# Direct photon spectra and Bose-Einstein correlations in Bi-Bi collisions at $\sqrt{s_{NN}}$ = 9.2 GeV

MPD Cross-PWG Meeting

Vladislav Kuskov
National Research Nuclear University MEPhI
21 January 2025

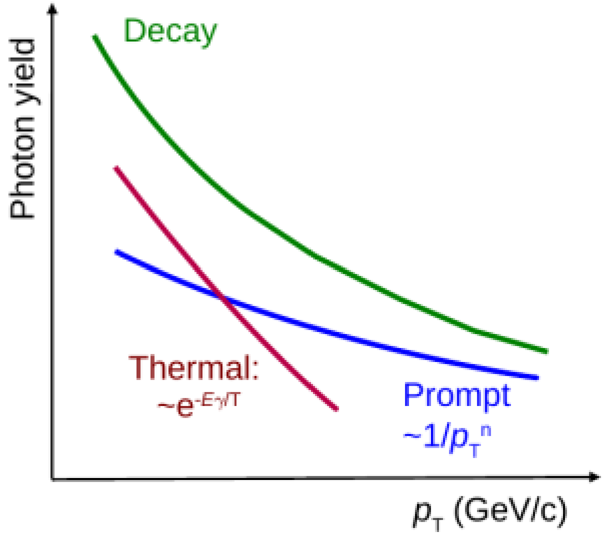
vakuskov@mephi.ru

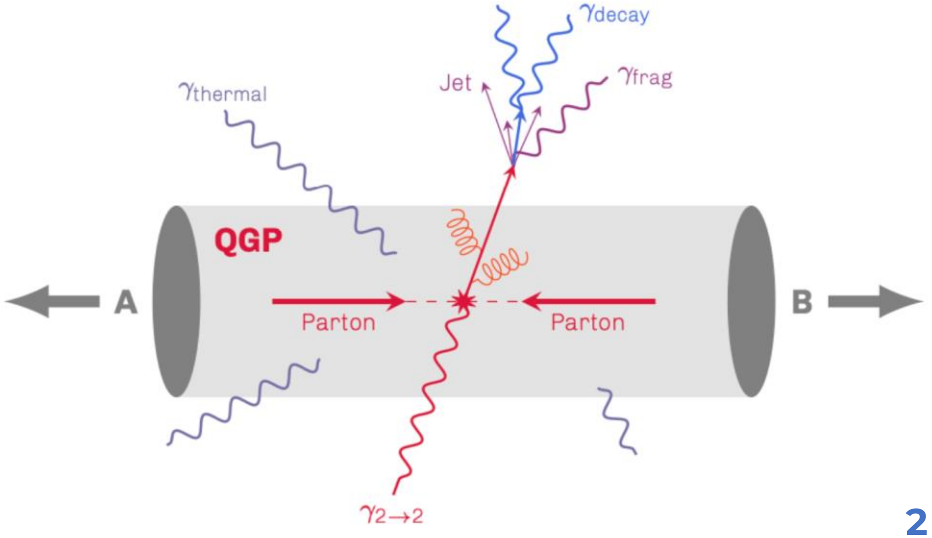
# Introduction

- **Direct photons** – photons not originating from hadron decays:
  - **thermal photons** (~$e^{-E_\gamma T}$), thermal radiation of QGP, space-time evolution of QGP
  - **prompt photons** (~$^1/_{p_T^n}$), 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 spectra correlations (interferometry) in Bi-Bi collisions at $\sqrt{s_{NN}}$ = 9.2 GeV





# Thermal photon emitting functions

**QGP emission:** JHEP 0112:009,2001

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

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

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

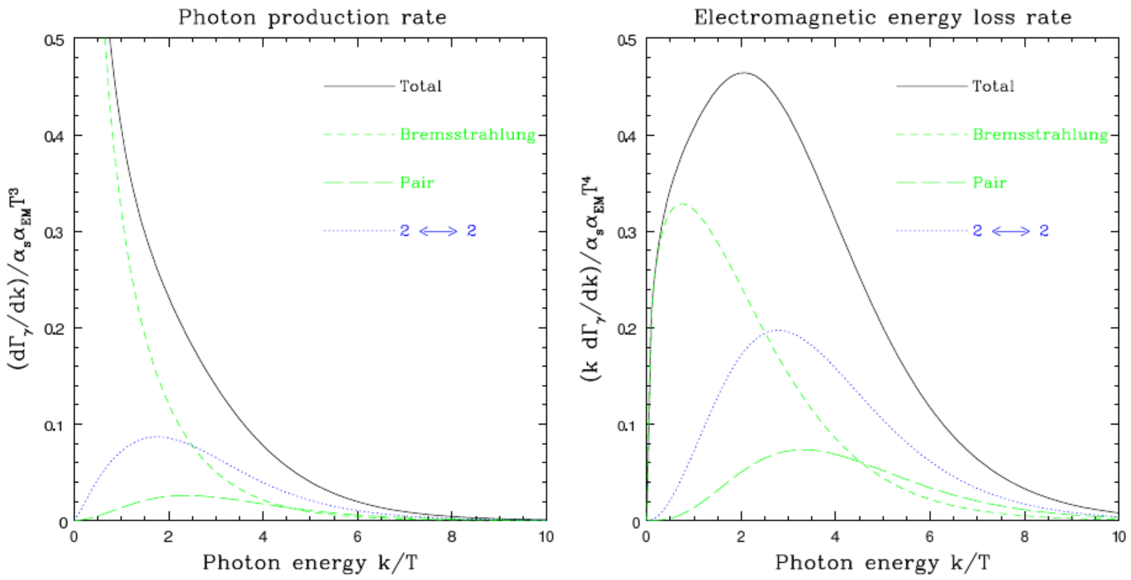


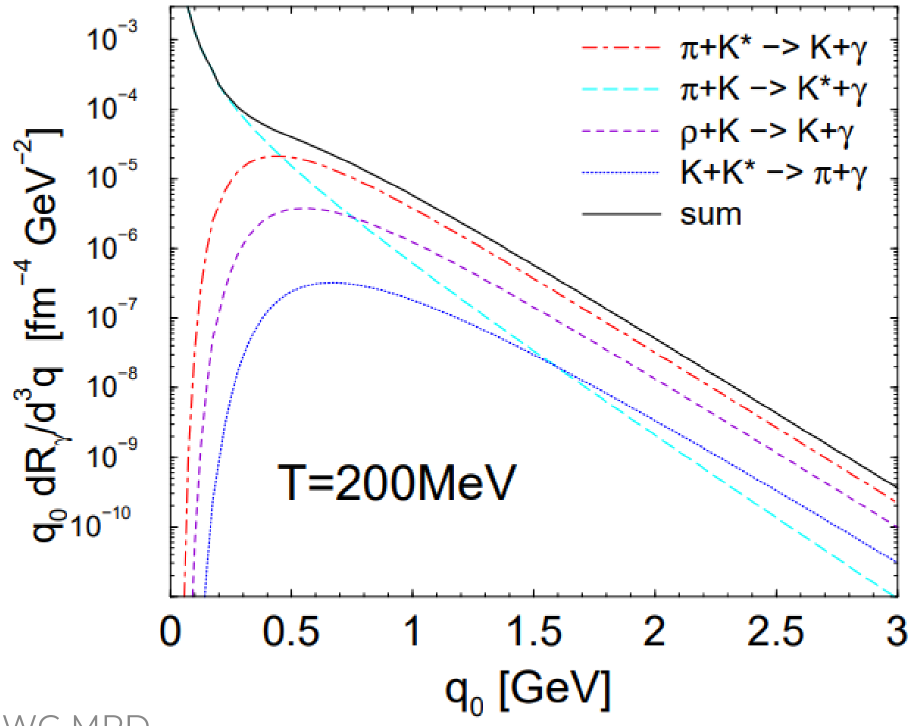
FIG. 9. Total photon emission rate, together with the bremsstrahlung, inelastic pair annihilation and $2 \leftrightarrow 2$ contributions, for two-flavor QCD with $\alpha_s = 0.2$. The left panel shows $d\Gamma_\gamma/dk$, divided by $\alpha_s\,\alpha_{\text{EM}}\,T^3$, while the right panel shows rates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

