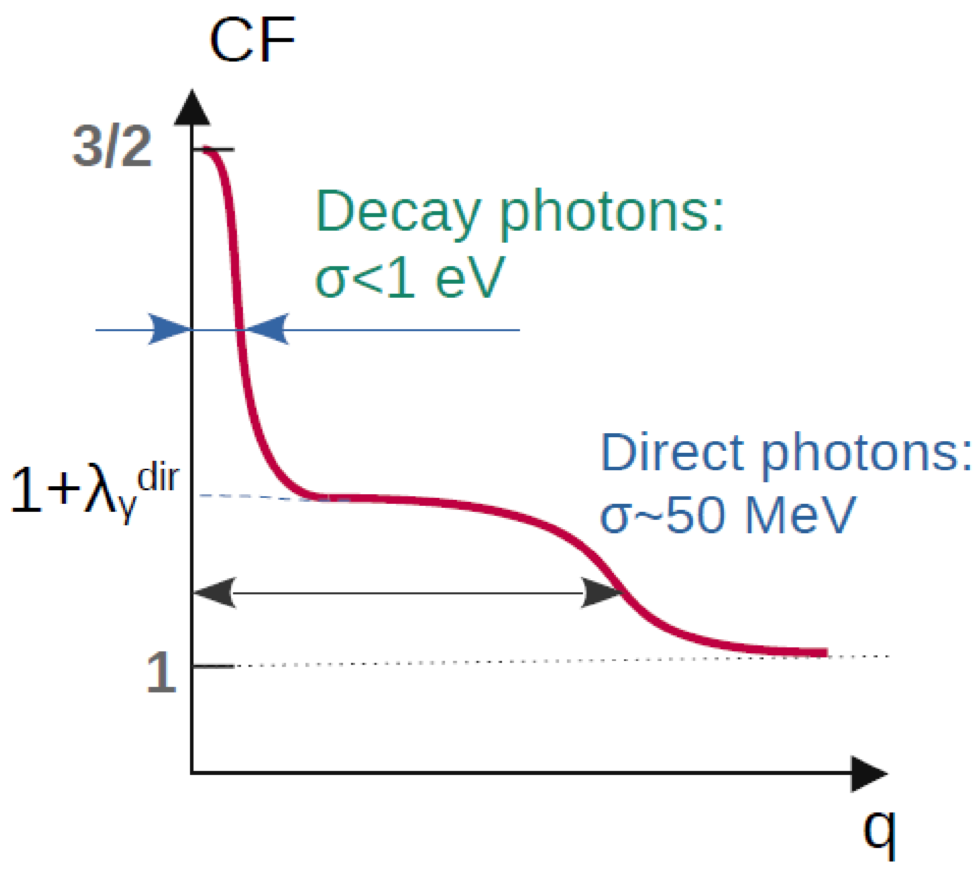
  - Other sources: fragmentation photons, pre-equilibrium photons
- Photons are color neutral: not affected by QGP ⟶ perfect probe for studying QGP properties
- **Two-photon Bose-Einstein correlations** could be used for measurements of direct photon yields and correlations radii
- In this talk we present results on hydrodynamic calculations of direct photon correlations (interferometry) in Bi-Bi collisions at $\sqrt{s_{NN}}$ = 9.2 GeV





Direct photon Bose-Einstein correlations

Correlation function:



- Interferometry in heavy-ion collisions is based on the symmetrization of the wave-functions of two identical particles
  ⟶ for bosons: **Bose-Einstein (BE) Correlation**

- Increased probability of finding particles with low **relative momentum of the pair (*q*)** ⟶ estimation of the size of the emitting source

- The observable for the interferometry is **correlation function (C_2)** – ratio of correlated two-photon distribution to noncorrelated distribution

