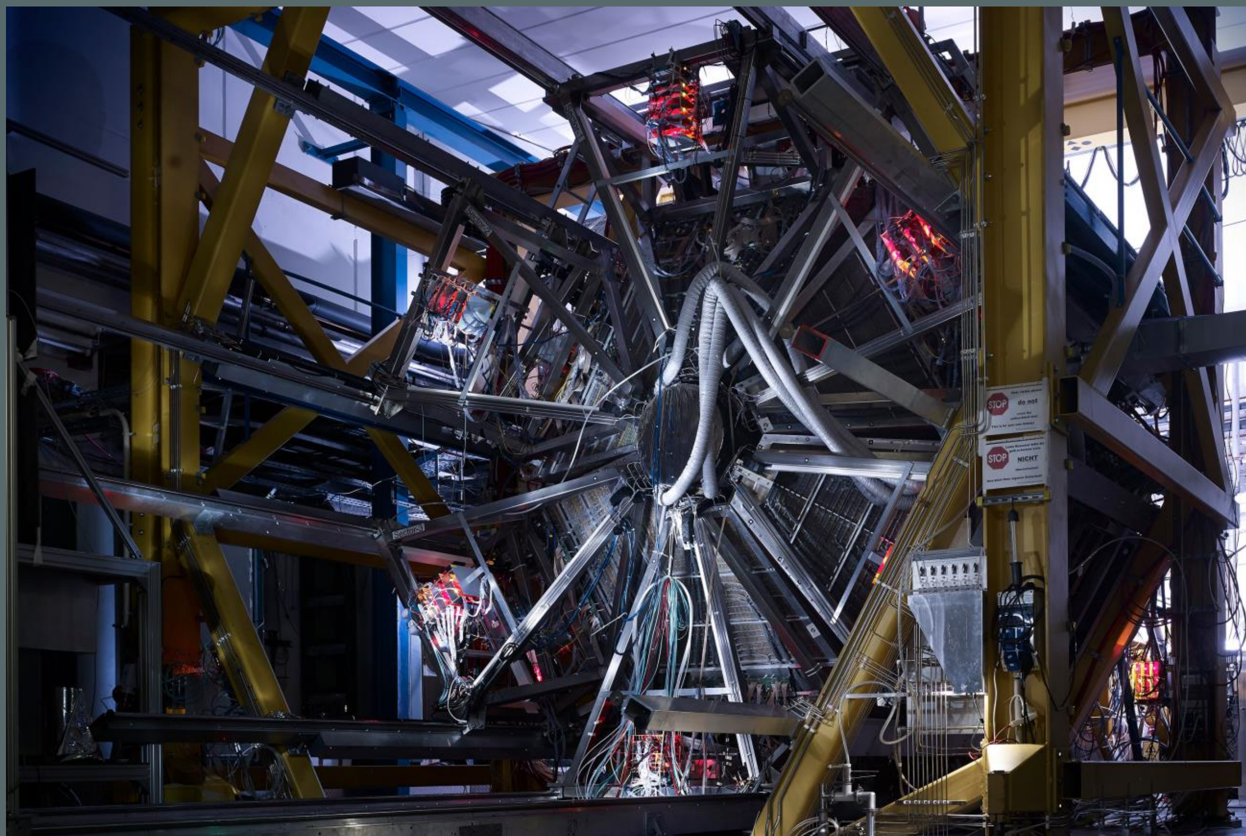
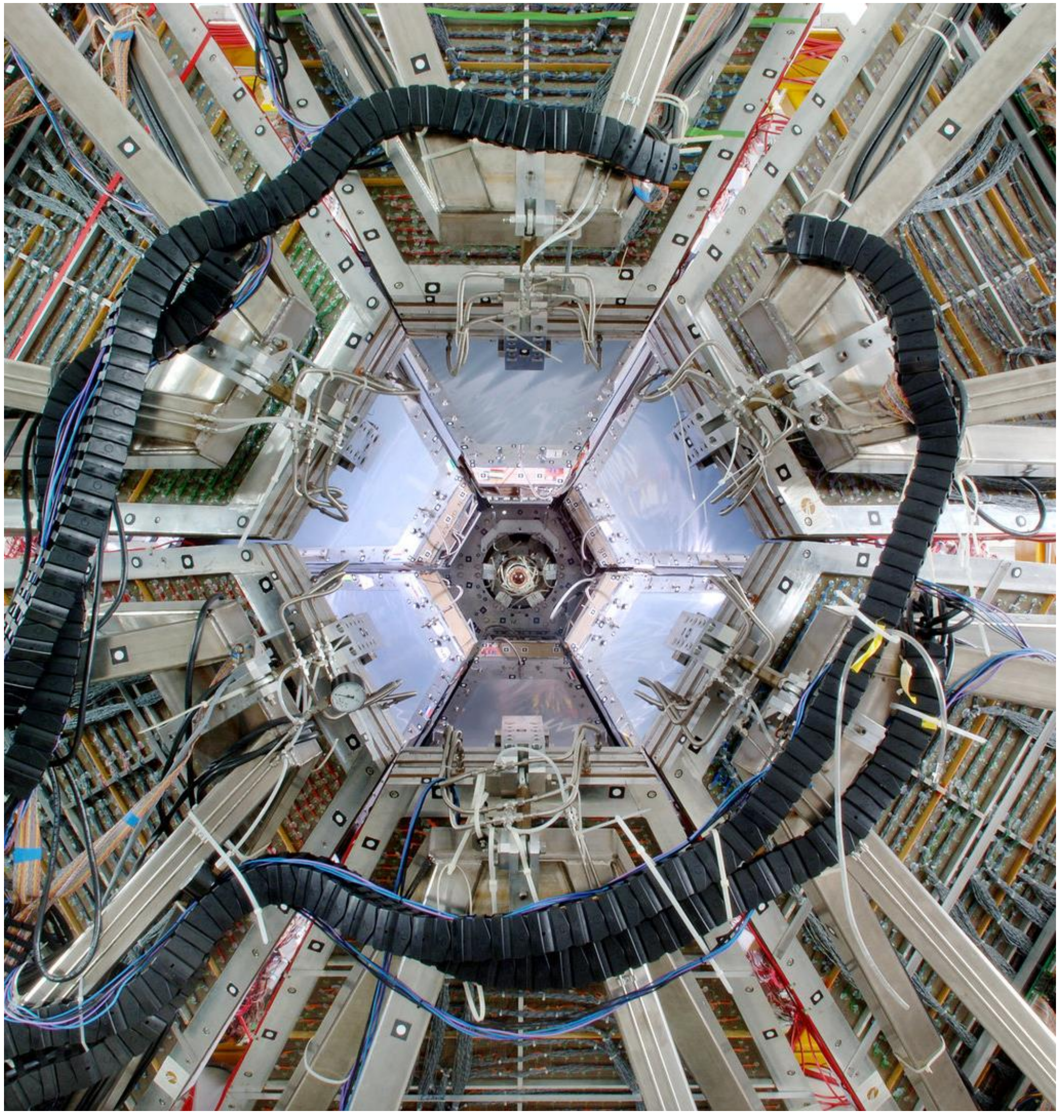
Photon-photon correlations in Ag+Ag collisions at $\sqrt{s_{NN}}$ =2.55 GeV



Mateusz Grunwald
for the HADES collaboration

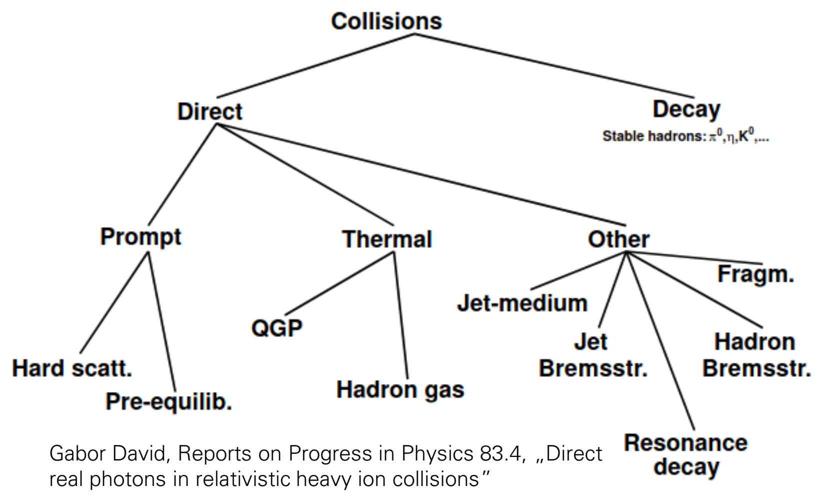
Outline

1) Motivation
    - Why photon femtoscopy?
2) Femtoscopy technique
3) HADES experiment
4) Results:
    - HADES data
    - SMASH
    - SCAM (toy) model
5) Summary

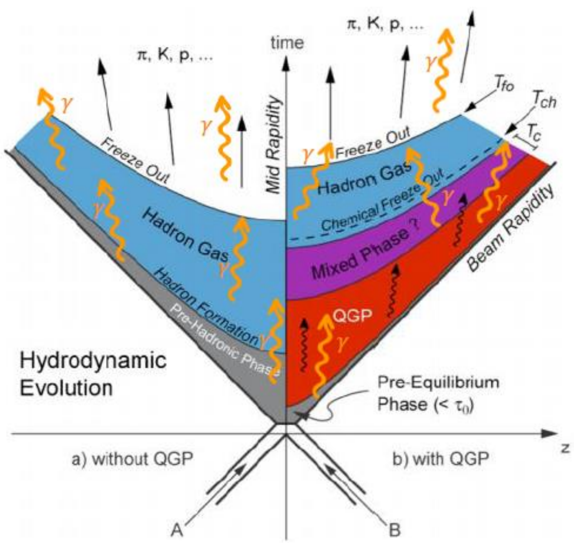


Motivation

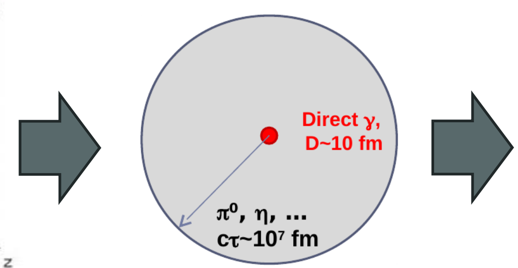
- Measure source properties **at early stages** -> inaccessible for hadrons
- Estimate **direct photon yield** via femtoscopy
- Experimentally challenging



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

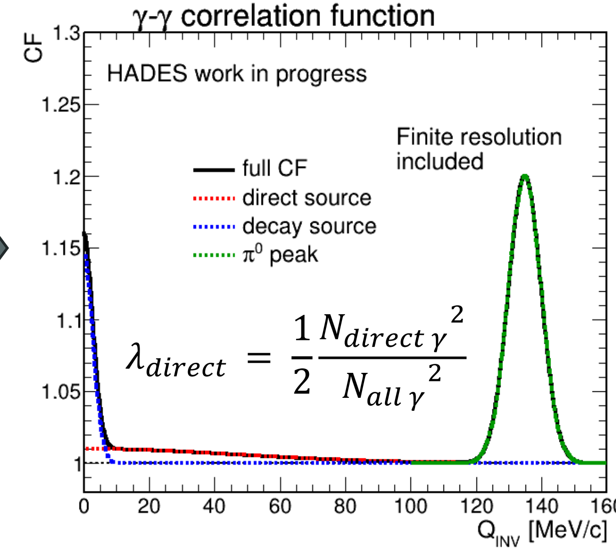


J. Stachel. K. Reygers, QGP physics SS2015 6., „Space-time evolution of the QGP"



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

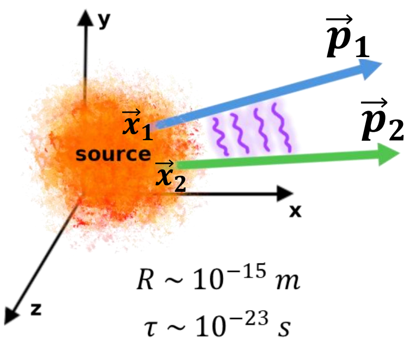
Cartoonish idea of experimental γ-γ correlation function



$$\lambda_{direct} = \frac{1}{2}\frac{N_{direct\,\gamma}^{2}}{N_{all\,\gamma}^{2}}$$

Femtoscopy

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



Theory

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

Correlation function: $CF(\vec{p}_1,\vec{p}_2) = \dfrac{P(\vec{p}_1,\vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)}$

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

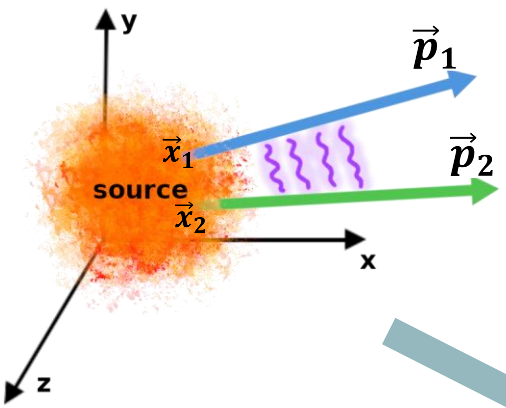
$N_{mixed}(q)$: mixed event distribution

