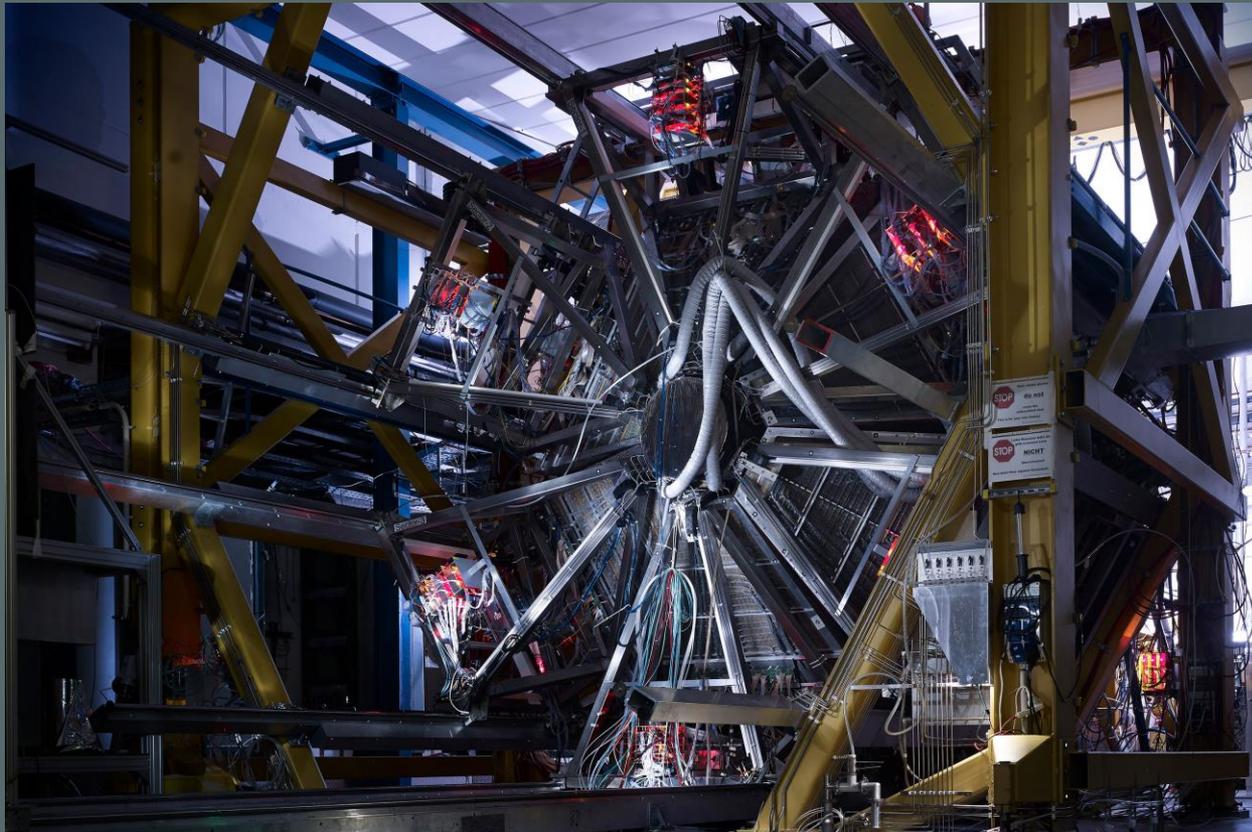
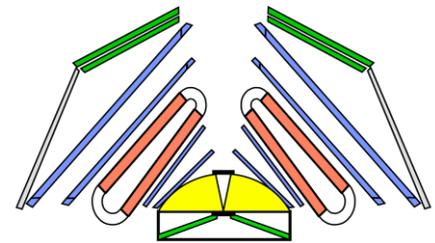


# Photon-photon correlations in Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV



Mateusz Grunwald  
for the HADES collaboration



**HADES**

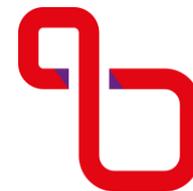
**GSII**



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WARSAW UNIVERSITY OF TECHNOLOGY

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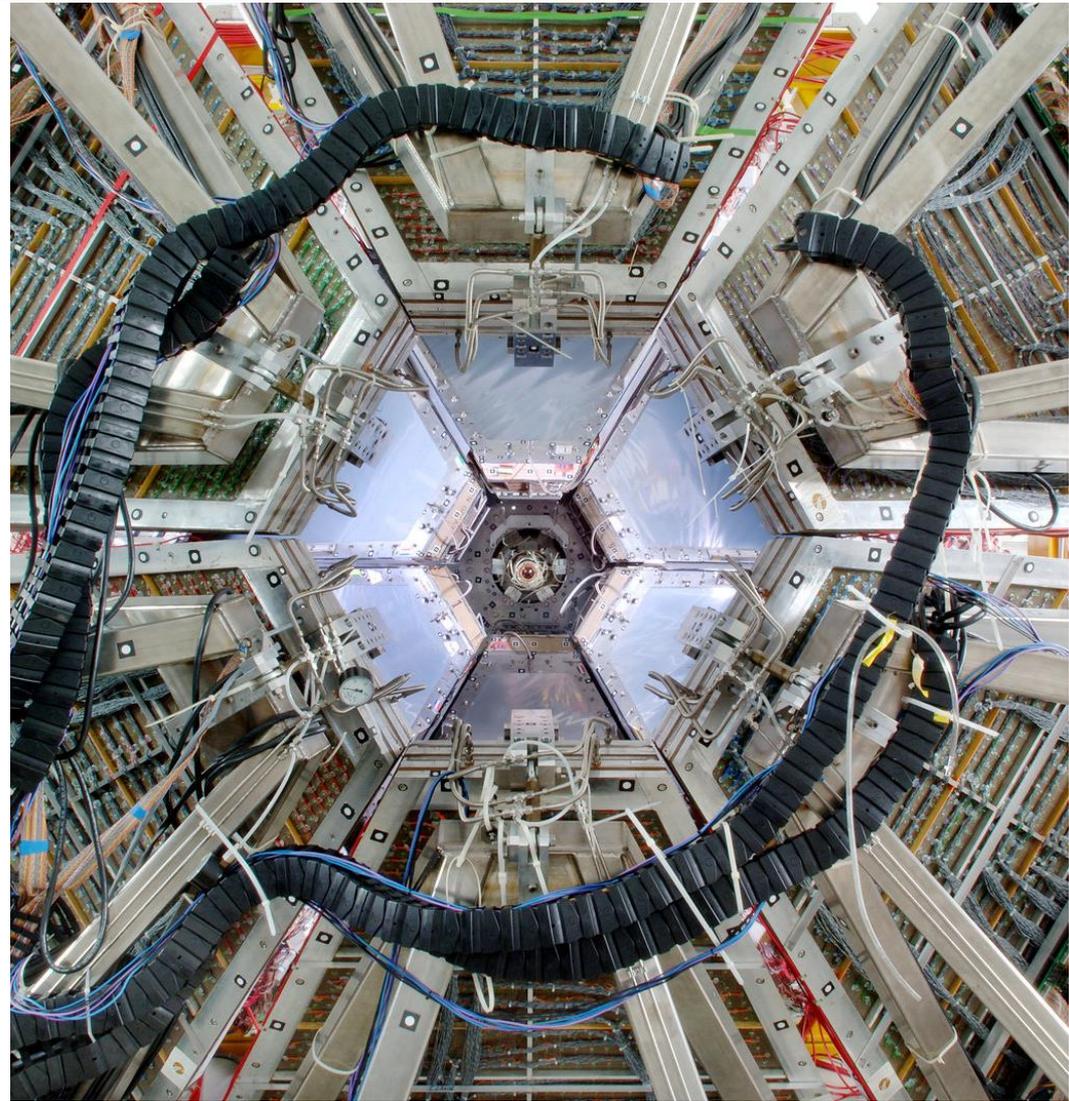
EXCELLENCE INITIATIVE

NATIONAL SCIENCE CENTRE  
POLAND

**FAIR**  
Phase-0  
Research Program

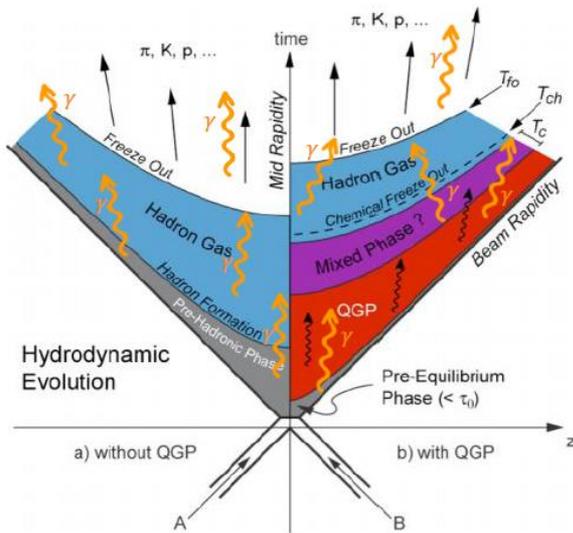
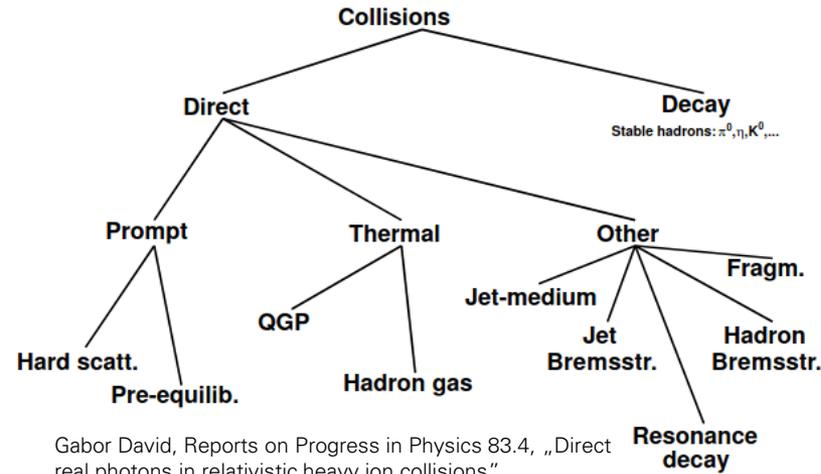
# Outline

- 1) Motivation (Why photon femtoscopy?)
- 2) Femtoscopy technique
- 3) HADES experiment
- 4) Results from HADES data
- 5) Summary

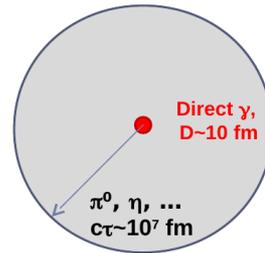


# Motivation

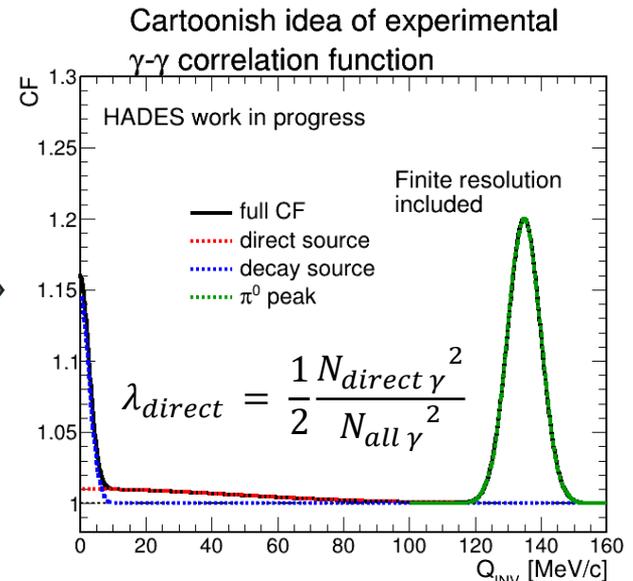
- Measure source properties **at early stages** -> inaccessible for hadrons
- Estimate **direct photon yield** via femtoscopy
- Experimentally challenging



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

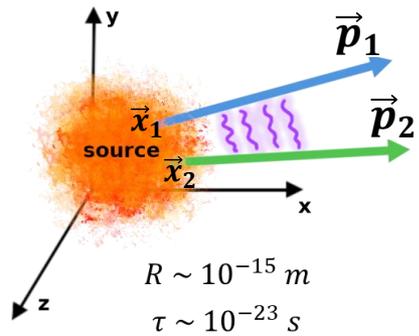


$$Q_{INV} = m_{\gamma\gamma} = \sqrt{2E_1 E_2 (1 - \cos(\alpha_{\gamma\gamma}))}$$



# Femtoscscopy

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



**Theory**

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

$\vec{x}$  : 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

$S(\vec{x}, \vec{p})$  : emission function

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

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

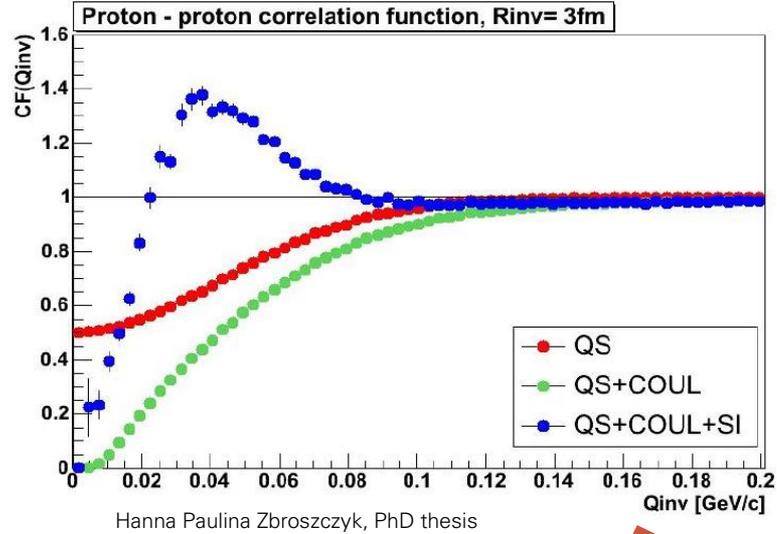
$N_{mixed}(q)$  : mixed event distribution

