Faculty of Physics
Warsaw University of Technology

Femtoscopy at HADES

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Budapest 1-5.12.2025 Zimányi school

Plan of the Presentation

- HADES experiment
- Femtoscopy
  - Historical background
  - Why study femtoscopy with HADES?
  - Physics of femtoscopy
- Obtained results
- Plans for future femtoscopy at HADES

Source:https://www.budapestinfo.hu/en/premier-outlet-budapest

HADES experiment

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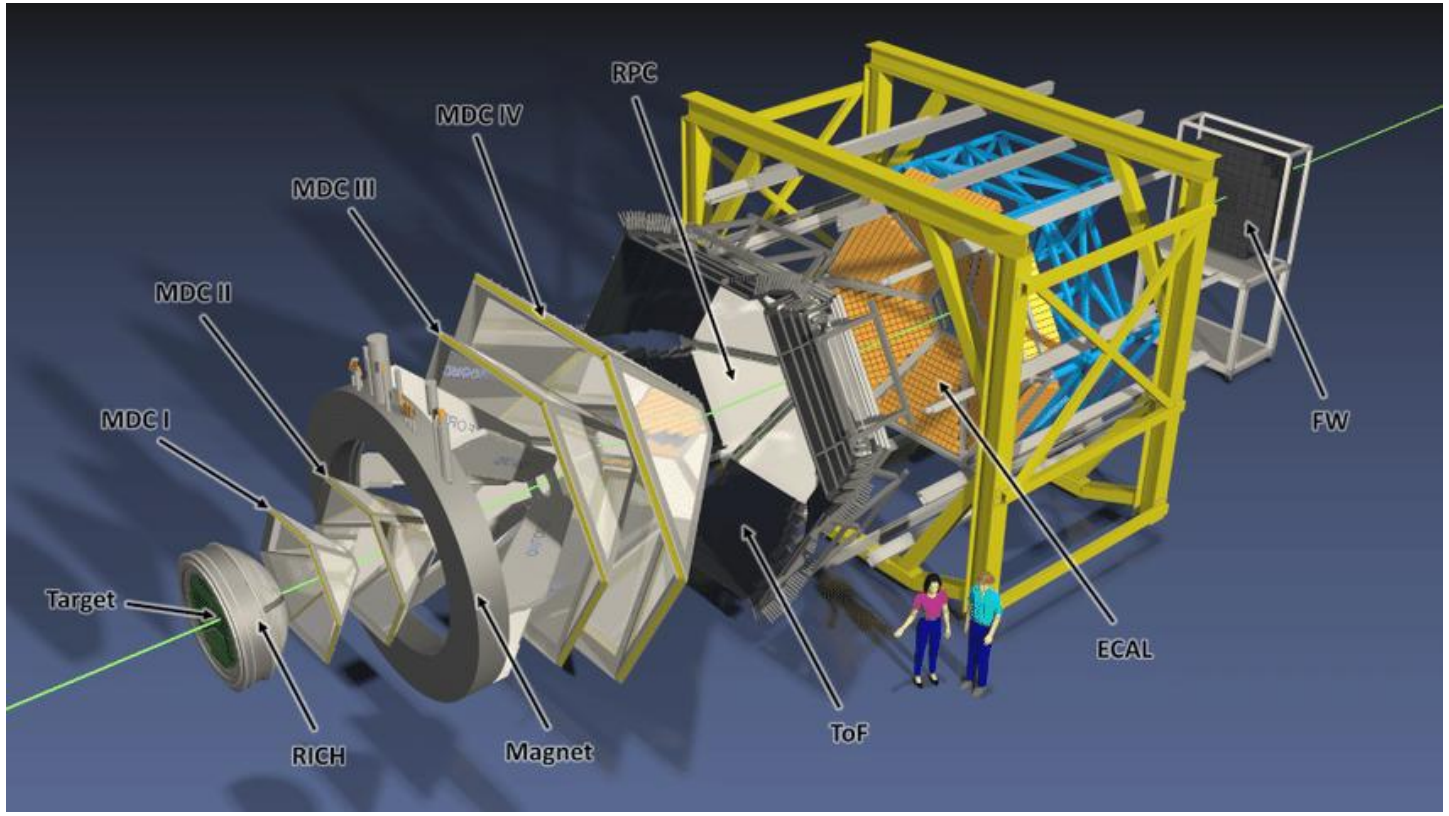
HADES experiment

- HADES – High Acceptance Di-Electron Spectrometer
- Fixed target experiment at SIS-18 accelerator in GSI, Darmstadt Germany
- Almost full azimuthal angle acceptance and polar angles between 18 and 85°
- Multi-wire Drift Chambers (MDCs) together with high DAQ rate (20 kHz) allow to gather data in large amounts

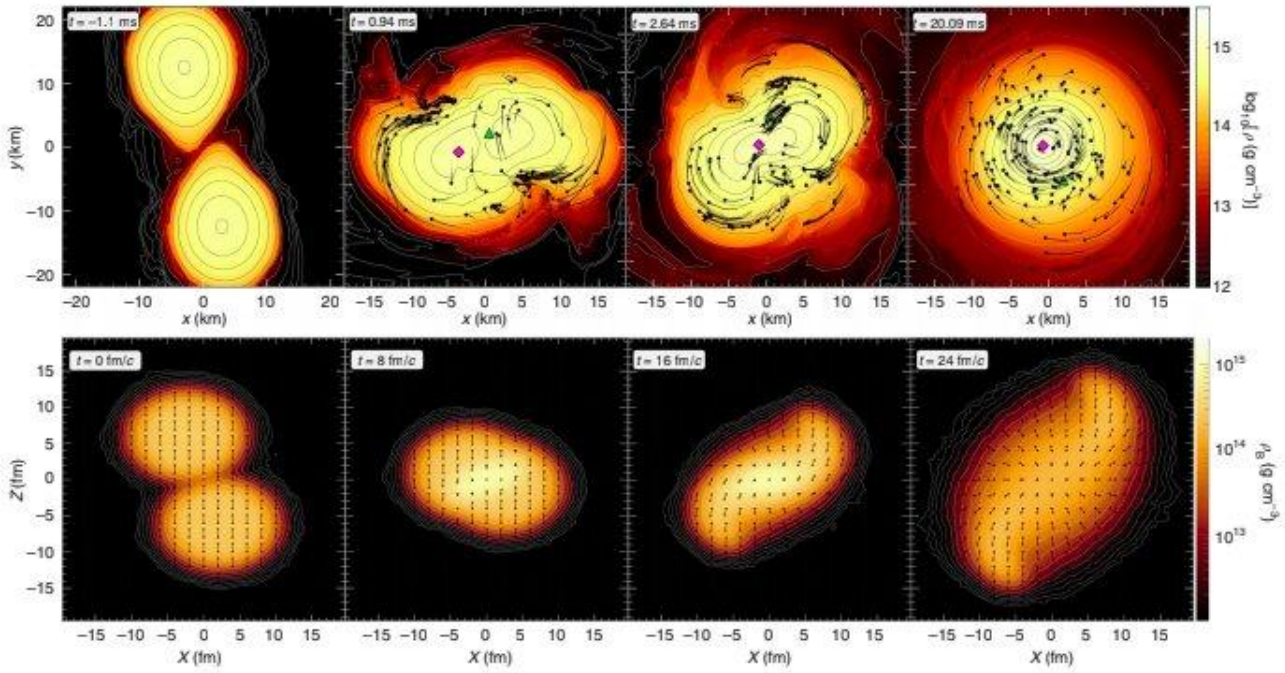


Source: **HADES Overview: Recent results from Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.55 GeV measured by HADES**