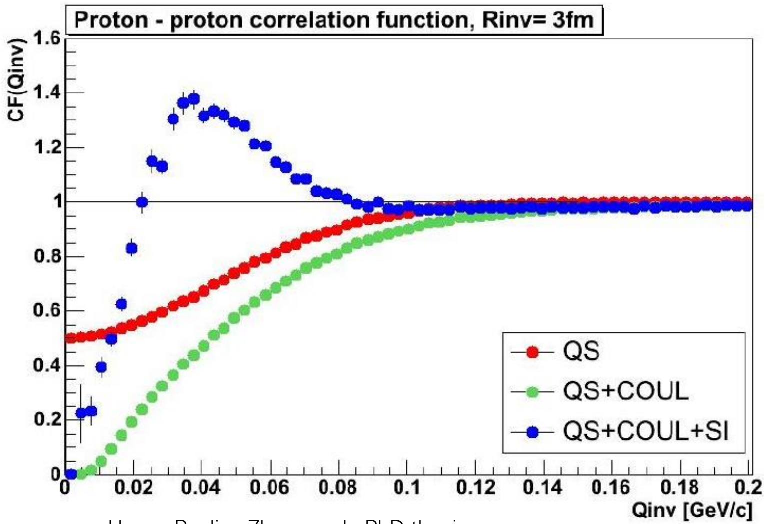
Experiment

Correlation function:

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

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

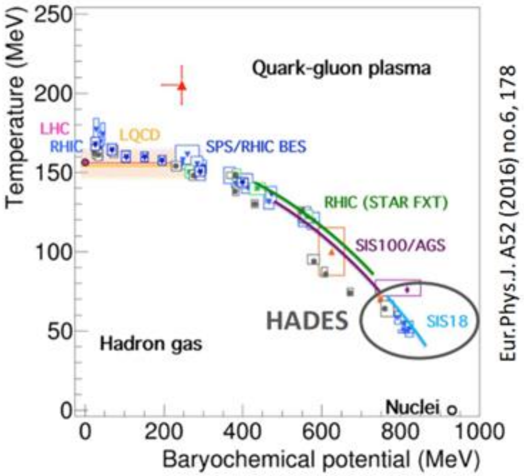
$r = |\vec{x}_1 - \vec{x}_2|$: relative distance

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

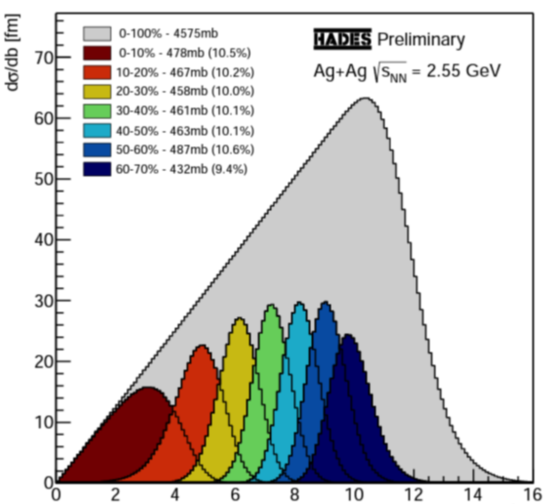
Determine the geometry and dynamic properties (traditional femtoscopy)

Determine the interactions (non-traditional femtoscopy)

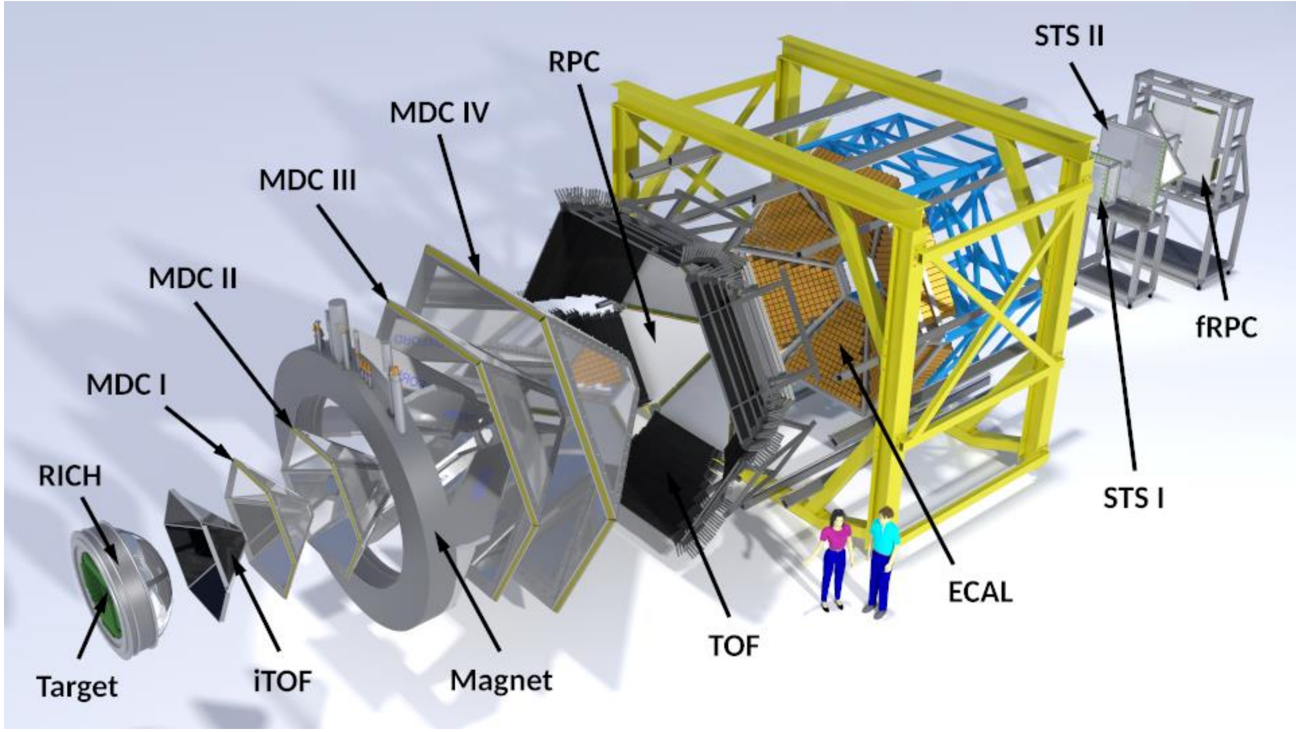
HADES experiment



- High Acceptance Di-Electron Spectrometer
- Fixed target, few (1-2) GeV beam kinetic energy
- Measurement of dilepton pairs from vector mesons (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)

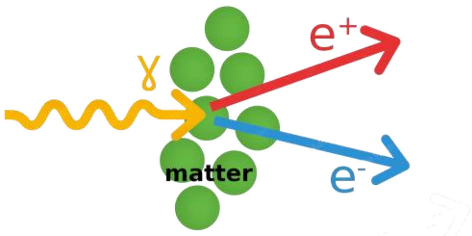


Simon Spies, PhD thesis



Photons at HADES

Photon Conversion Method (PCM)

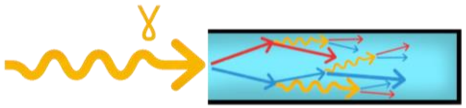


- High momentum and angular resolution
- Good lepton reconstruction efficiency at HADES
- Pure sample of photons

- 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)



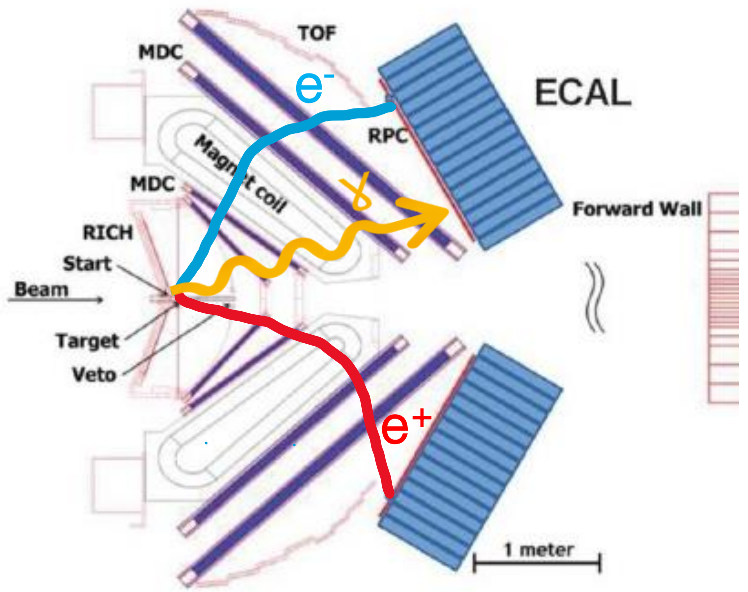
- Great efficiency due to direct reconstruction
- Covers wider energy & p_T range than PCM
- Decently pure sample with suitable criteria

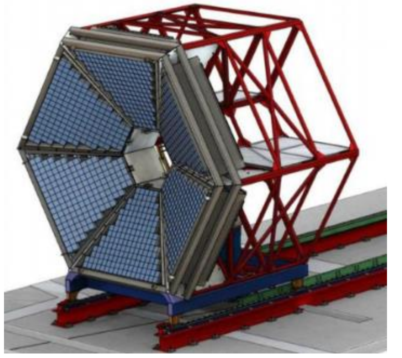
- Calorimeter modules are usually big → poor angular resolution
- Low-end energy resolution is low due to ~1/√E behavior → low Q_{INV} might be fairly smeared, since:

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

Photons at HADES - ECAL

Electromagnetic calorimeters (ECAL)

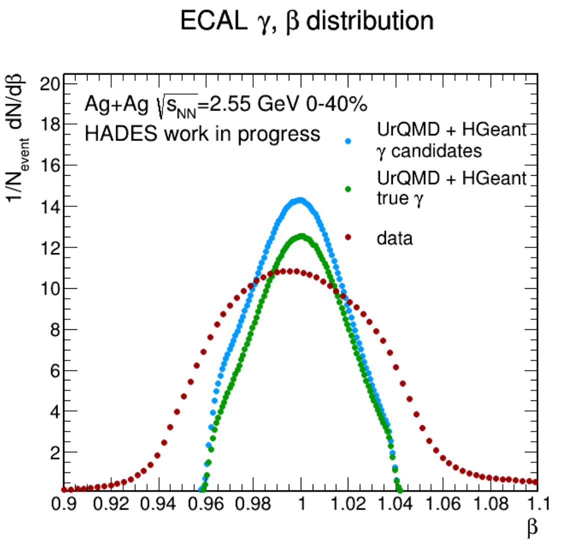


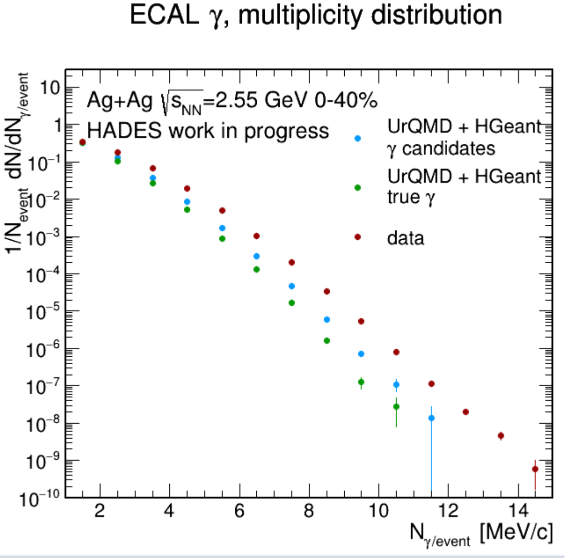


$$\frac{\sigma_E}{E} = \frac{6\%}{\sqrt{E(GeV)}}$$

$$\sigma_t < 300\ ps$$

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

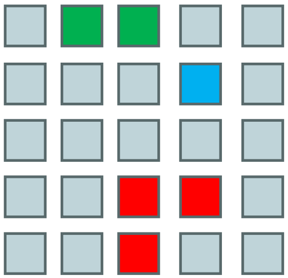




statistical uncertainties only

- **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
  - β within 2σ from expected photon peak (β=1), adjusted for each module (and day/hour of a beamtime)

Photons at HADES - ECAL



Modules are ~ 2.2° (92 mm) wide, Can't separate 2γ within $300\ ps$ interval

Opening angle „hardware threshold" ~ 4.4° (for 2 „size 1" clusters)

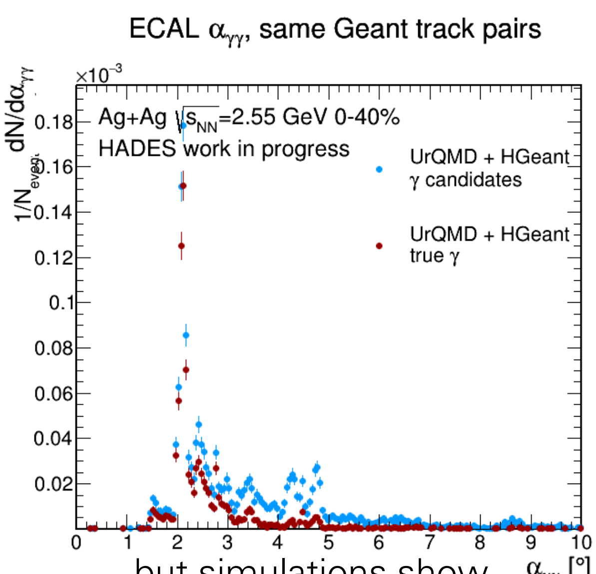
γ triggers:

1 module → cluster size 1

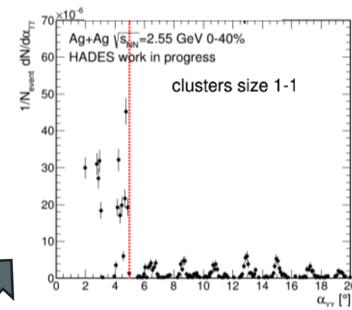
2 modules → cluster size 2

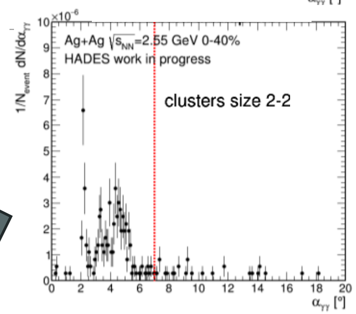
3 modules → cluster size 3

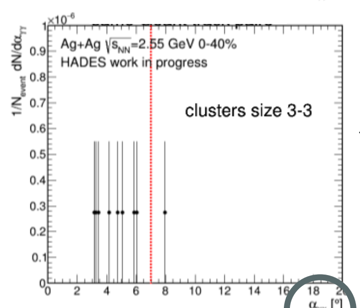
…

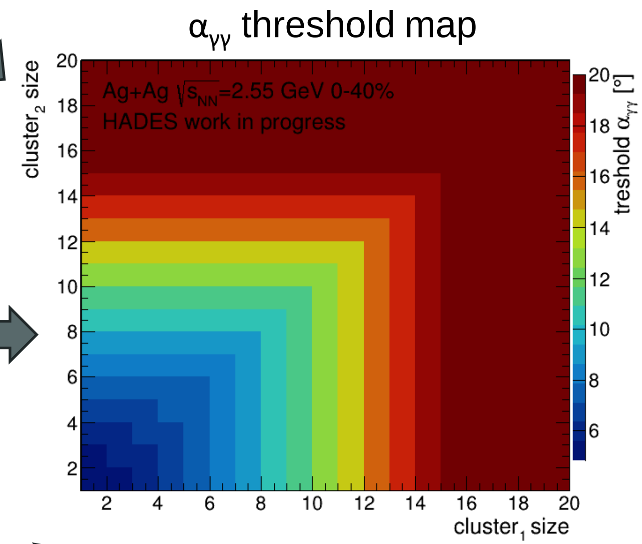


… but simulations show some „split" clusters





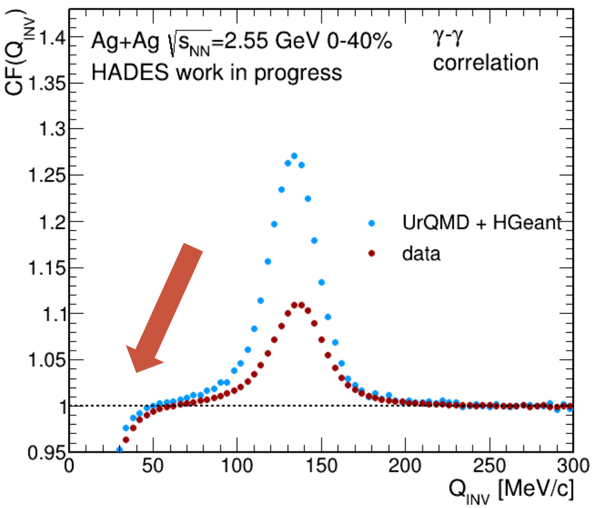




$\alpha_{\gamma\gamma}$ [°]

statistical uncertainties only

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



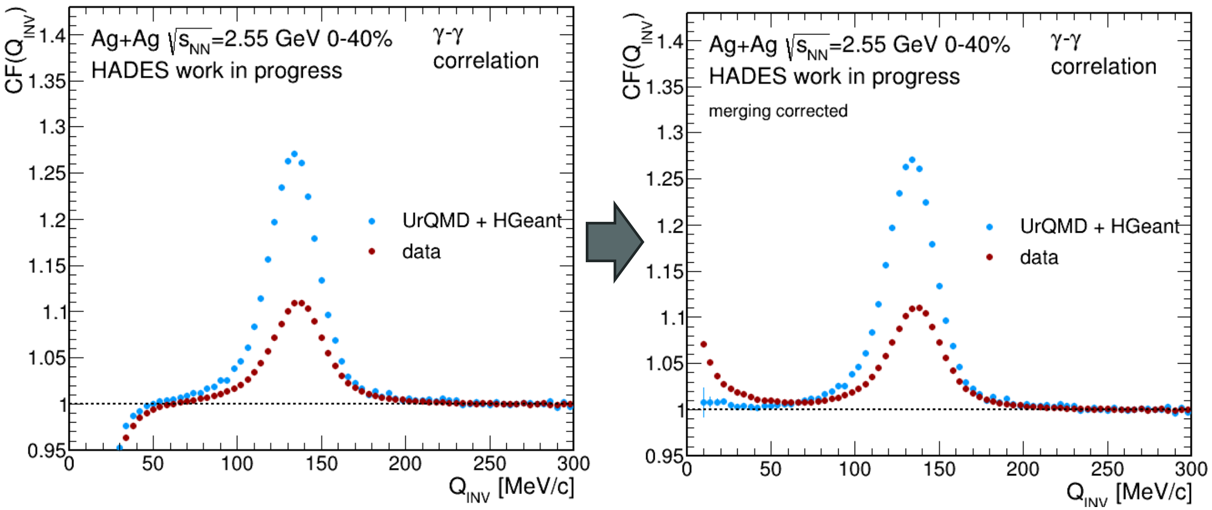
UrQMD + HGeant → no FSI/QS involved
data → real data gathered by HADES

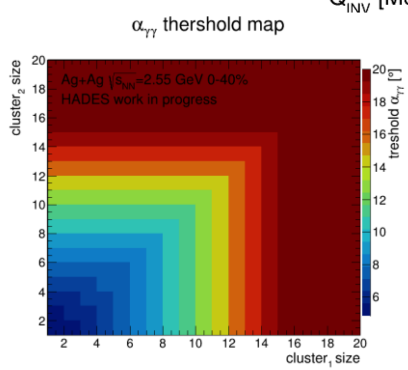
Anticorrelation caused by uneven $\alpha_{\gamma\gamma}$ acceptance in same & mixed events („hardware threshold")

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

statistical uncertainties only

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



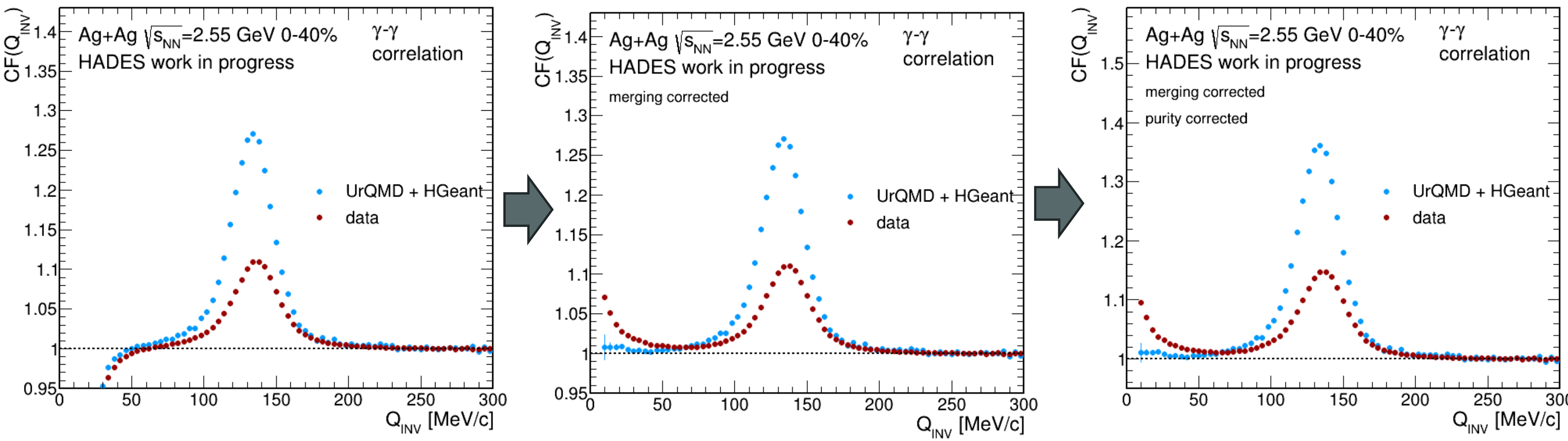


$$Q_{INV} = \sqrt{(\vec{p_1} - \vec{p_2})^2 - (E_1 - E_2)^2}$$

statistical uncertainties only

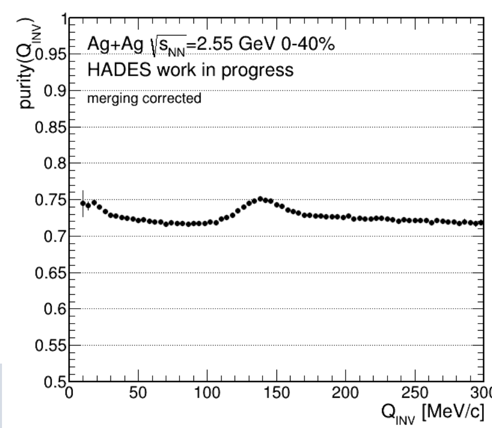
Photon-photon correlation functions, Ag+Ag at 2.55 GeV

Visible enhancement at low Q_{inv} over simulations!



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

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



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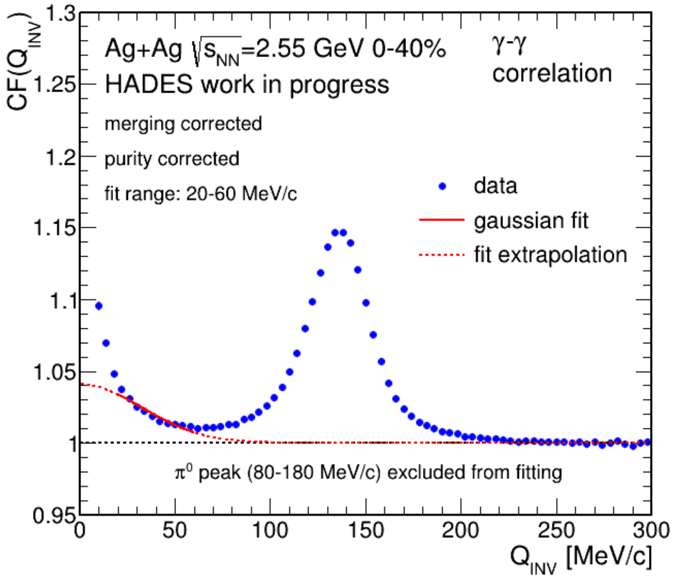
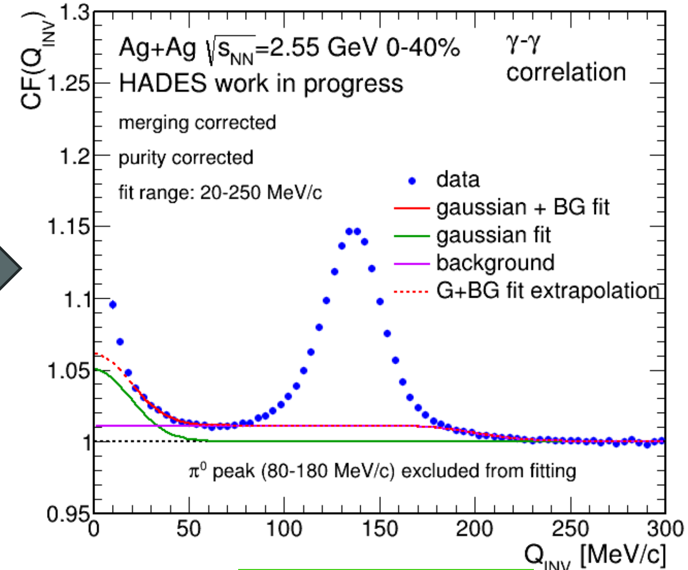
statistical uncertainties only

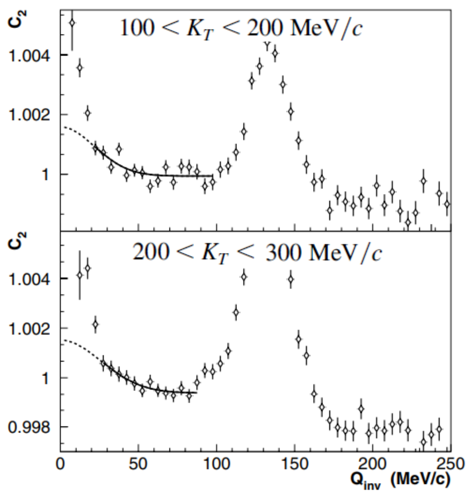
Photon-photon correlation functions, Ag+Ag at 2.55 GeV