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

includes such reactions as:

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

**Rate**



# 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) **HG EoS**

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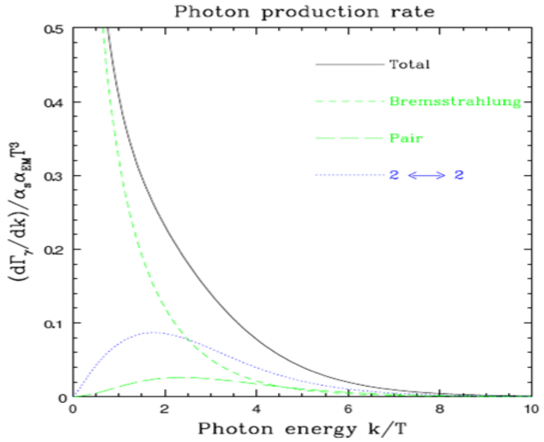
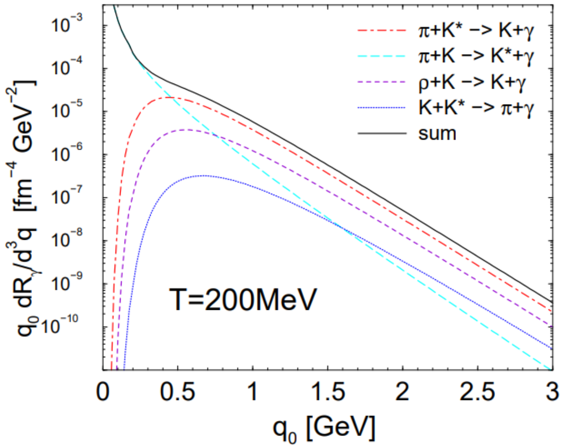
- For each cell (100x100x100) in hydro calculations emission rates of thermal photons are calculate according to functions from previous slide:

$$R(T(x), \mu_{\rm B}(x), p_\gamma \cdot u(x)) = f_{\rm QGP} \cdot R_{\rm QGP} + (1 - f_{\rm QGP}) \cdot R_{\rm HG}$$

$R_{\rm QGP}$ rate of pure QGP phase, $f_{\rm QGP}$ fraction of QGP phase in a given cell

$R_{\rm HG}$ rate of pure HG phase





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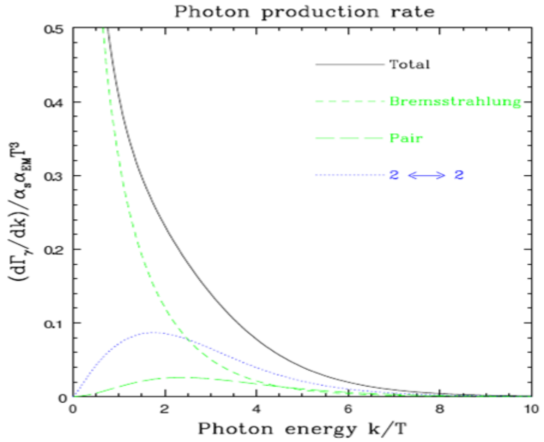
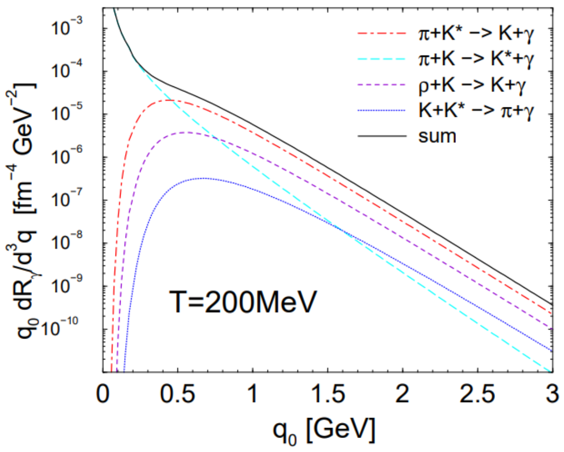
$R_\mathrm{QGP}$ rate of pure QGP phase, $f_\mathrm{QGP}$ fraction of QGP phase in a given cell

$R_\mathrm{HG}$ rate of pure HG phase

- The total spectra of direct photons are calculated as the integration of emission rates over all cells (in *x-y-z* in a lab system) in hydrodynamic evolution (over the whole time *t* of the evolution):

$$E_\gamma \frac{\mathrm{d}^3N}{\mathrm{d}p_\gamma^3} = \int \mathrm{d}^4x R(T(x), \mu_\mathrm{B}(x), p_\gamma \cdot u(x))$$





# Thermal photon spectra. Central collisions

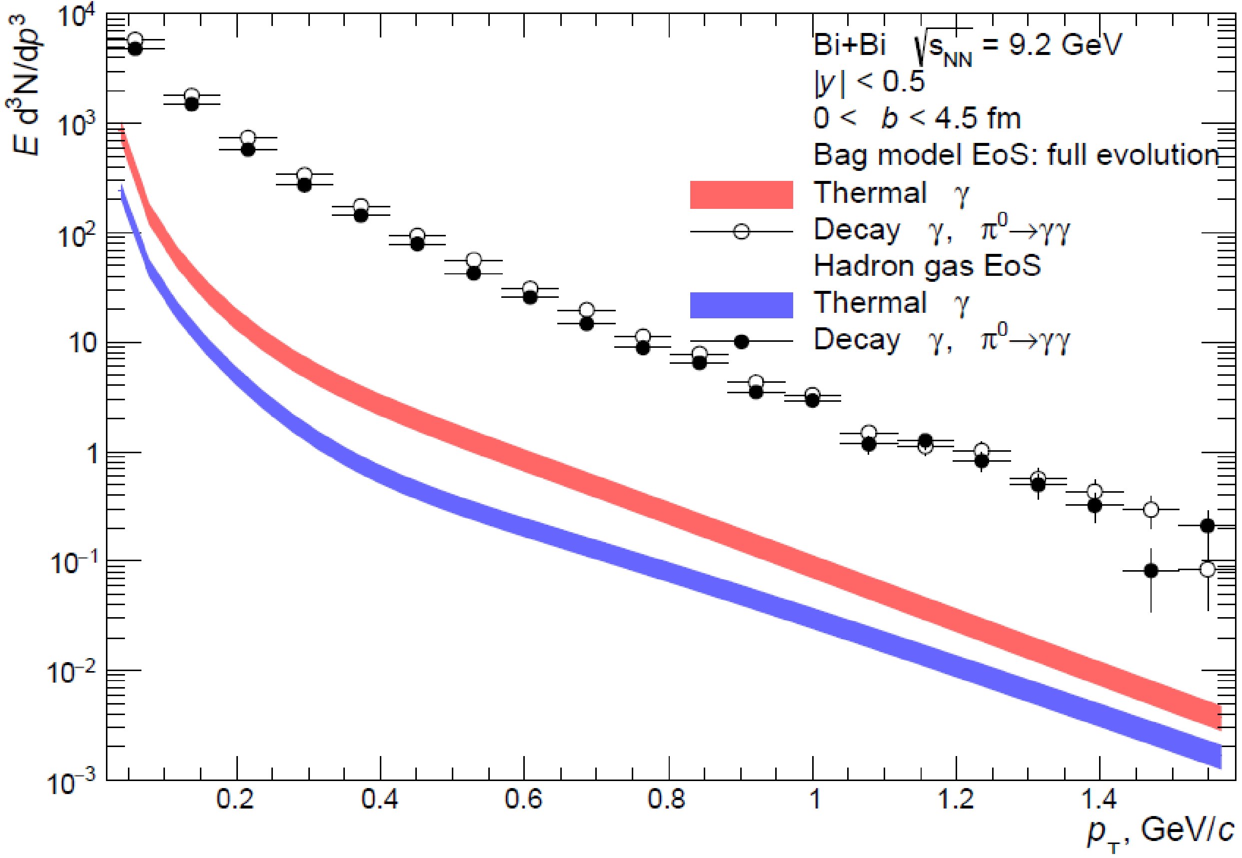
Emission rate in each cell:

$$R(T(x), \mu_{\mathrm{B}}(x), p_\gamma \cdot u(x)) = f_{\mathrm{QGP}} \cdot R_{\mathrm{QGP}} + (1 - f_{\mathrm{QGP}}) \cdot R_{\mathrm{HG}}$$

