Bose-Einstein correlations of direct photons

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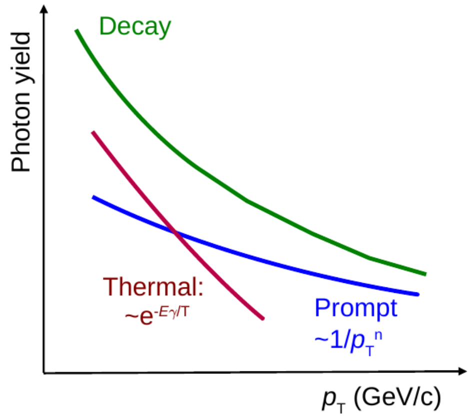
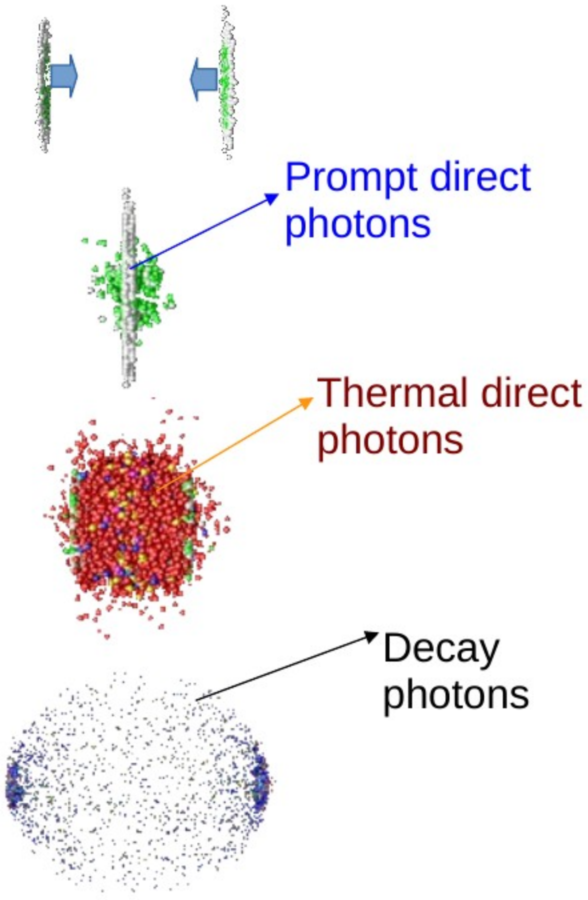
Photon classification

- Direct photons – photons not originating from hadronic decays but produced in electromagnetic interactions in course of collision
  - Prompt direct photons: ones from interaction of incoming nucleons
  - Thermal direct photons: thermal radiation of hot matter
- Decay photons: photons from decays of final hadrons

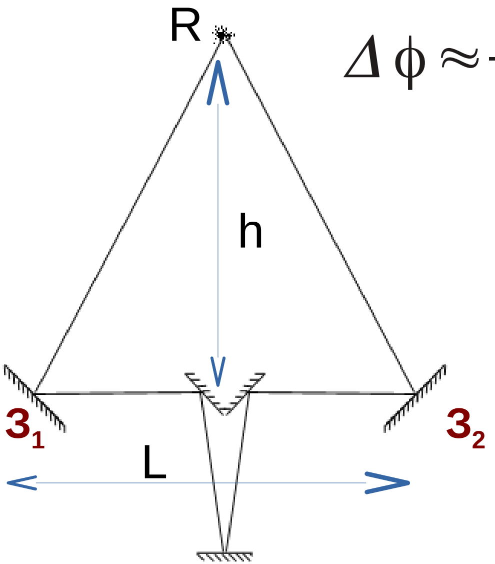


- Bose-Einstein correlations of direct photons provide possibility to test dimensions of hot part of collision
- Different p_T (K_T) will probe different stages of the collision



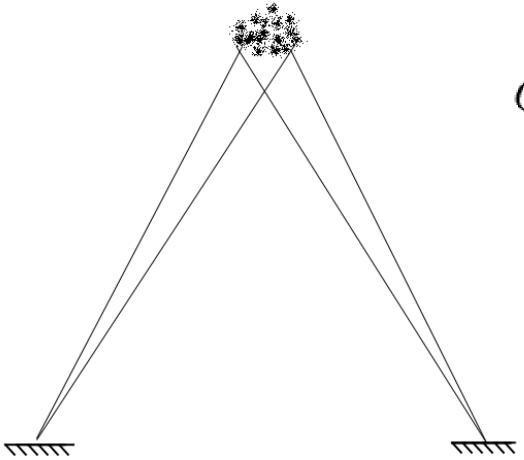
Intensity interferometry

$$C = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle}$$



$$\Delta\phi \approx \frac{L R}{\lambda h}$$

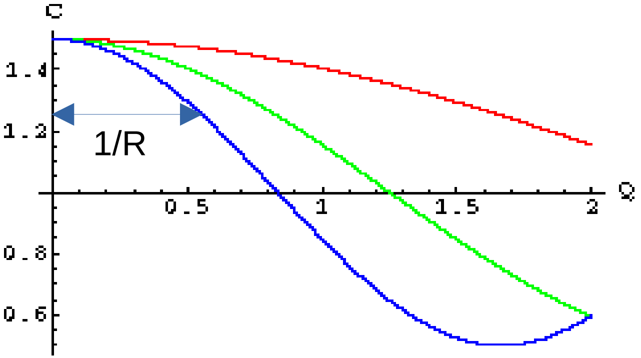
Amplitude interferometry:
Compare phases at two points, e.g. using mirrors
=> not possible for gamma, hadrons



Intensity interferometry:
Hanbury Brown and Twiss
compare intensities in two points
=> Applicable for radio-waves (super-large baseline), gamma, hadrons,...

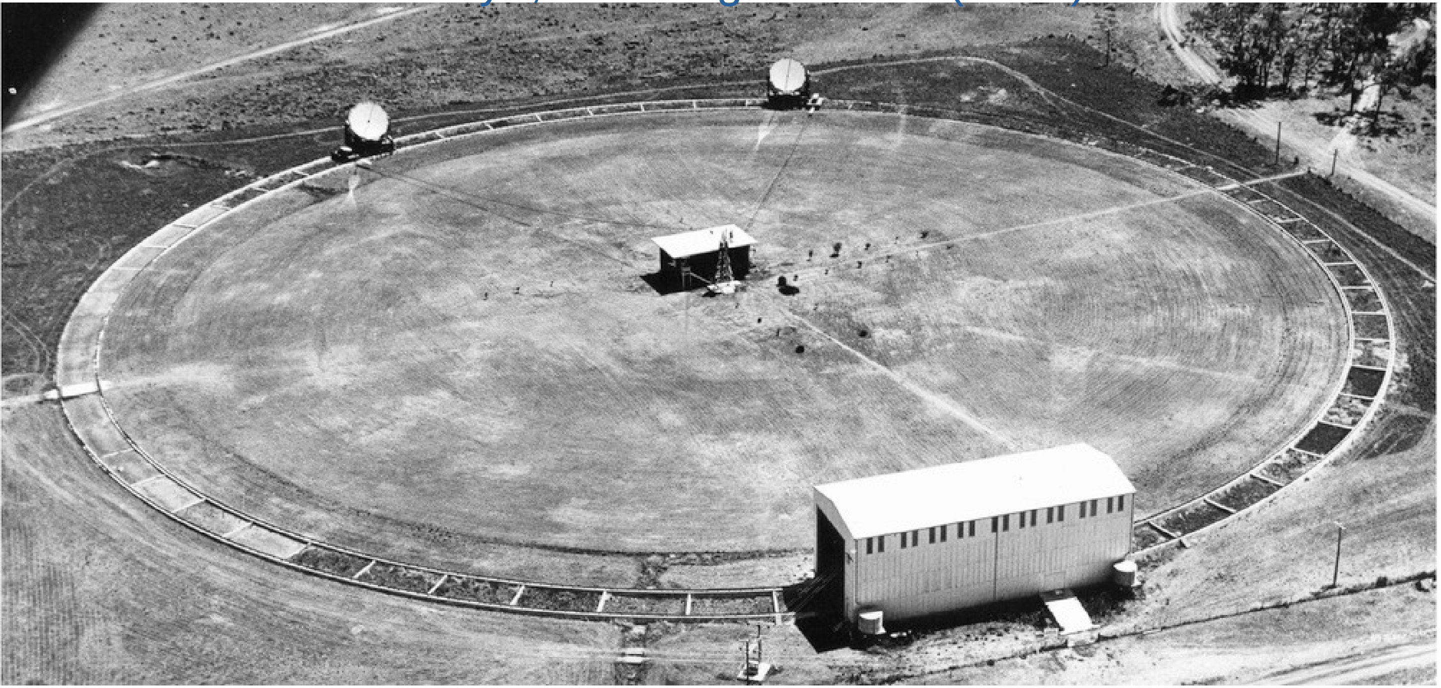
$$C(\boldsymbol{p}_1, \boldsymbol{p}_2) = \frac{E_1 E_2 dN/(d^3p_1 d^3p_2)}{(E_1 dN/d^3p_1)(E_2 dN/d^3p_2)}$$

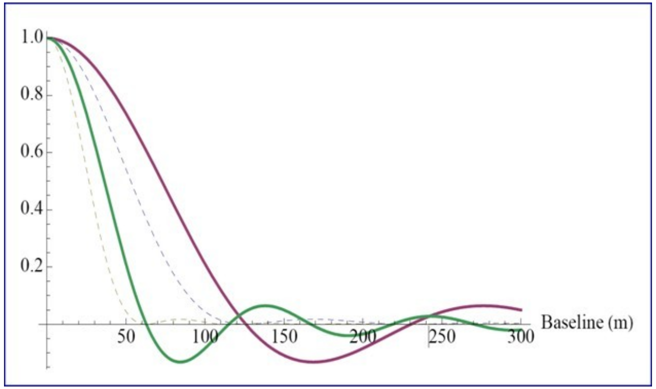
$$C_2 = 1 + \lambda \exp\left(-R^2 q^2\right)$$