HADES experiment

- Physics goal – study of high density baryonic matter
- Heavy-ion collisions at energies up to $\sqrt{S_{NN}} = 2.7$ GeV
- Conditions similar to neutron star mergers

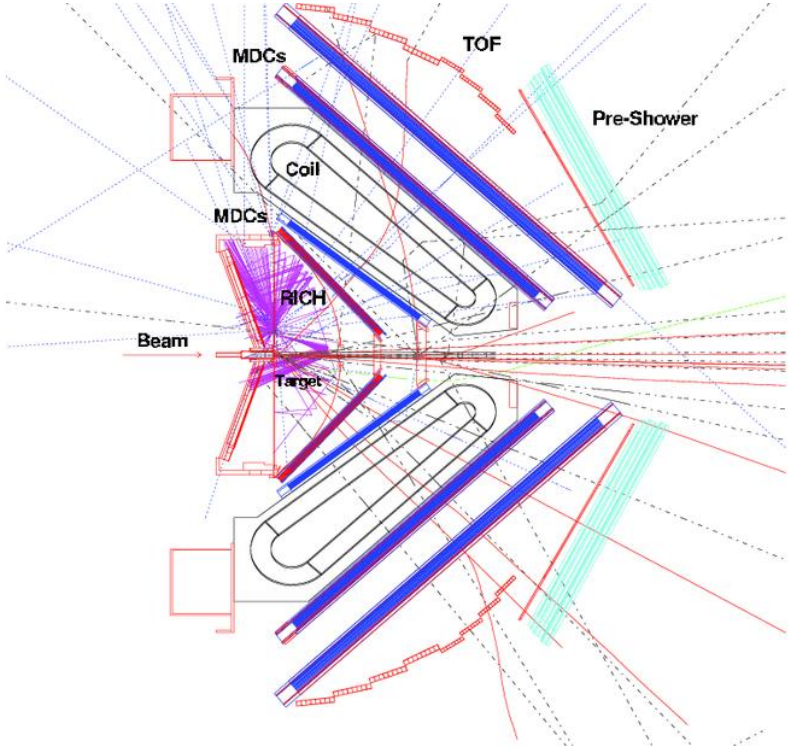
	HADES	Neutron Star Mergers
Baryonic density	Up to 3 times of nuclear matter	Around twice of nuclear matter
Temperature	~72 MeV	50-80 MeV



Source: HADES, Nature Phys. 15, 1040–1045 (2019)

HADES experiment

- Beamtimes:
  - C+C at 2 AGeV
  - p+LH_2 at 2.2 AGeV
  - C+C at 1 AGeV
  - **Ar+KCl at 1.765 AGeV**
  - p+p at 1.23 AGeV
  - C+C at 1 AGeV
  - p+p at 3.5 AGeV
  - d+p at 1.25 AGeV
  - **p+Nb at 3.5 AGeV**
  - **Au+Au at 1.23 AGeV**
  - π^-+W/C/PE at 1.7 AGeV
  - π^-+C/PE at 656, 612, 690, 748, 800 AMeV
  - **Ag+Ag at 1.58**, 1.23 AGeV
  - **p+p at 4.5**, 1.23 AGeV
  - Au+Au at 0.6, 0.8 AGeV
  - Au+Au at 0.6, 0.4, 0.2 AGeV



Example: C+C at 2 AGeV

More at HADES

- Of cource femtoscopy is but one of many scientific ventures
- HADES was first introduced to analyse dileptons, as they are hard to measure other kinds of analyses are automatically viable
- One must also mention hadronic analyses: strangeness, flow and fluctuations
- To learn more: talk by **Hanna Zbroszczyk: HADES/CBM overview**, 11:30, Friday 5th

Basics of femtoscopy

Origins

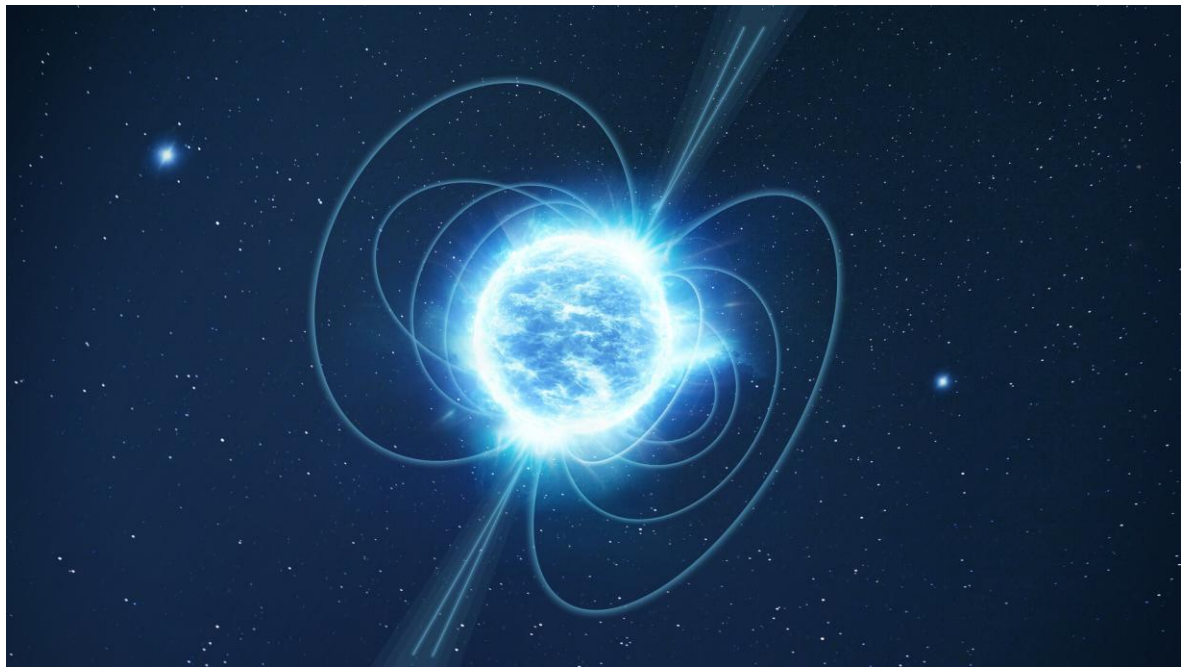
- In the 1950's Hanbury-Brown and Twiss suggested, that intensity interferometry of photons can be used to measure the angular sizes of stars
- Similar idea can be applied to particles in heavy ion collisions
- Although this time also different particles can be used