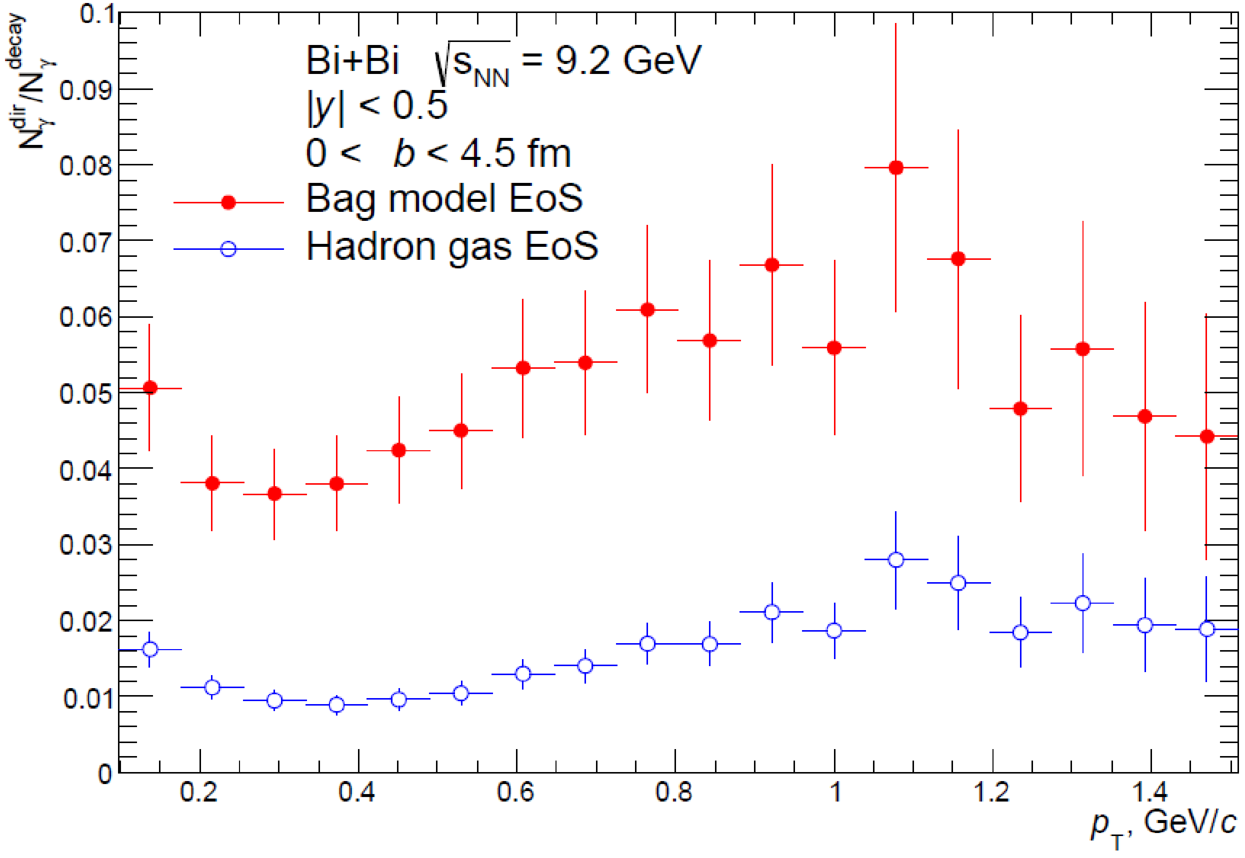
The total yield estimated as:

$$E_\gamma \frac{\mathrm{d}^3 N}{\mathrm{d}p_\gamma^3} = \int \mathrm{d}^4 x R(T(x), \mu_{\mathrm{B}}(x), p_\gamma \cdot u(x))$$

**Errors are taken as event-by-event fluctuations of 100 events**



**Ratios to decay photons:**



# Thermal photon spectra. Semi-central collisions

Emission rate in each cell:

$$R(T(x),\mu_{\mathrm{B}}(x),p_\gamma\cdot u(x)) = f_{\mathrm{QGP}}\cdot R_{\mathrm{QGP}} + (1-f_{\mathrm{QGP}})\cdot R_{\mathrm{HG}}$$

The total yield estimated as:

$$E_\gamma\frac{\mathrm{d}^3N}{\mathrm{d}p_\gamma^3} = \int \mathrm{d}^4x R(T(x),\mu_{\mathrm{B}}(x),p_\gamma\cdot u(x))$$

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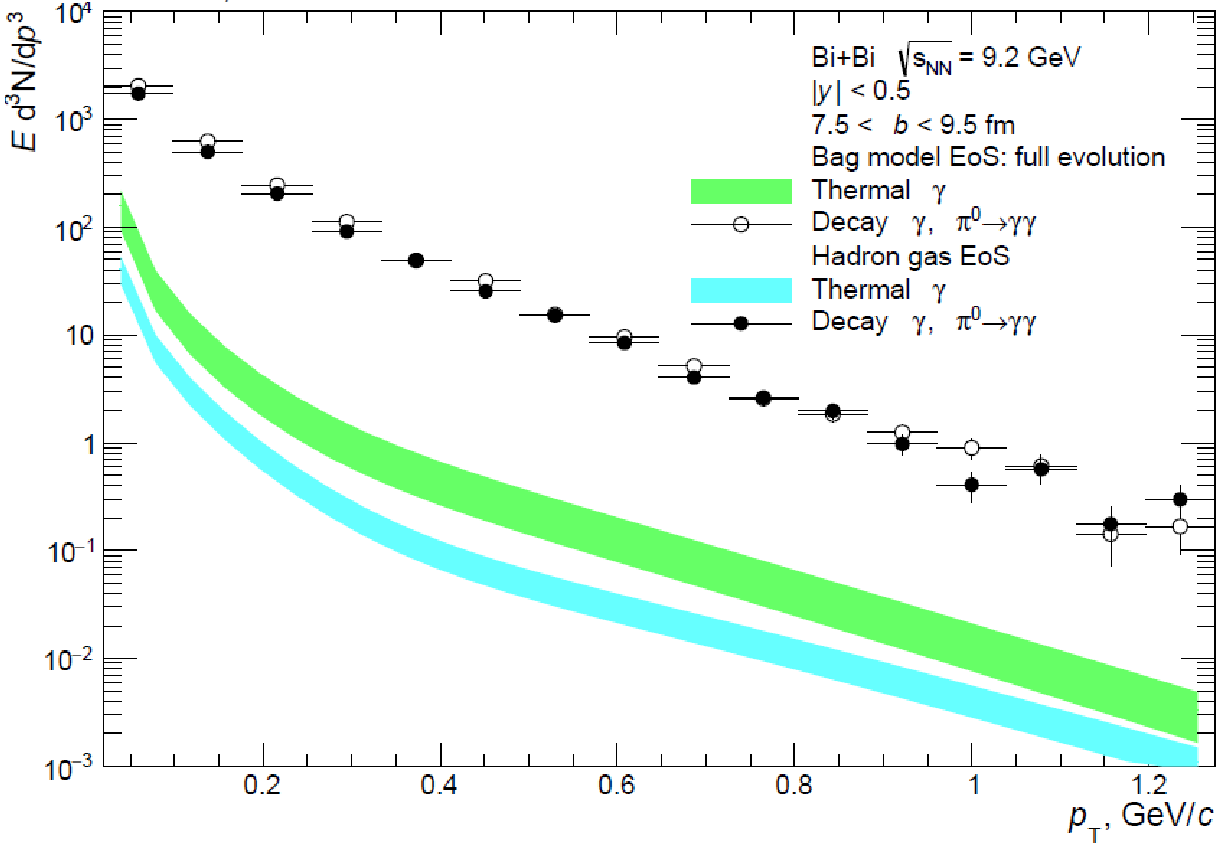