HBT correlations

R. Hanbury Brown, R.Q. Twiss, «A New type of interferometer for use in radio astronomy», Phil.Mag.Ser.7 45 (1954) 663-682

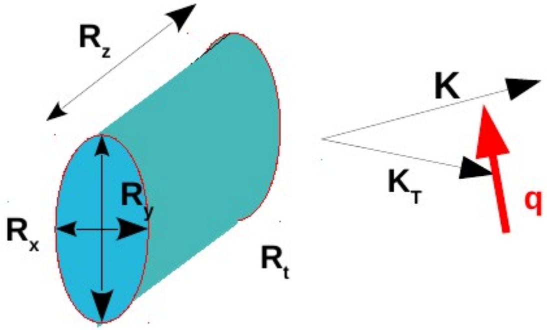




Narrabri Stellar Intensity Interferometer, University of Syndey, ~1970

3D and 1D correlation function parametrization

- Particles are identical
- Particles are on mass shell
  - => only 3 independent variables in q to describe 4-dimensional source



$$q = p_1 - p_2$$

$$K = \frac{1}{2}(p_1 + p_2)$$

Fir identical particles:

$$K \cdot q = 0$$

In out-side-long parameterization

$$R_s^2 = < x_s^2 >$$

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

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

In standard out-side-long parametrization out and long radii keep mixture of spacial and temporal source sizes

Influence of photon spin

For scalar bosons :

$$C_2(q,K) = 1 + \lambda \frac{\left| \int d^4x S(x,K) e^{iqx} \right|^2}{\left| \int d^4x S(x,K) \right|^2}$$

$$K = (k_1 + k_2)/2 \qquad q = k_1 - k_2$$

From microscopic approach, photons are emitted by elementary currents. Averaging over polarizations gives

$$R(k_1, k_2 | x, y) = 1 + (\cos\theta)^2 = \sum_{(\lambda_1, \lambda_2 = 1)}^{2} \left(\epsilon^{\lambda_1}(k_1) \epsilon^{\lambda_2}(k_2) \right)^2$$

$$\lambda = \frac{1}{4}\left(1 + \frac{\vec{k}_1 \cdot \vec{k}_2}{|\vec{k}_1||\vec{k}_2|} \right)$$

D. Neuhauser, Phys. Lett. B 182, 289 (1986)
L.V. Razumov and H. Feldmeier, Phys. Lett. B 377, 129 (1996)
R.M. Weiner, hep-ph/9809202

C_2 and ratio above are Lorentz scalars. λ is a scalar. One can not create dimensionless scalar from two massless 4-vectors:

$$\lambda = \frac{1}{2}$$

C. Slotta and U. Heinz, Phys. Lett. B 391, 469, (1997)
D.Peressounko, Phys.Rev.C 67 (2003) 014905

Photon 1D parametrization

- Difference of 4-vectors

$$Q_{inv} = (p_1 - p_2)^2$$

  - Lorentz-invariant
  - Averages over collinear photons

$$\lambda_{inv} \ll \lambda_{3D}$$

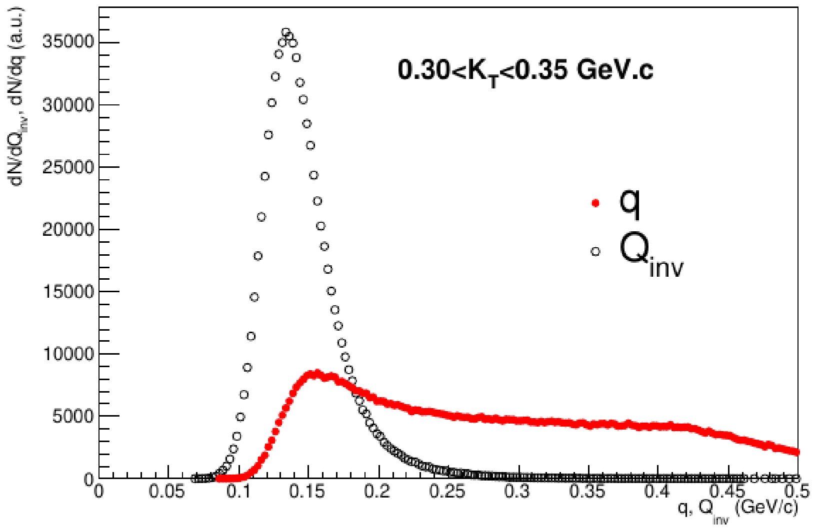
- Difference of 3-momenta in LCMS frame

$$q = |\vec{p}_1 - \vec{p}_2|$$

  - Radii interpretation depends on reference system
  - No averaging over collinear photons

$$\lambda_q = \lambda_{3D}$$

Toy simulation, how π^0 peak looks in Q_{inv} and q variables



Photon 1D parametrization

Toy model: particles with reasonable p_T and rapidity distributions and some 3D correlation radii R_o, R_s, R_l

$$C_2(Q_{\rm inv},K) = \frac{P_2^c(Q_{\rm inv},K)}{P_2^{nc}(Q_{\rm inv},K)}$$

$$P_2^c(Q_{\rm inv},K) = K_0\frac{dN}{dQ_{\rm inv}d^3K} = 8\,Q_{\rm inv}\,K_0\,P_1^2(K)\int d^3q\,\frac{\delta(Q_{\rm inv}^2+q^2)}{4K_0^2-q_0^2}C_2(q,K)$$

$$P_2^{nc}(Q_{\rm inv},K) = K_0\frac{dN}{dQ_{\rm inv}d^3K} = 8\,Q_{\rm inv}\,K_0\,P_1^2(K)\int d^3q\,\frac{\delta(Q_{\rm inv}^2+q^2)}{4K_0^2-q_0^2}$$

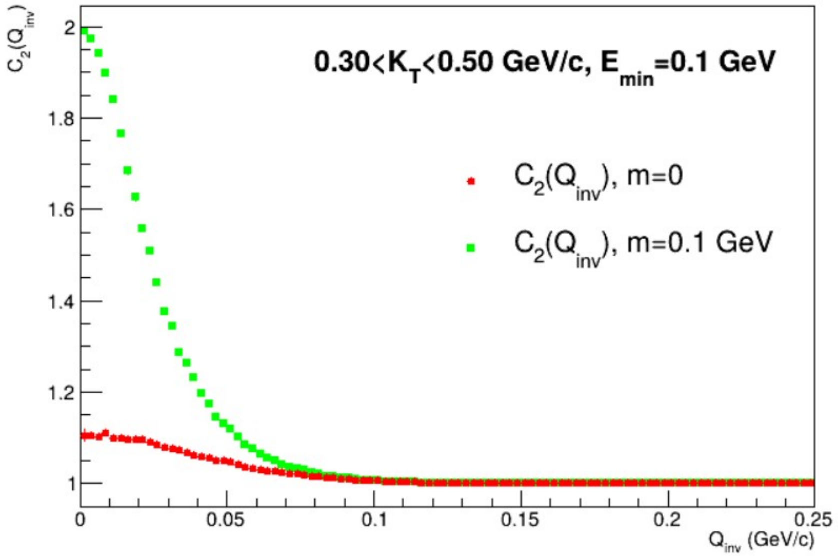
For spherically symmetric source:

$$P_2^c(Q_{\rm inv},K) = 64\,\pi\,K\,K_0\sqrt{Q_{\rm inv}^2+4K^2}\,Q_{\rm inv}\,P_1^2(K)\times$$

$$\int_{Q_{\rm inv}}^{\sqrt{Q_{\rm inv}^2+4K^2}} \frac{dq\,q^3\sqrt{q^2-Q_{\rm inv}^2}}{(q^2+4K^2)^2-4(q^2-Q_{\rm inv}^2)(Q_{\rm inv}^2+4K^2)}C_2(q,K)$$

$$C_2 = 1+\lambda_{inv}\exp\left(-R_{inv}^2 Q_{inv}^2\right)$$

where $$\lambda_{inv} = \frac{\lambda}{4\pi}\int do\,\exp\left(-4R^2K_T^2\cos^2\theta\right)$$



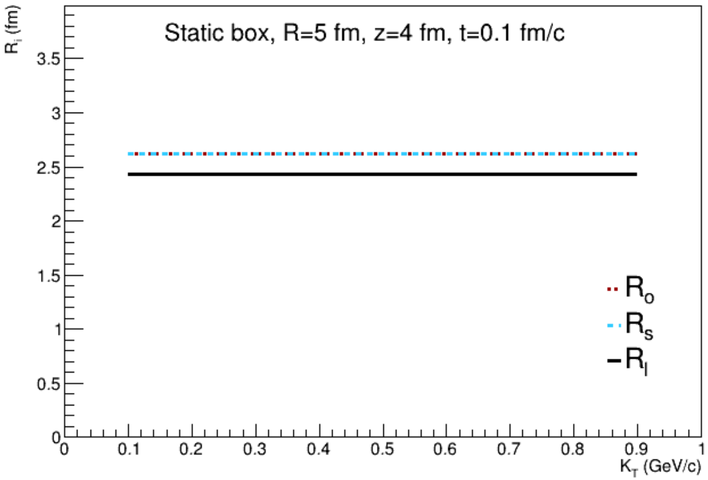
C.F. for particles with m>0 has unit strength, m=0 results in strong suppression.
$C_2(Q_{inv})$ involves averaging over out direction and correlation strength is reduced as erf(R_oK_T) if no (explicit or implicit) cuts on photon energy applied

D.Peressounko, Phys.Rev.C 67 (2003) 014905
M.M. Aggarwal et al. Phys.Rev.Lett. 93 (2004) 022301