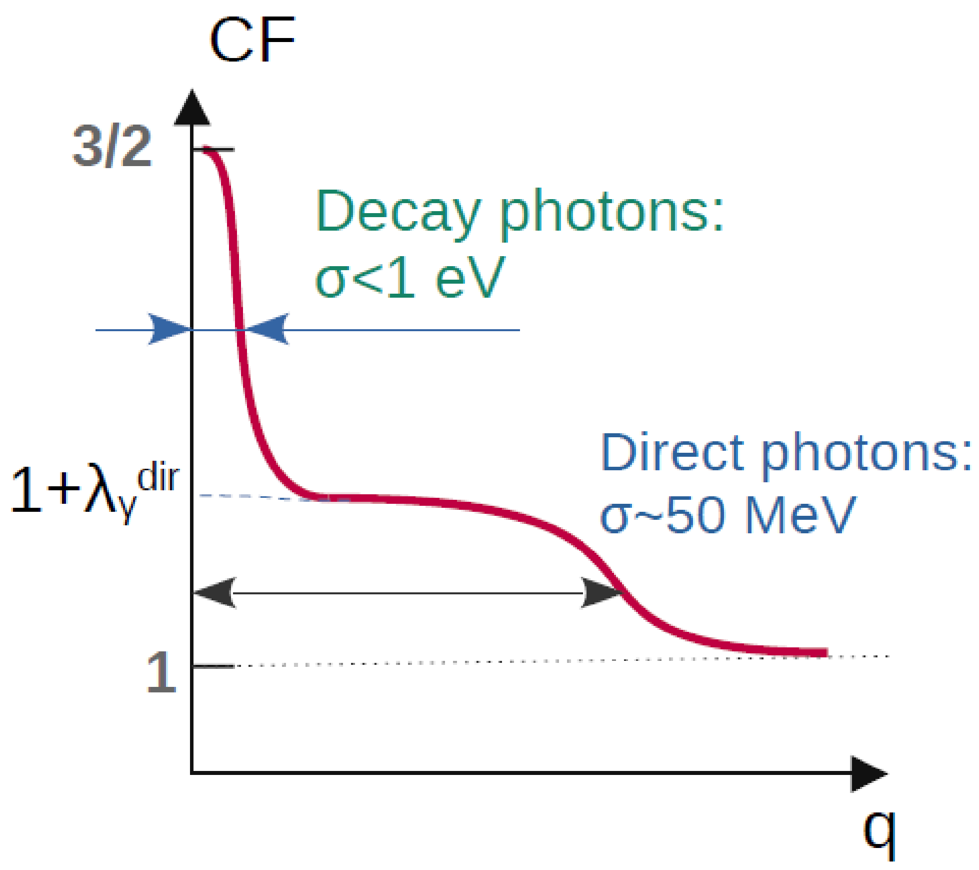
$$C_2(\boldsymbol{p}_1, \boldsymbol{p}_2) = \frac{E_1 E_2 dN/(d^3p_1 d^3p_2)}{(E_1 dN/d^3p_1)(E_2 dN/d^3p_2)}$$

Kinematics variables:

- Relative momentum of the pair: $\boldsymbol{q} = \boldsymbol{p}_1 - \boldsymbol{p}_2$
- Mean pair momentum: $\boldsymbol{K} = \frac{1}{2}(\boldsymbol{p}_1 + \boldsymbol{p}_2)$

Direct photon Bose-Einstein correlations

Correlation function:



- General definition:

$$C_2(\boldsymbol{p}_1, \boldsymbol{p}_2) = \frac{E_1 E_2 dN/(d^3p_1 d^3p_2)}{(E_1 dN/d^3p_1)(E_2 dN/d^3p_2)}$$

- This expression could be written as

$$C_2(\boldsymbol{q}, \boldsymbol{K}) = 1 \pm \frac{|\int d^4x S(x,K)\, e^{iq\cdot x}|^2}{\int d^4x_1 S(x_1, K + 1/2\cdot q) \int d^4x_2 S(x_2, K + 1/2\cdot q)}$$

where ***S*** is emitting function, (-) for fermions, and (+) for bosons

- It was shown that the ***smoothness approximation*** is valid for calculations in heavy-ion collisions **Pratt S. *Phys. Rev. C* 56:1095 (1997)**

$$C_2(\boldsymbol{q}, \boldsymbol{K}) \approx 1 + \left|\frac{\int d^4x S(x,K)\, e^{iq\cdot x}}{\int d^4x S(x,K)}\right|^2$$

Kinematics variables:

- Relative momentum of the pair: $\boldsymbol{q} = \boldsymbol{p}_1 - \boldsymbol{p}_2$
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Thermal photon emitting functions

QGP emission: JHEP 0112:009,2001

$$S(K) = A(K) \cdot (\ln(T/m) + C_{\text{tot}})$$

$$C_{\text{tot}} = \frac{1}{2}\ln(2K/T) + C_{\text{bream}}(K/T) + C_{\text{annih}}(K/T) + C_{2\to2}(K/T)$$

Combination of photons produced in bremsstrahlung, quark annihilation and scattering processes in QGP