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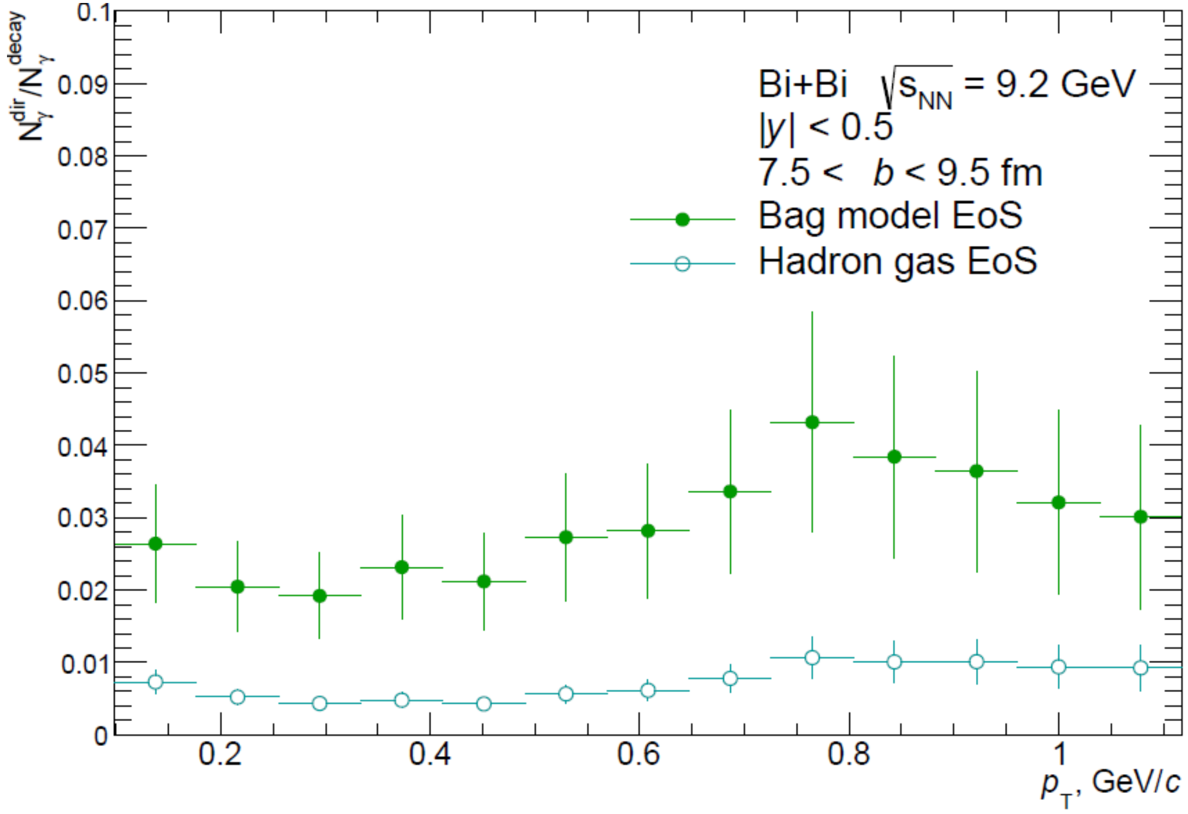

# Pseudorapidity distribution

Emission rate in each cell:

$$R(T(x), \mu_B(x), p_\gamma \cdot u(x)) = f_{QGP} \cdot R_{QGP} + (1 - f_{QGP}) \cdot R_{HG}$$

The total yield estimated as:

$$E_\gamma \frac{d^3N}{dp_\gamma^3} = \int d^4x R(T(x), \mu_B(x), p_\gamma \cdot u(x))$$

