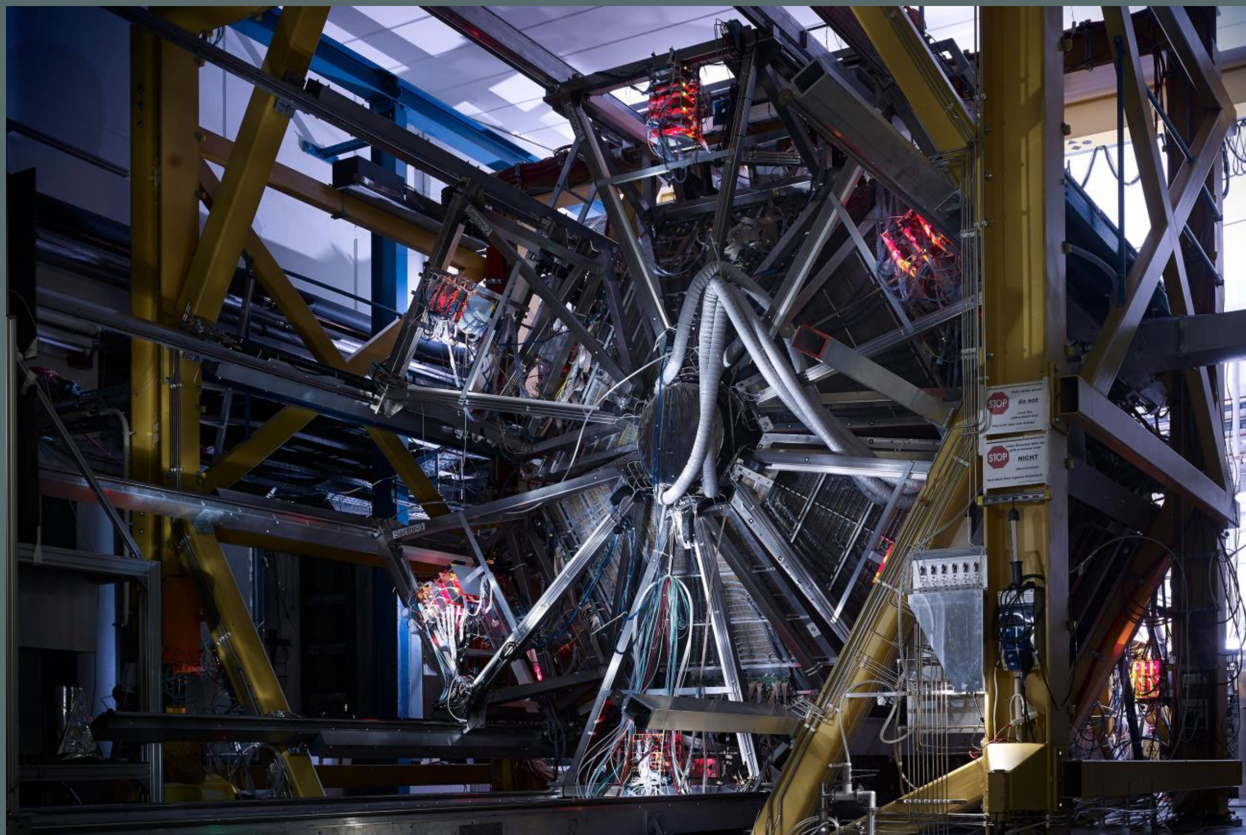
Photon-photon femtoscopy in Ag+Ag collisions at $\sqrt{s_{NN}}$ =2.55 GeV



Mateusz Grunwald
for the HADES collaboration

WPCF 2024 welcomes you in Toulouse France

HADES

GSI

Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY
Warsaw University of Technology

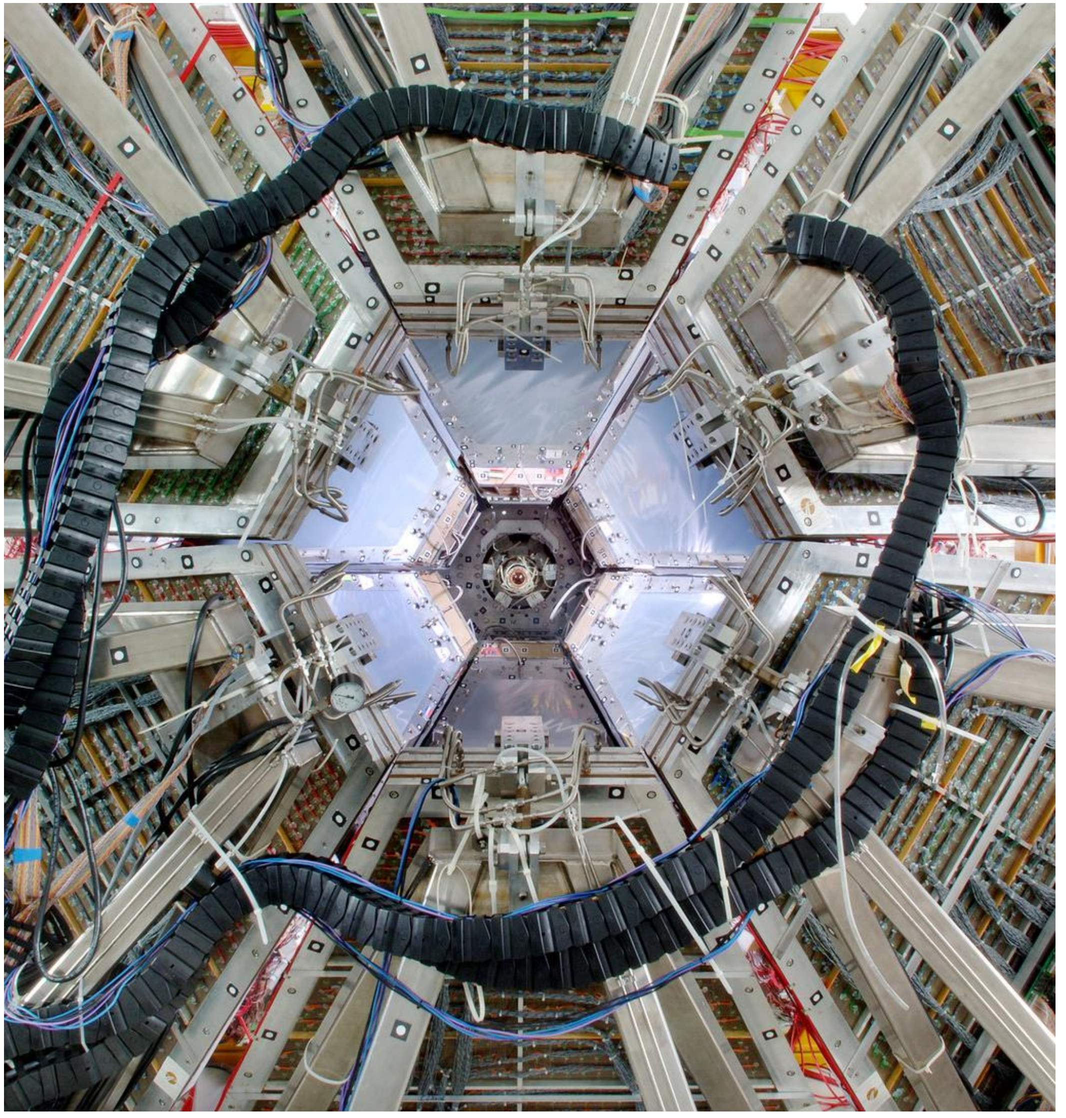
RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE