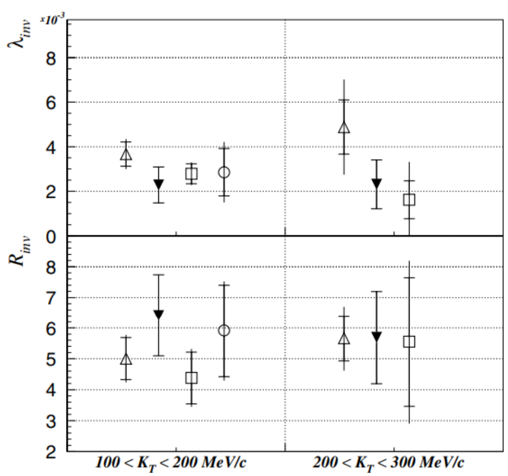




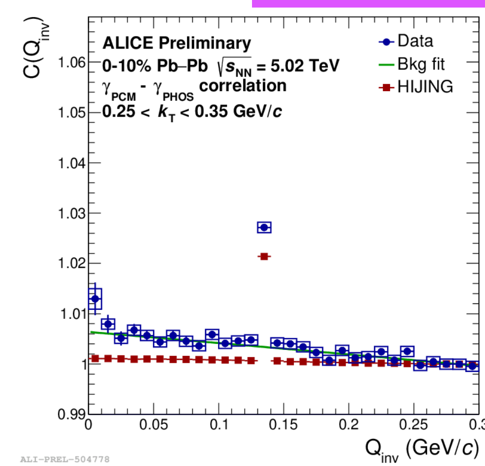
$$CF(Q_{INV}) = 1 + \lambda e^{(-Q_{INV}{}^2 \cdot R_{INV}{}^2)}$$

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



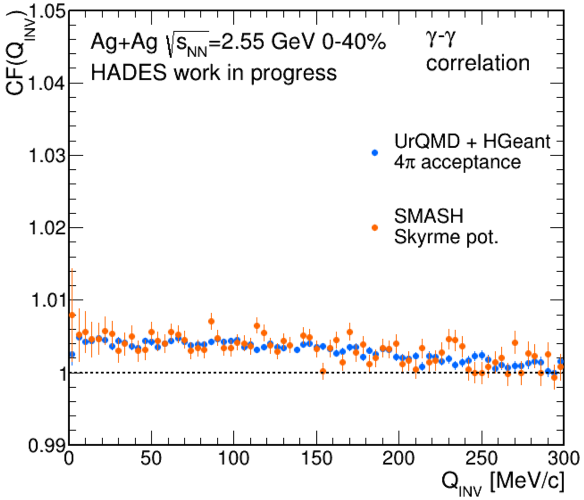


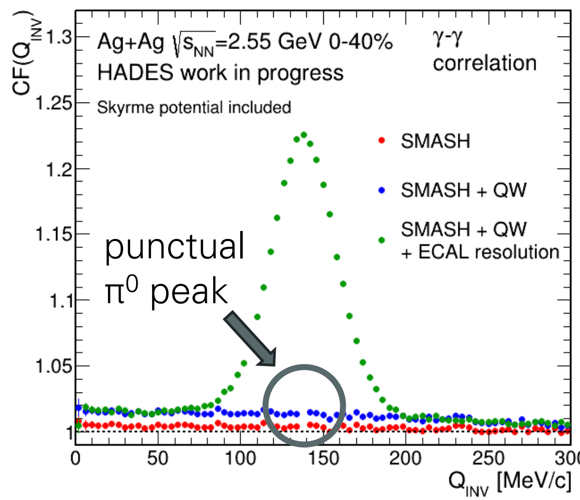
Interferometry of Direct Photons in Central 208Pb 208Pb Collisions at 158A GeV, Aggarwal, M. M., Physical Review Letters, 93(2). doi:10.1103/physrevlett.93.022301

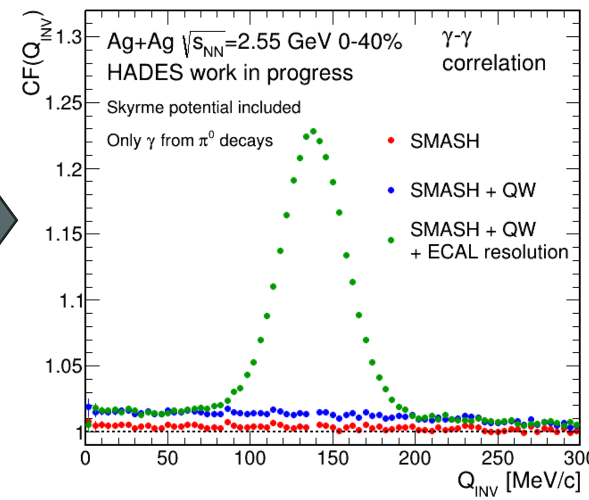


Mike Sas for the ALICE Collaboration, Quark Matter 2022

SMASH, Ag+Ag at 2.55 GeV







- **Skyrme potential**
  - Effective interaction between nucleons
  - Attractive at nuclear ground state density ($\rho_0 \approx 0.16$ 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
- **Symmetry potential**
  - Accounts for symmetric/ antisymmetric nuclei in terms of proton and neutron densities
  - $U_{\text{Symmetry}} = \pm 2\, S_{\text{pot}}\, \frac{\rho_n - \rho_p}{\rho_0}$

	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
τ	1.17	1.35	2.00
K	200 MeV	210 MeV	380 MeV

SMASH - A Novel Transport Model to Simulate Low-Energy Hadronic Interactions Anna Schäfer and Hannah Elfner GSI, Frankfurt U., FIAS

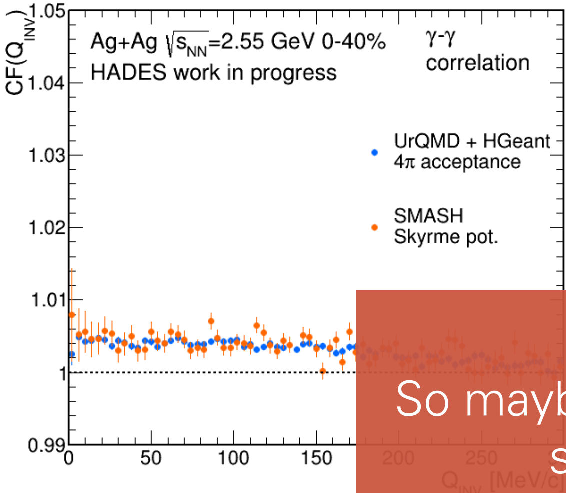
$$QW = 1 + \frac{1}{2}\cos(\Delta x \Delta q)$$

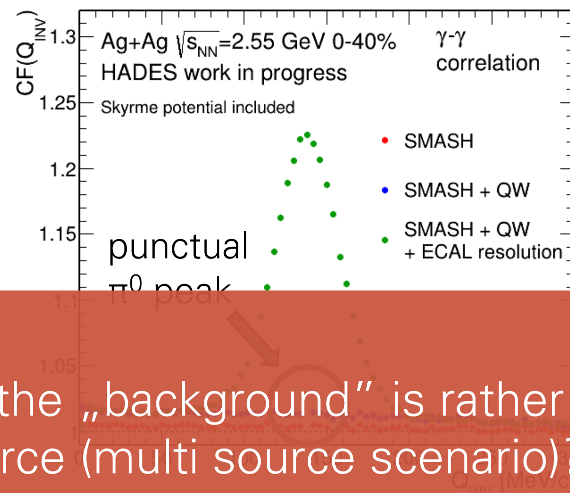
QW : quantum weight (impact of quantum statistics)
Δx : position difference
Δq : momentum difference

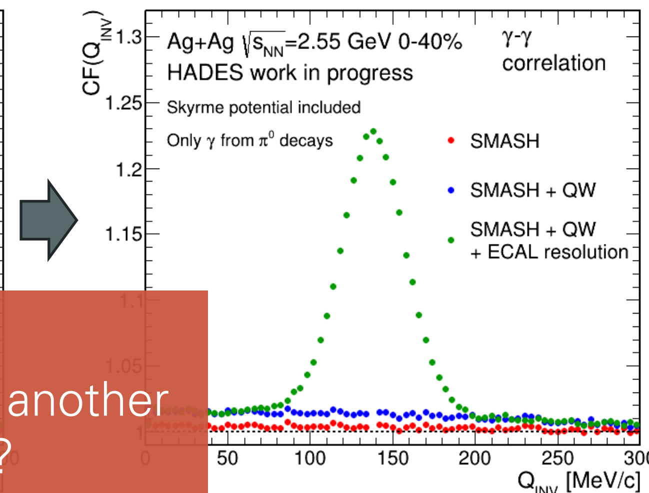
Identical behavior for all photons from SMASH (only decay γ, mostly from π^0, η and Σ^0 decays) to only π^0 photons → background related to π^0 correlations?

statistical uncertainties only

SMASH, Ag+Ag at 2.55 GeV







So maybe the „background" is rather another source (multi source scenario)?

- **Skyrme potential**
  - Effective interaction between nucleons
  - Attractive at nuclear ground state density ($\rho_0 \approx 0.16$ fm^{-3}), repulsive for higher densities
  - $U_{Skyrme} = a \frac{\rho}{\rho_0} + b \left(\frac{\rho}{\rho_0}\right)^\tau$
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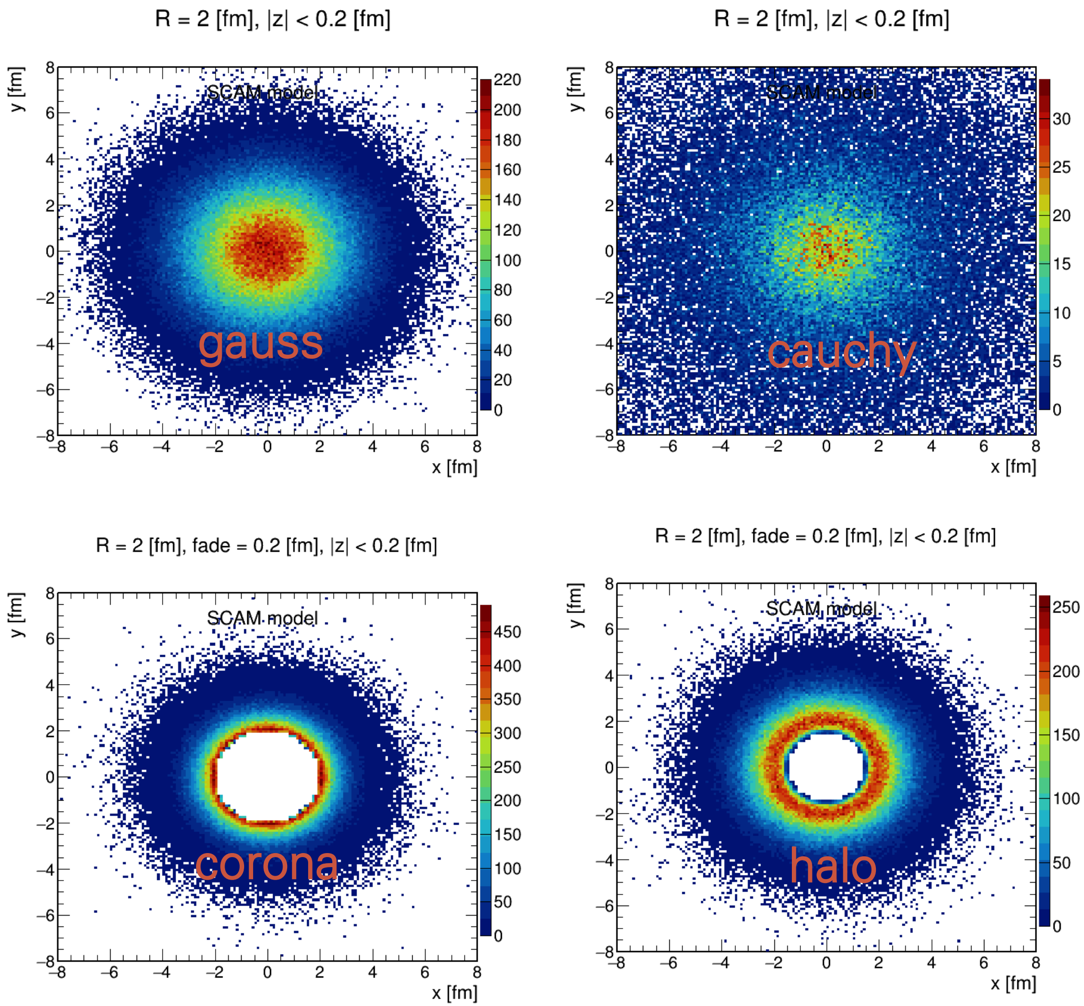
statistical uncertainties only

SCAM model

Silly Correlation-Alike Maker

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

- Position → randomized from the source's surface function



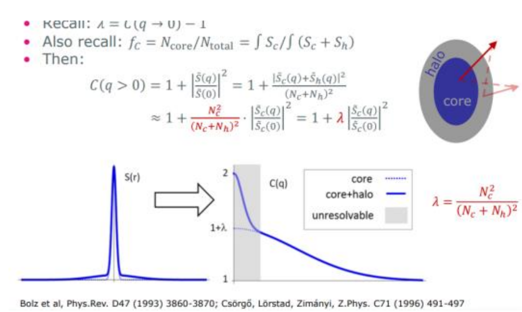
$$gauss\,(x,y,z) = e^{-0.5\,(x^2+y^2+z^2)/R}$$

