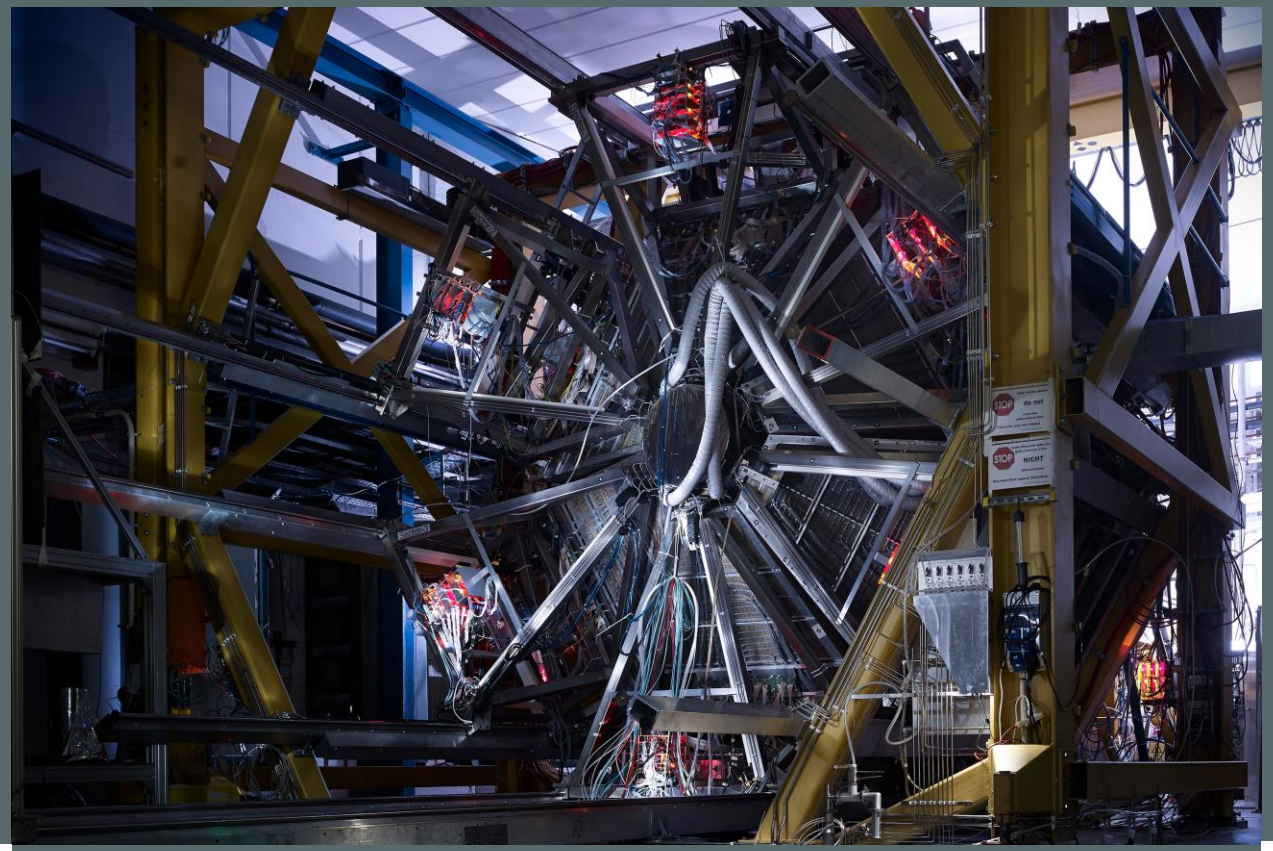
Two-particle femtoscopy at the HADES experiment



Mateusz Grunwald
for the HADES collaboration

2023

HADES

GSI

Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Warsaw University of Technology

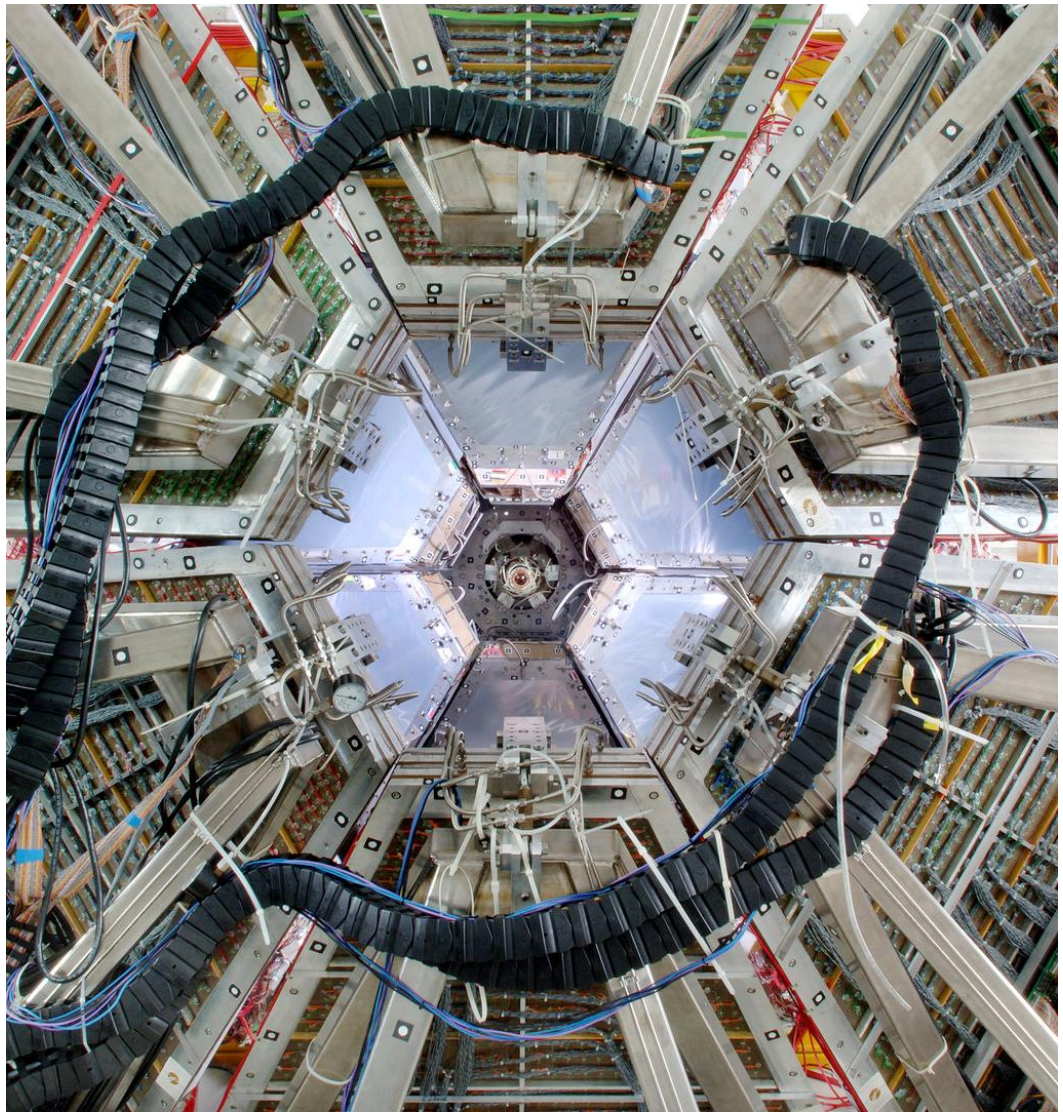
RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE

FAIR
Phase-0
Research Program

NATIONAL SCIENCE CENTRE
POLAND

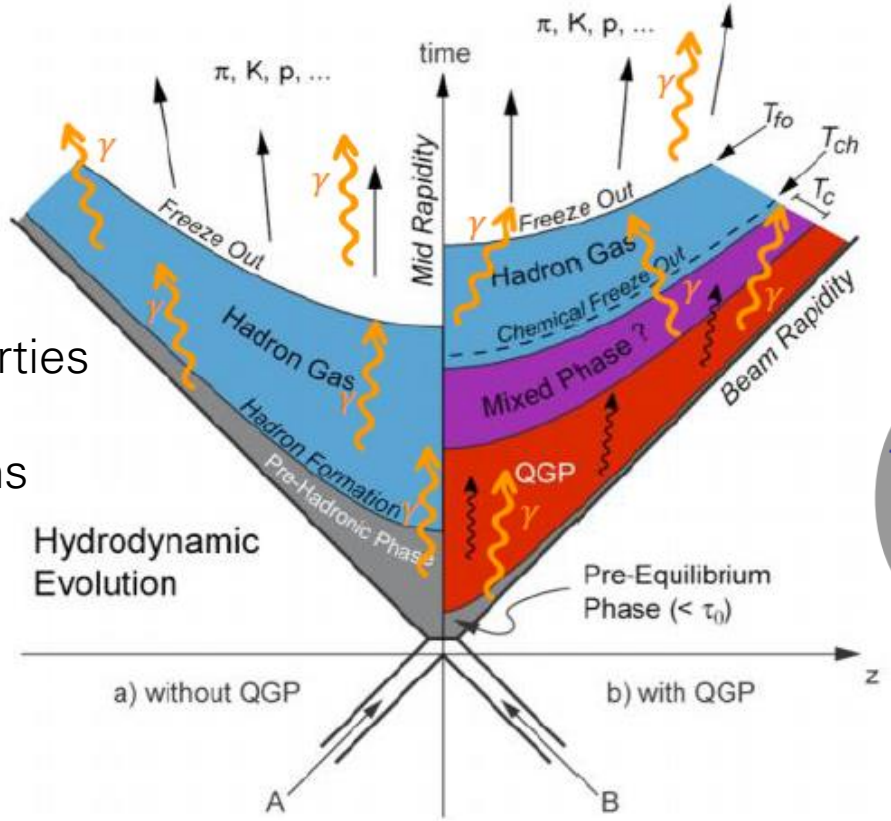
Outline

1) Motivation
   - Early stage measurements
   - Hyperon puzzle
   - Multi-nucleon system
2) Femtoscopy technique
3) HADES experiment
4) Results:
   - Photon – photon
   - Proton – lambda
   - Proton – cluster
5) Summary

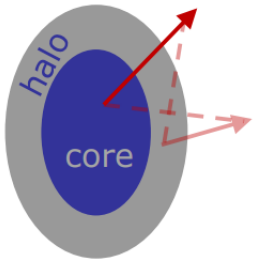


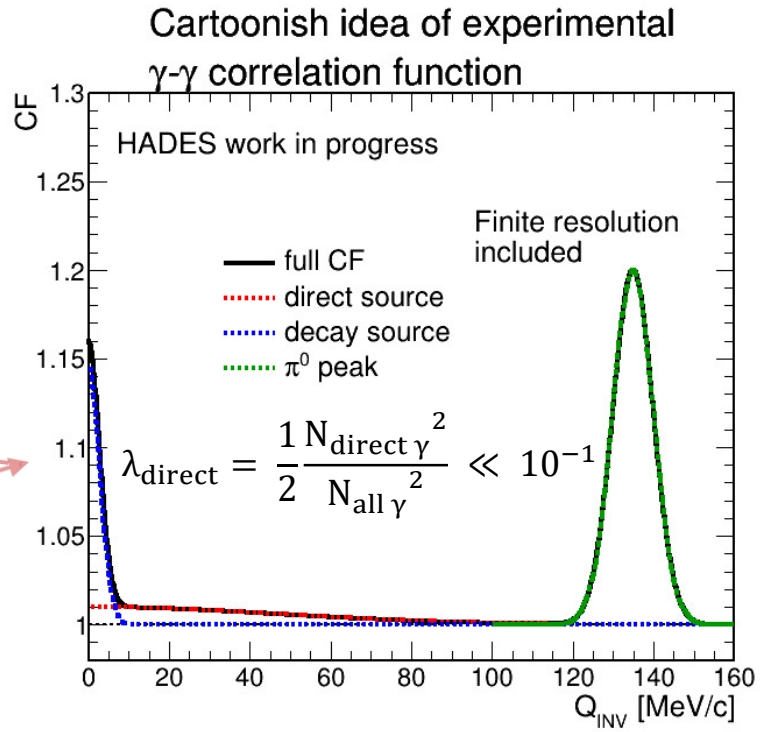
Motivation – EM probes

- Photon – photon:
  - Measure source properties **at early stages** -> inaccessible for hadrons
  - Estimate direct photon yield via femtoscopy

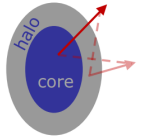


J. Stachel. K. Reygers, QGP physics SS2015 6., „Space-time evolution of the QGP"





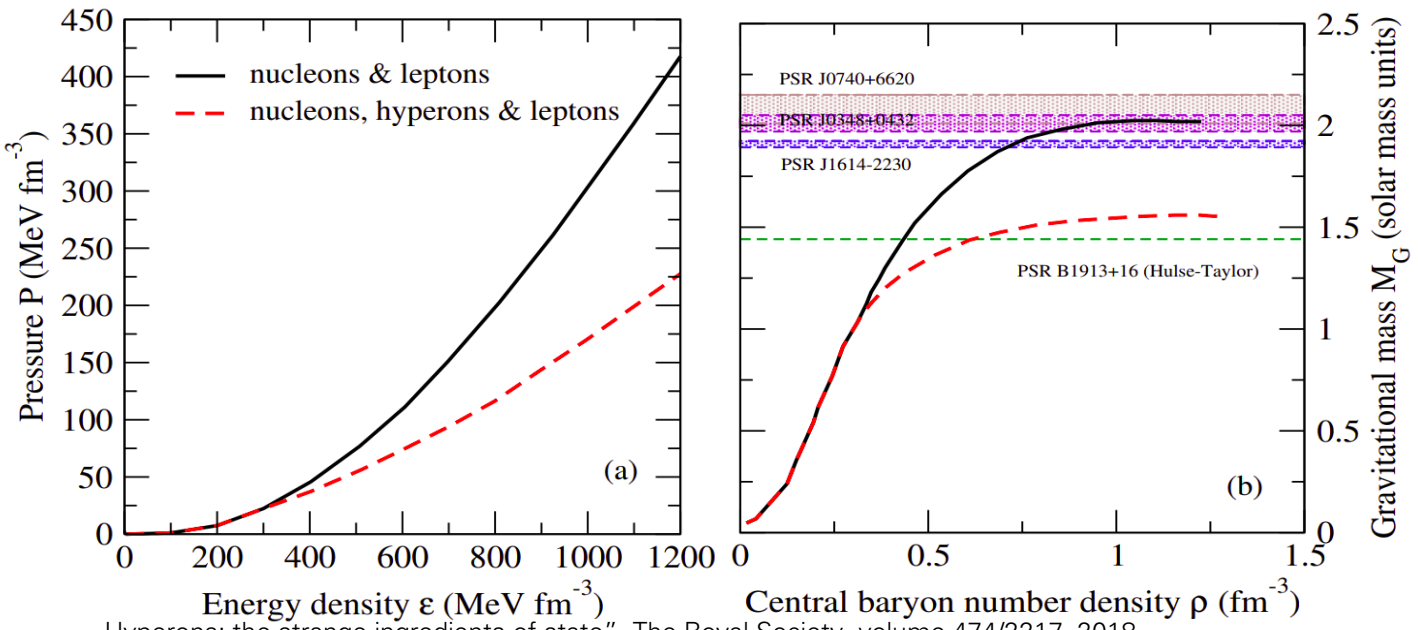
$$\lambda_{direct} = \frac{1}{2}\frac{N_{direct\,\gamma}{}^2}{N_{all\,\gamma}{}^2} \ll 10^{-1}$$



Máté Csanád „Quantumstatistical correlations and femtoscopy in high energy physics", Eötvös University, March 2021

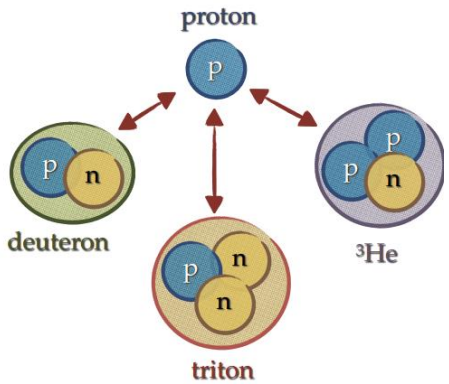
Motivation – hadron probes

- Proton– lambda:
  - Investigate Y-N interaction -> Relevant for EoS of neutron star matter
  - Existence of hyperons softens EoS --> towards solving **hyperon puzzle**

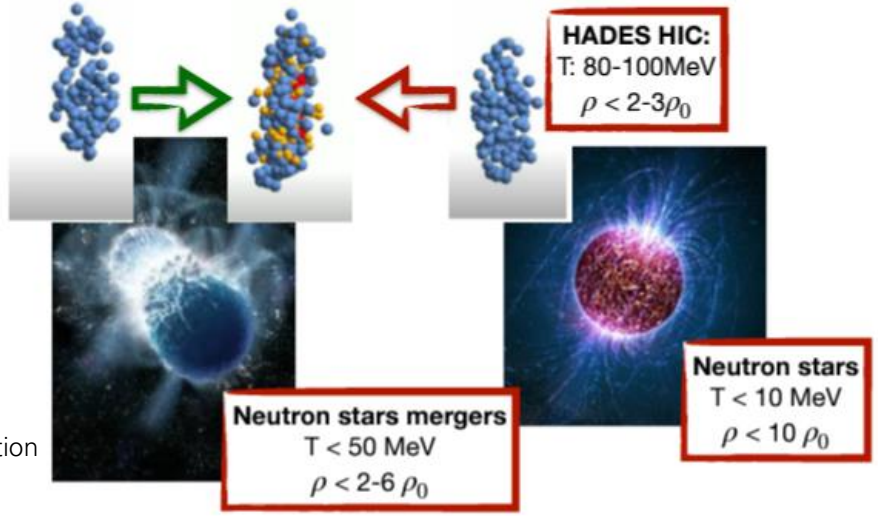


„Hyperons: the strange ingredients of state", The Royal Society, volume 474/2217, 2018