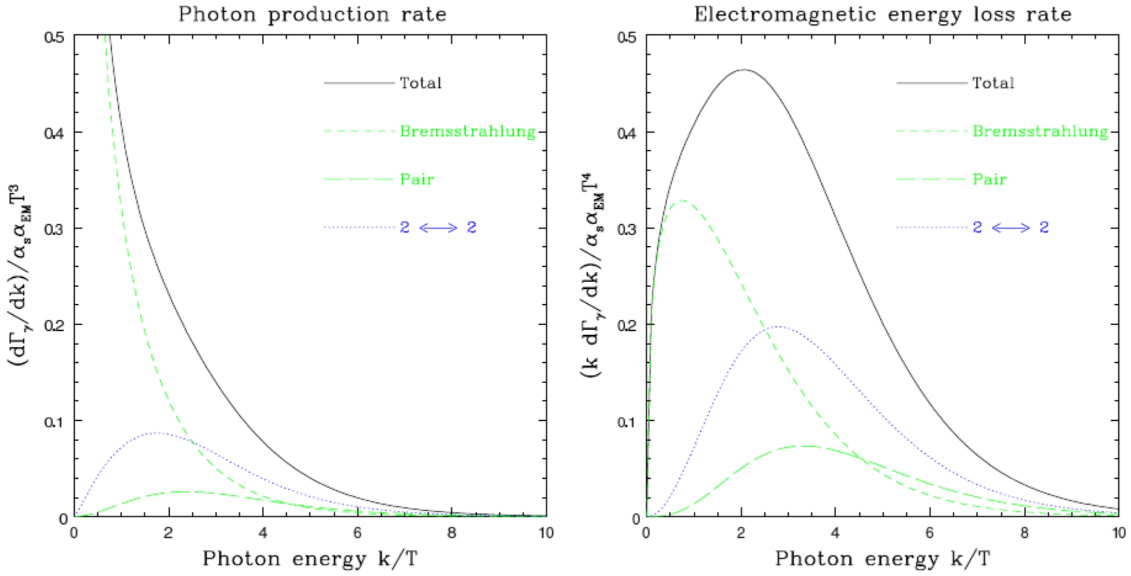
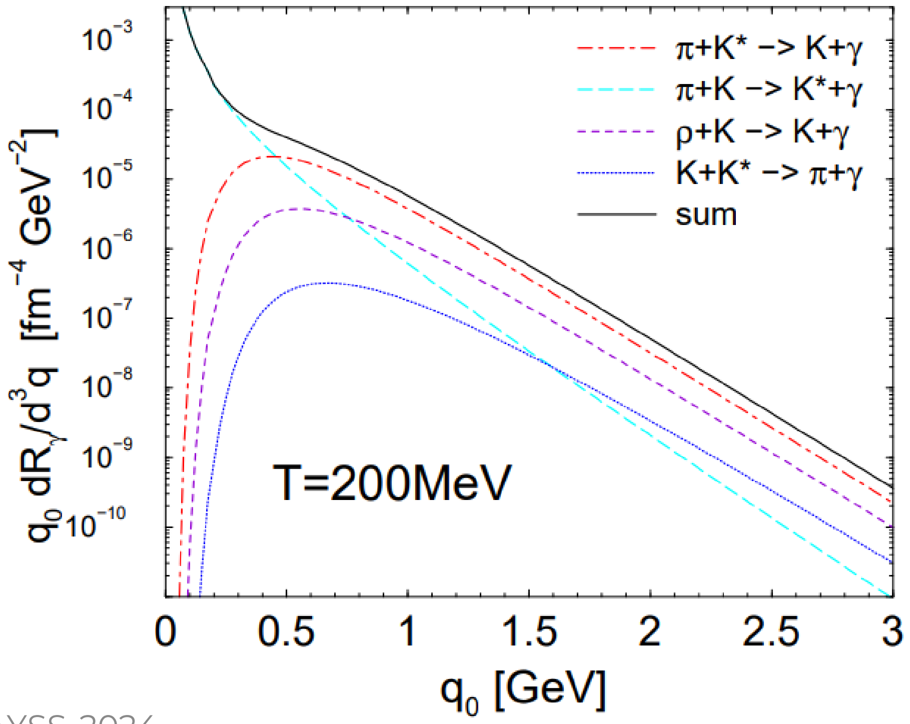


FIG. 9. Total photon emission rate, together with the bremsstrahlung, inelastic pair annihilation and $2 \leftrightarrow 2$ contributions, for two-flavor QCD with $\alpha_s = 0.2$. The left panel shows $d\Gamma_\gamma/dk$, divided by $\alpha_s\,\alpha_{EM}\,T^3$, while the right panel shows rates weighted by photon energy.