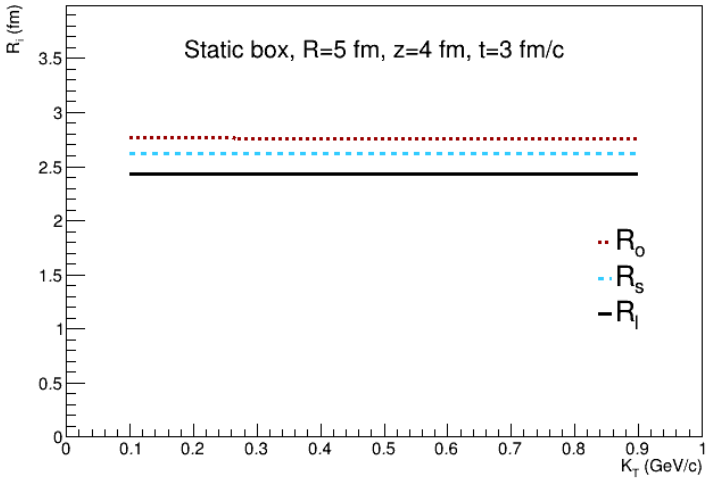
Photon correlations from toy sources

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

Static box: static cylinder with R=5 fm, -4<z<4 fm, 0<t<0.1 fm/c, constant T and no flow



Static box with final lifetime: R=5 fm, -4<z<4 fm, 0<t<3 fm/c, constant T and no flow



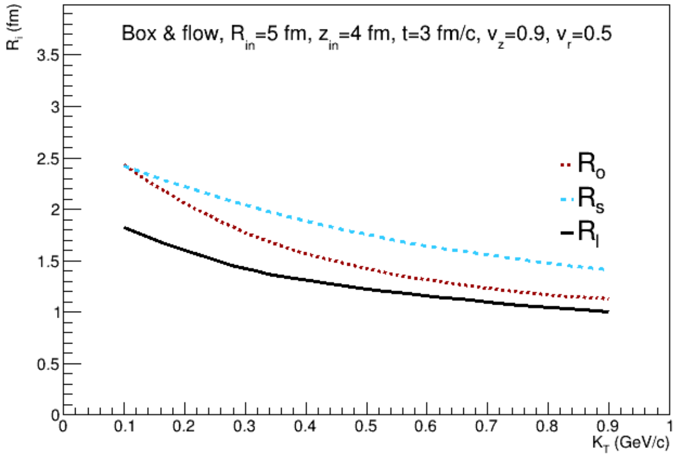
Correlation radii represent RMS of the emitting coordinates => for 2D box $R_o = R_s = R_{box}/2$, for 1D $R_l = z/\sqrt{6}$
No difference between R_o and R_s for short-living source
For source with final lifetime $R_s < R_o$, and R_l is reduced

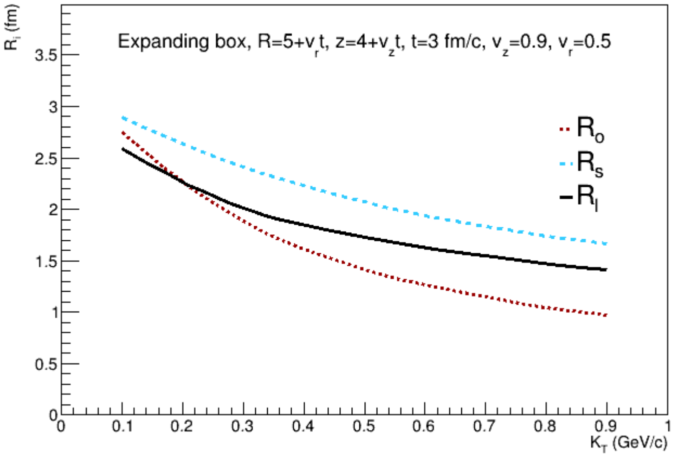
Photon correlations from toy sources (2)

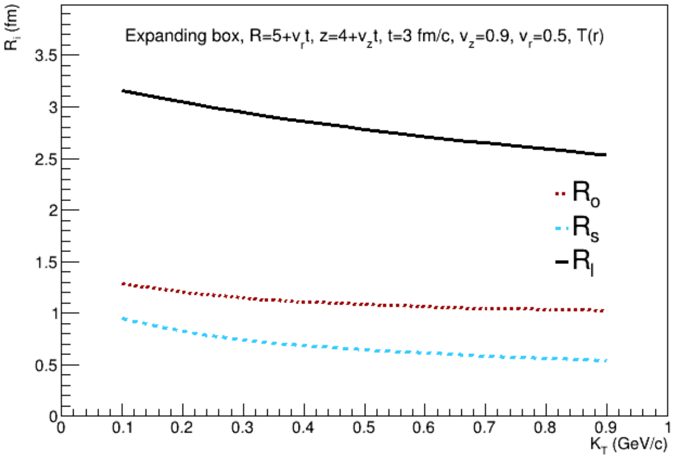
Box with flow but no expansion:
$R=5$ fm, $-4<z_{in}<4$ fm, $0<t<3$ fm/c
$v_z=0.9c\ z/z_{in}$, $v_r=0.5c\ r/R$

Box with flow and expansion:
$R_{in}=5$ fm, $-4<z_{in}<4$ fm, $0<t<3$ fm/c
$v_z=0.9c\ z/z_{max}$, $v_r=0.3c\ r/R_{max}$

Box with flow, expansion, T profile:
$R_{in}=5$ fm, $-4<z_{in}<4$ fm, $0<t<3$ fm/c
$v_z=0.9c\ z/z_{max}$, $v_r=0.3c\ r/R_{max}$,
$T=0.5\exp(-r^2/2^2)$

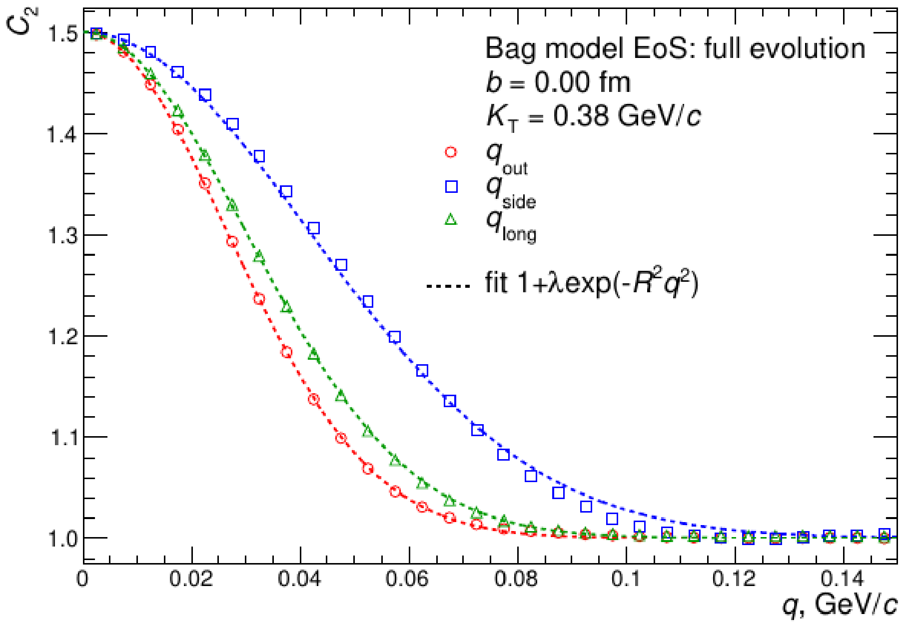






Correlation radii reflect size of the *region of homogeneity*: region, emitting photons with given K_T => characteristic K_T dependence
Accounting expansion and temperature profile can significantly change radii

Calculation in real model



Use UrQMD model to describe evolution of AA collision.
Extract tempereture ***T***, ch. potential ***μ*** and 4-velosity ***u*** at each space-time point ***x***
Use know emission rates of thermal photons in QGP and HG

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

(Single-particle) thermal photon spectrum:

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

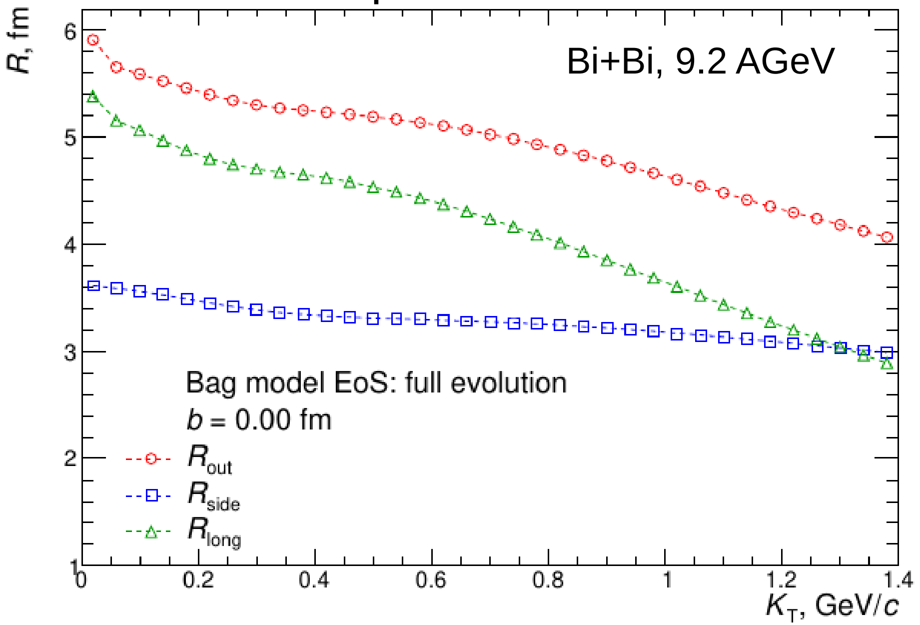
Two-photon correlation function:

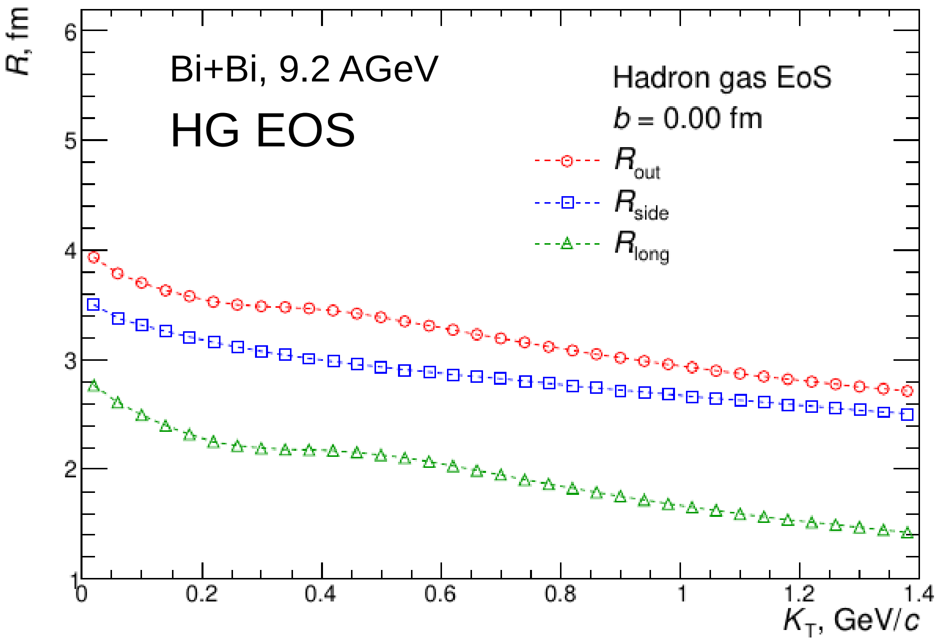
$$C_2(K, q) = 1 + \frac{1}{2} \cdot \frac{\left| \int {\rm d}^4 x S(x, K) e^{iqx} \right|^2}{\left| \int {\rm d}^4 x S(x, K) \right|^2}$$

Sensitivity to equation of state

Idea: mixed phase increases lifetime of the hot matter and its presence can be tested as a difference of R_o and R_s

EOS with phase transition

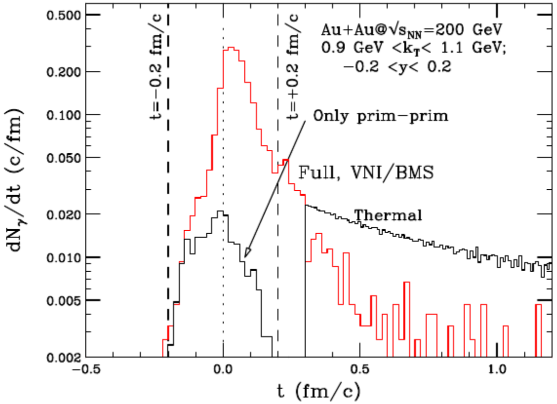




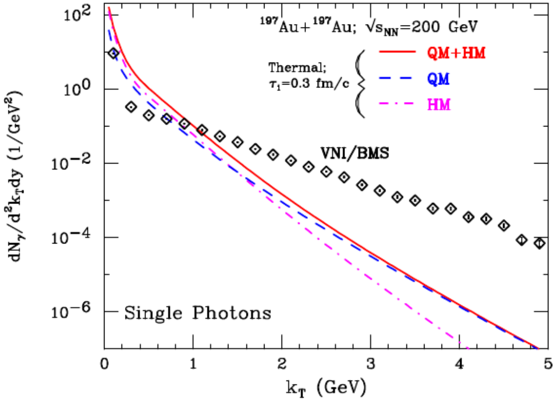
Indeed, presence of mixed phase with zero acceleration introduces difference in lifetime, seen in R_l and R_o radii, while R_s remains the same

=> needs tuning on hadron spectra and radii hydrodynamic description of hot matter evolution

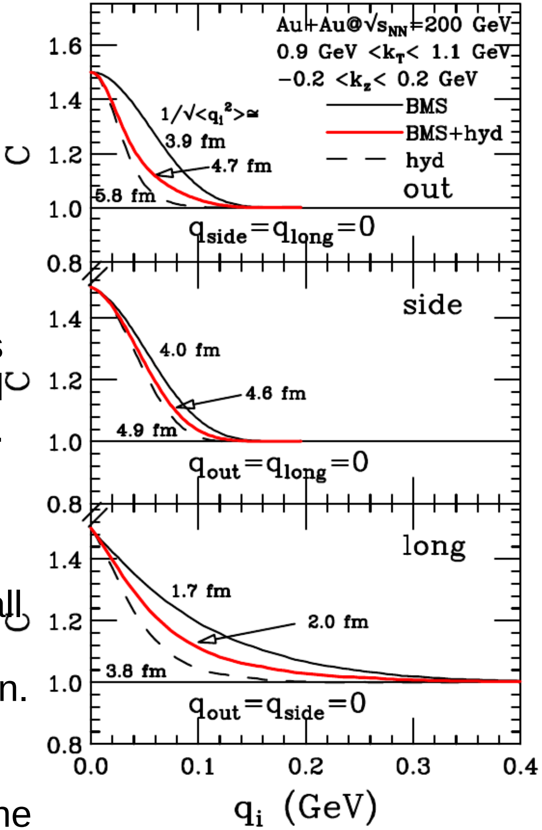
Contribution of pre-equilibrium stage



The production rate (per event) of hard photons as a function of time in the center-of-mass system.
Lower panel: Spectrum of photons from various sources: from parton cascade, QGP and hadron gas.



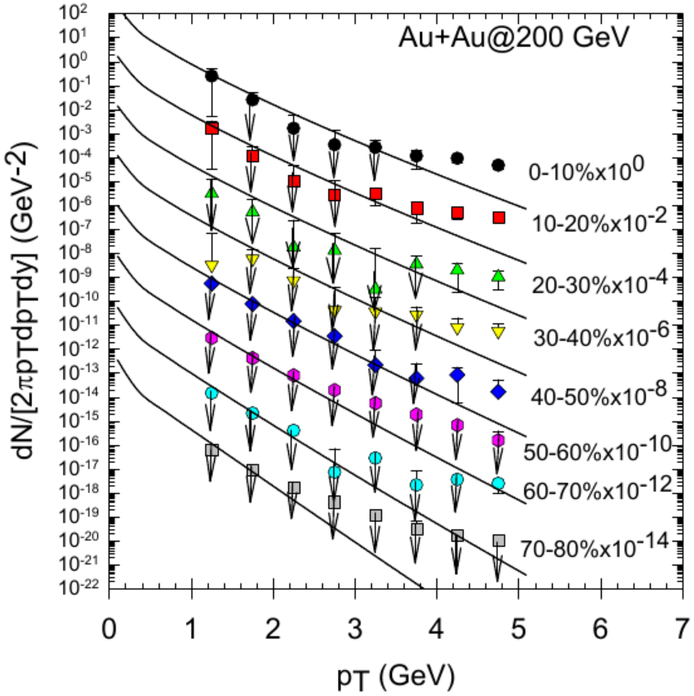
Out, side and long intensity correlation of photons at 1 GeV, considering only parton cascade model (BMS), only thermal (hyd), and both.

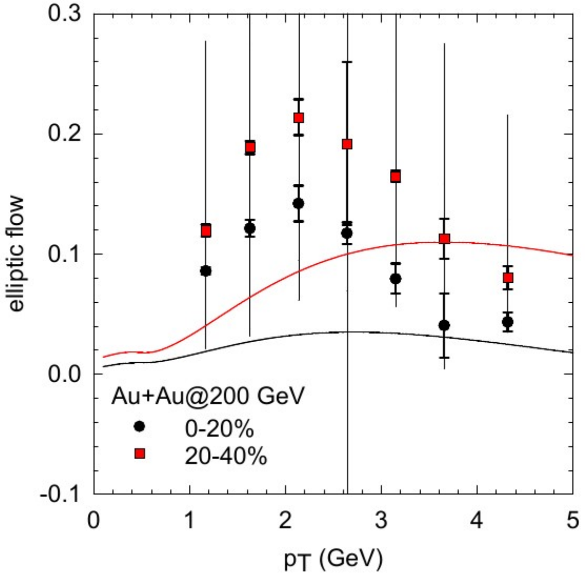


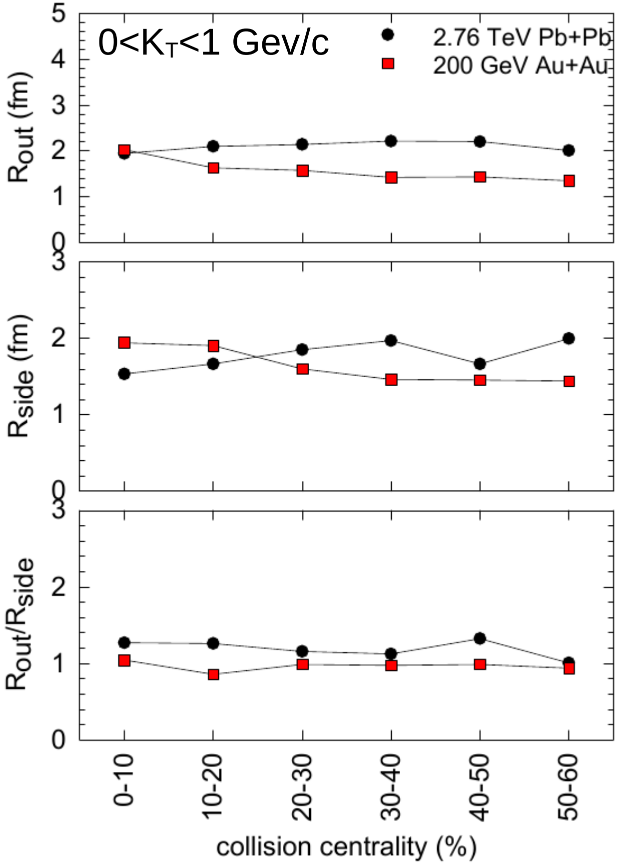
Prediction that photon interferometry will reveal a small source of brief duration for photons at transverse momenta $k_T \geq 2$ GeV/c due to pre-equilibrium emission. This contrasts with a much larger source, revealed by thermal photons at lower momenta, as they mostly originate from the QGP and hadron gas stage when the system has already expanded significantly.

