https://www.innovationnewsnetwork.com/heavy-ion-physics-and-its-applications/8996/

Outline:

- Femtoscopic correlations
- Motivation
- HADES
- Experimental results
- EoS and correlations
- Summary and outlook

Maria Stefaniak for HADES collaboration

Proton-cluster Femtoscopy at HADES

INT Workshop, Seattle 5-9.12.2022

GSI

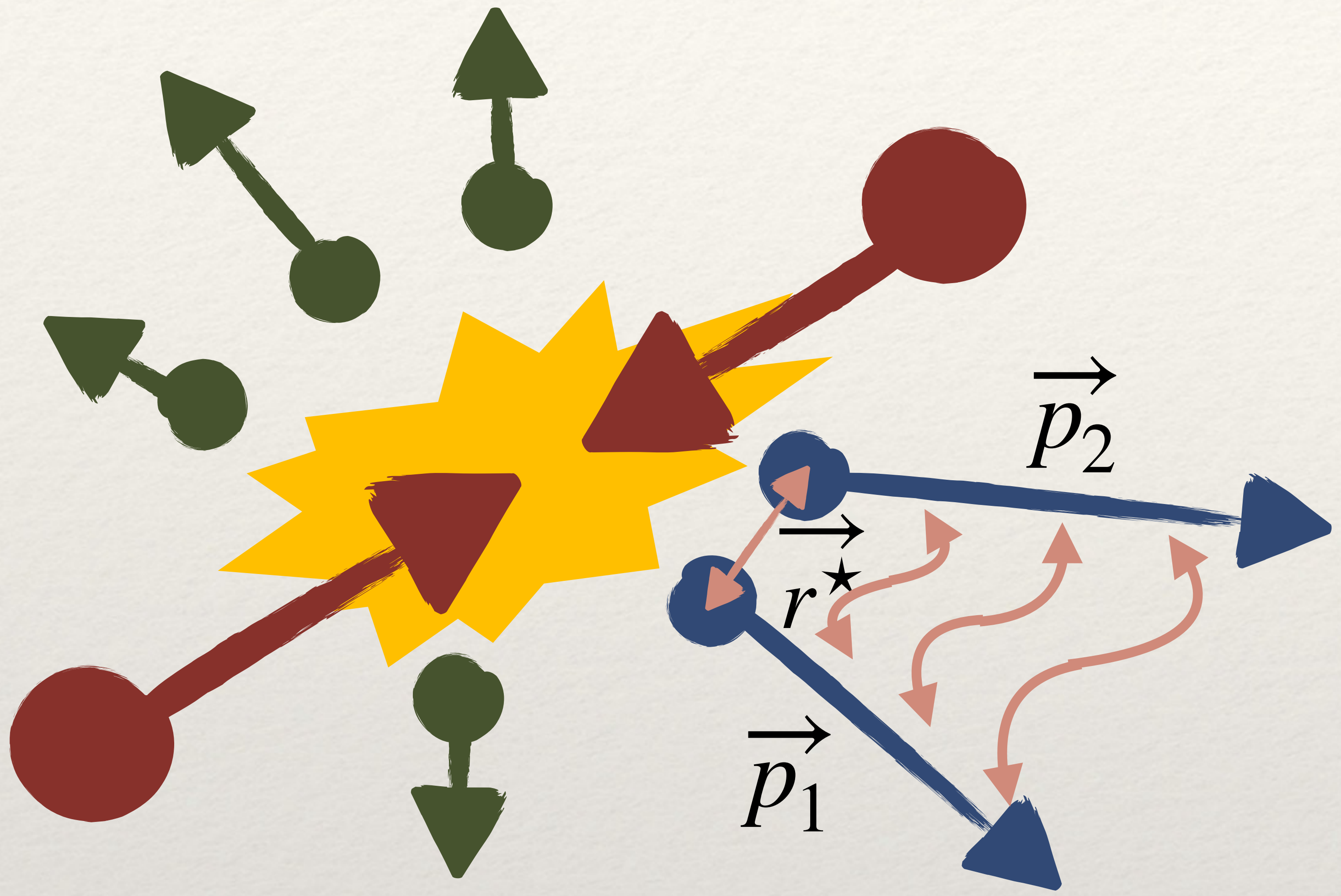
Warsaw University of Technology

RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE

Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

Femtoscopy Correlations

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

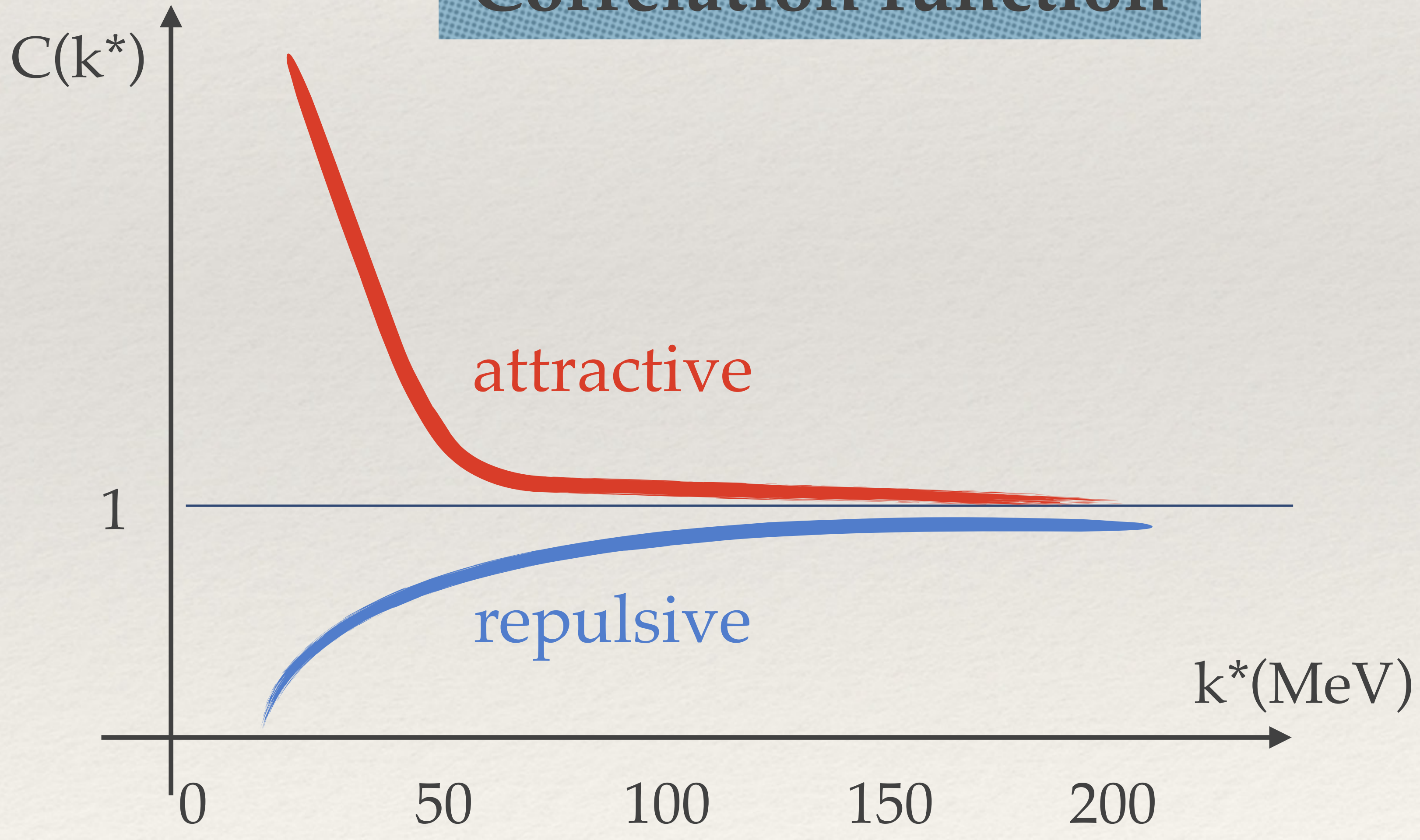


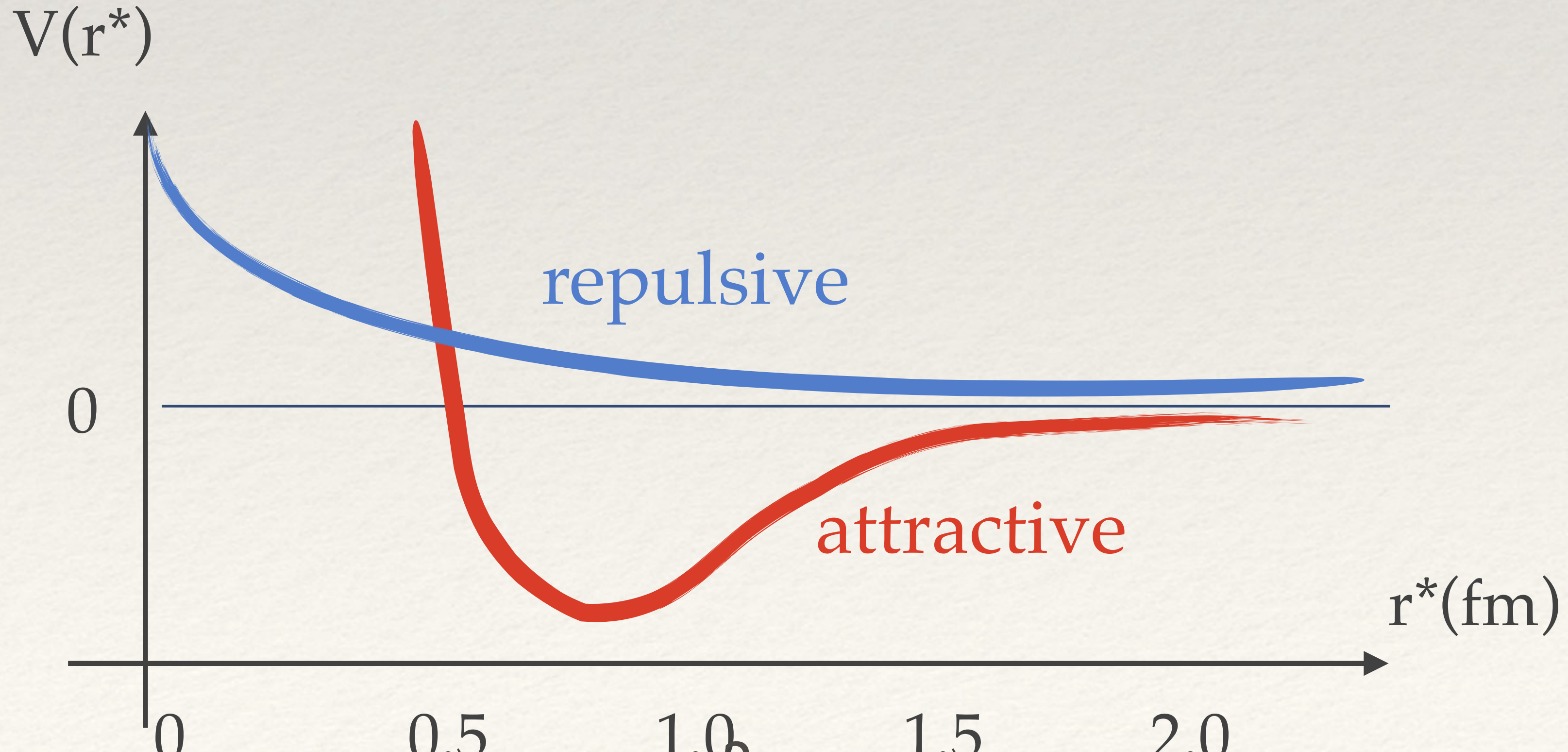
Emission source S(r*)

