The Ohio State University

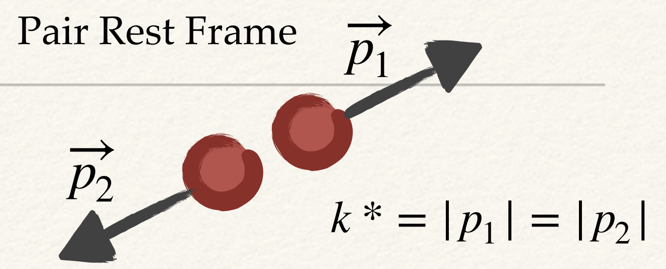
GSI

Proton-proton and proton-cluster femtoscopy at the HADES experiment

Maria Stefaniak for HADES Collaboration

HADES

06.11.2023, Catania, WPCF 2023

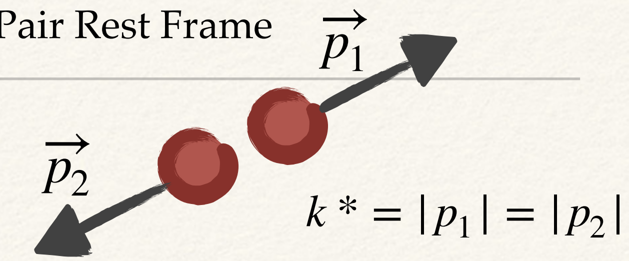


Femtoscopy

Koonin-Pratt formula:

$$C(k^\star) = \int S(r^\star) |\Psi(k^\star, r^\star)|^2 d^3 r^\star$$

Femtoscopy



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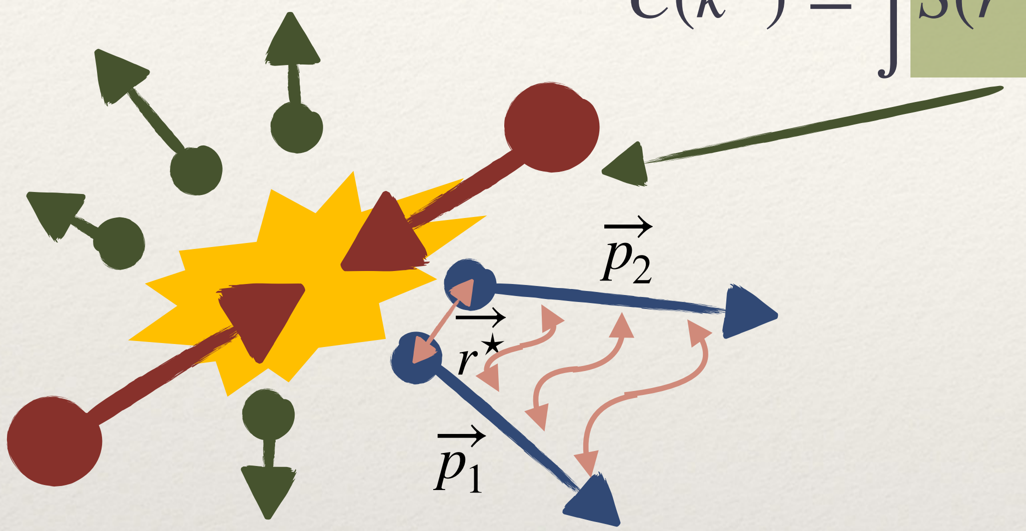

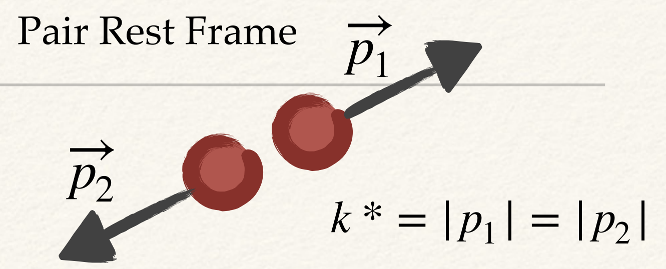

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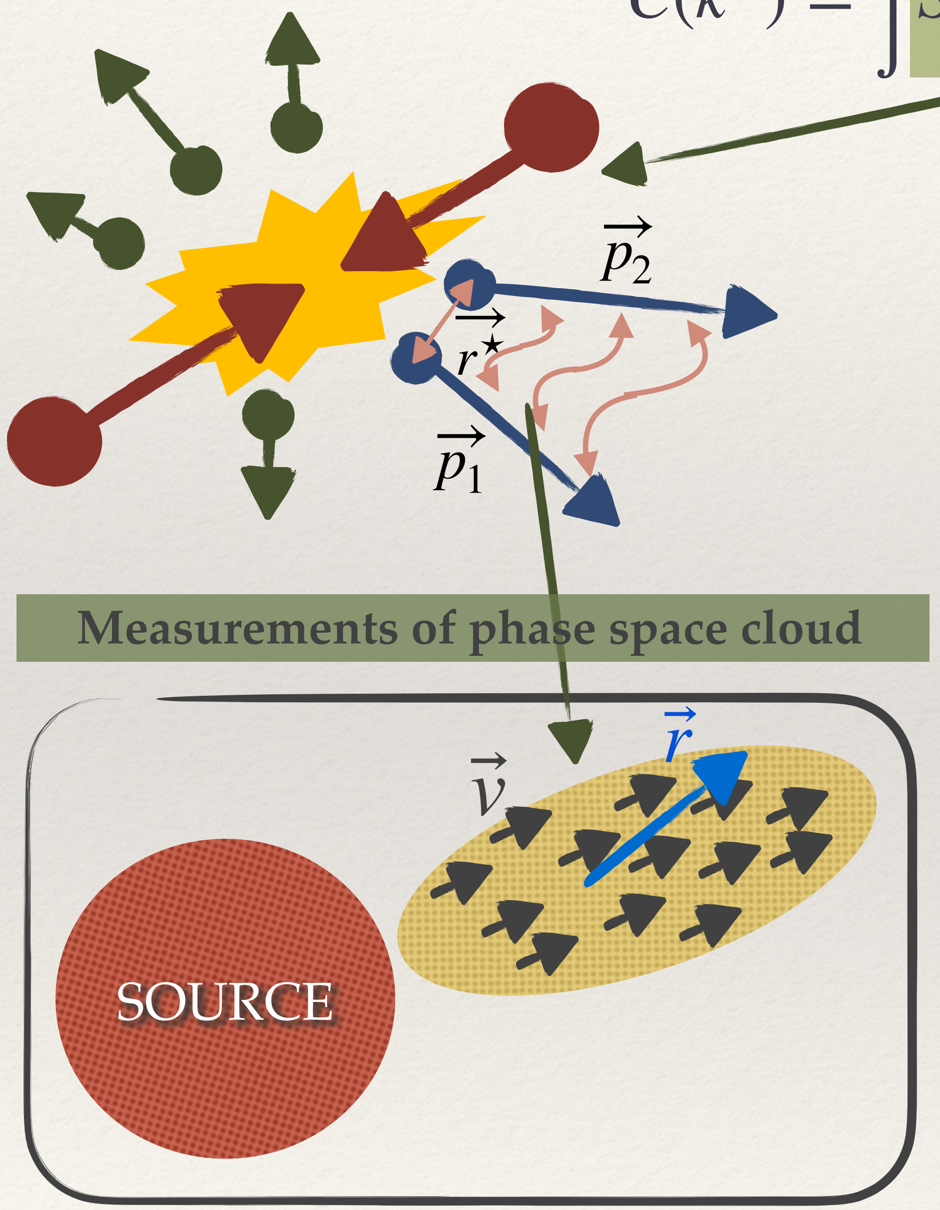

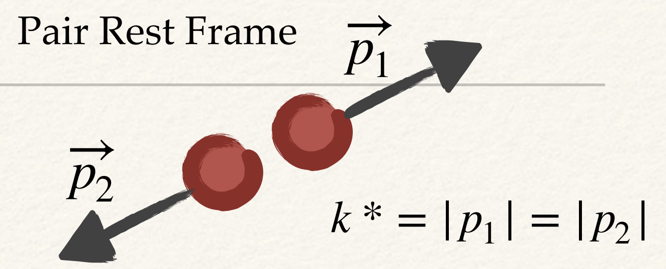

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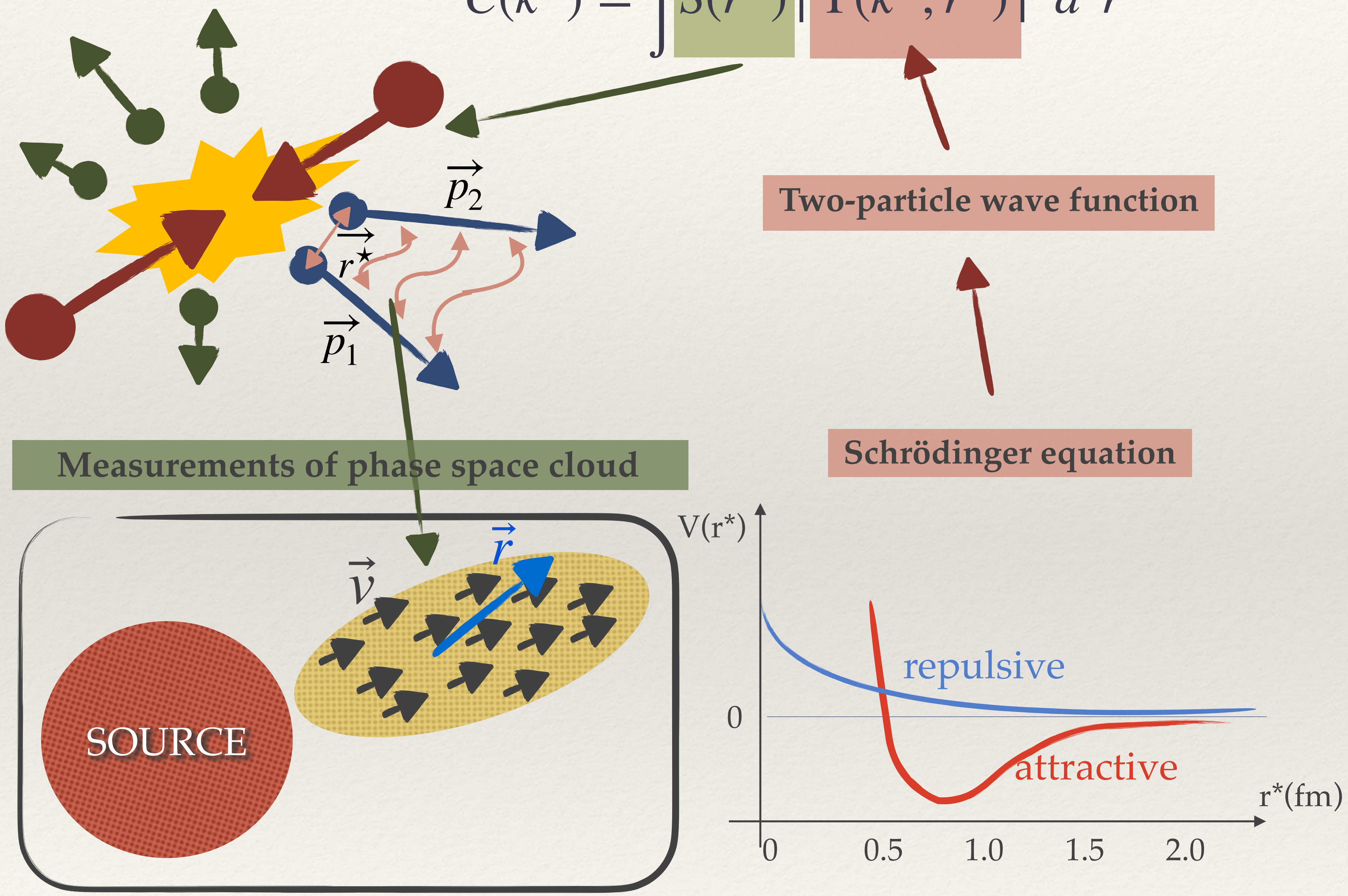
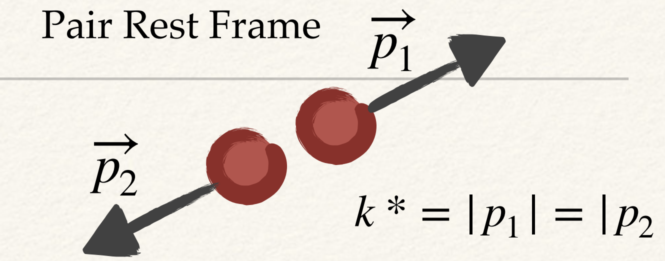
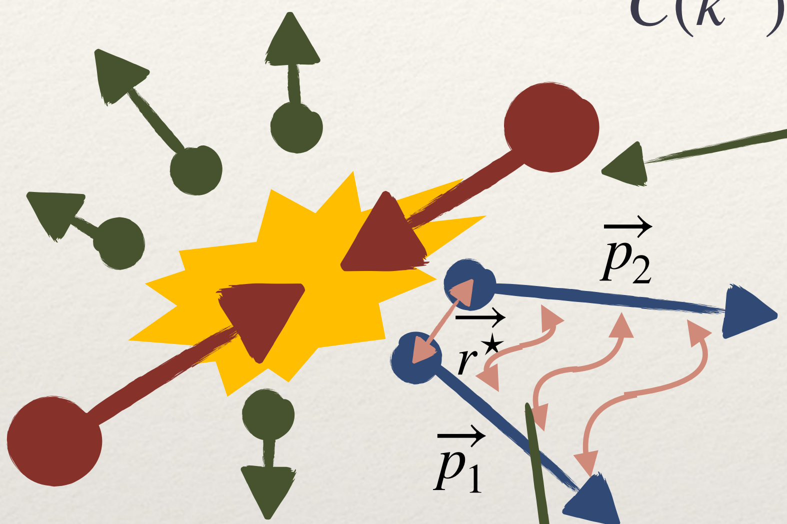




Femtoscopy

Koonin-Pratt formula:

$$C(k^\star) = \int S(r^\star)\,|\Psi(k^\star, r^\star)|^2\, d^3r^\star = \frac{Sgnl(k^\star)}{Bckg(k^\star)}$$



Two-particle wave function

In experiment:
combination of all possible pairs in

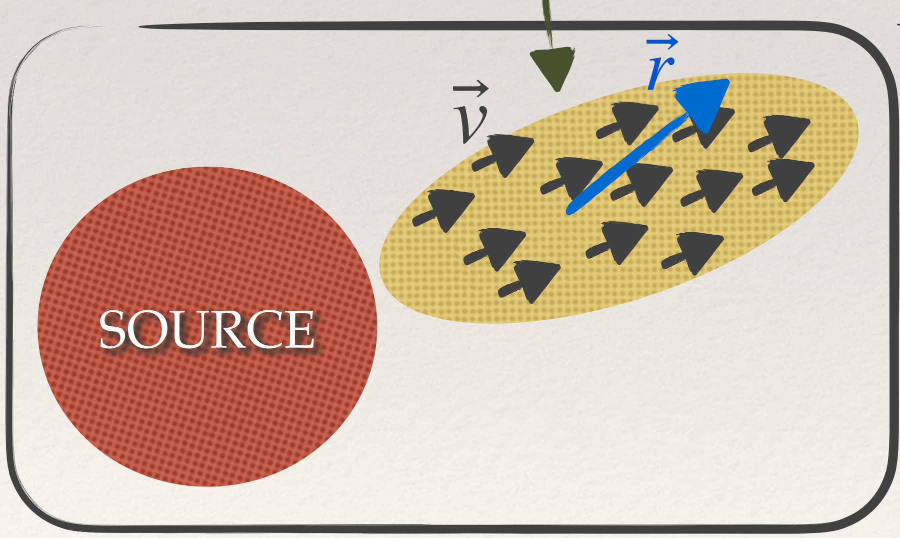
Signal: the <u>same</u> event

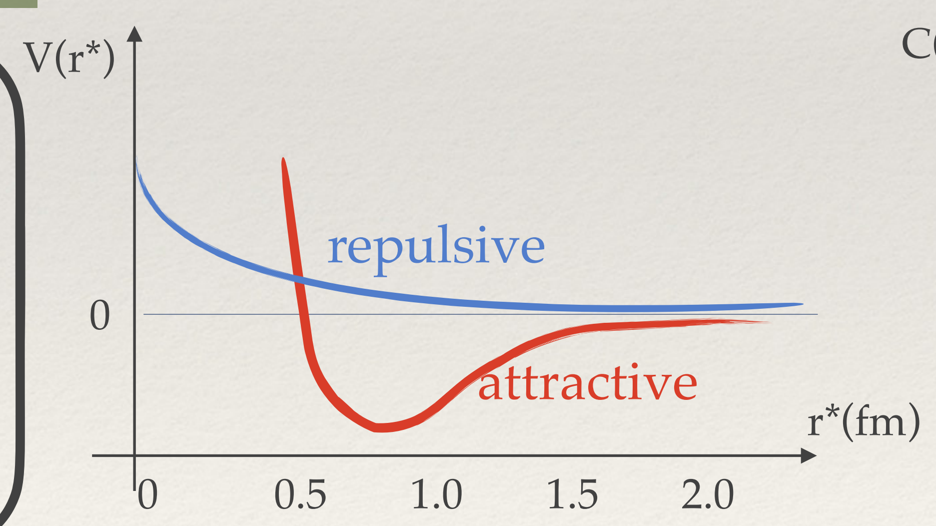
Background : <u>different</u> events.