**Experiment**

Correlation function:

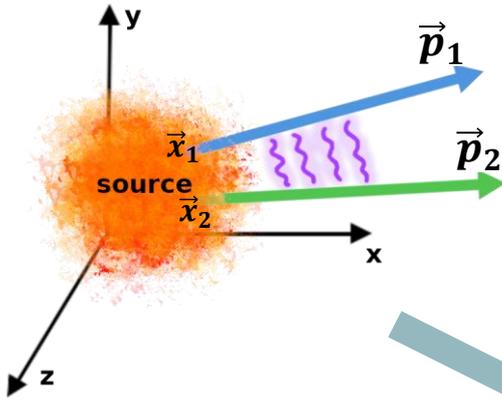
$$CF(q) = \frac{N_{same}(q)}{N_{mixed}(q)}$$

# Femtoscscopy



Effects and interactions:

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



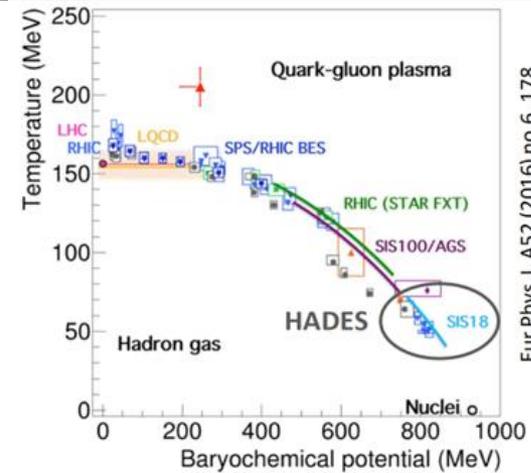
$q = |\vec{p}_1 - \vec{p}_2|$  : momentum difference  
 $r = |\vec{x}_1 - \vec{x}_2|$  : relative distance

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

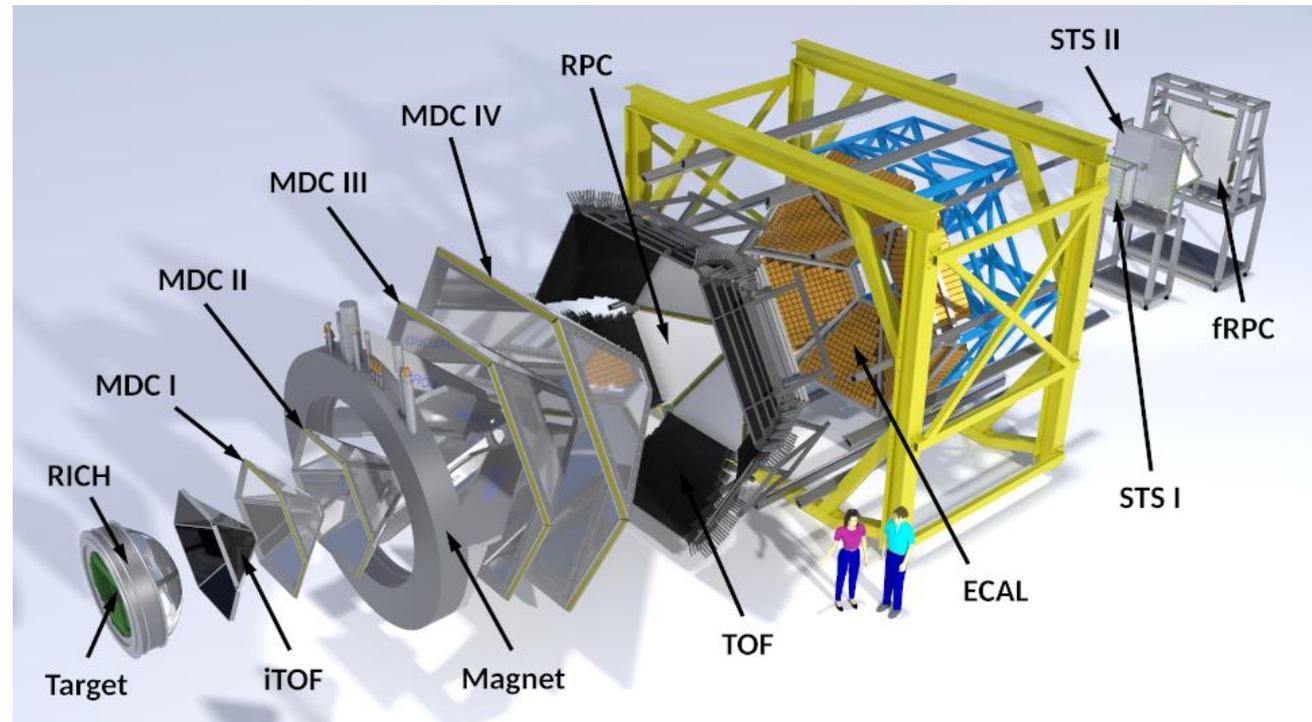
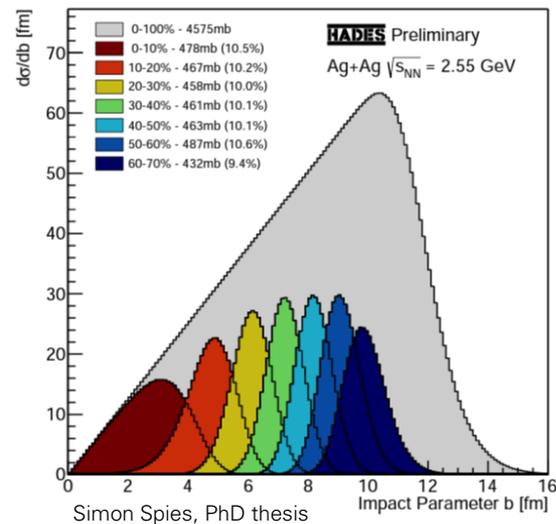
Determine the geometry and dynamic properties (traditional femtoscopy)

Determine the interactions (non-traditional femtoscopy)

# HADES experiment

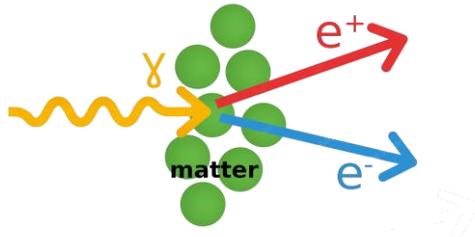


- High Acceptance Di-Electron Spectrometer
- Fixed target, few (1-2) GeV beam kinetic energy
- Measurement of dilepton pairs from vector mesons ( $\omega$ ,  $\phi$ ,  $\rho$ )
- High angular acceptance ( $0^\circ < \phi < 360^\circ$ ,  $18^\circ < \theta < 85^\circ$ ) split into 6 sectors
- High  $e^\pm$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



# Photons at HADES

## Photon Conversion Method (PCM)

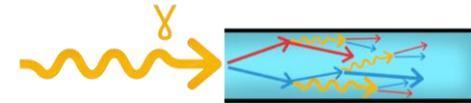


- High momentum and angular resolution
- Good lepton reconstruction efficiency at HADES
- Pure sample of photons

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

**Not enough photons reconstructed via PCM for femtosopic measurements!**

## Electromagnetic calorimeters (ECAL)



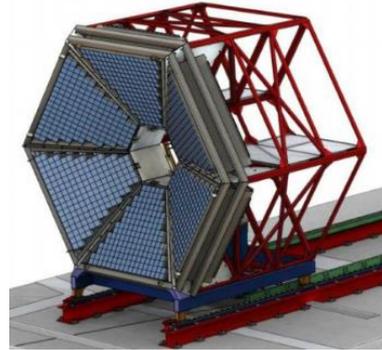
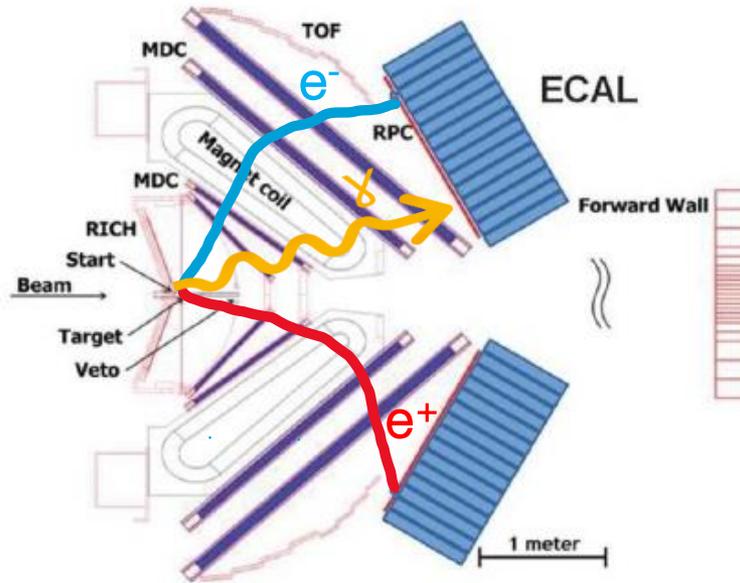
- Great efficiency due to direct reconstruction
- Covers wider energy &  $p_T$  range than PCM
- Decently pure sample with suitable criteria

- Calorimeter modules are usually big  $\rightarrow$  poor angular resolution
- Low-end energy resolution is low due to  $\sim 1/\sqrt{E}$  behavior  $\rightarrow$  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)



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

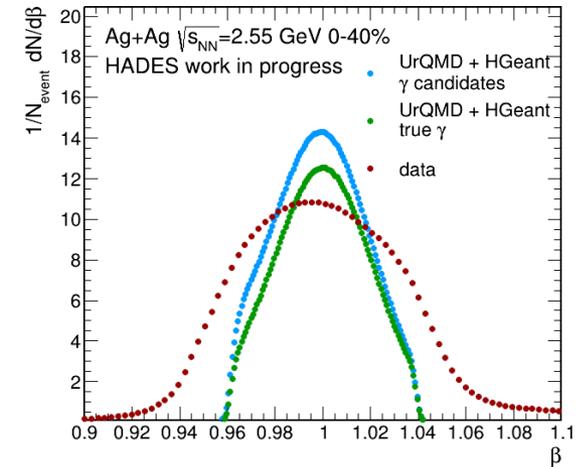
$$\sigma_t < 300 \text{ ps}$$

$$\sigma_{\alpha_{\gamma\gamma}} = 2.2^\circ$$

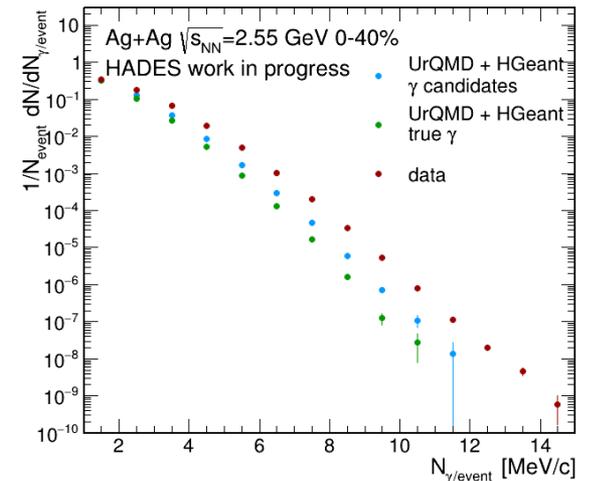
- Photon definition:

- No matching with charged tracks or hits in ToF detectors
- Cells closest to the beam line are not used
- Total (cluster) energy > 100 MeV, minimal energy in each module > 50 MeV
- $\beta$  within  $2\sigma$  from expected photon peak ( $\beta=1$ ), adjusted for each module (and day/hour of a beamtime)