- Proton– cluster:
  - Studies of excited/bound states
  - From **2 nucleons to many nucleons** system, relevant reference for neutron star studies

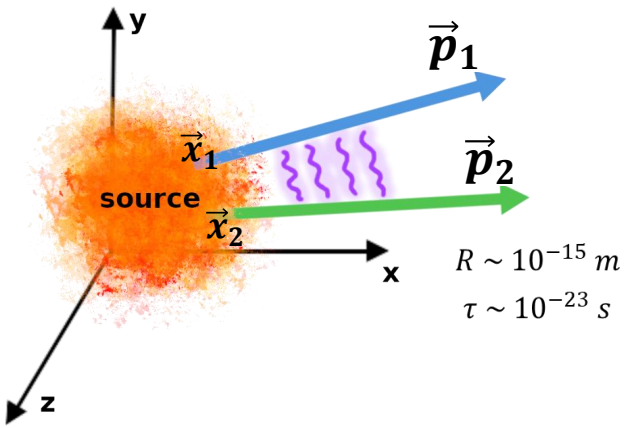


Maria Stefaniak, private communication



Femtoscopy

Goal - measure source's space-time characteristics and 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:

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

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

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

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

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

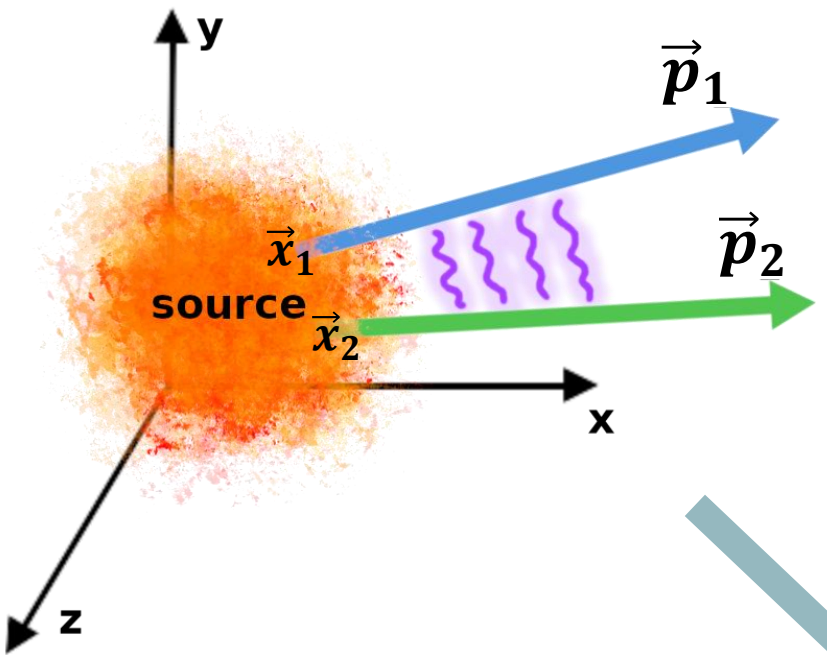
$N_{mixed}(q)$: mixed event distribution

Experiment

Correlation function:

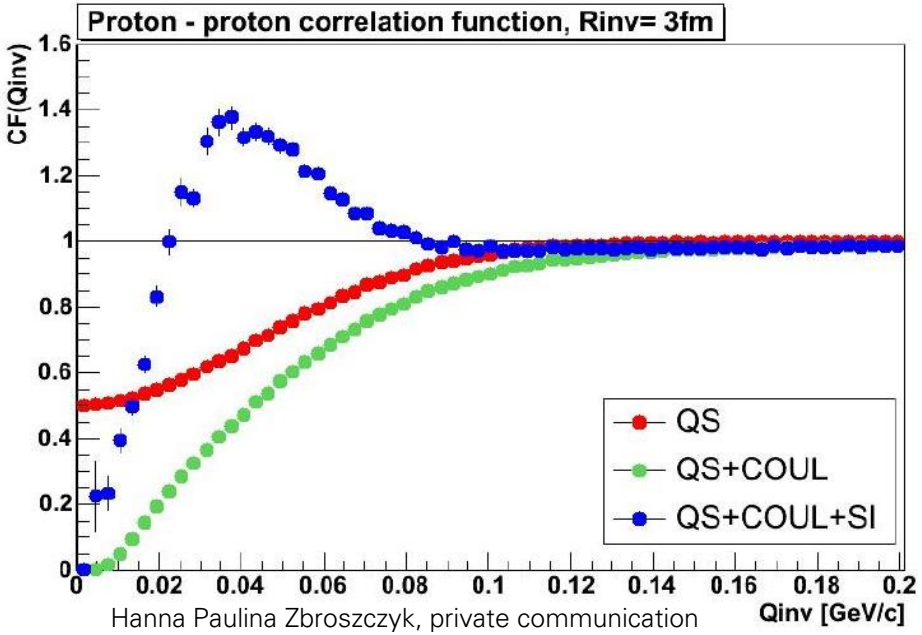
$$CF(q) = \frac{N_{same}(q)}{N_{mixed}(q)}$$

Femtoscopy



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

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



Hanna Paulina Zbroszczyk, private communication

Effects and interactions:

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

$CF < 1$: repulsion

$CF = 1$: no correlation

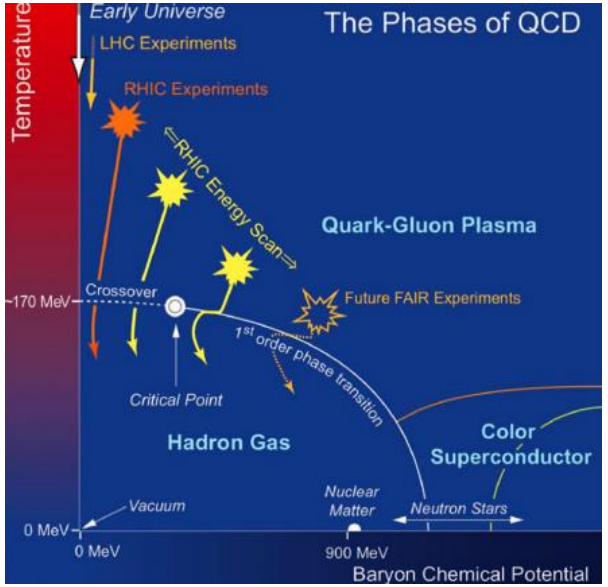
$CF > 1$: attraction

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

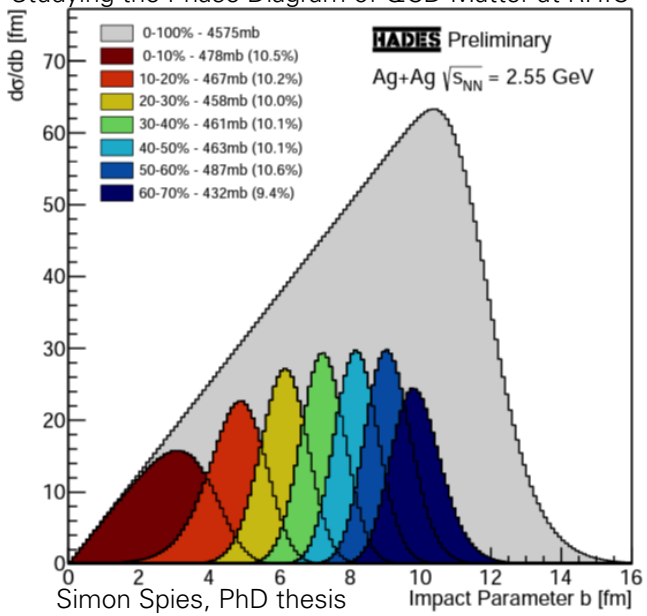
Determine the geometry and dynamic properties (traditional femtoscopy)

Determine the interactions (non-traditional femtoscopy)

HADES experiment

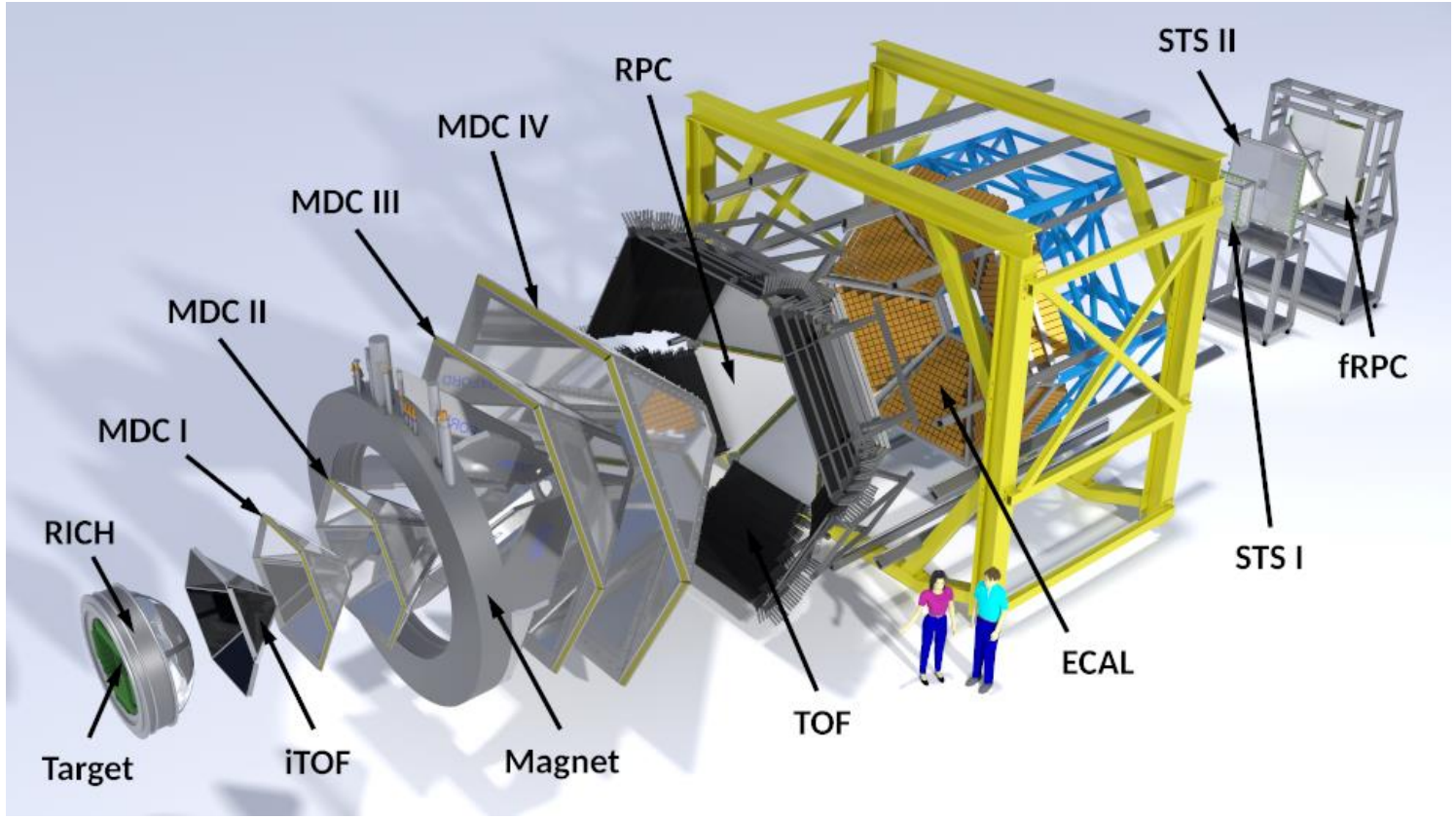


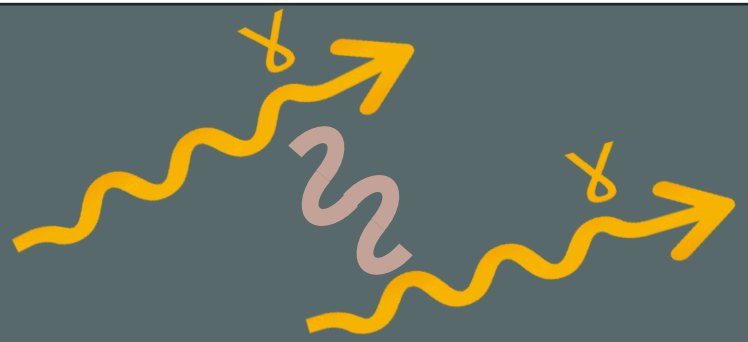
Studying the Phase Diagram of QCD Matter at RHIC



Simon Spies, PhD thesis

- 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)

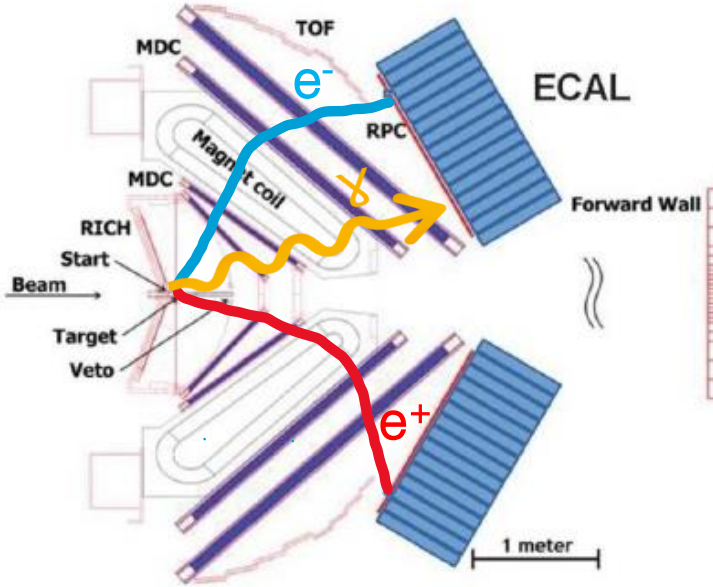


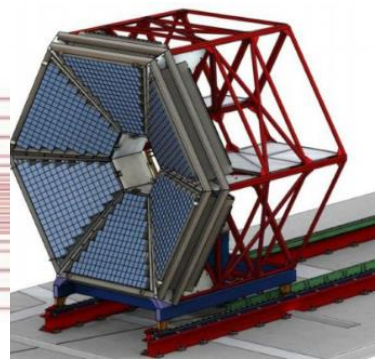


Photon-photon correlations

Photons at HADES

Electromagnetic calorimeters (ECAL)



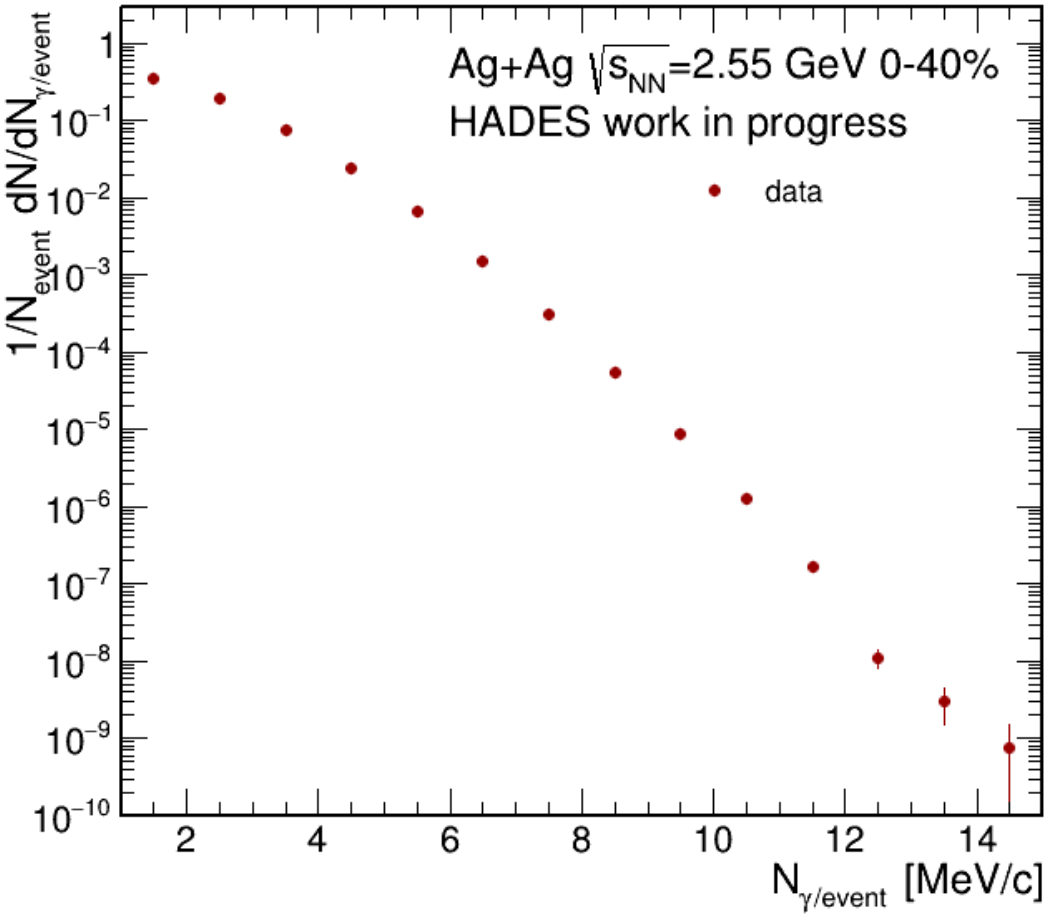


Resolution
(Energy, time, angular):