Hadron gas emission: Phys. Rev. C 69, 014903 (2004)

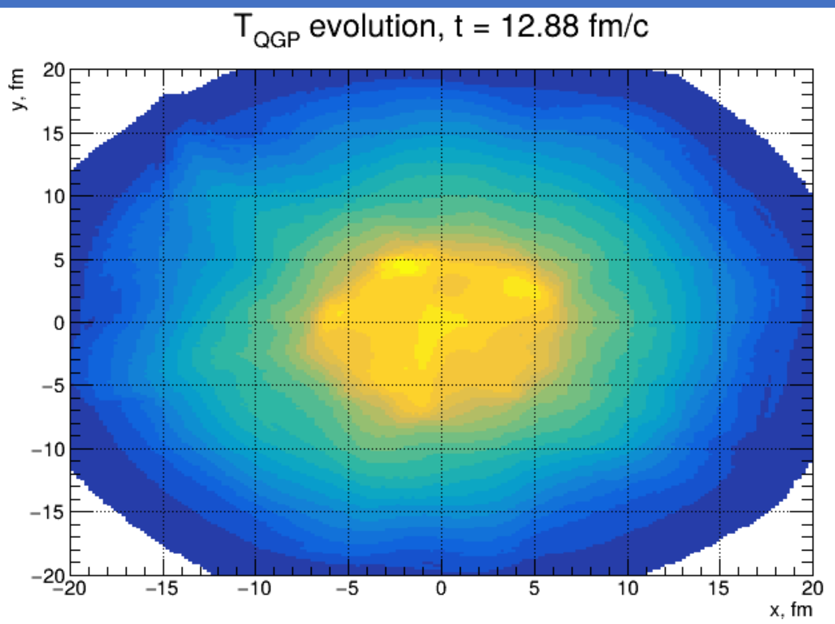
includes such reactions as:

$$\pi + \rho \to \pi + \gamma$$
$$\pi + \pi \to \rho + \gamma$$
$$\rho \to \pi + \pi + \gamma$$
$$\pi + K^* \to K + \gamma$$
$$\pi + K \to K^* + \gamma$$
$$\rho + K \to K + \gamma$$
$$K^* + K \to \pi + \gamma$$



Hydrodynamic model

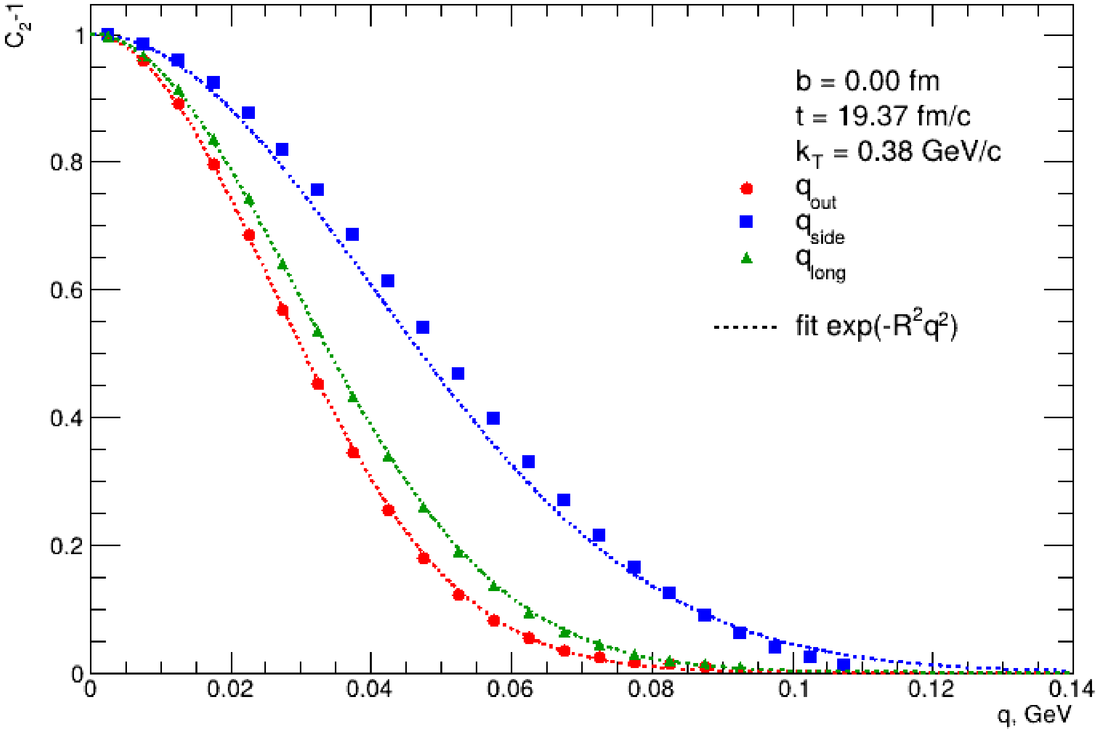
- Calculations were done using UrQMD hydro model
- We consider two scenarios of hydrodynamic evolution:
  - Thermalized hot dense nuclear matter with a first-order phase transition from QGP to hadronic phase (Bag model EoS)
  - Hadron gas including the same degrees of freedom as UrQMD (hadrons with masses up to 2.2 GeV)