Comparison with HBT

	„Traditional” HBT	Femtoscopic correlations
What is analysed?	Photons	Any pair of particles
Correlations due to…	Bose-Einstein statistics	Bose-Einstein or Fermi-Dirac statistics, strong and Coulomb interactions
What we measure	Intensity interference	Four-momenta difference
What we can obtain	Angular sizes of stars	Parameters of the emission source

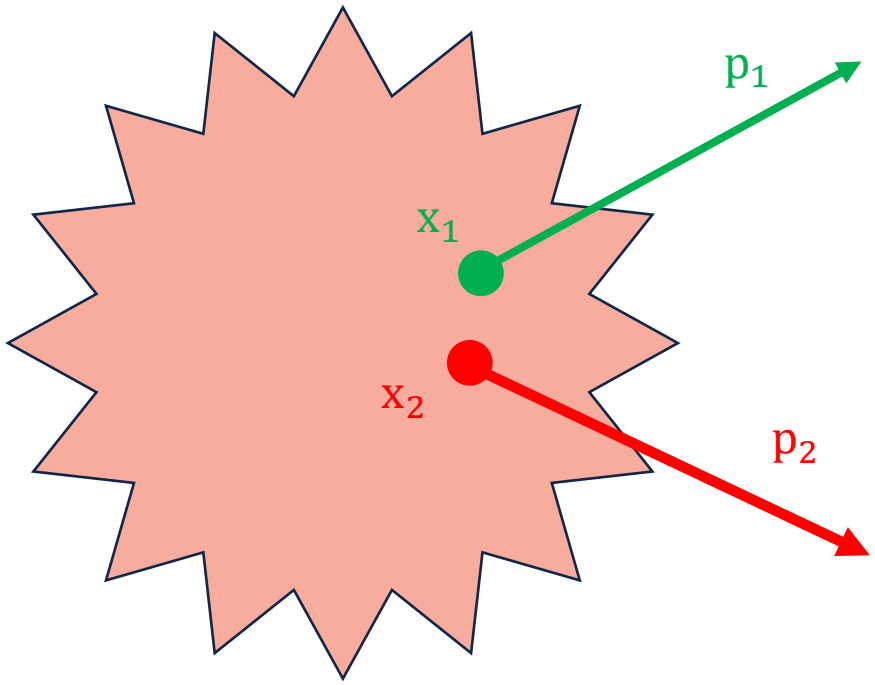
Why femtoscopy at HADES?

- High baryonic density = conditions similar to neutron star mergers
- Investigation of the Neutron Star Puzzle
- NY and YY interactions could create repulsive forces explaining the existence of large neutron star masses



https://www.esa.int/ESA_Multimedia/Images/2024/03/What_is_a_neutron_star

Basics of femtoscopy



- x_1, x_2 - Space-time coordinates, **cannot be measured directly**
- p_1, p_2 - momenta (and their difference), **can be measured directly**
- Correlation due to quantum statistics (B-E and F-D) and interactions (Coulomb and strong)

Basics of femtoscopy

- Femtoscopic correlations – information about the source size and dynamics

- Basis for the femtoscopic analyses – Koonin-Pratt equation:

$$CF(q_{inv}) = \int d^3r \, \mathrm{S}(\vec{\mathrm{r}})|\Psi(\vec{\mathrm{q}}_{\mathrm{inv}}, \vec{\mathrm{r}})|^2 = \frac{\mathrm{Same\ Event}(q_{inv})}{\mathrm{Mixed\ Event}(q_{inv})}$$

$\mathrm{S}(\vec{\mathrm{r}})$ – source function

$\Psi(\vec{\mathrm{q}}_{\mathrm{inv}}, \vec{\mathrm{r}})$ - pair wave function

$\vec{\mathrm{q}}_{\mathrm{inv}} = \sqrt{(\overrightarrow{p_1} - \overrightarrow{p_2})^2 + (E_1 - E_2)^2}$ - relative four-momentum of particles in LCMS

$\vec{\mathrm{r}}$ - relative distance of particles

Basics of femtoscopy

$$CF(q_{inv}) = \int d^3r \, S(\vec{r})|\Psi(\vec{q}_{inv}, \vec{r})|^2 = \frac{\text{Same Event}(q_{inv})}{\text{Mixed Event}(q_{inv})}$$

If we assume that we know $\Psi(\vec{q}_{inv}, \vec{r})$ …	**If we assume that we know $S(\vec{r})$ …**
More of a „traditional” femtoscopy	Less similar to classical HBT
We can obtain the source parameters	We can obtain interaction parameters
e.g. Bowler-Sinyukov formula	e.g. Lednicky-Lyuboshitz (L-L) parametrization

Basics of femtoscopy

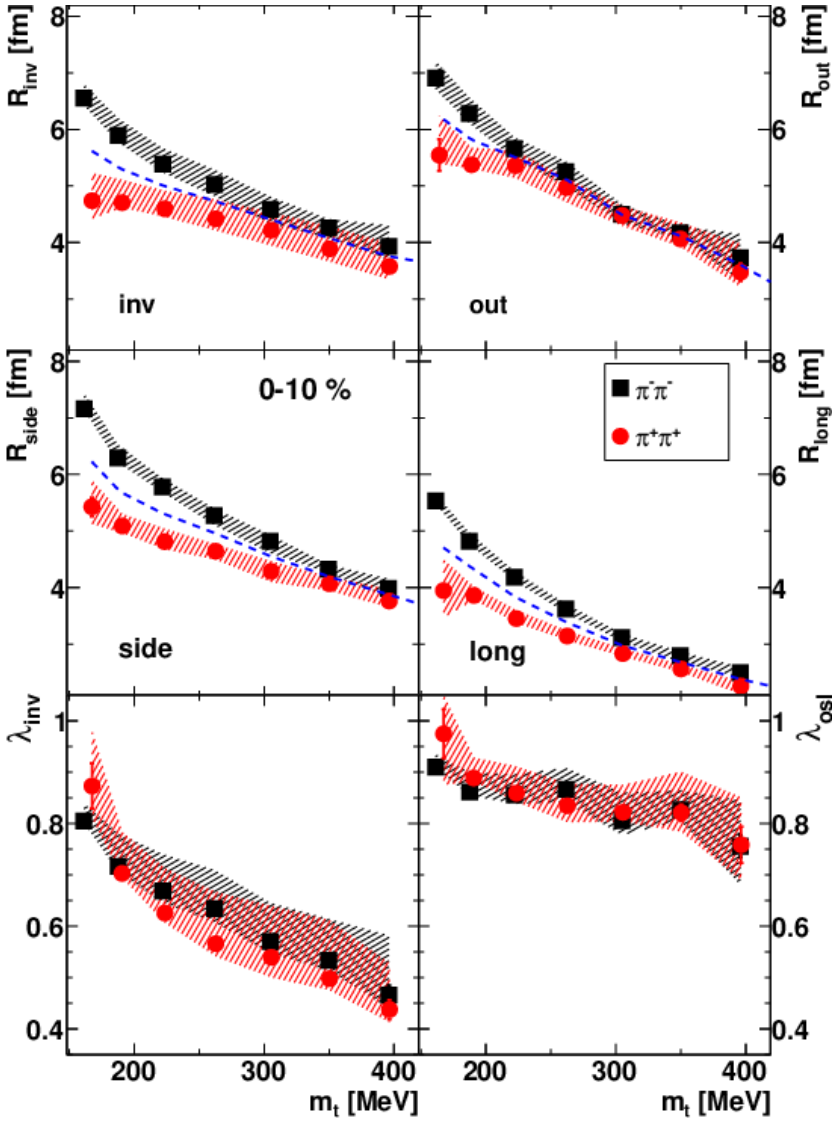
- **Bowler-Sinyukov formula**: $C(\mathrm{q_{inv}}) = 1 - \lambda + \lambda \cdot \mathrm{k_{Coulomb}} \cdot (1 + \mathrm{e}^{-(\mathrm{q_{inv}} \cdot \mathrm{R})^2})$
  - λ – (in)coherence parameter, R – length of homogenity, $\mathrm{k_{Coulomb}}$ - Coulomb interaction correction