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

$$\sigma_t < 300\ ps$$

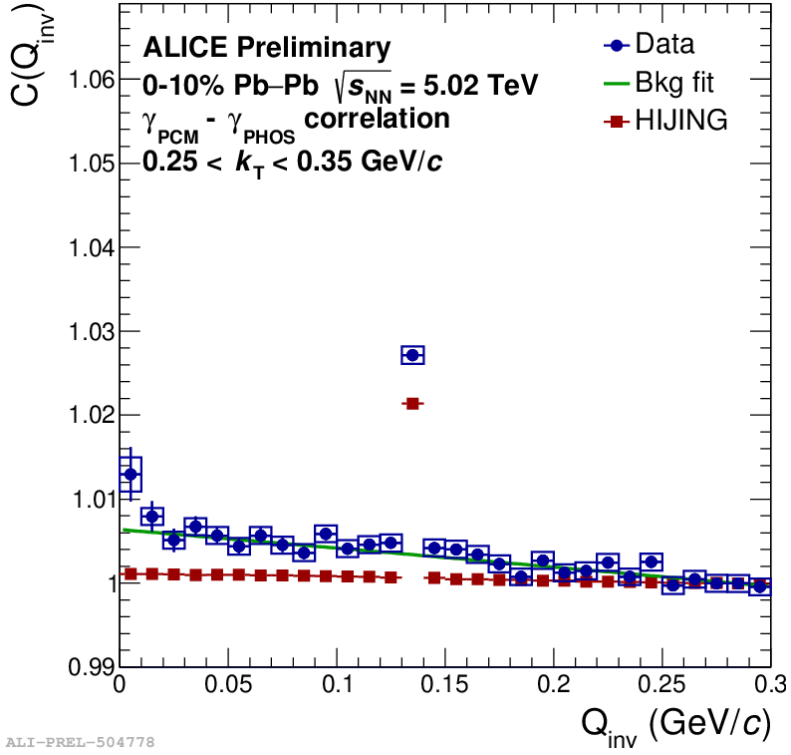
$$\sigma_{\theta,\phi} = 2°$$

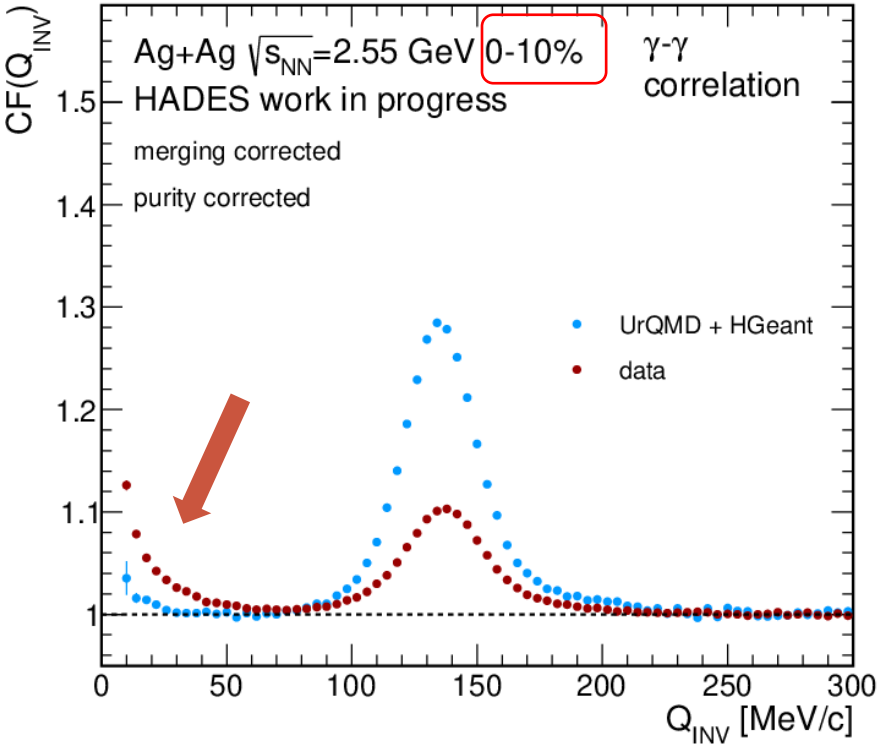


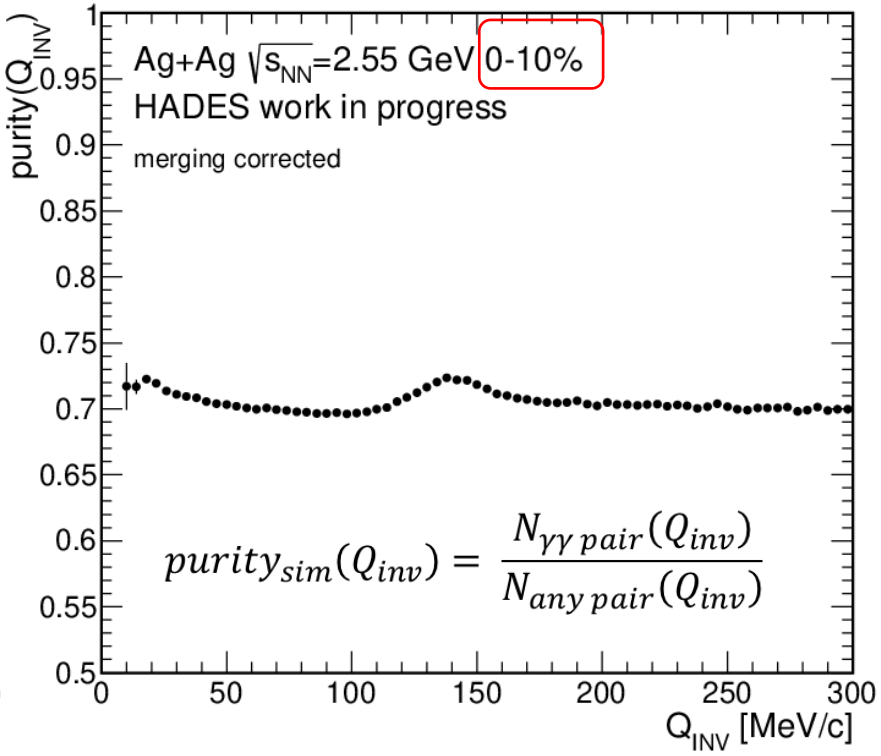
- Photon definition:
  - No matching with charged tracks or hits in ToF detectors
  - Energy > 100 MeV
  - β within 2σ from expected photon peak (β=1), adjusted for each module (and time of beamtime)

statistical uncertainties only

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







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

Mike Sas for the ALICE Collaboration, Quark Matter 2022

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

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

statistical uncertainties only

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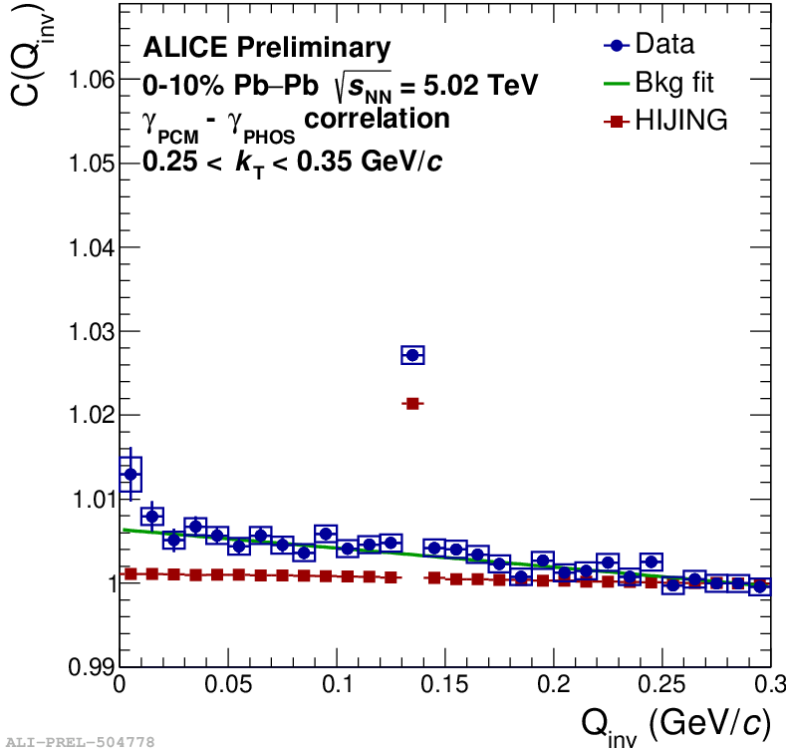

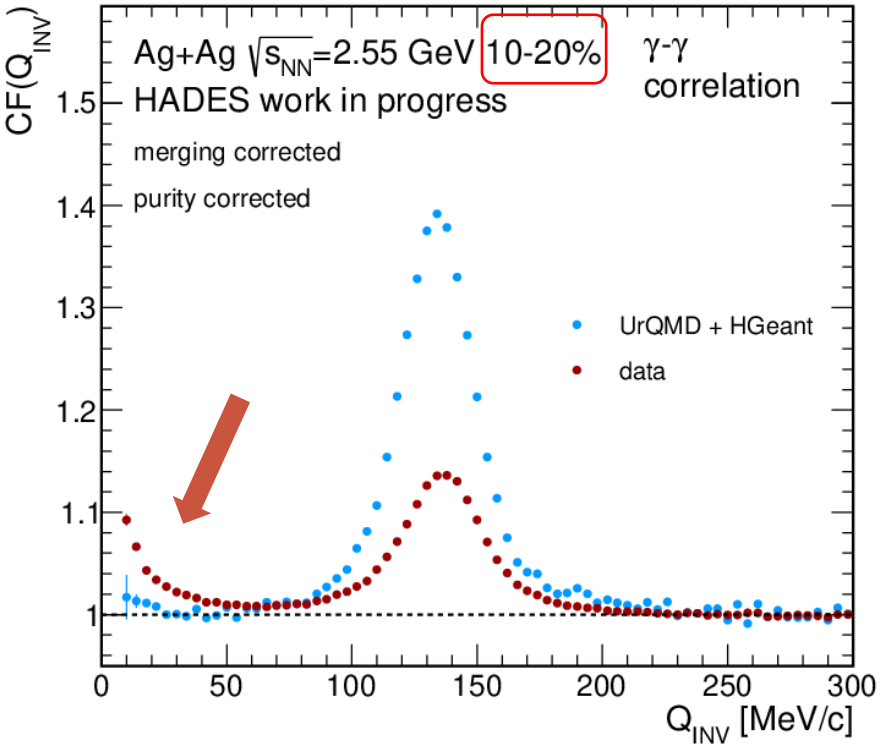

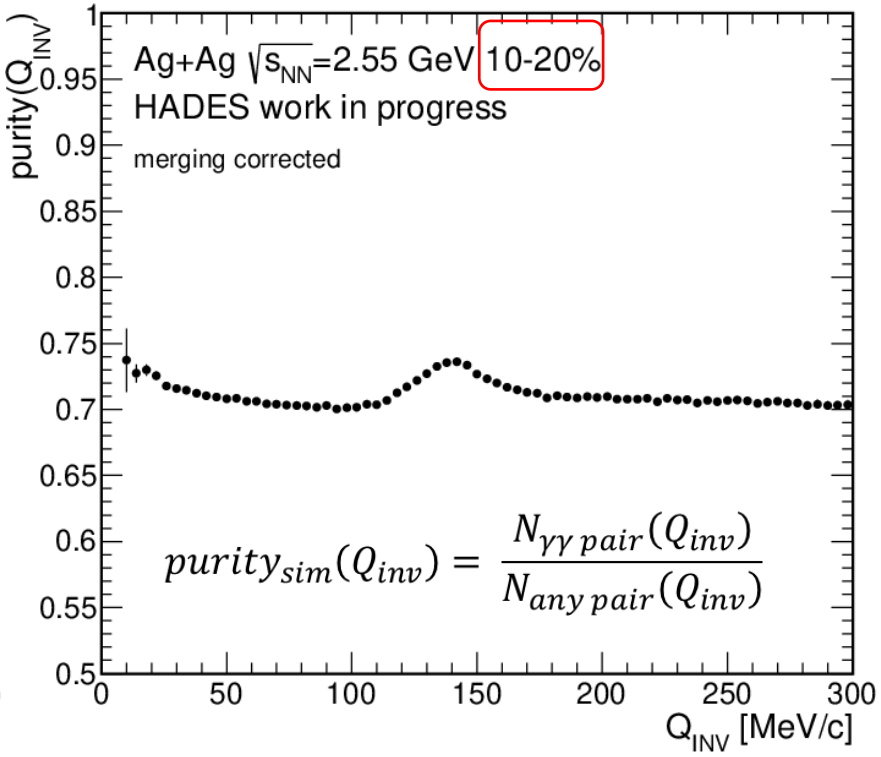

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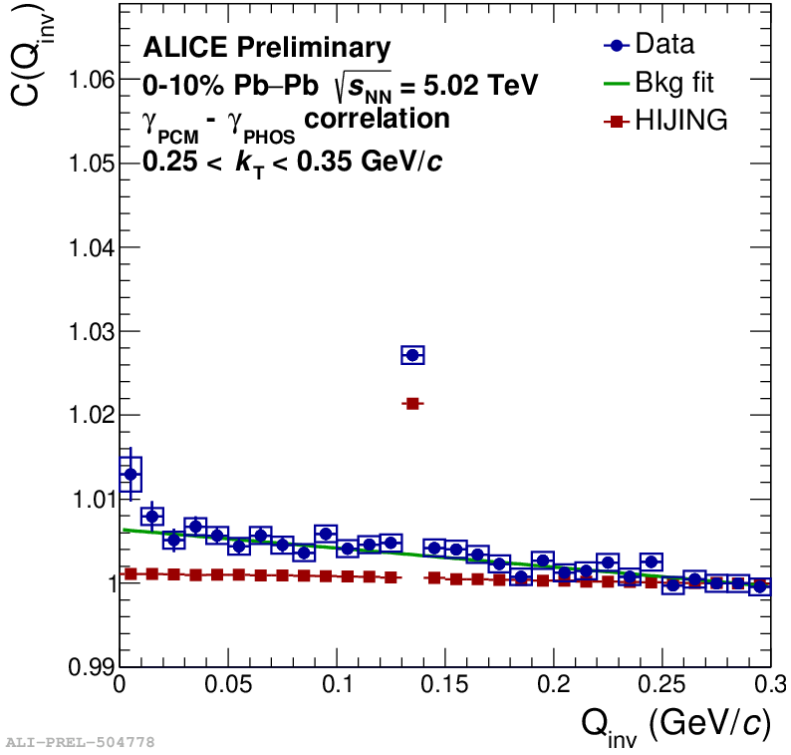

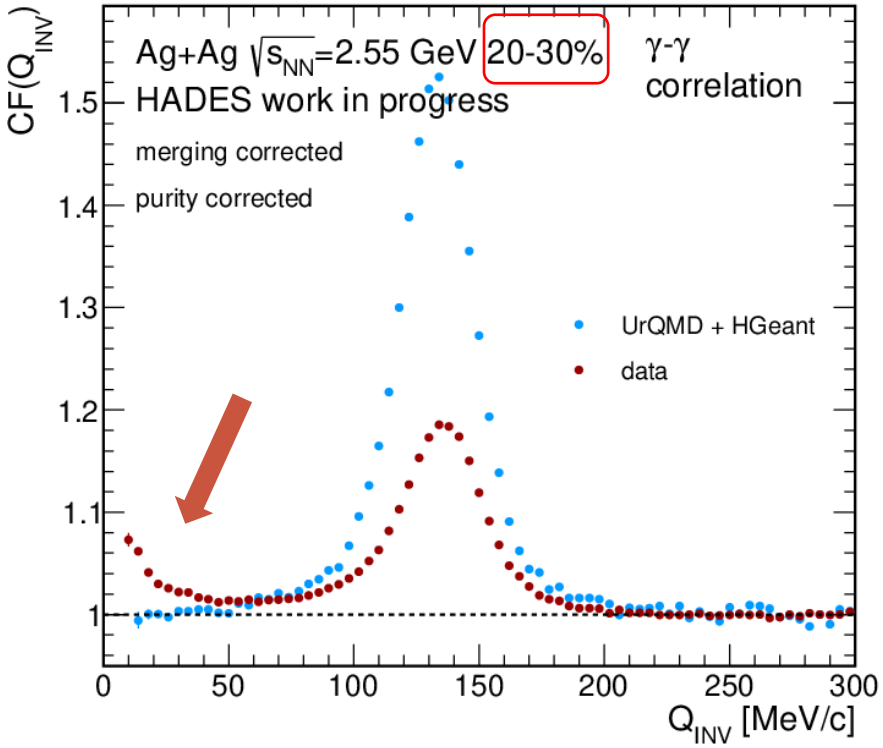

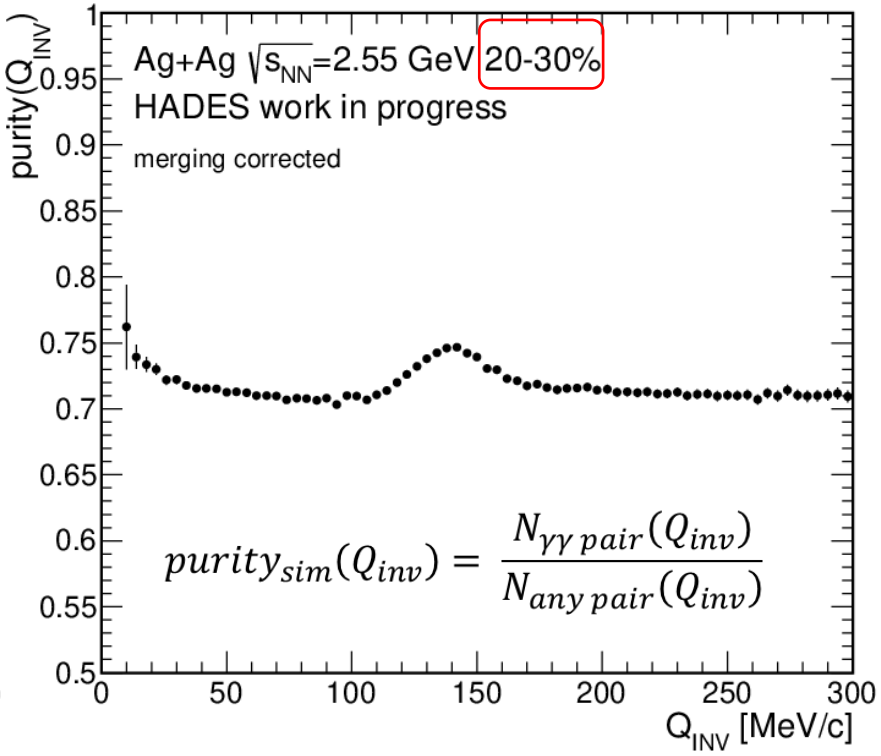

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statistical uncertainties only