S.A. Bass, B. Muller, D. K. Srivastava,
Phys.Rev.Lett. 93 (2004) 162301, nucl-th/0404050

Hydrodynamics tuned to other direct photon signals



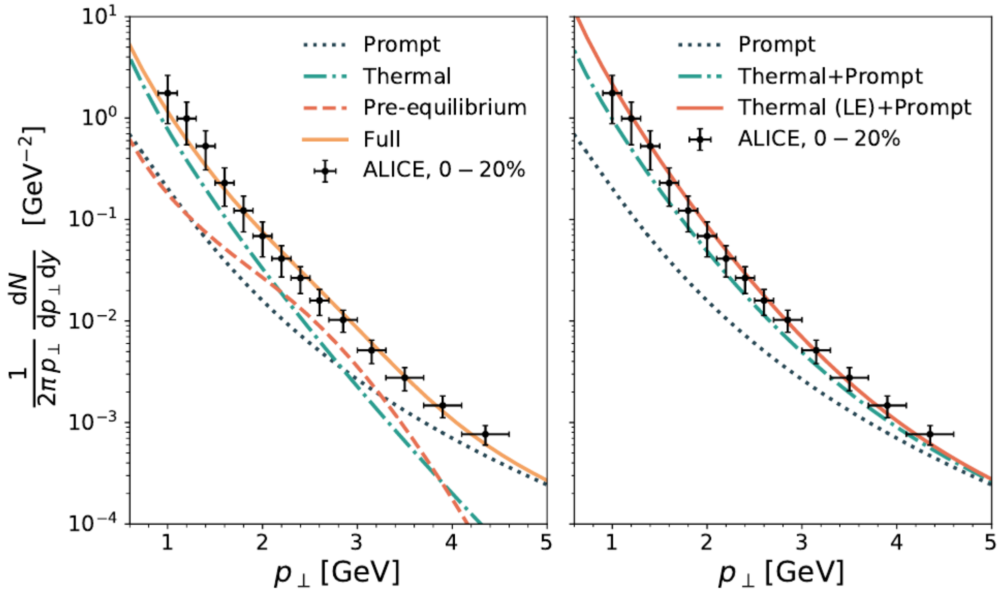


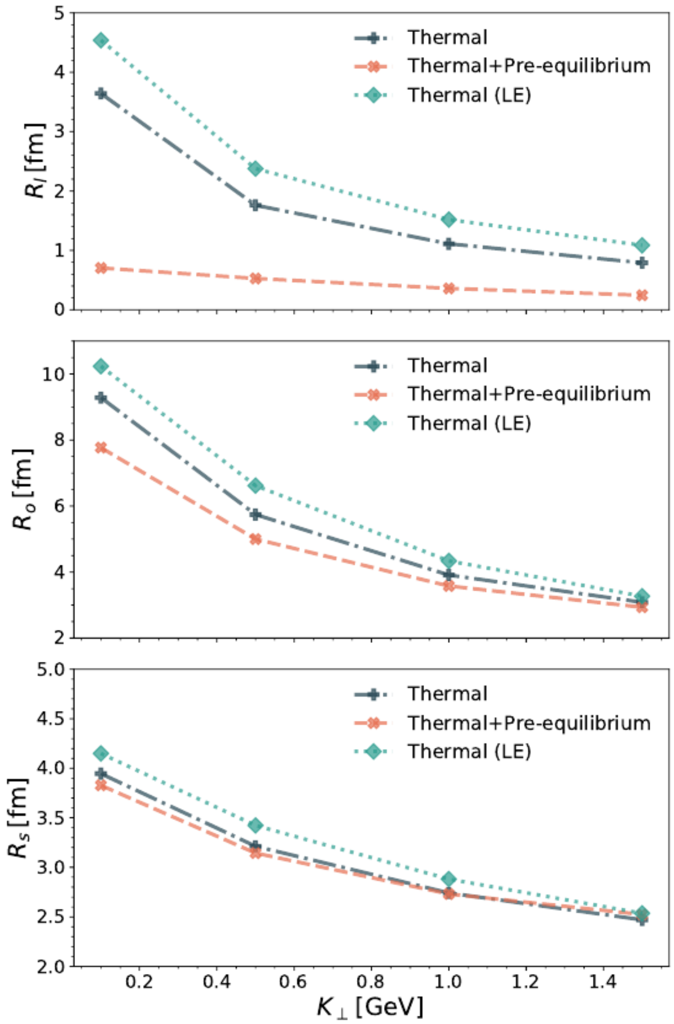


Hydrodynamic description was tuned using final hadron spectra.
Compared predictions for spectrum, flow and HBT radii of direct photons
No centrality dependence of radii expected in RHIC and LHC

A.K. Chaudhuri, 1305.6121 [nucl-th]

Identify enhancement production on some stage?



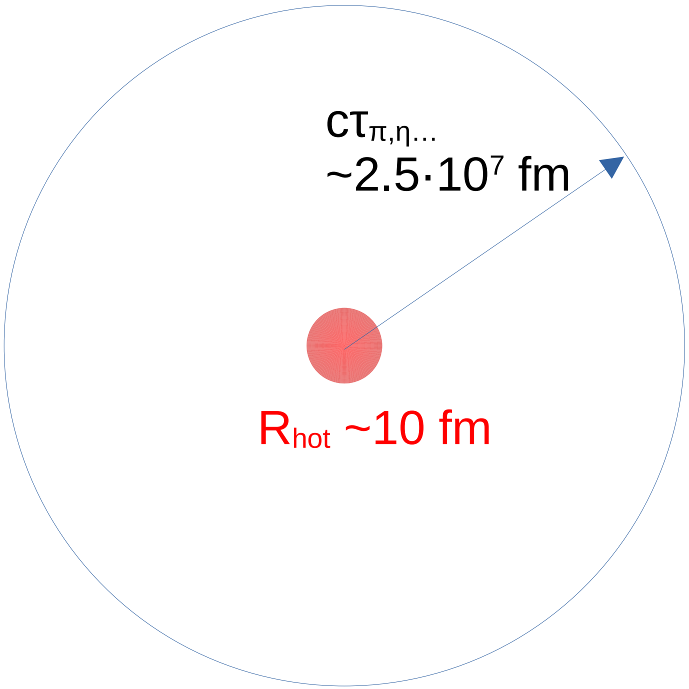


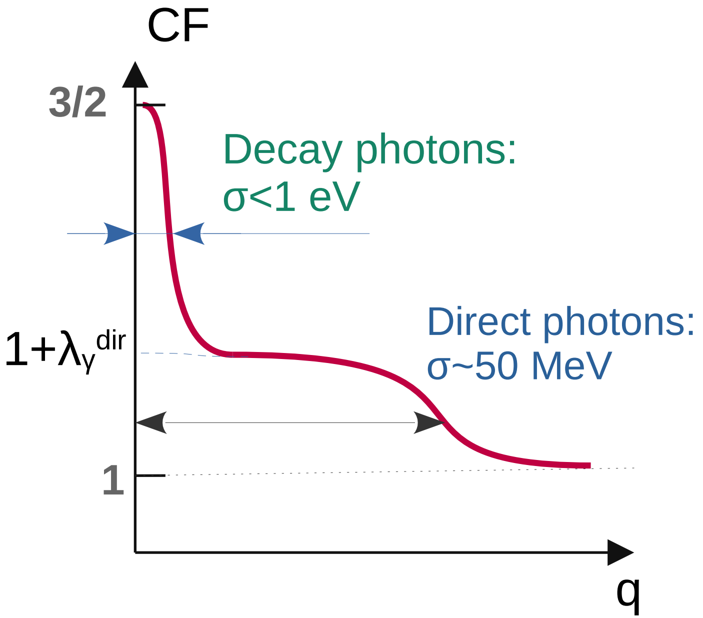
Enhance direct photon production on pre-equilibrium stage or in mixed stage (a-la critical enhancement) still consistent with measured spectrum
=>Minor modification in R_o and R_s but significant change in R_l

O. Garcia-Montero et al., Phys.Rev.C 102 (2020) 2, 024915

Experimental measurements

Inclusive photon vs direct photon correlations





Bose-Einstein correlations of *decay* photons have too small width and not visible.
Once correlations are observed, they should be attributed to *direct* photon correlations

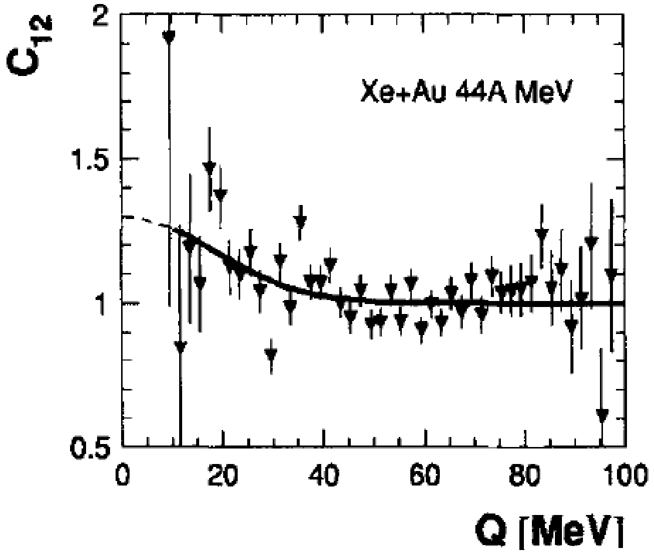
NB! Take into account residual correlations, e.g. between photons from BE correlated π^0s