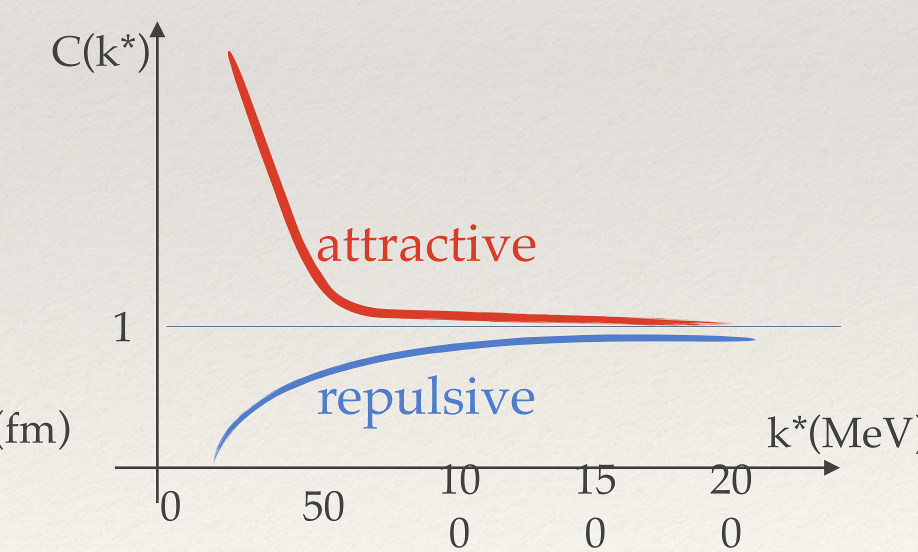
Measurements of phase space cloud

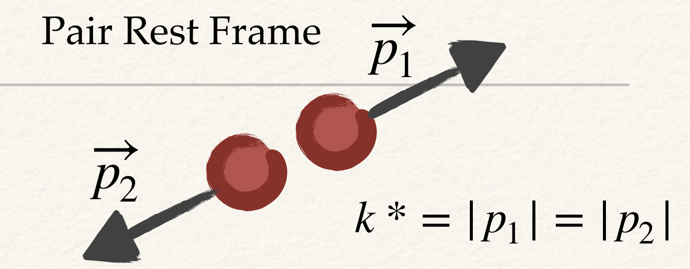
Schrödinger equation

Correlation function







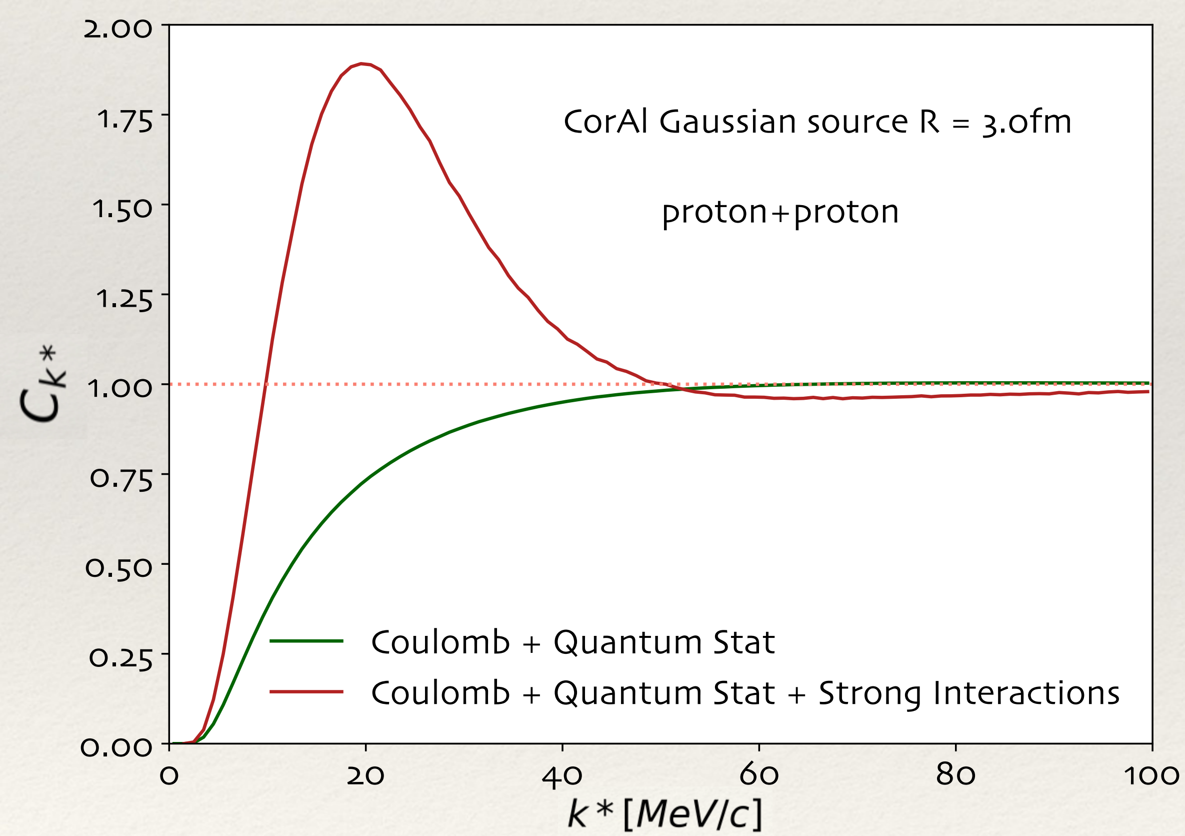


Femtoscopy

Koonin-Pratt formula:

$$C(k^\star) = \int S(r^\star) |\Psi(k^\star, r^\star)|^2 d^3 r^\star = \frac{Sgnl(k^\star)}{Bckg(k^\star)}$$

Origin of the Correlation Function:

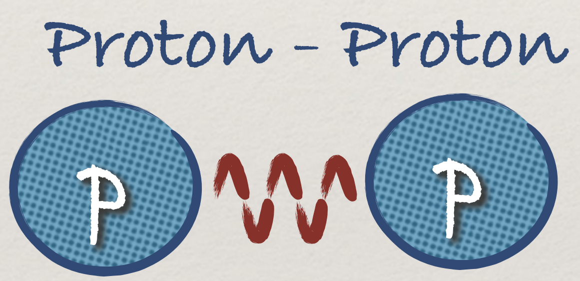


1. Coulomb:
   - Attractive for opposite sign particles
   - **Repulsive for same sign particles**
2. Quantum Statistic:
   - Bosons: positive
   - **Fermions: negative**
3. Strong Interactions:
   - Can be both **attractive** or repulsive, depending on potentials

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

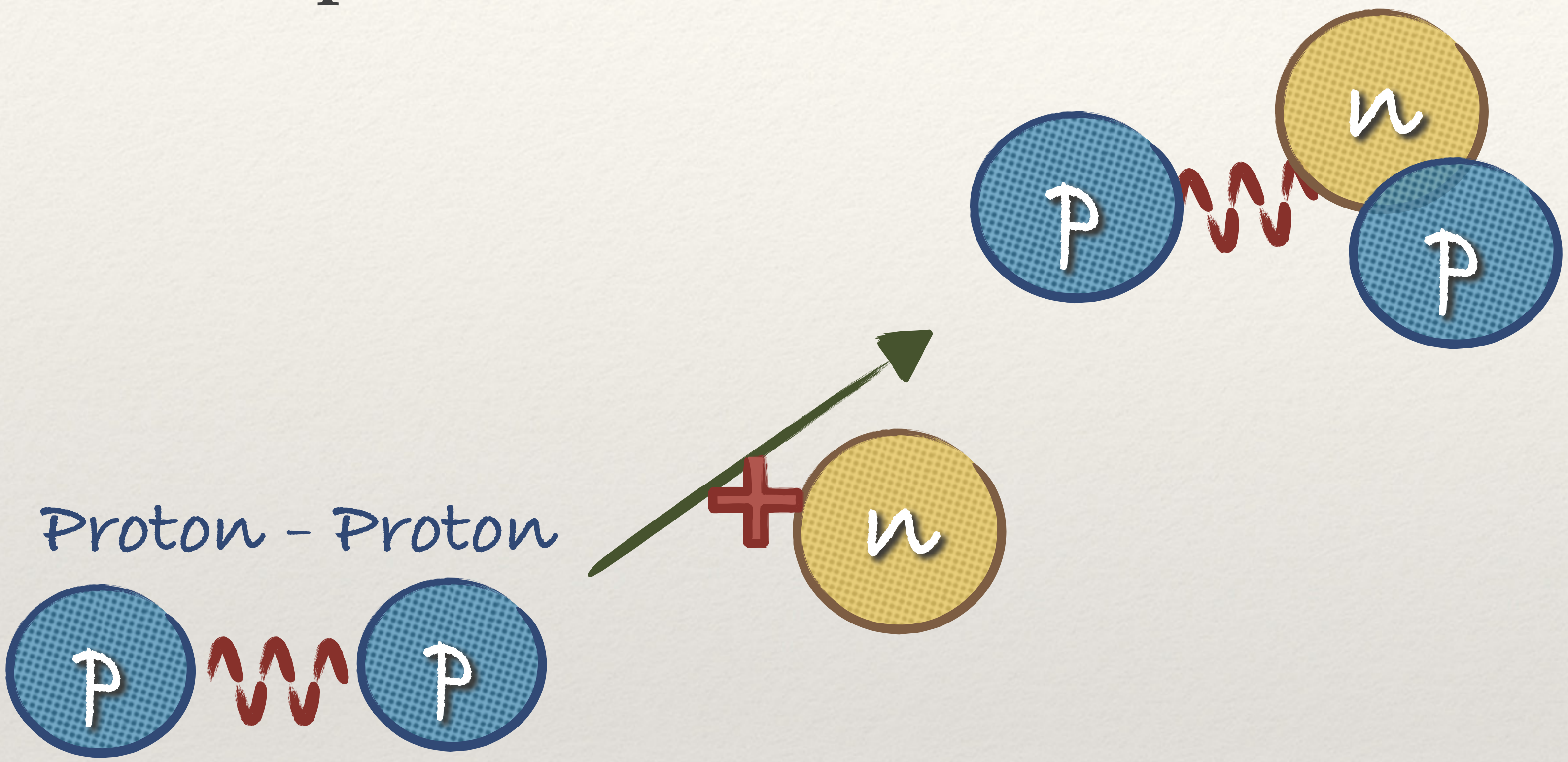
Measurements

Femtoscopic correlations of:



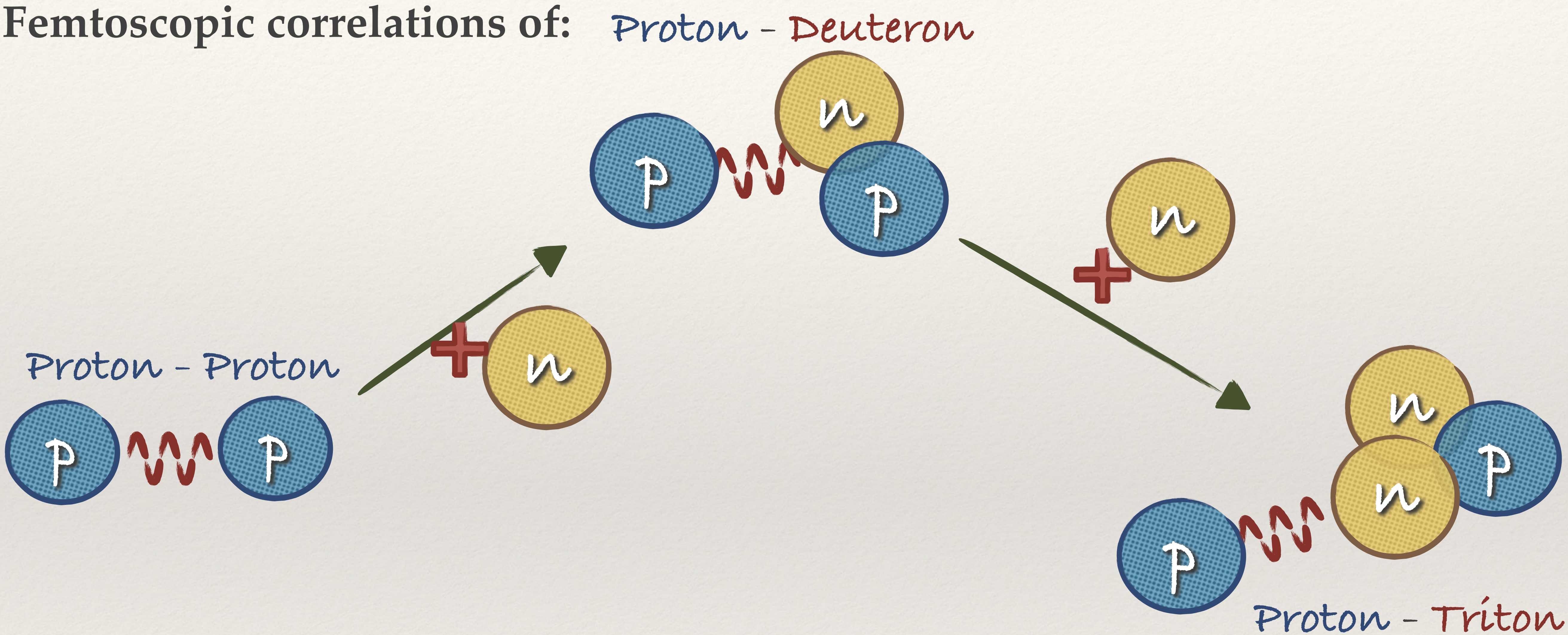
Measurements

Femtoscopic correlations of: Proton - Deuteron



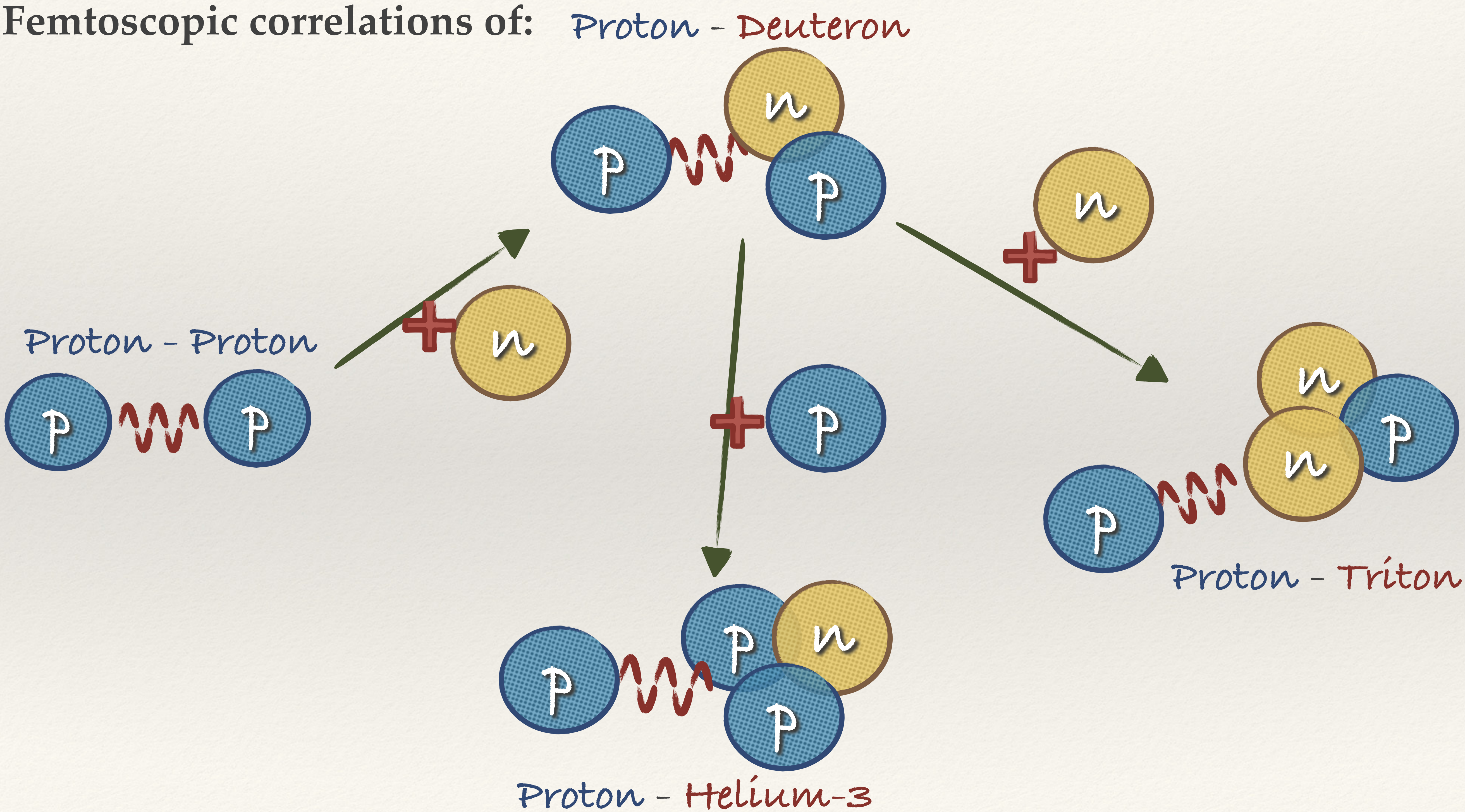
Measurements

Femtoscopic correlations of:



Measurements

Femtoscopic correlations of:

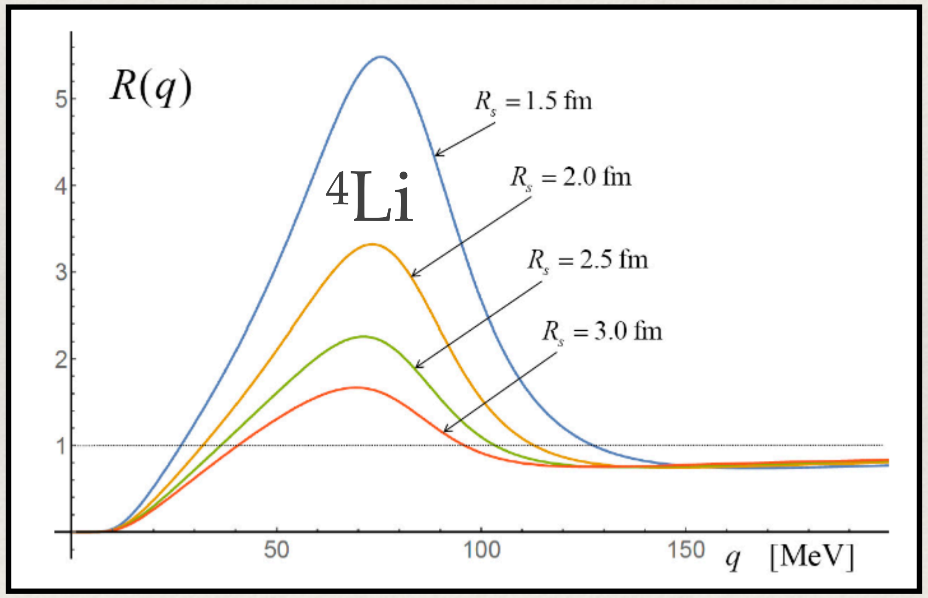


Motivation

1. Studies of decaying nuclear state presence

Some of them impossible to see in traditional "mass invariant" distributions

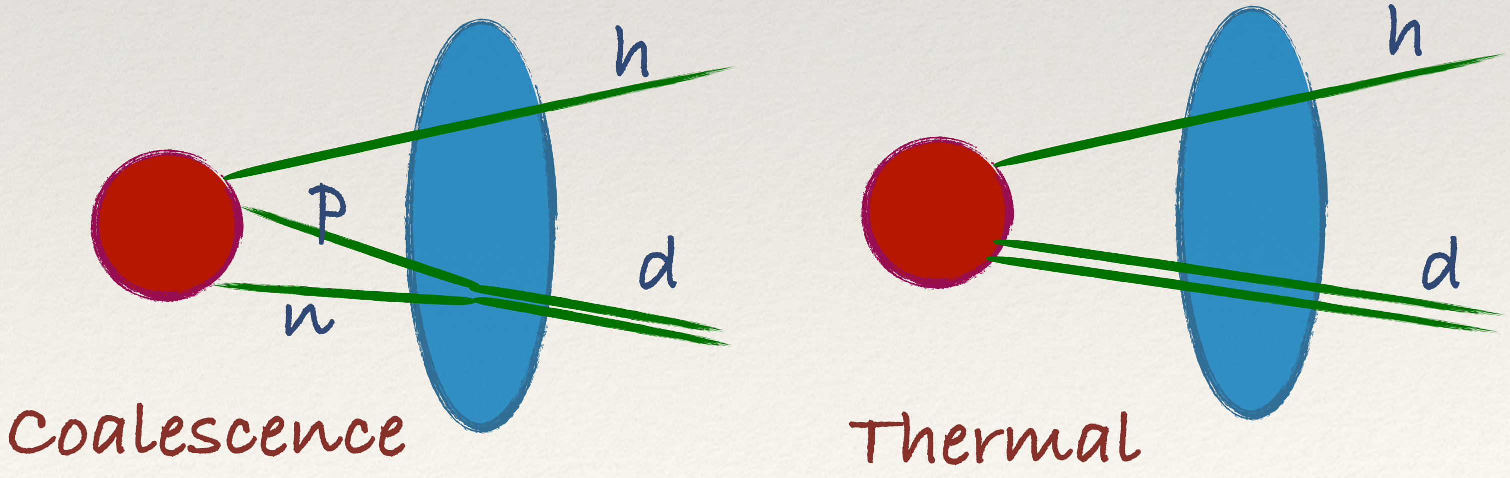
S. Mrówczyński, S. Bazak: Eur. Phys. J. A 56, 193 (2020)



p-^{3}He with ^{4}Li resonance + Coulomb

Femtoscopic correlations provide the access to these studies

Possible validation of the production mechanism



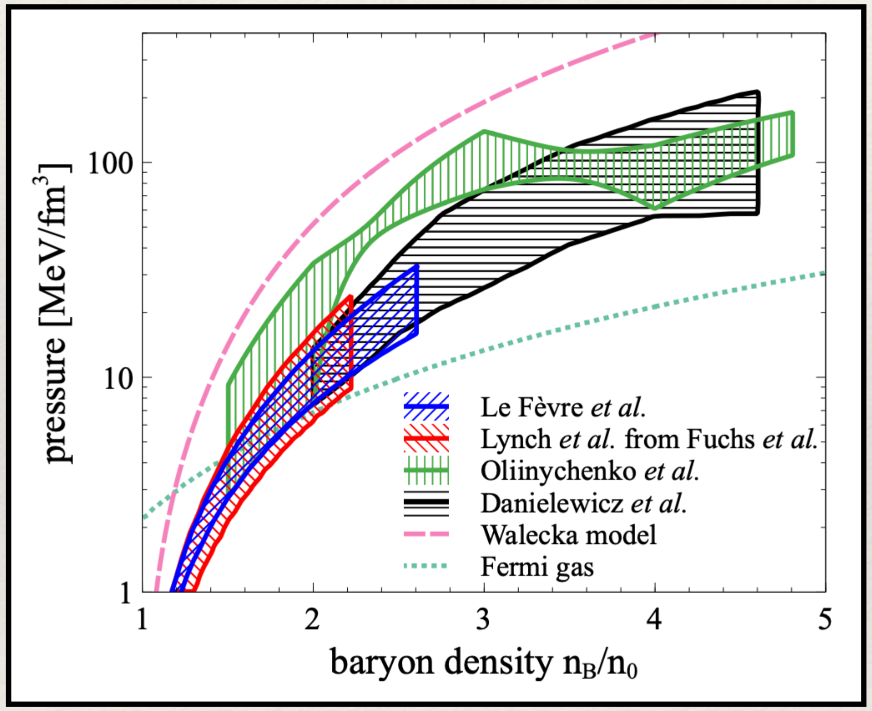
D. Olinychenko: Nuclear Physics A 00 (2020) 1-9

Motivation

2. Sensitivity to EoS

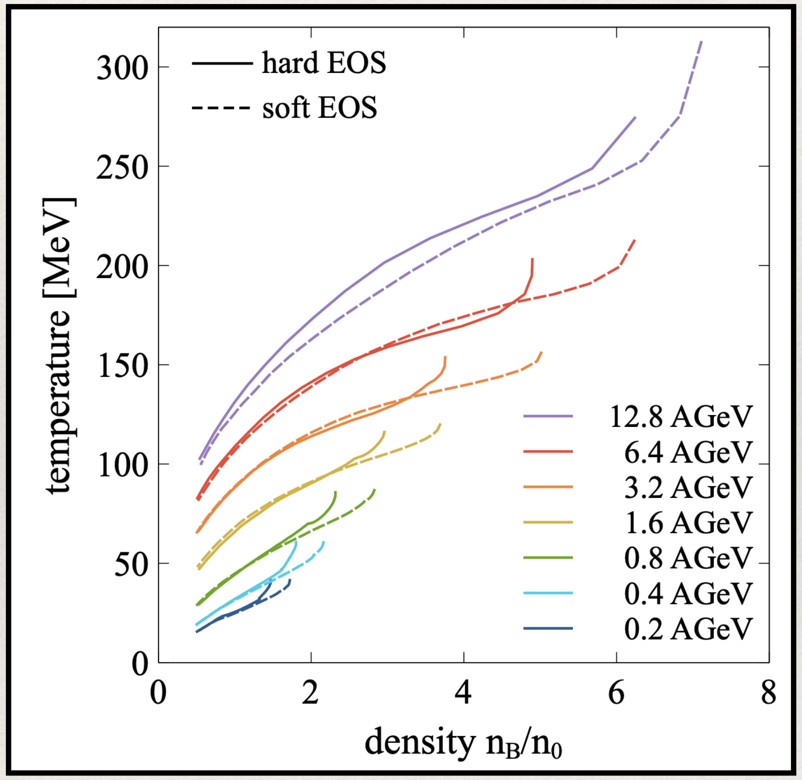
*A. Sorensen, **M. Stefaniak**, et al: White Paper "Dense Nuclear Matter Equation of State from Heavy-Ion Collisions" arXiv:2301.13253*

Experimental constraints on the EoS searches



Selected constraints on the symmetric EOS obtained from comparisons of experimental data to hadronic transport simulations

How to access different system's temperatures and densities



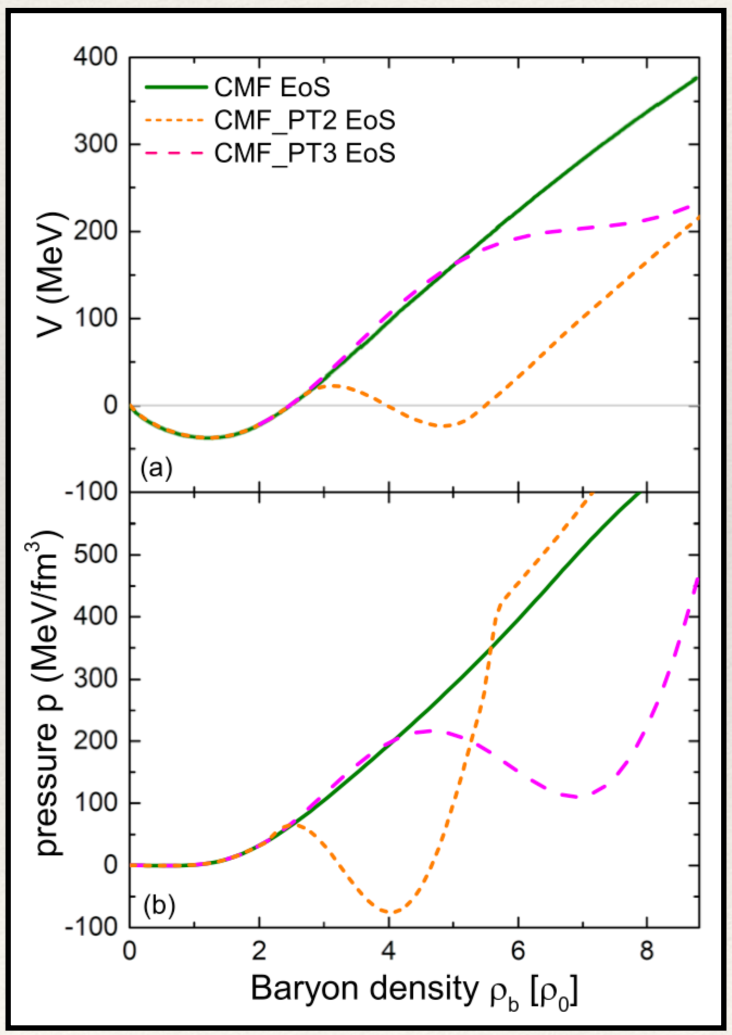
Prepared with UrQMD Skyrme potential, Temperature in the center of mass frame

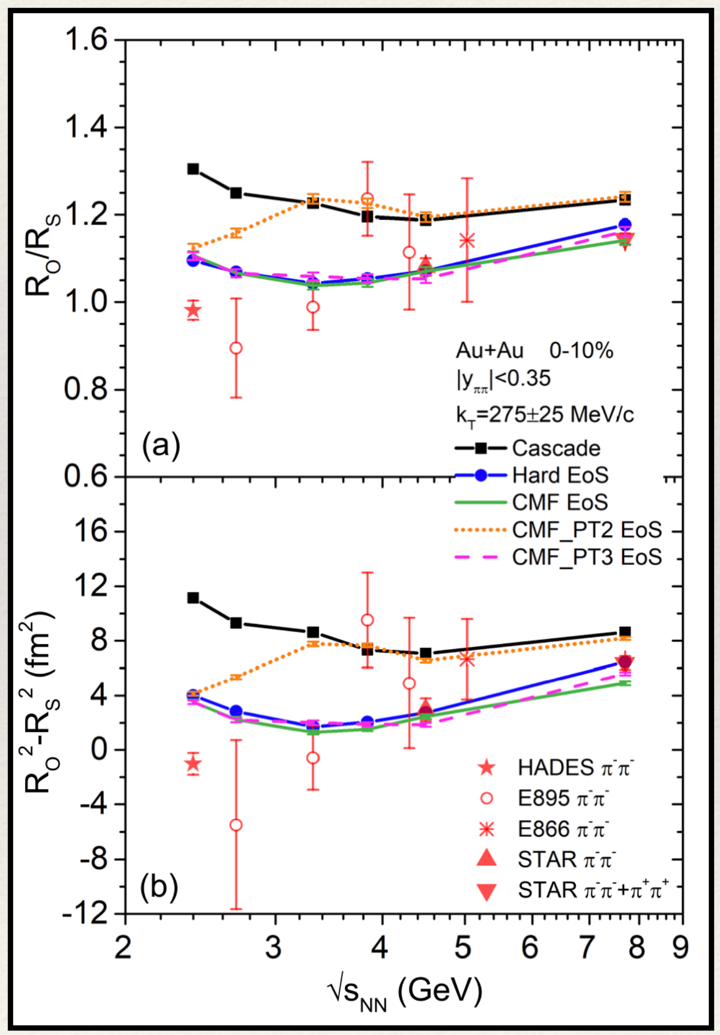
Low baryon densities well explored, while in higher ones still huge uncertainty.