- **Lednicky-Lyuboshitz parametrization**: $C(\mathrm{q_{inv}}) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{{f_0}^S(\mathrm{q_{inv}})}{r_0} \right|^2 \left(1 - \frac{{d_0}^S}{2\sqrt{\pi} r_0} \right) + \frac{2\Re {f_0}^S(\mathrm{q_{inv}})}{\sqrt{\pi} r_0} F_1(2k^* r_0) - \frac{\Im {f_0}^S(\mathrm{q_{inv}})}{r_0} F_2(2\mathrm{q_{inv}} r_0) \right]$
  - f_0 - scattering length, d_0 - effective range, ρ_S - normalized emission probability of identical particles with similar momenta in a state with summary spin S, $F_1 = \frac{1}{z} e^{-z^2} \int_0^z e^{x^2} dx$, $F_2 = \frac{1}{z} \left(1 - e^{-z^2}\right)$

Results from HADES

Au+Au at $\sqrt{s_{NN}} = 2.4$ GeV – 3D pion correlations

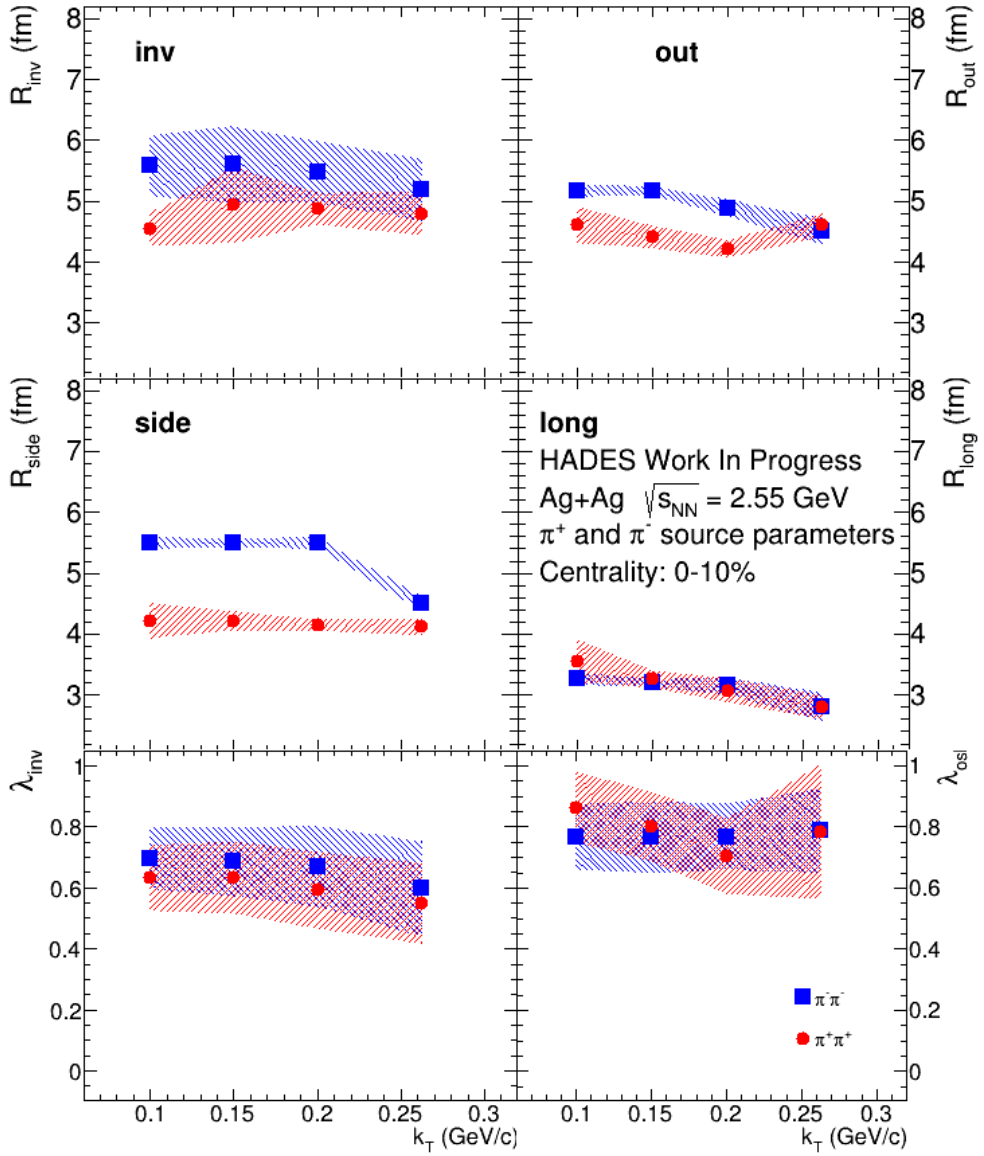
- Dependence of 1D and 3D parameters on $m_T = \sqrt{k_T^2 + m_\pi^2}$
- Blue dashed lines – constructed radii of neutral pion pairs
- Differences (especially at low p_T) due to Coulomb interaction with fireball



Eur. Phys, J. A 56 140 (2020)