Schrödinger equation

Two-particle wave function
$|\Psi(k^\star, r^\star)|$

Correlation function





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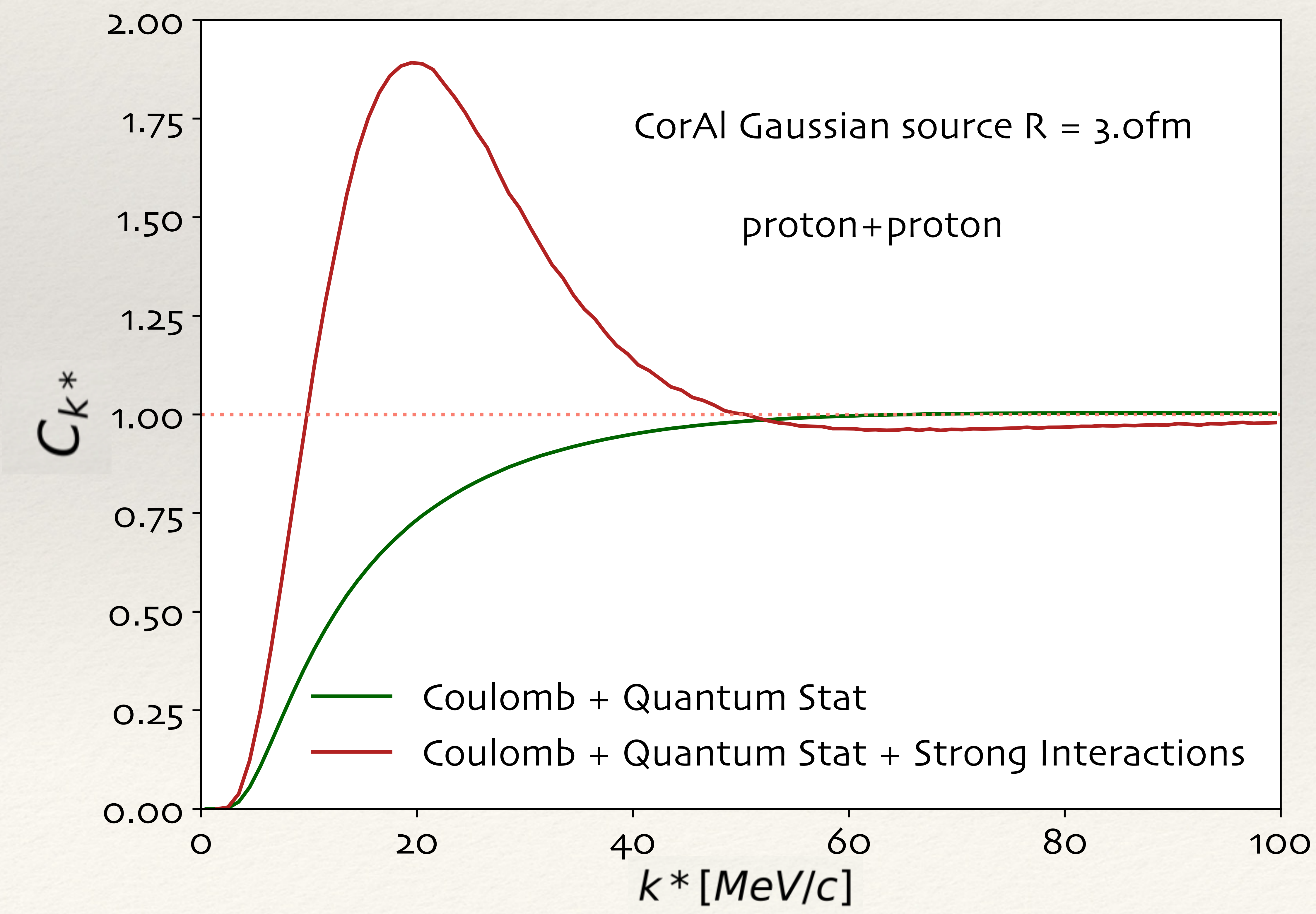
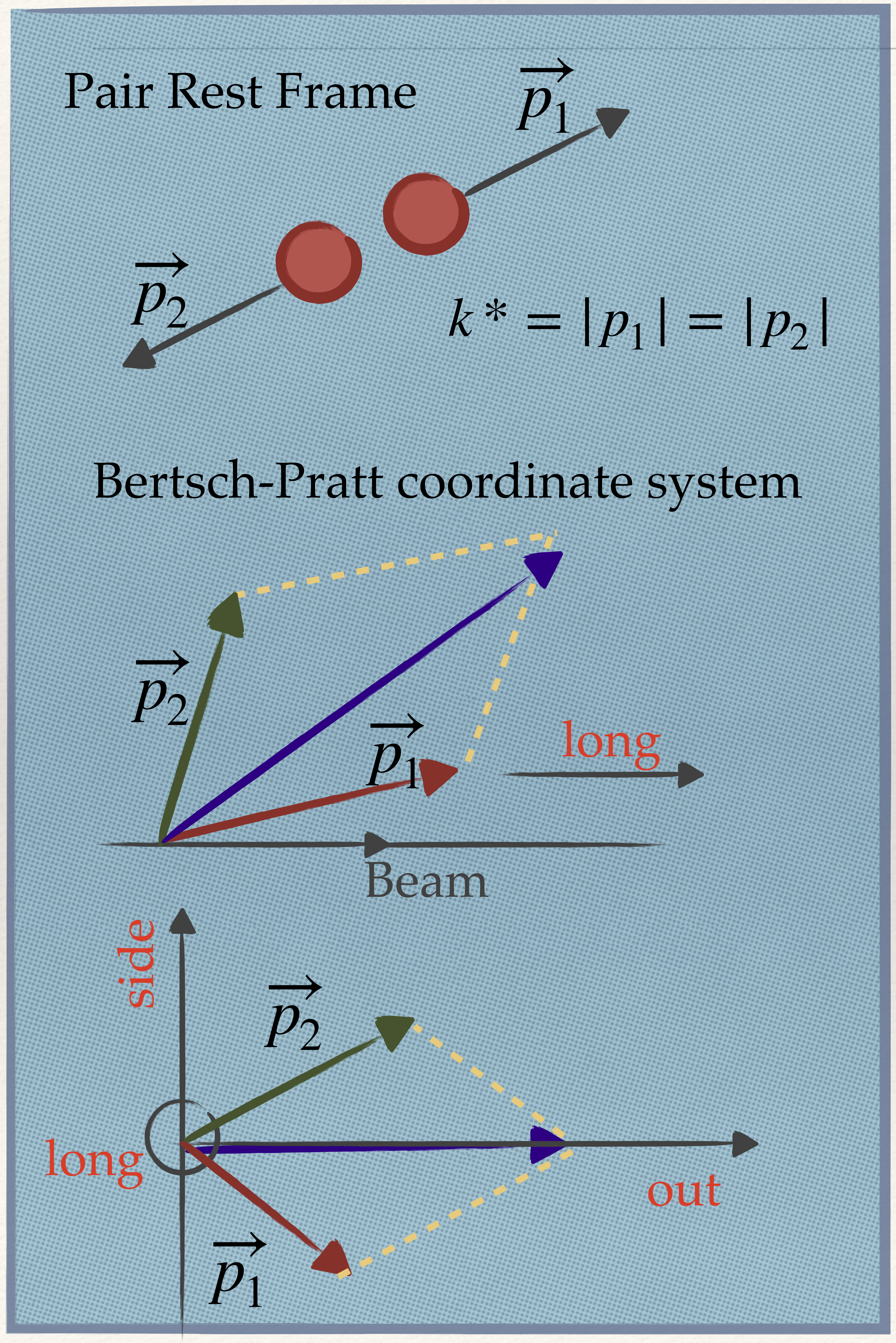


1. Coulomb:
   - Attractive for opposite sign particles
   - **Repulsing for same sign particles**
2. Quantum Statistic:
   - Bosons: positive
   - **Fermions: negative**
3. Strong Interactions:
   - Can be both **positive** or negative, depending on potentials