Low energy AA collisions

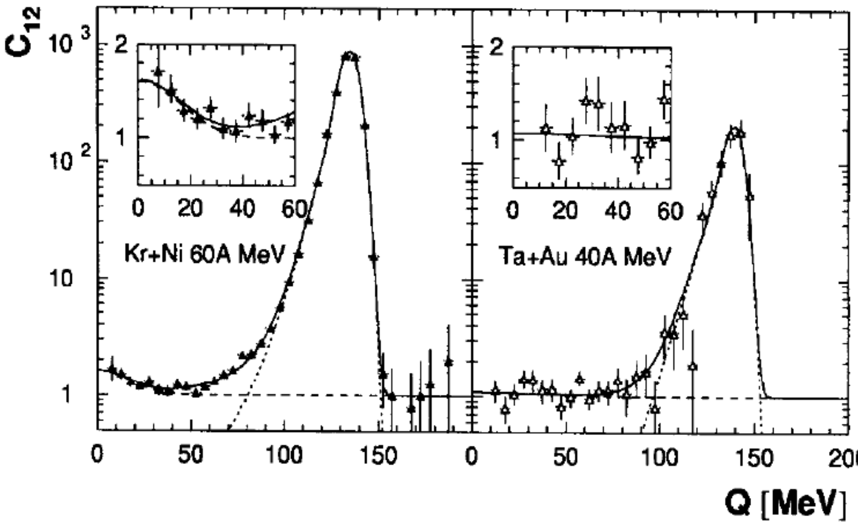
$$C_{12}(Q) = 1 + \lambda \exp(-Q^2 R_Q^2) + K G_A(Q - m_{\pi^0})$$

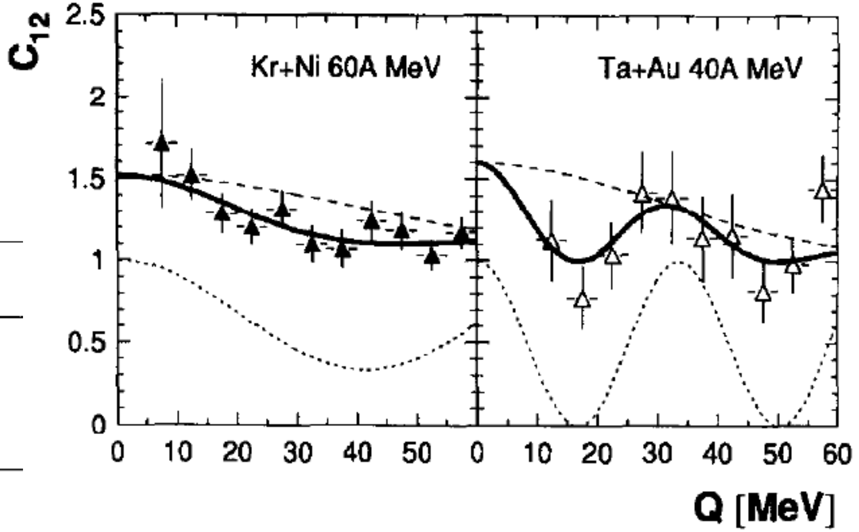
First measurement in heavy ion physics by **TAPS** collaboration

- High granularity calorimeter
- Low multiplicity environment: pion and direct photon peaks well separated
- Correlation strength close to ½ => no background
- Very low K_T, little averaging over R_{out} component for λ_{inv}
- Radii comparable with BUU predictions



System		λ	R_Q (fm)
Xe + Au	44*A* MeV	0.3 $\pm$ 0.5	8 $\pm$ 6
Kr + Ni	60*A* MeV	0.60 $\pm$ 0.20	8.6 $\pm$ 2.2
Ta + Au	40*A* MeV	0.07 $\pm$ 0.13	4^{+7}_{-4}

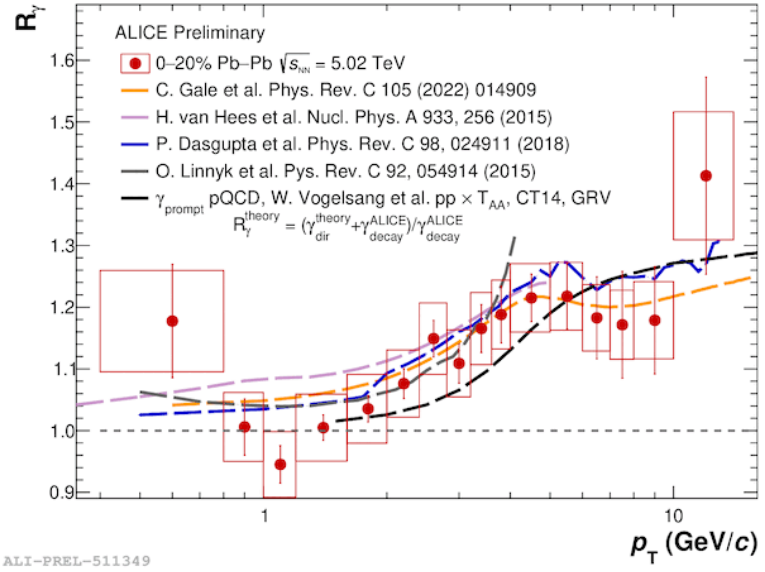




F.M. Marqués et al., «Two-photon correlations: from Young experiments to heavy-ion collision dynamics», Physics Reports v 284, 3, 1997, p 91-136

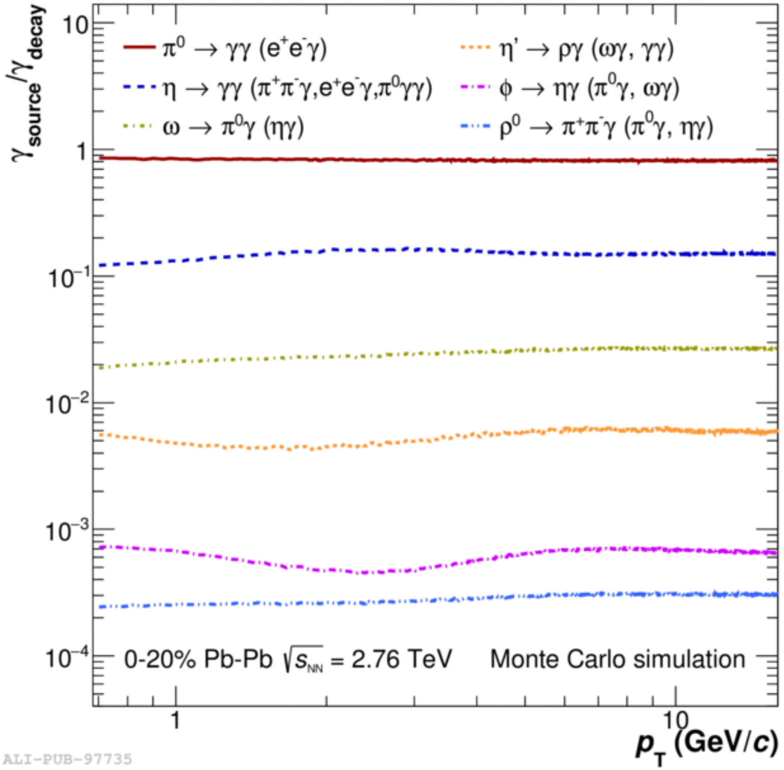
Direct photon yield and proportion

$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{decay}} = 1 + \frac{N_\gamma^{dir}}{N_\gamma^{decay}}$$



Direct photon yield ~5-10% of the decay photon yield

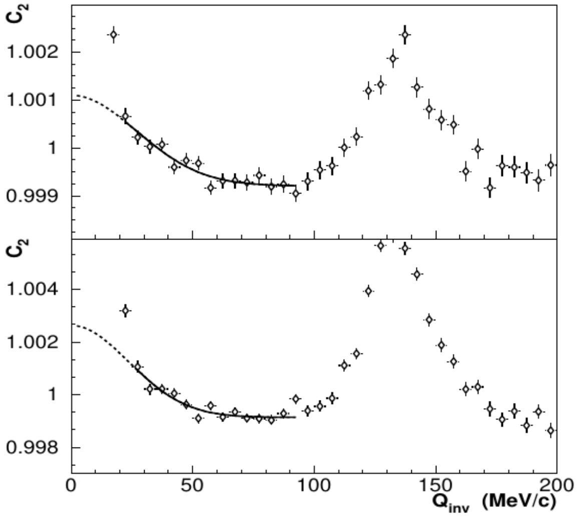
$$\lambda_\gamma^{dir} \approx \frac{1}{2}\left(\frac{N_\gamma^{dir}}{N_\gamma^{incl}}\right)^2 \sim 10^{-3}$$