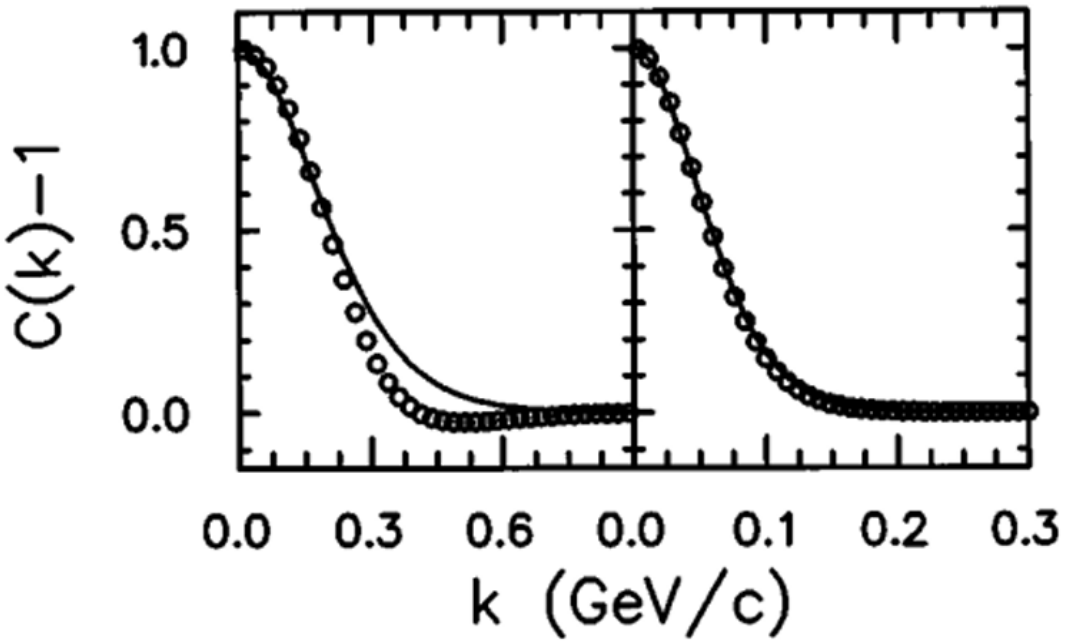
Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV – 3D pion correlations

- Very preliminary results to compare with Au+Au in the future
- More can be seen on poster by Anna Kodym on Thursday poster session



Quick intermission – smoothness approximation

- Koonin-Pratt equation assumes a so-called „smoothness approximation”
- This approximation requires a large number of particles, as it is a kind of a mean-field approxmiation
- Either large energy or large system (or both)
- None of those are present in p+p collisions at 4.5 GeV
- The goal of my PhD is to test the limits of this approximation

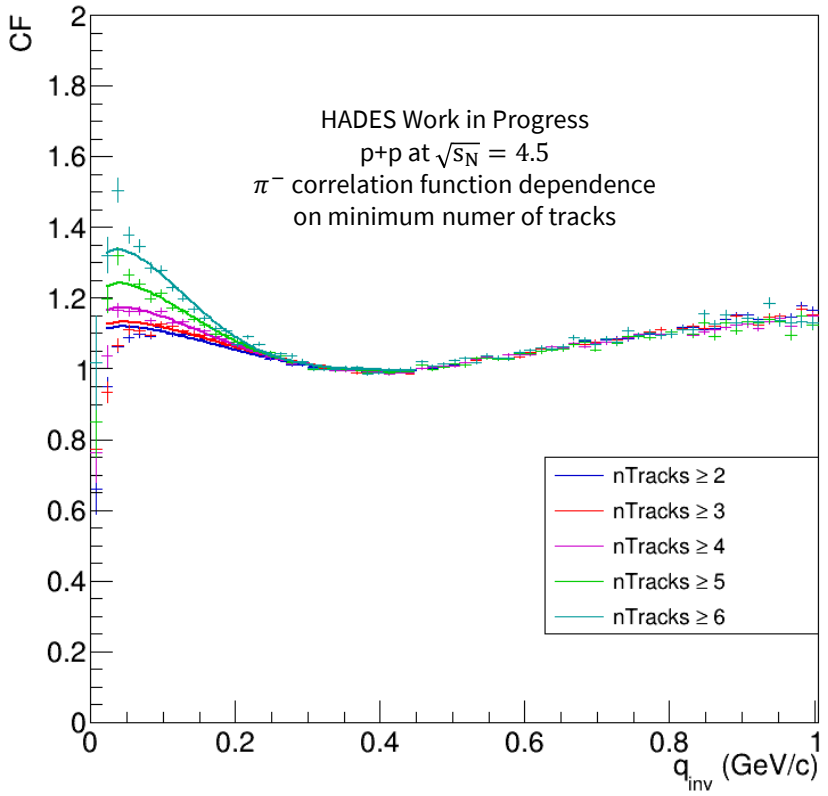


[1]

- Circles – CF with smoothness approximation
- Solid line – CF without smoothness approximation
- Left – R=1 fm, Right R = 2 fm

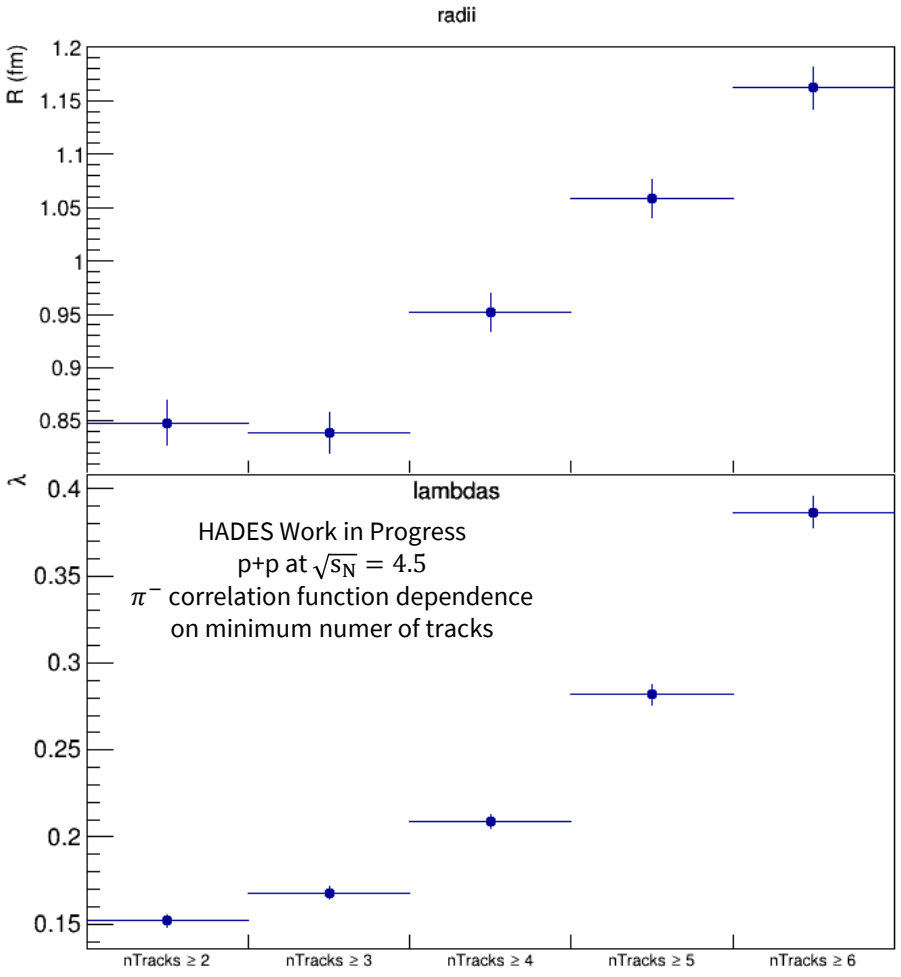
p+p at $\sqrt{s} = 4.5$ GeV – like-sign pion correlations