Motivation A: Sensitivity to EoS

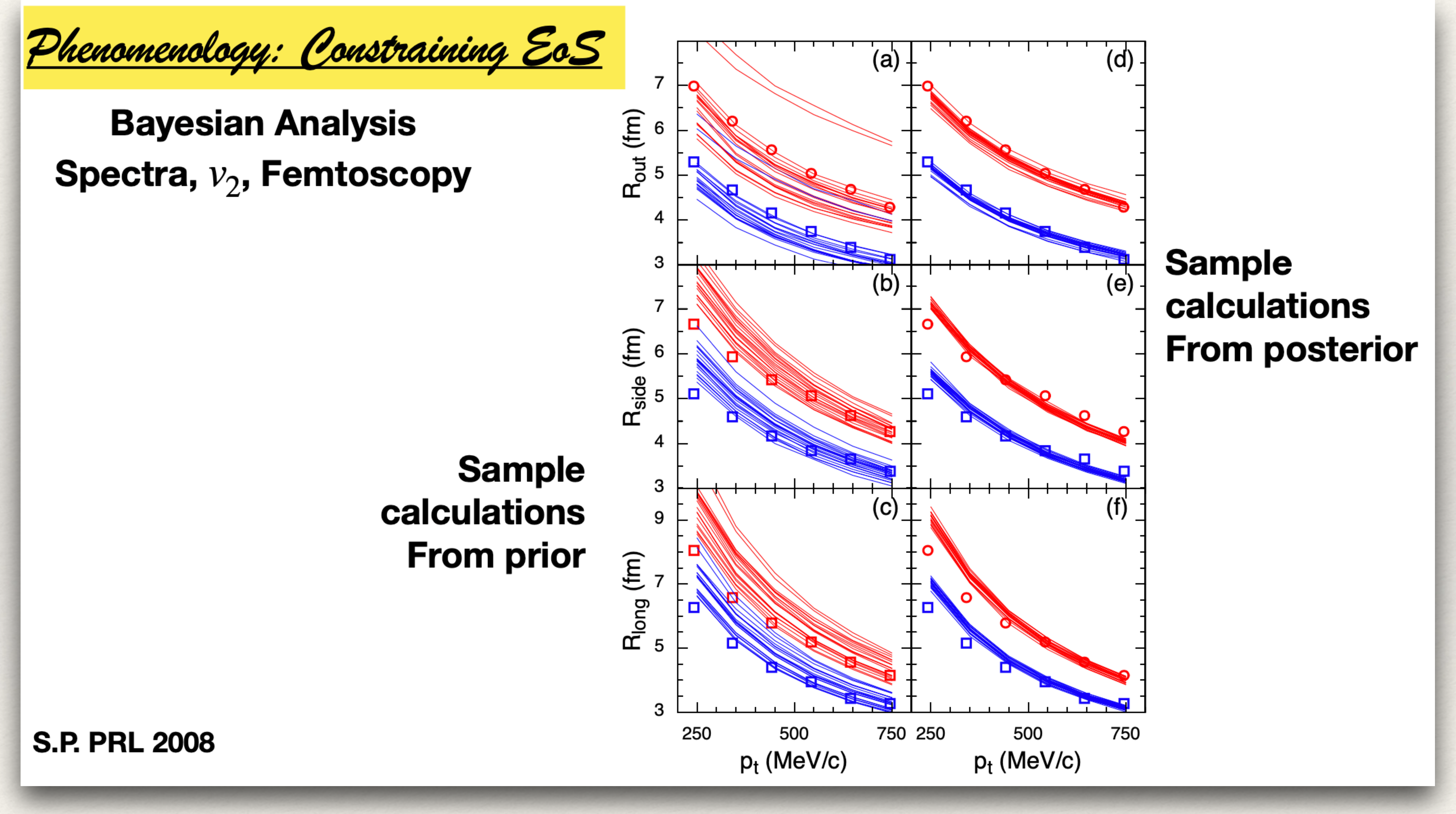


Pair Rest Frame

$k^* = |p_1| = |p_2|$

Bertsch-Pratt coordinate system

Scott Pratt lecture at GSI: *„Foundation of femtoscopy”*



Phenomenology: Constraining EoS

Bayesian Analysis

Spectra, v_2, Femtoscopy

Sample calculations From prior

Sample calculations From posterior

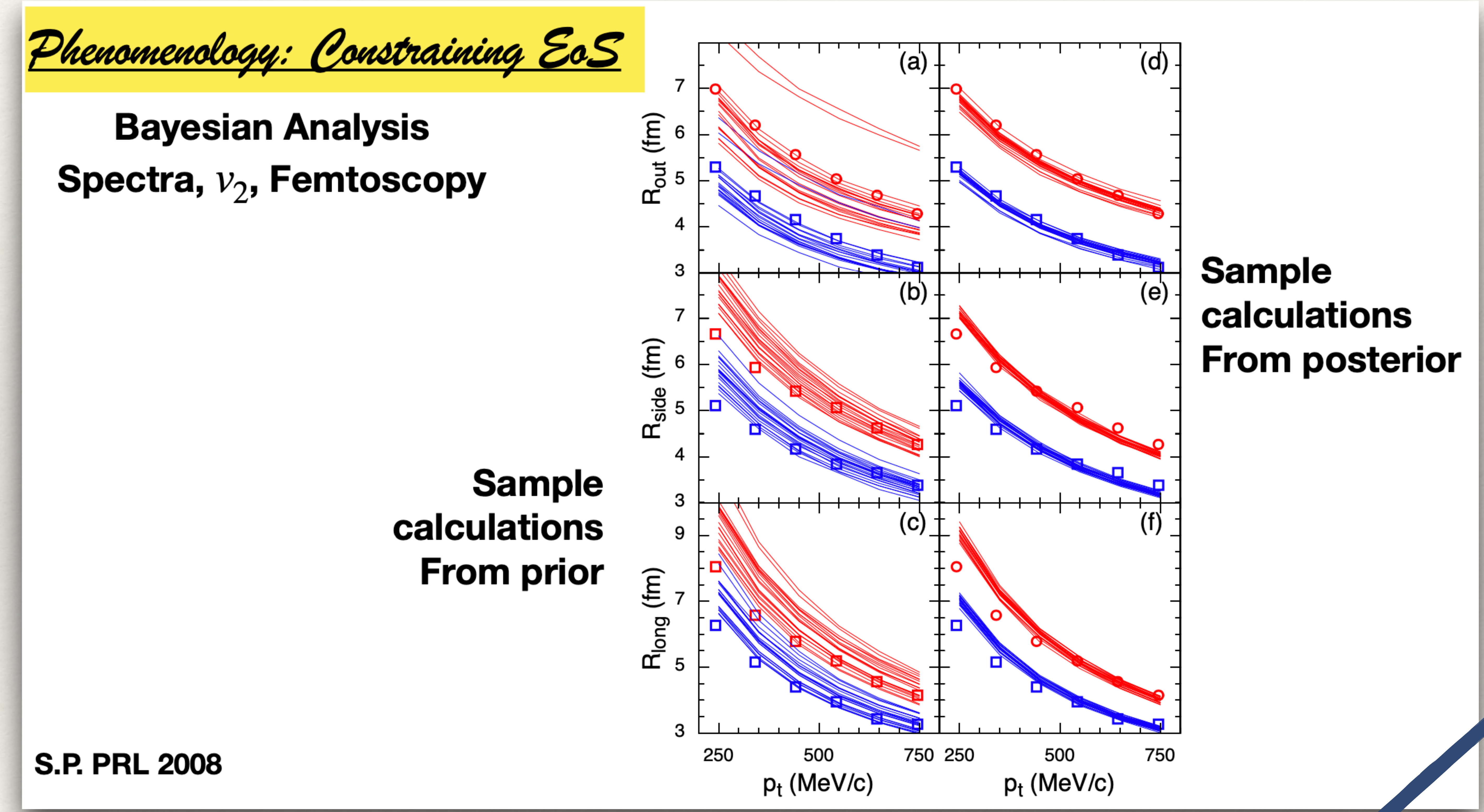
S.P. PRL 2008

S.Pratt: Phys. Rev. D33:1314,1986

G. Bertsch, M.Gong, M.Tohyama: Phys. Rev.C37:1896-1900,1988

Motivation A: Sensitivity to EoS

Scott Pratt lecture at GSI: *„Foundation of femtoscopy"*



Phenomenology: Constraining EoS

Bayesian Analysis

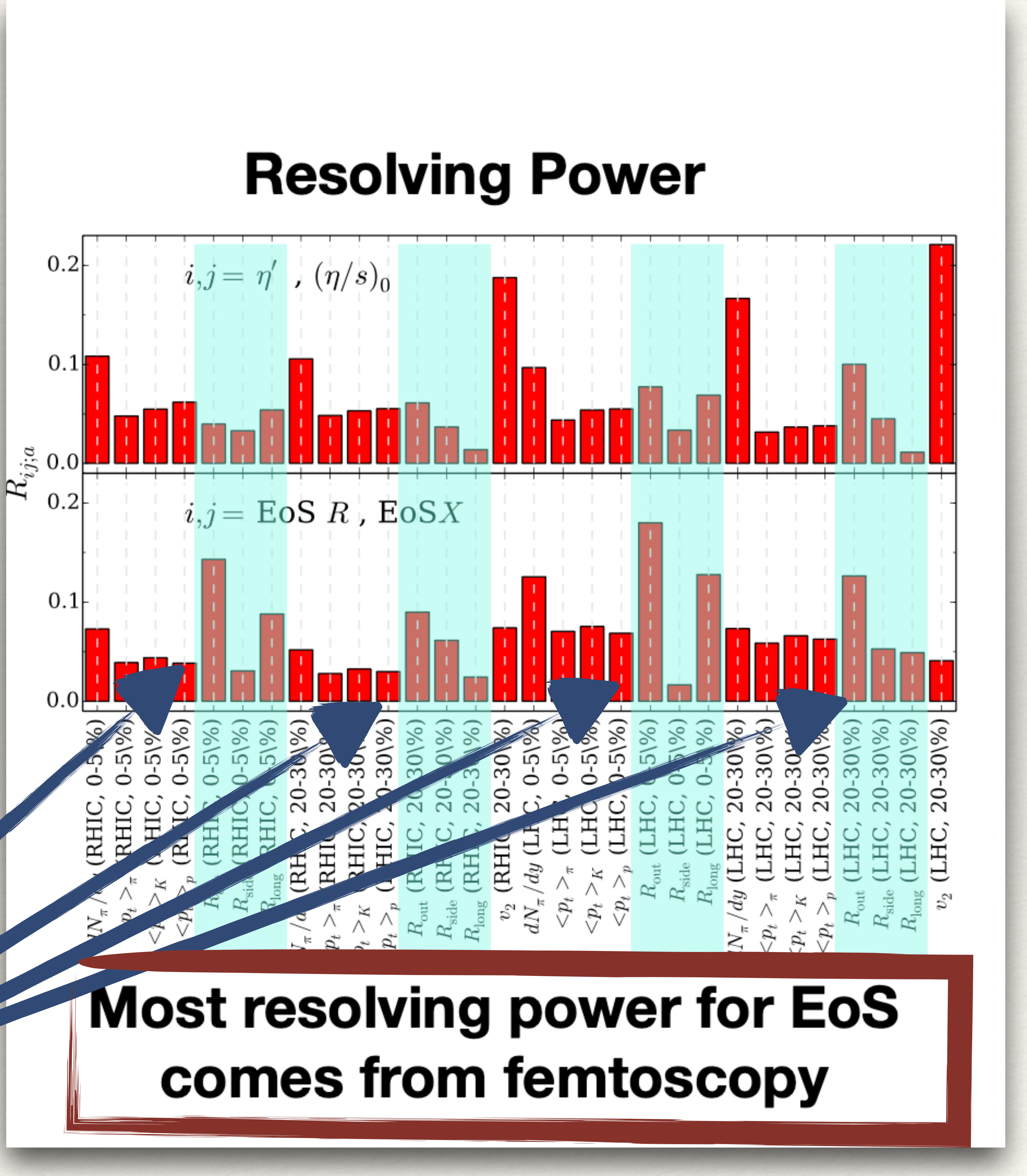
Spectra, v_2, Femtoscopy

Sample calculations From prior

Sample calculations From posterior

S.P. PRL 2008

R_{out}, R_{side}, R_{long}



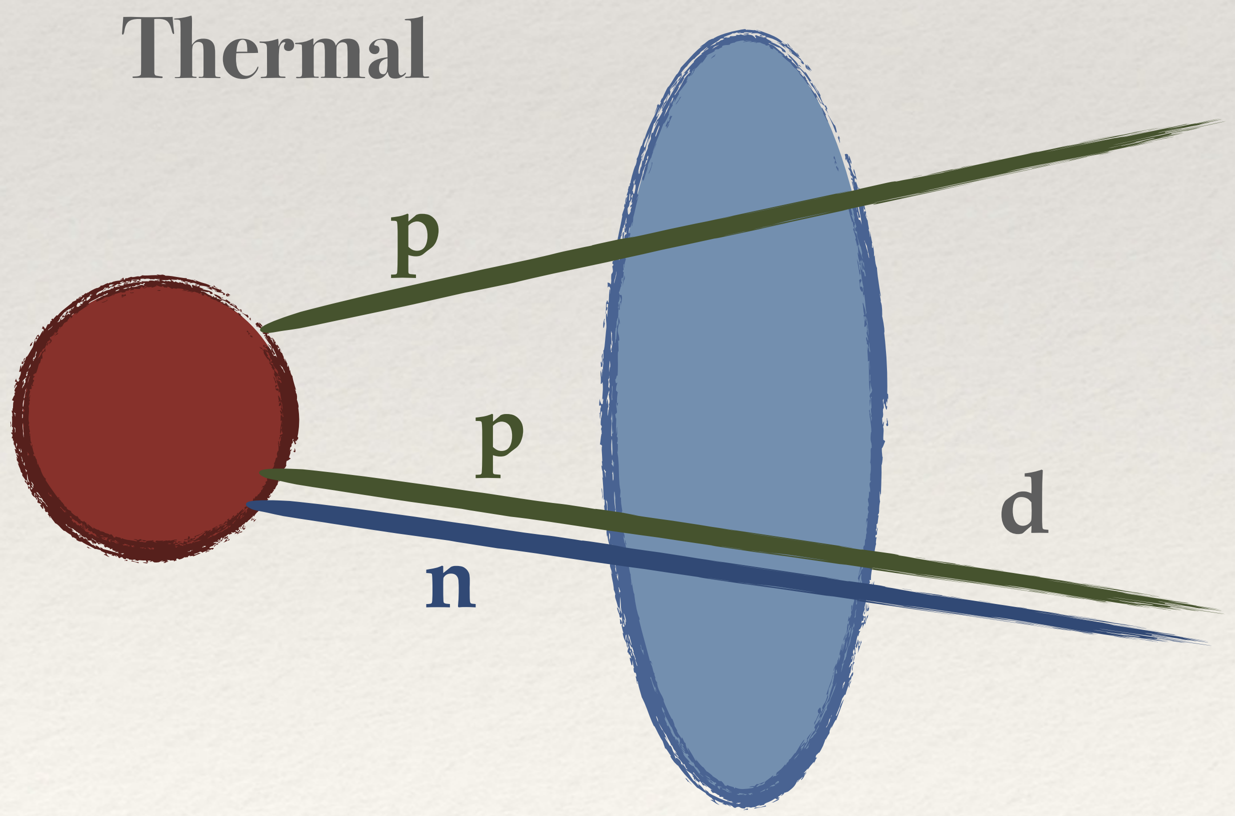
Resolving Power

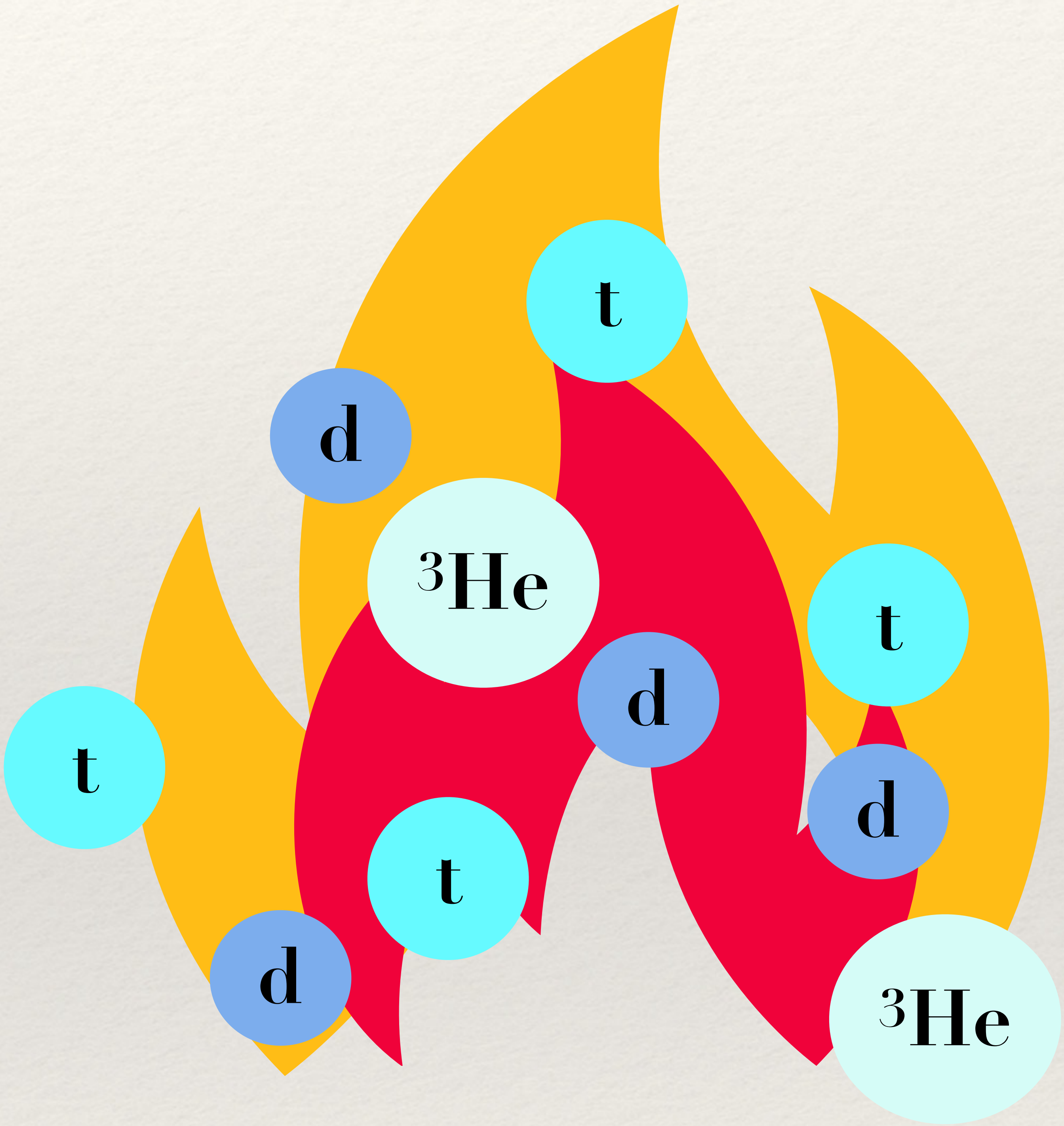
Most resolving power for EoS comes from femtoscopy

Motivation B: Thermal vs Coalescence

Snowball in hell puzzle

- Thermal models well reproduce the yields of hadrons and light nuclei
- For light clusters the binding energy per nucleon < 10 MeV
- Temperature of the source ~ 60 MeV (@ SIS18)