ECAL  $\gamma, \beta$  distribution

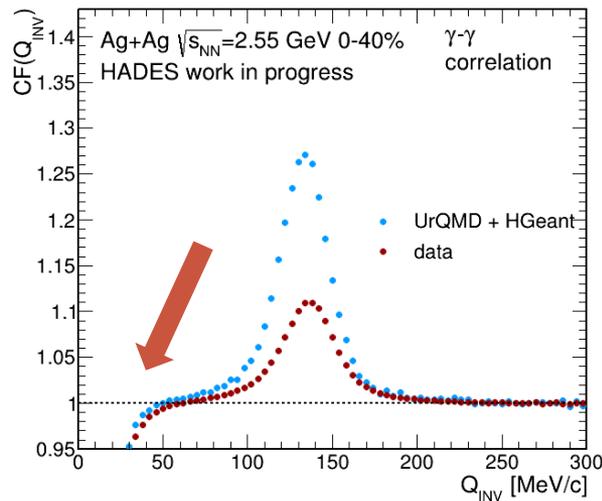


ECAL  $\gamma$ , multiplicity distribution



statistical uncertainties only

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



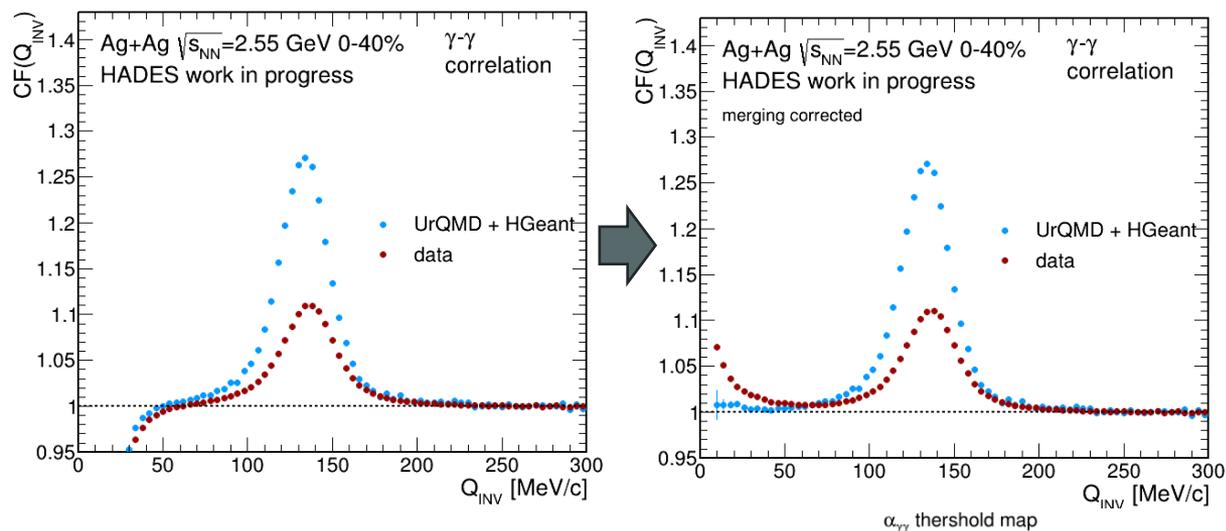
UrQMD + HGeant  $\rightarrow$  no FSI/QS involved  
data  $\rightarrow$  real data gathered by HADES

Anticorrelation caused by uneven  $\alpha_{\gamma\gamma}$   
acceptance in same & mixed events  
(„hardware threshold“)

$$Q_{INV} = \sqrt{(\vec{p}_1 - \vec{p}_2)^2 - (E_1 - E_2)^2}$$

statistical uncertainties only

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

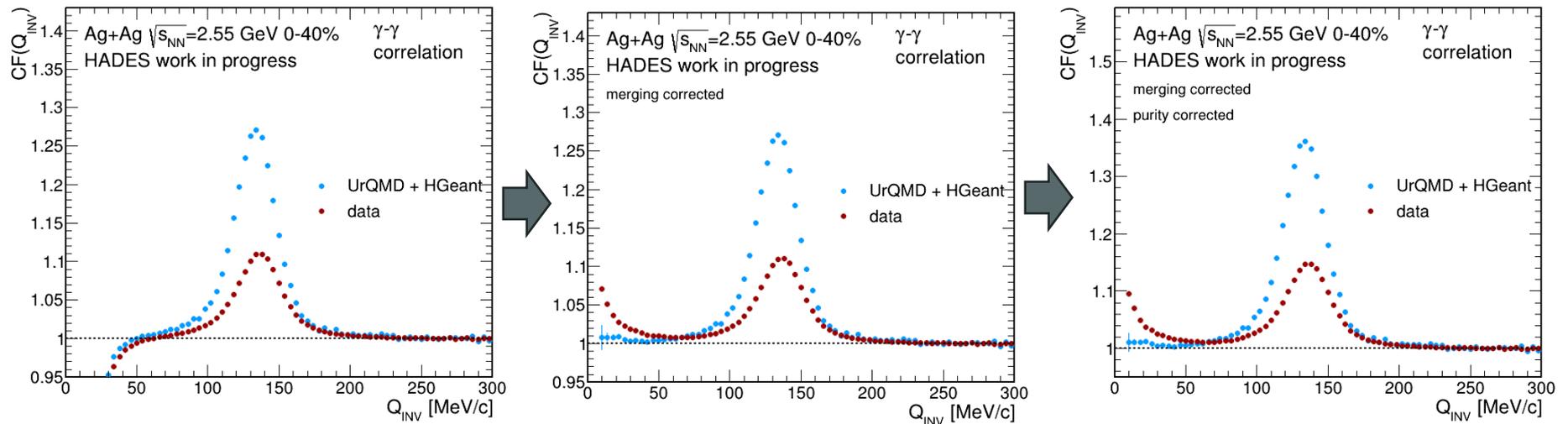


$$Q_{INV} = \sqrt{(\vec{p}_1 - \vec{p}_2)^2 - (E_1 - E_2)^2}$$

statistical uncertainties only

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

Visible enhancement at low  $Q_{INV}$  over simulations!

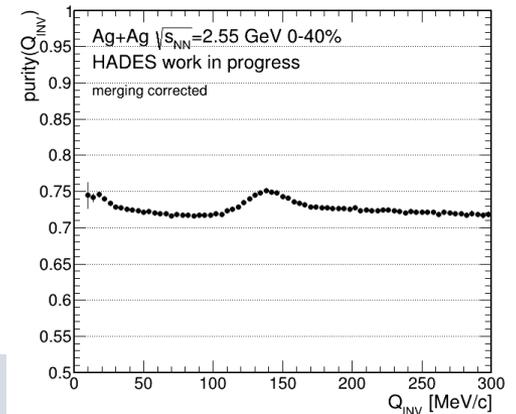


$$purity_{sim}(Q_{INV}) = \frac{N_{\gamma\gamma pair}(Q_{INV})}{N_{any pair}(Q_{INV})}$$

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

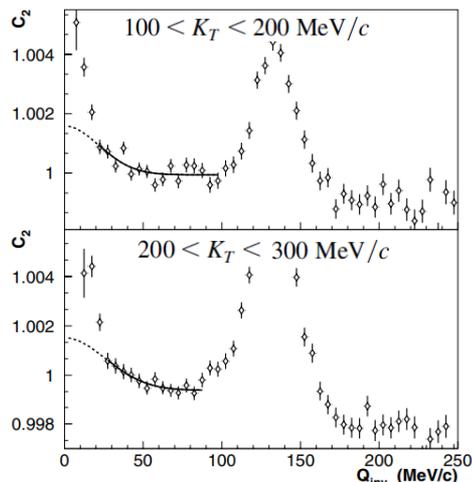
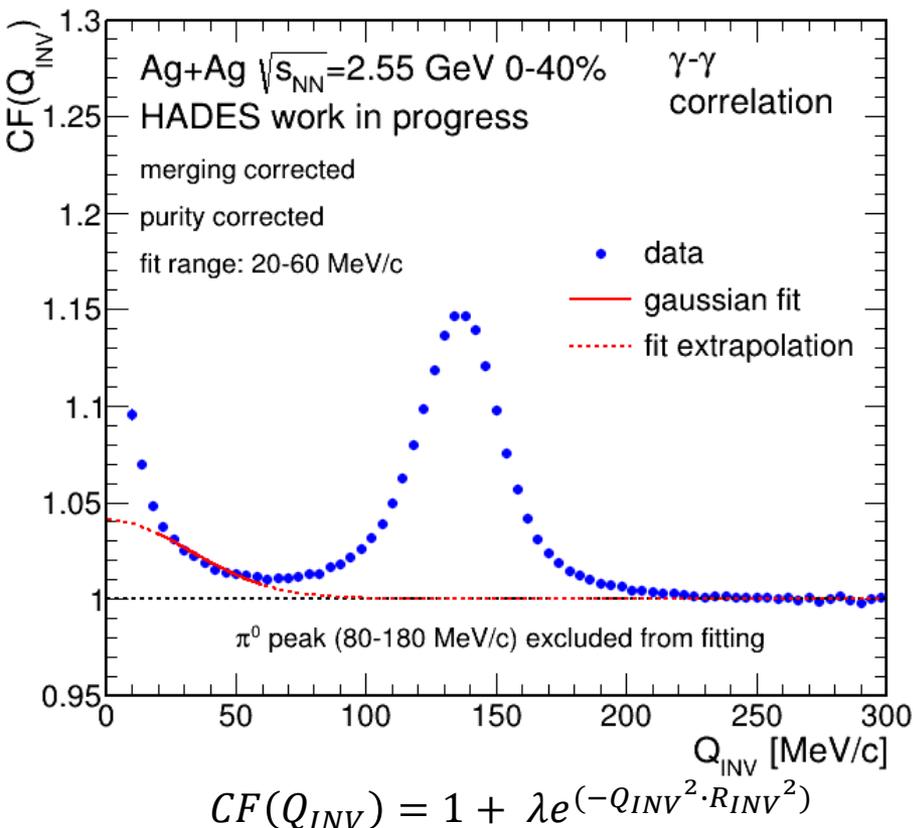
$$Q_{INV} = \sqrt{(\vec{p}_1 - \vec{p}_2)^2 - (E_1 - E_2)^2}$$

statistical uncertainties only

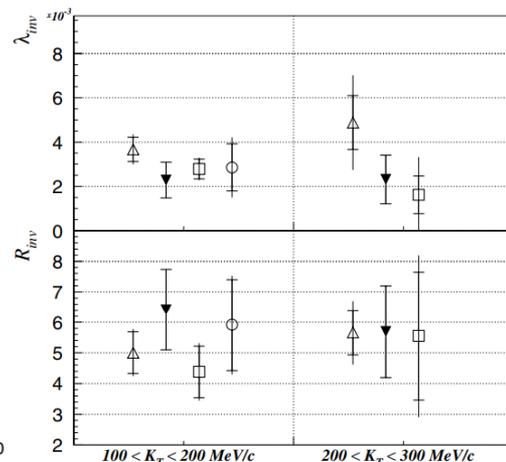


# Photon-photon correlation functions, Ag+Ag at 2.55 GeV

Classical single gaussian source:



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

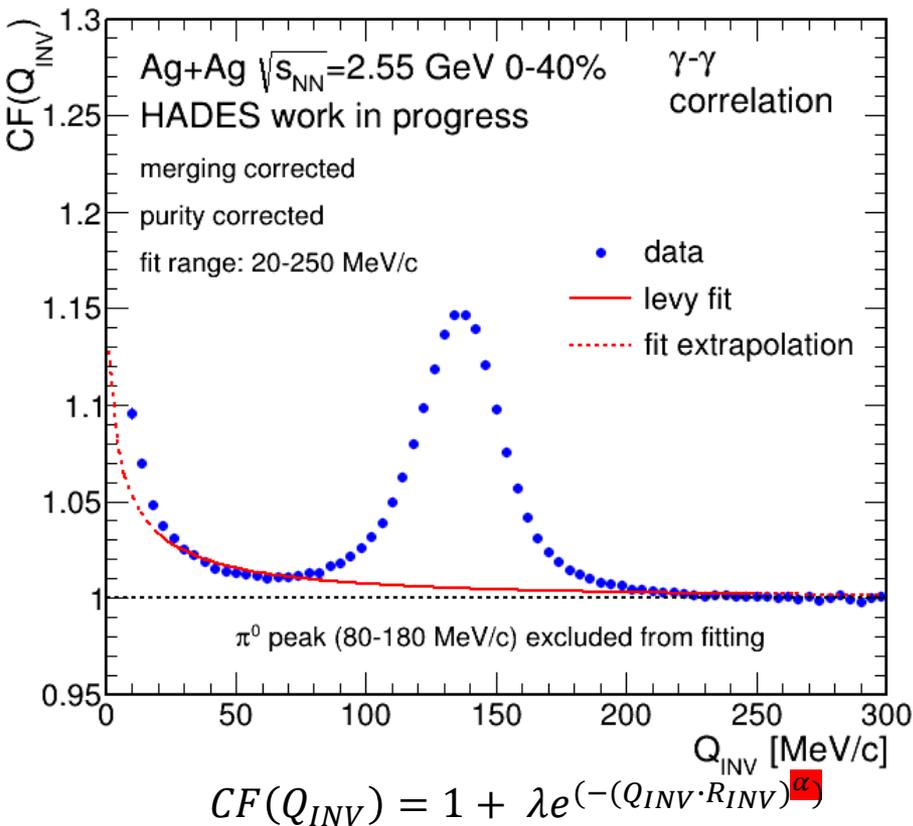


- Well established and widely used
- expected for non-interacting bosons

- Doesn't explain (neglects) visible additional contribution
- Difficulties to establish fitting range

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

Levy source:



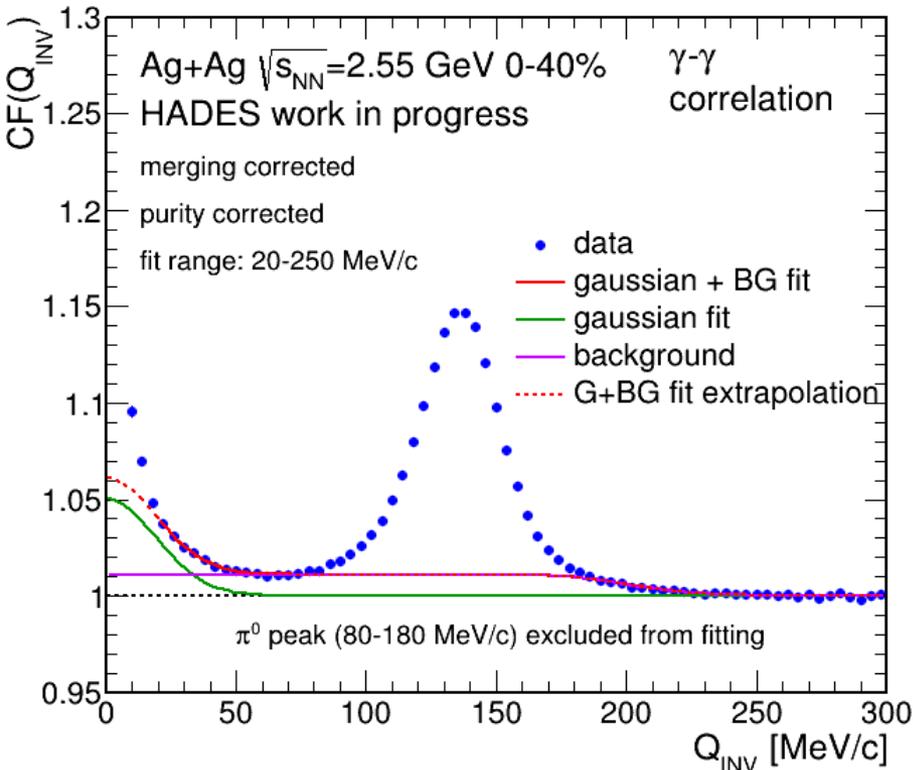
- Critical phenomena (Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828 (2006) no.1, 525-532)
- Direction averaging and non-sphericity (Cimerman et al., Phys.Part.Nucl. 51 (2020) 282)
- Event averaging (Cimerman et al., Phys.Part.Nucl. 51 (2020) 282)
- Resonance decays (Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002; Kincses, Stefaniak, Csanád, Entropy 24 (2022) 308)
- Hadronic rescattering, Lévy flight (Braz.J.Phys. 37 (2007) 1002; Entropy 24 (2022) 308)

M. Csanád, WPCF 2023, Catania, Nov 9, 2023

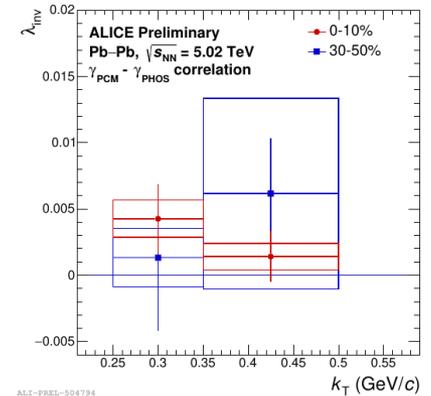
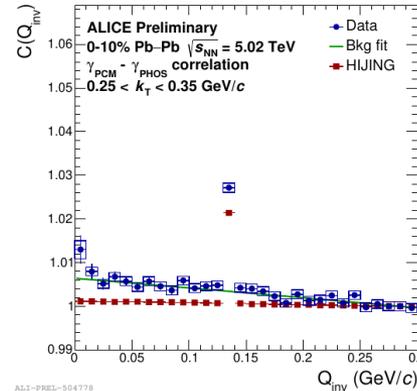
- Might model non-symmetric/"stretched" source without need for 3D (out-side-long) correlations
- Fairly simple (just and extra parameter)
- Physical interpretation (there might be correlation between R and  $\alpha$ )
- Found it hard to fit well (parameters like to capture at range borders)

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

My idea - gaussian source + background:



$$CF(Q_{INV}) = 1 + \lambda e^{-Q_{INV}^2 \cdot R_{INV}^2} + \frac{a_0}{1 + (a_1 \cdot Q_{INV})^{a_2}}$$



Direct photon production and HBT correlations in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV with ALICE experiment, Meike Charlotte Danisch on behalf of the ALICE Collaboration, Acta Physica Polonica B Proceedings Supplement

There are a large number of effects which may give rise to small  $Q_{inv}$  correlations and mimic a direct photon pair Bose-Einstein correlation. These include: 1) single hadron or photon showers that are split into nearby clusters, 2) photon conversions, 3) HBT correlations from charged pions, or other hadrons, mis-identified as photons, 4) residual photon correlations from  $\pi^0$  HBT correlations, 5) radiative decays of heavier resonances and 6) collective flow.

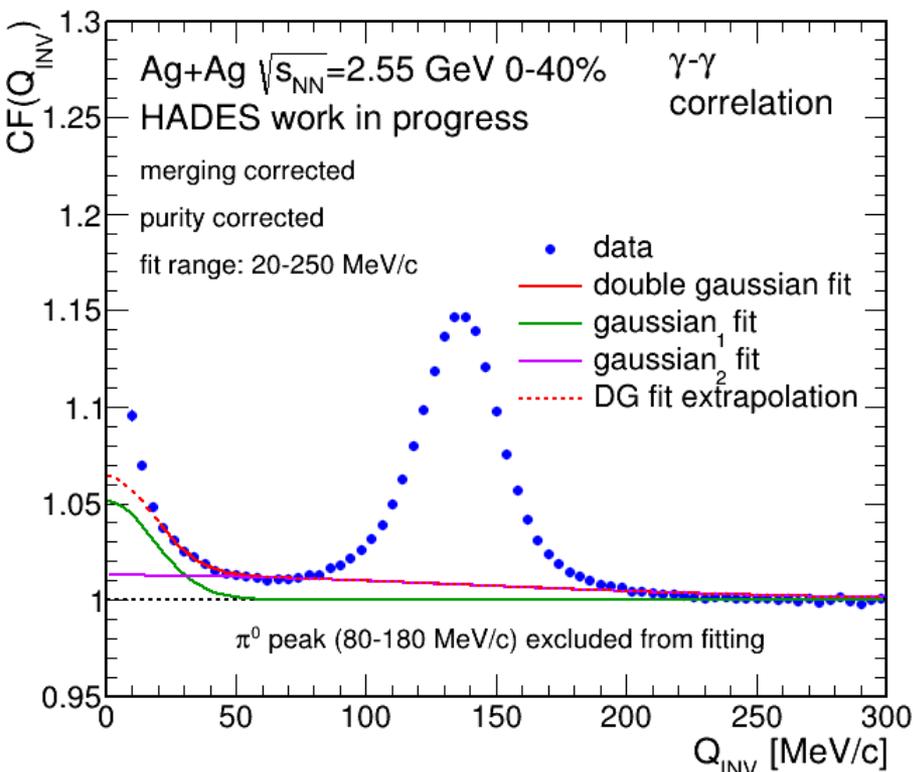
Interferometry of Direct Photons in Central 208Pb+208Pb Collisions at 158 A-GeV, WA98 Collaboration, arXiv:nucl-ex/0310022v1 22 Oct 2003

- Seems to describe extra contribution well (and data in general)

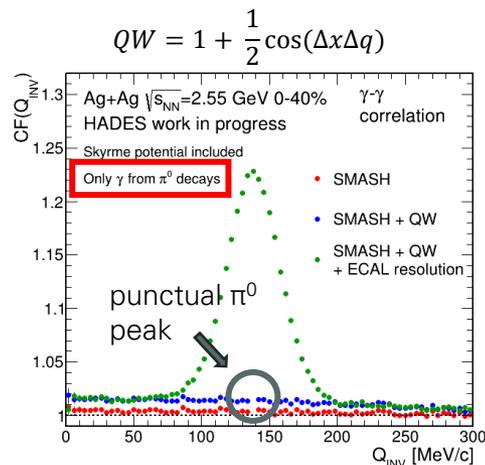
- Arbitrary background formula
- Doesn't explain background's origin

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

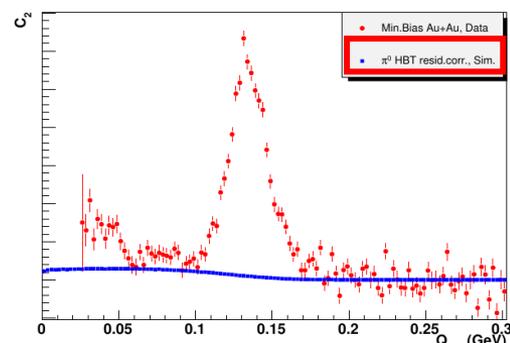
My idea – 2 gaussian sources:



$$CF(Q_{inv}) = 1 + \lambda_1 e^{-Q_{INV}^2 \cdot R_{1INV}^2} + \lambda_2 e^{-Q_{INV}^2 \cdot R_{2INV}^2}$$



and position resolution of LEDA were applied. The simulations indicated that elliptic flow results in the appearance of a small slope to the correlation function on the order of  $5 \cdot 10^{-6} (\text{MeV}/c)^{-1}$ . Bose-Einstein correlations of  $\pi^0$ 's lead to a specific step-like correlation function, in agreement with analytical calculations of [5], and residual correlations due to decays of heavier resonances are found to be negligible. We have checked for flow effects



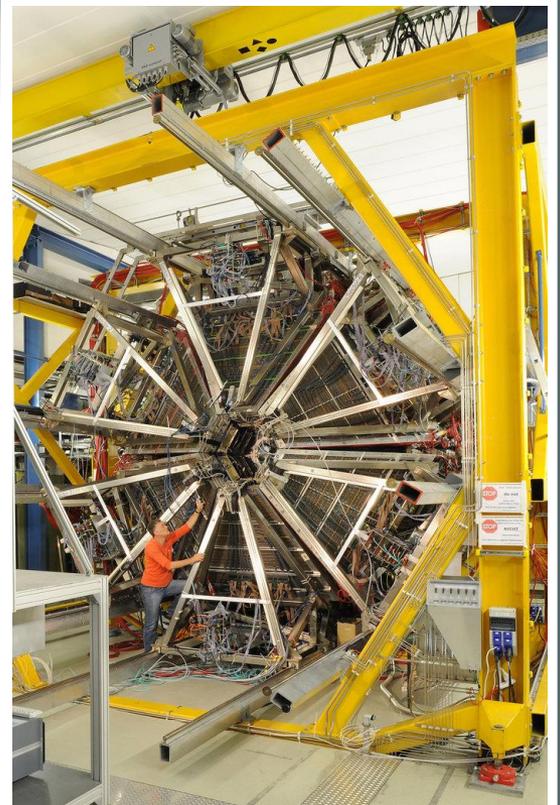
Bose-Einstein correlations of direct photons in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV, D. Peressounko for the PHENIX collaboration, <https://arxiv.org/abs/0704.0852v1>

Interferometry of Direct Photons in Central 208Pb+208Pb Collisions at 158 A-GeV, WA98 Collaboration, arXiv:nucl-ex/0310022v1 22 Oct 2003

- Very similar description to previous example, also fitting quite nicely
- Does explain the other contribution (neutral pions correlation)
- Quite brave statement (although somehow proposed before)

# Summary & Outlook

- Photon-photon correlation **can be obtained** in HADES with use of calorimeters.
  - **An enhancement** at low  $Q_{INV}$  ( $< 50$  MeV/c) over simulations **is visible**, with additional contribution (up to  $\sim 200$  MeV/c). It is not caused by calorimeters resolution  $\rightarrow$  likely physics based.
  - The extra contribution is observed, might be caused by  $\pi^0$ - $\pi^0$  correlations (however it is just a hypothesis).
- 
- Complementary study with use of hybrid approach (combining ECAL & PCM photons) is ongoing.
  - Systematic uncertainties are crucial for a solid conclusion (to be done).



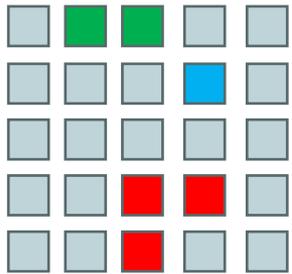
Thank you for your attention!



**Don Quixote's quest continues!**

**Backup**

# Photons at HADES - ECAL



Modules are  $\sim 2.2^\circ$  (92 mm) wide,  
Can't separate  $2\gamma$  within 300 ps interval

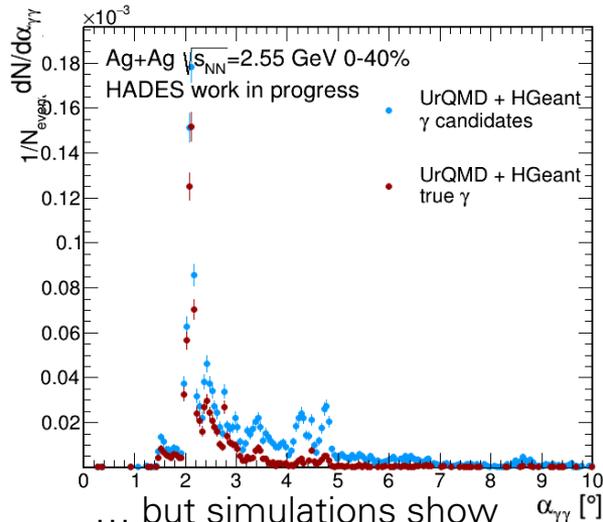
Opening angle „hardware threshold“  
 $\sim 4.4^\circ$  (for 2 „size 1“ clusters)

$\gamma$  triggers:

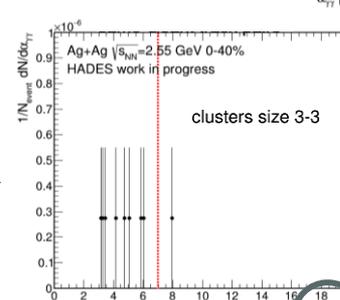
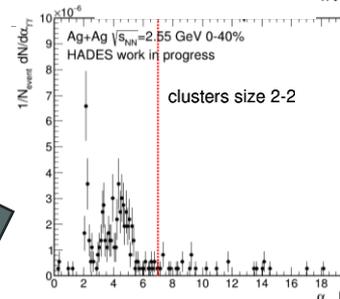
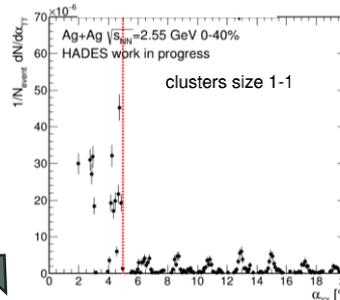
- 1 module  $\rightarrow$  cluster size 1
- 2 modules  $\rightarrow$  cluster size 2
- 3 modules  $\rightarrow$  cluster size 3

...