Motivation

2. Sensitivity to EoS

P. Li, J. Steinheimer, et al: Sci. China-Phys. Mech. Astron. 66, 232011 (2023)
S.Pratt: Phys. Rev. D33:1314,1986





Pion femtoscopy with UrQMD

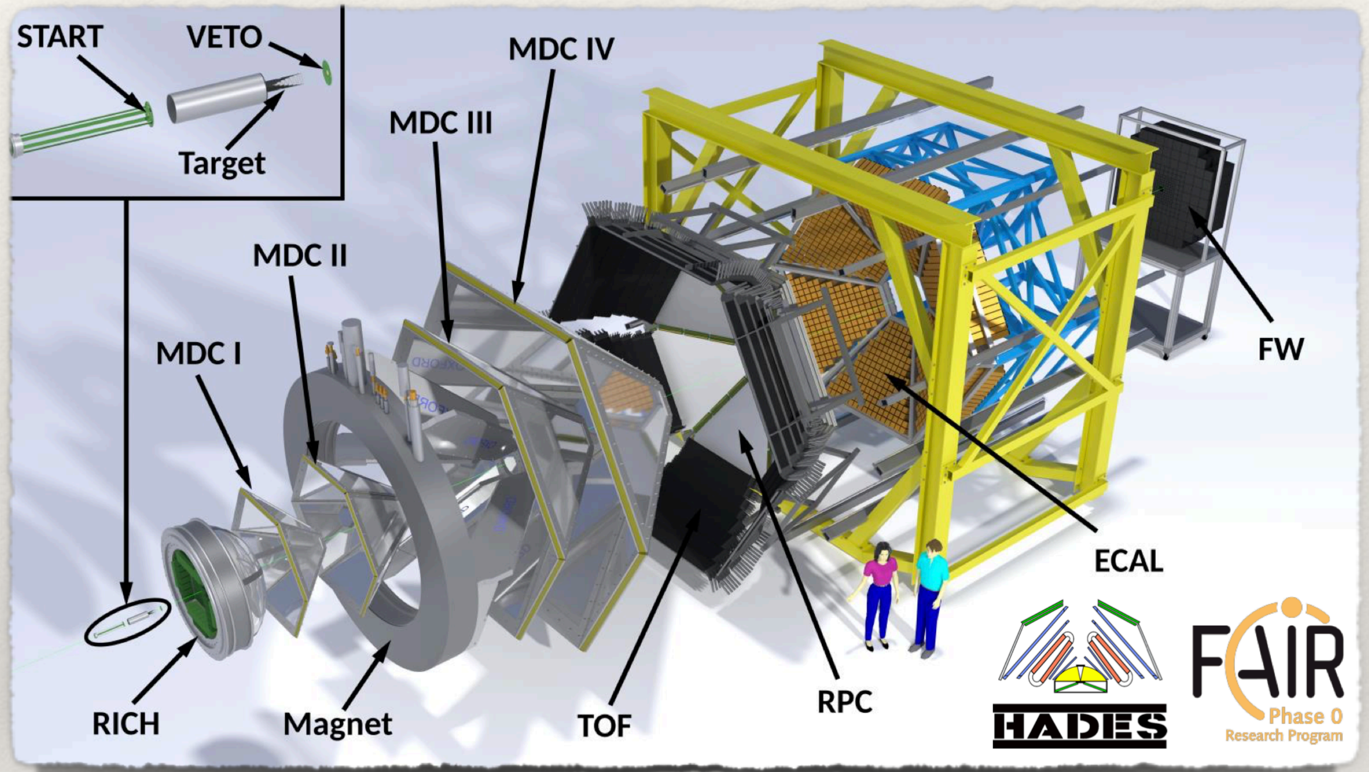
EoS sensitivity by pion femtoscopy decreases for lower net baryon densities

CMF PT2 EoS: phase transition at low baryon densities
CMF PT3 EoS: phase transition at higher baryon densities

HADES Experiment

High Acceptance Di-Electron Spectrometer

- Fixed target experiment at SIS18 (GSI, Germany)
- Low mass Mini-Drift-Chambers used for tracking
- Time of flight walls RPC and TOF
- Almost full azimuthal angle and polar angles between 18° and 85° covered



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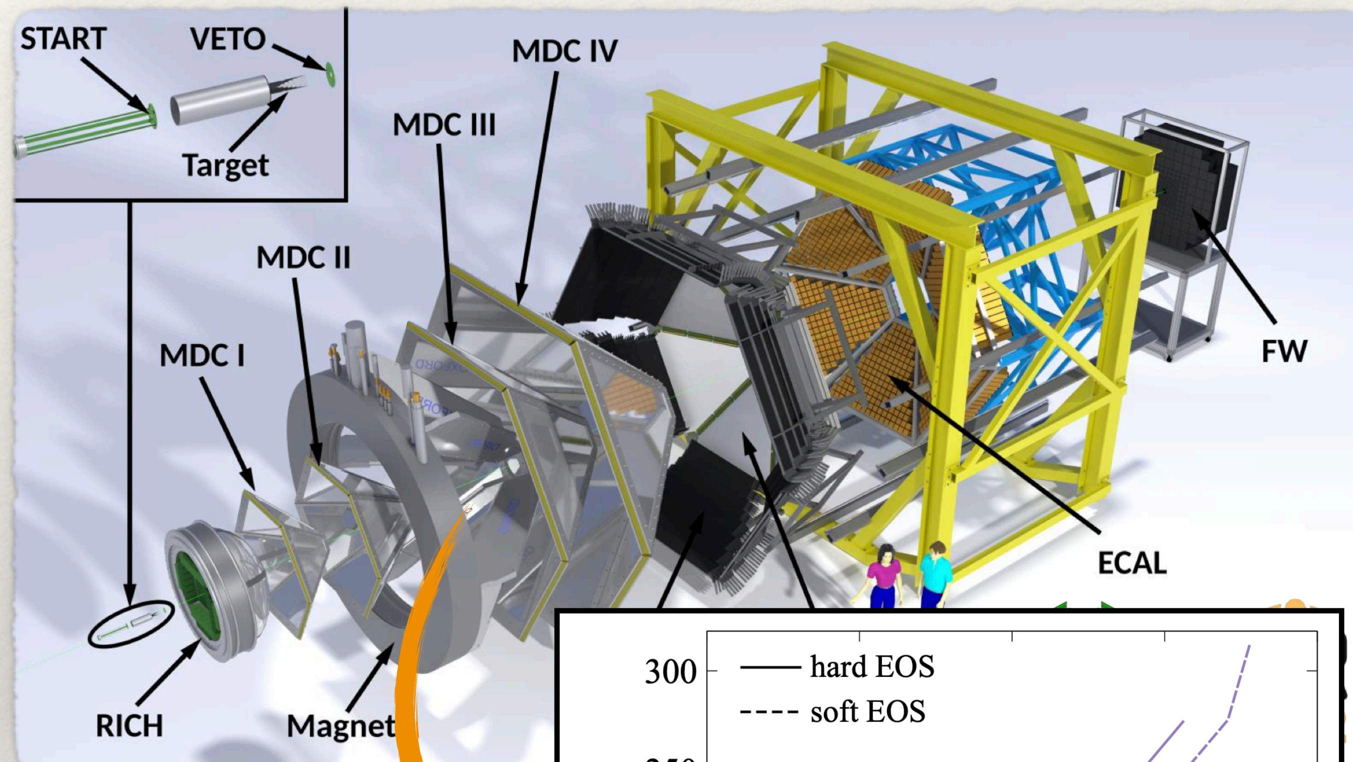
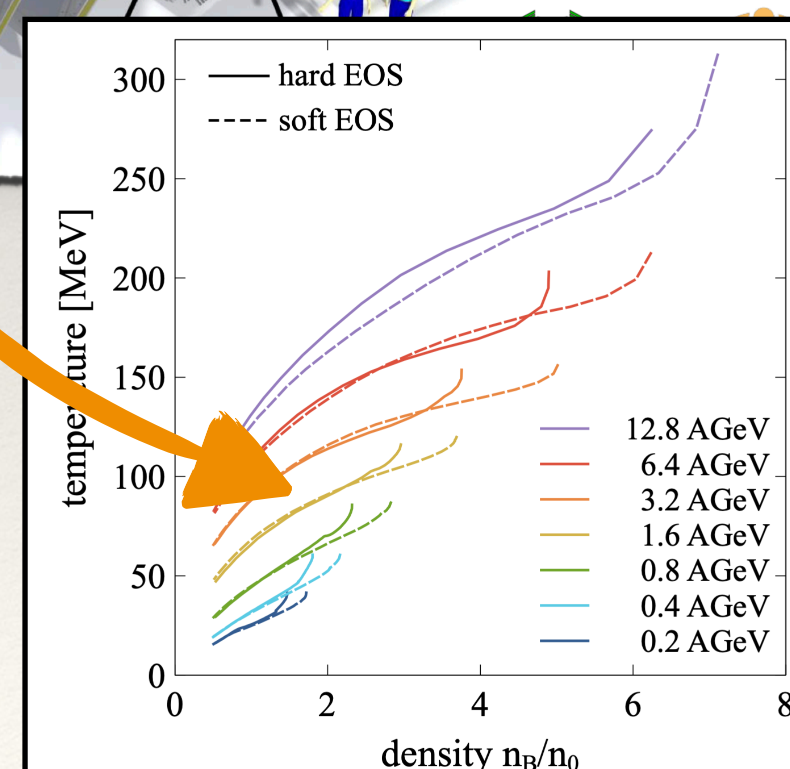
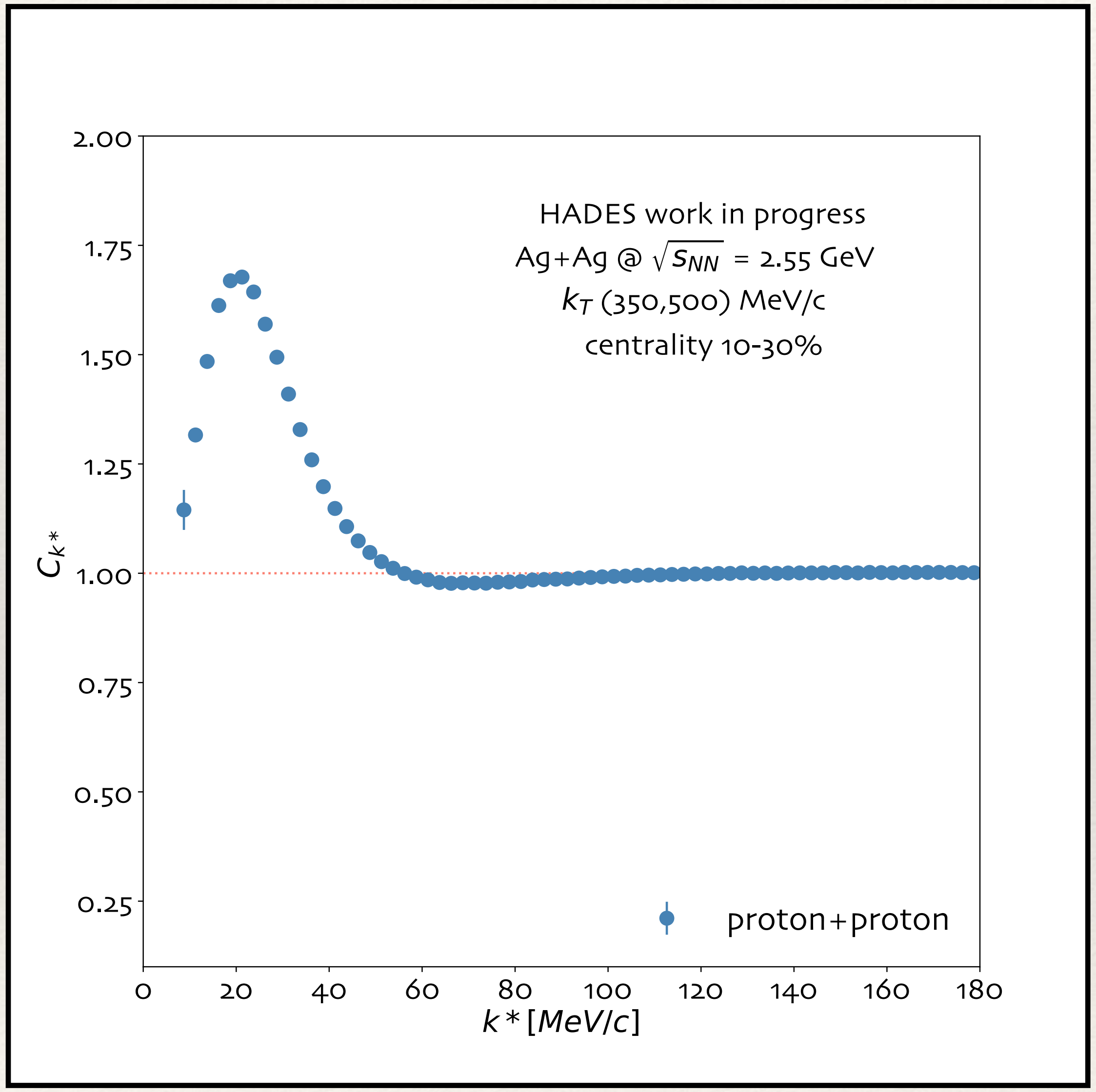
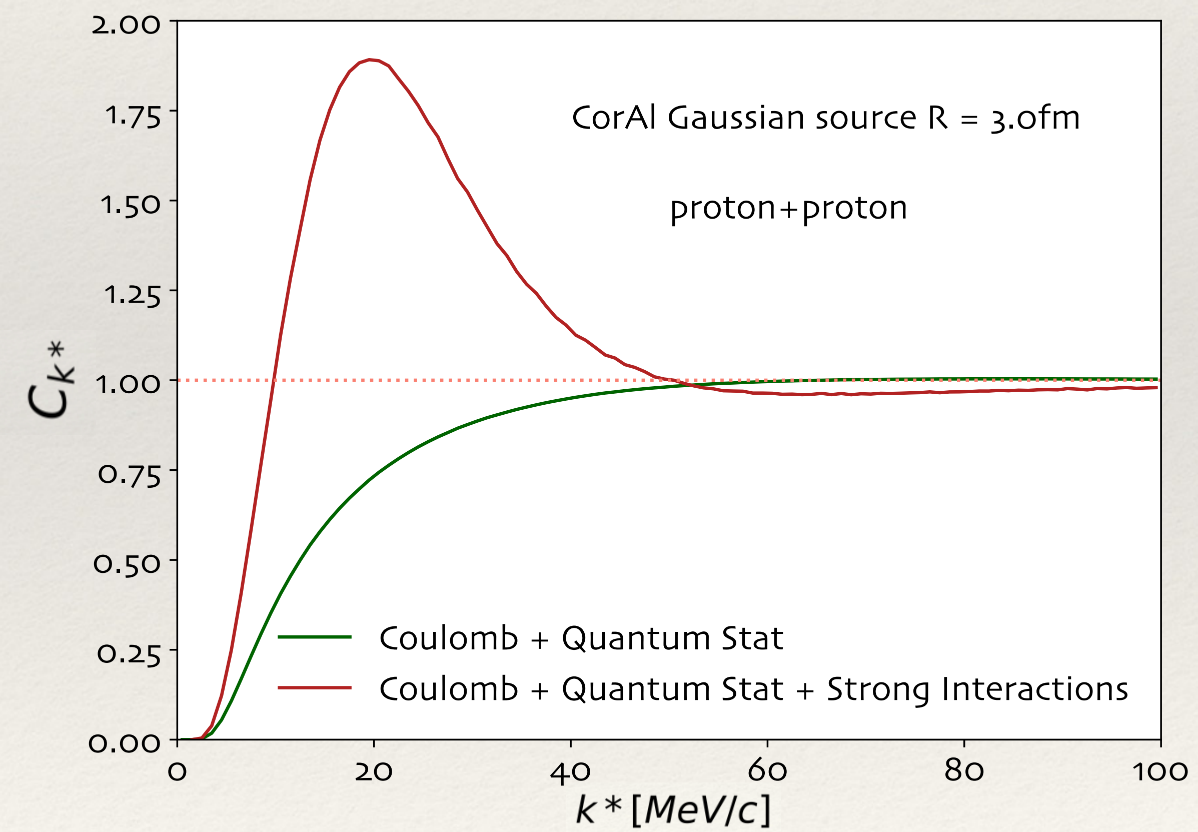