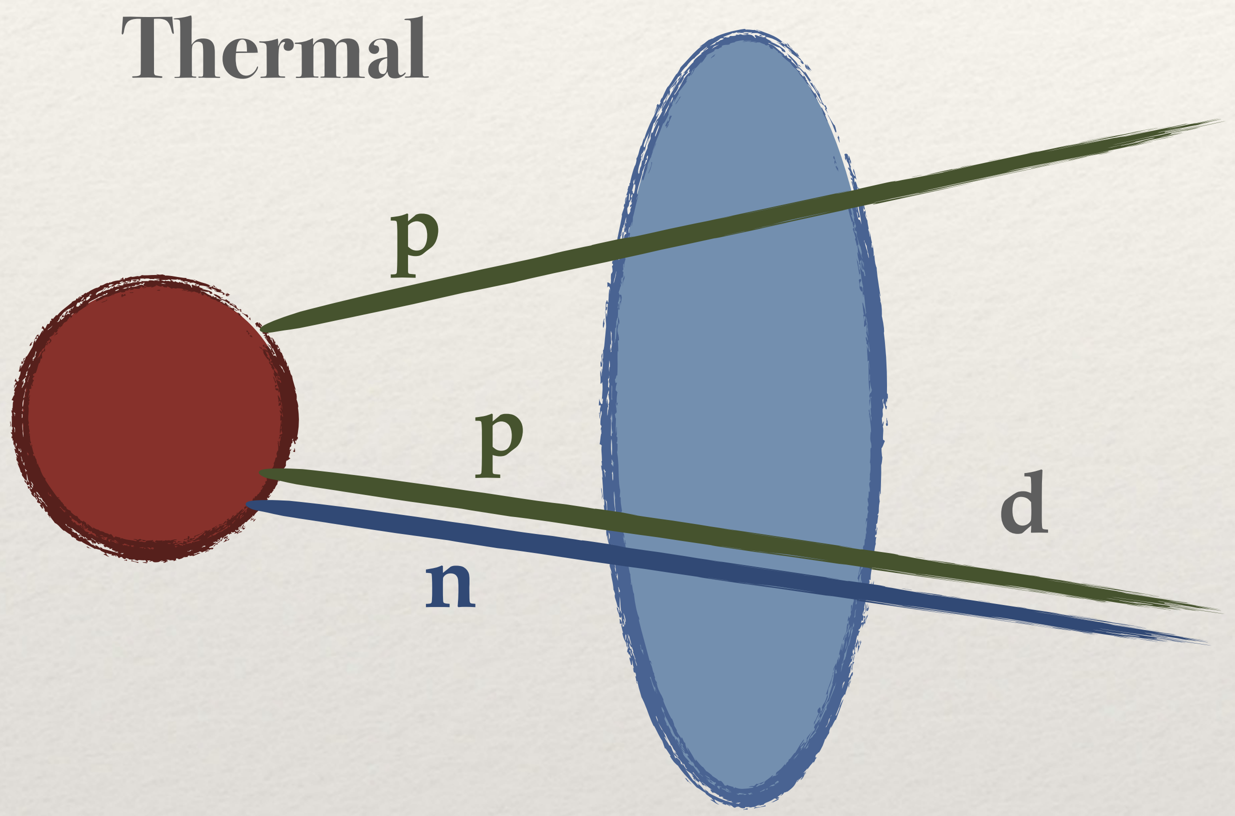




D. Oliinychenko: Nuclear Physics A 00 (2020) 1-9
A. Bzdak, S. Esumi, V. Koch, J. Liao, M. Stephanov, N. Xu: arXiv:1906.00936
D. Oliinychenko, L.-G. Pang, H. Elfner, V. Koch: Phys. Rev. C 99 (4) (2019) 044907
V.Vovchenko, K.Gallmeister, J.Schaffner-Bielich, C.Greiner: Phys. Lett. B 800 (2020) 135131
X. Xu, R. Rapp: Eur. Phys. J. A 55 (5) (2019) 68

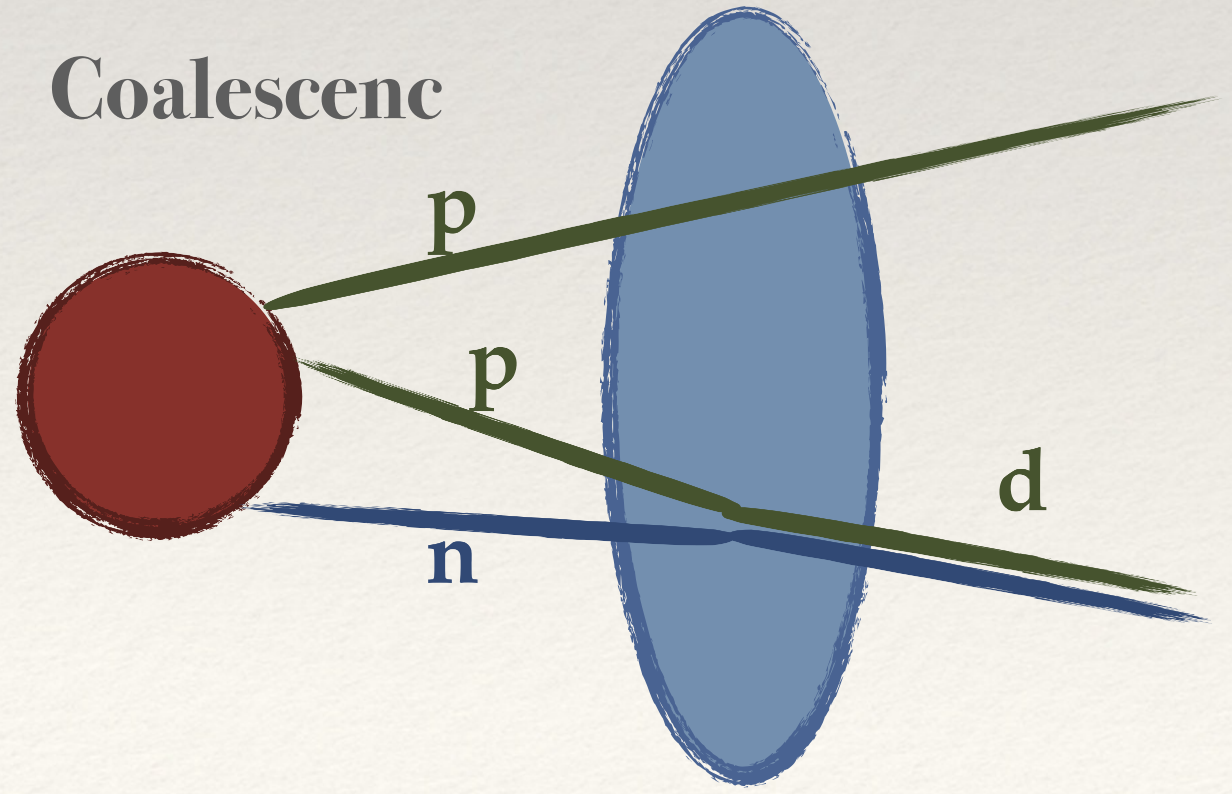
Motivation B: Thermal vs Coalescence

Snowball in hell puzzle



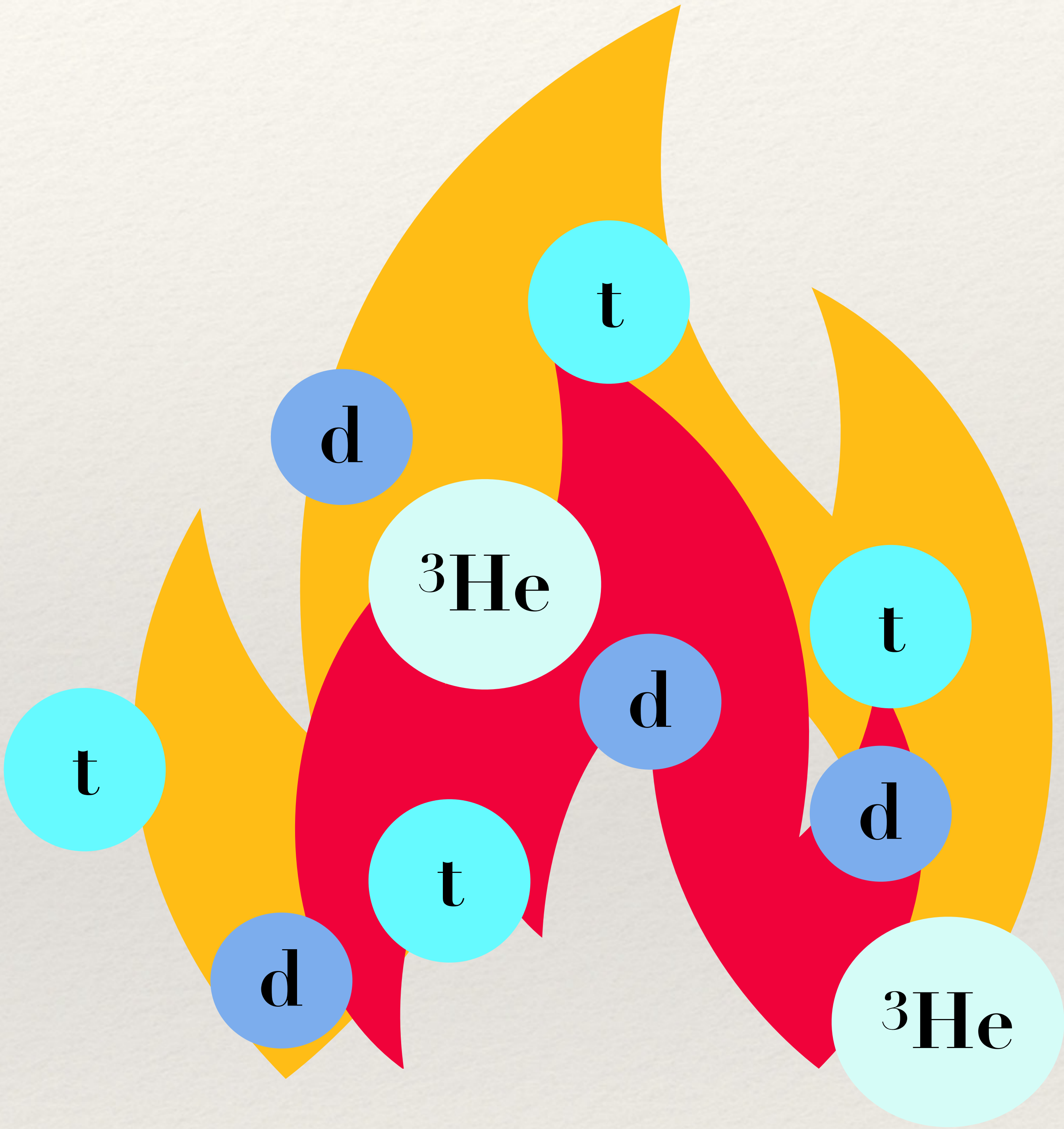
Thermal:

- ✱ Hadron resonance gas in a global equilibrium until sudden chemical freeze-out
- ✱ So good agreement with data that starts the discussion about puzzle



Coalescence:

- ✱ Light nuclei are not created at the chemical freeze-out
- ✱ Nucleons bound together later