- Presented are the correlation functions of π^- in proton-proton collisions
- Unlike in heavy-ion collisions, here the smoothness approximation does not work! Another approach is needed
- Strong contribution from long-range correlations is visible



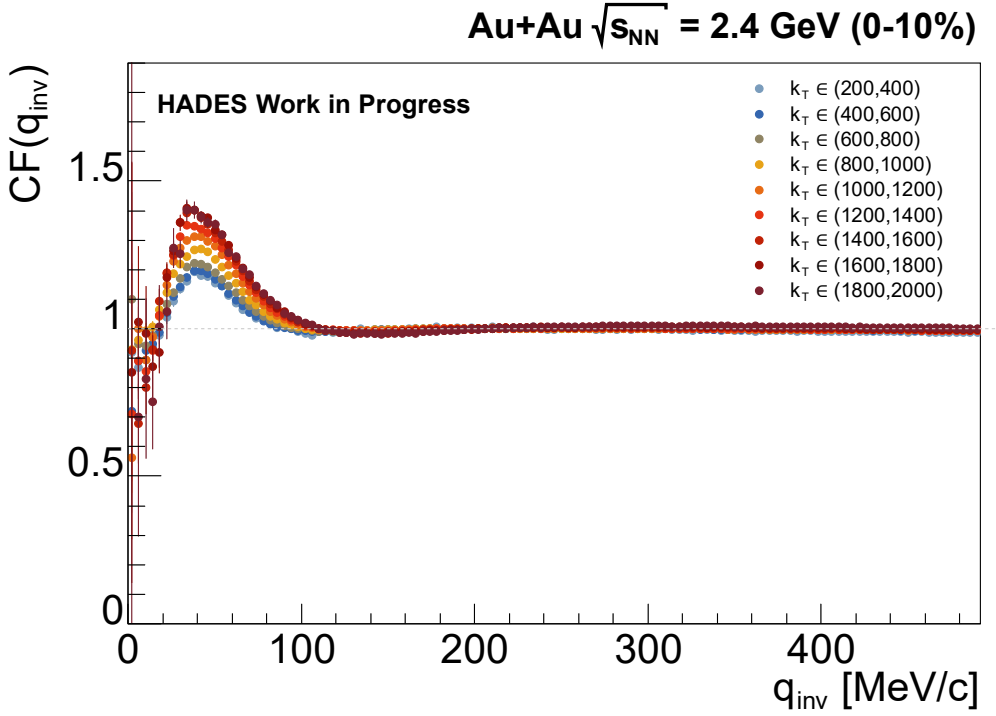
p+p at $\sqrt{s} = 4.5$ GeV – like-sign pion correlations

- A strong trend of both R and λ increase with minimum number of tracks in event can be observed
- Similar trend for both λ and R



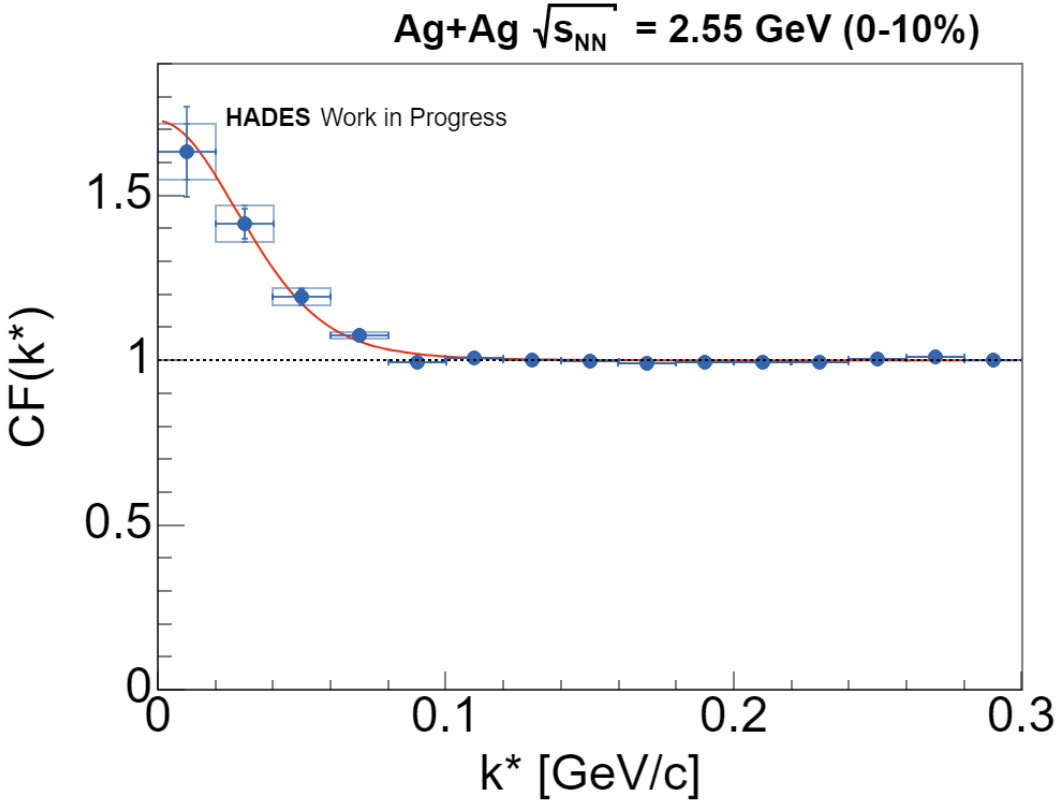
Au+Au at $\sqrt{s_{NN}} = 2.4$ GeV – proton-proton correlations

- High stopping in heavy-ion collisions at HADES energies implies a large abundance of protons
- Dynamics of heavy-ion collisions at high baryonic densities are not well known
- Protons carry integrated information from the moment of collision up to the freeze-out
- So far, only 1D analysis has been done, 3D analysis is in progress, out-side-long parameters to be compared with pions