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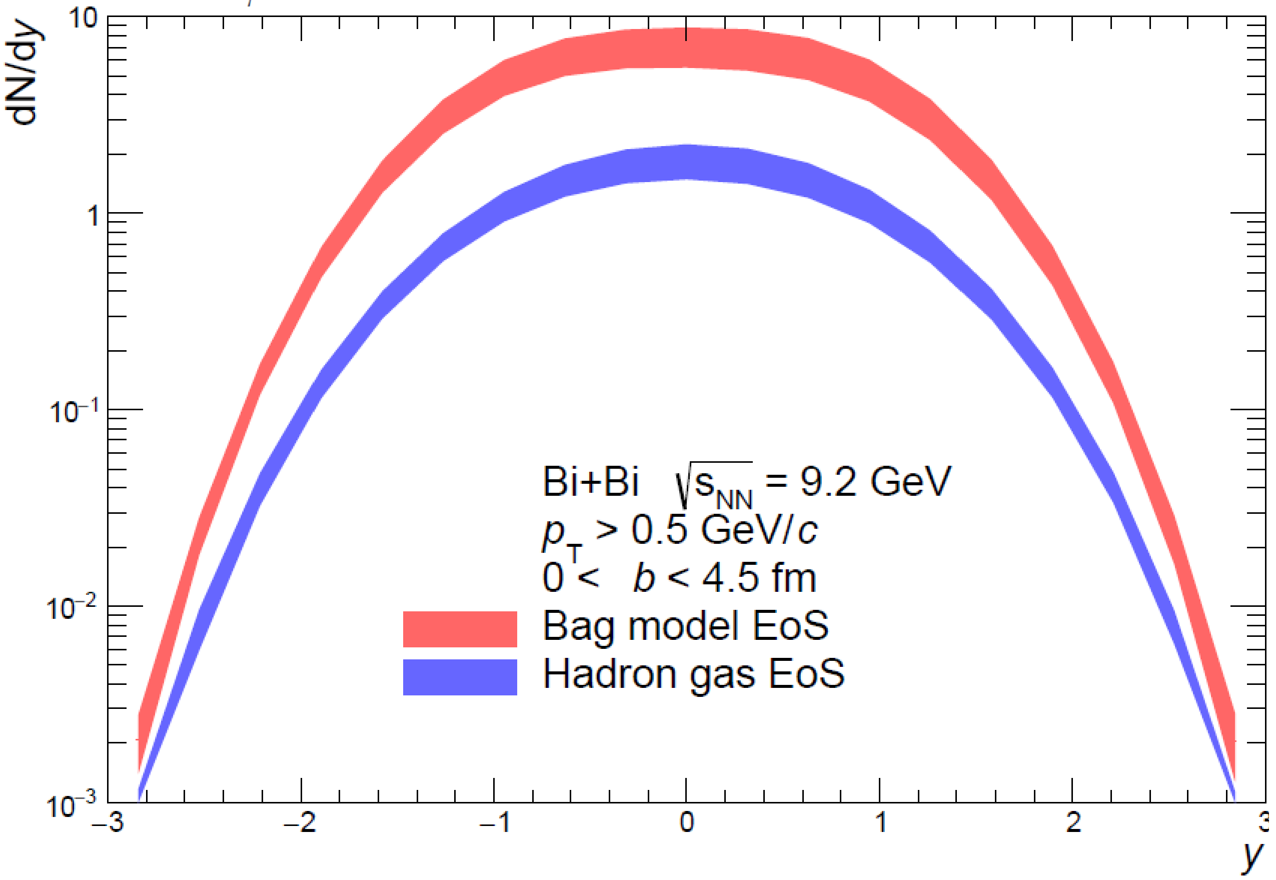
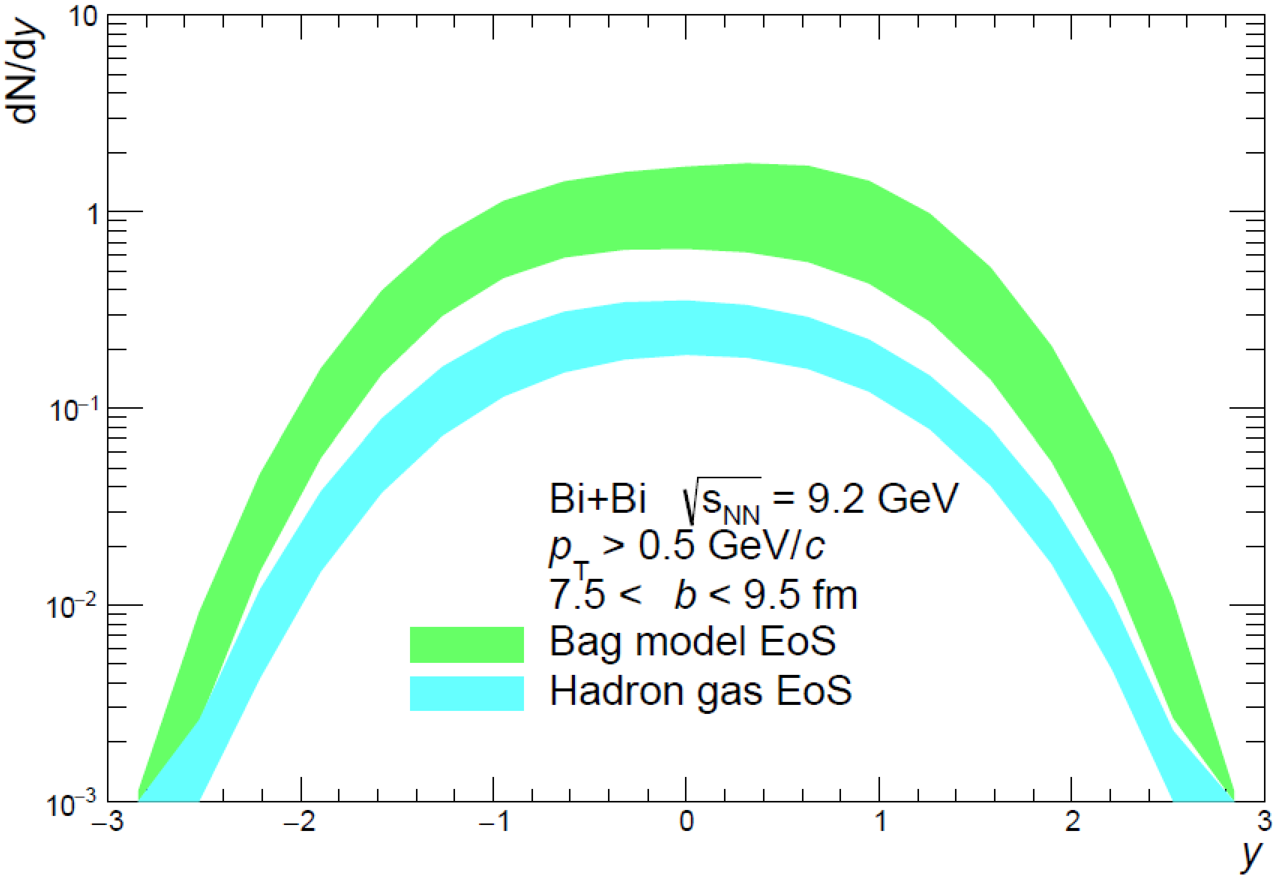
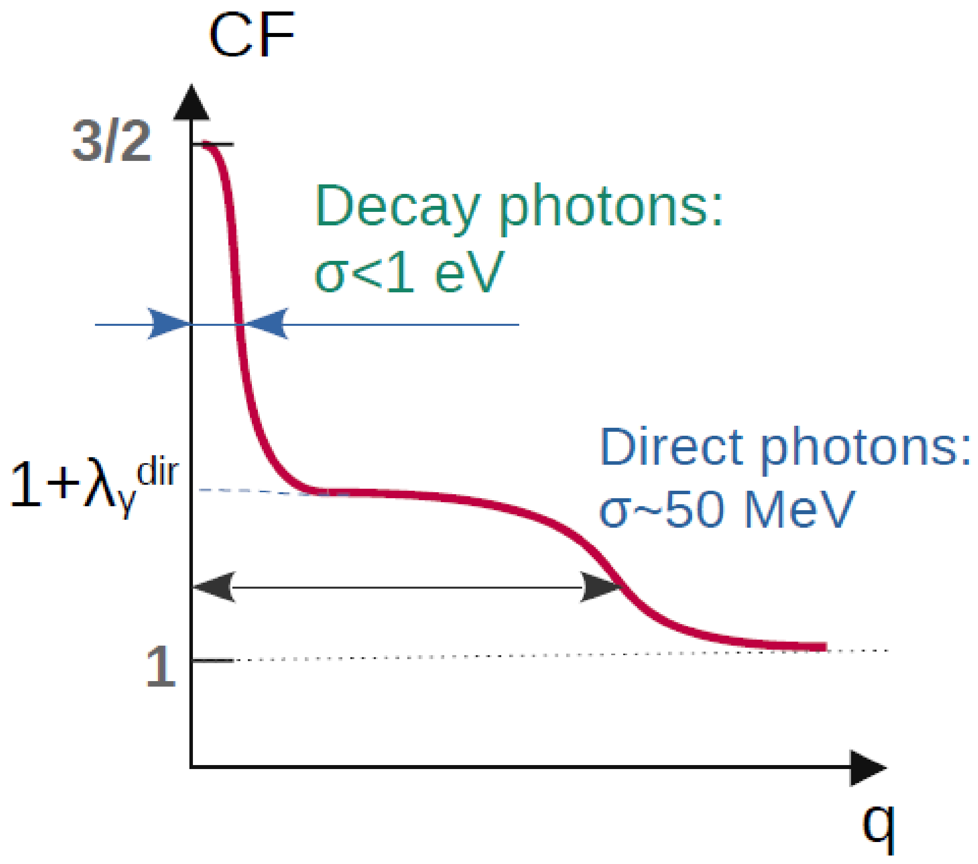




# Direct photon Bose-Einstein correlations

**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

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

**Kinematics variables:**

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

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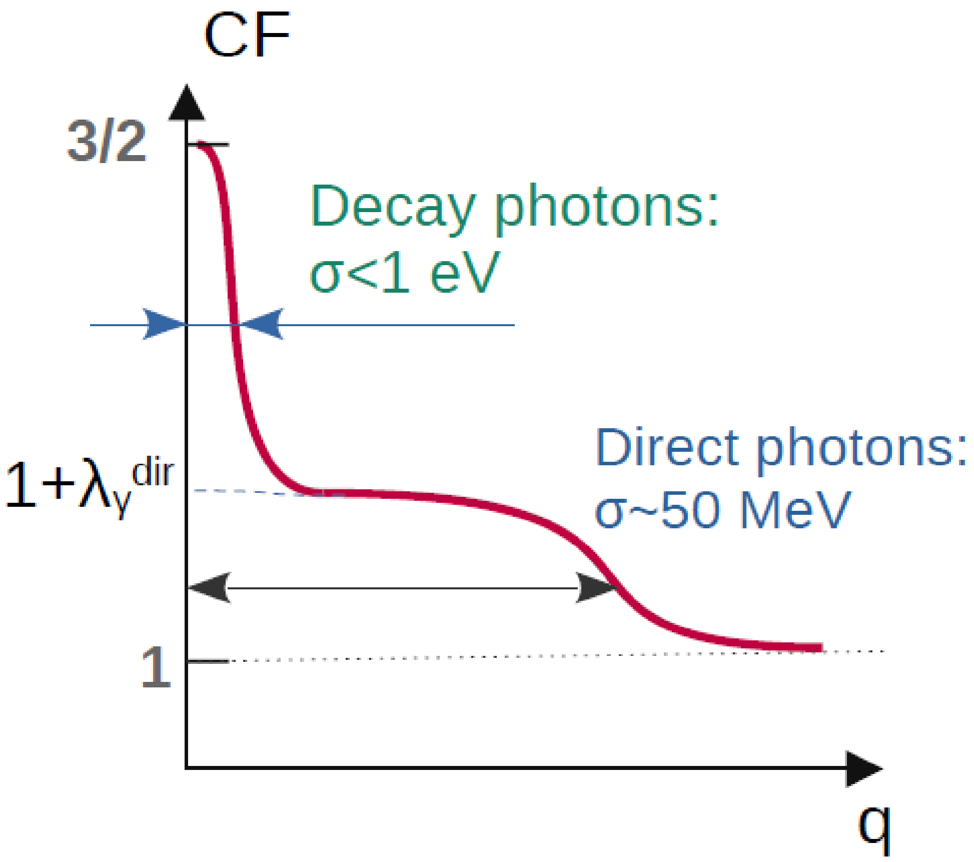