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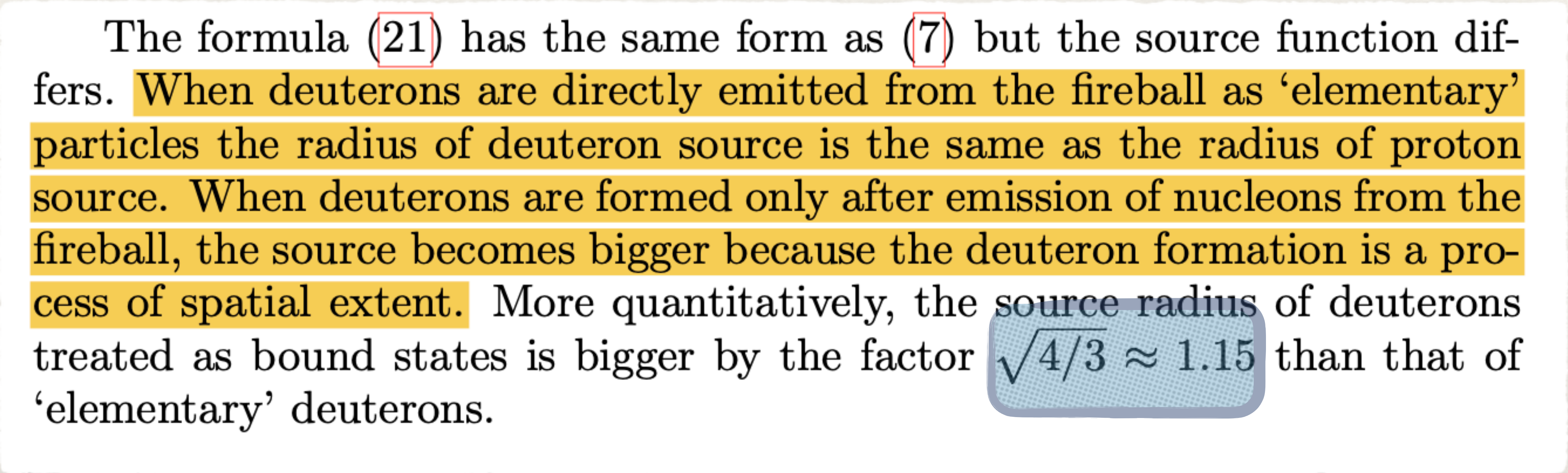
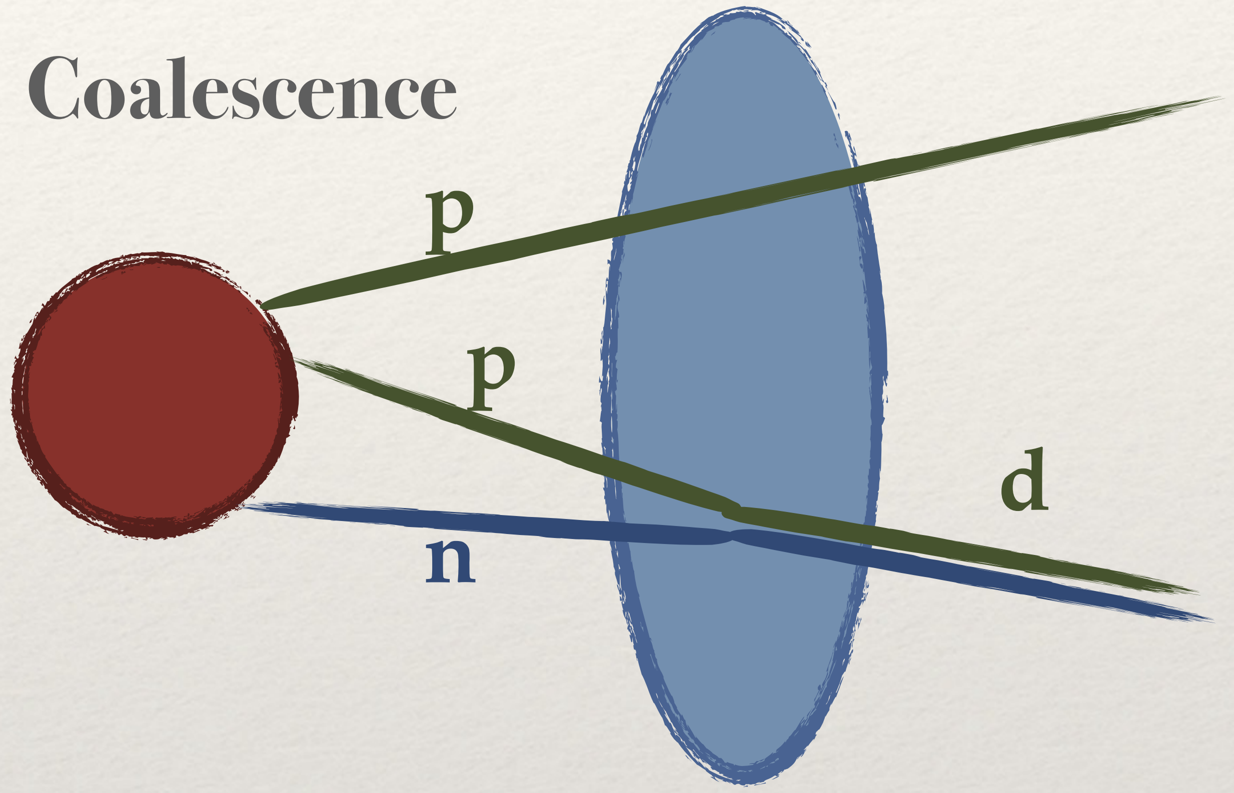
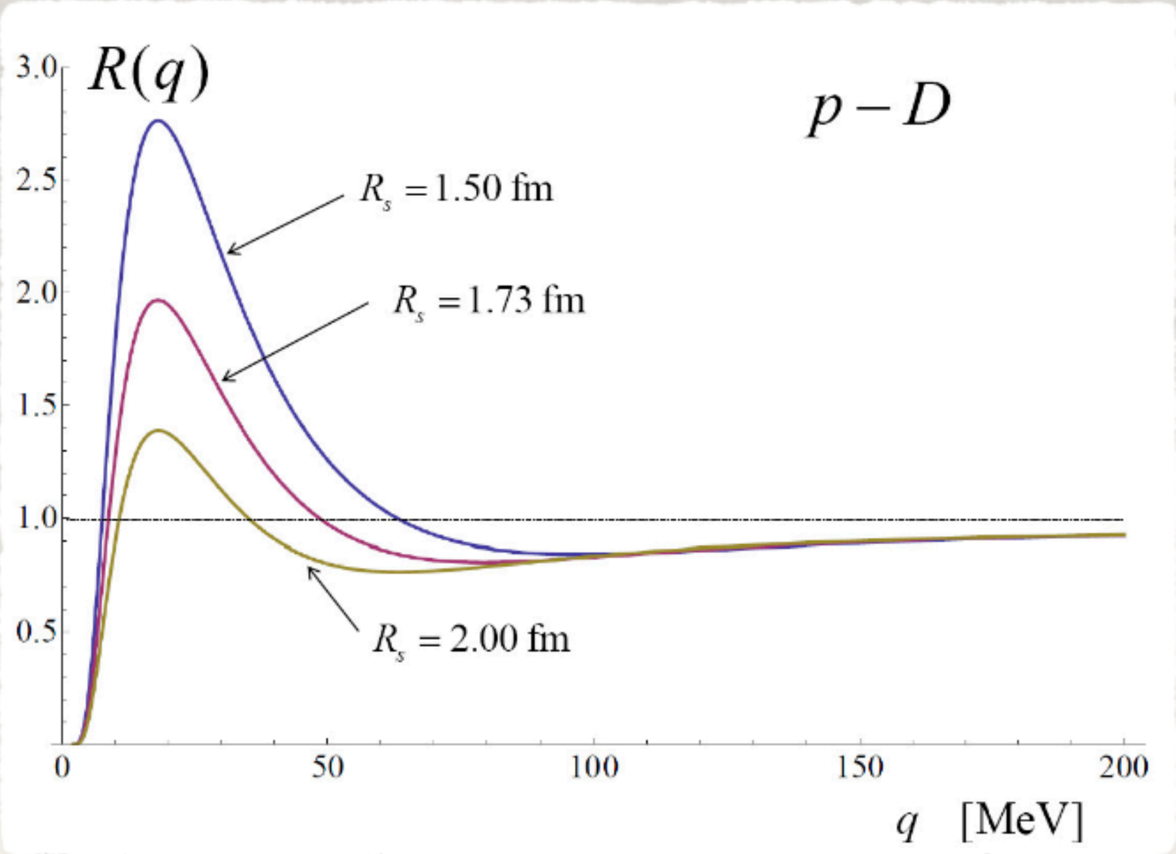
Motivation B: Thermal vs Coalescence



The formula (21) has the same form as (7) but the source function differs. When deuterons are directly emitted from the fireball as ‘elementary’ particles the radius of deuteron source is the same as the radius of proton source. When deuterons are formed only after emission of nucleons from the fireball, the source becomes bigger because the deuteron formation is a process of spatial extent. More quantitatively, the source radius of deuterons treated as bound states is bigger by the factor $\sqrt{4/3} \approx 1.15$ than that of ‘elementary’ deuterons.

S. Mrówczyński, P. Słoń, Acta Phys.Polon.B 51 (2020) 8, 1739-1755
S. Mrówczyński, P. Słoń, arXiv:2103.15761[nucl-th]





Validation method:

Compare the radius of proton emission source and deuteron’s one

Thermal:

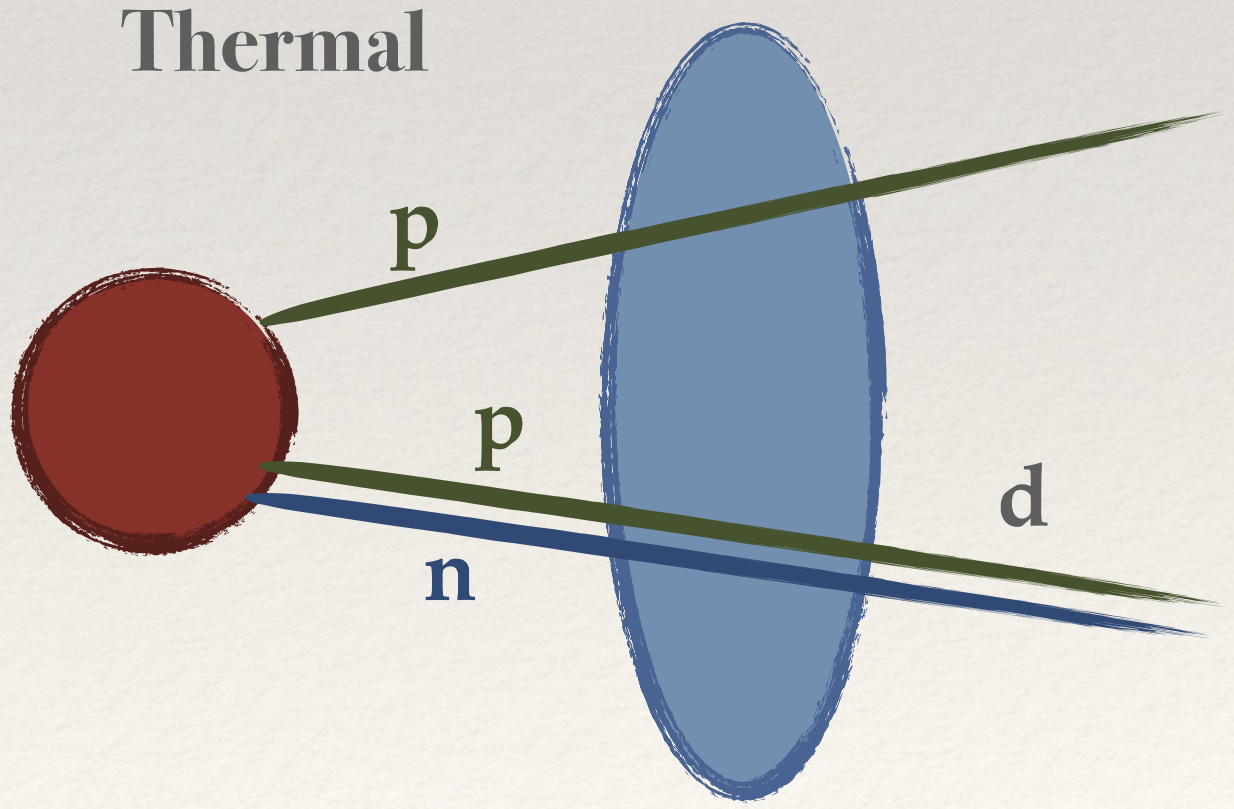
$$R_d = R_p$$

$$R_{pd} = \sqrt{R_p^2 + R_p^2} = R_p\sqrt{2}$$

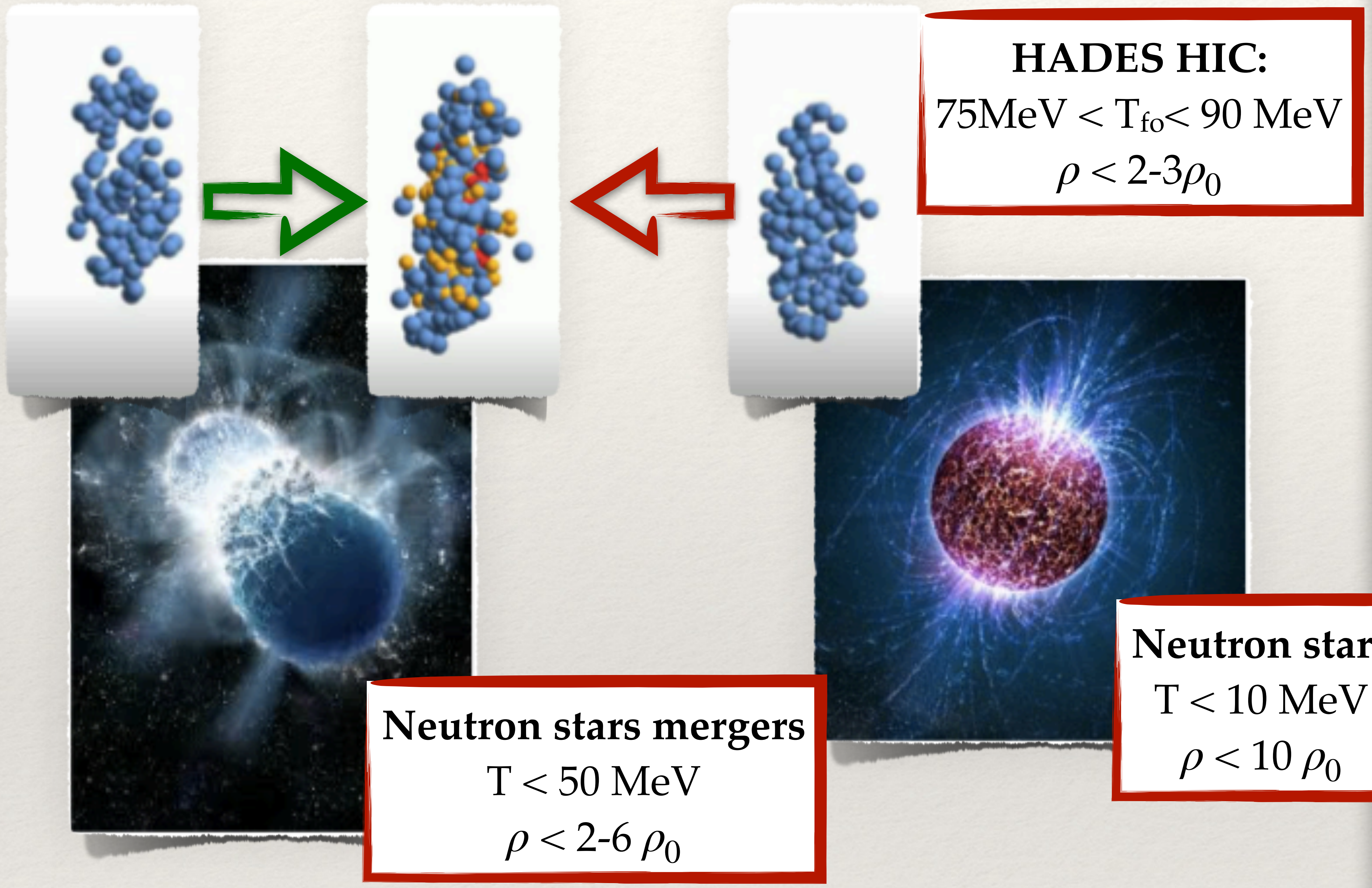
Coalescence

$$R_d = \sqrt{4/3}R_{pd}$$

$$R_{pd} = \sqrt{R_p^2 + 4/3R_d^2}$$



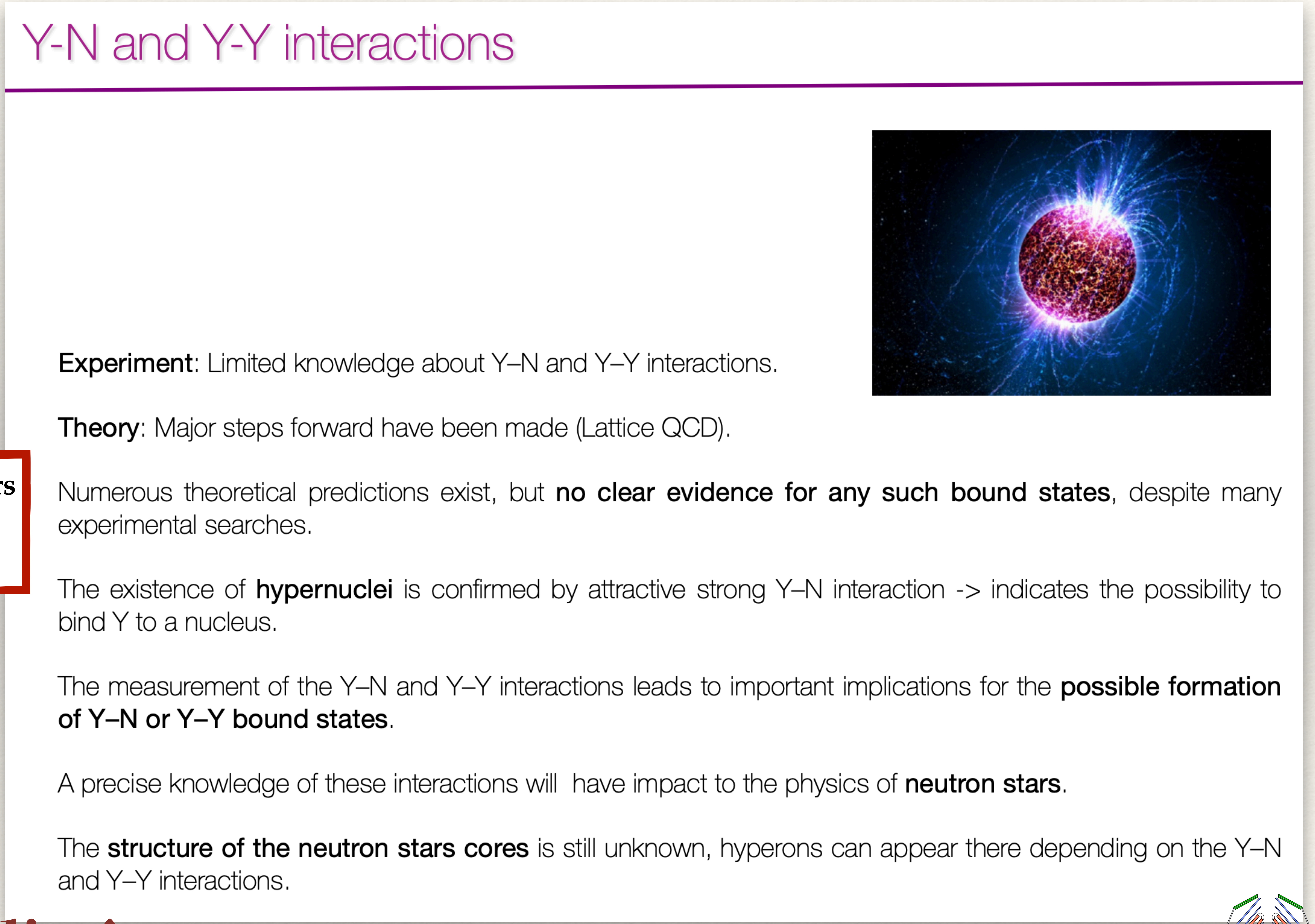
Motivation C: Bound States



HADES HIC:
75MeV < T_{fo}< 90 MeV
$\rho < 2\text{-}3\rho_0$

Neutron stars mergers
T < 50 MeV
$\rho < 2\text{-}6\ \rho_0$

Neutron stars
T < 10 MeV
$\rho < 10\ \rho_0$



Y-N and Y-Y interactions

Experiment: Limited knowledge about Y–N and Y–Y interactions.

Theory: Major steps forward have been made (Lattice QCD).

Numerous theoretical predictions exist, but **no clear evidence for any such bound states**, despite many experimental searches.

The existence of **hypernuclei** is confirmed by attractive strong Y–N interaction -> indicates the possibility to bind Y to a nucleus.

The measurement of the Y–N and Y–Y interactions leads to important implications for the **possible formation of Y–N or Y–Y bound states**.

A precise knowledge of these interactions will have impact to the physics of **neutron stars**.

The **structure of the neutron stars cores** is still unknown, hyperons can appear there depending on the Y–N and Y–Y interactions.

Relevant reference for the NS studies!

M. Stefaniak

HADES experiment

High Acceptance Di-Electron Spectrometer

Fixed target setup:

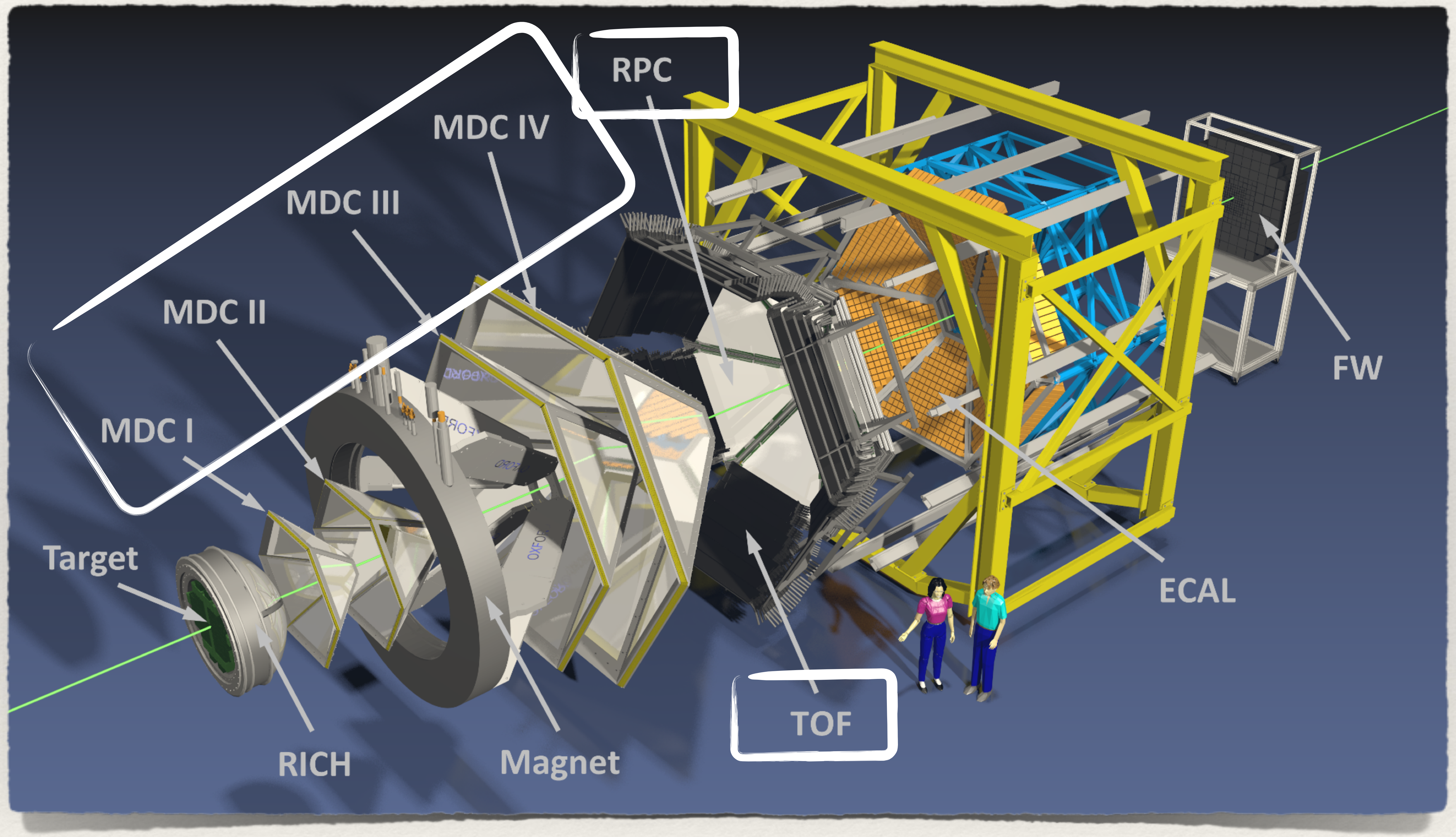
- Higher interaction rate than in the collider mode
- Challenges: δ rays, γ conversion, interactions of beam with the surrounding material

Acceptance:

- Full in the azimuthal angle
- From 18° to 85° in the polar angle: adjusted for good coverage around mid-rapidity @ ~1A GeV

New detectors installed since 2019:

- RICH photodetection plane in cooperation with CBM
- Electromagnetic calorimeter
- Set of forward detectors in cooperation with PANDA



Results

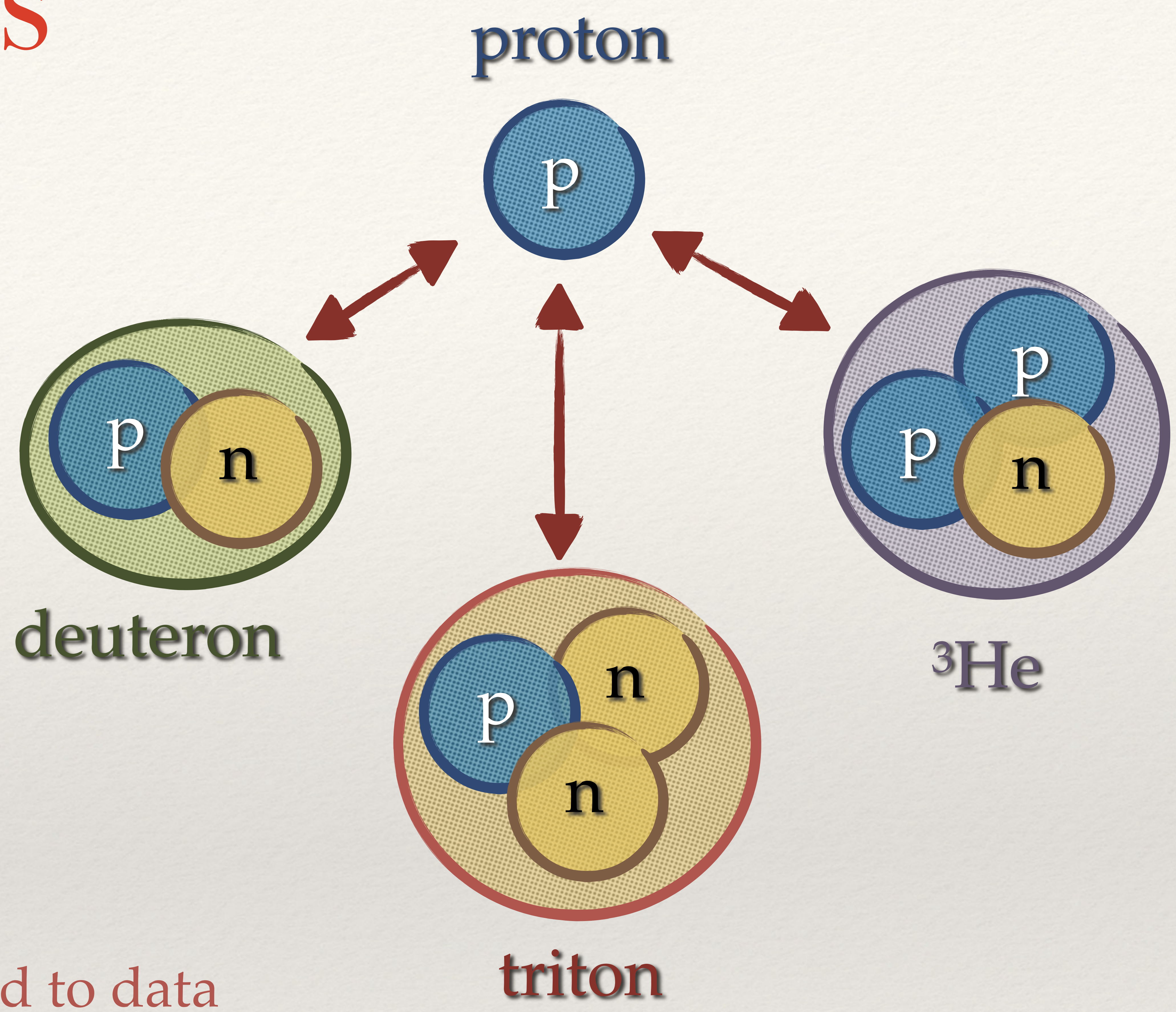
Work in progress

In experimental analysis:

- Applied corrections for the 2-track effects (merging) with double ratio method (more in backup)
- Residual corrections negligible
- Purity corrections negligible
- Only statistical uncertainties

No yet applied:

- Momentum smearing on theoretical functions compared to data
- Systematic uncertainties



Due to expected high systematic uncertainties the results for $k^* < 15$ MeV/c are covered with blue band.

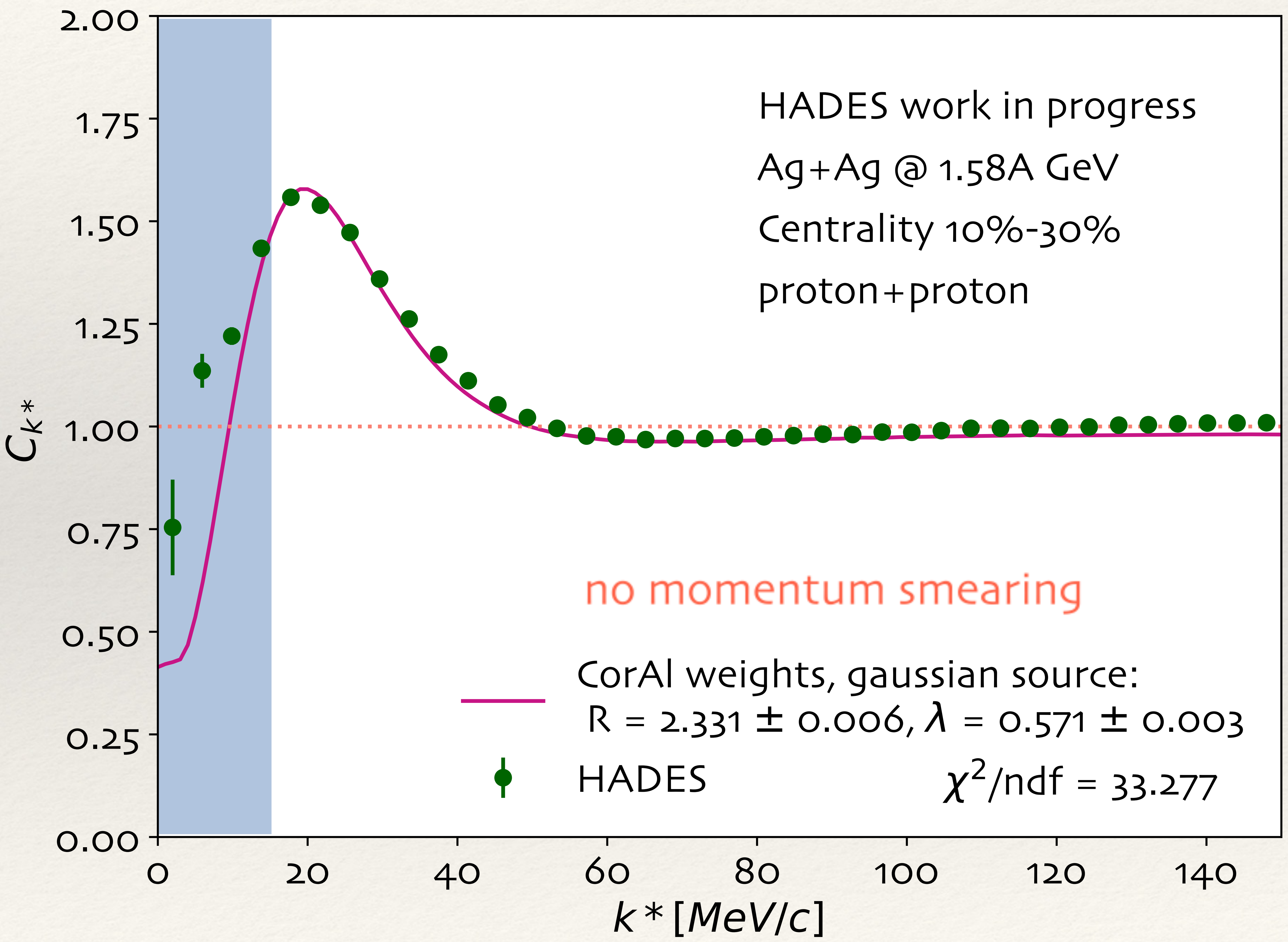
Proton - proton

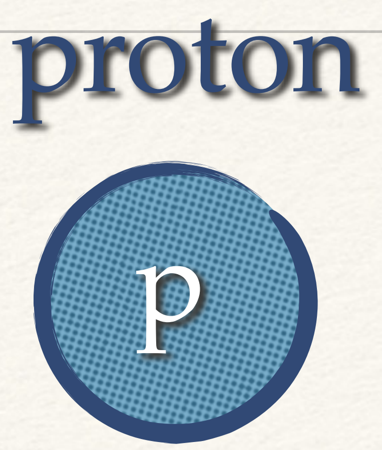
- Visible strong negative correlation due to Coulomb and positive caused by Strong Interactions
- Initially extracted Radius equal to 2.33 fm *(work in progress)*

Strong interactions: wave functions solved using Reid soft-core potential - *from CorAl software*

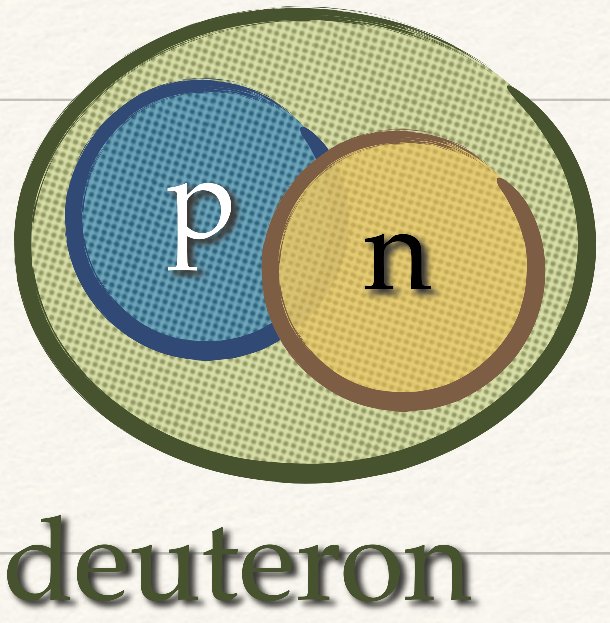
- Reference for the further studies *(next slides)*

Fitting procedure using the CorAl software (author: Scott Pratt, MSU) and HAL (author: Daniel Wielanek, WUT)





Proton - deuteron



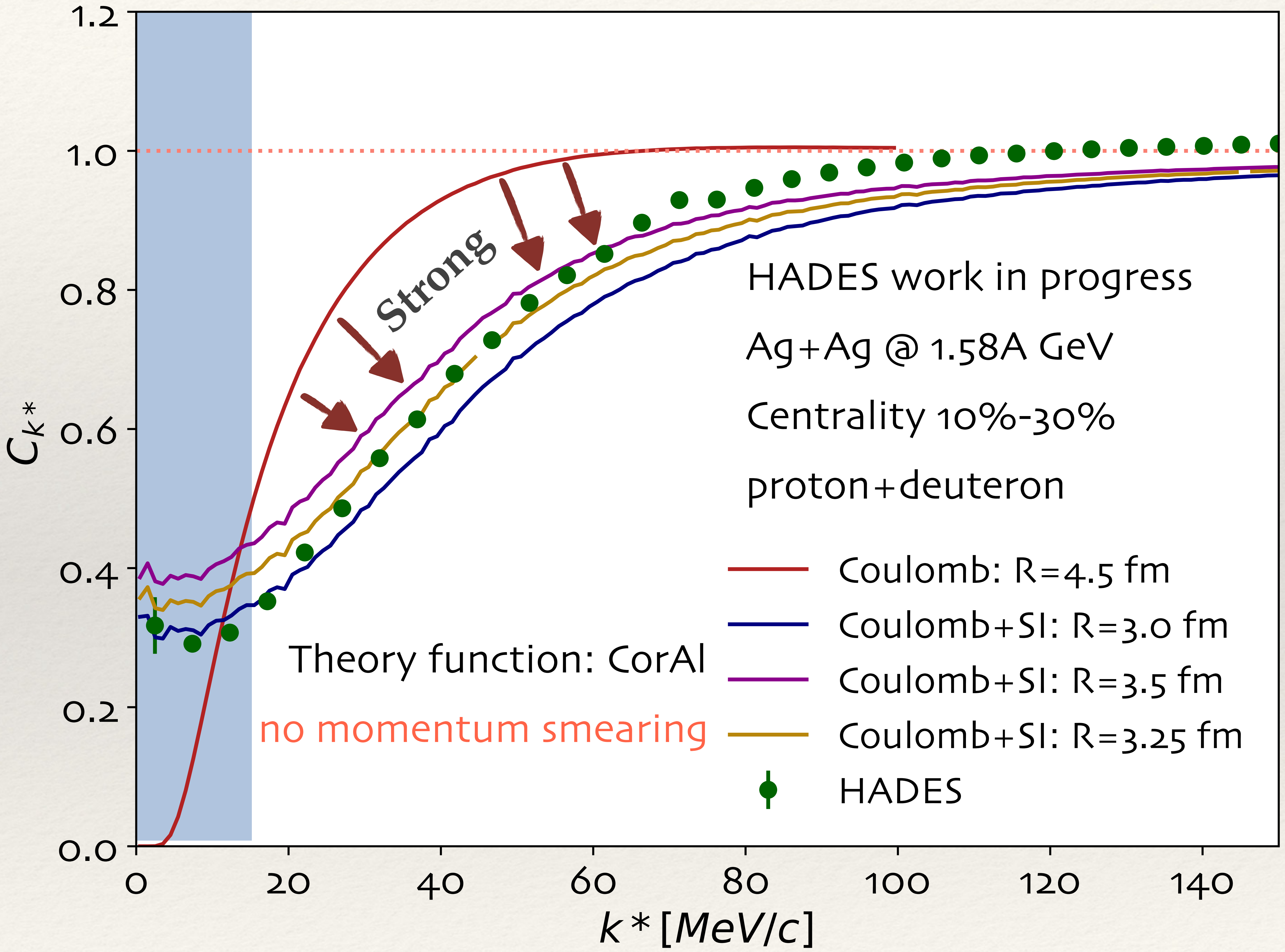
- Negative correlation originating from both Coulomb and Strong Interactions
- **Approximate** radius from theoretical function: $R_{pd} \approx 3.25$ fm

Strong interactions: wave functions solved using potential fitted to phase shifts - *from CorAl software*