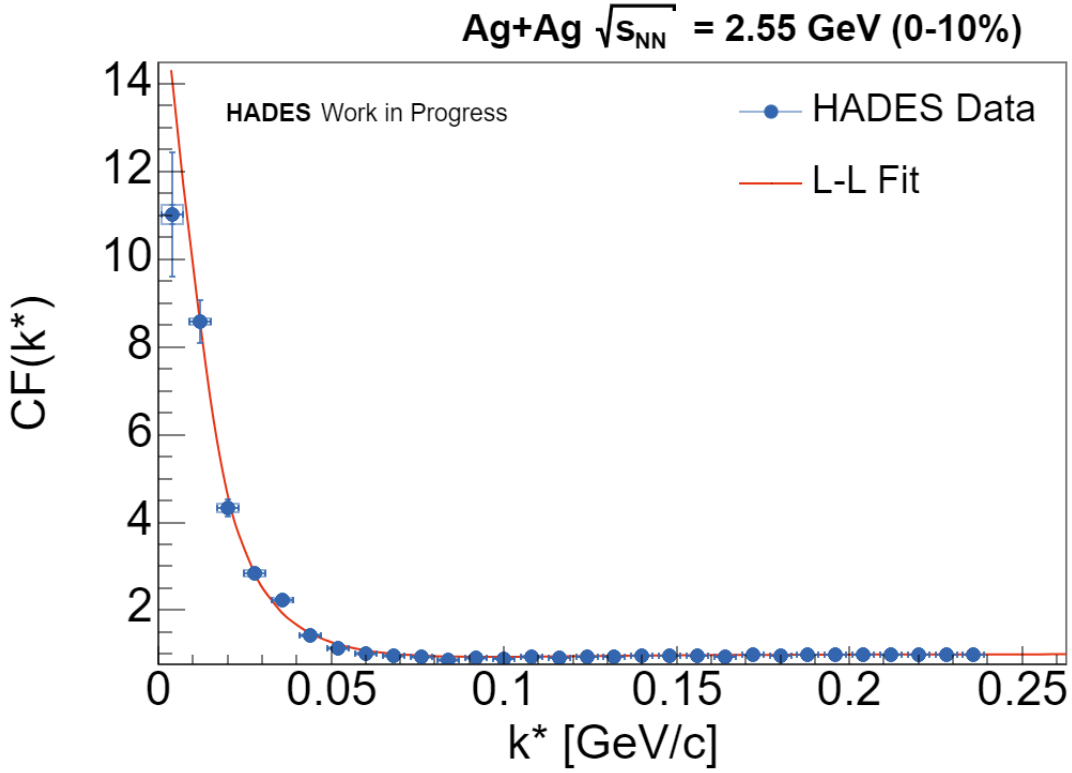
Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV - $p - \Lambda$ correlations

- $p - \Lambda$ correlations – first step in studying nucleon-hyperon interactions in heavy-ion collisions
- Presented is the correlation function obtained in Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV fitted using L-L parametrisation
- First spin separated measurements of strong interaction parameters of the $p - \Lambda$ interaction obtained from heavy-ion collisions:
  - $f_0 = 1.93^{+0.48}_{-0.42}$, $d_0 = 0.01$ Singlet
  - $f_0 = 1.76^{+0.14}_{-0.49}$, $d_0 = 3.44^{+0.36}_{-0.49}$ Triplet



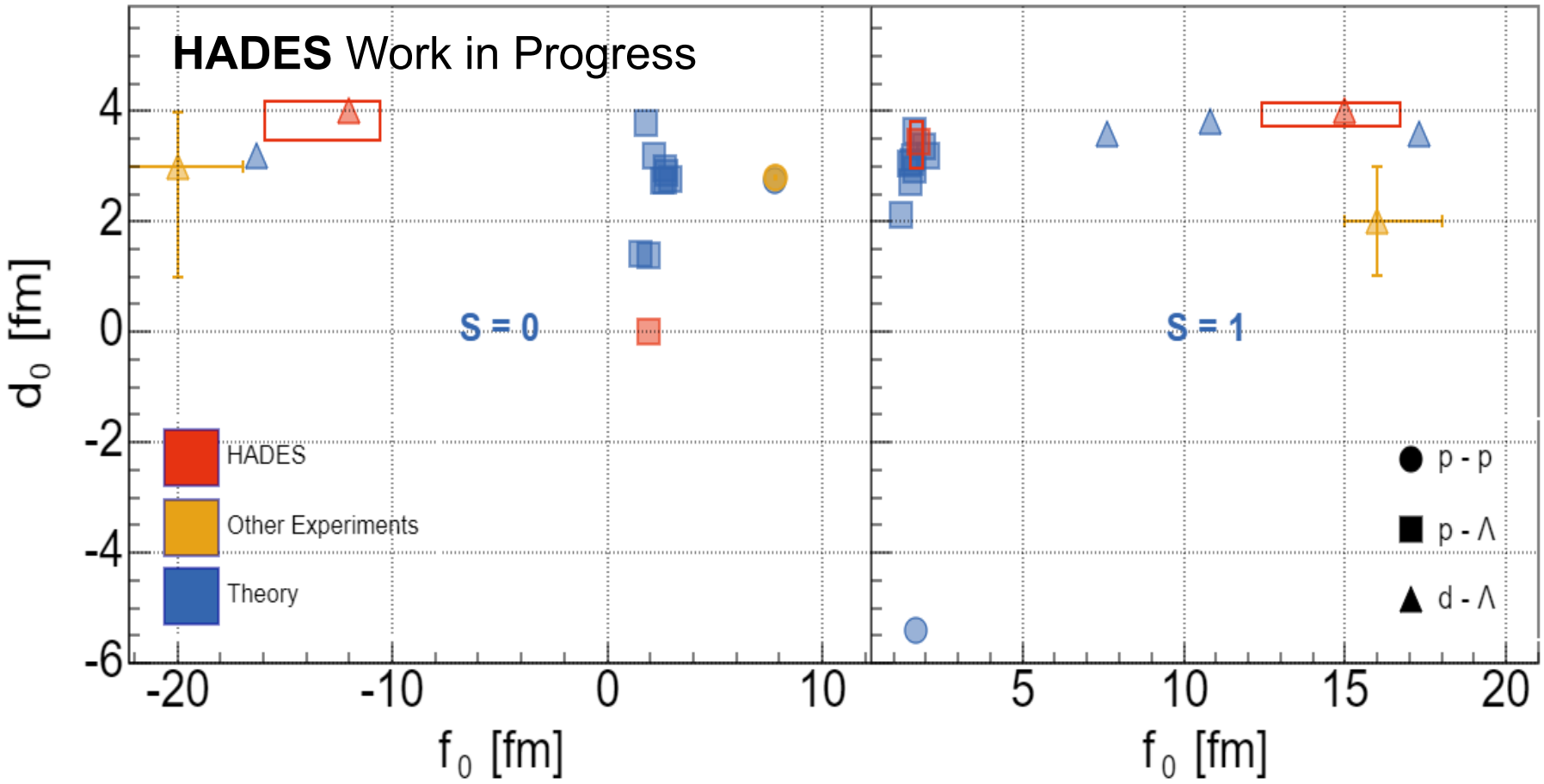
Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV - $\mathbf{d-\Lambda}$ correlation

- $\mathrm{d}-\Lambda$ correlations – provide constraints to the equation of state of compact stars
- Offer insight into the structure of hypertriton ${}^{3}_{\Lambda}\mathrm{H}$
- Also three-body interaction in ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{p} + \pi^{-} + \mathrm{d}$ decay
- Highest statistics when compared to other similar analyses
  - $\mathrm{f}_0 = -12^{+1.44}_{-3.92}$, $\mathrm{d}_0 = 4^{+0.18}_{-0.53}$ Doublet
  - $\mathrm{f}_0 = 15^{+1.73}_{-2.58}$, $\mathrm{d}_0 = 4^{+0.13}_{-0.28}$ Quartet



Final state interactions

- One can separate the scattering length (f_0) and effective range (d_0) into two spin states: singlet or doublet (**S=0**) and triplet or quartet (**S=1)**
- Overall following trend can be observed: $f_0^{p-p} < f_0^{p-\Lambda} < f_0^{d-\Lambda}$
- Theory and other experiments are taken from [2-9]



Future plans

Future plans of HADES

- HADES plans to continue data taking at least up to 2030

- Planned is continuation of the pion beam experiments

- More analyses planned:
  - Cold nuclear matter (in-medium vector mesons, strangeness)
  - Hadron spectroscopy, structure and exotics (baryon-meson couplings, EM couplings, exotic mesons, rare η decays)
  - Effective interactions (hyperon polarization, hypernuclei formation, hyperon-meson interaction)

- After that, it wil be working in tandem with CBM to explore the high μ_B region

Thank you for your attention!