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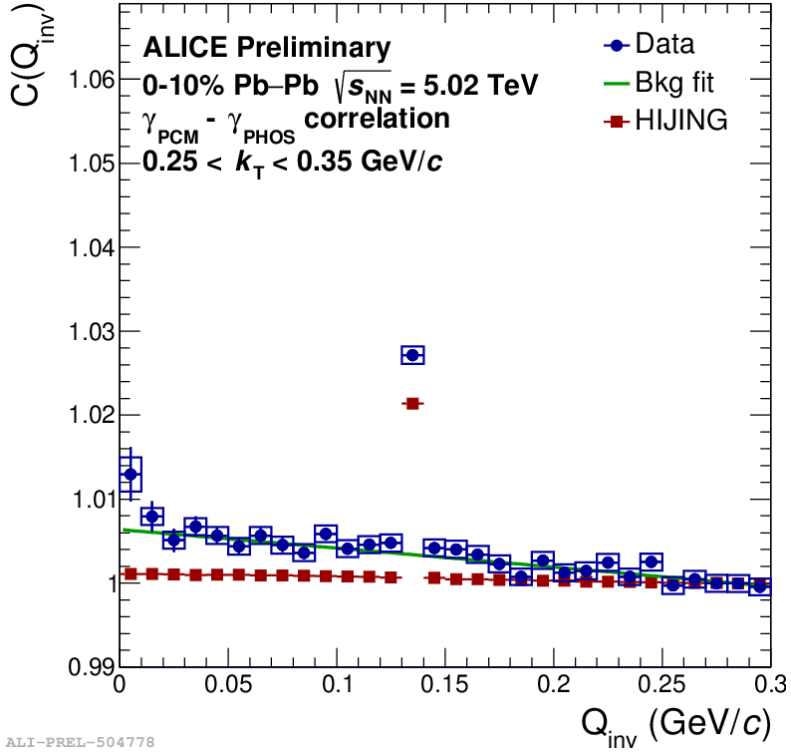
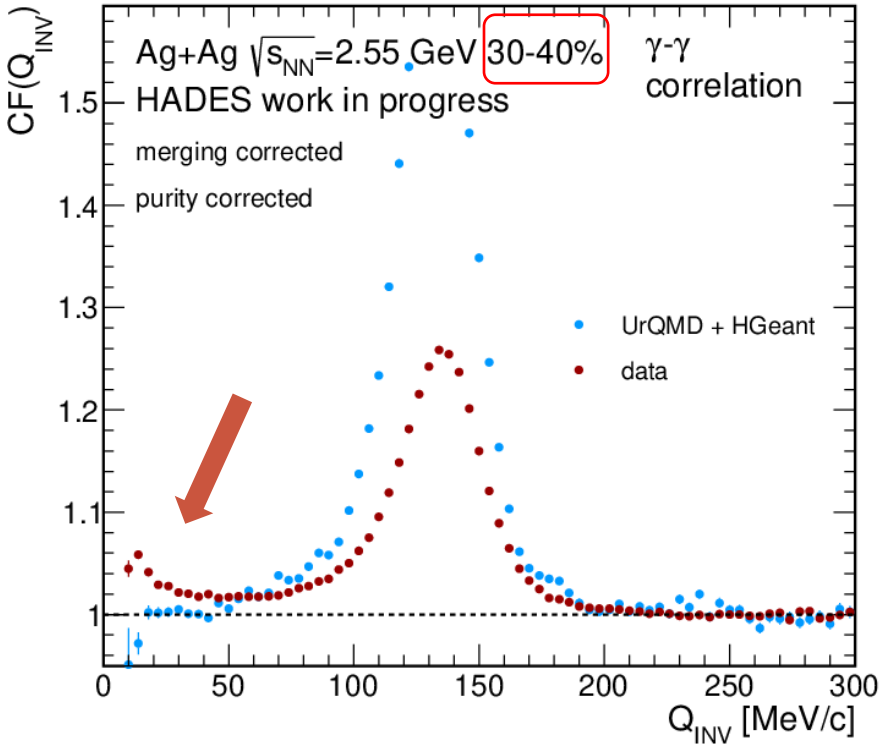
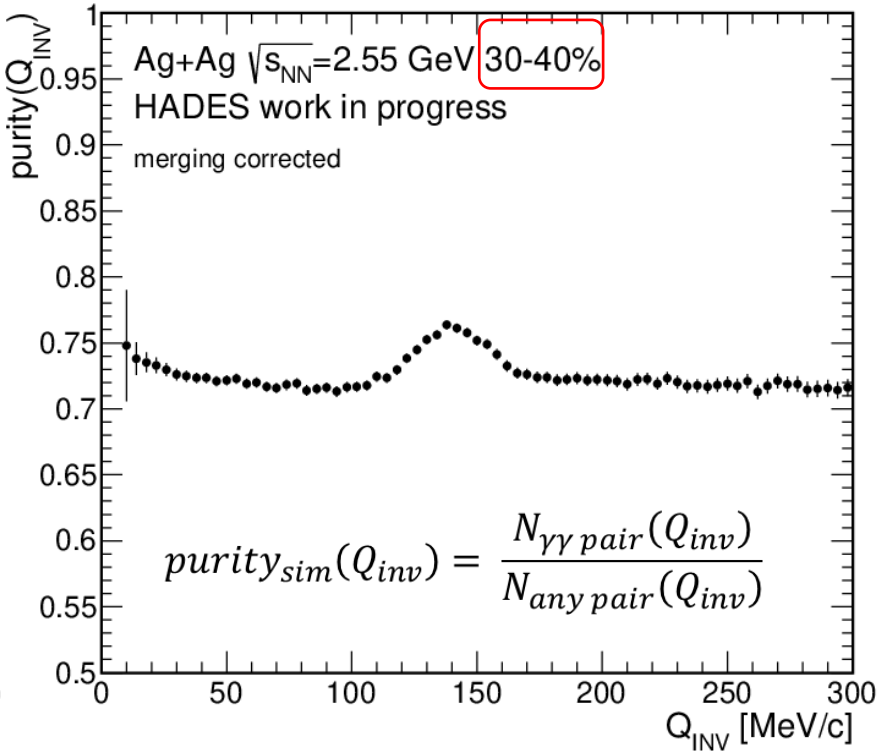


Mike Sas for the ALICE Collaboration, Quark Matter 2022





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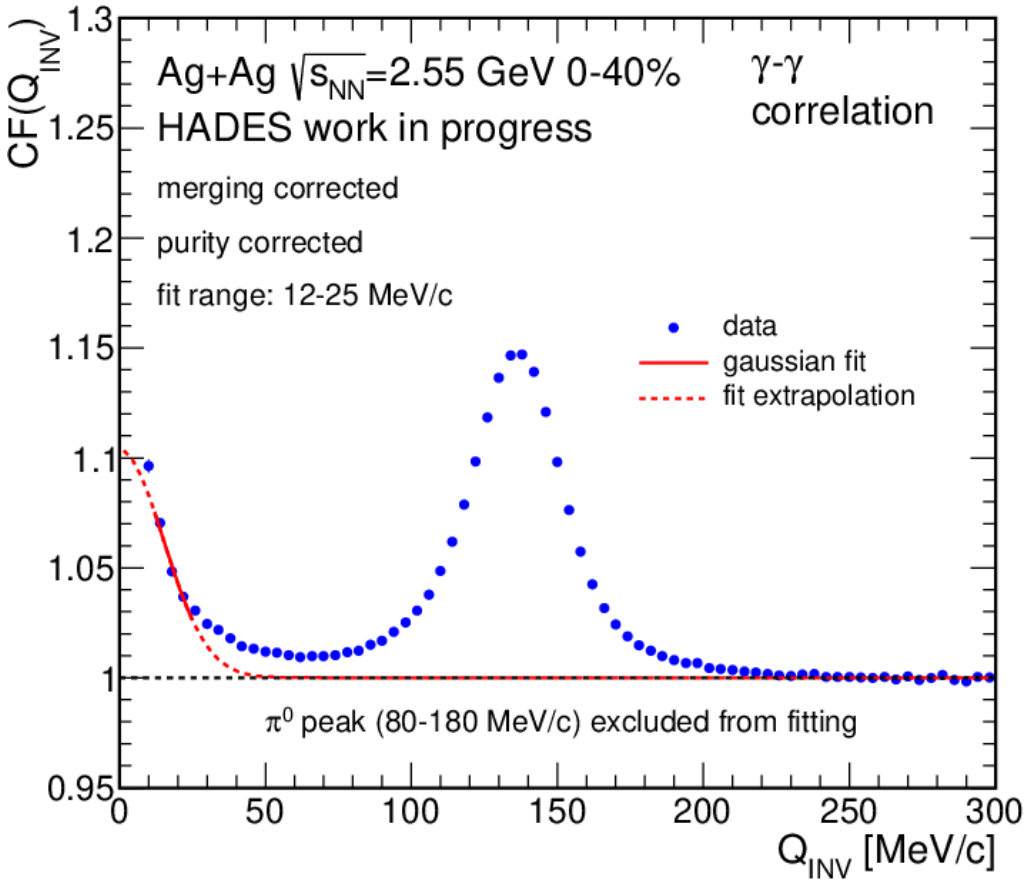
$$Q_{inv} = \sqrt{(\vec{p}_1 - \vec{p}_2)^2 - (E_1 - E_2)^2}$$

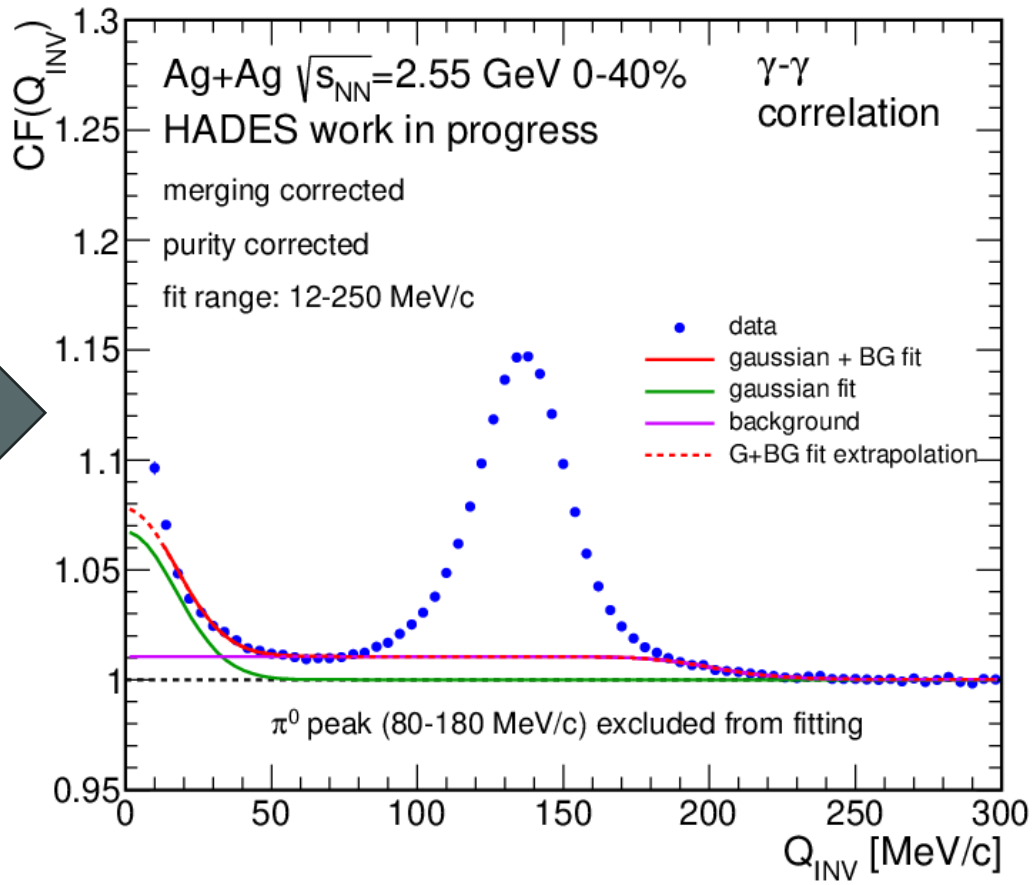
Visible enhancement at low Q_{inv}

statistical uncertainties only

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



Including background

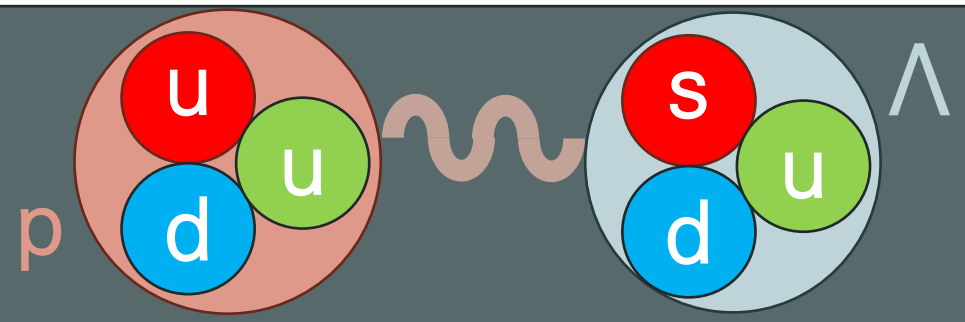


$$CF(Q_{inv}) = 1 + \lambda e^{(-Q_{inv}{}^2 \cdot R_{inv}{}^2)}$$

statistical uncertainties only

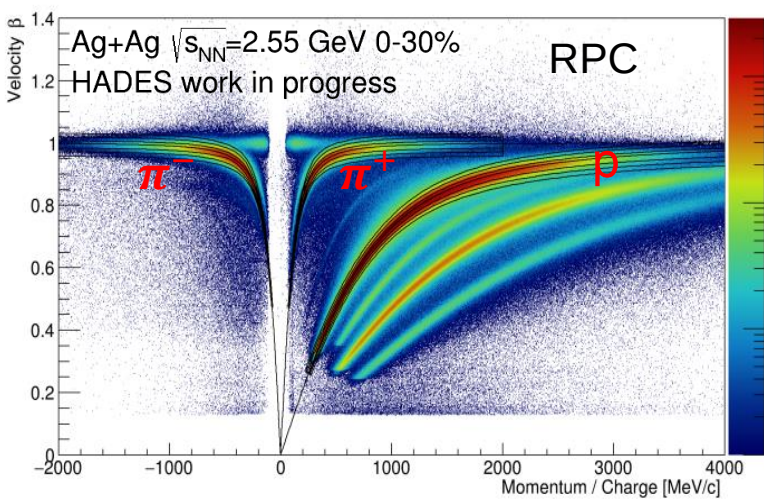
$$CF(Q_{inv}) = 1 + \lambda e^{(-Q_{inv}{}^2 \cdot R_{inv}{}^2)} + \frac{a_0}{1+(a_1 \cdot Q_{inv})^{a_2}}$$

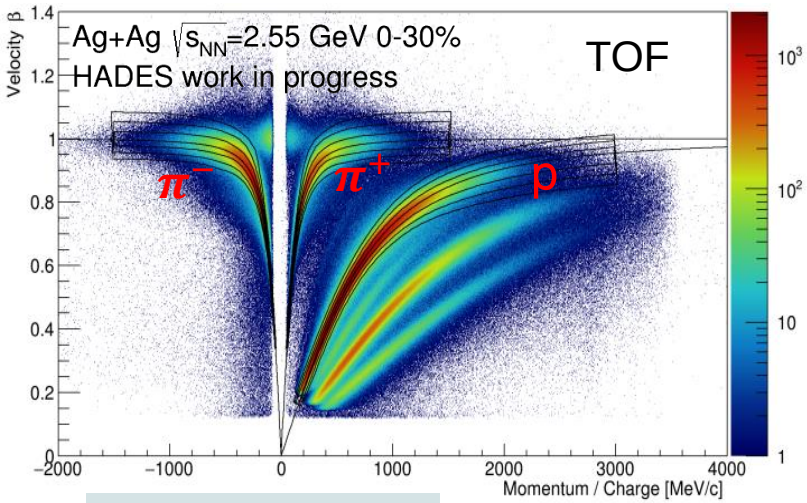
- Good description of background
- Ongoing study of low Q_{inv} peak