- General definition:

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

- 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)**

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

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$$K^{\mu} = (K^0, K_{\perp}, 0, K^z),$$

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both photons are on mass shell

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$$q_{\mathrm{o}} = (\boldsymbol{q}_{\perp} \cdot \boldsymbol{K}_{\perp})/K_{\perp},\ q^0 = \frac{\boldsymbol{q} \cdot \boldsymbol{K}}{K^0}$$
$$q_{\mathrm{s}} = |\boldsymbol{q}_{\perp} - (\boldsymbol{q}_{\perp} \cdot \boldsymbol{K}_{\perp})\boldsymbol{K}_{\perp}/K_{\perp}^2|,$$
$$q_{\mathrm{l}} = q_z.$$

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$$\Rightarrow$$

$$R_s^2 = < x_s^2 >$$
$$R_o^2 = <(x_o - \beta_T t)^2>$$
$$R_L^2 = <(x_l - \beta_L t)^2>$$

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$$K^\mu = (K^0, K_\perp, 0, K^z),\qquad q^\mu = (q^0, q_o, q_s, q_l),$$

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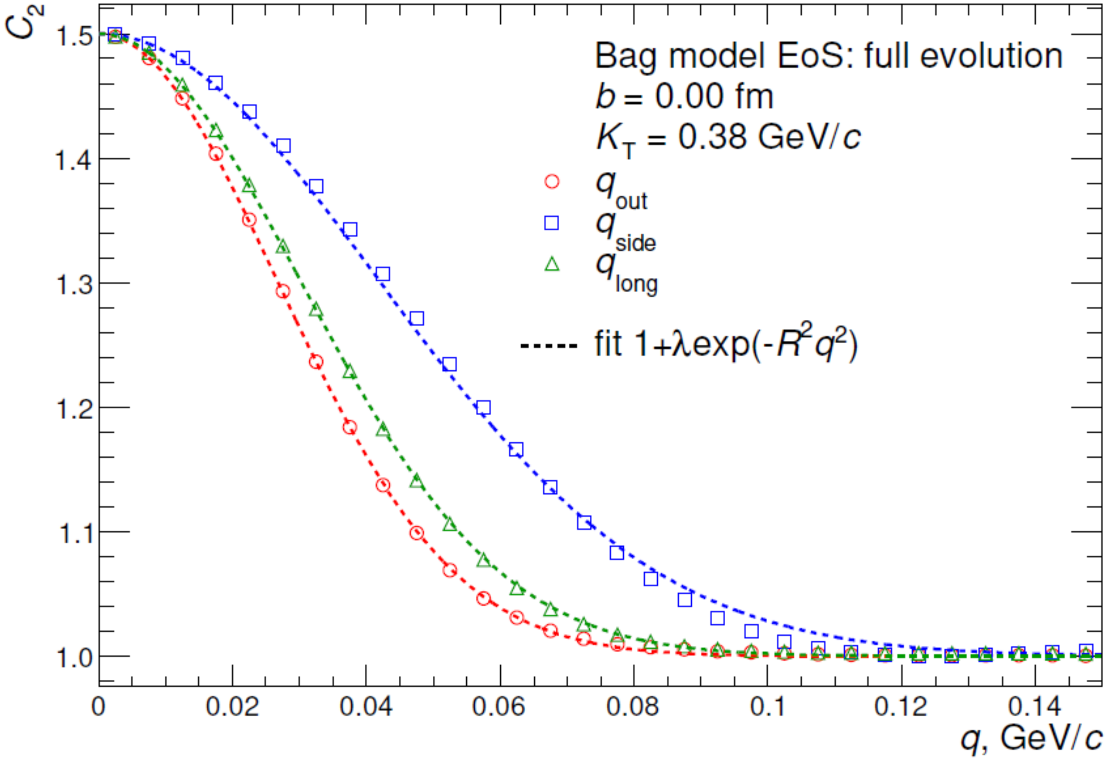
$$R_o^2 = <(x_o - \beta_T t)^2>$$

$$R_L^2 = <(x_l - \beta_L t)^2>$$

- 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 $\varphi$ in lab system **integration** over all cells and evolution time

# Correlation functions

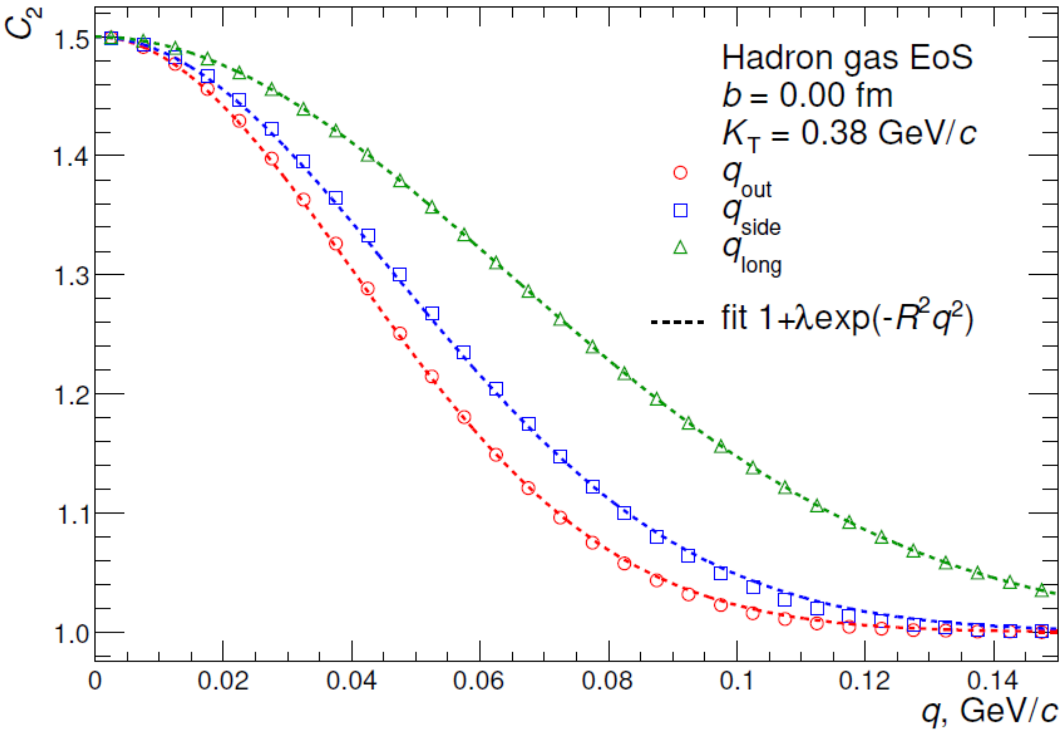
**Hydro calculations including QGP phase transition:**