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

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

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

Inspired by:



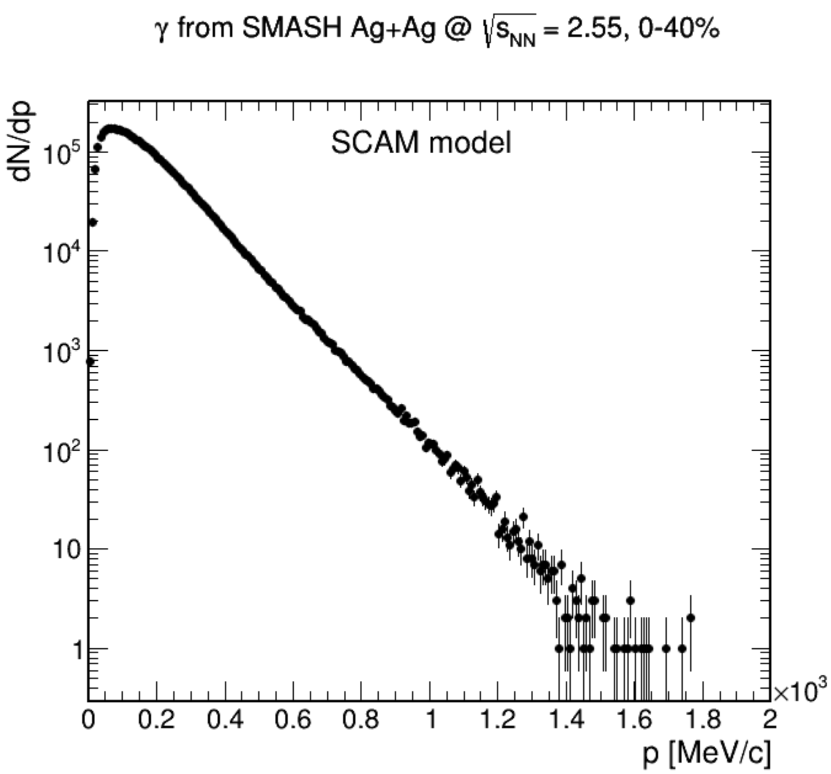
Quantumstatistical correlations and femtoscopy in high energy physics, Máté Csanád

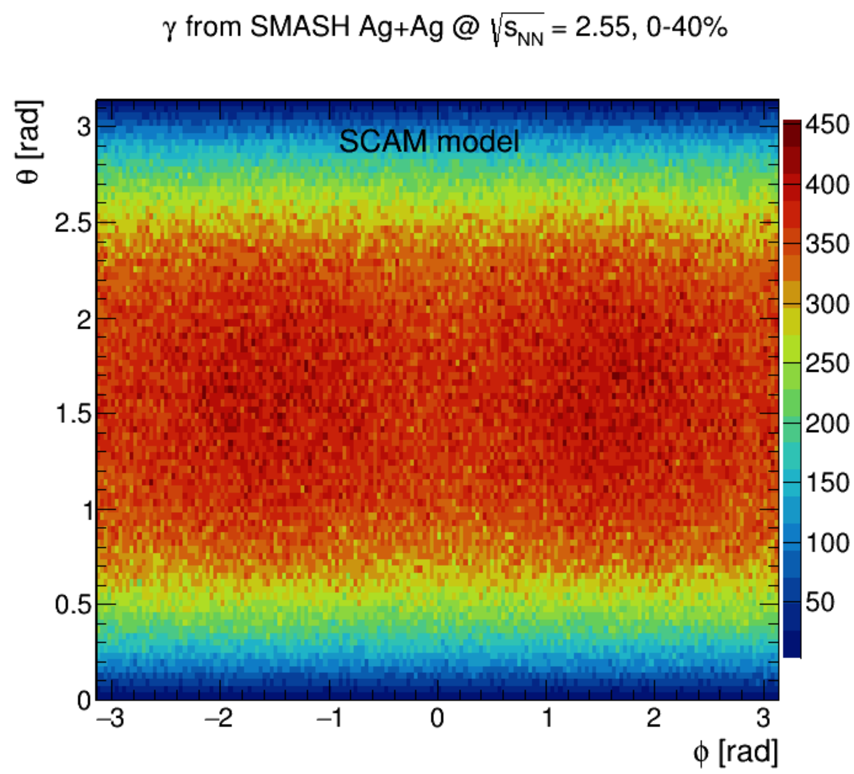
SCAM model

Silly Correlation-Alike Maker

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

- Position → randomized from the source's surface function
- Momenta → randomized using p and ϕ-θ distributions (currently taken from SMASH for Ag+Ag @ 2.55 GeV photons)





SCAM model

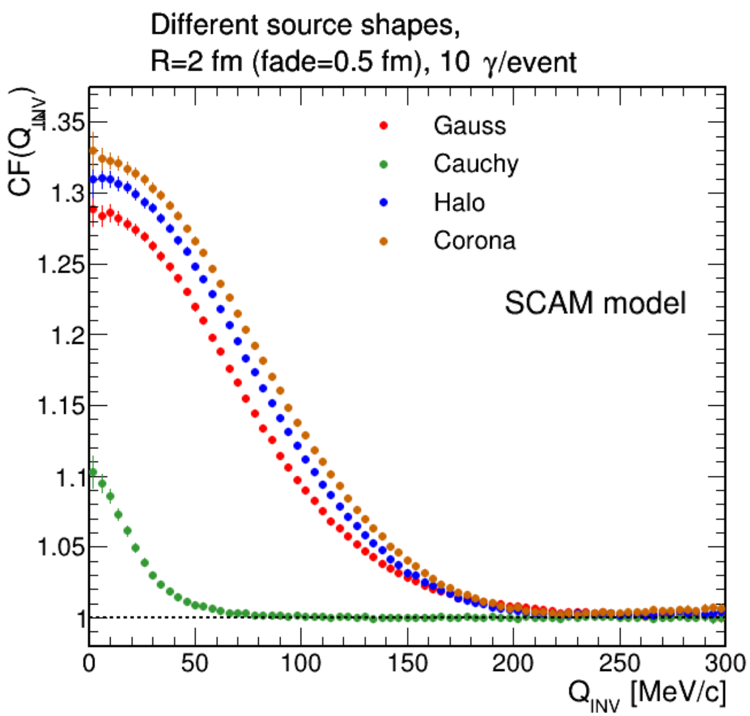
Silly Correlation-Alike Maker

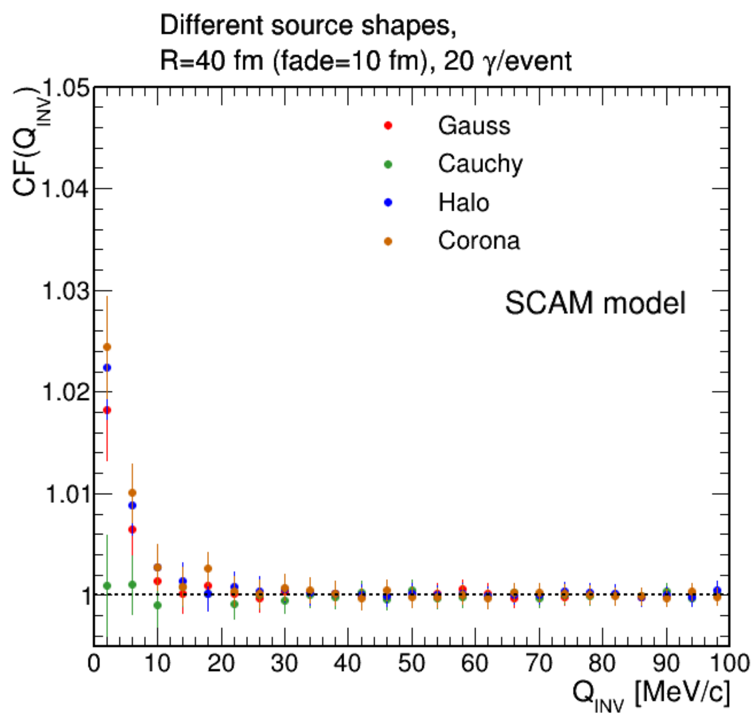
Create correlation function from user-defined source(s):

- Position → randomized from the source's surface function (time = radius)
- Momenta → randomized using p and ϕ-θ 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.)

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

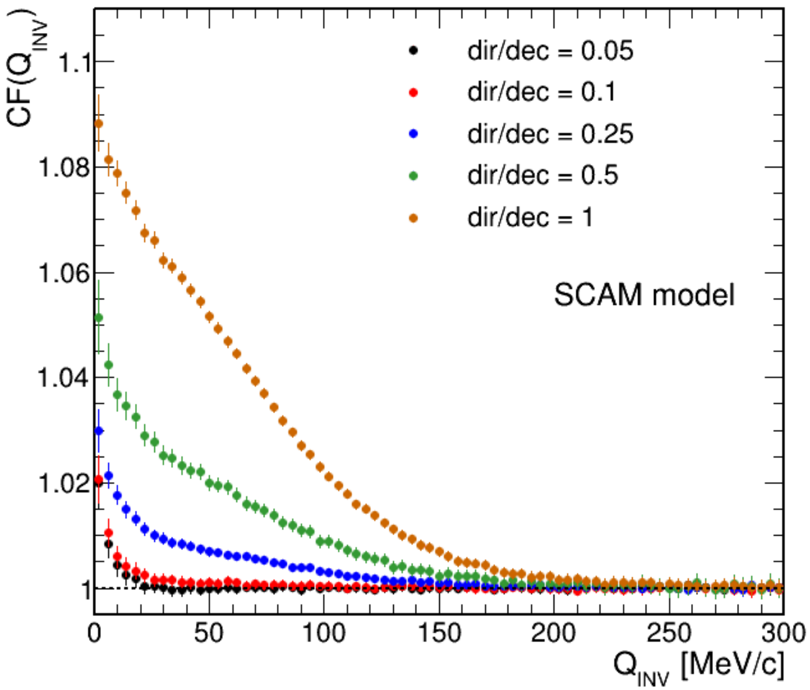




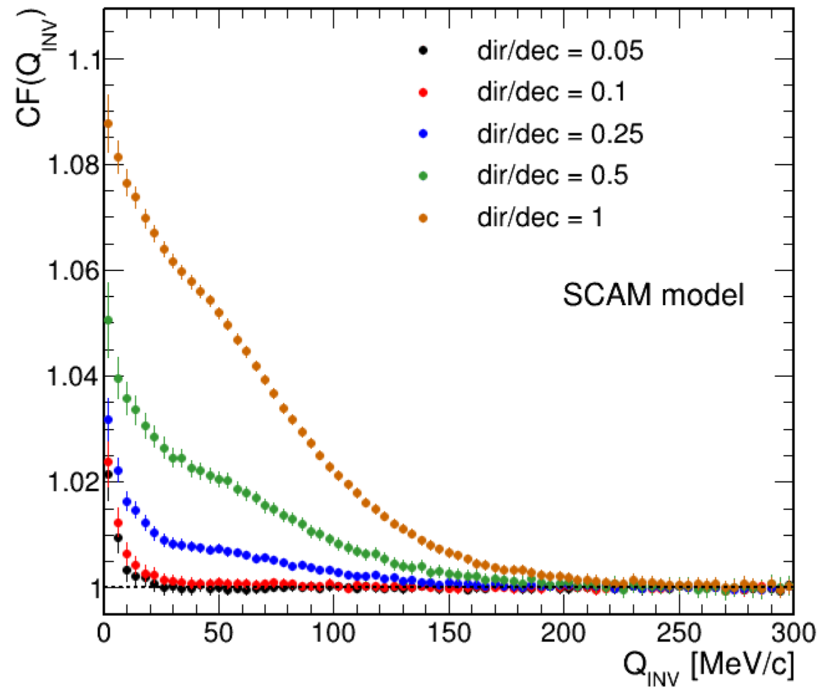
SCAM

Silly **C**orrelation-**A**like **M**aker

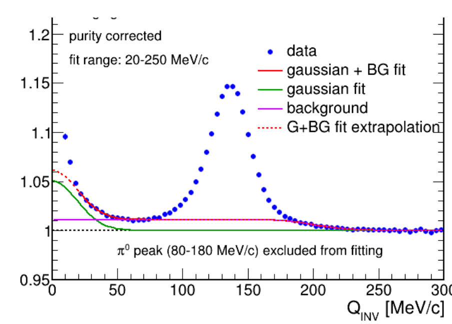
Double source (gauss 2 fm + gauss 40 fm)