NATIONAL SCIENCE CENTRE
POLAND

FAIR
Phase-0
Research Program

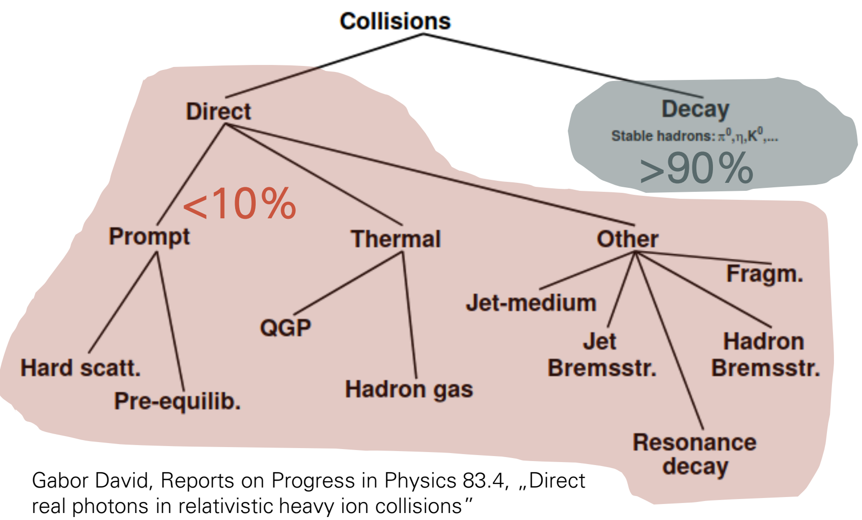
Outline

1) Motivation
   - Why photon femtoscopy?
2) Femtoscopy technique
   - Well known, but it's good to remind
3) HADES experiment
4) Results:
   - Photon selection
   - Necessary corrections
   - Correlation functions + fits
5) Summary

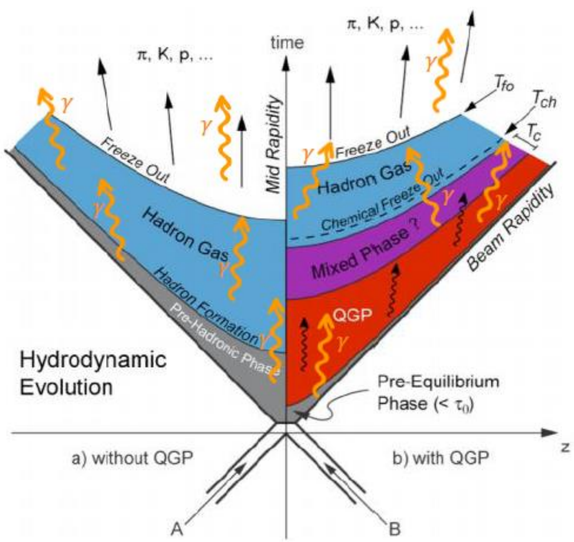


Motivation

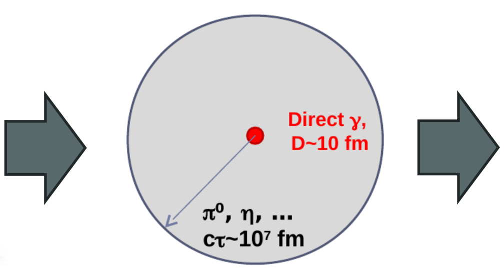
- Measure source properties **at early stages** -> inaccessible for hadrons
- Estimate average **direct photon yield**
- Easy in theory, challenging in practice



Gabor David, Reports on Progress in Physics 83.4, „Direct real photons in relativistic heavy ion collisions"

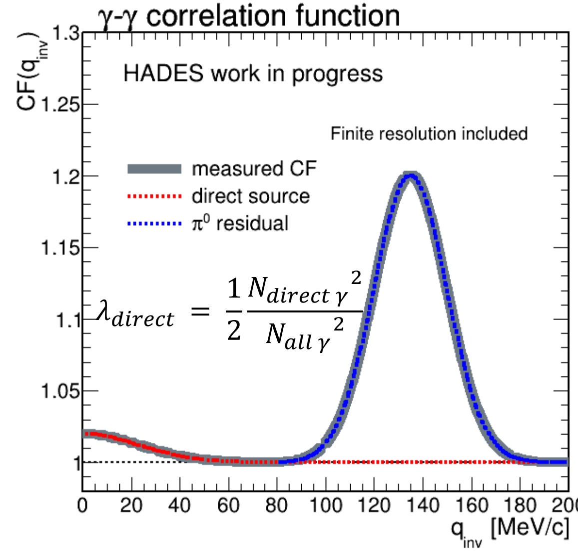


J. Stachel. K. Reygers, QGP physics SS2015 6., „Space-time evolution of the QGP"



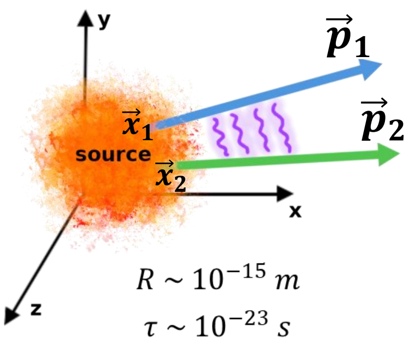
$$q_{inv} = M_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos(\alpha_{\gamma\gamma}))}$$

Cartoonish idea of experimental γ-γ correlation function



Femtoscopy

Goal - measure source's space-time characteristics and/or interactions between particles through low relative momentum correlations.



$R \sim 10^{-15}\, m$

$\tau \sim 10^{-23}\, s$

Theory

Single particle emission function: $P(\vec{p}) = \int S(\vec{x})\, d^3x$

Correlation function:

$$CF(\vec{p}_1, \vec{p}_2) = \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)}$$

Two particle emission function: $P(\vec{p}_1, \vec{p}_2) = \int S(\vec{x}_1; \vec{x}_2)\, |\Psi(\vec{x}_1, \vec{p}_1; \vec{x}_2, \vec{p}_2)|^2 d^3x_1 d^3x_2$

$\vec{x}$: particle's position

$\vec{p}$: particle's momentum

$\Psi(\vec{x}_1, \vec{p}_1; \vec{x}_2, \vec{p}_2)$: two particle's wave function

$S(\vec{x})$: source function

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

$N_{same}(q)$: same event distribution

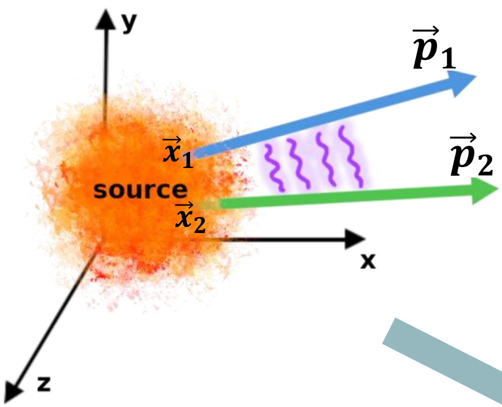
$N_{mixed}(q)$: mixed event distribution

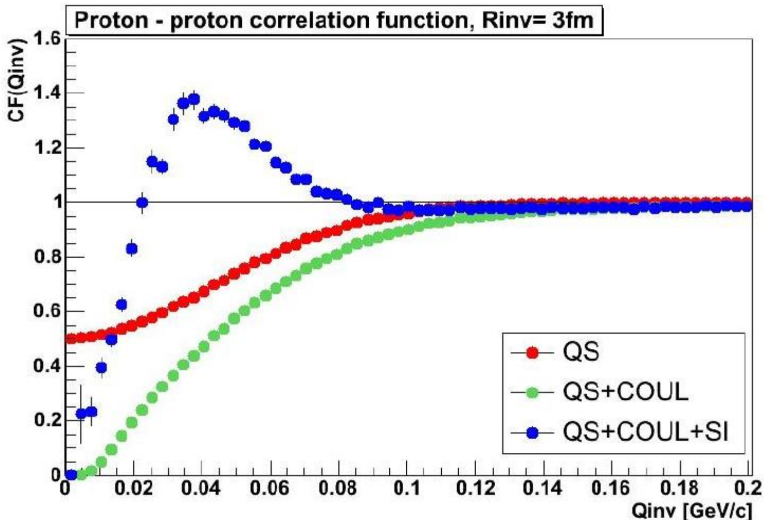
Experiment

Correlation function:

$$CF(q) = \frac{N_{same}(q)}{N_{mixed}(q)}$$

Femtoscopy





Hanna Paulina Zbroszczyk, PhD thesis

Effects and interactions:

- QS – quantum statistics (Bose-Einstein or Fermi-Dirac), identical particles
- Coul – Coulomb interactions, charged particles
- SI – strong interactions, hadrons