Proton - cluster



- Positive correlation originating from Strong Interactions
- Negative caused by Coulomb and Quantum Statistics



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

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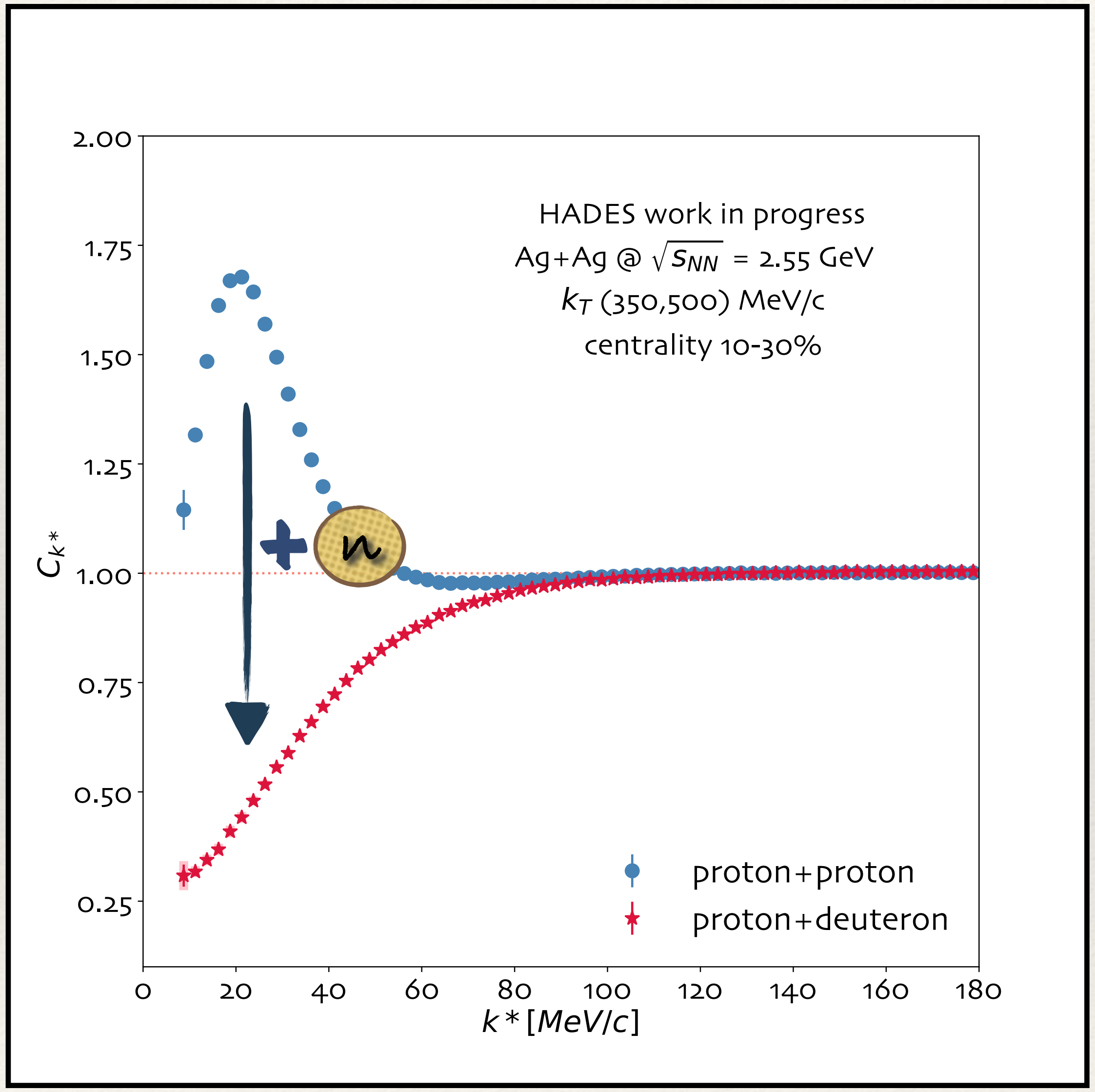
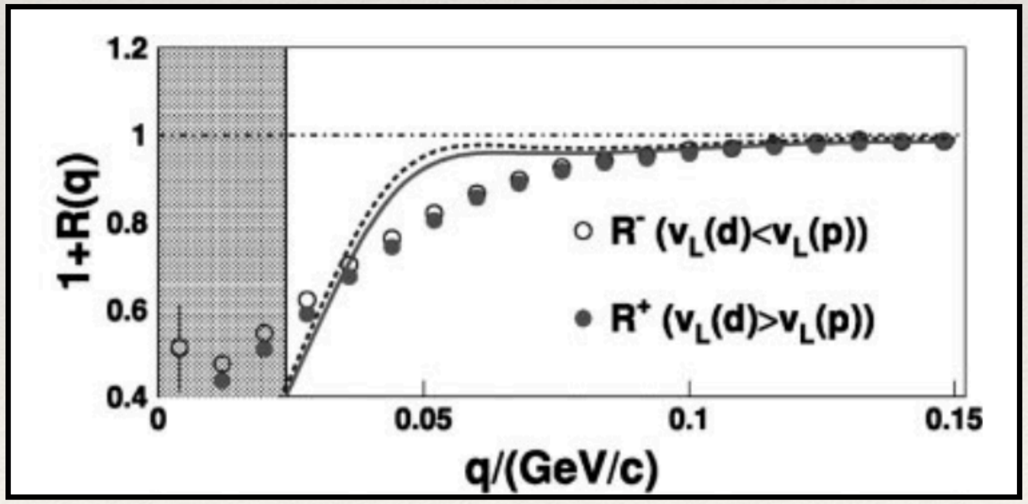


- After "adding" neutron to correlated system: repulsive interactions between p-d
- Better measurement precision than other published results

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



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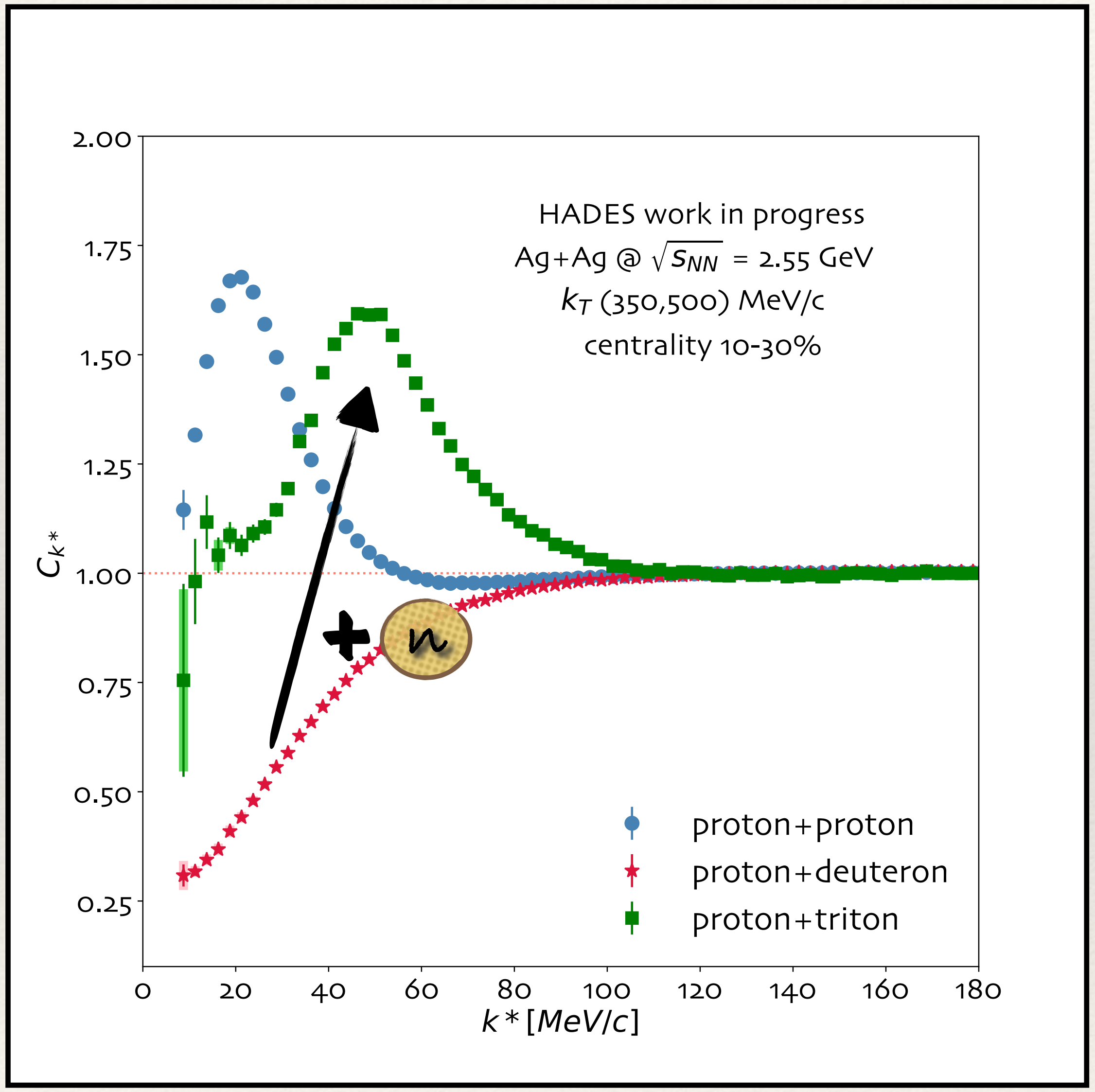
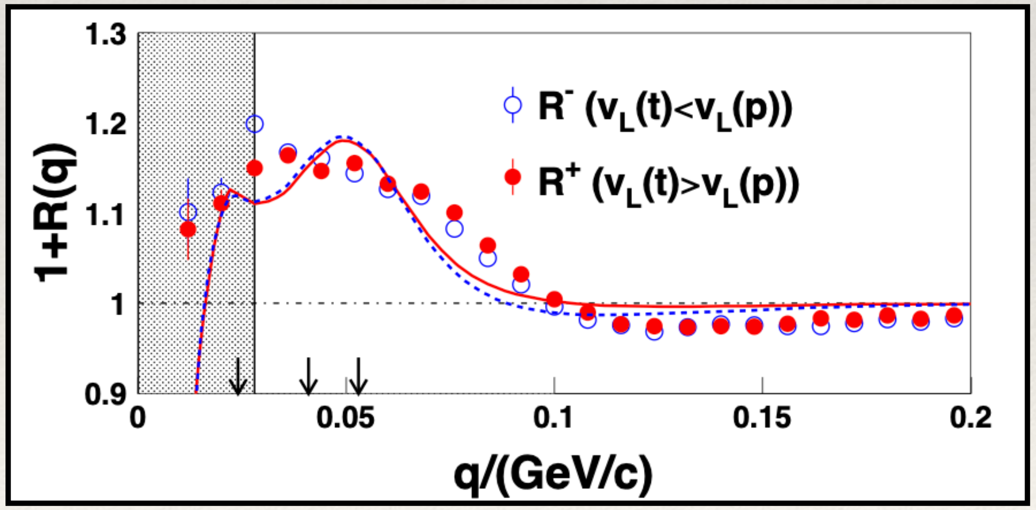
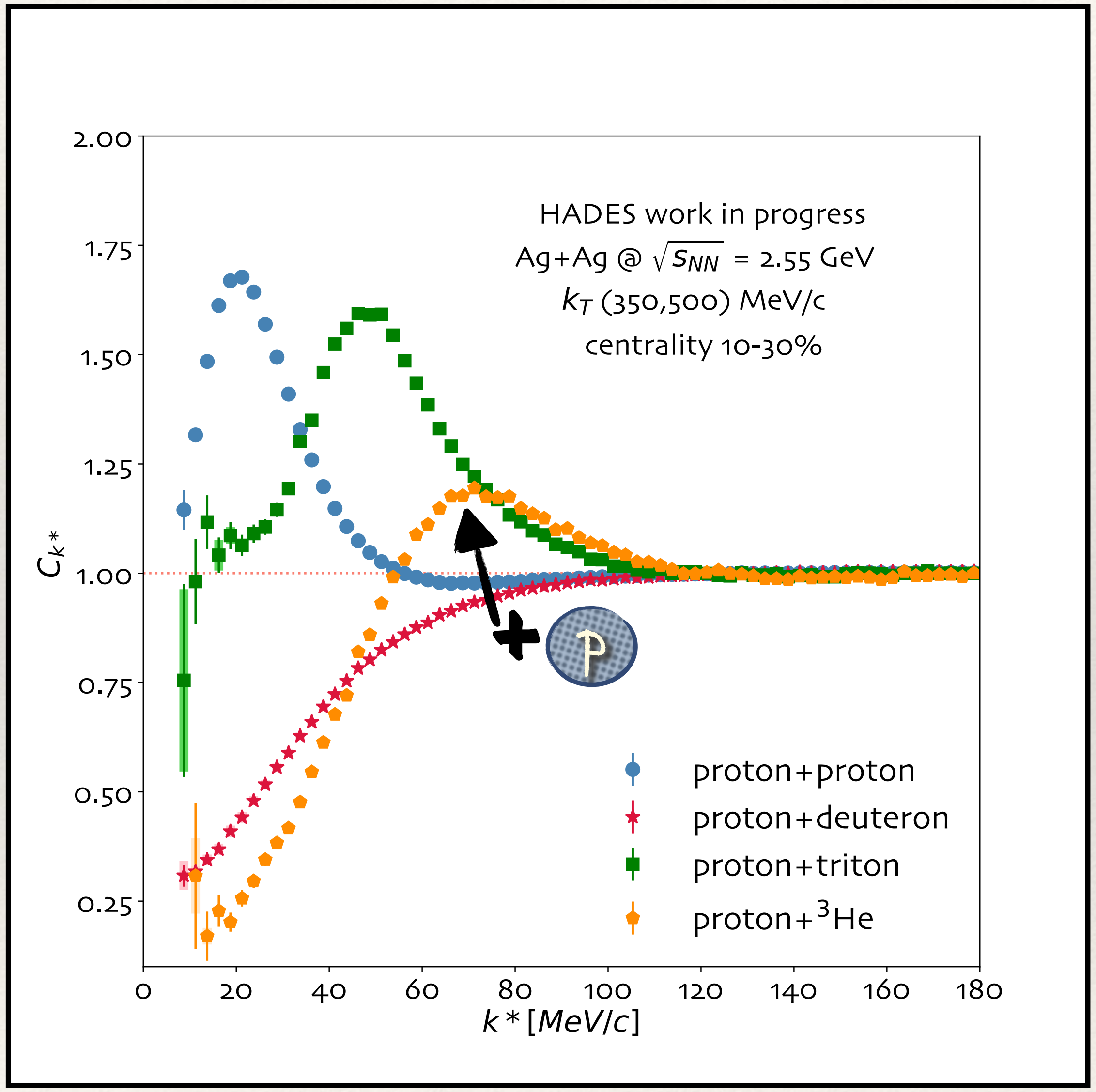