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



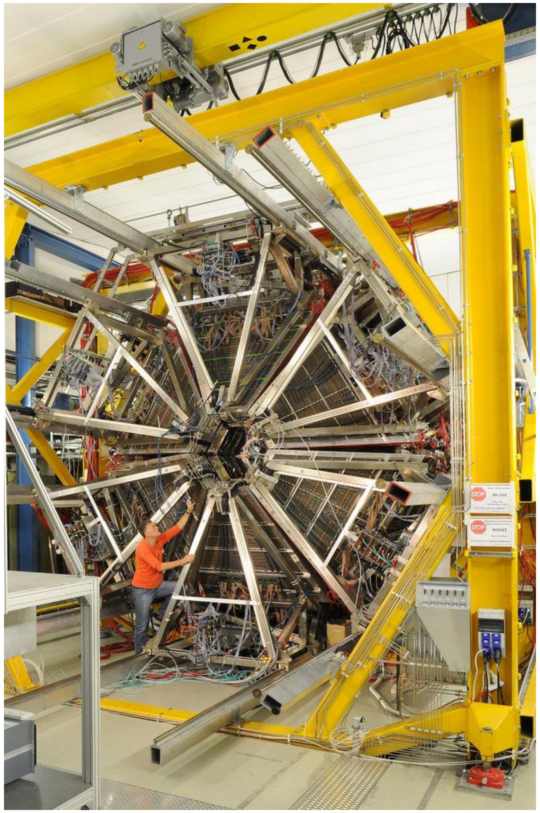
- Not much of a difference between shapes
- Ratio between 0.1 and 0.25 should be somewhat like what is seen in HADES data
- Further investigations/checks needed…



Summary & Outlook

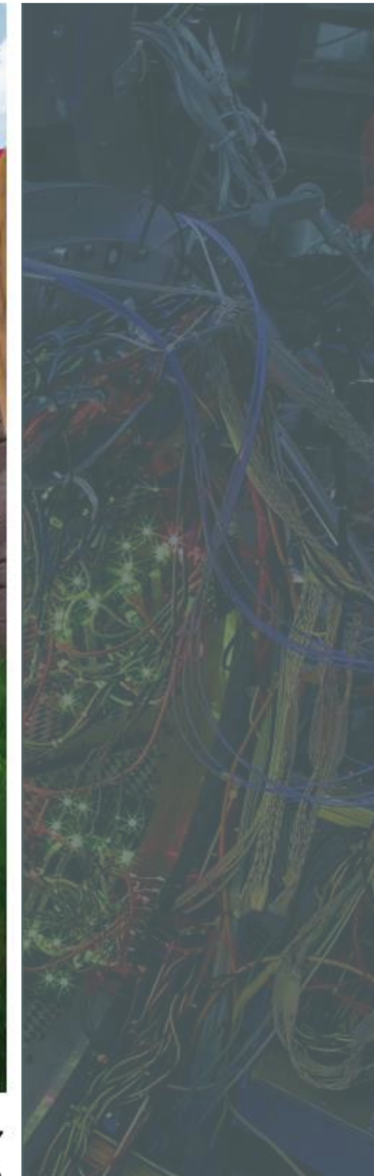
- Photon-photon correlation **can be obtained** in HADES with use of calorimeters.
- **An enhancement** at low Q_{INV} (< 50 MeV/c) over simulations **is visible**, with additional contribution (up to ~ 200 MeV/c). It is not caused by calorimeters resolution → likely physics based.
- The extra contribution might be caused by π^0-π^0 correlations (however it <u>is just a hypothesis</u>).

- 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!

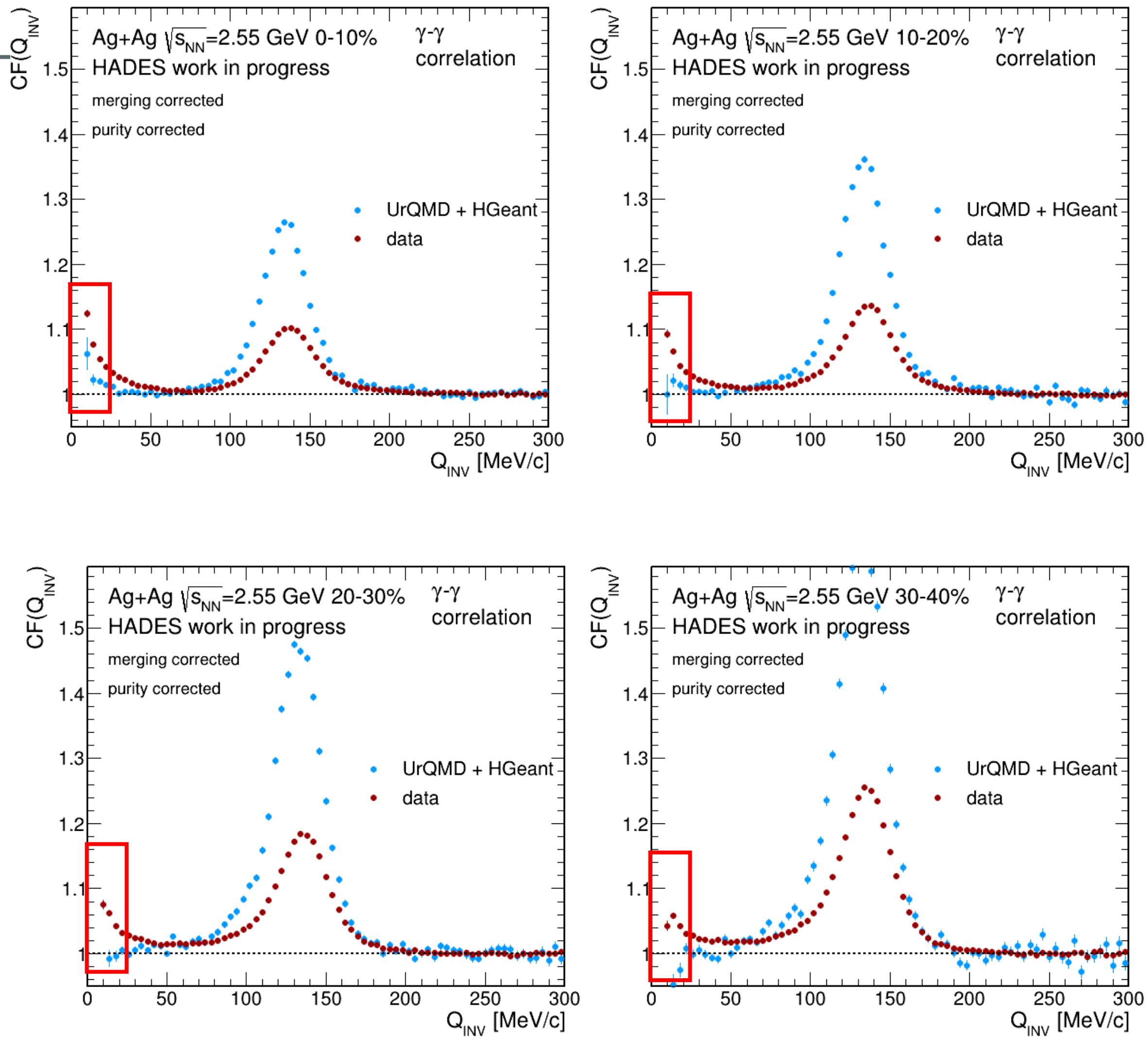
Don Quixote's quest continues!



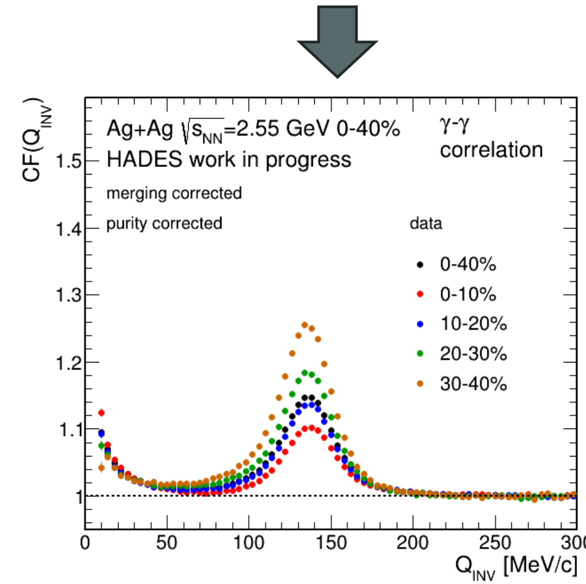
Backup

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)