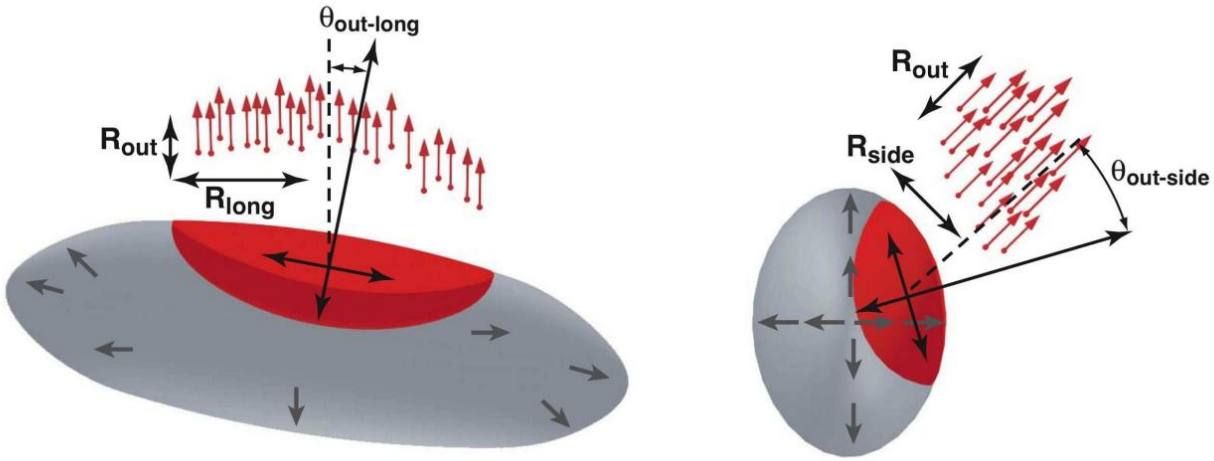
References

- [1] Scott Pratt – Validity of the smoothness assumption for calculating two-boson correlations in high-Energy collisions, Physical Review C (1997)
- [2] The ALICE Collaboration, Phys. Rev. C 99.2 (2019): 024001
- [3] T.A. Rijken, Phys. Rev. C—Nucl. Phys. 73.4 (2006): 044007
- [4] A. ES Green, M. H. MacGregor, and R. Wilson. International Conference on the nucleon-nucleon interaction, University of Florida, Gainesville, March 23 - 25, 1967
- [5] A. Cobis, J.Phys. G 23, 401 (1997)
- [6] H.W. Hammer, Nucl. Phys. A 705, 173 (2002)
- [7] G. Alexander, Phys. Rev. 173, 1452 (1968)
- [8] T.A. Rijken, Prog. Theor. Phys. Suppl. 185, 14 (2010)
- [9] Y. Hu, CPOD 2024

Bonus slides

3D femtoscopy

- Sources in real collisions aren't perfectly spherical
- Thus they have different radii in different directions



Source:Femtoscopy in Relativistic Heavy Ion Collisions: Two Decades of Progress

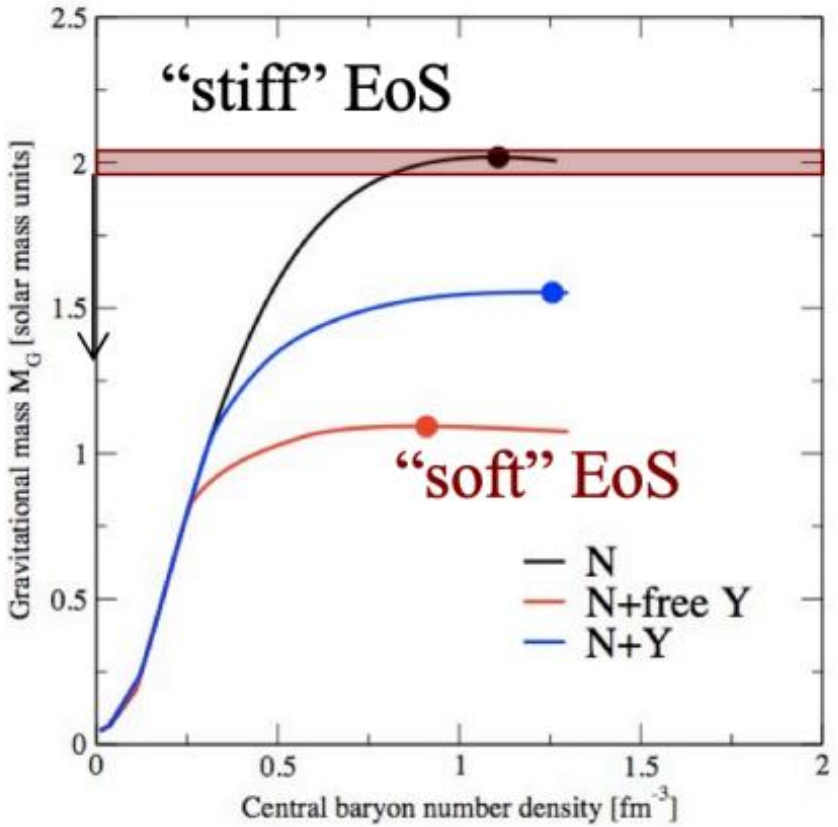
3D femtoscopy - parametrization

- $C(q_{out}, q_{side}, q_{long}) = N[1 - \lambda_{osl} + \lambda_{osl} K_C(q, R_{inv}) C_{qs}(q_{out}, q_{side}, q_{long})]$

- Where:
  - $C_{qs}(q_{out}, q_{side}, q_{long}) = 1 + exp\left(-(2q_{out}R_{out})^2 - (2q_{side}R_{side})^2 - \left(2q_{long}R_{long}\right)^2\right)$ - quantum-statistical part
  - $q = q_{inv}(q_{out}, q_{side}, q_{long}, \bar{\mathrm{k}}_{\mathrm{T}})$ - average invariant momentum difference for given intervals of relative momentum and k_{T}

Neutron Star Puzzle

- Nucleons converting to hyperons – Energy favorable
- Appearance of Y → smaller Fermi pressure → mass reduction (incompatible with observation)
- Some mechanism needs to introduce additional pressure at high densities
- NY and YY interactions could provide such a repulsive force



Source: Benhar, O. (2023). Observational Constraints on Theoretical Models. In: Structure and Dynamics of Compact Stars. Lecture Notes in Physics, vol 1019