Proton-lambda correlations

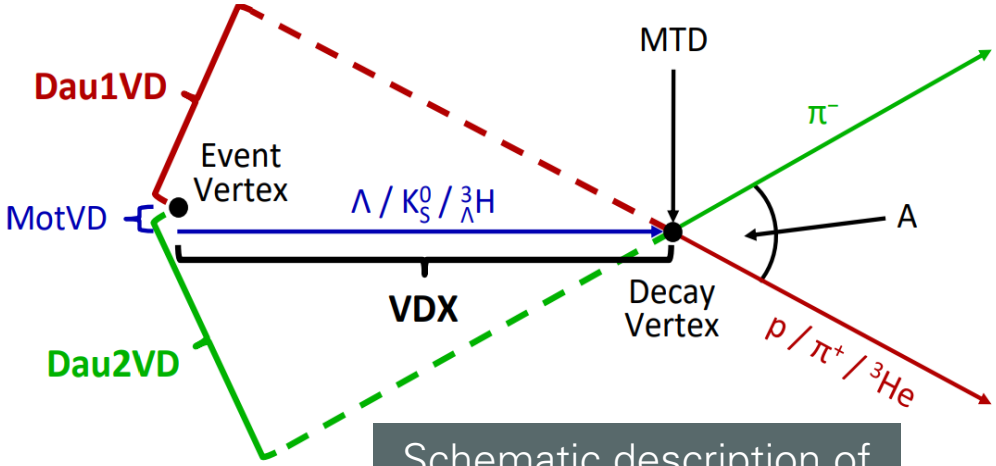
Weak decay reconstruction



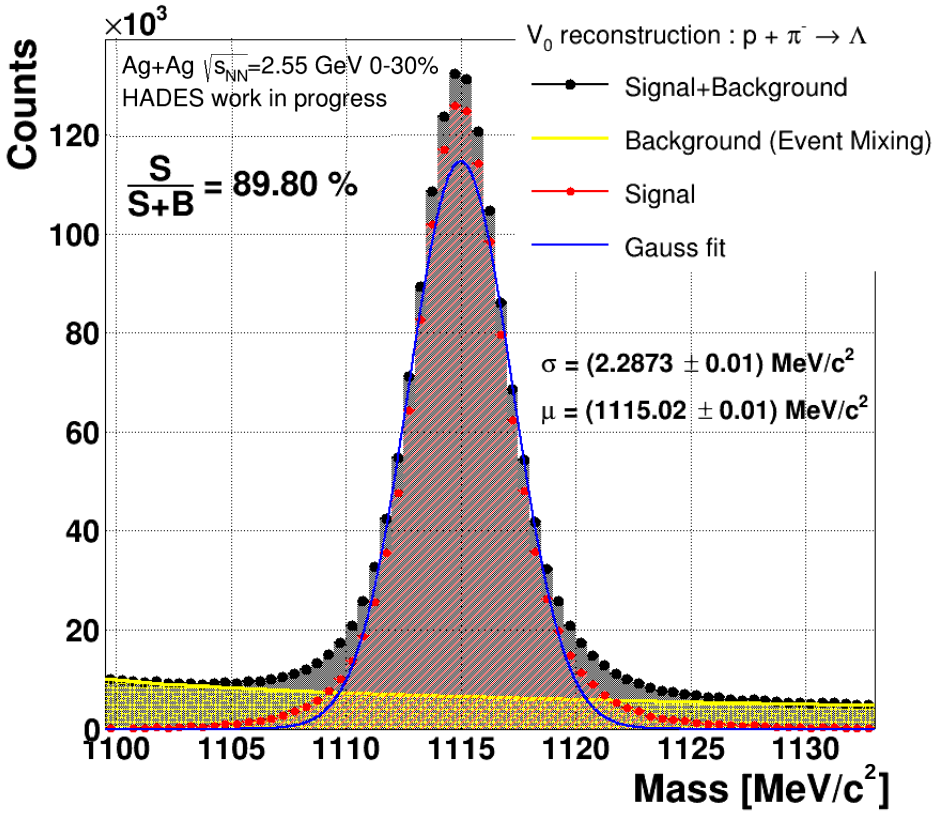


$$\Lambda \rightarrow p + \pi^-$$

DCA parameters	
VDX	>65 mm
Dau1VD	>8 mm
Dau1VD	>24 mm
MotVD	<5 mm
MTD	<6 mm
A	>15°



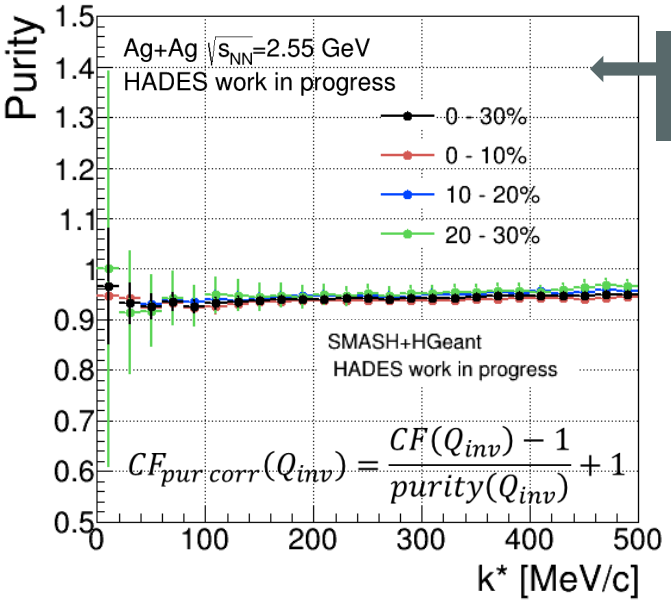
Schematic description of the off-vertex topology



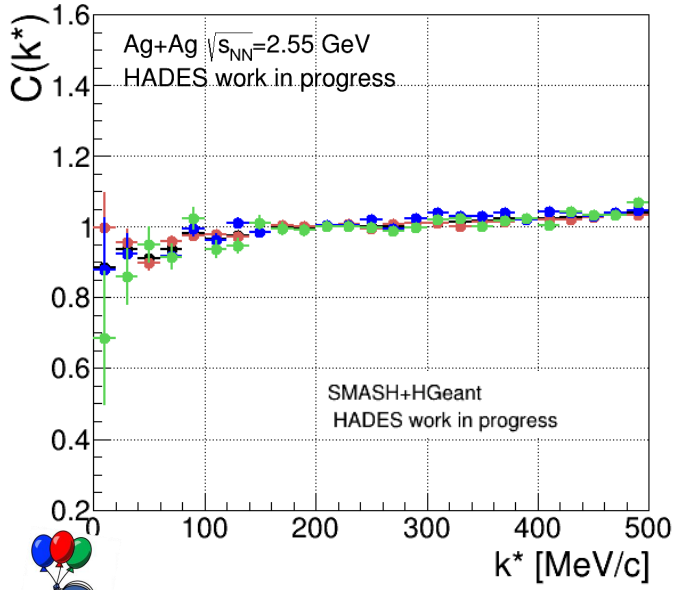
PDG:

$$m = 1115.683 \pm 0.006 \text{ MeV/c}^2$$

Proton-lambda correlation functions, Ag+Ag at 2.55 GeV

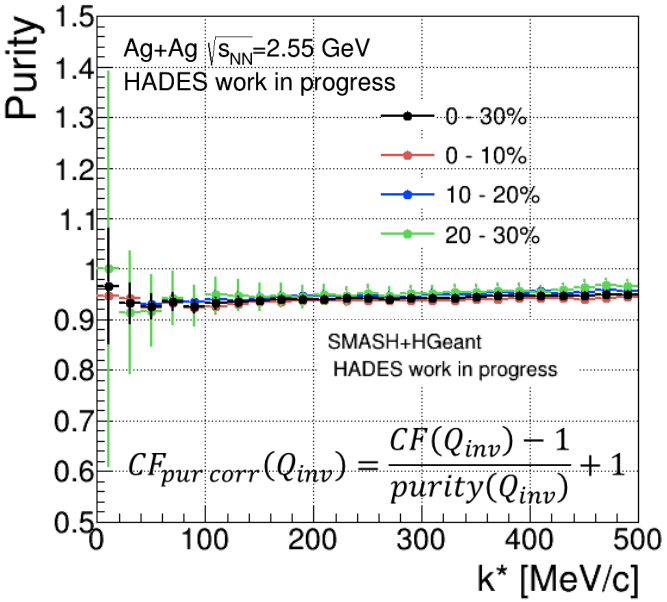


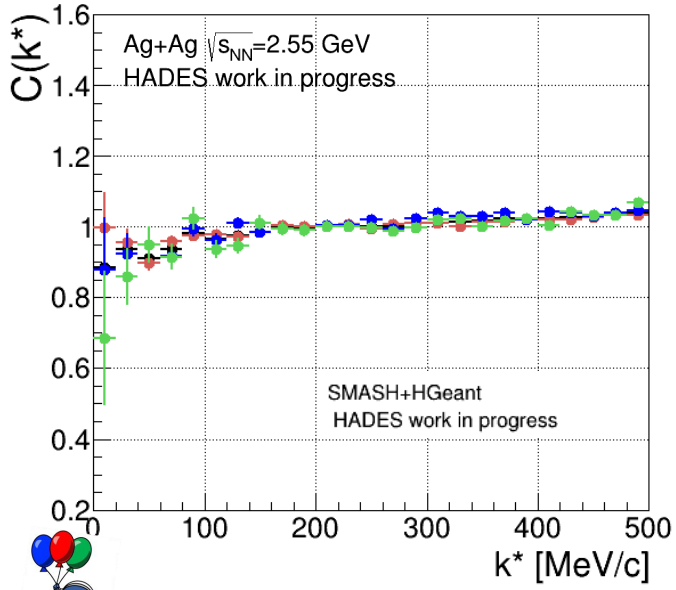
For all centrality classes estimated purity for p-Λ :
90% -92% ± 3% (data) (<400 MeV/c)

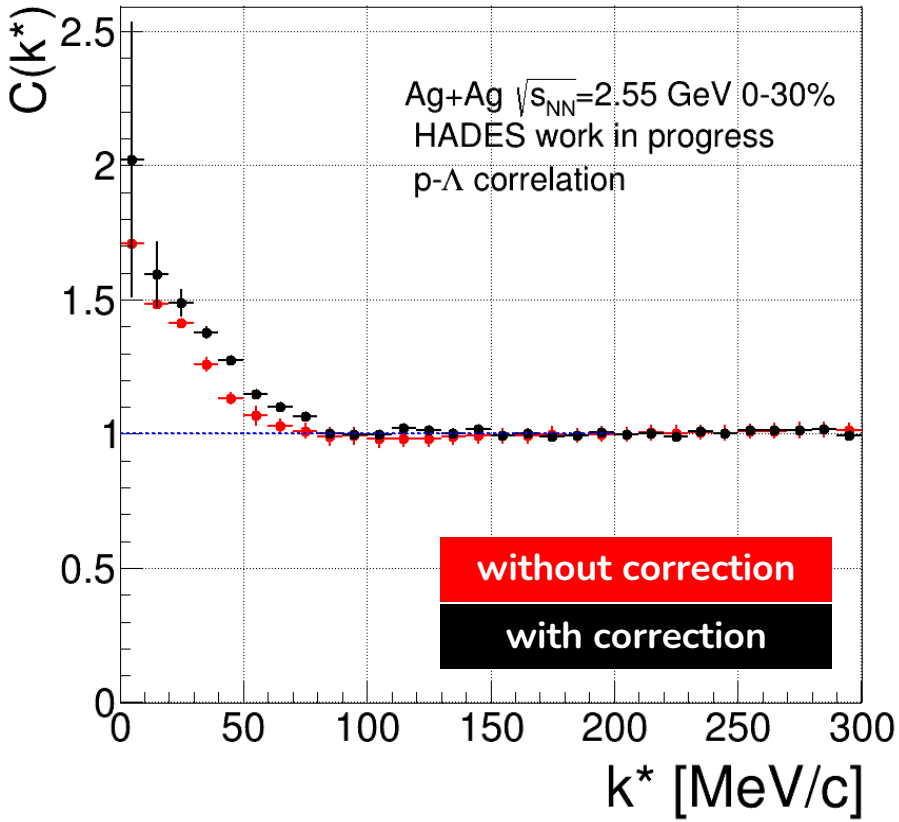


$$k^* = \frac{|\vec{p}_1 - \vec{p}_2|}{2}$$ in PRF

Proton-lambda correlation functions, Ag+Ag at 2.55 GeV



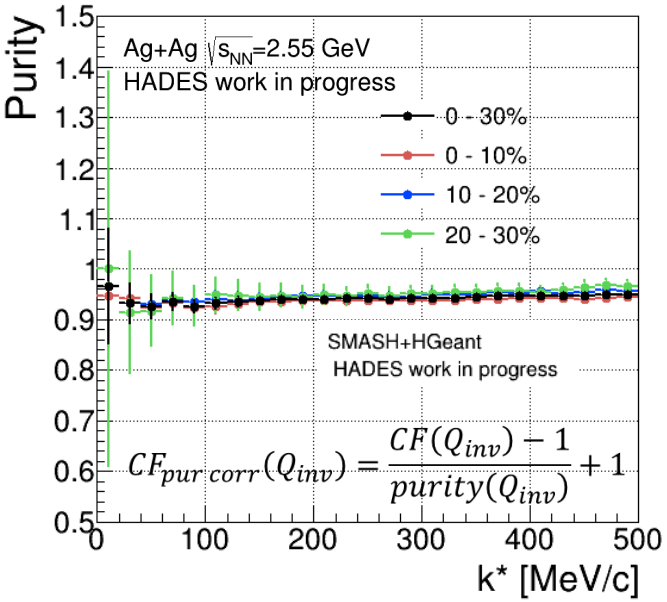


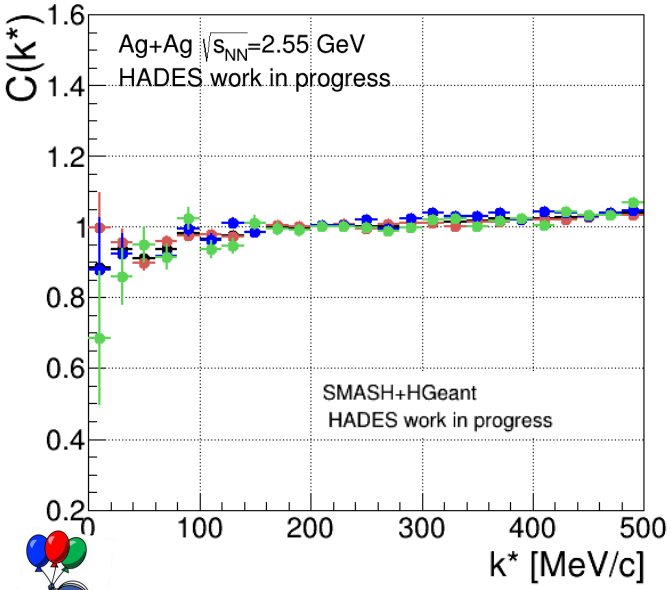


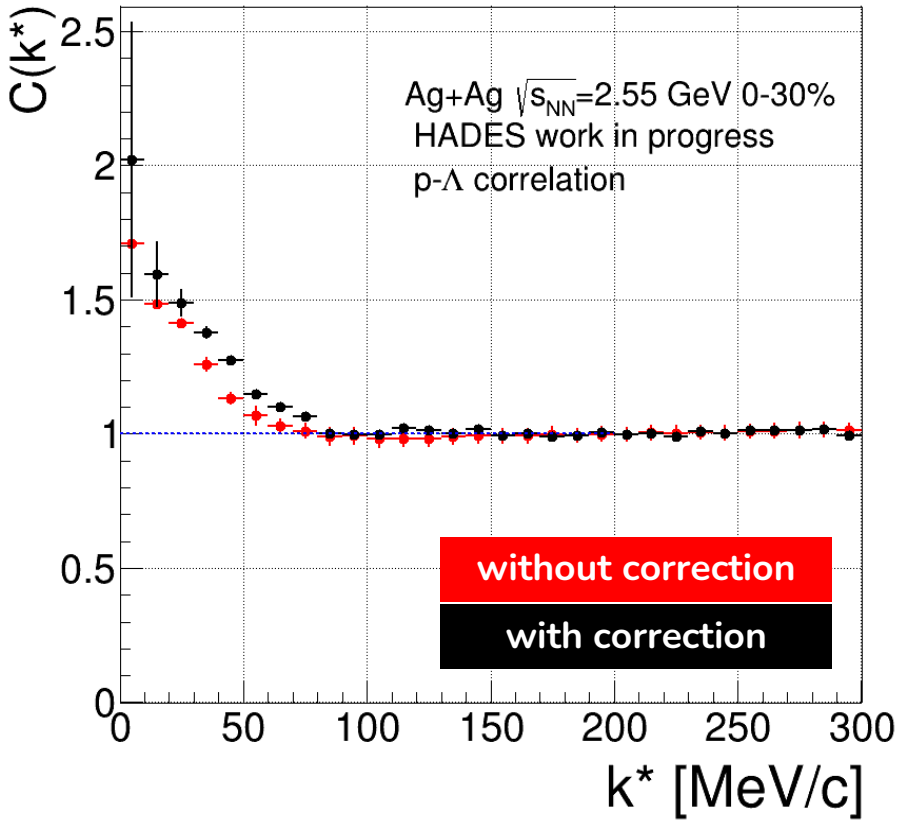
Final black data:
Detector effects + pair purity + model interference