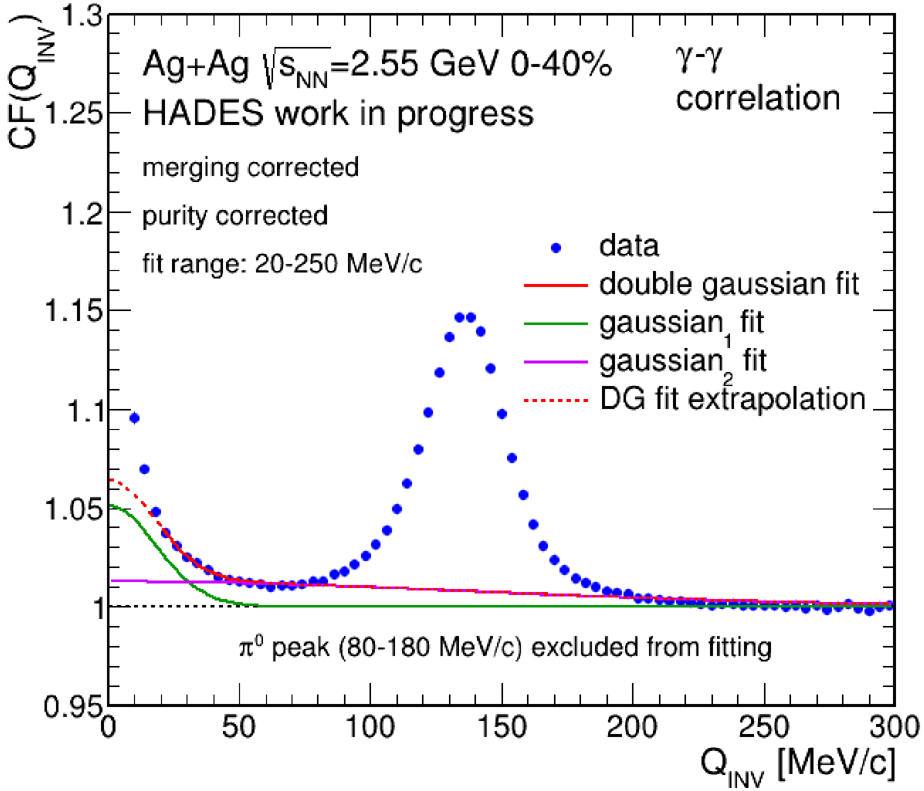


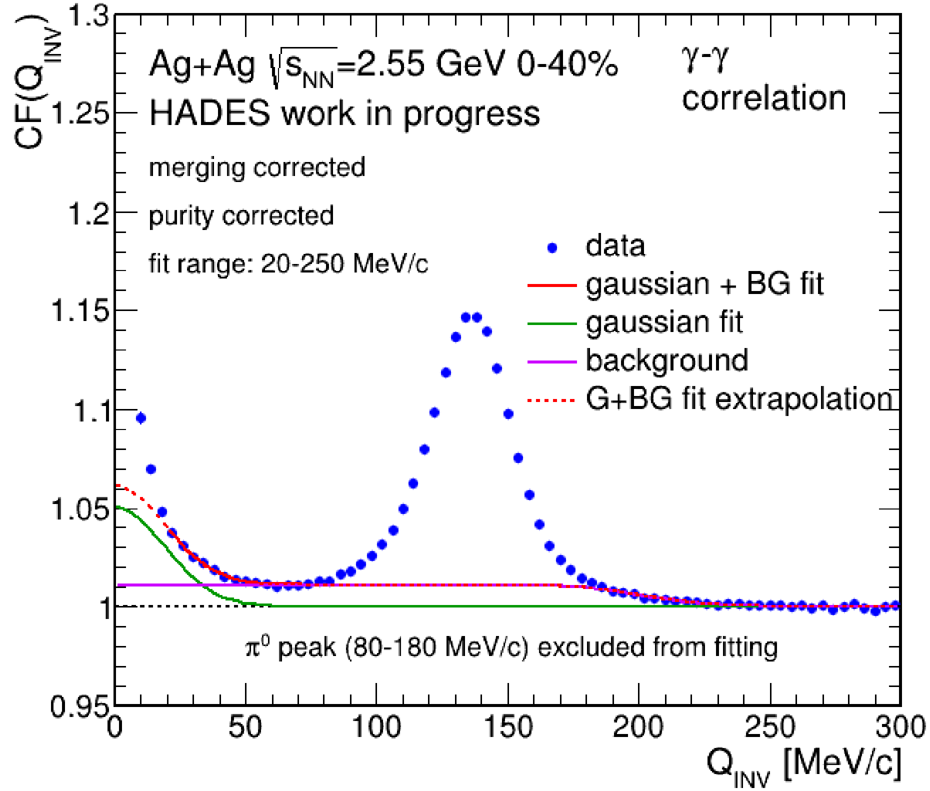
Backup – ECAL – alternative fits

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

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

Very similar predictions for both options



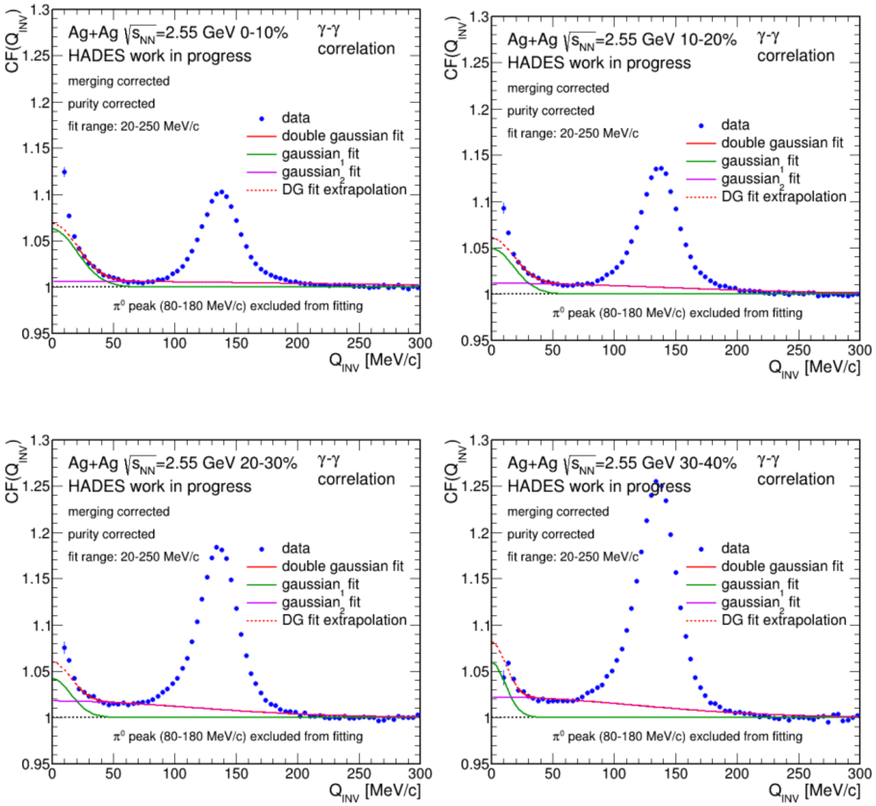


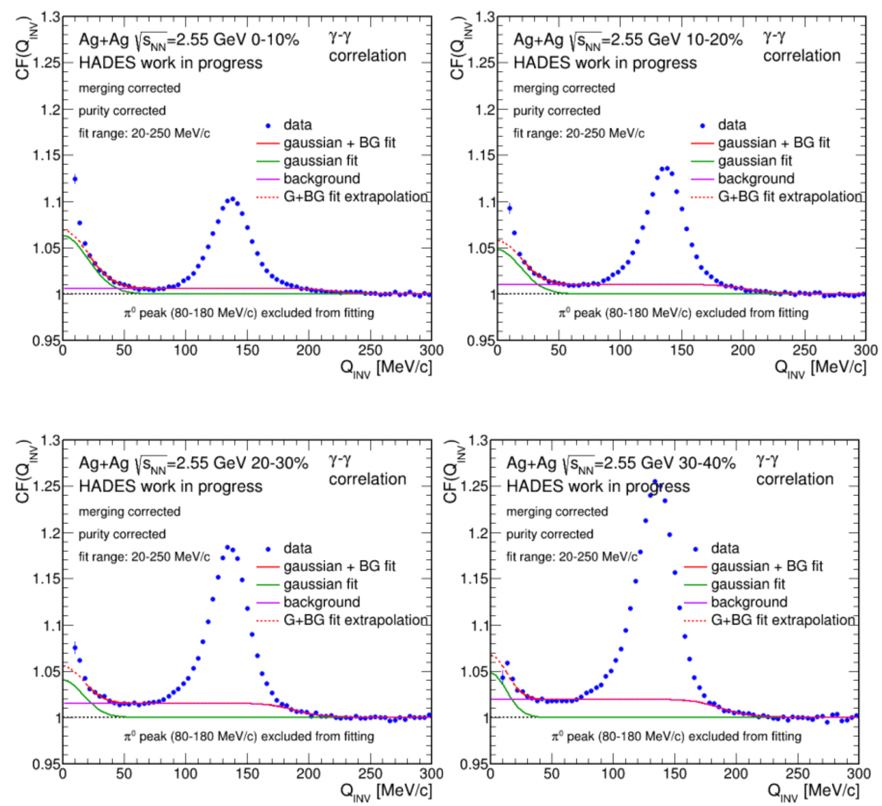
Backup – ECAL – alternative fits & centrality

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

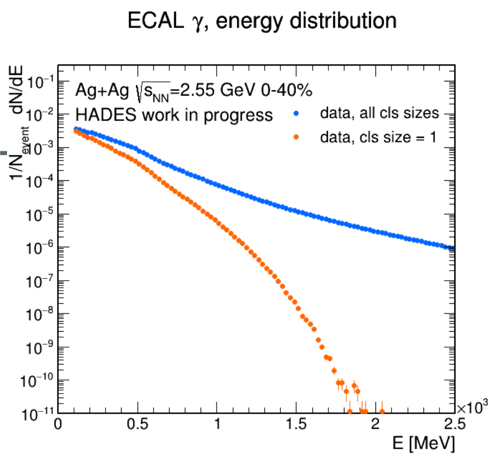
$$CF(Q_{inv}) = 1 + \lambda e^{\left(-Q_{INV}{}^2 \cdot R_{inv}{}^2\right)} + \frac{a_0}{1+(a_1 \cdot Q_{INV})^{a_2}}$$

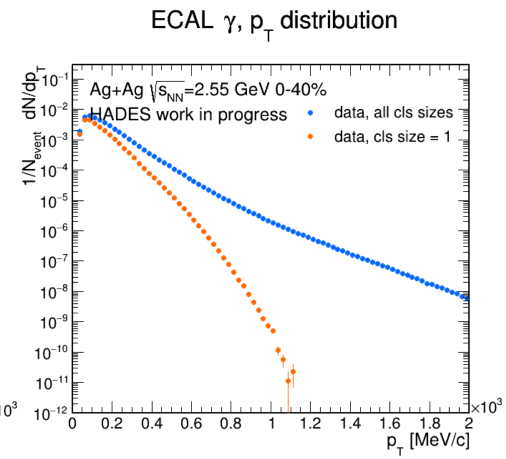
Very similar predictions for both options

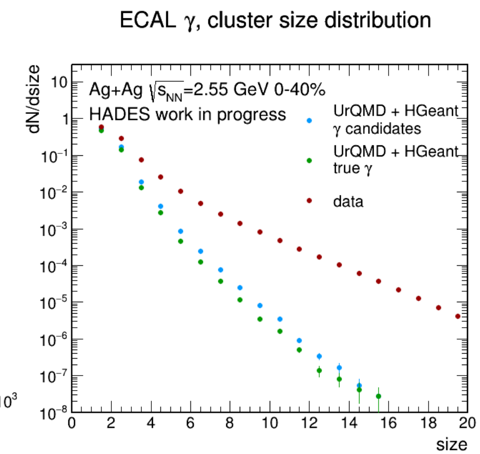


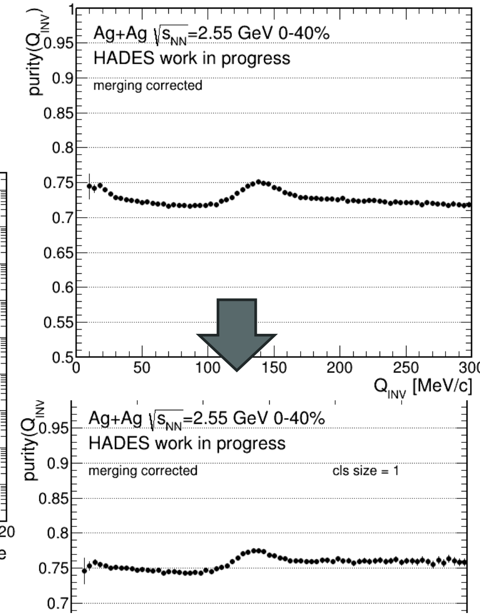


Backup – ECAL – size 1 clusters vs all size clusters



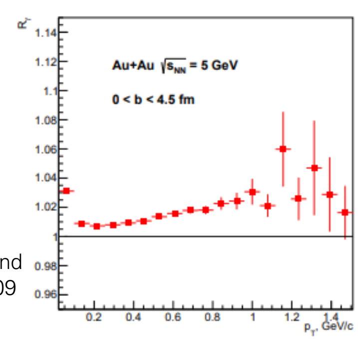


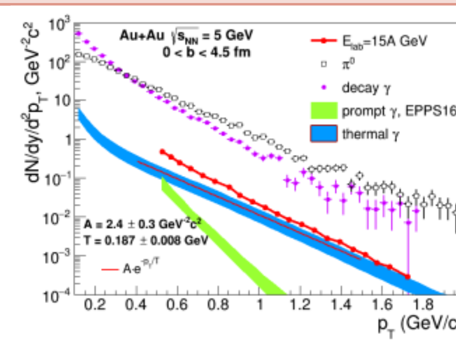




- Size 1 clusters have better energy resolution (higher energy threshold and better reconstruction overall) → higher quality of photon sample
- Only 1 module triggered → less impact of „hardware threshold” (dependent on size)

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

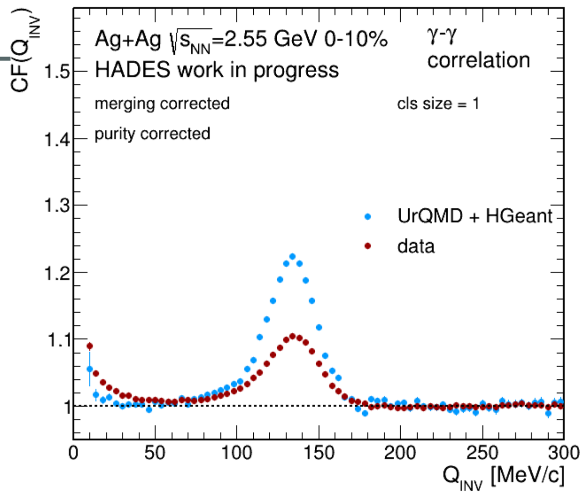


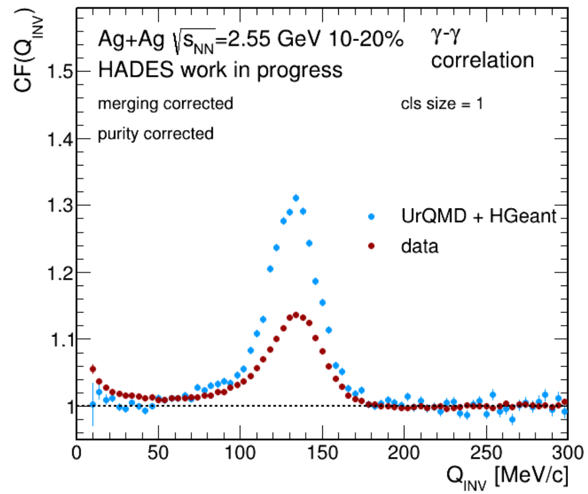


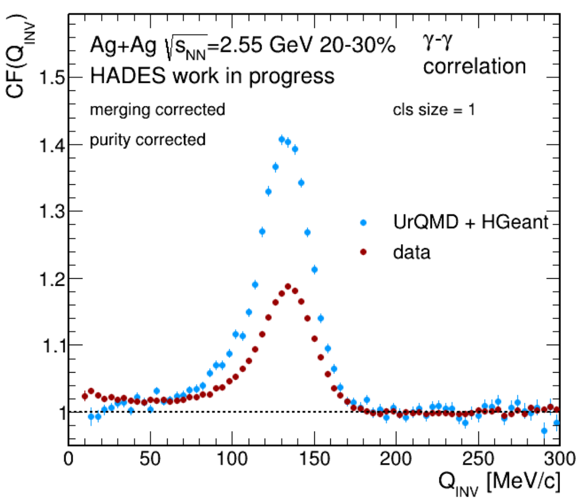
Direct Photon Production in Heavy-Ion Collisions: Theory and Experiment Dmitry Blau and Dmitri Peresunko, . Particles 2023, 6, 173–187. https://doi.org/10.3390/ particles6010009

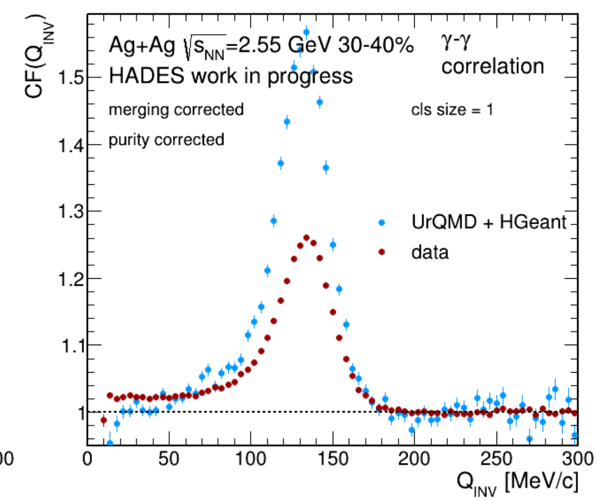
Backup – ECAL – size 1 clusters vs all size clusters