- 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:**

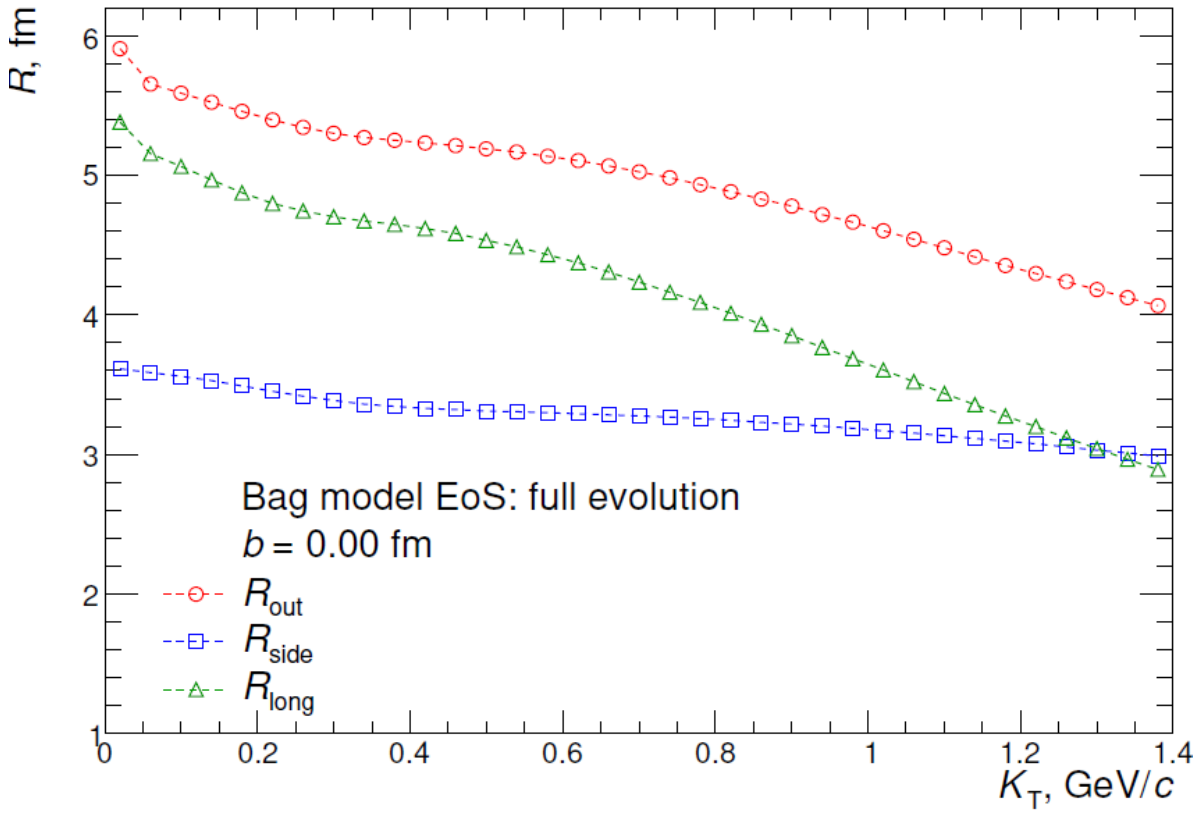


- $C_2$ are taken at a given mean transverse momentum of a pair

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

# Correlation radius

**Hydro calculations including QGP phase transition:**



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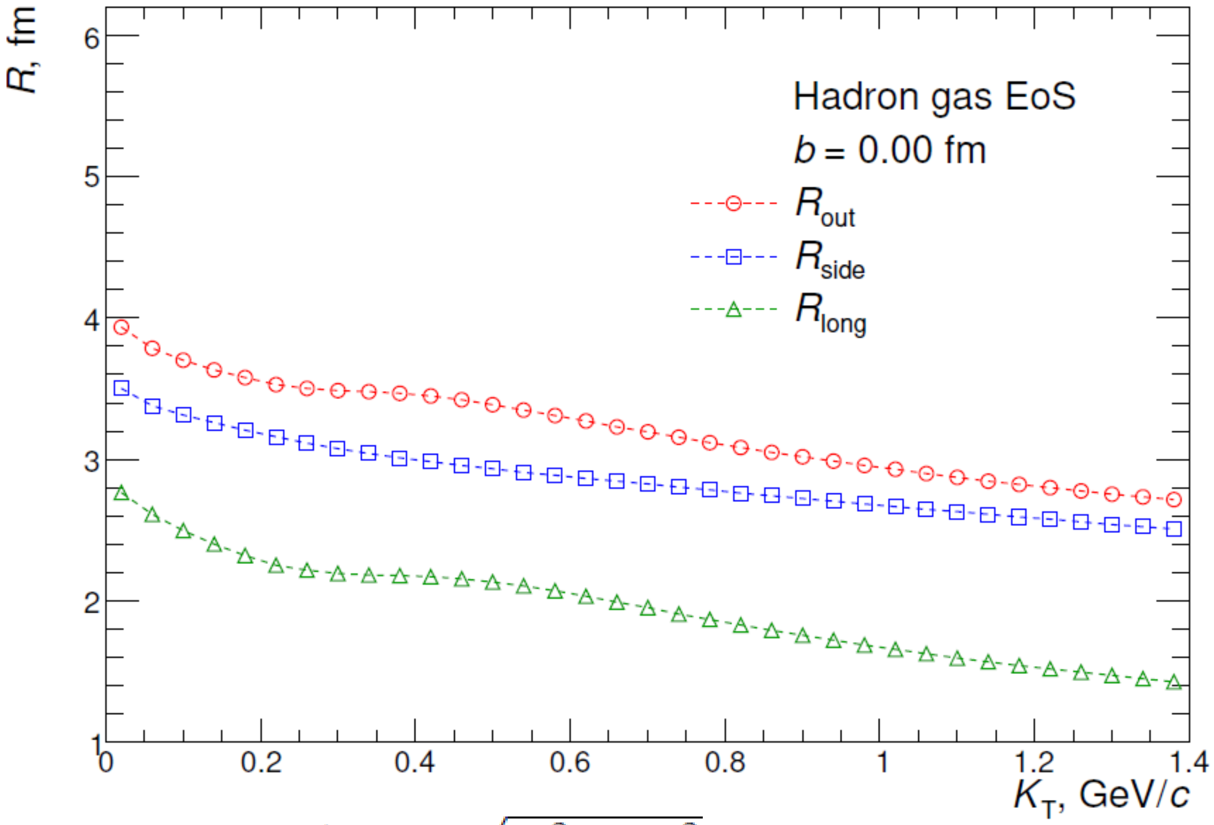


The presence of mixed phase causes increasing of the lifetime ($\Delta\tau \approx \sqrt{R_o^2 - R_s^2}$ ) of the fireball in scenario including QCD phase transition

# Summary and outlook

- Calculation of direct photons spectra and correlations 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 ~ $10^{-3}$)

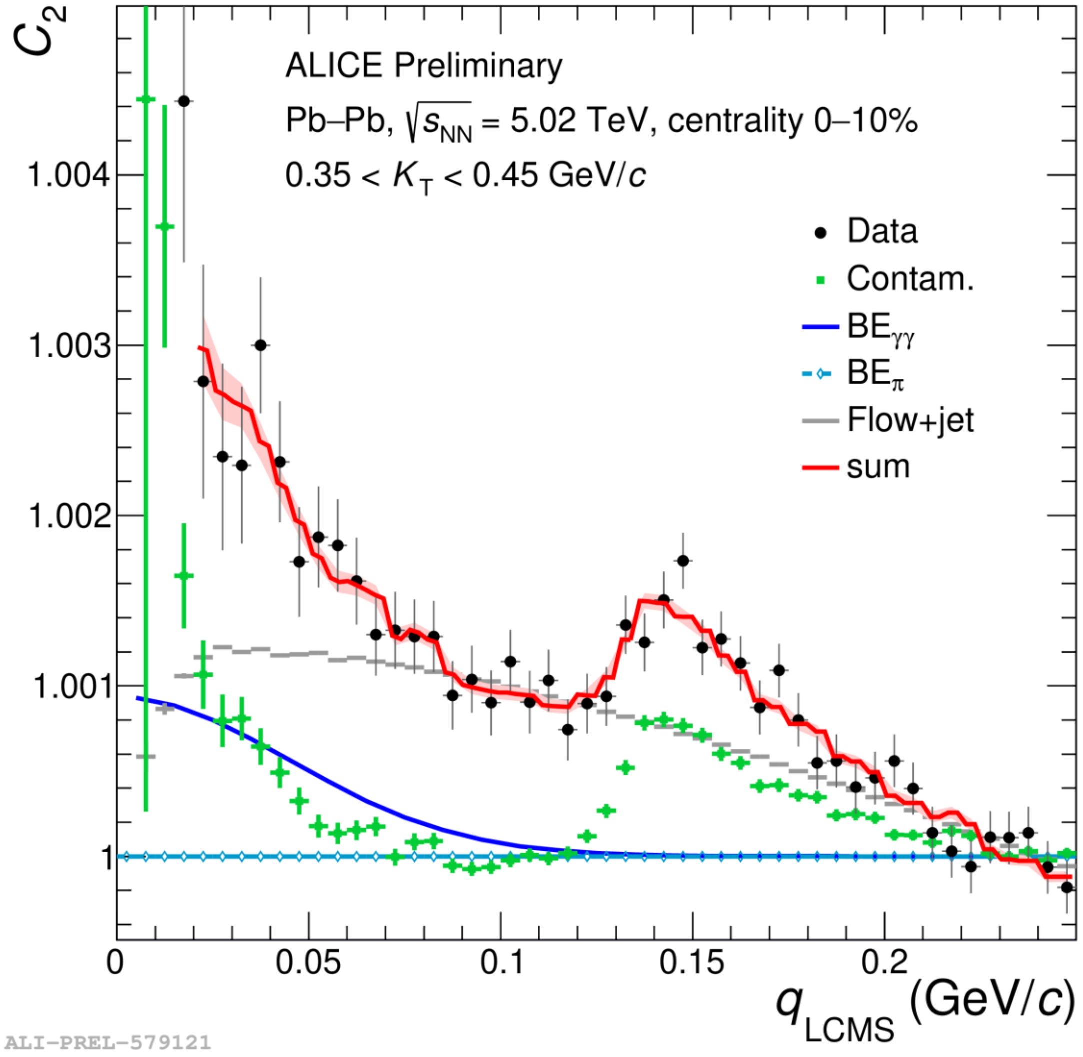
# THANK YOU FOR THE ATTENTION!