- We used **out-side-long parametrization** of relative momentum (and corresponding observables):
  - out – direction along the transverse momentum
  - long – along the longitudinal momentum
  - side – perpendicular to previous directions
- For each cell in hydro calculations emission rates of thermal photons are calculate according to functions from previous slide:
  - estimation of thermal photon yields for given p_T (K_T) and φ in lab system ⟶ **integration** over all cells and evolution time
  - this study was conducted for midrapidity region (***y* = 0**)

Correlation functions

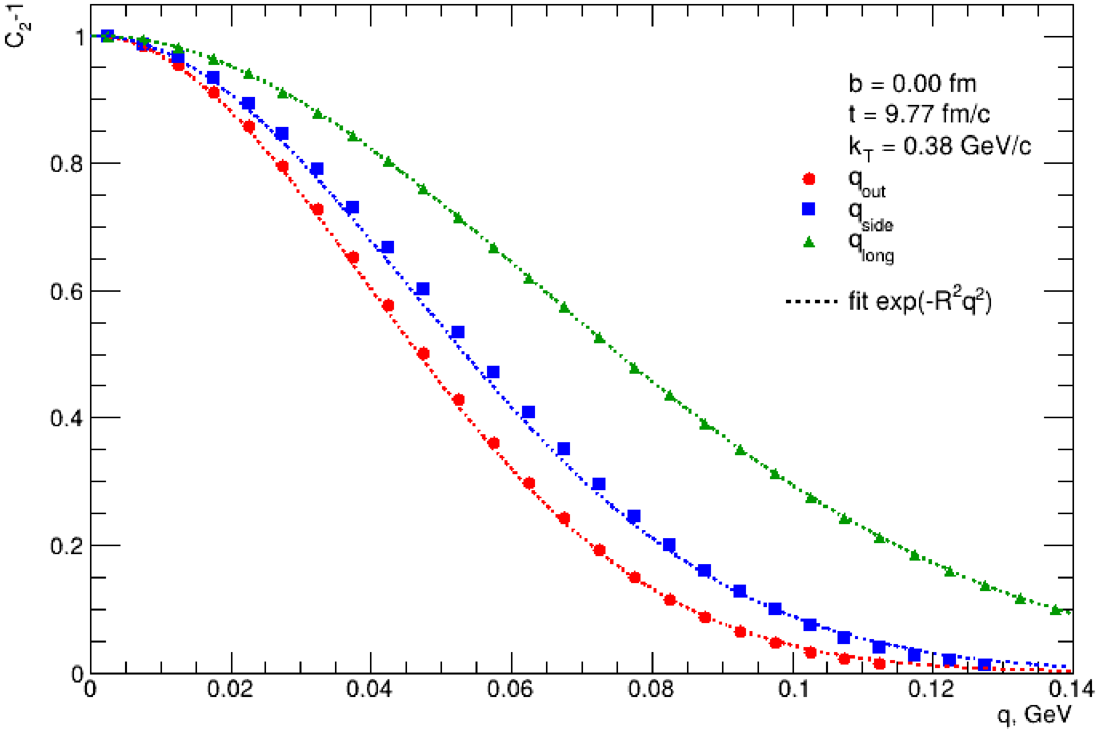
Hydro calculations including QGP phase transition:



- Assuming gaussian source with radius R, C_2 might be described as

$$C_2(q) = \lambda \exp(-q^2 R^2)$$

Hydro calculations including pure hadron gas:

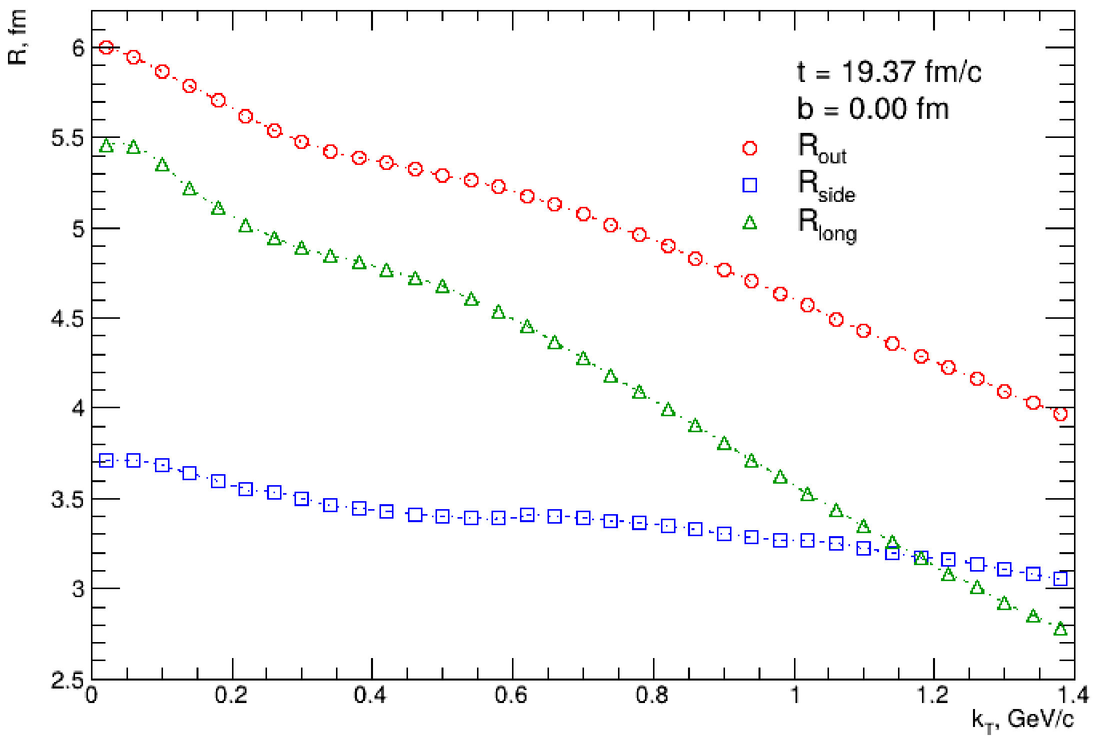


- C_2 are taken at a given mean transverse momentum of a pair

$$K_T = \frac{1}{2}(p_{1_T} + p_{2_T})$$

Correlation radius

Hydro calculations including QGP phase transition:



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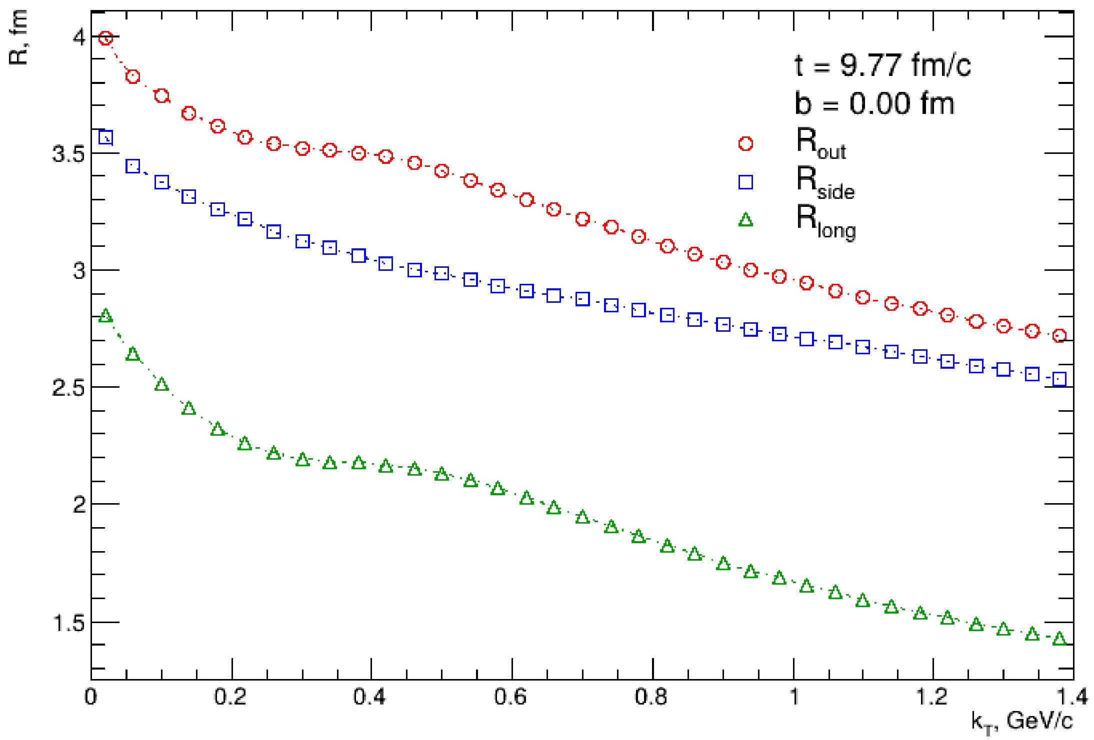
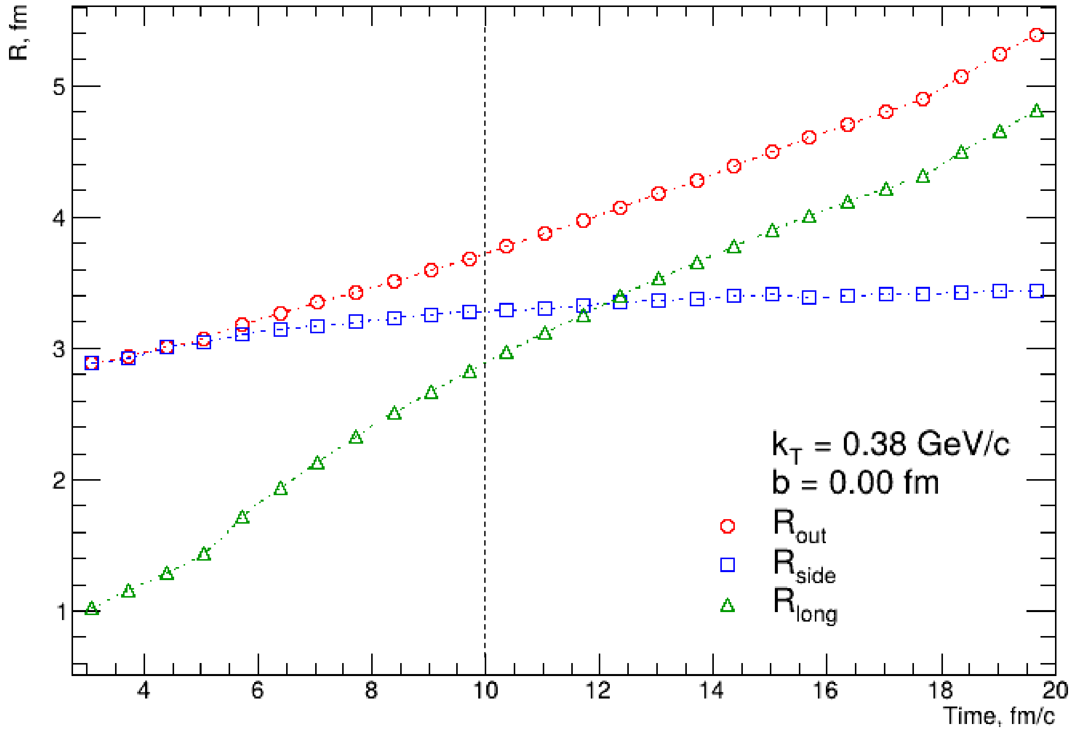