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

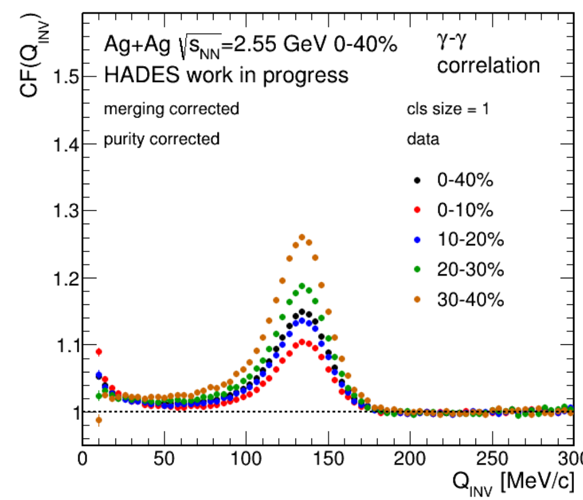








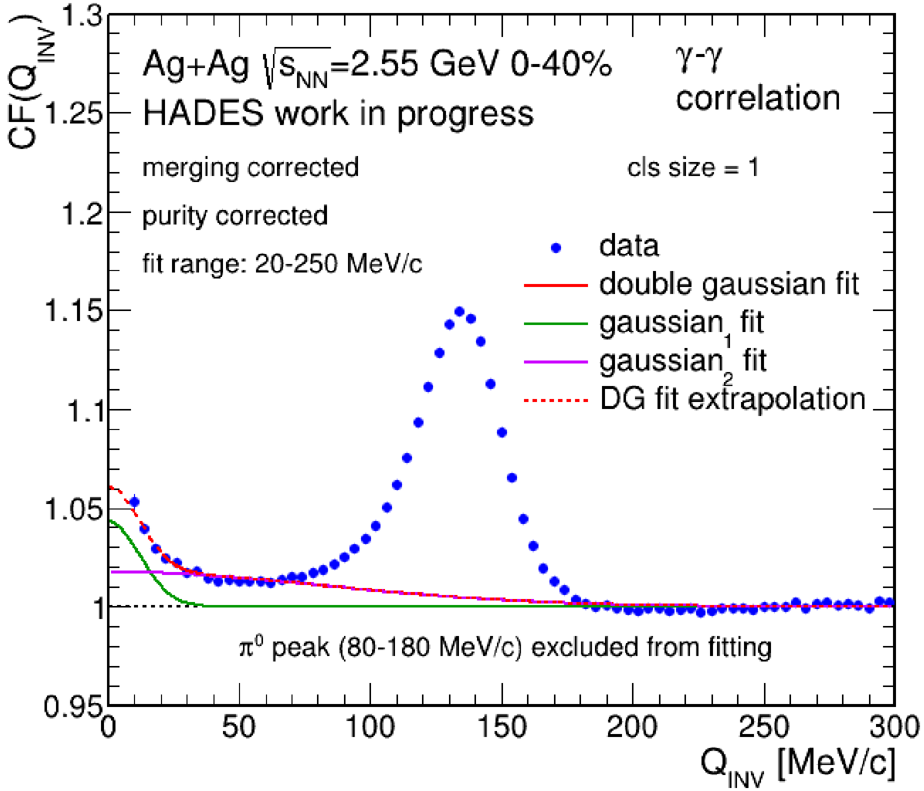
"Background" contribution still increasing with more peripheral events, however only for Q_{INV} < 80 MeV.

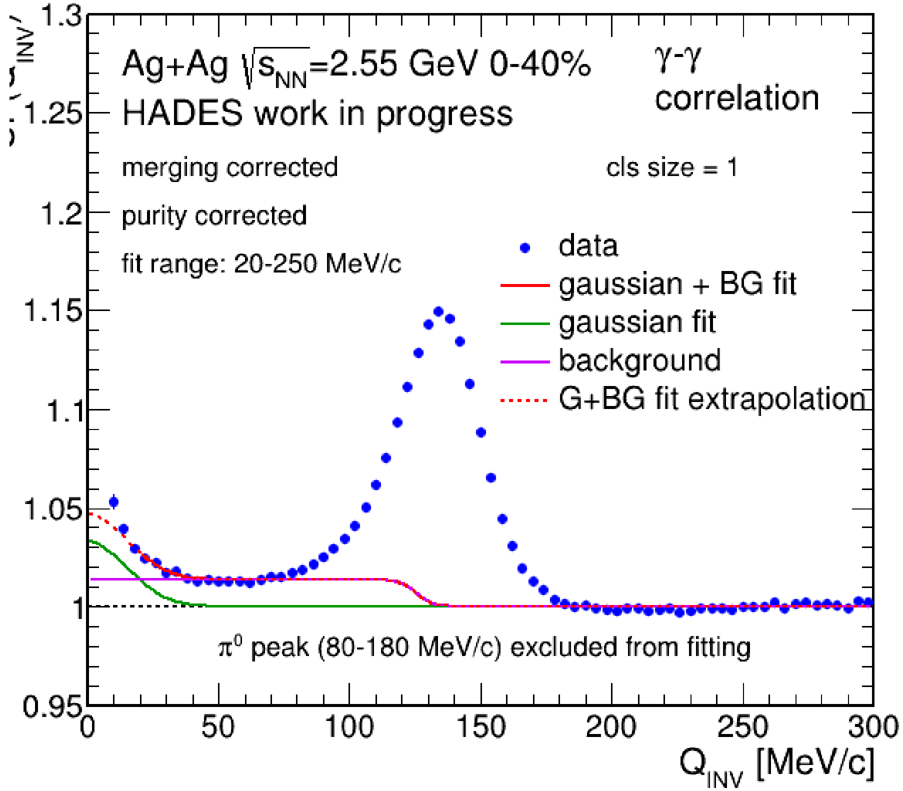


Backup – ECAL – size 1 – alternative fits

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

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

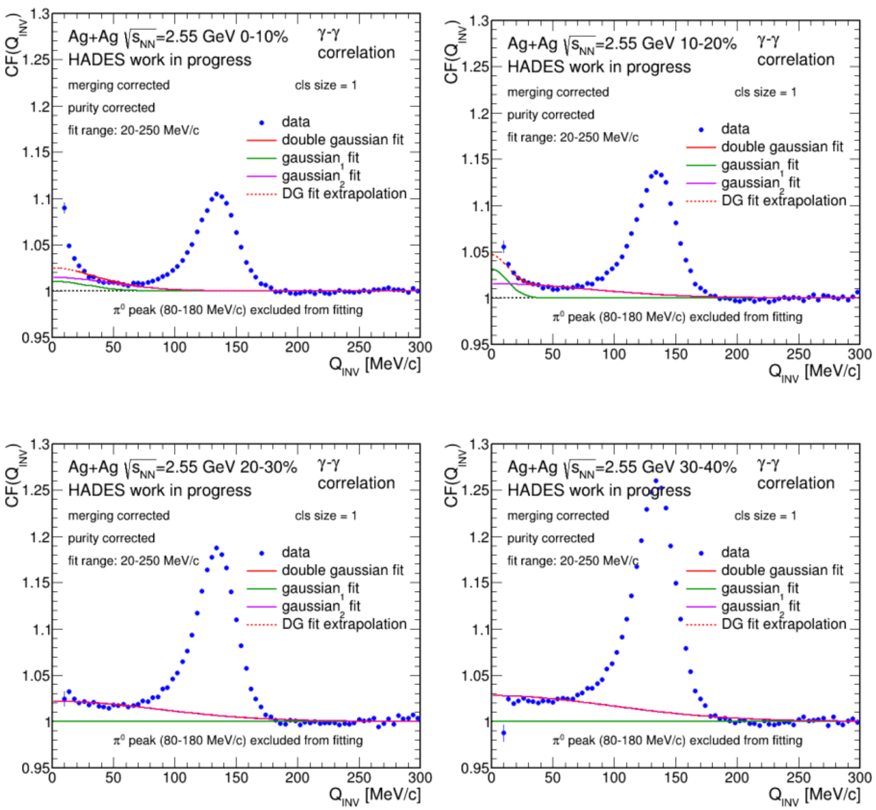


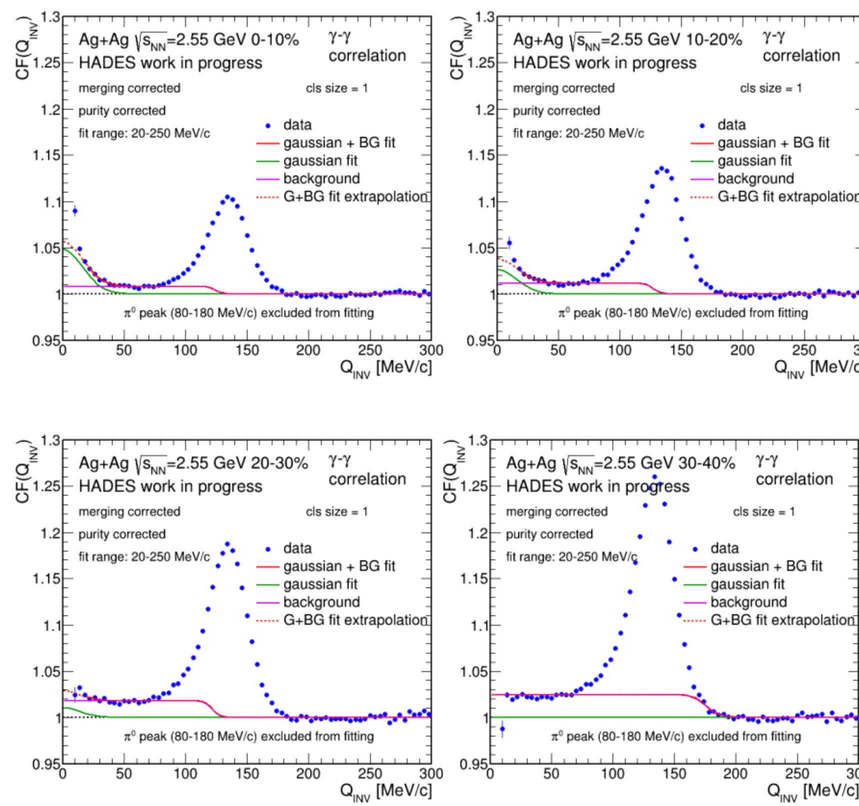


Backup – ECAL – size 1 alternative fits & centrality

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

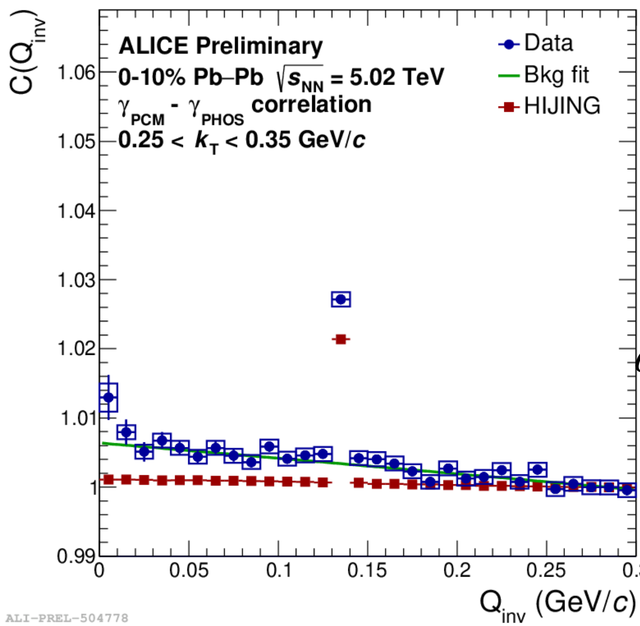
$$CF(Q_{inv}) = 1 + \lambda e^{(-Q_{INV}{}^2 \cdot R_{inv}{}^2)} + \frac{a_0}{1+(a_1 \cdot Q_{INV})^{a_2}}$$



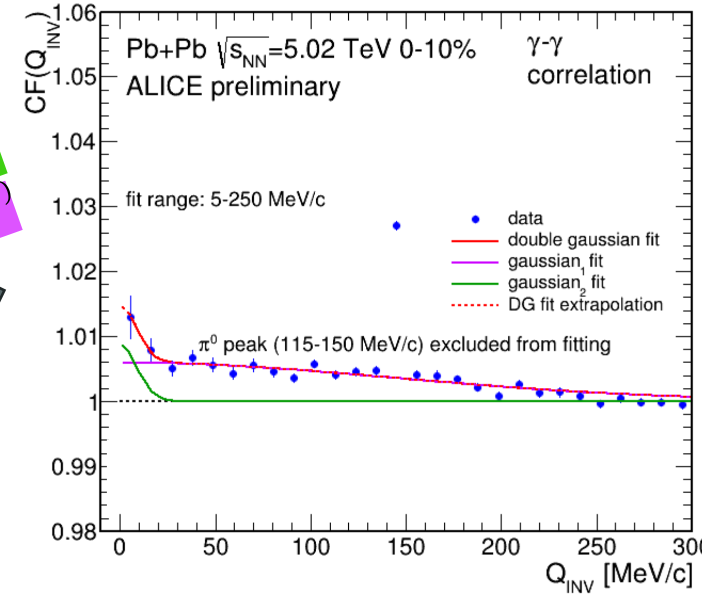


Lack of low Q_{INV} peak for most central events → some correlation is vanishing?

Backup – fits to ALICE data



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



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