- After "adding" neutron to correlated system: Strong positive correlation
- Visible sharp peak caused by the possible light nuclei decay

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

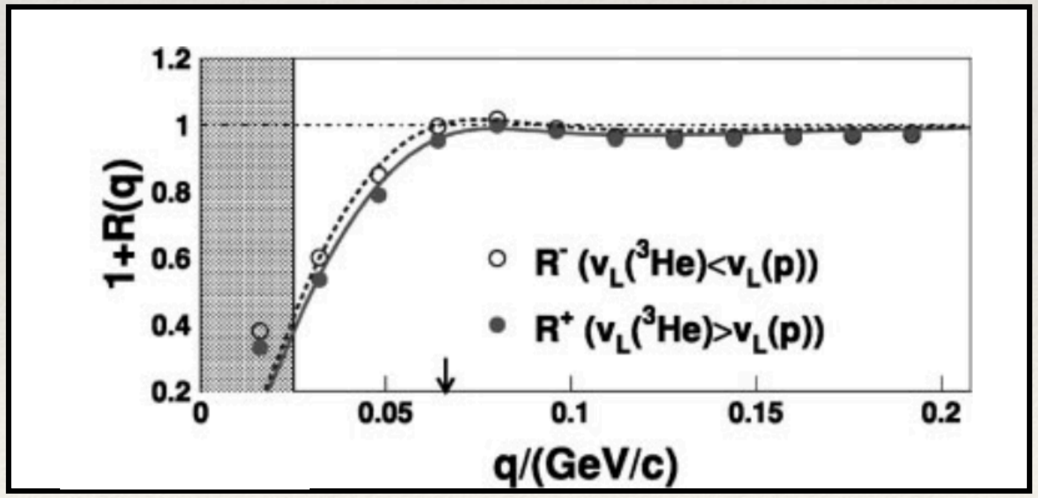


Proton - cluster



- After "adding" proton to correlated system: Strong positive correlation
- The positive enhancement barely visible in FOPI's data

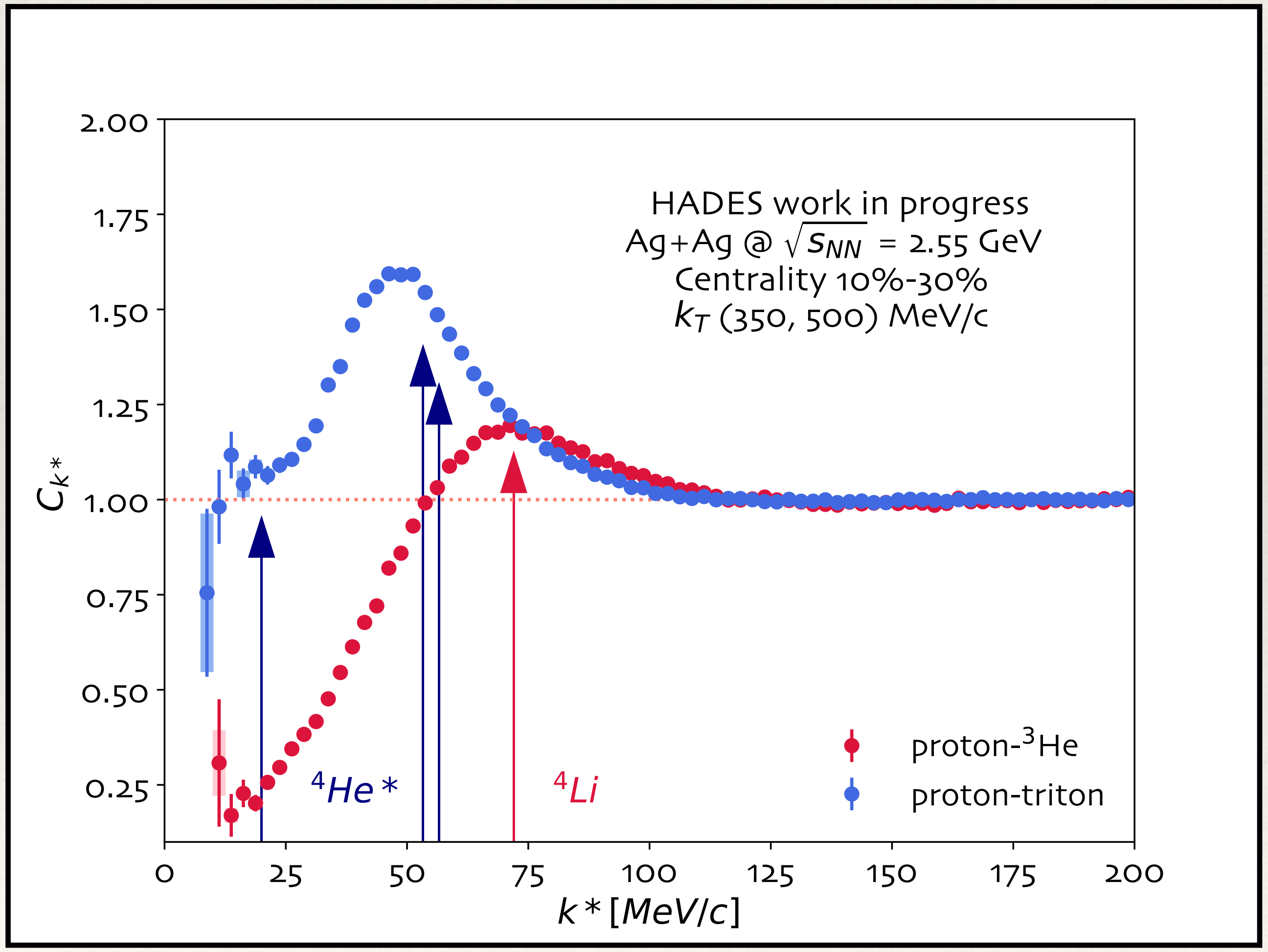
***FOPI Collaboration:** Eur. Phys. J. A 6, 185–195 (1999)*



Proton - cluster

Proton-Triton vs Proton-³He

- Similar masses
- Same baryon number
- Different electric charges!



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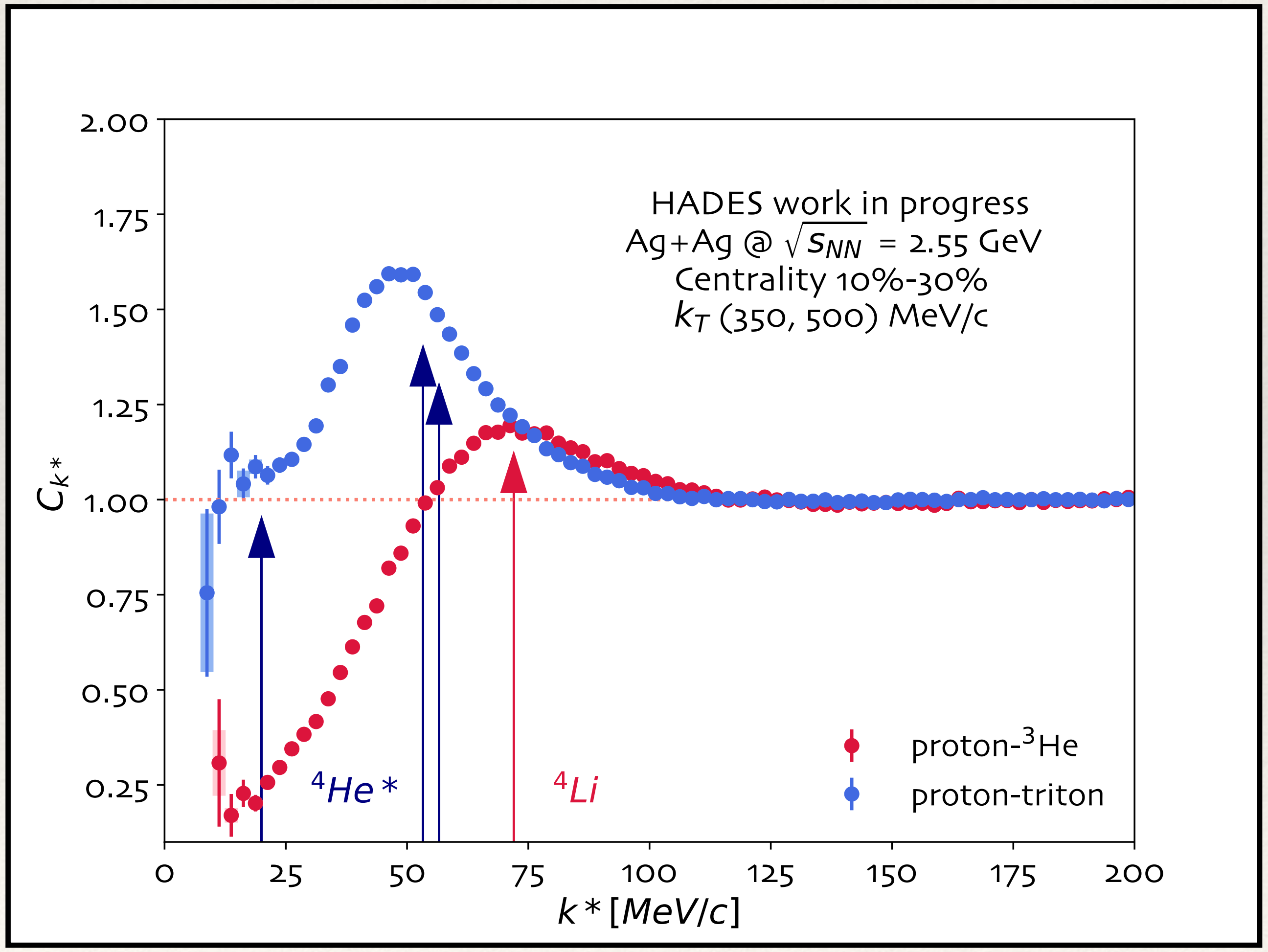


Positive correlations caused by decays of unstable light nuclei

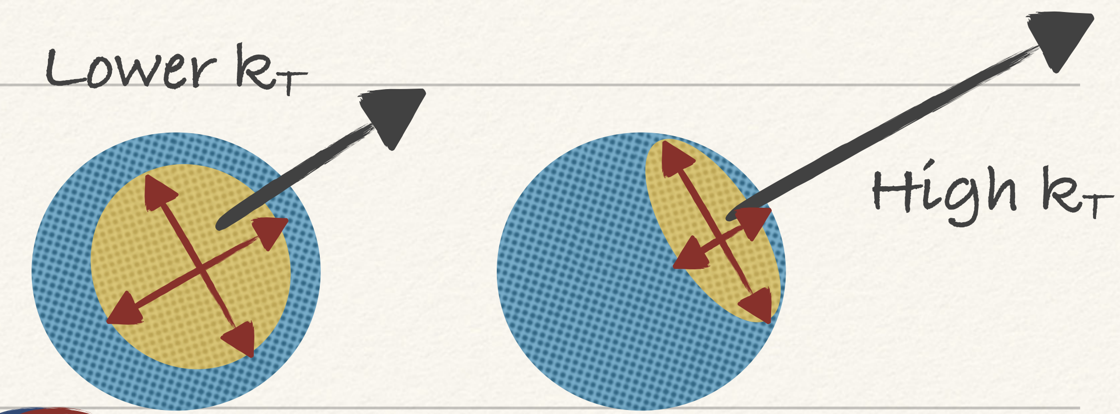
$^4Li \rightarrow p + {}^3He$

- ($J^\pi = 2^-$, $\Gamma = 6.0$ MeV, $\Gamma p/\Gamma = 1$, $k^*_1 \approx 72$ MeV/c)