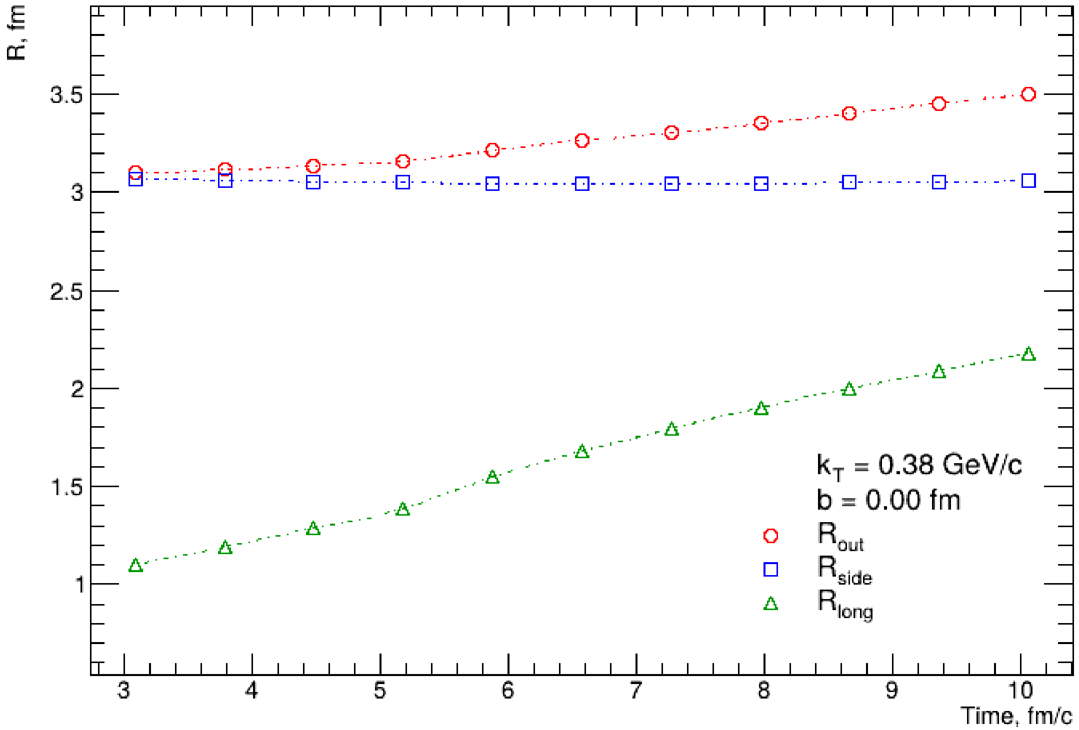
Despite significantly larger evolution time for QGP, model with the phase transition shows larger scales of a system and more rapid evolution, especially in long direction

Correlation radius vs evolution time

Hydro calculations including QGP phase transition:



Hydro calculations including pure hadron gas:



Despite significantly larger evolution time for QGP, model with the phase transition shows larger scales of a system and more rapid evolution, especially in long direction

Summary and outlook

- Calculation of two-photon correlation in Bi-Bi collisions at $\sqrt{s_{NN}}$ = 9.2 GeV was performed in hydrodynamic approach for two model with and w/o phase-transition to QGP

- Work in progress:
  - From the experimental point of view, considered out-side-long parametrization is not applicable – it is more convenient to use averaged $q_{inv} = -\sqrt{\boldsymbol{q}^2}$ or parametrization in **longitudinal co-moving system** (LCMS)
  - With this approach it is also possible to extract **yields of direct photons** at low p_T region:

$$\lambda = \frac{1}{2}\left(\frac{N_\gamma^{\mathrm{dir}}}{N_\gamma^{\mathrm{inc}}}\right)^2 \rightarrow R_\gamma = \frac{N_\gamma^{\mathrm{inc}}}{N_\gamma^{\mathrm{decay}}} = \frac{1}{1-\sqrt{2\lambda}} \qquad \frac{1}{2\pi\, N_{\mathrm{ev}}} \frac{\mathrm{d}^2\, N_{\gamma \mathrm{dir}}}{p_{\mathrm{T}}\, \mathrm{d}p_{\mathrm{T}}\, \mathrm{d}y} = \frac{1}{2\pi\, N_{\mathrm{ev}}} \frac{\mathrm{d}^2\, N_{\gamma \mathrm{inc}}}{p_{\mathrm{T}}\, \mathrm{d}p_{\mathrm{T}}\, \mathrm{d}y} \times \left(1 - \frac{1}{R_\gamma}\right)$$

  - Fraction of direct photons as well might be estimated with UrQMD ⟶ more realistic C_2 (suppressed down to ~ 10^{-3})

This work has been supported by the Ministry of Science and Higher Education of the Russian Federation, Project "Fundamental and applied research at the NICA megascience experimental complex" № FSWU-2024-0024

THANK YOU FOR THE ATTENTION!

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29 October 2024

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