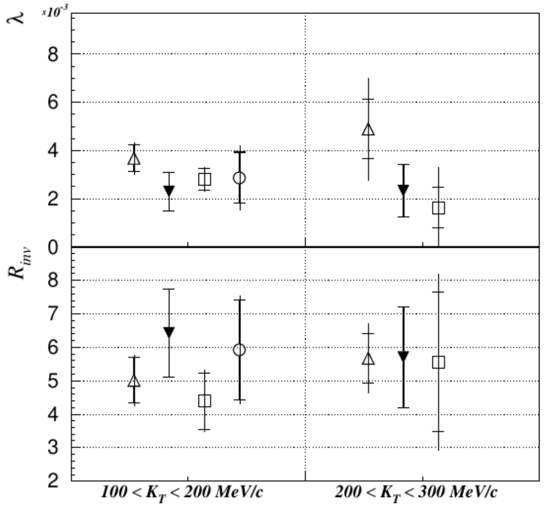


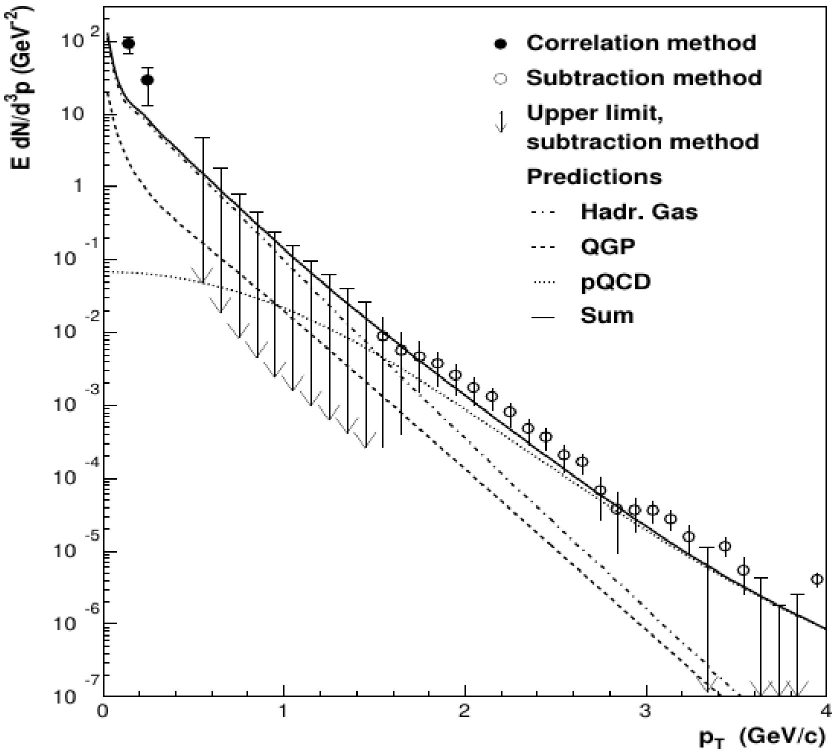
~85% of decay photons come from π^0, ~10% from η

SPS (WA98)

Pb-Pb, 158 AGeV







Experiment WA98 provided first measurement of direct photon interferometry in relativistic heavy ion collisions.

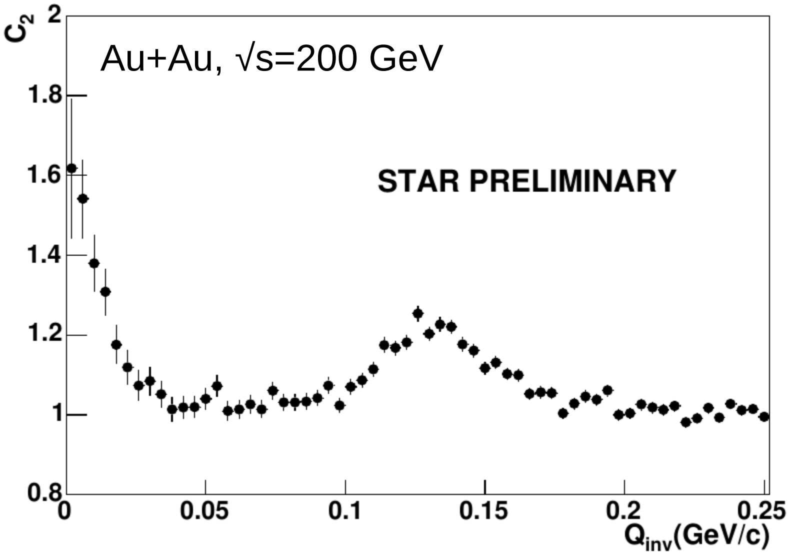
Correlation strength extremely small, ~10^{-3}, but apparatus was favorable for such measurements

Correlation radius was comparable with pion one. Measurements extended direct photon yield to lower p_T, suggesting additional source in this region.

M.M. Aggarwal et al., Phys.Rev.Lett. 93 (2004) 022301

Correlations at RHIC

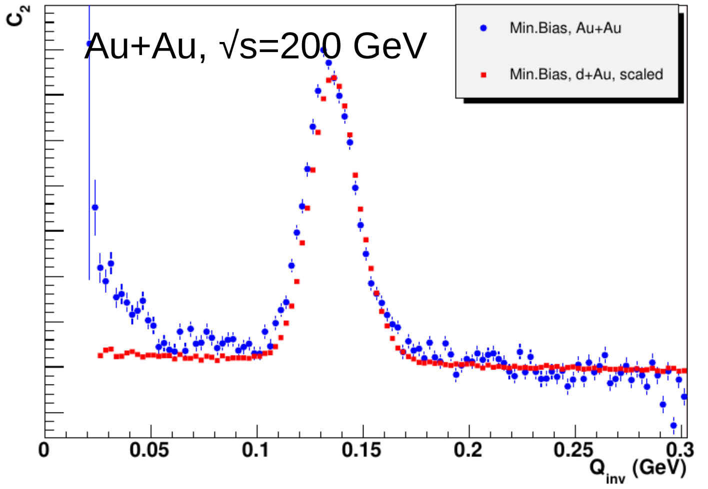
D. Das et al., Nukleonika 51 (2006) 55-58, nucl-ex/0511055 [nucl-ex]

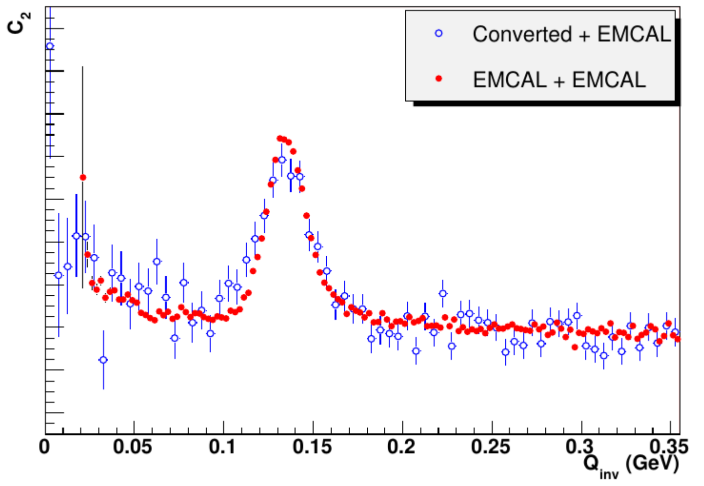


Both STAR and PHENIX provided preliminary results on direct photon interferometry in Au+Au collisions at √s=200 GeV.

PHENIX demonstrated consistency of photon correlation function, measured in calorimeter and using conversion method. Also expected difference in d+Au and Au+Au collisions observed.

D.Peressounko et al., Int.J.Mod.Phys.E 16 (2007) 2235-22400704.0852 [nucl-ex]



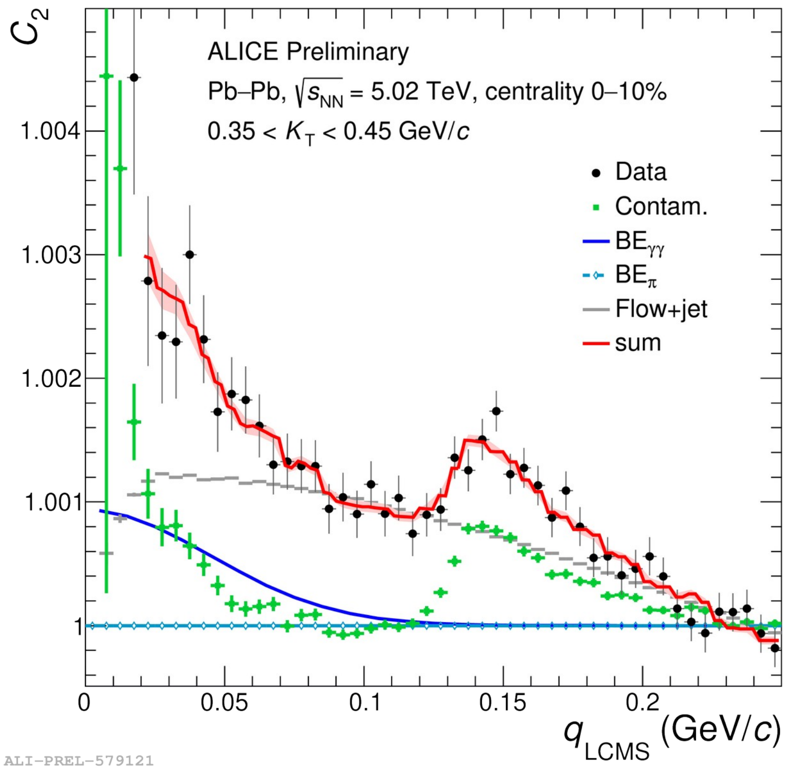


Correlation strength, measured in STAR looks too large (2 orders of magnitude). Probably, some background was not rejected.