$$k^* = \frac{|\vec{p}_1 - \vec{p}_2|}{2}$$ in PRF

Proton-lambda correlation functions, Ag+Ag at 2.55 GeV

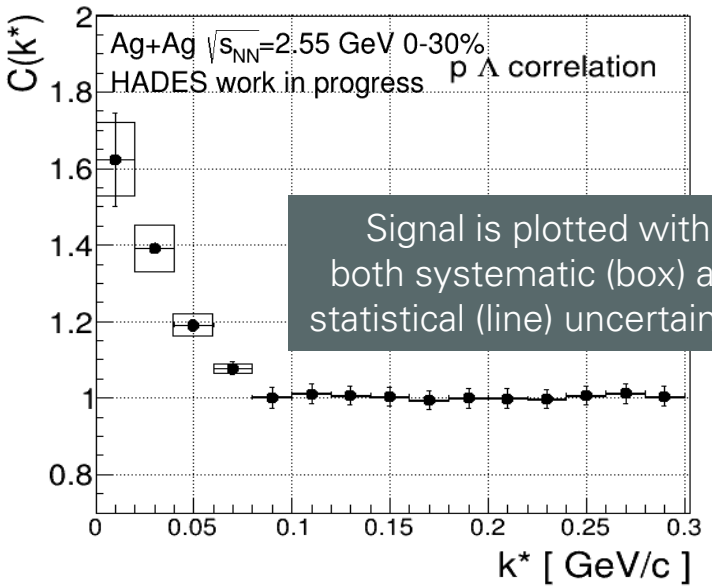




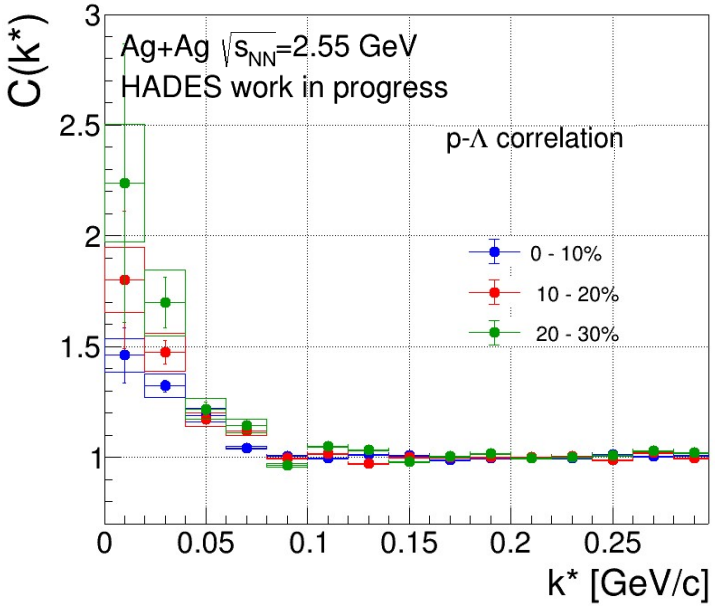


Quality correlation function achieved

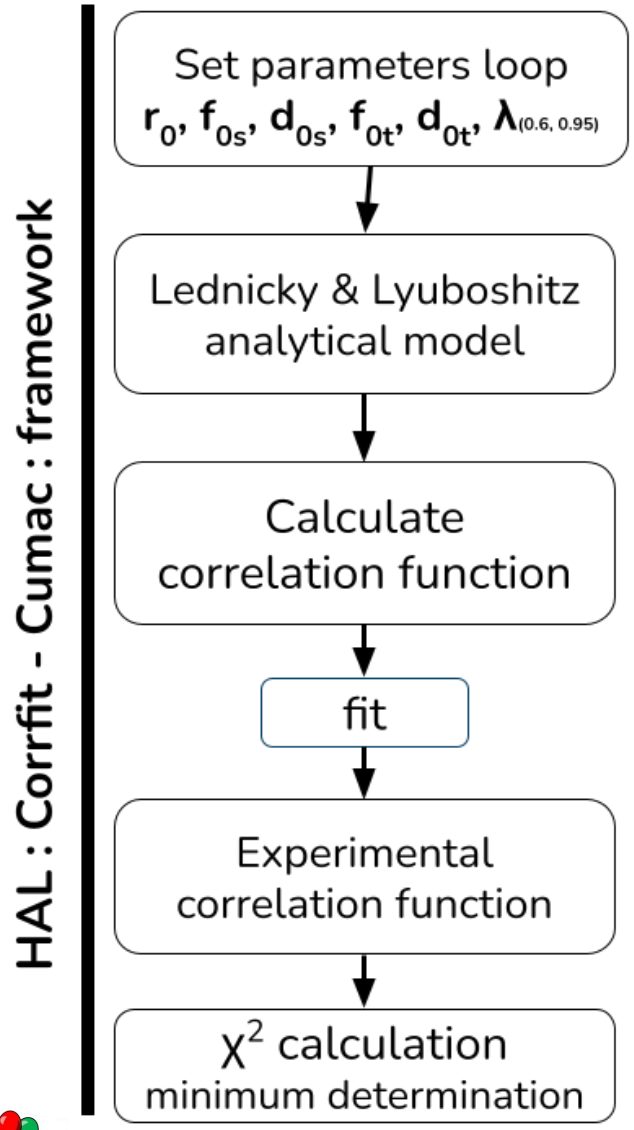
$$k^* = \frac{|\vec{p}_1 - \vec{p}_2|}{2}$$ in PRF



Signal is plotted with both systematic (box) and statistical (line) uncertainties



Proton-lambda correlation functions, Ag+Ag at 2.55 GeV



r_0 : correlation radius (length of homogeneity)
λ : correlation strength (coherence parameter)
d_{0s}, d_{0t} : effective range (singlet, triplet)
f_{0s}, f_{0t} : scattering lenght(singlet, triplet)

Lednicky, Richard & Lyuboshits, V.L.. (1982). Effect of the final-state interaction on pairing correlations of particles with small relative momenta. Sov. J. Nucl. Phys. (Engl. Transl.); (United States). 35:5.

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private communication

Proton-lambda correlation functions, Ag+Ag at 2.55 GeV

HAL : Corrfit - Cumac : framework

Set parameters loop
r_0, f_{0s}, d_{0s}, f_{0t}, d_{0t}, $\lambda_{(0.6, 0.95)}$

↓

Lednicky & Lyuboshitz analytical model

↓

Calculate correlation function

↓

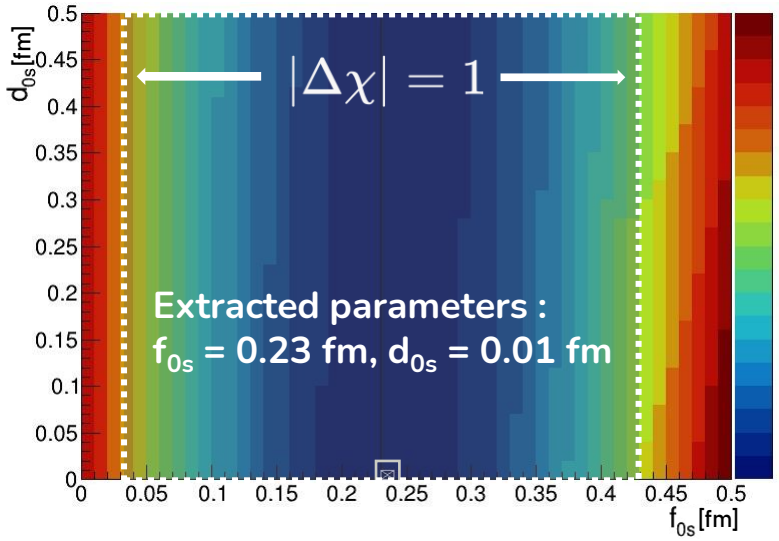
fit

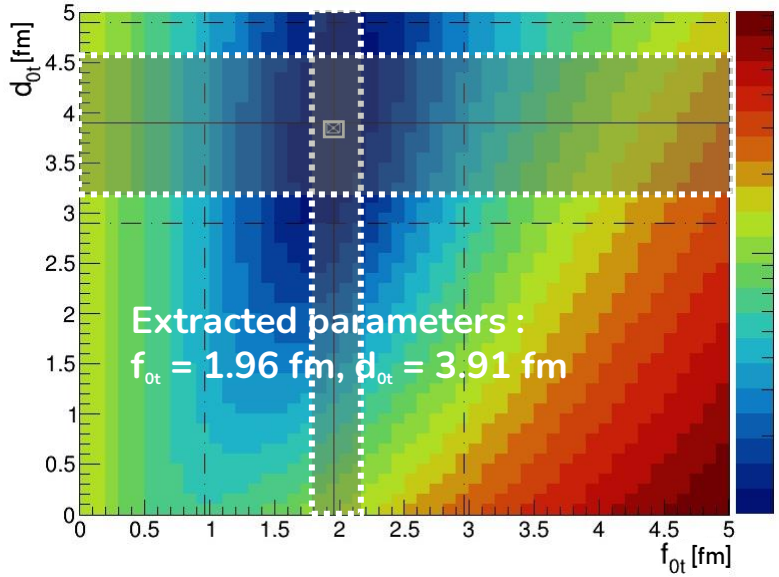
↓

Experimental correlation function

↓

χ^2 calculation
minimum determination





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Proton-lambda correlation functions, Ag+Ag at 2.55 GeV

HAL : Corrfit - Cumac : framework

Set parameters loop
r_0, f_{0s}, d_{0s}, f_{0t}, d_{0t}, $\lambda_{(0.6,\ 0.95)}$

↓

Lednicky & Lyuboshitz analytical model

↓

Calculate correlation function

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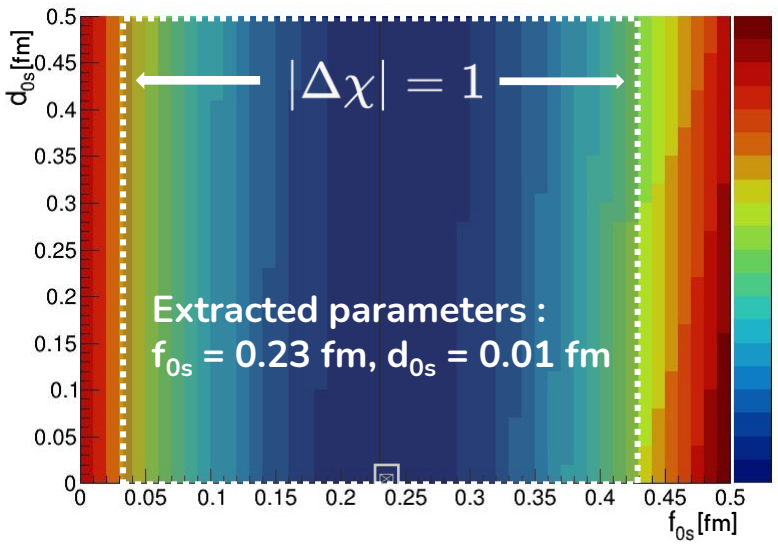
fit

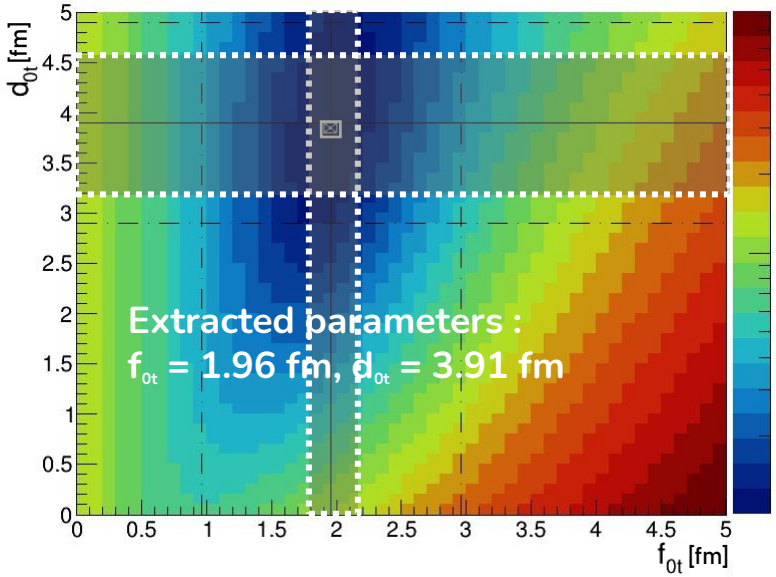
↓

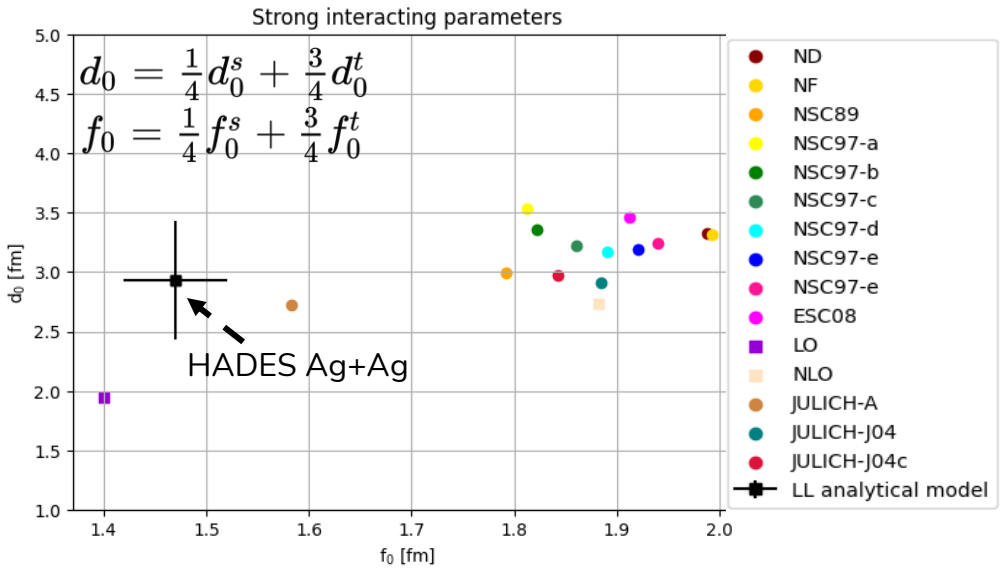
Experimental correlation function

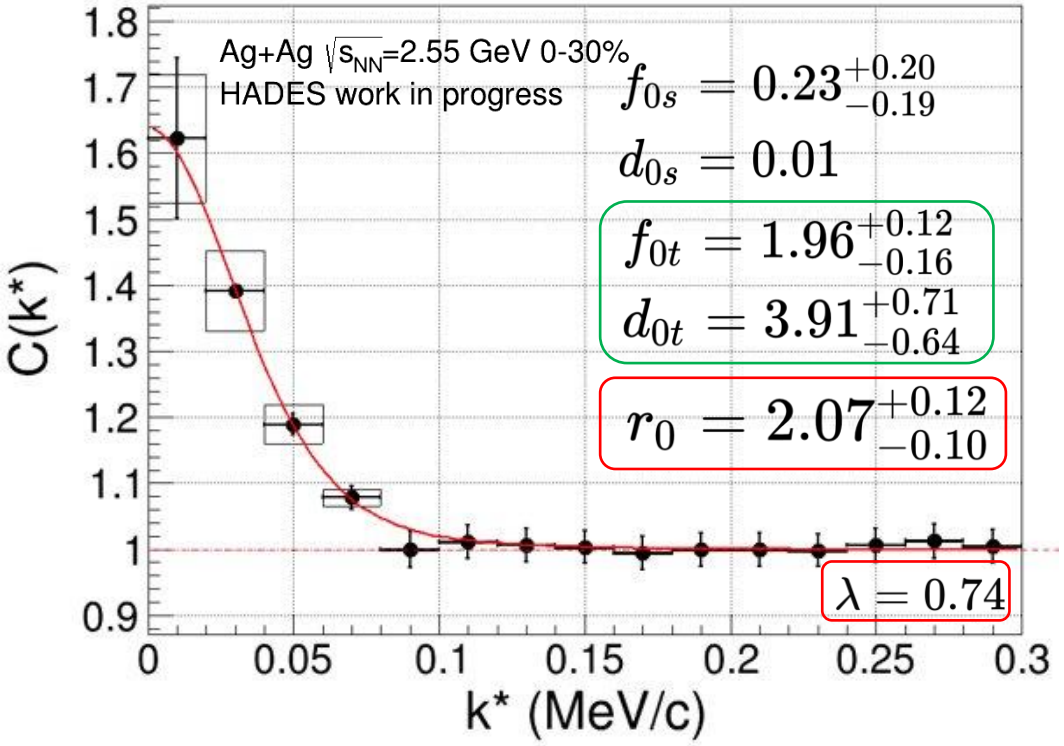
↓

χ^2 calculation minimum determination









Good description of measured CF

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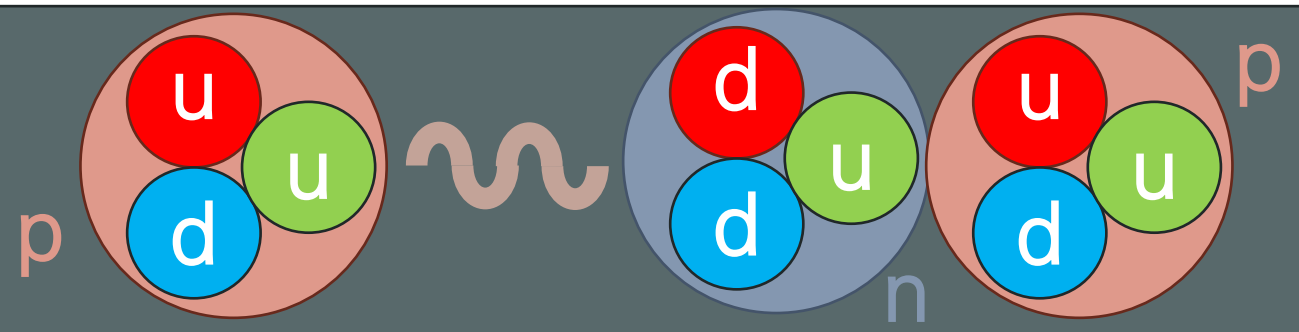
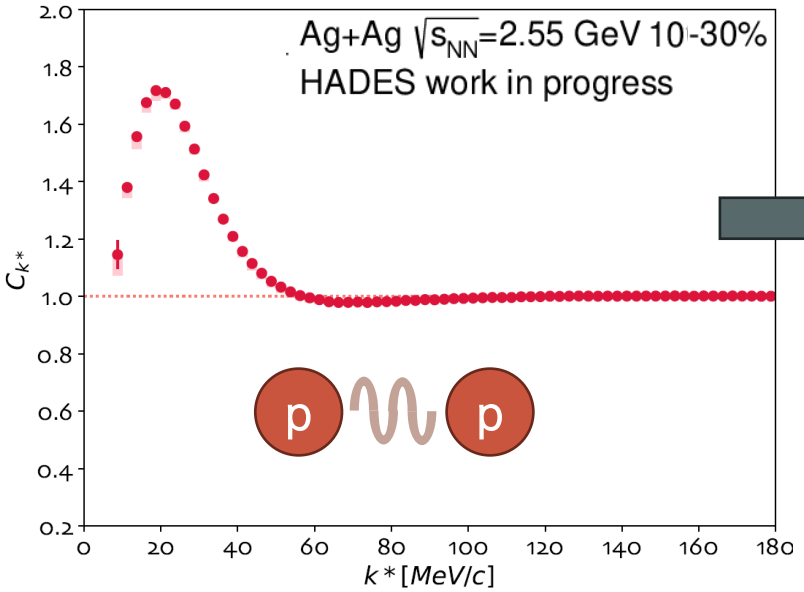