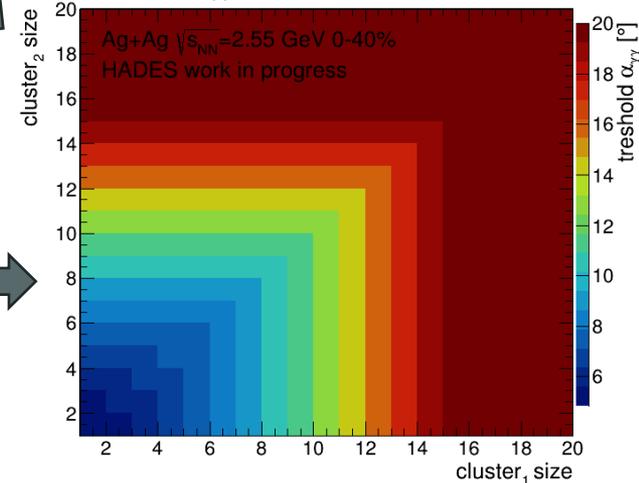
ECAL  $\alpha_{\gamma\gamma}$ , same Geant track pairs



... but simulations show some „split“ clusters



$\alpha_{\gamma\gamma}$  threshold map

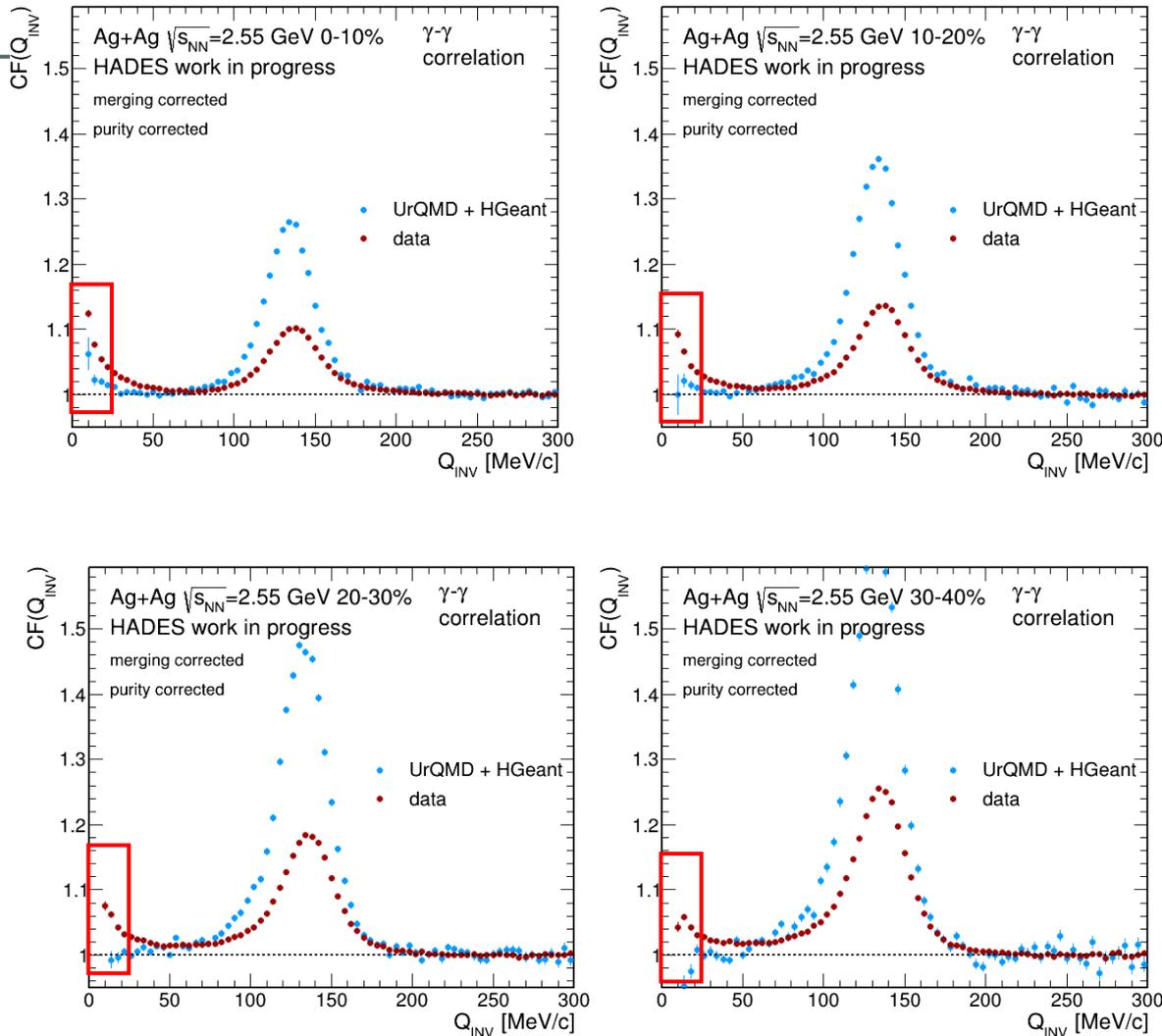


$\alpha_{\gamma\gamma} [^\circ]$

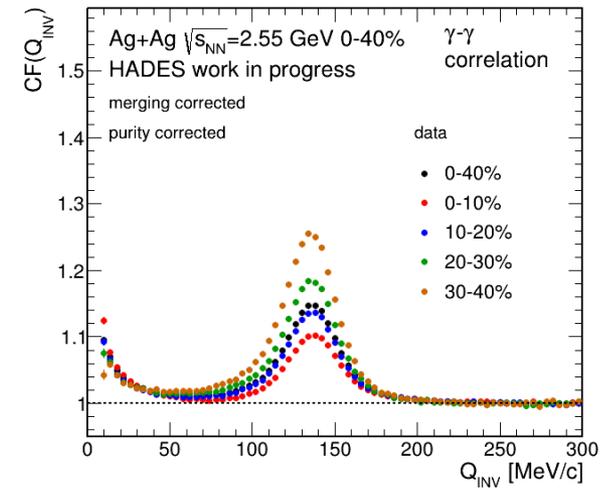
statistical uncertainties only

# Backup – ECAL – centrality dependence

Some of detector effects are still present below  $Q_{INV} < 20$  MeV/c for separate centrality bins (since threshold map was created for min bias events) → region excluded from fitting



“Background” contribution increases with less central events → rather **not** related to direct photons (should be the opposite)

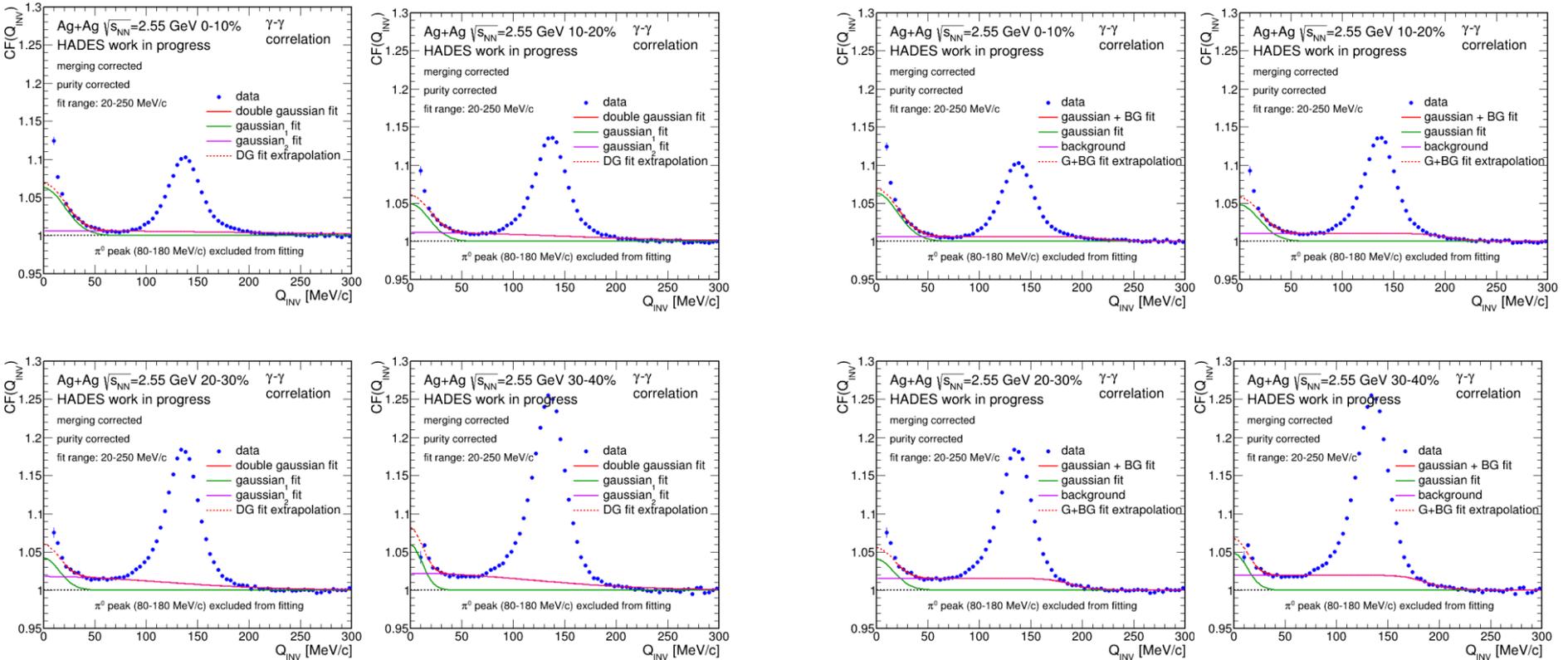


# Backup - ECAL - alternative fits & centrality

$$CF(Q_{inv}) = 1 + \lambda_1 e^{-Q_{INV}^2 \cdot R_{1INV}^2} + \lambda_2 e^{-Q_{INV}^2 \cdot R_{2INV}^2}$$

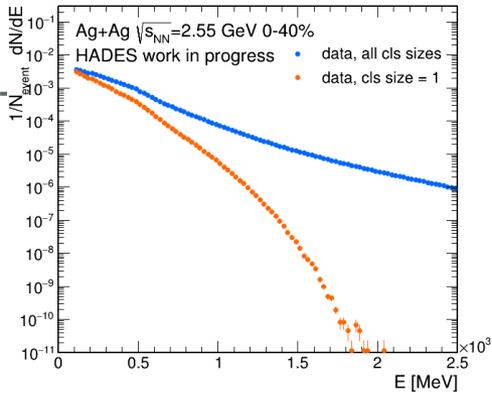
$$CF(Q_{inv}) = 1 + \lambda e^{-Q_{INV}^2 \cdot R_{inv}^2} + \frac{a_0}{1 + (a_1 \cdot Q_{INV})^{a_2}}$$

Very similar predictions for both options

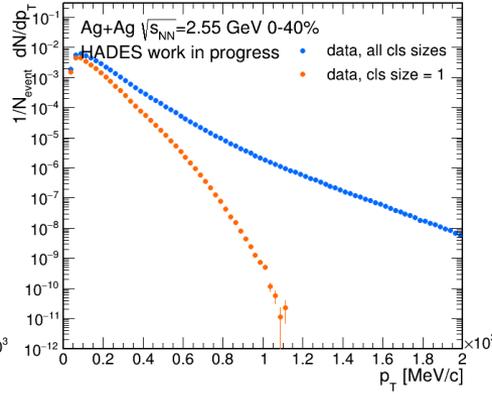


# Backup – ECAL – size 1 clusters vs all size clusters

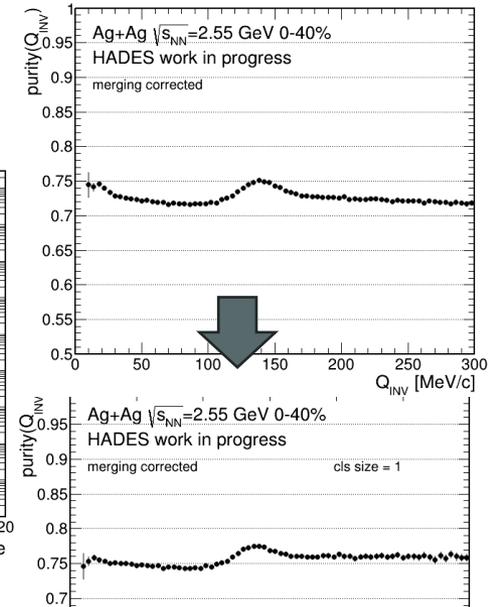
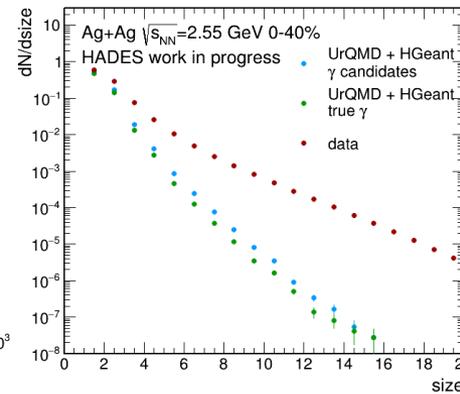
ECAL  $\gamma$ , energy distribution