Vladislav Kuskov
21 January 2025

vakuskov@mephi.ru

# Backup. ALICE measurements (by Dmitry Peresunko)

**$C_2$ measured with PHOS:**



**$C_2$ is decomposed into the contributions:**

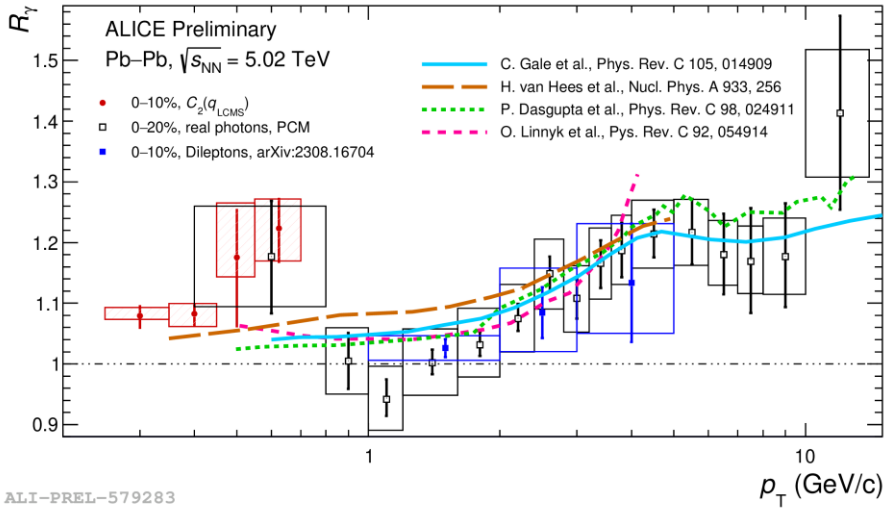
- **Contamination**: photon conversion, hadron bremsstrahlung, residual correlations in resonance decays
- **Direct photon BE** correlations
- Residual correlation in decays of BE correlated $\pi^0$ (negligible in this $K_T$ bin)
- **Long-range** (flow and jet) correlations
- **Summary** of all contributions

**Kinematics variables:**

- 3D relative momentum of the pair in Longitudinally Co-Moving System: $q_{\rm LCMS} = |\vec{p_1} - \vec{p_2}|$
- Mean pair transverse momentum: $K_{\rm T} = \frac{1}{2}(p_{1_{\rm T}} + p_{2_{\rm T}})$

# Backup. ALICE measurements (by Dmitry Peresunko)

## Double ratio estimated with $C_2$:



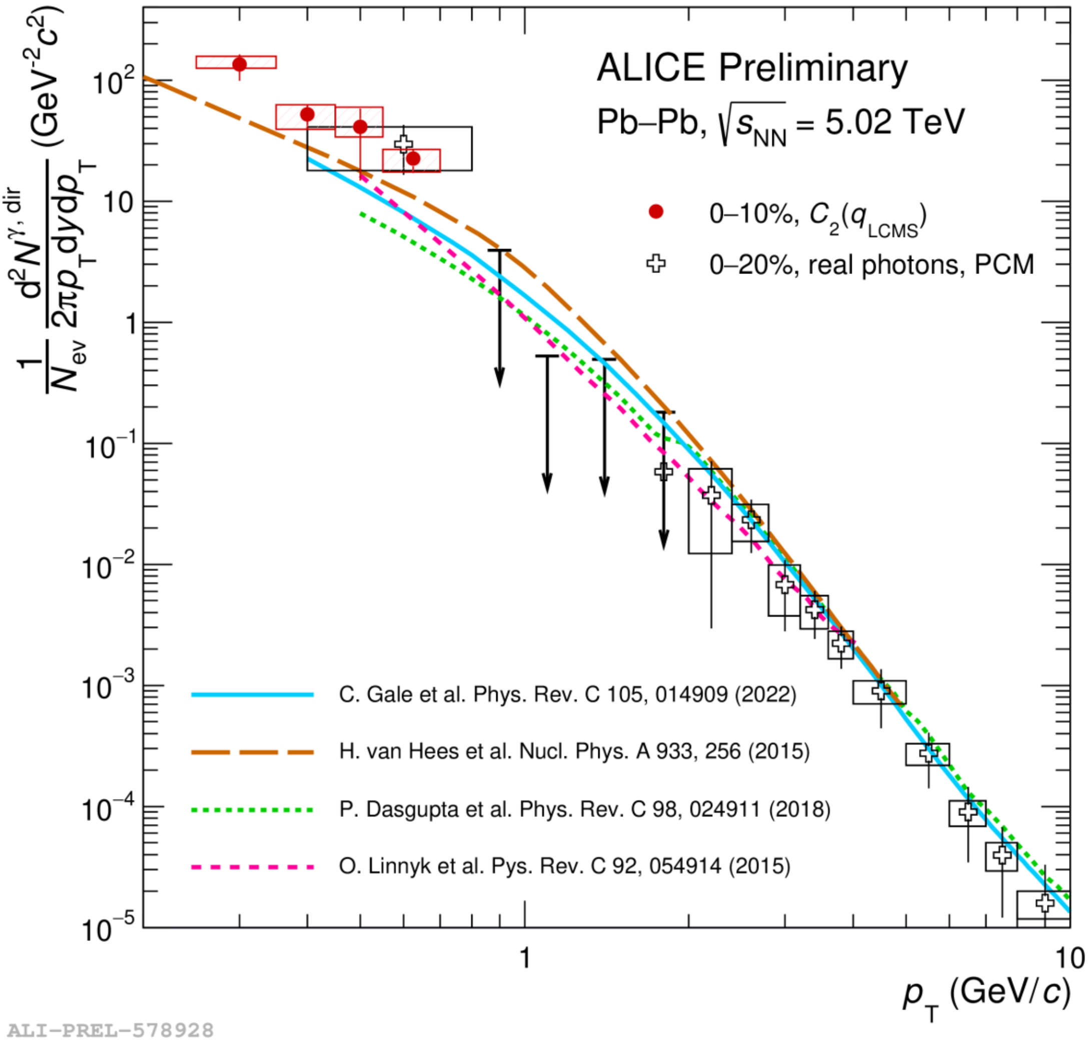
ALI-PREL-579283

Correlation strength (**λ**) of $C_2 \longrightarrow$ ***$R_\gamma$***:

$$\lambda = \frac{1}{2}\left(\frac{N_\gamma^{\mathrm{dir}}}{N_\gamma^{\mathrm{inc}}}\right)^2 \rightarrow R_\gamma = \frac{N_\gamma^{\mathrm{inc}}}{N_\gamma^{\mathrm{decay}}} = \frac{1}{1-\sqrt{2\lambda}}$$

- Extended measurements down to **250 MeV/c**
- Method provide consistent results in the overlap region
- Measured spectrum exceeds predictions at low $p_T$ **by factor ≈ 2**

## Direct photon yield:



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