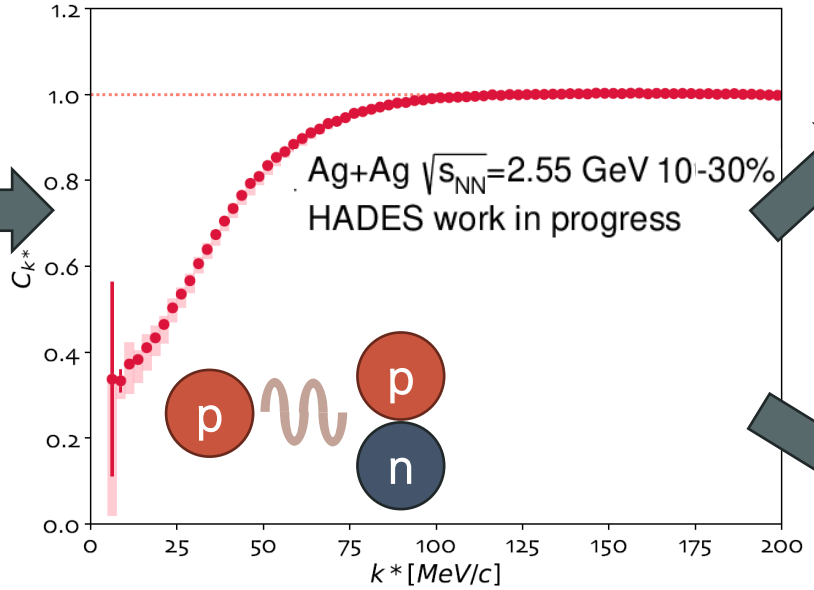
Proton-cluster correlations

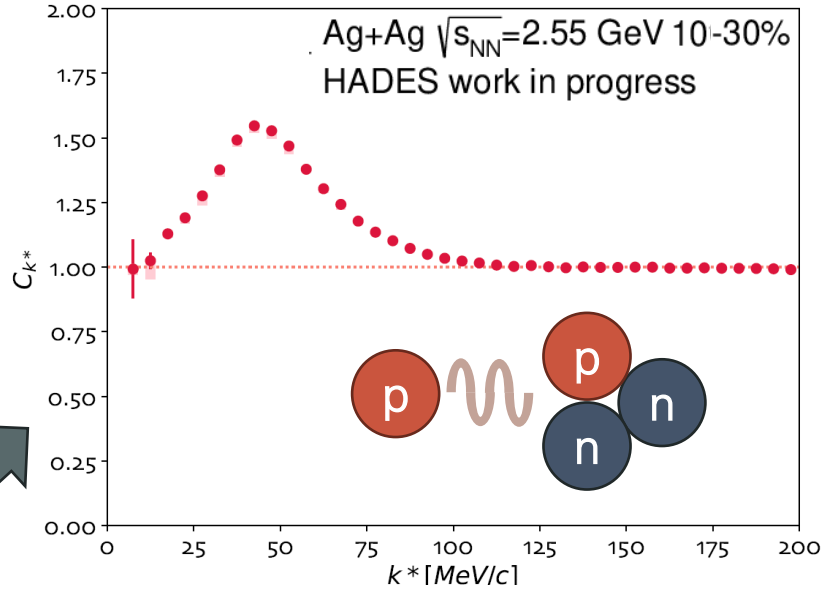
Proton-cluster correlation functions, Ag+Ag at 2.55 GeV

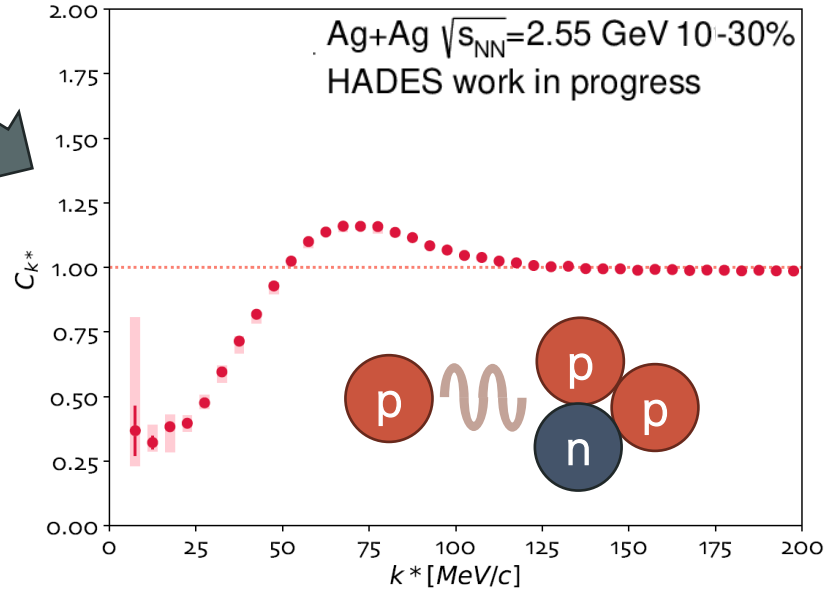
From proton proton (**2 nucleons**) to proton – cluster (**many nucleons**)

k_T: (350,500) MeV/c









Systematic uncertainties:

- Variation of Δθ and Δϕ
- Variation of nσ for PID

Proton-cluster correlation functions, Ag+Ag at 2.55 GeV

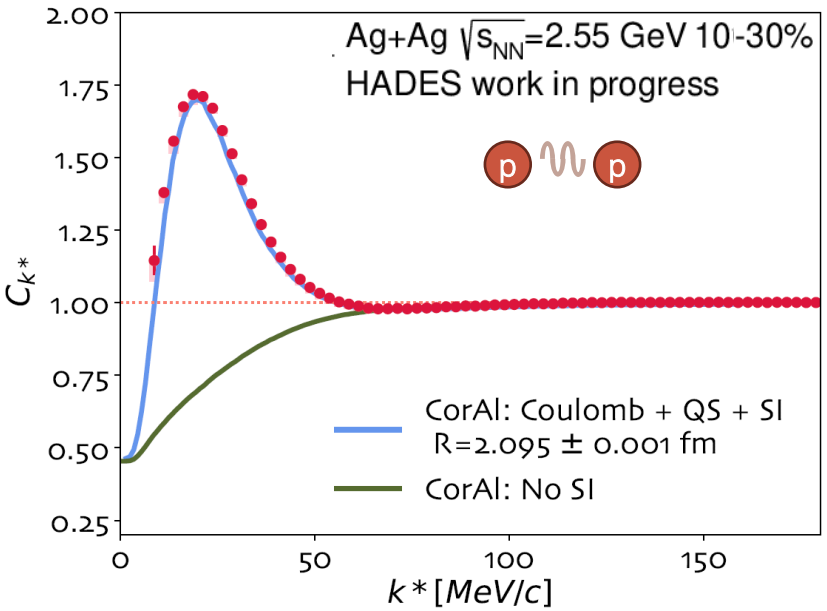
$$CF(k^*) = \int S(r^*)|\Psi(r^*, k^*)|^2 \, dr^*$$

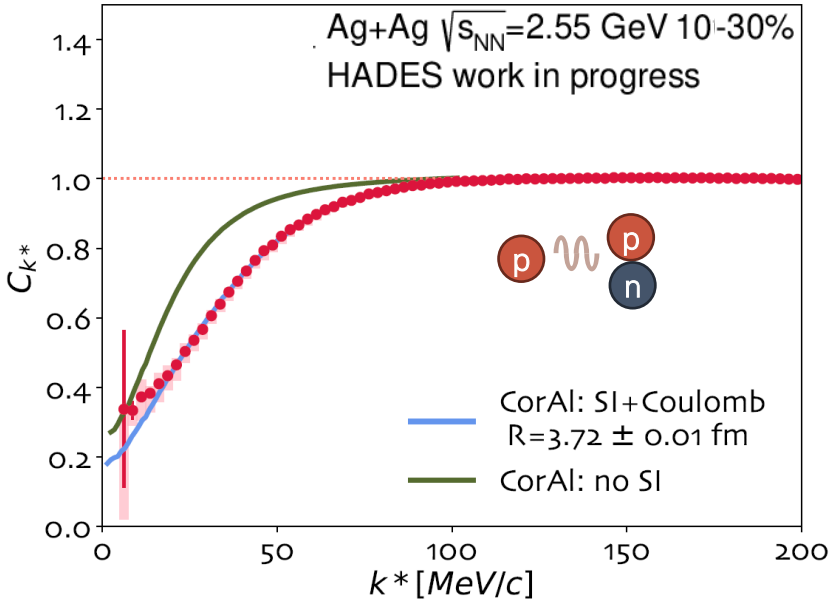
Gaussian source with a given radius

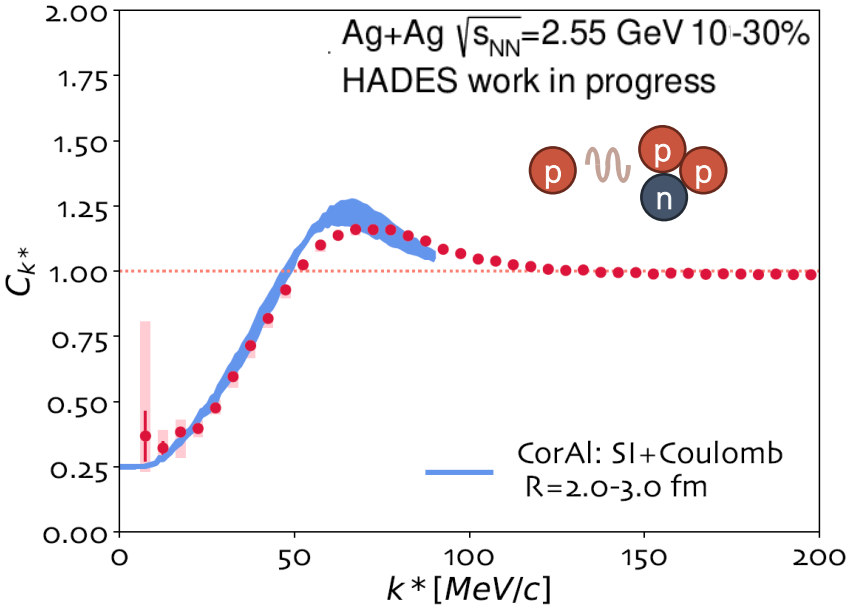
Calculated with potentials:

p+p: V.G.J. Stoks et al., Phys. Rev. C 49, 2950 (1994)
p+d: T.C. Black at al: Phys.Lett.B 471 (1999) 103-107
p+3He: T. V. Daniels at al. PRC 82, 034002 (2010)

k_T: (350,500) MeV/c





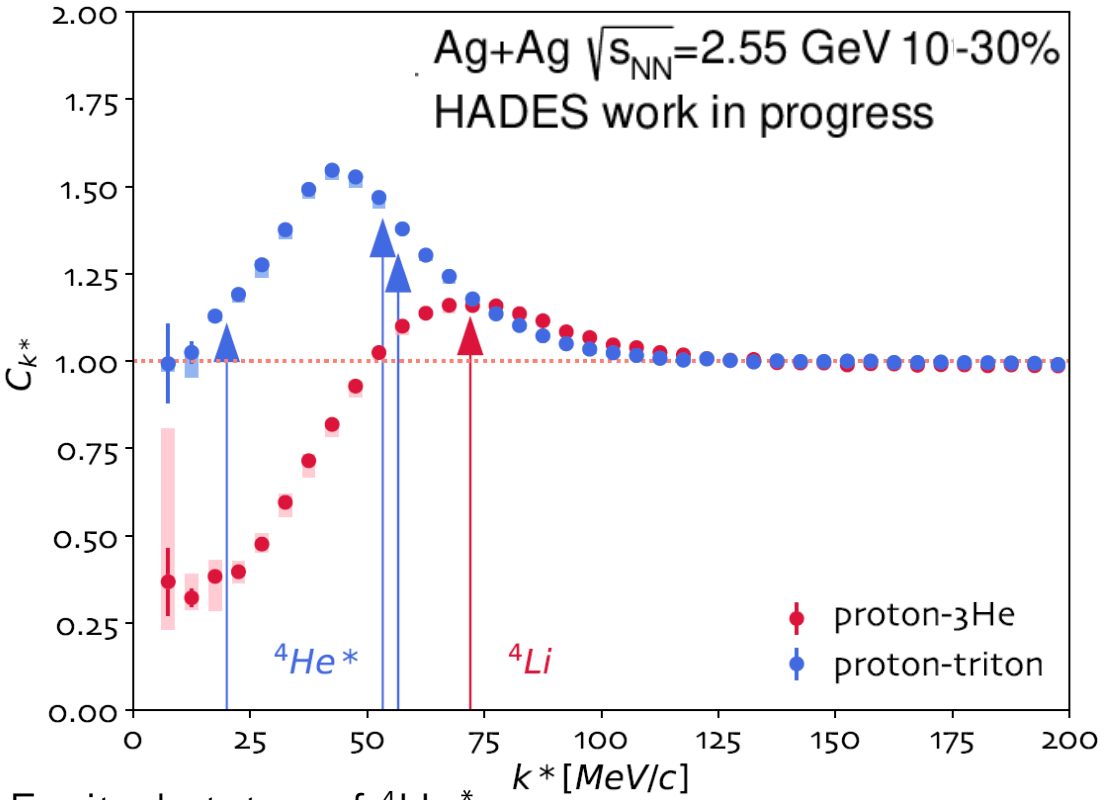


Fitting using CorAl: https://github.com/scottedwardpratt/hades_hbt

Good description of p-cluster CFs

Proton-cluster correlation functions, Ag+Ag at 2.55 GeV

k_T: (350,500) MeV/c



Proton - ^{3}He and proton - triton comparison

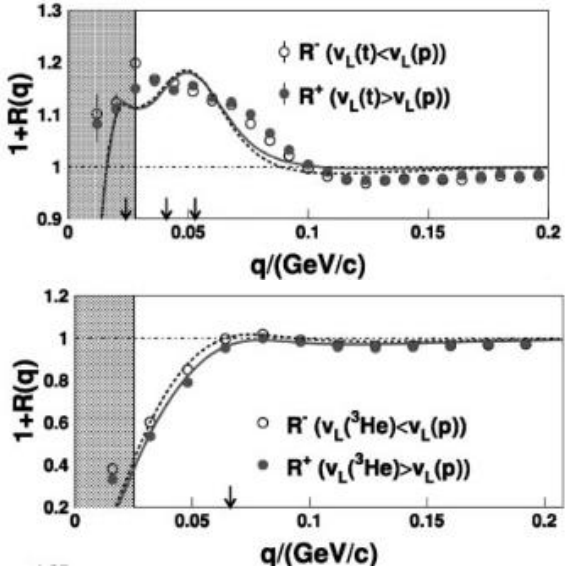
- Similar masses
- Same baryon number

- Different charges -> different strength of coulomb interactions
- Different stability

Decay sources

$$^4_2He^* \longrightarrow \mathrm{t} + \mathrm{p}$$

$$^4_3Li \longrightarrow {}^3_2He + \mathrm{p}$$



FOPI Collaboration:Eur. Phys. J. A 6, 185–195 (1999)

Excited states of $^4He^*$:

- E = 20.21 MeV, $J^\pi = 0^+$, Γ = 0.5 MeV, Γ_p/Γ = 1, k^*_1 = 20 MeV/c
- E = 21.01 MeV, $J^\pi = 0^-$, Γ = 0.84 MeV, Γ_p/Γ = 0.76, k^*_2 =53.3 MeV/c
- E = 21.84 MeV, $J^\pi = 2^-$, Γ =2.01 MeV, Γ_p/Γ = 0.63, k^*_3 = 56.6 MeV/c

Unbound ground state of ^{4}Li:

- J^π = 2-, Γ = 6.0 MeV, Γ_p/Γ = 1, $k^*_0 \approx$ 72 MeV/c

Check Maria Stefaniak poster
(n.o. 682. „Proton-cluster femtoscopy at the HADES experiment")

Effect of (possible) resonances might be visible

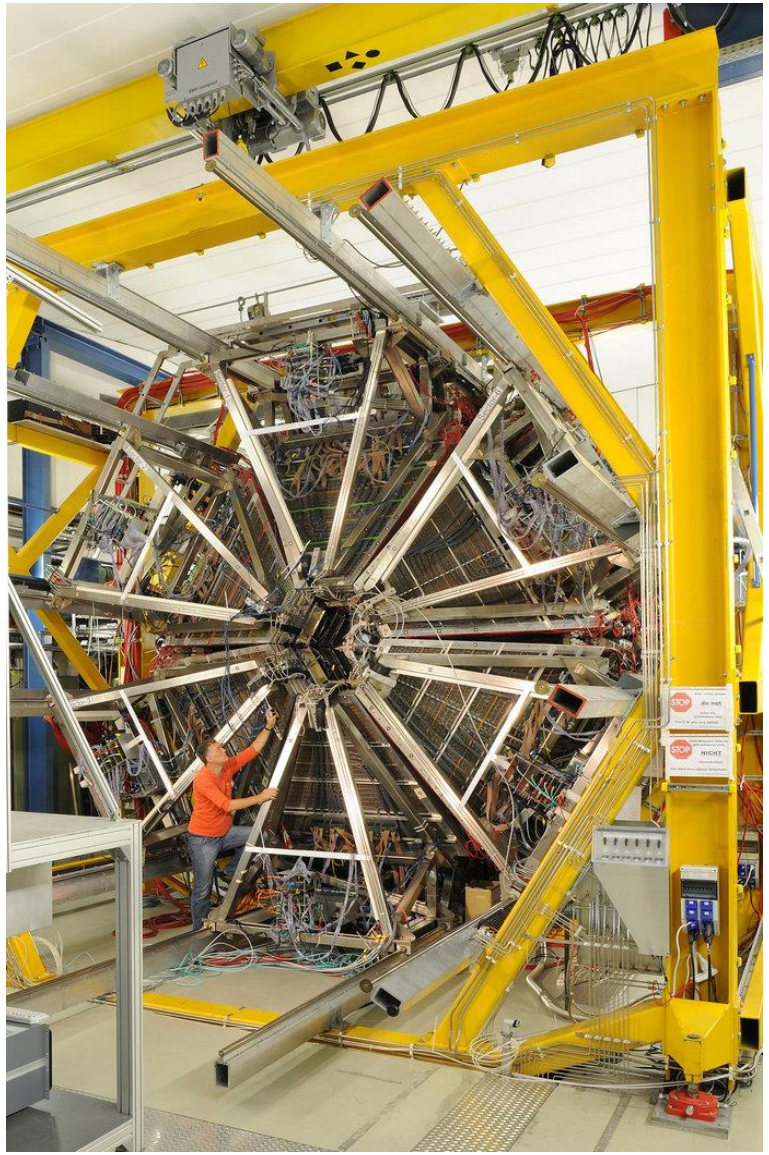
Summary

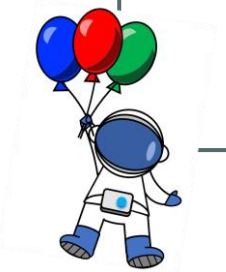
- **Photon-photon** correlation **exhibits an enhancement** at low Q_{inv}. Additional, unknown background contribution was observed. Complementary study with photons reconstructed via conversion method is ongoing.