ECAL  $\gamma$ ,  $p_T$  distribution

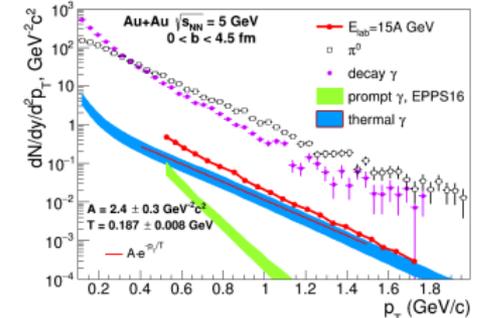
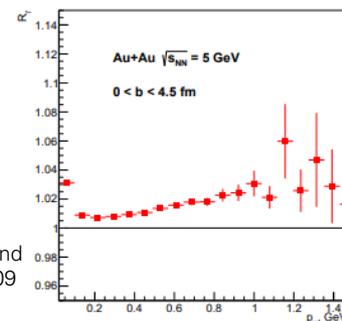


ECAL  $\gamma$ , cluster size distribution



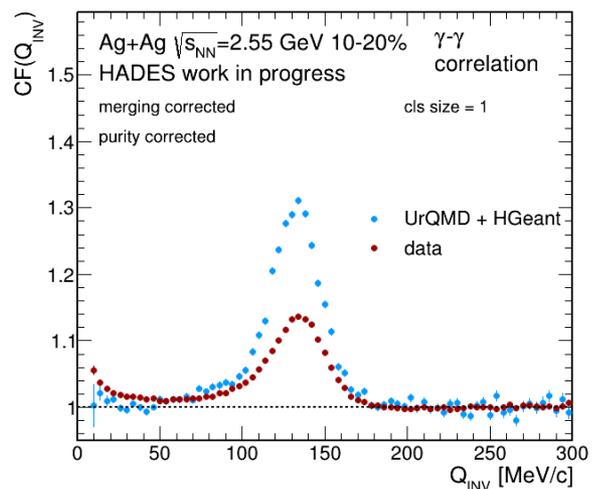
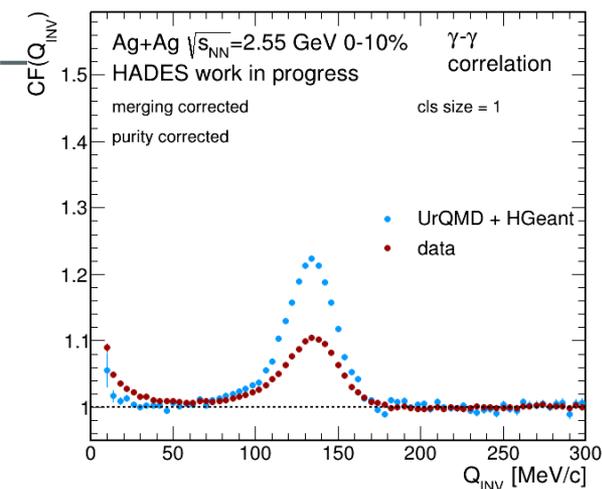
- Size 1 clusters have better energy resolution (higher energy threshold and better reconstruction overall)  $\rightarrow$  higher quality of photon sample
- Only 1 module triggered  $\rightarrow$  less impact of „hardware threshold“ (dependent on size)

- Limited statistics (around 60% of clusters have size  $> 1$ )
- Less energy and  $p_T$  coverage  $\rightarrow$  less chance to pinpoint direct photons (since they have on average higher  $p_T$  than decay photons)

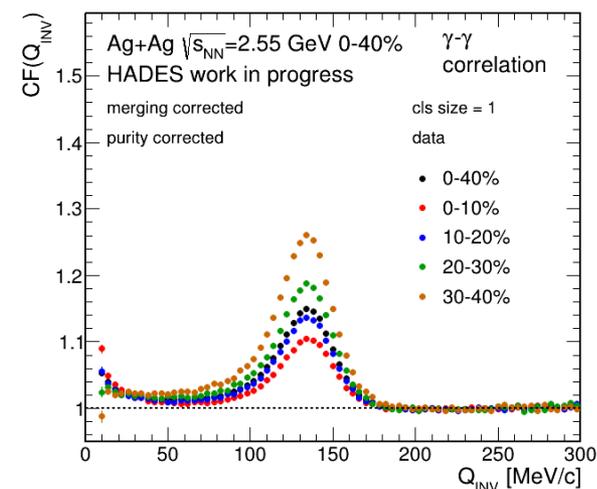
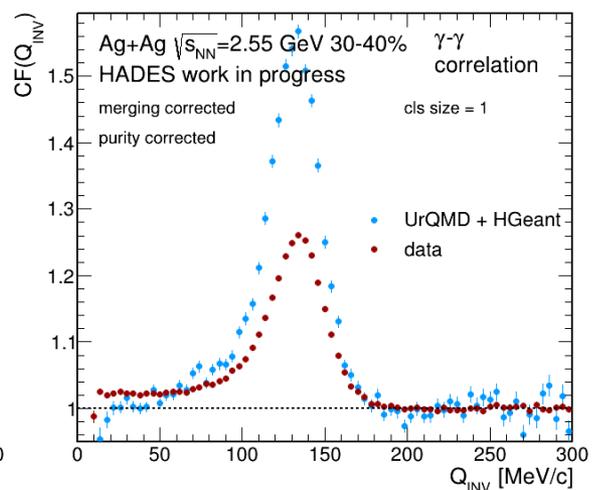
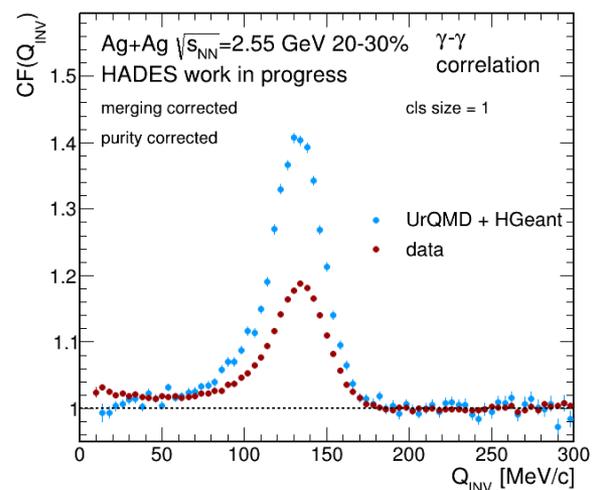


# Backup – ECAL – size 1 clusters vs all size clusters

Still some signatures of detector effects for very low  $Q_{INV}$  ( $\sim 15$  MeV/c), however way smaller than in slide 24. Also, no „background“ visible for  $Q_{INV} > 150$  MeV/c (only  $\pi^0$  peak).



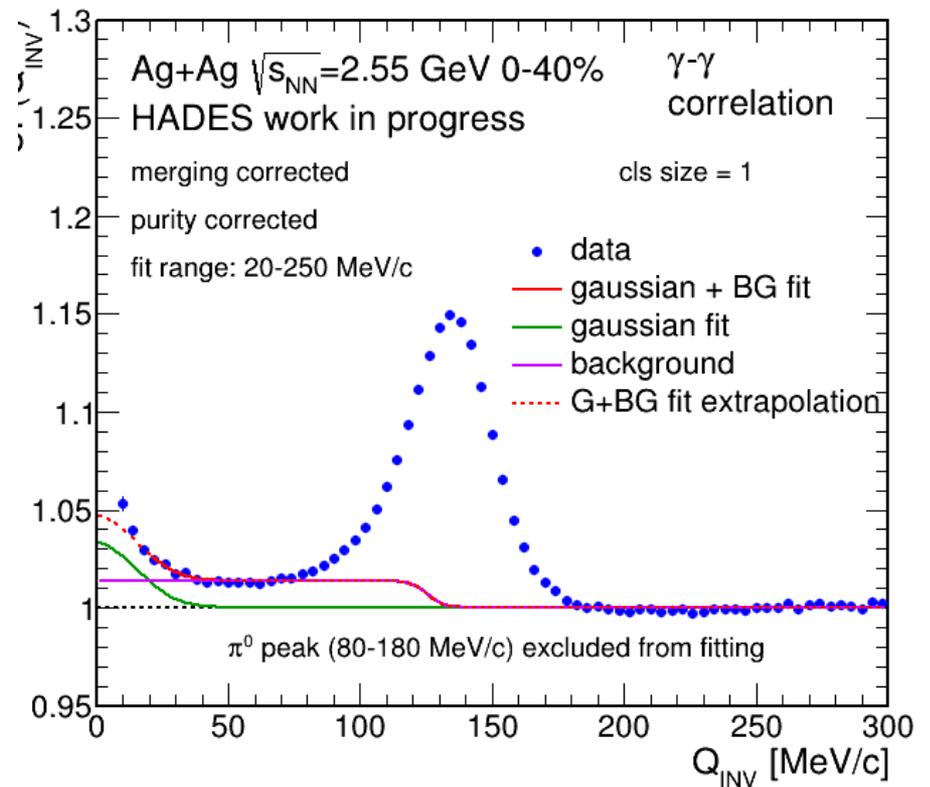
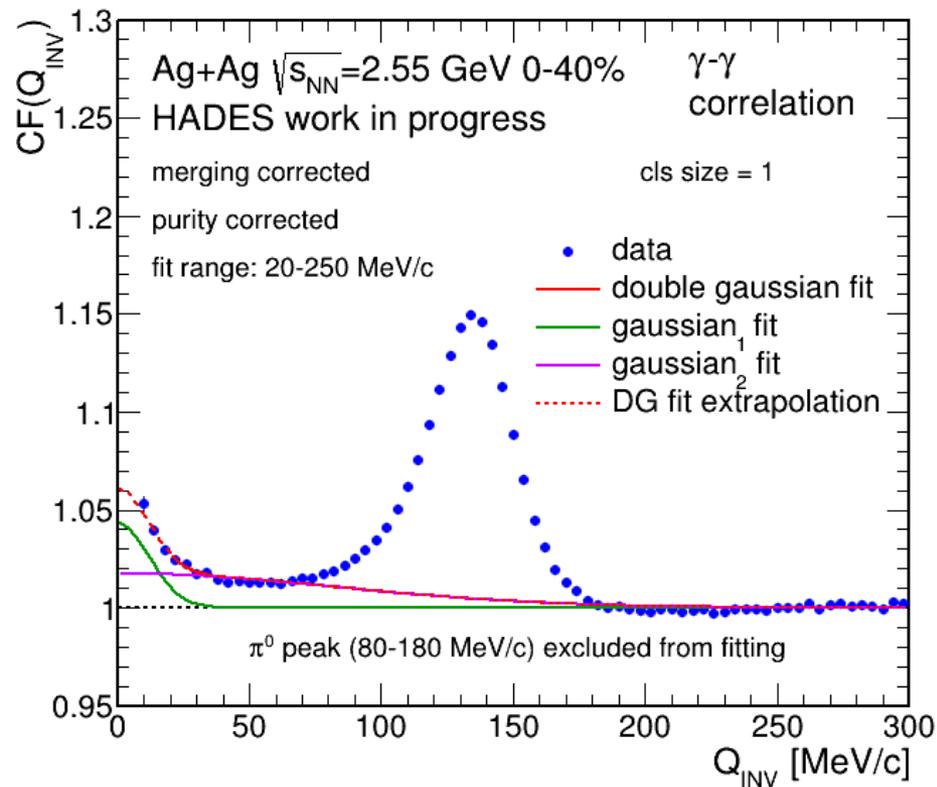
“Background” contribution still increasing with more peripheral events, however only for  $Q_{INV} < 80$  MeV.