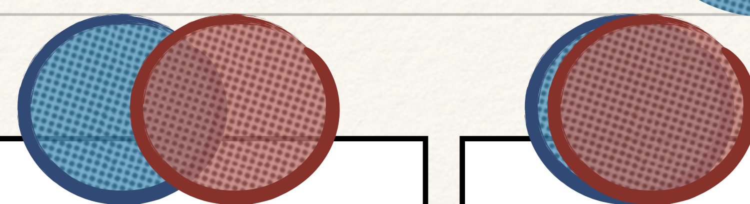
$^4He^* \longrightarrow p + t$

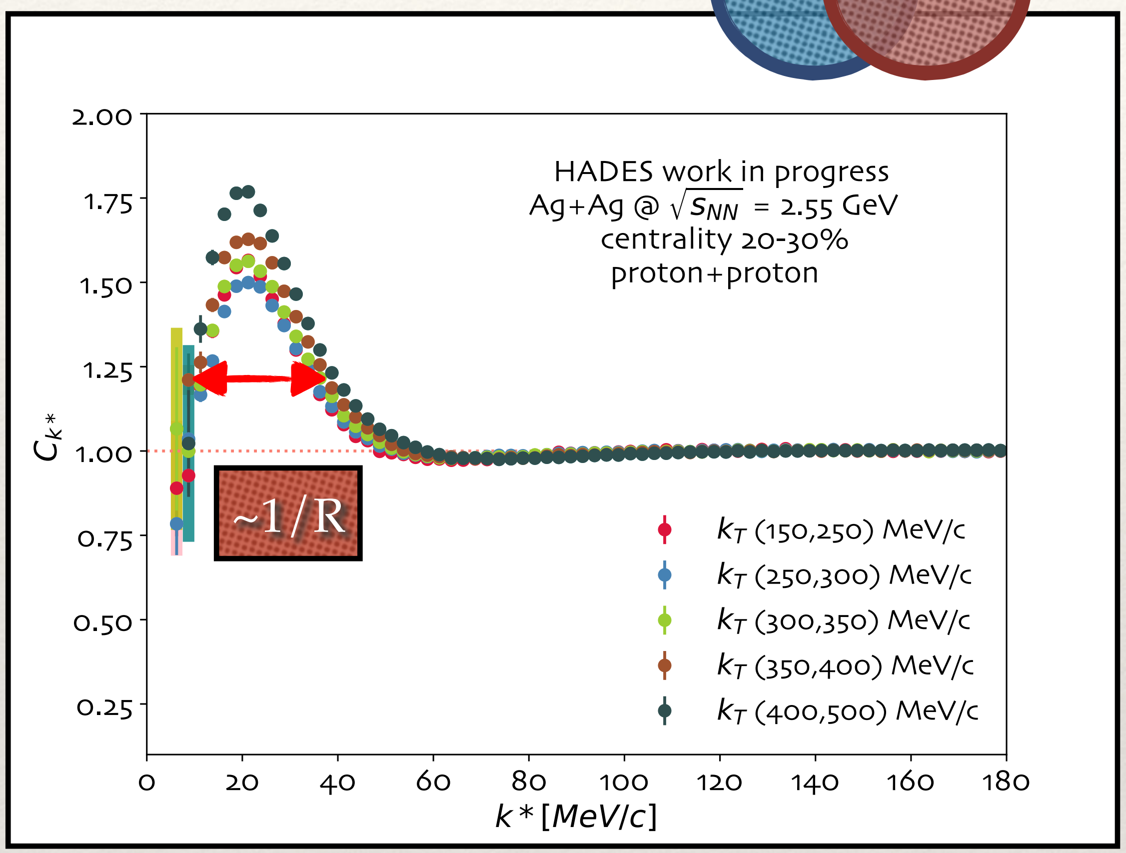
- ($E = 20.21$ MeV, $J^\pi = 0^+$, $\Gamma = 0.5$ MeV, $\Gamma p/\Gamma = 1$, $k^*_1 = 20$ MeV/c)
- ($E = 21.01$ MeV, $J^\pi = 0^+$, $\Gamma = 0.84$ MeV, $\Gamma p/\Gamma = 0.76$, $k^*_2 = 53.3$ MeV/c)
- ($E = 21.84$ MeV, $J^\pi = 2$, $\Gamma = 2.01$ MeV, $\Gamma p/\Gamma = 0.63$, $k^*_3 = 56.6$ MeV/c)

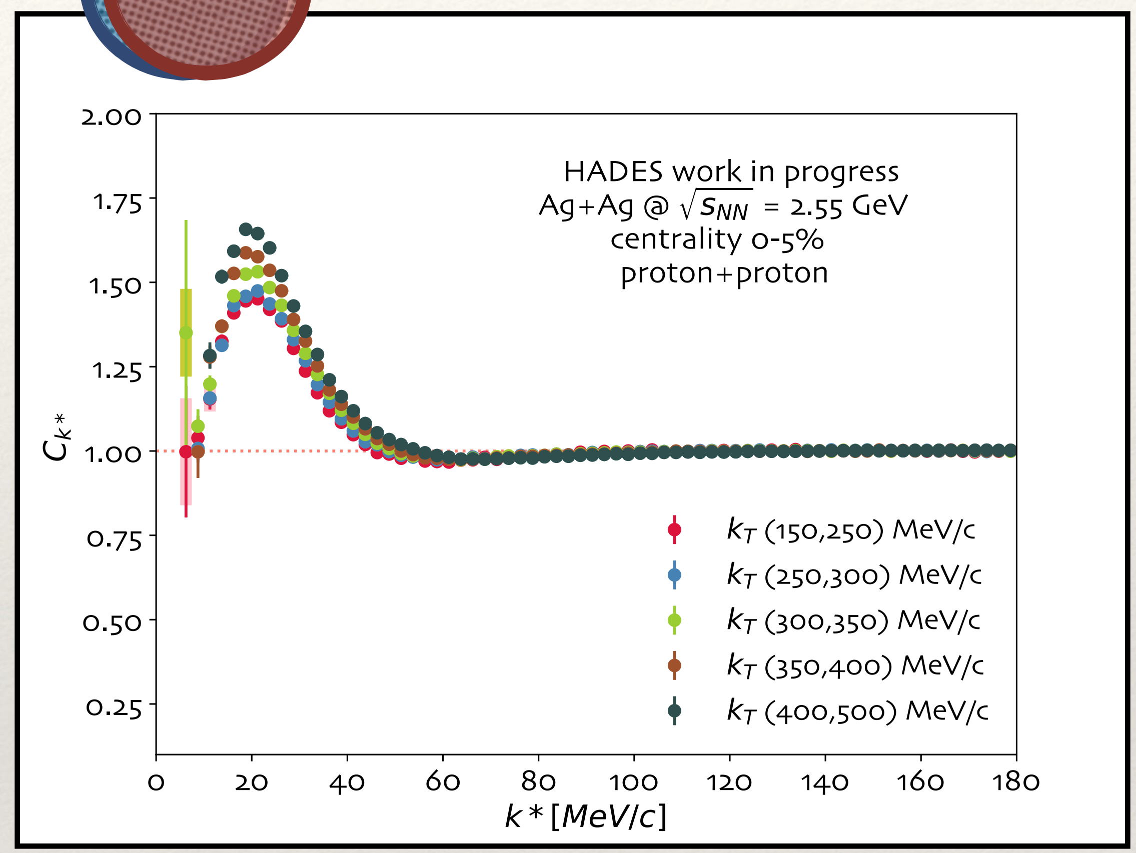
Proton - Proton



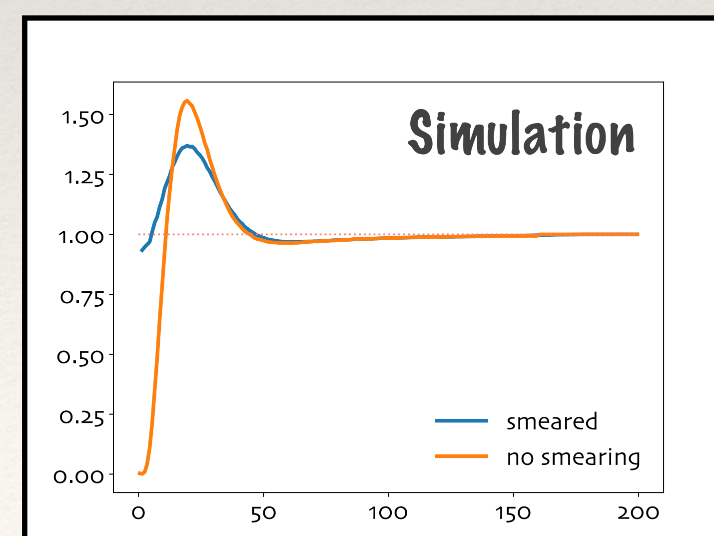
k_T - average transverse momentum of pair







- High statistics allows the extended k_T dependence studies
- Strength of correlations increasing with k_T - smaller R of source
- Low $k^\star$ strongly affected by the momentum resolution and track merging suppression



Proton - Proton vs EoS

UrQMD

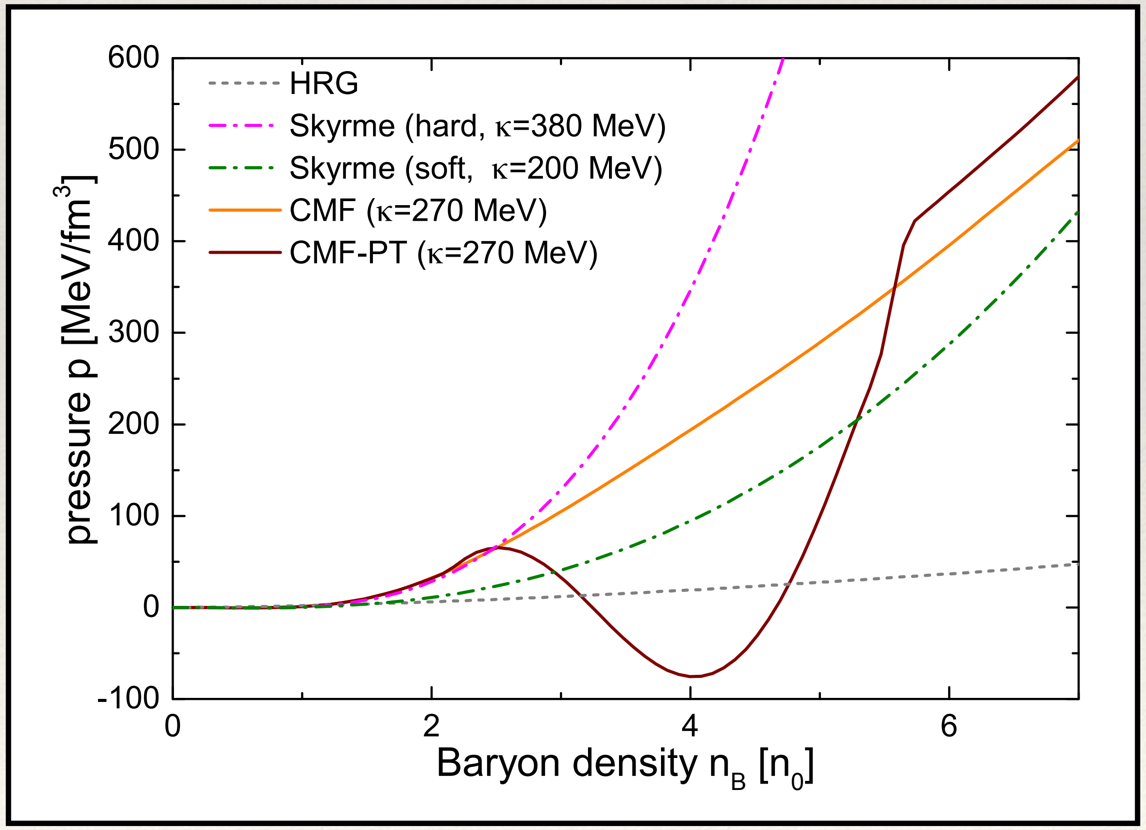
- Soft (Skyrme)
- Hard (Skyrme)
- Chiral Mean Field
- Chiral Mean Filed + Phase Transition

- Cascade mode (HRG)

J. Steinheimer, at al: Eur.Phys.J.C 82 (2022) 911

S.A. Bass, at al: Prog. Part. Nucl. Phys. 41 (1998) 225-370

M. Bleicher J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859-1896



Proton - Proton vs EoS

UrQMD

- Soft (Skyrme)
- Hard (Skyrme)
- Chiral Mean Field
- Chiral Mean Filed + Phase Transition

- Cascade mode (HRG)

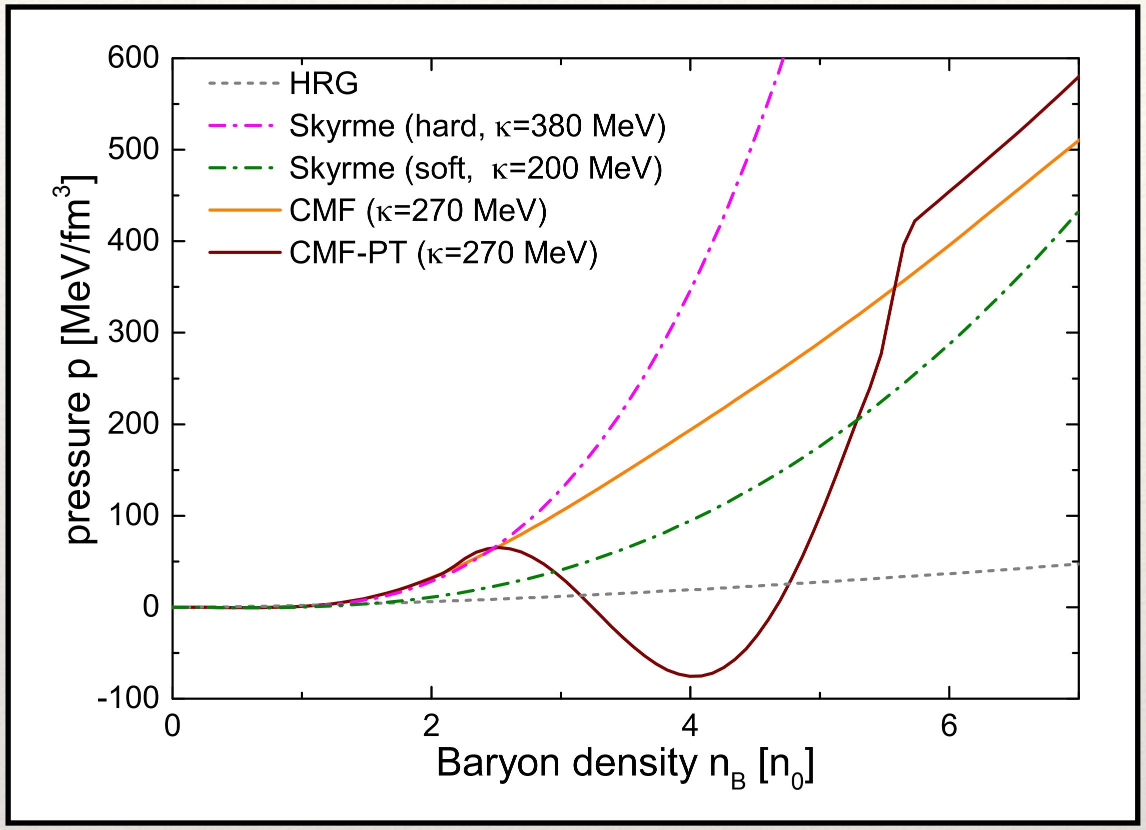
+ CorAl

https://github.com/scottedwardpratt/coral/

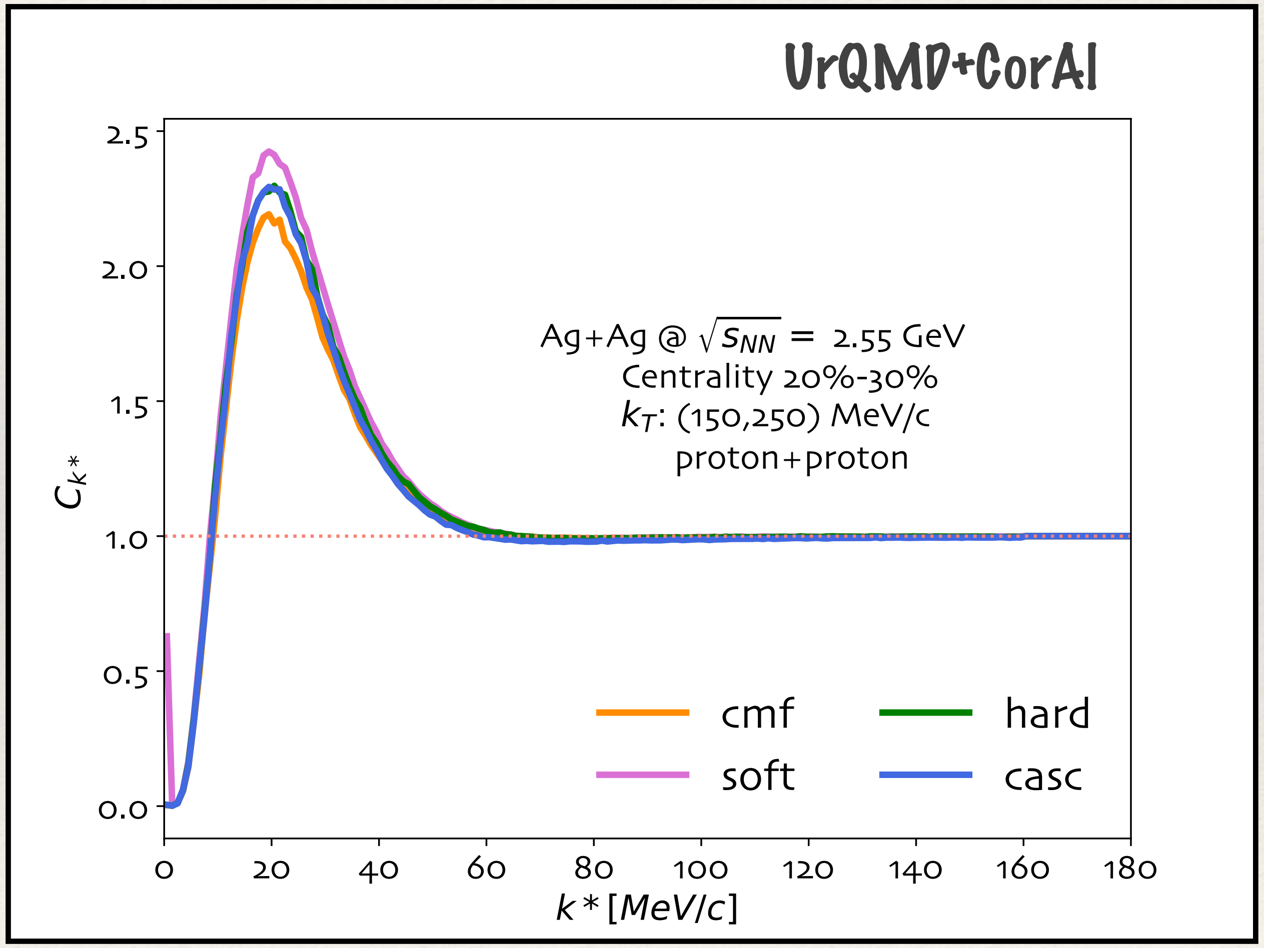
$$C(k^\star) = \int S(r^\star)\,|\Psi(k^\star, r^\star)|^2 d^3 r^\star$$