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

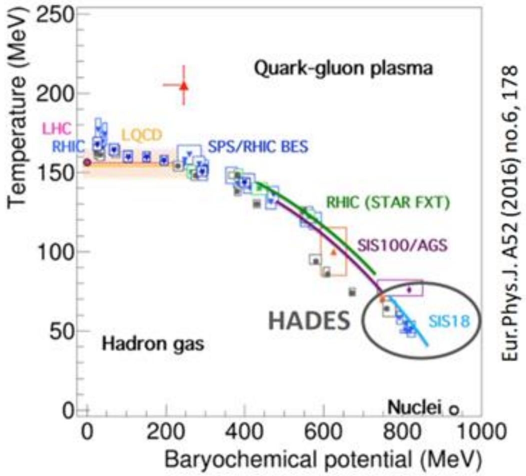
$r = |\vec{x}_1 - \vec{x}_2|$: relative distance

$$CF(q) = \int S(r)|\Psi(r,q)|^2 d^3r$$

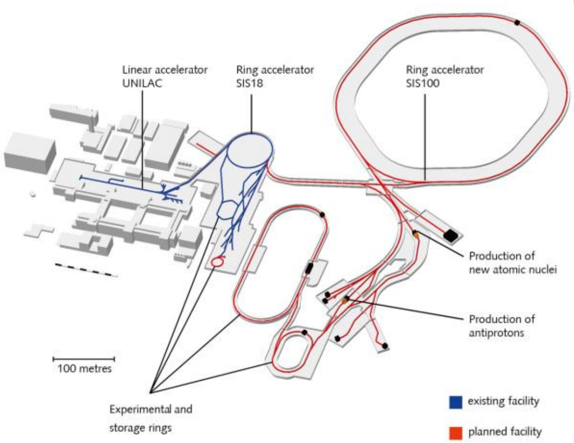
Determine the geometry and dynamic properties (traditional femtoscopy)

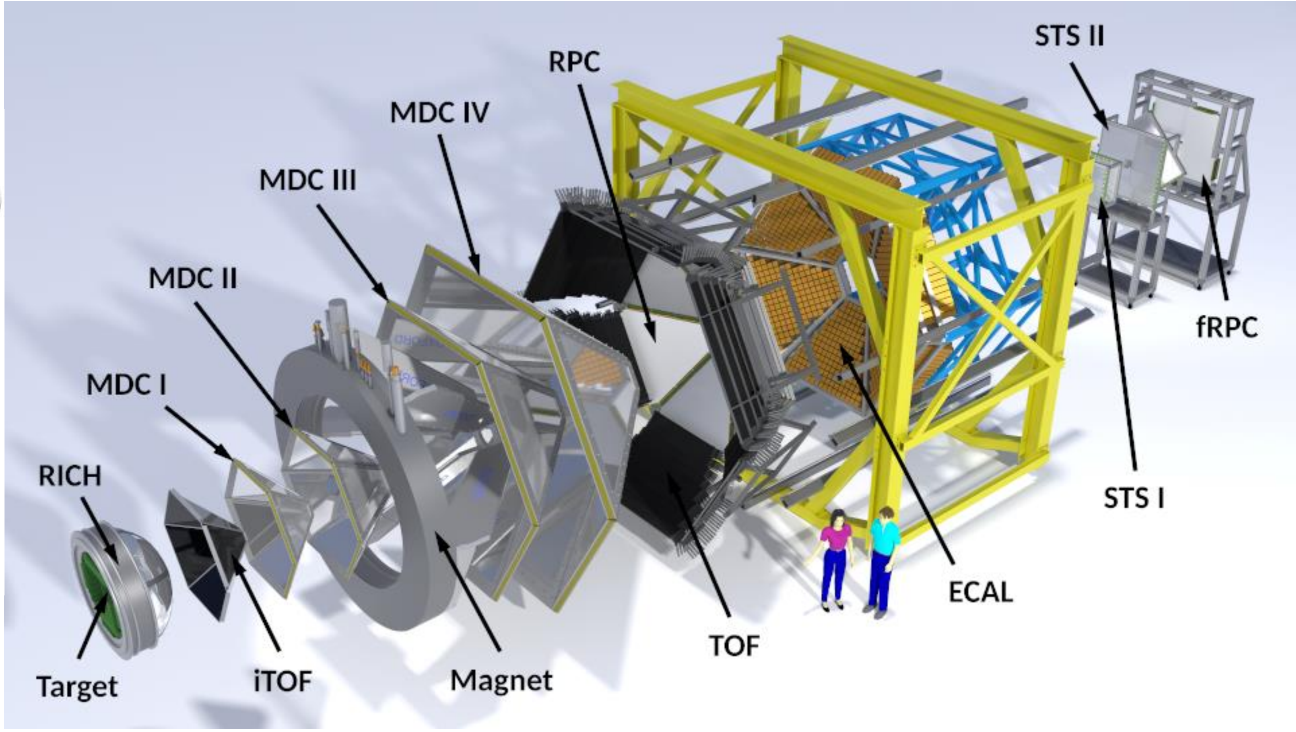
Determine the interactions (non-traditional femtoscopy)

HADES experiment



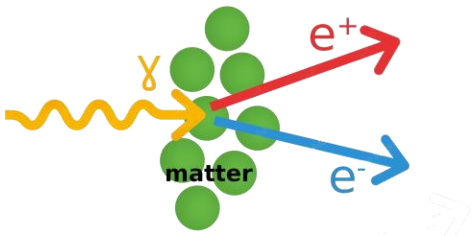
- High Acceptance Di-Electron Spectrometer
- Fixed target, few (1-2) GeV beam kinetic energy
- Measurement of dilepton pairs from vector mesons (ω, ϕ, ρ)
- High angular acceptance (0°<ϕ<360°, 18°<θ<85°) split into 6 sectors
- High $e^{\pm}$ reconstruction efficiency (RICH, ECAL) and $\pi^{\pm}$ /p separation (TOF)





Photons at HADES

Photon Conversion Method (PCM)

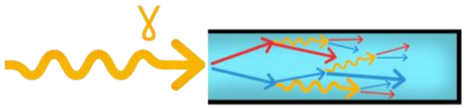


- High momentum and angular resolution
- Good lepton reconstruction efficiency at HADES
- Pure sample of photons

- Possible lepton close track effects due to small opening angle
- 2-step reconstruction (leptons → photons) → **low efficiency**
- **Low conversion** probability due to very small material budget of HADES
- **(~10^{-5} prob. of reconstructing 2γ/event)**

Not enough photons reconstructed via PCM for femtoscopic measurements!

Electromagnetic calorimeters (ECAL)



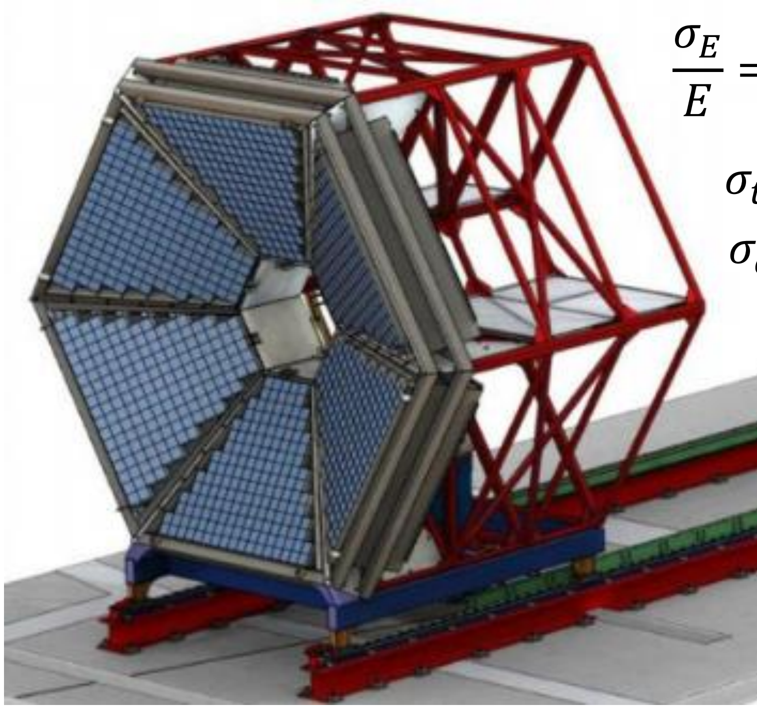
- Great efficiency due to direct reconstruction of neutral particles
- Decently pure sample with suitable criteria