# Backup - ECAL - size 1 - alternative fits

$$CF(Q_{inv}) = 1 + \lambda_1 e^{-Q_{INV}^2 \cdot R_{1INV}^2} + \lambda_2 e^{-Q_{INV}^2 \cdot R_{2INV}^2}$$

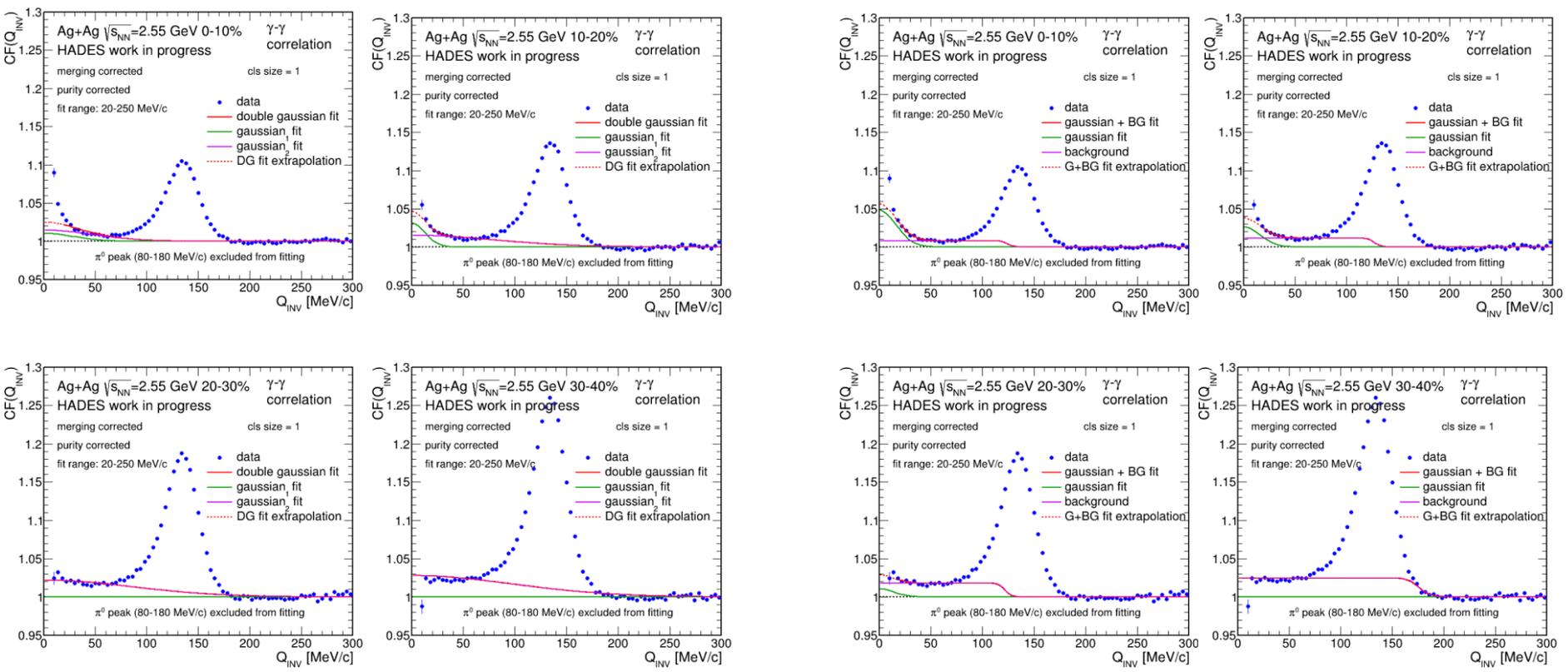
$$CF(Q_{inv}) = 1 + \lambda e^{-Q_{INV}^2 \cdot R_{inv}^2} + \frac{a_0}{1 + (a_1 \cdot Q_{INV})^{a_2}}$$



# Backup - ECAL - size 1 alternative fits & centrality

$$CF(Q_{inv}) = 1 + \lambda_1 e^{-Q_{INV}^2 \cdot R_{1INV}^2} + \lambda_2 e^{-Q_{INV}^2 \cdot R_{2INV}^2}$$

$$CF(Q_{inv}) = 1 + \lambda e^{-Q_{INV}^2 \cdot R_{inv}^2} + \frac{a_0}{1 + (a_1 \cdot Q_{INV})^{a_2}}$$

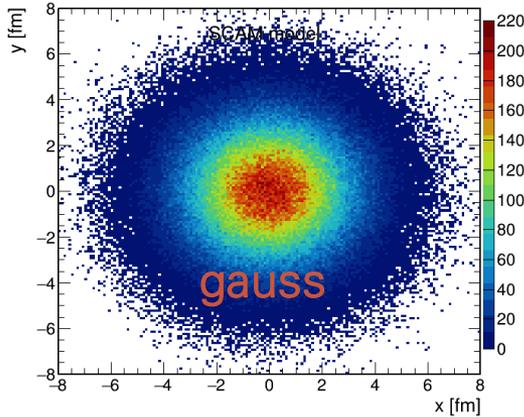


Lack of low  $Q_{INV}$  peak for most central events → some correlation is vanishing?

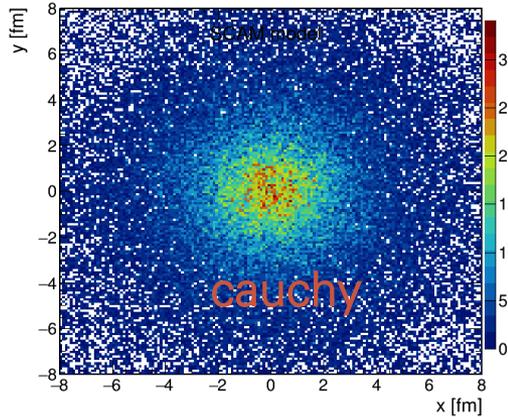
Create correlation function from user-defined source(s):

- Position → randomized from the source's surface function

R = 2 [fm], |z| < 0.2 [fm]



R = 2 [fm], |z| < 0.2 [fm]



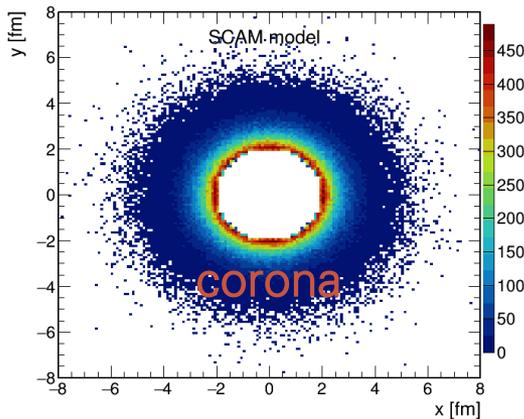
$$gauss(x, y, z) = e^{-0.5(x^2+y^2+z^2)/R}$$

$$cauchy(x, y, z) = e^{-0.5\sqrt{x^2+y^2+z^2}/R}$$

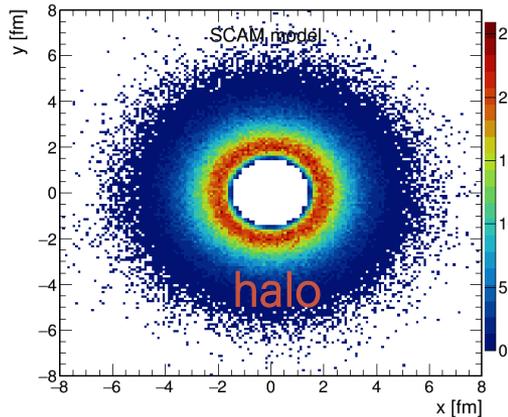
$$halo(x, y, z) = \frac{\sqrt{x^2+y^2+z^2} - R + fade}{fade \cdot e^{-\frac{\sqrt{x^2+y^2+z^2} + R - fade}{fade}}}$$

$$corona(x, y, z) = \frac{1}{e^{\frac{\sqrt{x^2+y^2+z^2} - R + fade}{fade}}}$$

R = 2 [fm], fade = 0.2 [fm], |z| < 0.2 [fm]



R = 2 [fm], fade = 0.2 [fm], |z| < 0.2 [fm]



Inspired by:

- Keesari:  $\lambda = L(q \rightarrow U) - 1$
- Also recall:  $f_c = N_{core}/N_{total} = \int S_c / \int (S_c + S_h)$
- Then:

$$C(q > 0) = 1 + \frac{|S(q)|^2}{|S(0)|^2} = 1 + \frac{|S_c(q) + S_h(q)|^2}{(N_c + N_h)^2}$$

$$\approx 1 + \frac{N_c^2}{(N_c + N_h)^2} \cdot \frac{|S_c(q)|^2}{|S_c(0)|^2} = 1 + \lambda \frac{|S_c(q)|^2}{|S_c(0)|^2}$$

$\lambda = \frac{N_c^2}{(N_c + N_h)^2}$

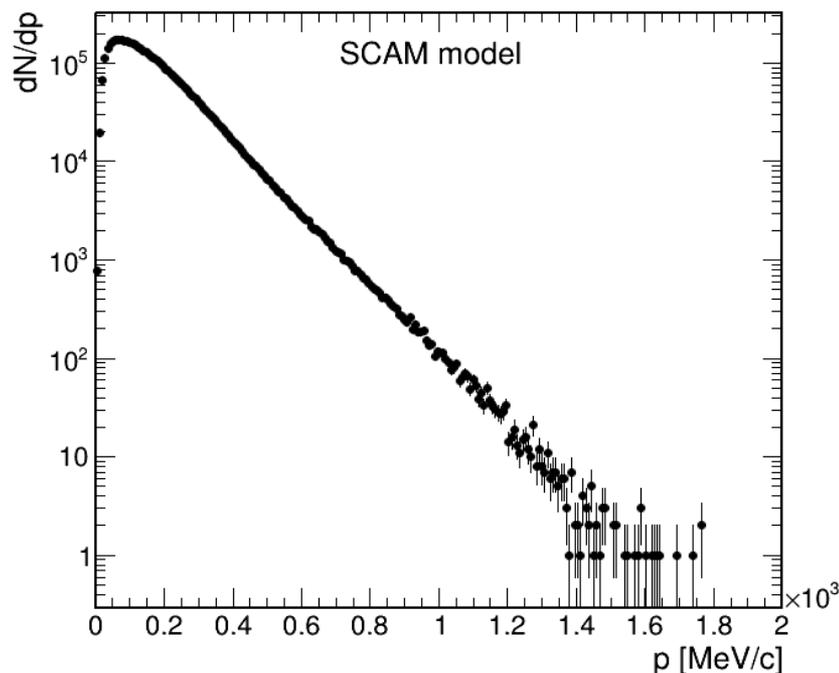
Bolz et al, Phys.Rev. D47 (1993) 3860-3870; Csörgő, Lörstod, Zimányi, Z.Phys. C71 (1996) 491-497

Quantumstatistical correlations and femtoscopy in high energy physics, Máté Csanád

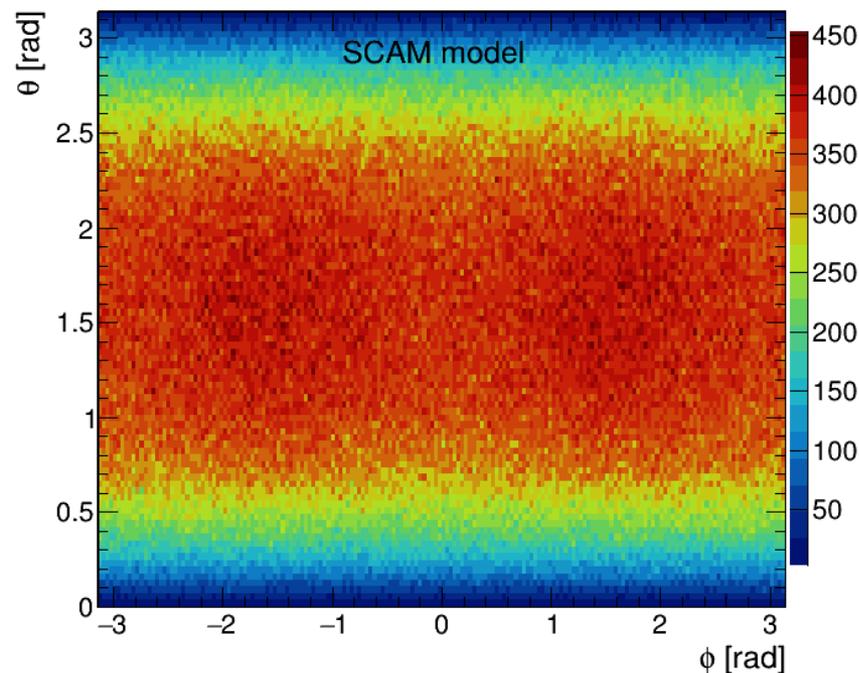
Create correlation function from user-defined source(s):

- Position  $\rightarrow$  randomized from the source's surface function
- Momenta  $\rightarrow$  randomized using  $p$  and  $\phi$ - $\theta$  distributions (currently taken from SMASH for Ag+Ag @ 2.55 GeV photons)