Measurements at LHC: ALICE

$$A\left(1+\lambda\exp\left(-q^2R^2\right)+a_{contam}Cont+a_{BE\,\pi\pi}\left(C_2^{BE\,\pi\pi}-1\right)+a_{Flow}\left(C_2^{Flow}-1\right)\right)$$

- Template fit
  - **Contamination**: photon conversion, hadron bremsstrahlung, residual correlations in resonance decays
  - **Direct photon BE** correlations
  - Residual correlation in decays of BE correlated π^0 (negligible in this K_T bin)
  - **Long-range** (flow and jet) correlations



$$K_T=\frac{1}{2}\left(\vec{p}_1+\vec{p}_2\right)_T \qquad q_{LCMS}=\left|\vec{p}_1-\vec{p}_2\right|$$

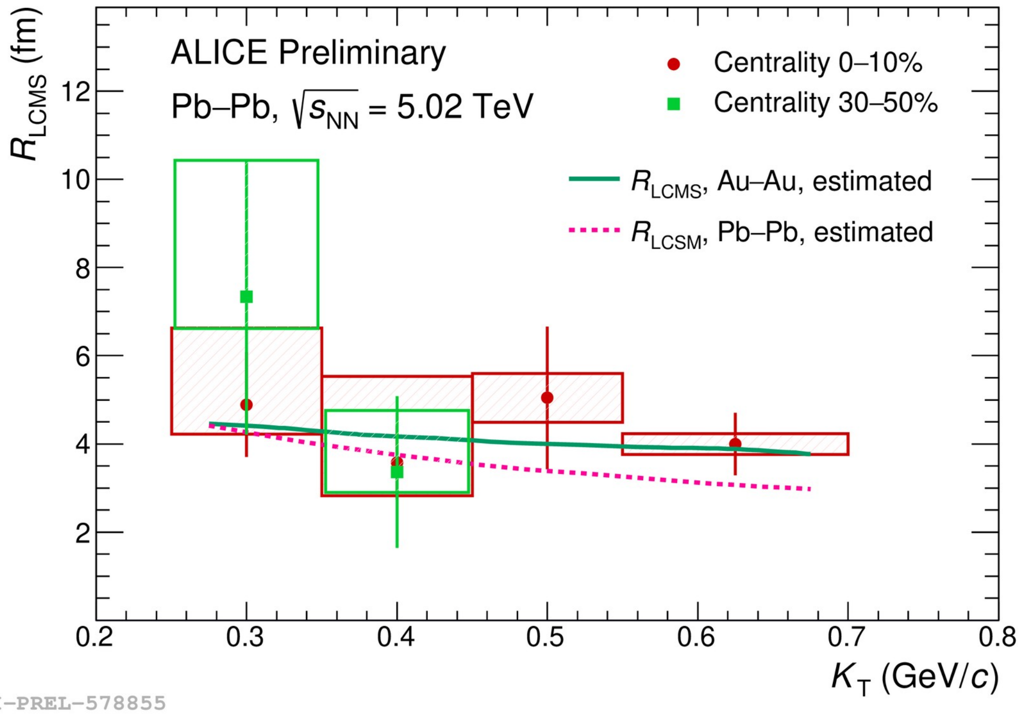
Correlation radius

- Correlation radius R_{LCMS} is an average of all 3 source radii
- Correlation radius shows minor K_T dependence
  - No significant radial flow or interplay of early and later contributions?
- Agrees with estimated radii from hydro predictions
  - Theoretical curves were stimated by averagind of published R_{out}, R_{side}, R_{long} radi

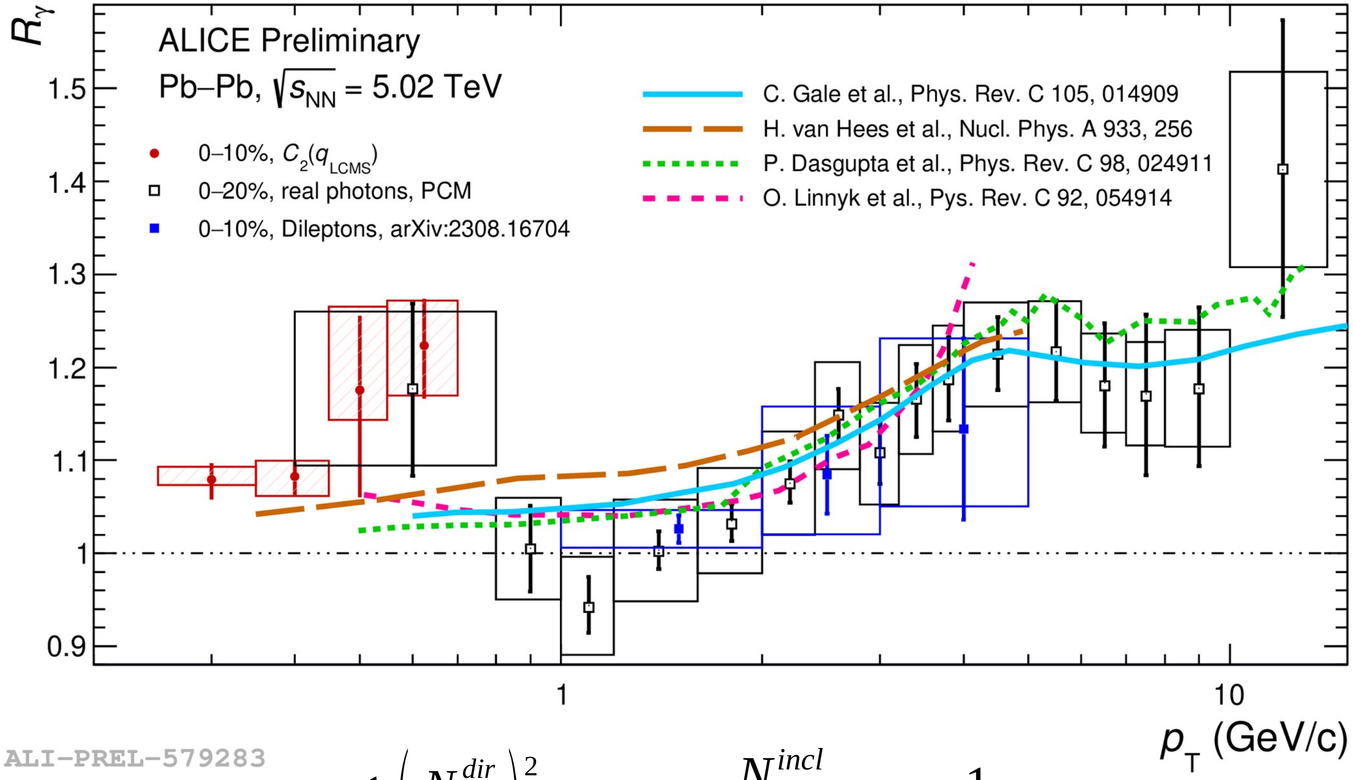
Hydrodynamic calculations:

Pb-Pb: O. Garcia-Montero et al., Phys.Rev.C 102 (2020) 2, 024915

Au-Au: D. Peressounko, Phys.Rev.C 67



Direct photon excess

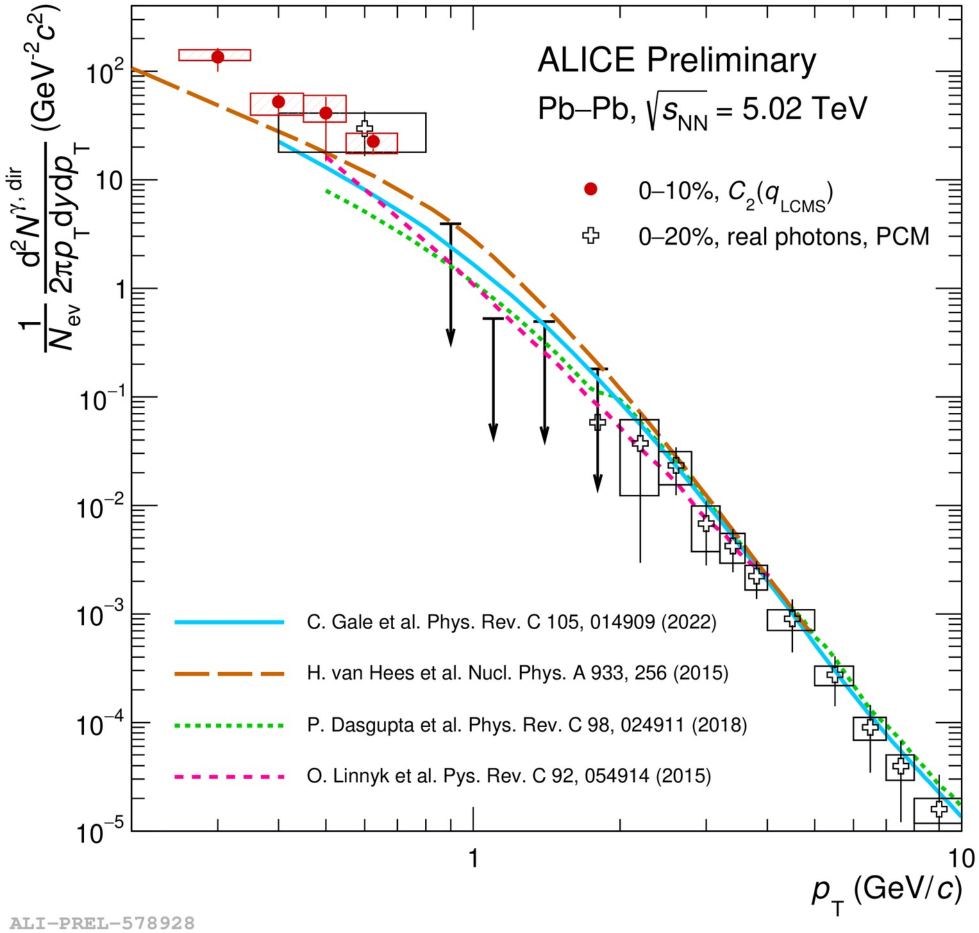


$$\lambda = \frac{1}{2}\left(\frac{N_\gamma^{dir}}{N_\gamma^{incl}}\right)^2 \qquad R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{decay}} = \frac{1}{1-\sqrt{2\lambda}}$$

- BE correlations provide possibility to measure direct photon yield with unprecedented accuracy
- In the overlap region measurements are consistent with measured with PCM subtraction method
- At low p_T measured direct photon yield is larger than predictions by factor ~2

Direct photon spectrum

- Extended measurements down to 250 MeV
- Methods provide consistent results in the overlap region
- Measured spectrum exceeds predictions at low p_T by factor ~2



Conclusions

- Direct photon Bose-Einstein correlations provide possibility to study sizes of the innermost, hottest part of the collision
- Photon interferometry has few peculiarities due to photon massless nature
- Theoretical calculations show some sensitivity to equation of state, relative yield of photons on different stages
  - However, the number of studies is rather limited
- Experimental measurements were performed at non-relativistic energies (TAPS) and relativistic at SPS (WA98), preliminary data exist at RHIC (PHENIX, STAR) and LHC (ALICE)