- Calorimeter modules are usually big → poor angular resolution
- Low-end energy resolution is low due to ~1/√E behavior → low Q_{INV} might be fairly smeared, since:

$$q_{inv} = m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos(\alpha_{\gamma\gamma}))}$$

Photons at HADES - ECAL

Electromagnetic calorimeters (ECAL)

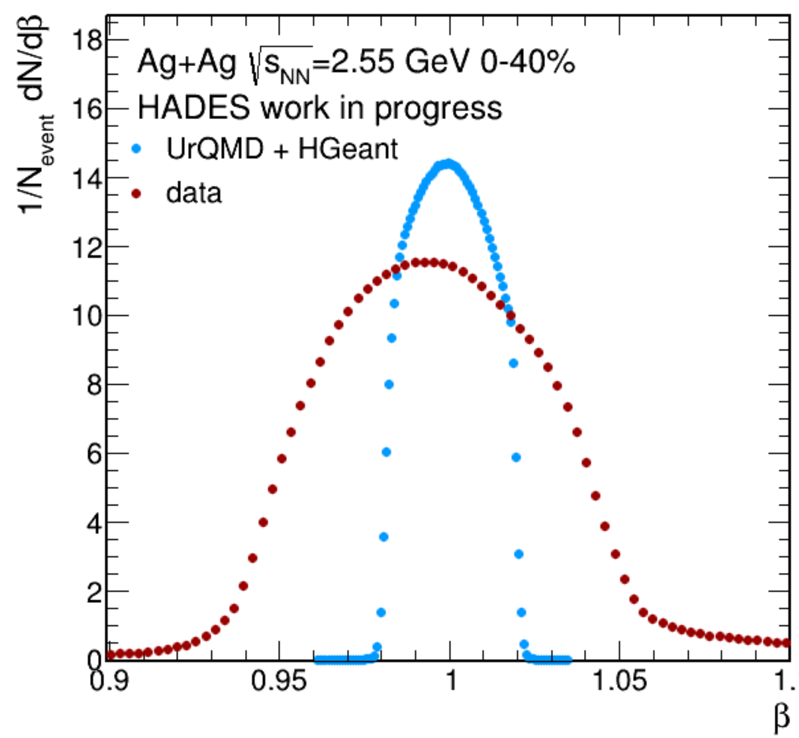


$$\frac{\sigma_E}{E} = \frac{6\%}{\sqrt{E(GeV)}}$$

$$\sigma_t < 300\ ps$$

$$\sigma_{\alpha_{\gamma\gamma}} = 2.2°$$

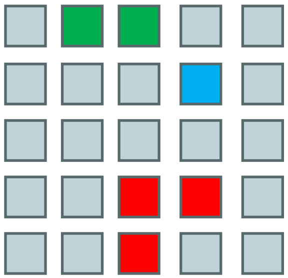
ECAL γ β distribution



- **Photon definition:**
  - No matching with charged tracks or hits in ToF detectors within 6σ
  - No charged particle with opening angle to cluster > 2.8 °
  - Cells closest to the beam line are not used
  - Total cluster energy > 100 MeV, minimal energy in each module > 50 MeV
  - β within 1σ from expected photon peak (β~1), adjusted for each module (and day/hour of a beamtime)

statistical uncertainties only

Photons at HADES - ECAL



Modules are ~ 2.2° (92 mm) wide, Can't separate 2γ within 300 ps interval → **1 module detects 1 γ**

Minimum opening angle by geometry, aka. „hardware limit" ~ 4.4° (for 2 „size 1" clusters)

γ triggers:

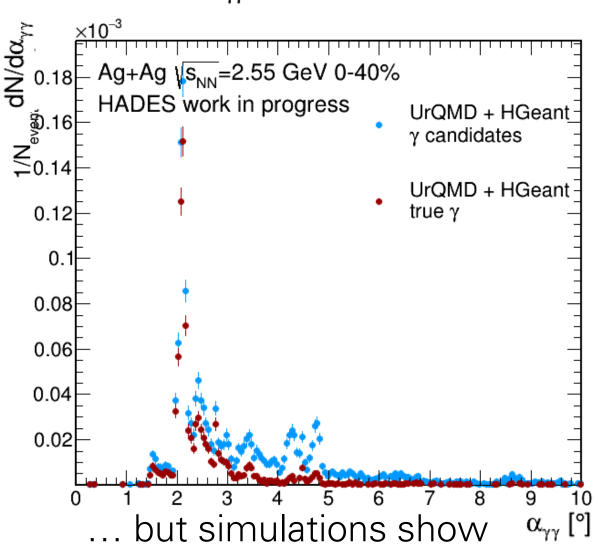
1 module → cluster size 1

2 modules → cluster size 2

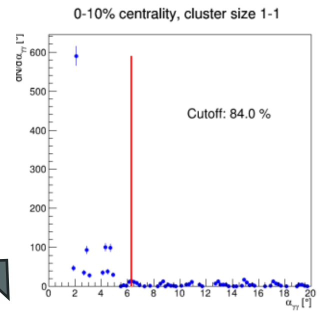
3 modules → cluster size 3

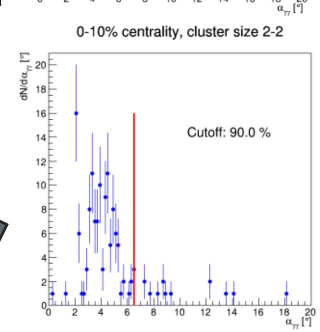
…

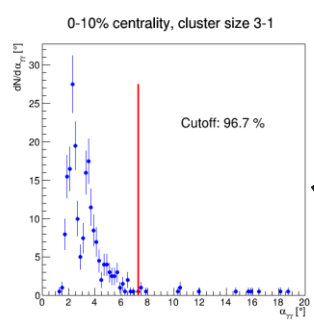
ECAL $\alpha_{\gamma\gamma}$, same Geant track pairs



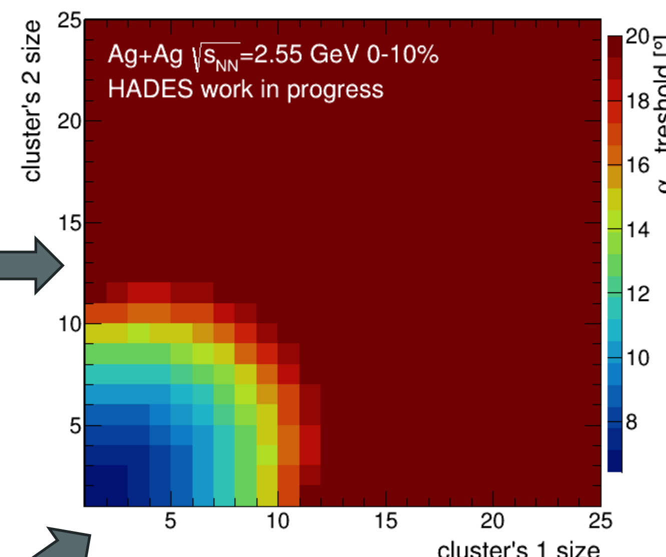
… but simulations show some „split" clusters