- **Strong interaction parameters** have been **determined** from **proton-lambda** correlations. Estimated source radius is consistent with proton-proton correlation.

- **Proton-proton** and **proton-deuteron** correlation functions show **good match with theory**. Signatures from $^{4}_{2}He^{*}$ and $^{4}_{3}Li$ **decays** of were observed.

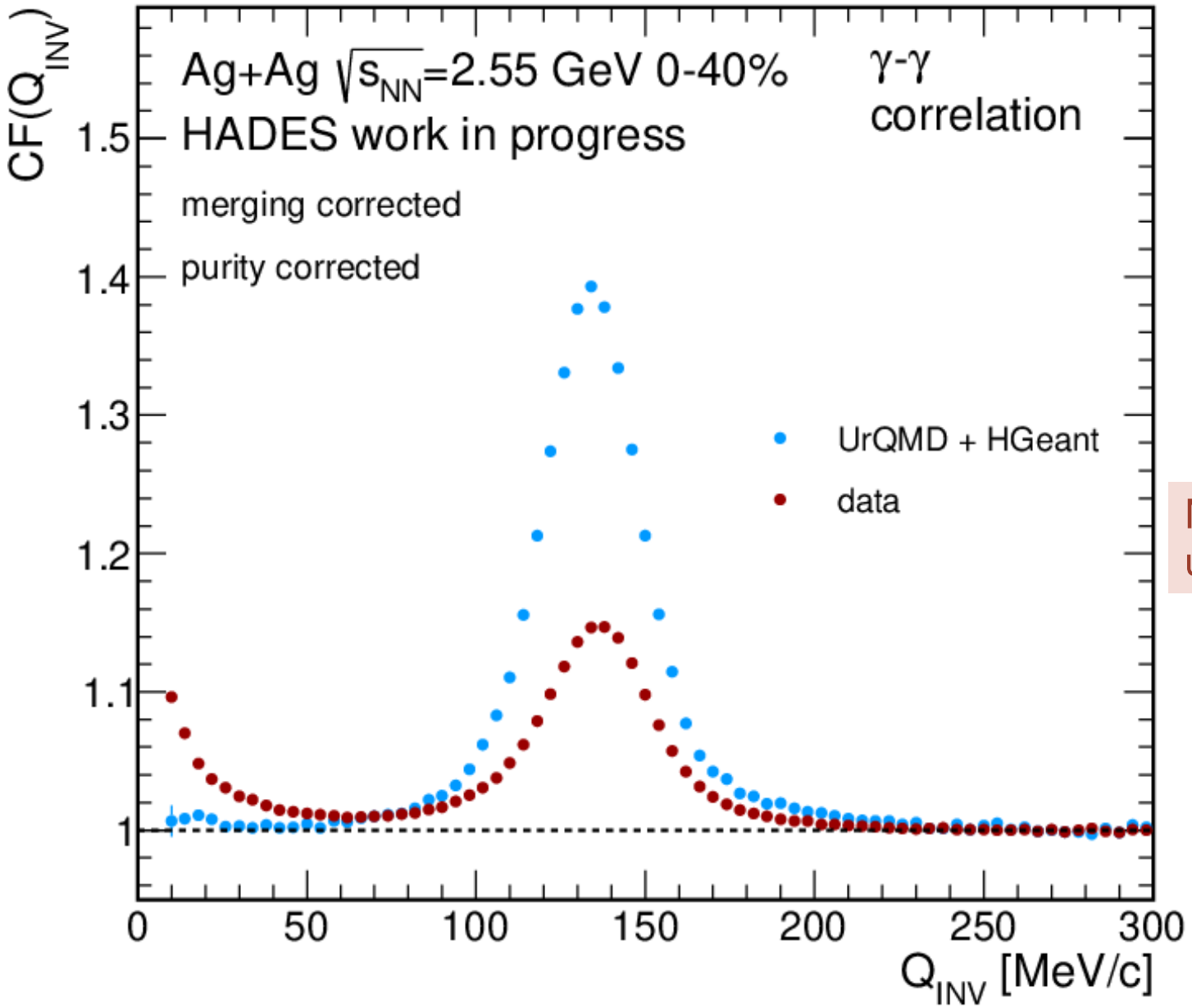
- The same analyses will be performed new HADES data from p-p at $\sqrt{s_{NN}}$ = 3.46 GeV.





Backup

Backup – photon-photon – min bias

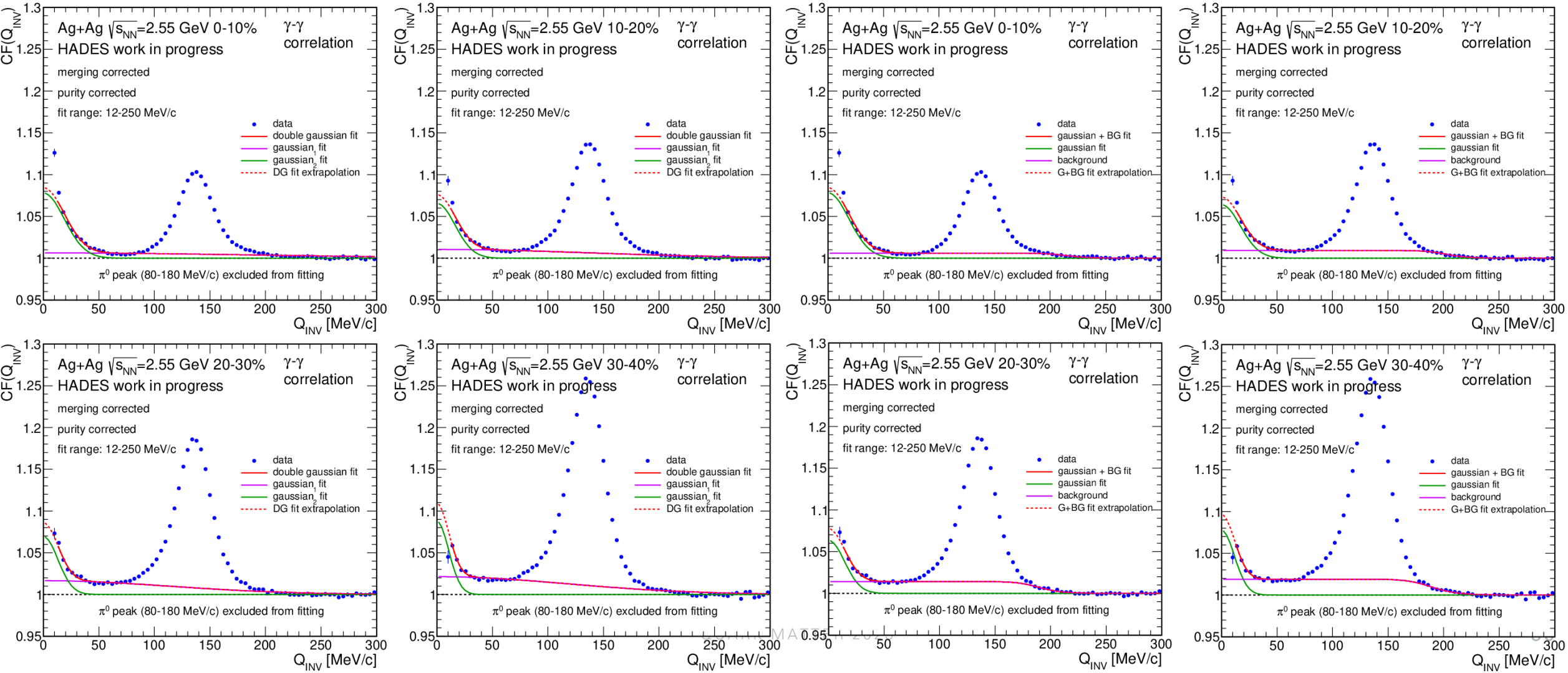


Minor/neglectable deviation from unity for simulation

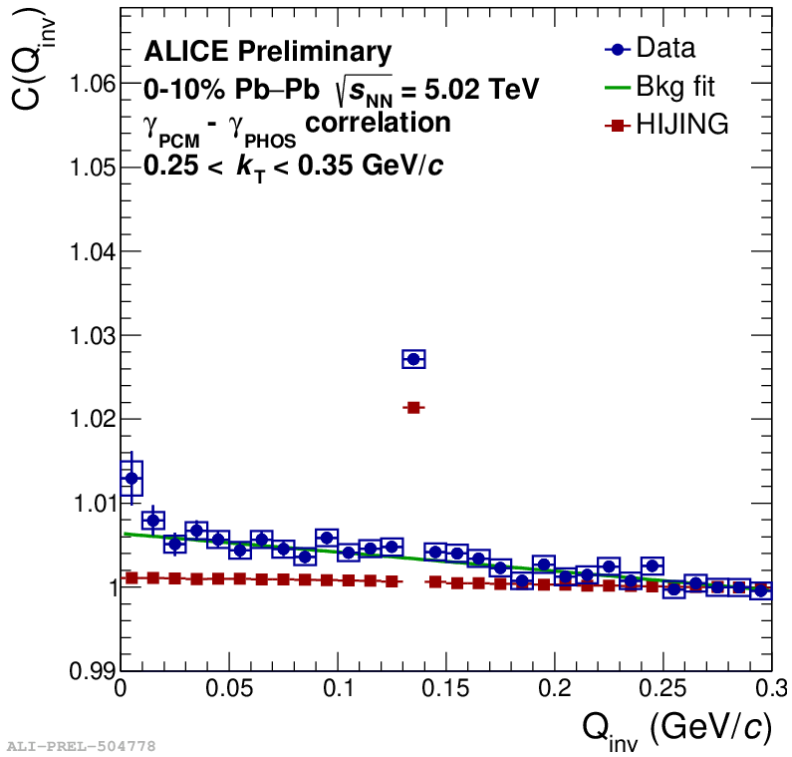
Backup – photon-photon – alternative fits

$$CF(Q_{inv}) = 1 + \lambda_1 e^{(-Q_{inv}{}^2 \cdot R_{inv1}{}^2)} + \lambda_2 e^{(-Q_{inv}{}^2 \cdot R_{inv2}{}^2)}$$

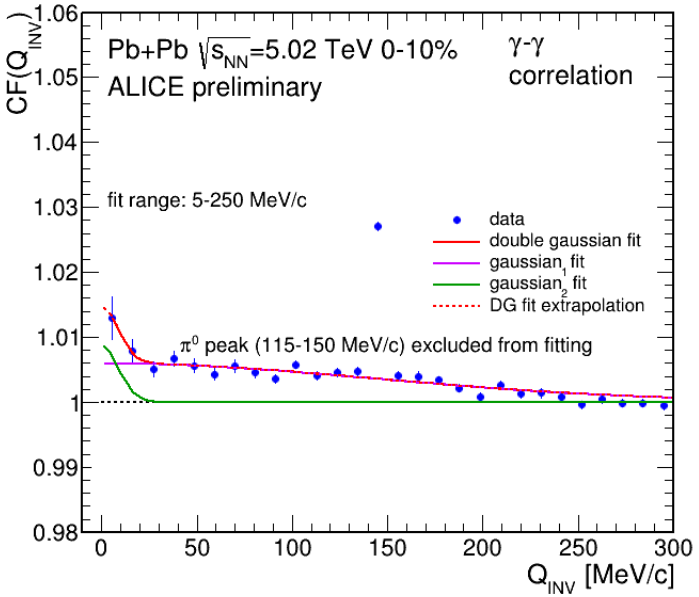
$$CF(Q_{inv}) = 1 + \lambda e^{(-Q_{inv}{}^2 \cdot R_{inv}{}^2)} + \frac{a_0}{1+(a_1 \cdot Q_{inv})^{a_2}}$$



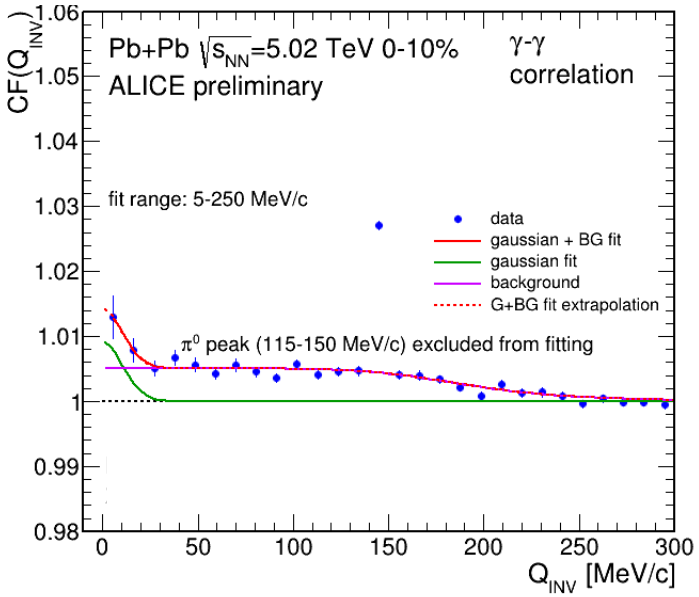
Backup – photon-photon – fit for ALICE data



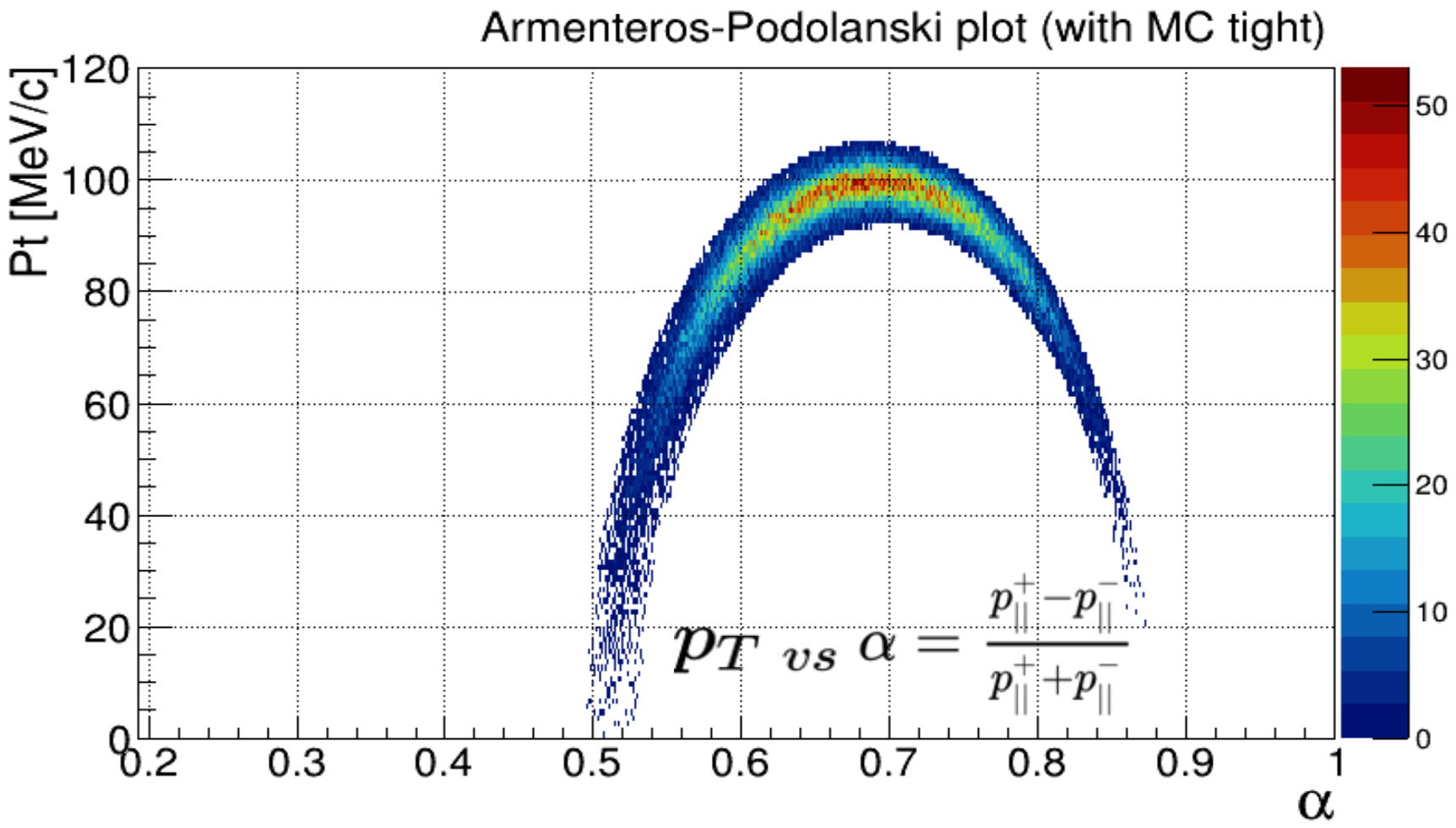
$$CF(Q_{inv}) = 1 + \lambda_1 e^{(-Q_{inv}{}^2 \cdot R_{inv1}{}^2)} + \lambda_2 e^{(-Q_{inv}{}^2 \cdot R_{inv2}{}^2)}$$



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



Backup – proton-lambda – Armanteros-Podolansky plot



SPS : Pb+Pb @ 17.3 TeV and STAR : Au+Au @ 200 GeV