$\gamma$  from SMASH Ag+Ag @  $\sqrt{s_{NN}} = 2.55$ , 0-40%



$\gamma$  from SMASH Ag+Ag @  $\sqrt{s_{NN}} = 2.55$ , 0-40%

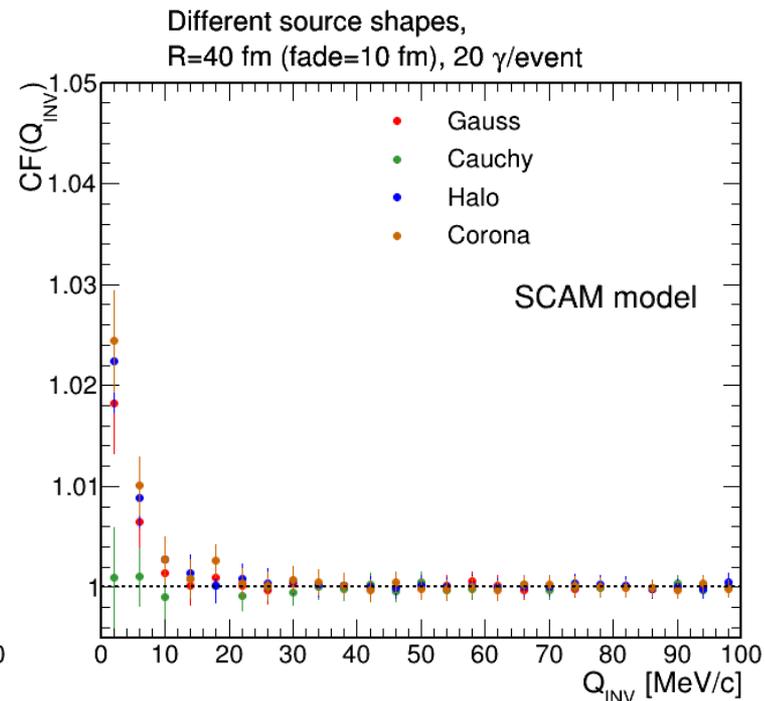
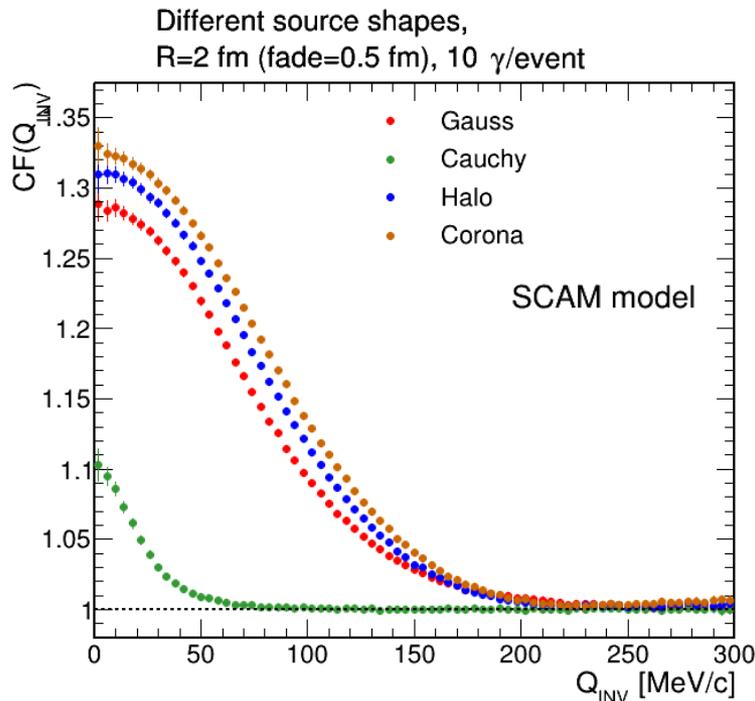


Create correlation function from user-defined source(s):

- Position → randomized from the source's surface function (time = radius)
- Momenta → randomized using  $p$  and  $\phi$ - $\theta$  distributions (currently taken from SMASH for Ag+Ag @ 2.55 GeV photons)
- Interactions → calculate it directly for photon pairs with:

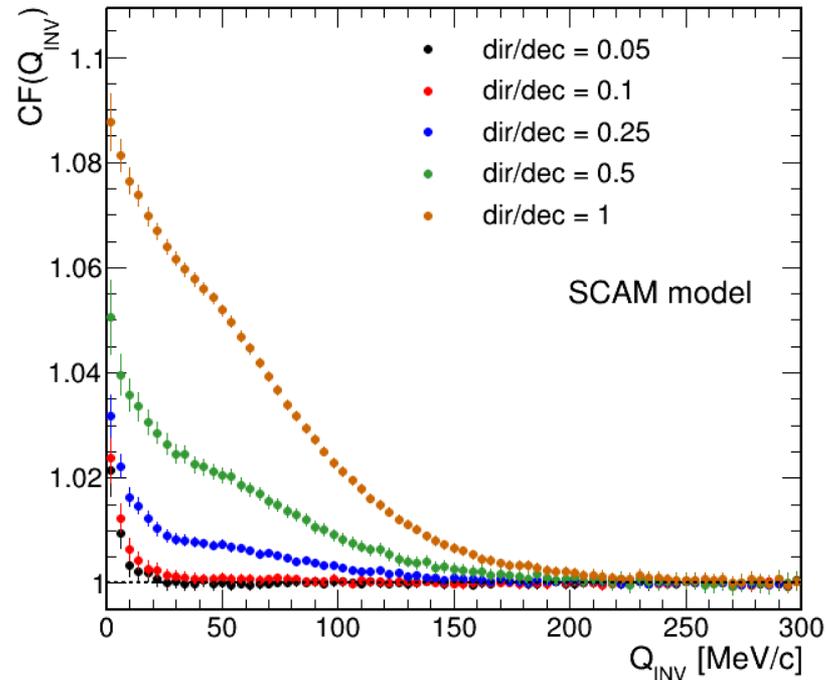
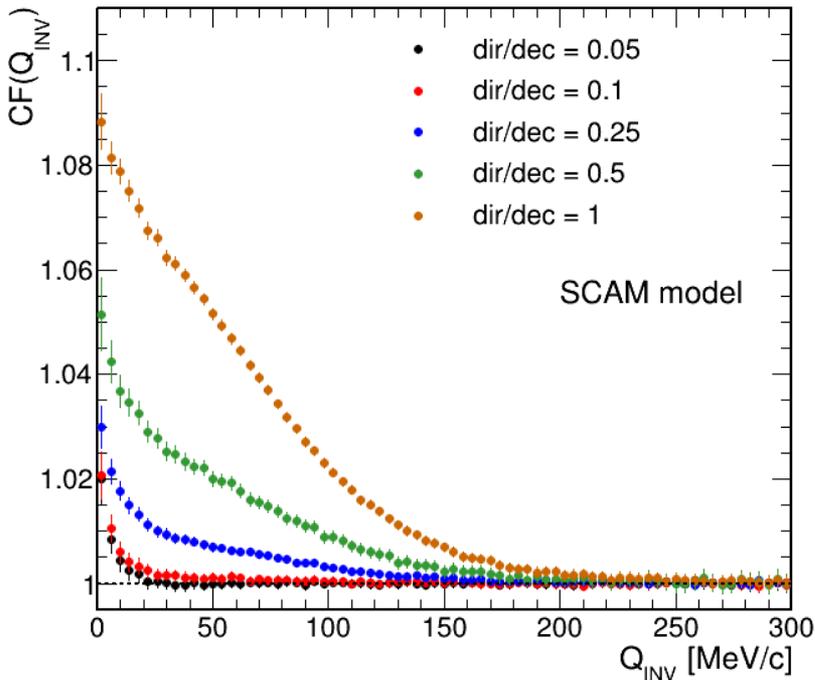
Non-femtoscopic effects are neglected!  
(flow, energy conservation ect.)

$$QW = 1 + \frac{1}{2} \cos(\Delta x \Delta q)$$

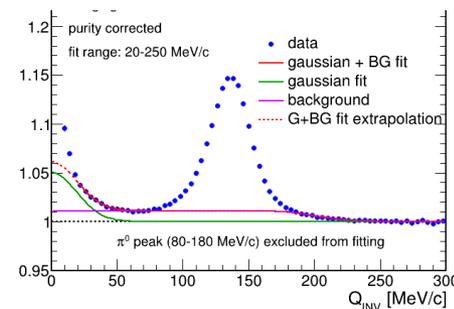


Double source (gauss 2 fm + gauss 40 fm)

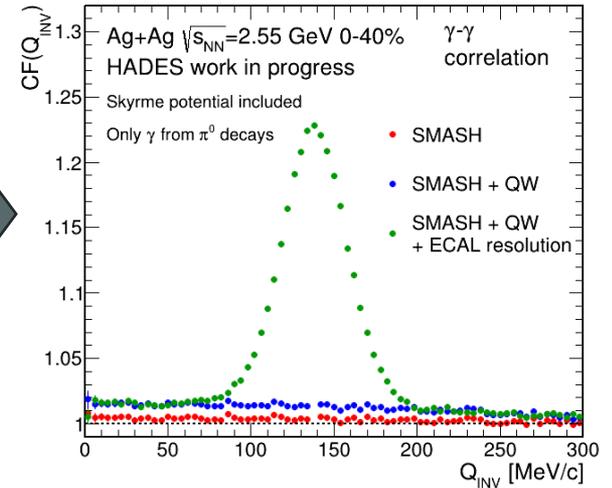
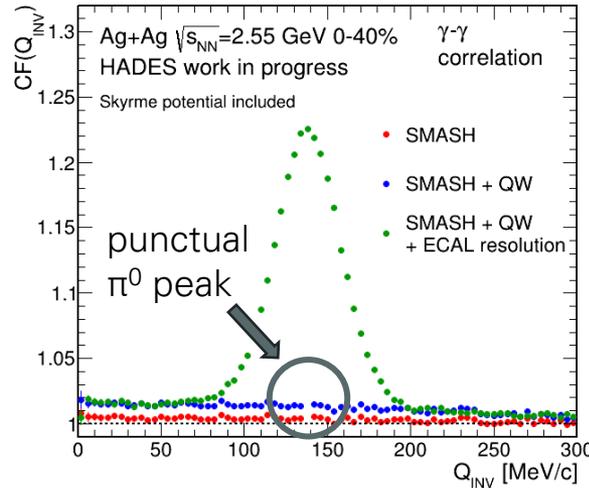
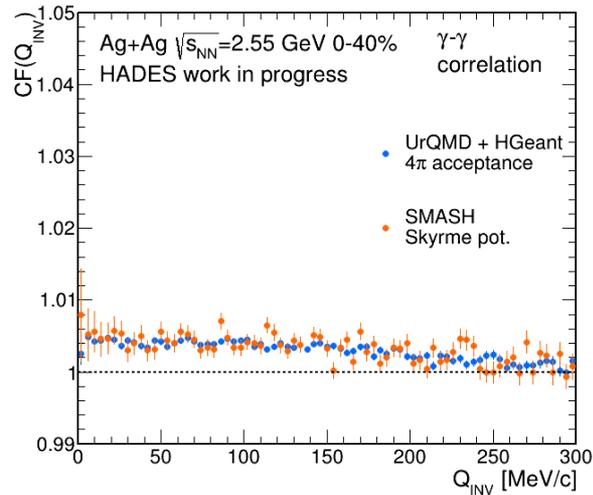
Double source (gauss 2 fm + halo 40 fm, fade 10 fm)



- Not much of a difference between shapes
- Ratio between 0.1 and 0.25 should be somewhat like what is seen in HADES data
- Further investigations/checks needed...



# SMASH, Ag+Ag at 2.55 GeV



## • Skyrme potential

- Effective interaction between nucleons
- Attractive at nuclear ground state density ( $\rho_0 \approx 0.16 \text{ fm}^{-3}$ ), repulsive for higher densities

$$U_{\text{Skyrme}} = a \frac{\rho}{\rho_0} + b \left( \frac{\rho}{\rho_0} \right)^\tau$$

- Skyrme parameters related to equation of state in terms of compressibility K

	Soft EoS	Default EoS	Hard EoS
a	-356.0 MeV	-209.2 MeV	-124.0 MeV
b	303.0 MeV	156.4 MeV	71.0 MeV
$\tau$	1.17	1.35	2.00
K	200 MeV	210 MeV	380 MeV

## • Symmetry potential

- Accounts for symmetric/antisymmetric nuclei in terms of proton and neutron densities

$$U_{\text{Symmetry}} = \pm 2 S_{\text{pot}} \frac{\rho_n - \rho_p}{\rho_0}$$

$$QW = 1 + \frac{1}{2} \cos(\Delta x \Delta q)$$

$QW$  : quantum weight (impact of quantum statistics)

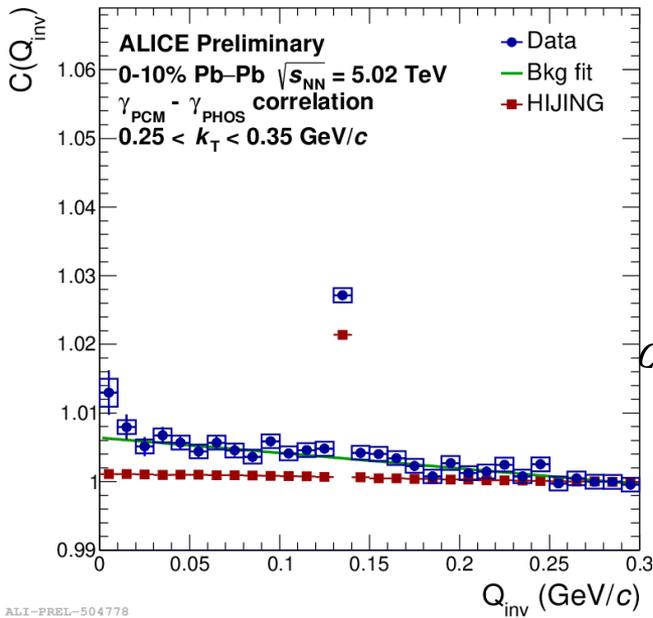
$\Delta x$  : position difference

$\Delta q$  : momentum difference

Identical behavior for all photons from SMASH (only decay  $\gamma$ , mostly from  $\pi^0$ ,  $\eta$  and  $\Sigma^0$  decays) to only  $\pi^0$  photons  $\rightarrow$  background related to  $\pi^0$  correlations?

statistical uncertainties only

# Backup - fits to ALICE data



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

$$CF(Q_{inv}) = 1 + \frac{\lambda e^{-Q_{INV}^2 \cdot R_{INV}^2}}{1 + (a_1 \cdot Q_{INV})^{a_2}}$$