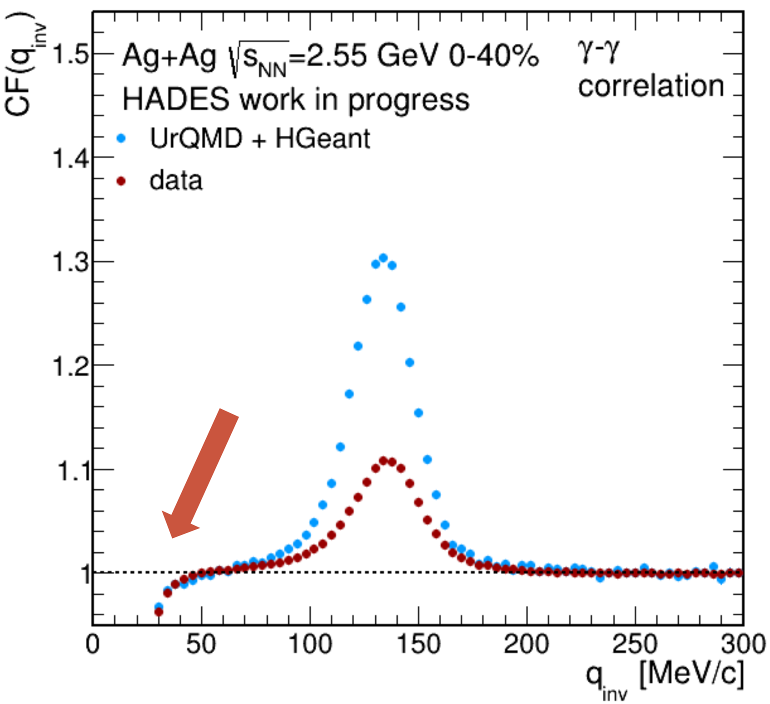
Two ECAL γ $\alpha_{\gamma\gamma}$ treshold map



Made for each 10% centrality interval separately

statistical uncertainties only

Photon-photon correlation functions, Ag+Ag at 2.55 GeV



Anticorrelation caused by uneven $\alpha_{\gamma\gamma}$ acceptance between same & mixed events („hardware limit")

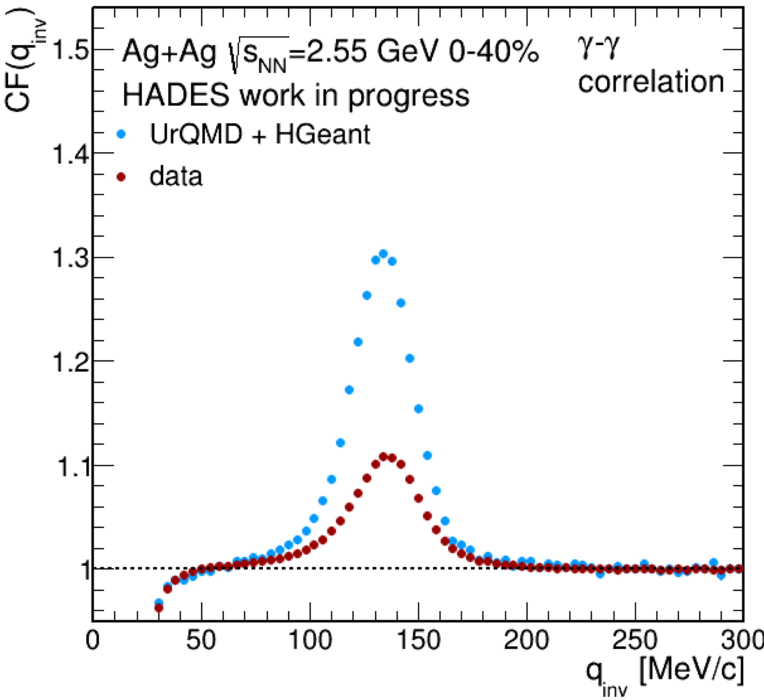
UrQMD + HGeant → HADES's simulations.
No FSI/QS involved, no direct photons present.
Used as a benchmark of detector effects

data → real data gathered by HADES

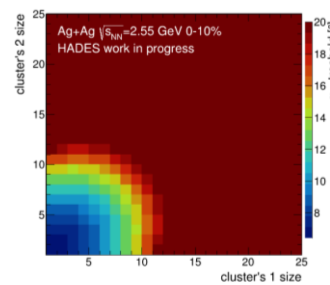
$$q_{inv} = \sqrt{(\overrightarrow{p_1} - \overrightarrow{p_2})^2 - (E_1 - E_2)^2}$$

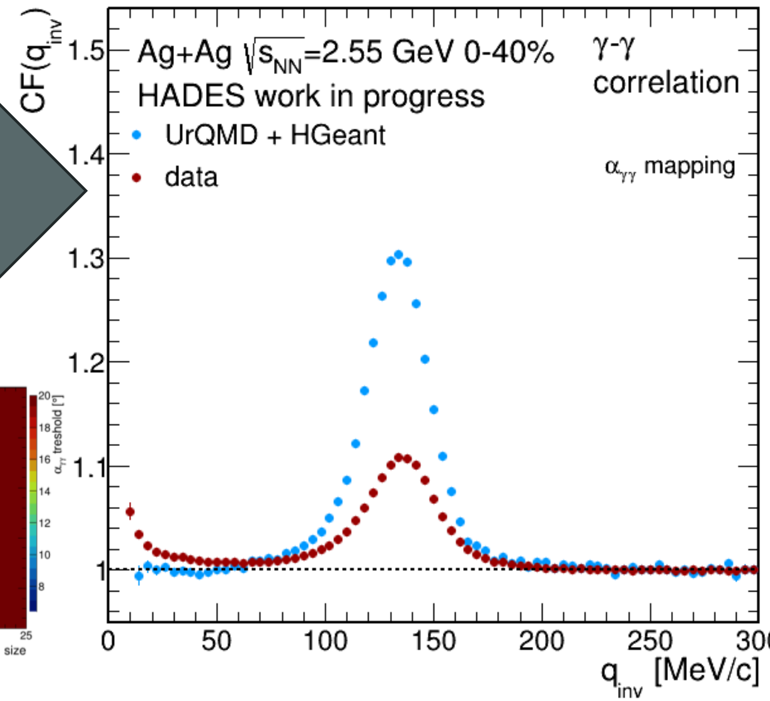
statistical uncertainties only

Photon-photon correlation functions, Ag+Ag at 2.55 GeV



Opening angle „mapping"





Visible enhancement at low q_{inv} over simulations!

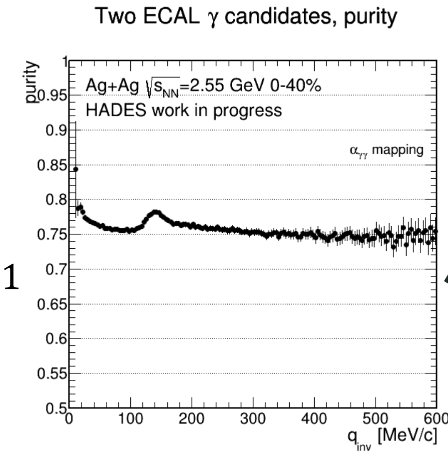
$$q_{inv} = \sqrt{(\vec{p_1} - \vec{p_2})^2 - (E_1 - E_2)^2}$$

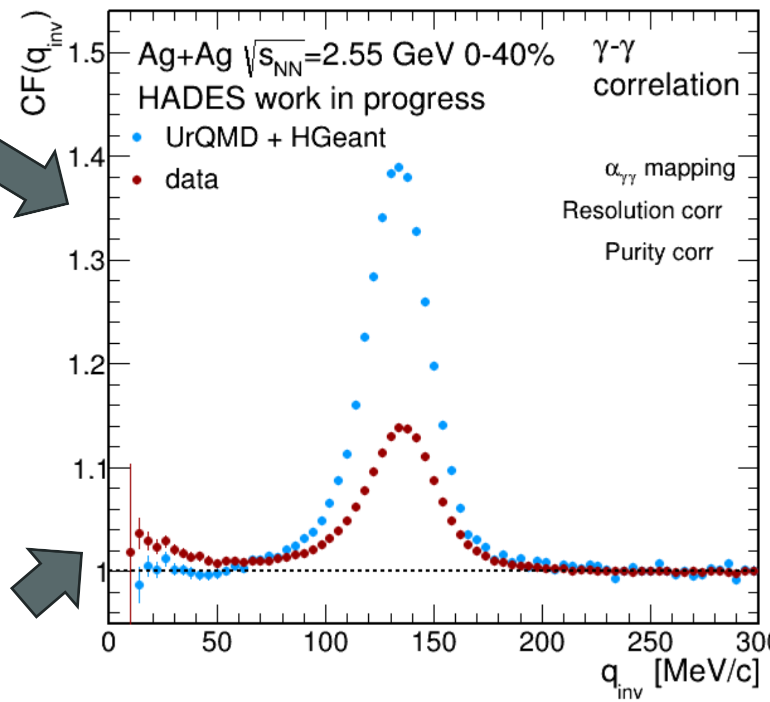
statistical uncertainties only

Photon-photon correlation functions, Ag+Ag at 2.55 GeV

$$purity_{sim}(q_{inv}) = \frac{N_{\gamma\gamma\ pair}(q_{inv})}{N_{any\ pair}(q_{inv})}$$