Reid potential for p+p from:
V.G.J. Stoks et al., Phys. Rev. C 49, 2950 (1994)

Proton - Proton vs EoS

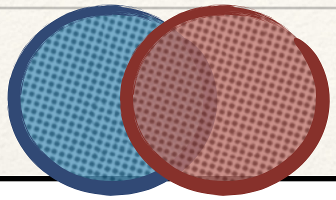


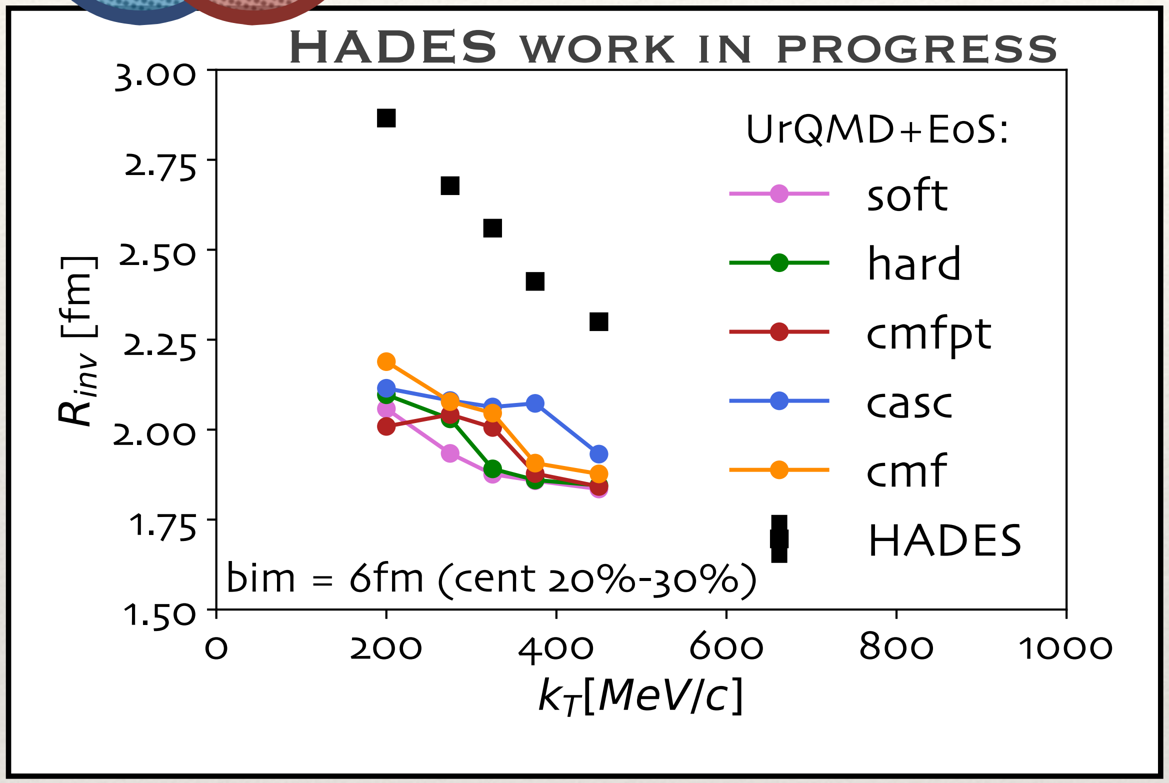
HRG = casc



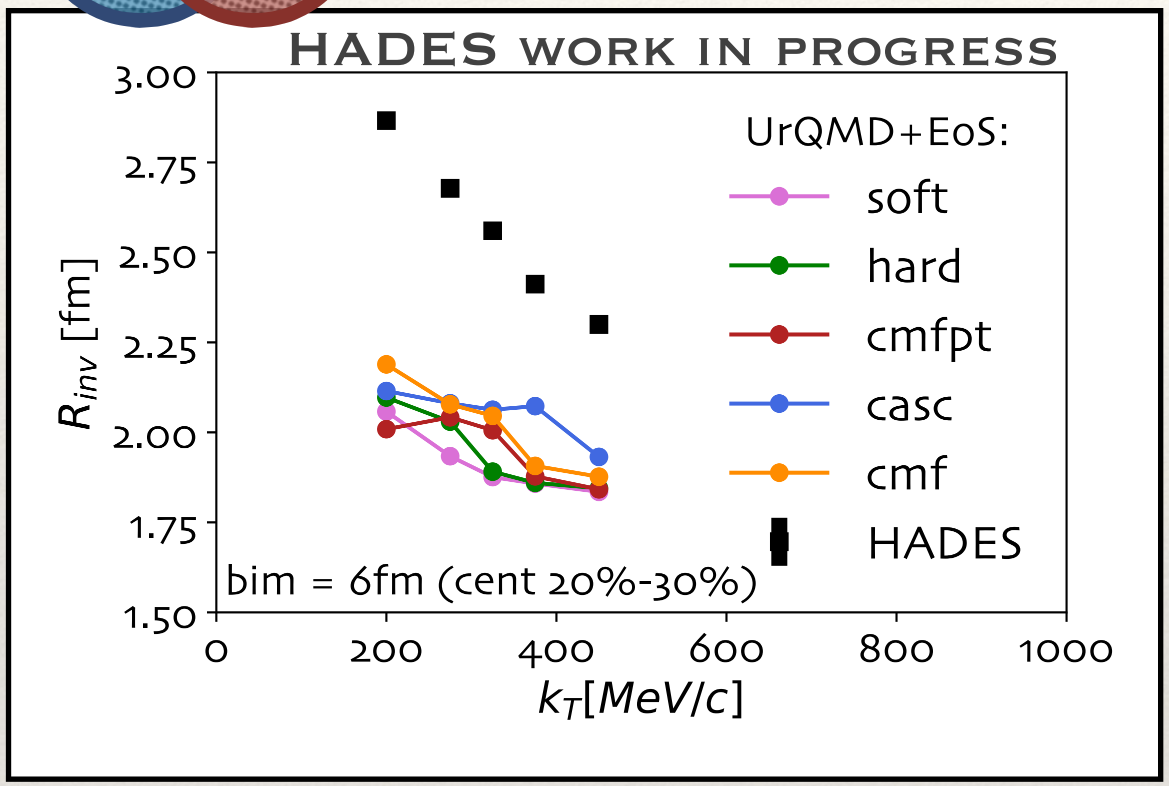
- Smallest source - Soft EoS
- Biggest one - Chiral mean field
- No difference between hard Skyrme and cascade mode (HRG)

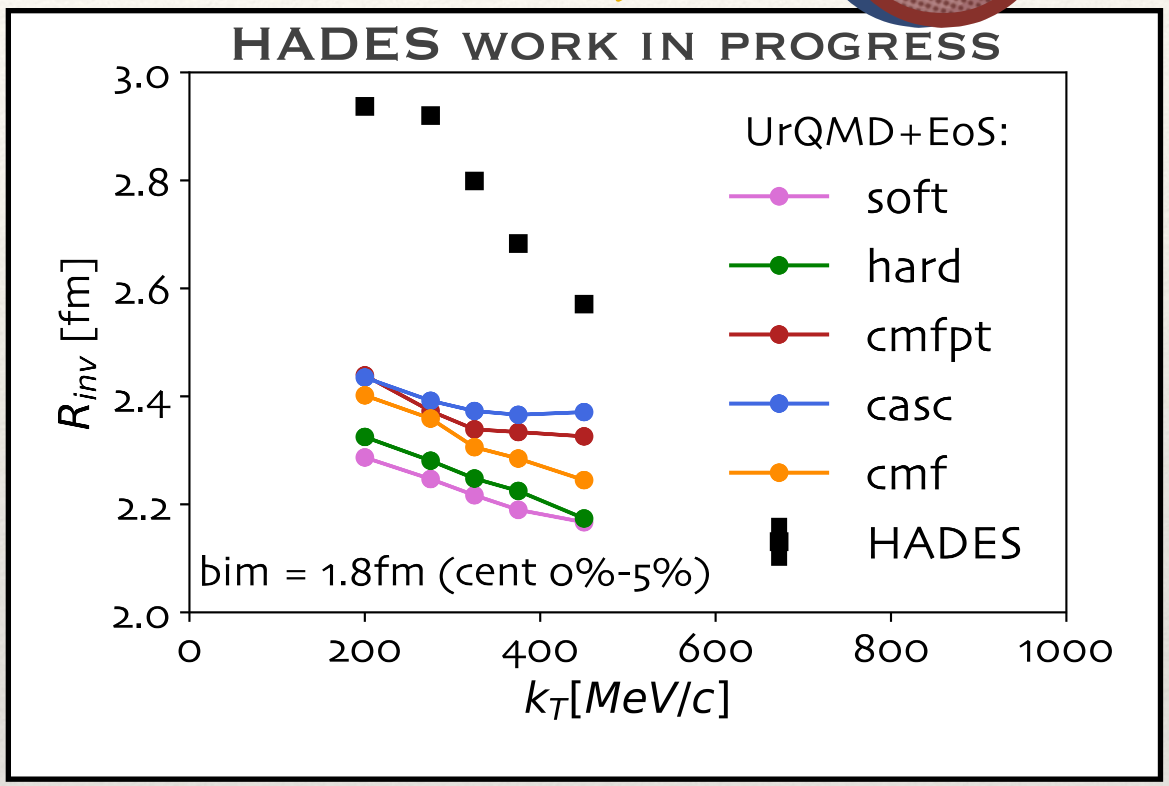
Proton - Proton vs EoS





Proton - Proton vs EoS

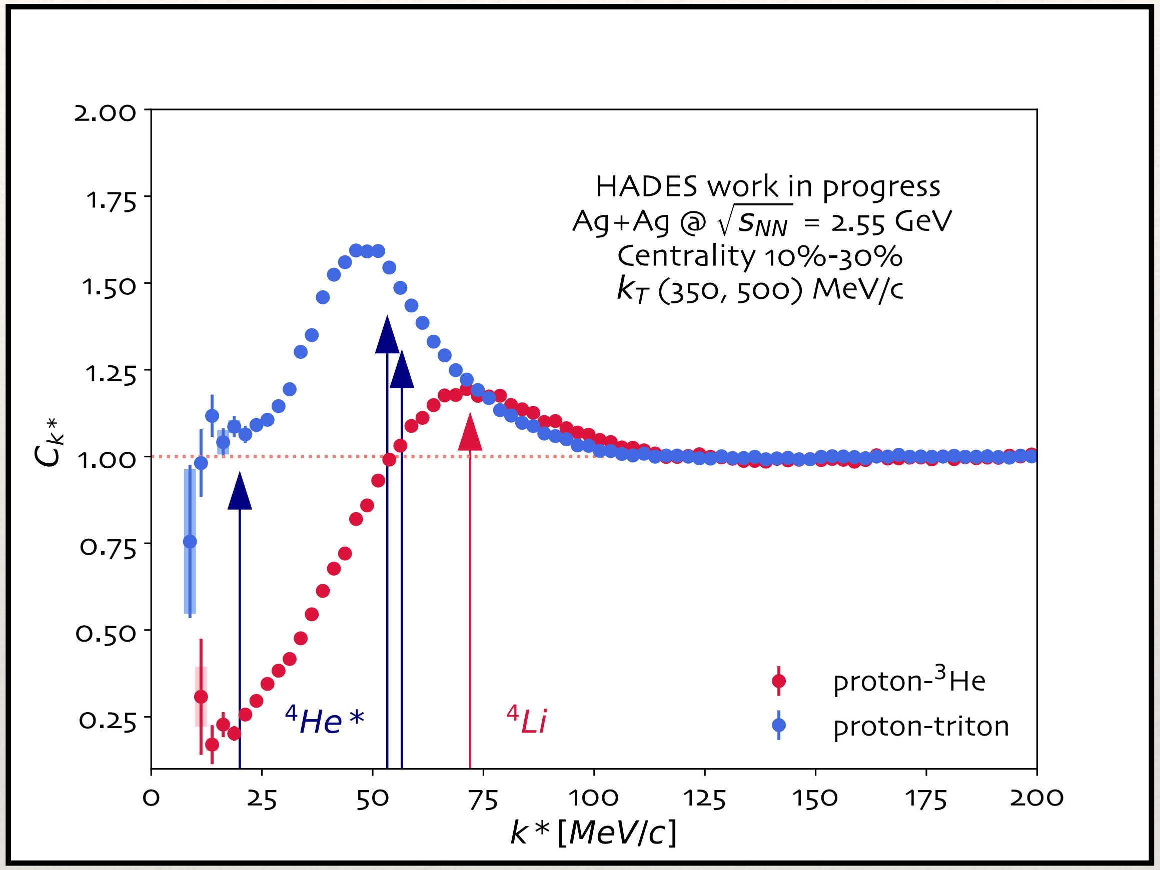




- UrQMD does not reproduce the HADES data. Possible reasons:
  - Simulations do not include productions of d, t, He-3…
  - Difficult to estimate the contribution of protons “feed-down” (e.g. ^{5}Li)
  - Assumption of gaussian source in fitting procedure
- For central collisions (higher n_b) differences between EoS increasing
- Skyrme EoS the furthest from experimental data

Summary and outlook

- High precision measurements of proton - proton and proton - cluster correlation functions
- Identified presence and decays of exotic states of $^{4}He^{*}$ and ^{4}Li
- Extended studies of k_T dependance of proton-proton correlations
- EoS sensitive to proton femtoscopy



Finalizing of:

- Studies of SI in proton - cluster interactions
- Systematic uncertainty analysis

THANK YOU

for your attention!