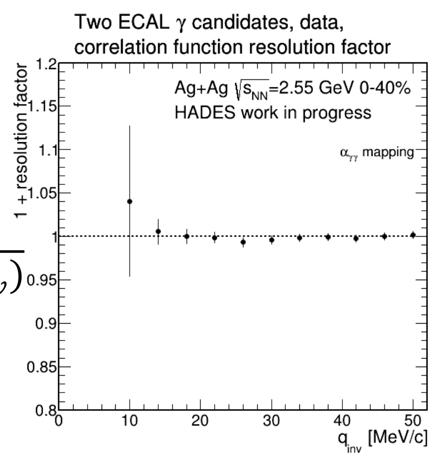
$$CF_{pur\ corr}(q_{inv}) = \frac{CF(q_{inv}) - 1}{purity\ (q_{inv})} + 1$$





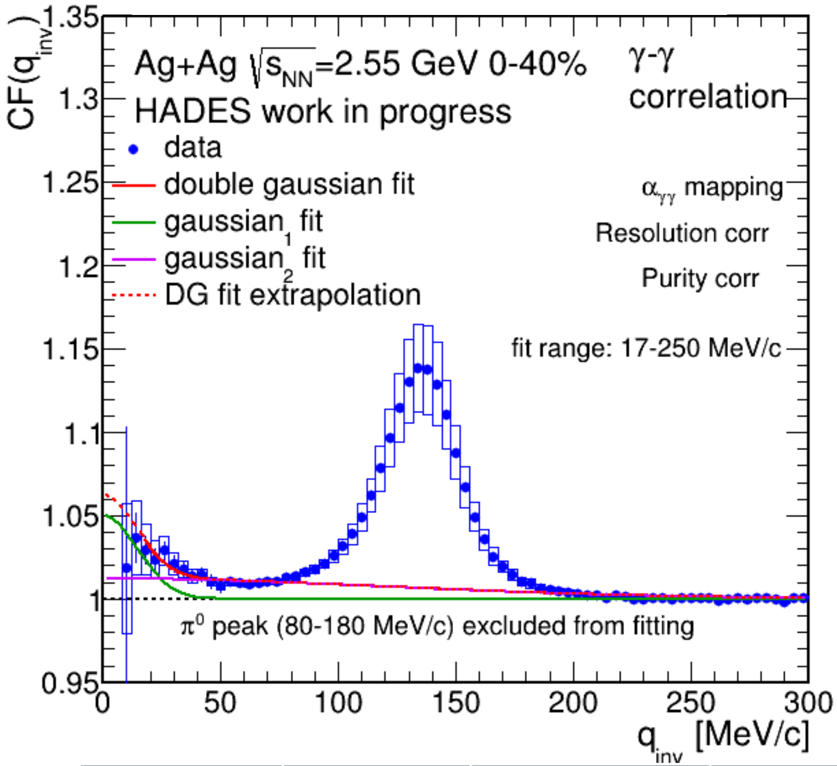
$$1 + res_{\ sim}(q_{inv}) = \frac{CF_{smeared}(q_{inv})}{CF_{not\ smeared}(q_{inv})}$$

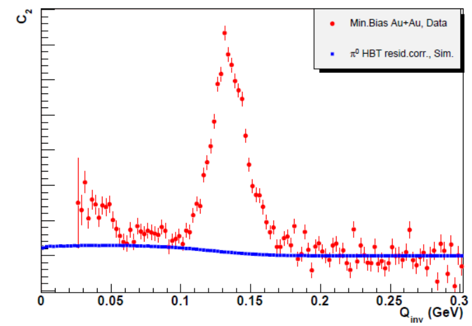
$$CF_{res\ corr}(Q_{INV}) = \frac{CF(q_{inv})}{1 +\ res.\ factor(q_{inv})}$$



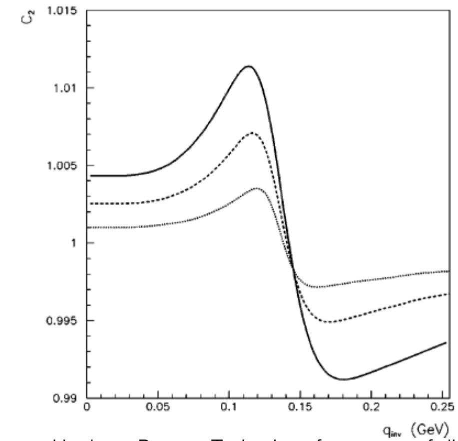
statistical uncertainties only

Photon-photon CF, Ag+Ag at 2.55 GeV, fits





„Bose-Einstein correlations of direct photons in Au+Au collisions at sNN = 200 GeV", D. Peressounko for the PHENIX collaboration, International Journal of Modern Physics E



„Hanbury Brown–Twiss interferometry of direct photons in heavy ion collisions", D. Peressounko PHYSICAL REVIEW C 67, 014905 (2003)

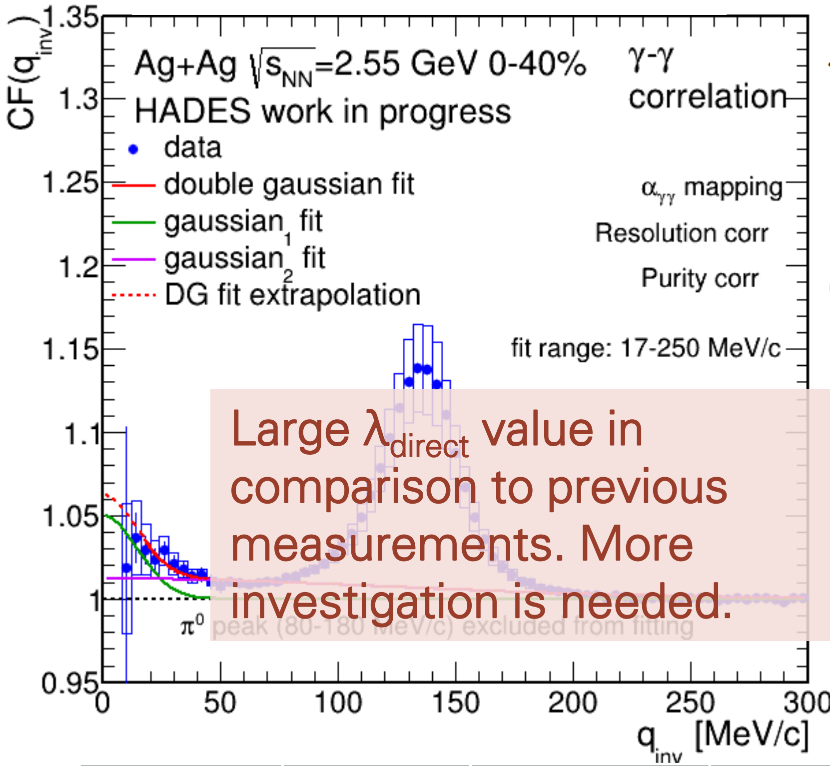
$$CF(q_{inv}) = 1 + \lambda_1 e^{(-q_{inv}{}^2 R_1{}^2)} + \lambda_2 e^{(-q_{inv}{}^2 R_2{}^2)}$$

variable	value	stat. uncert.	syst. uncert.	syst. uncert. (+ Barlow test)
R_1 [fm]	9.605	± 0.911	+ 0.779 - 1.253	+ 0.426 - 1.096
λ_1	0.0502	± 0.0162	+ 0.0286 - 0.0361	+ 0.0265 - 0.0346
R_2 [fm]	1.166	± 0.016	+ 0.134 - 0.159	+ 0.133 - 0.157
λ_2	0.0121	± 0.0002	+ 0.0025 - 0.0019	+ 0.0025 - 0.0018

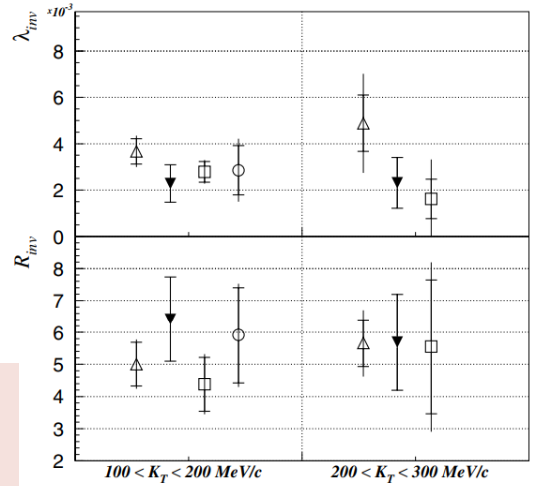
Direct-like γ signal

Neutral π-π residual

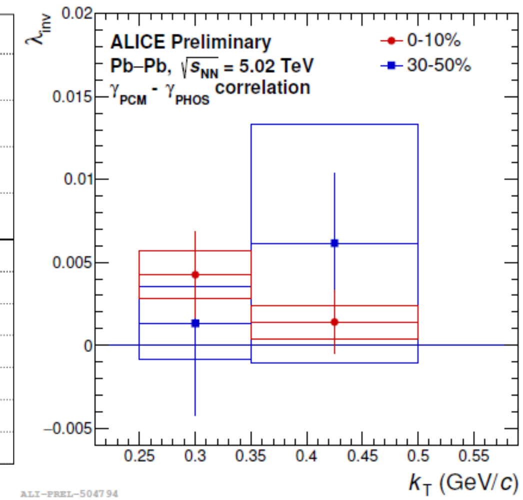
Photon-photon CF, Ag+Ag at 2.55 GeV, fits



Large λ_{direct} value in comparison to previous measurements. More investigation is needed.



Interferometry of Direct Photons in Central 208Pb 208Pb Collisions at 158A GeV, Aggarwal, M. M., Physical Review Letters, 93(2). doi:10.1103/physrevlett.93.022301



„DIRECT PHOTON PRODUCTION AND HBT CORRELATIONS IN Pb–Pb COLLISIONS AT √sNN = 5.02 TeV WITH THE ALICE EXPERIMENT", Meike Charlotte Danisch on behalf of the ALICE Collaboration, Acta Physica Polonica B Proceedings Supplement 16, 1-A122 (2023)

variable	value	stat. uncert.	syst. uncert.	syst. uncert. (+ Barlow test)
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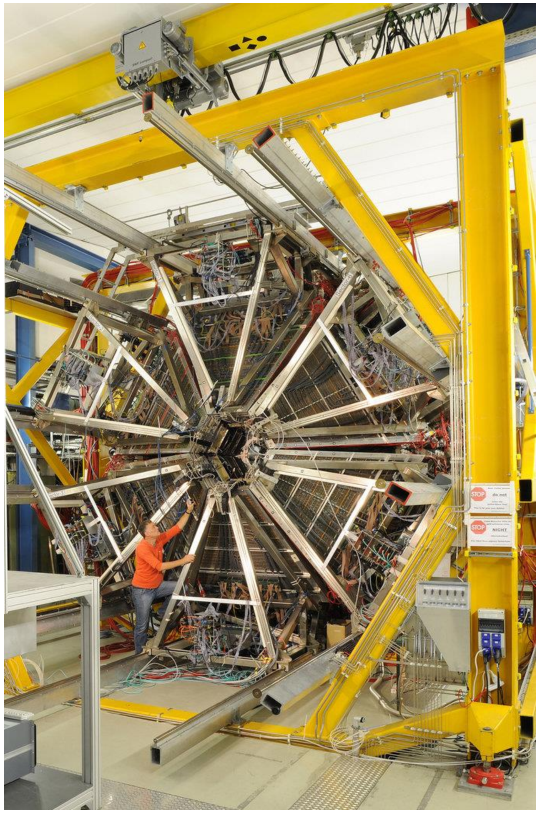
Direct-like γ signal

Neutral π-π residual

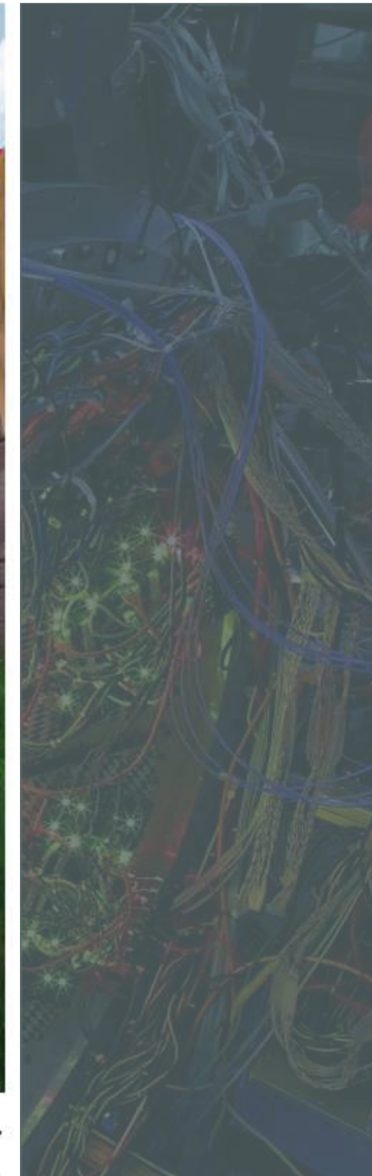
Summary & Outlook

- Photon correlation functions at low collision energy were achieved using HADES's calorimeters, with full systematical analysis as well.
- Expected HBT-like signal was observed for q_{inv}< 50 MeV/c, with additional contribution most likely coming from π^0- π^0 residua correlation
- The HBT parameters were extracted, although they suffer from high systematical uncertainty due to fitting variation differences. λ_{direct} parameter shows higher than expected value. Additional study to explain such phenomenon is needed.



Thank you for your attention!

Don Quixote's quest continues!



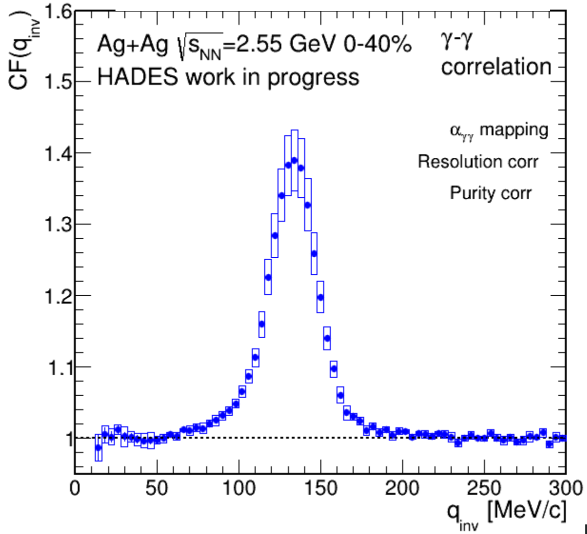
Backup

Photon-photon CF, Ag+Ag at 2.55 GeV, systematics

Single particle	Default value	variation	
Nσ matching to charged track	> 6	± 2	Strength of charged particle's VETO
Opening angle with any charged track	< 2.8 °	± 0.8 °	Contribution from charged particles not matched with clusters
Minimal energy in module	> 50 MeV	± 20 MeV	Minimal energy resolution
Nσ for β	< 1	± 0.5	Contamination from other (fast) particles

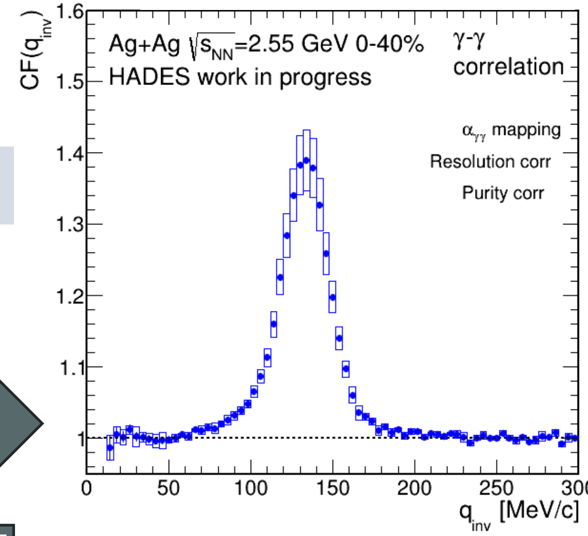
Pair	Default value	variation	
Opening angle mapping	> value from map	± 10%	Stability/strength of two track effects correction
Resolution correction	value from function	± 10%	Impact of resolution correction
Purity correction	value from function	± 10%	Impact of purity correction

Photon-photon CF, Ag+Ag at 2.55 GeV, systematics



UrQMD + HGeant

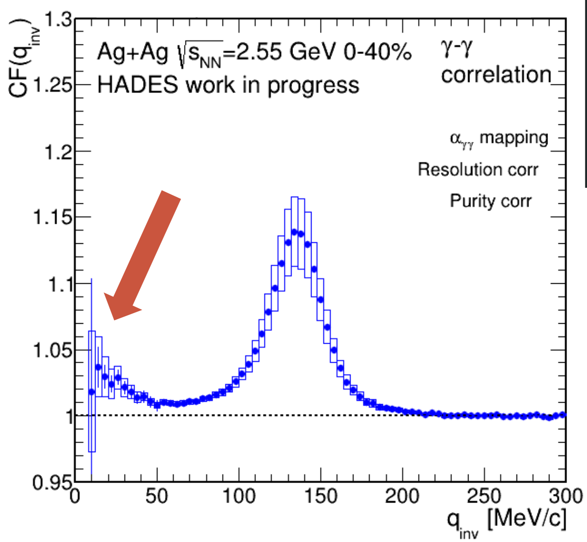
„Barlow test"



$$diff = CF_{default} - CF_{var}\ ,\quad \sigma_{diff} = \sqrt{|\,stat^2_{def} - stat^2_{var}\,|}$$

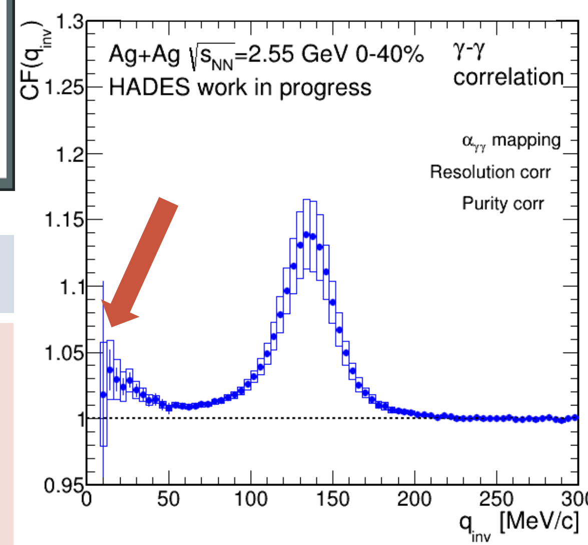
If diff < σ_{diff} , sys = 0 . Else, sys = $\sqrt{diff^2 - \sigma^2_{diff}}$

$$sys_{total} = \sqrt{(sys^2_{var1} + sys^2_{var2} + \ldots + sys^2_{varn})}$$

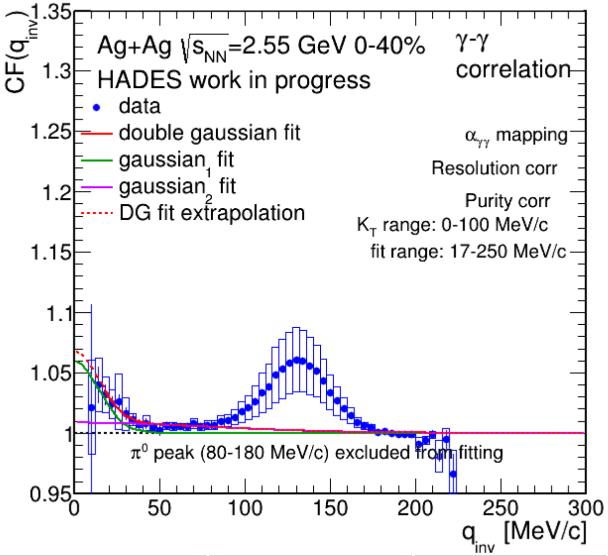


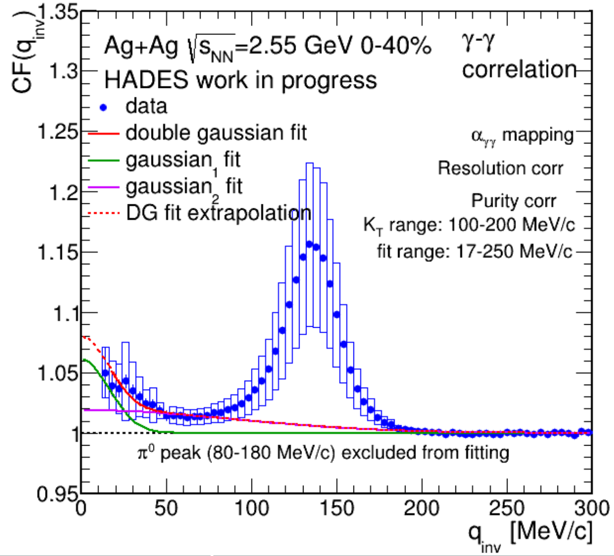
data

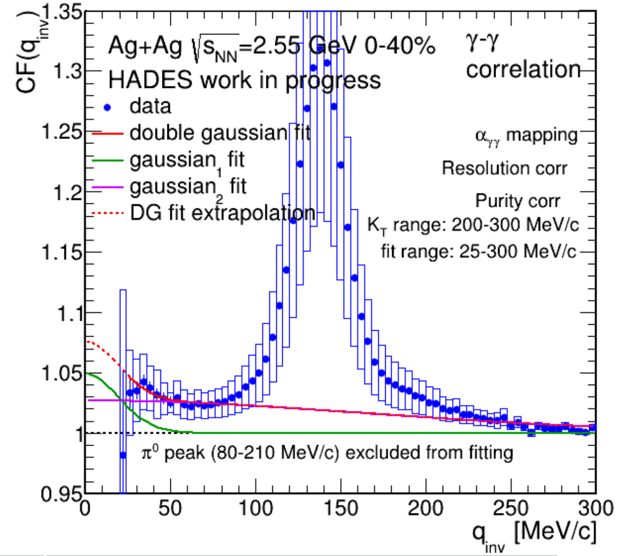
Very subtle change introduced by Barlow test → small impact of statistics on data points



Photon-photon CF, Ag+Ag at 2.55 GeV, fits, K_T bins







K_T [MeV/c]	variable	value	stat. uncert.	syst. uncert.	syst. uncert. (+ Barlow test)
0-100	R_1 [fm]	9.646	± 1.184	+ 0.618 - 0.684	+ 0 - 0 (failed)
	λ_1	0.0589	± 0.0210	+ 0.0434 - 0.0570	+ 0.0361 - 0.0511
100-200	R_1 [fm]	8.601	± 0.553	+ 1.002 - 1.257	+ 0.778 - 1.112
	λ_1	0.0609	± 0.0125	+ 0.0543 - 0.0676	+ 0.0501 - 0.0645
200-300	R_1 [fm]	7.164	± 0.851	+ 1.204 - 0.814	+ 0.564 - 0.195
	λ_1	0.0489	± 0.0217	+ 0.0590 - 0.0542	+ 0.0494 - 0.0434