Work in progress

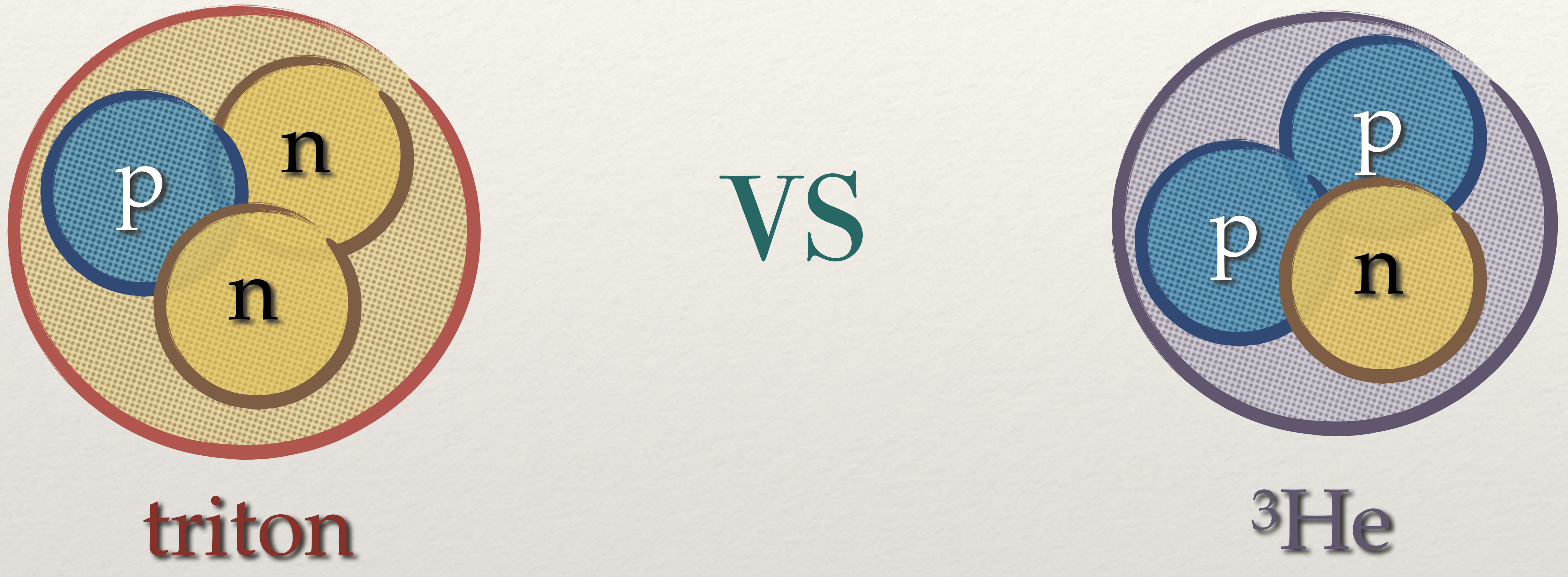
$$R_d = \sqrt{R_{pd}^2 - R_p^2} \approx 2.26 \textbf{ fm}$$

$$R_p = 2.331(6) \textbf{ fm}$$

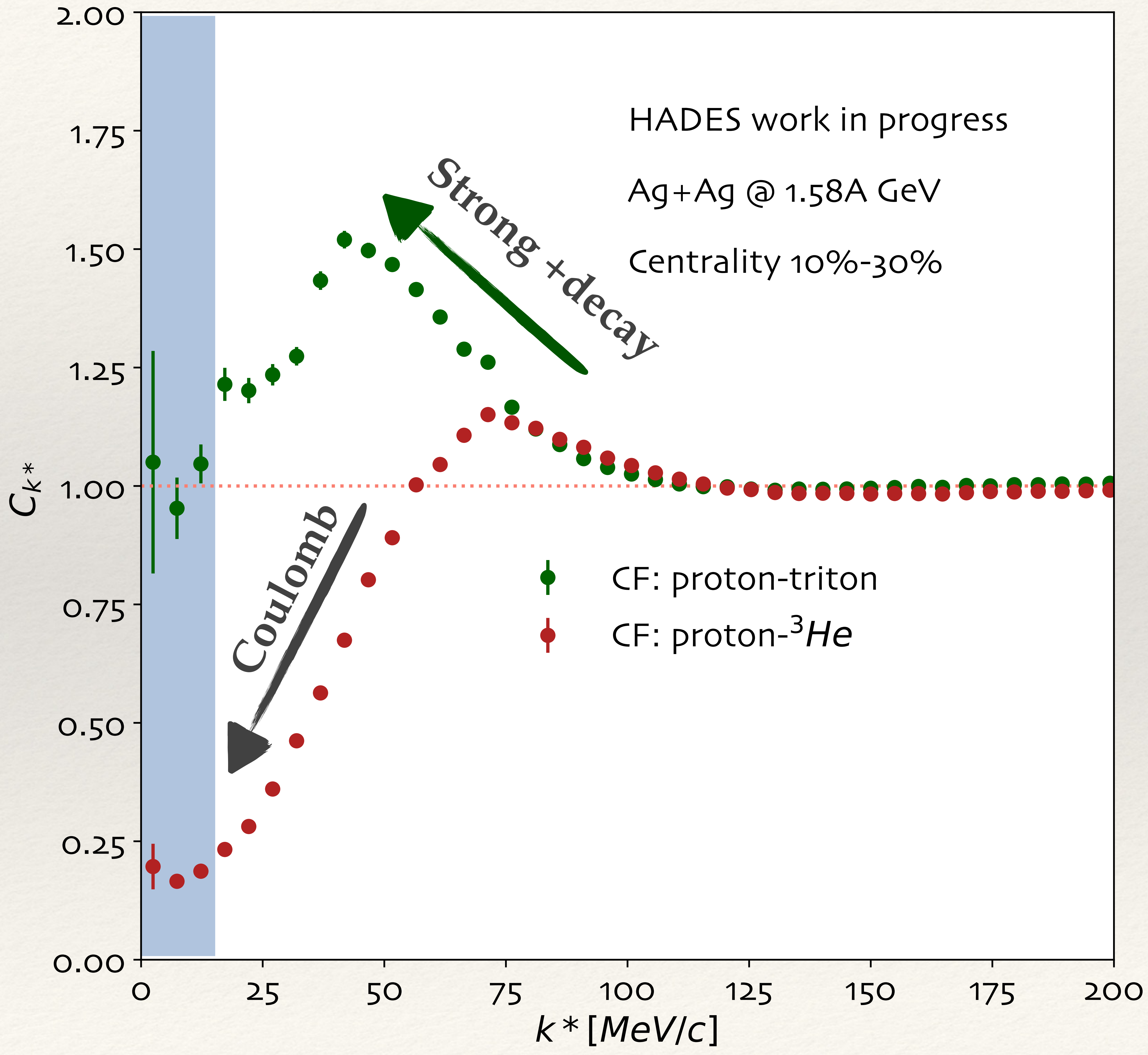


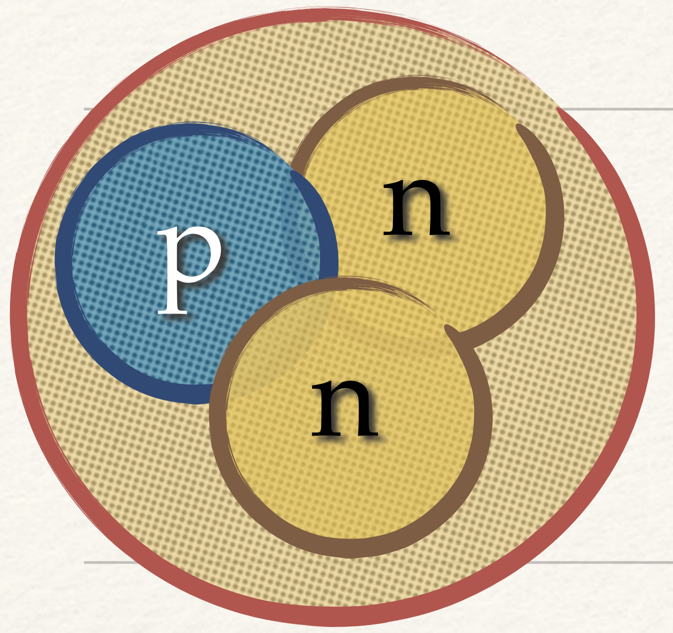
Proton - triton vs proton - ^{3}Helium

Similar masses, differentiate **p ↔ n**



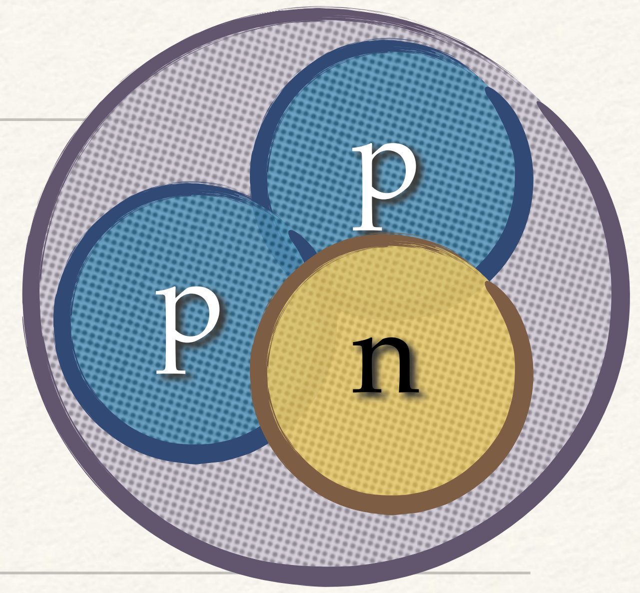
- Due to 2 protons stronger Coulomb in p-3He
- Higher positive correlation in p-t as a result of strong interactions and possible excited states (^{4}He*)





triton

Proton - triton vs proton - ^{3}Helium



^{3}He

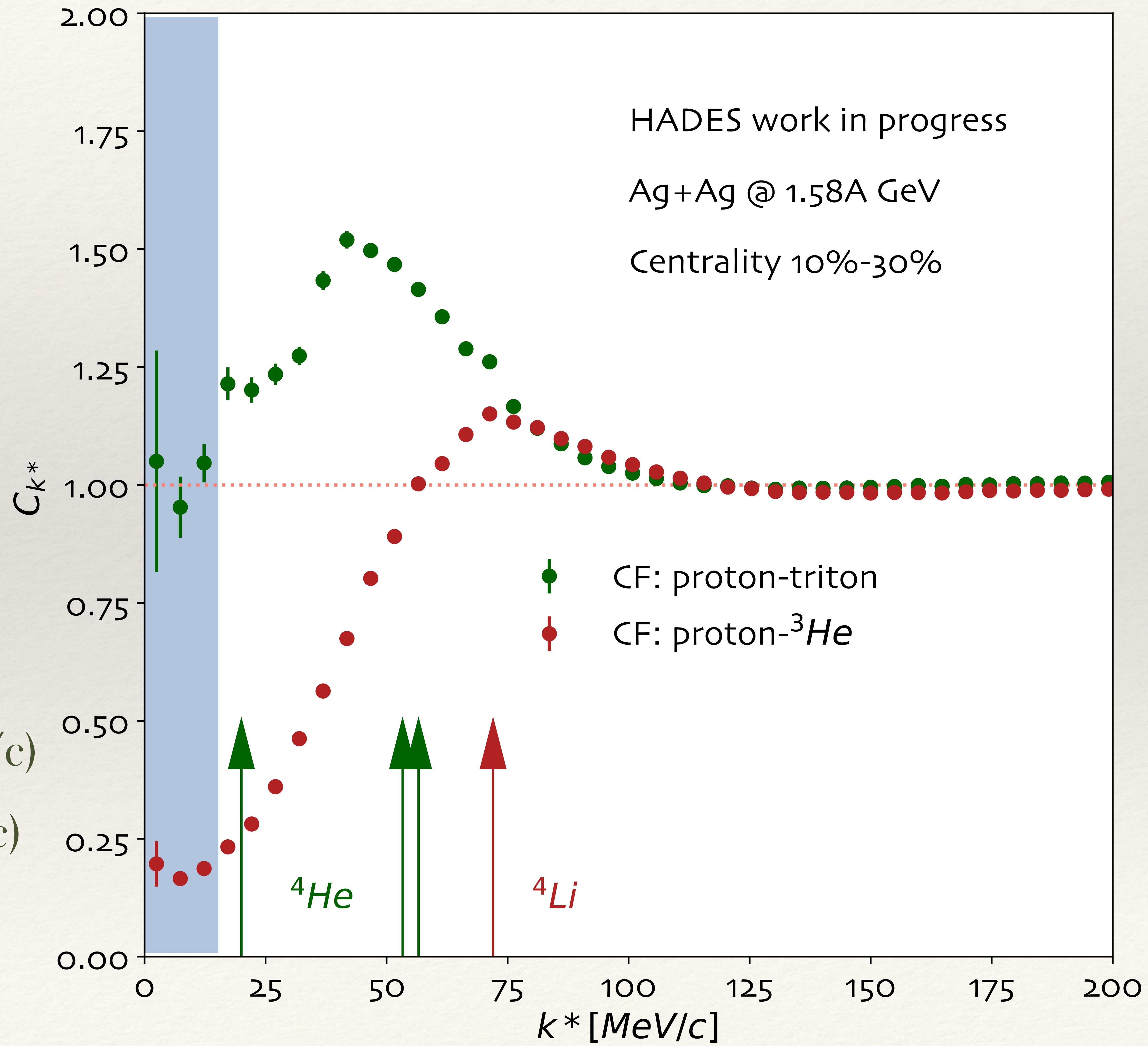
- Visible decays of
  - unbound ground state of ^{4}Li → p + 3He
  - excited states of ^{4}He* → p + t

Unbound ground state ^{4}Li:

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

Excited states of ^{4}He:

- ($E = 20.21$ 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)

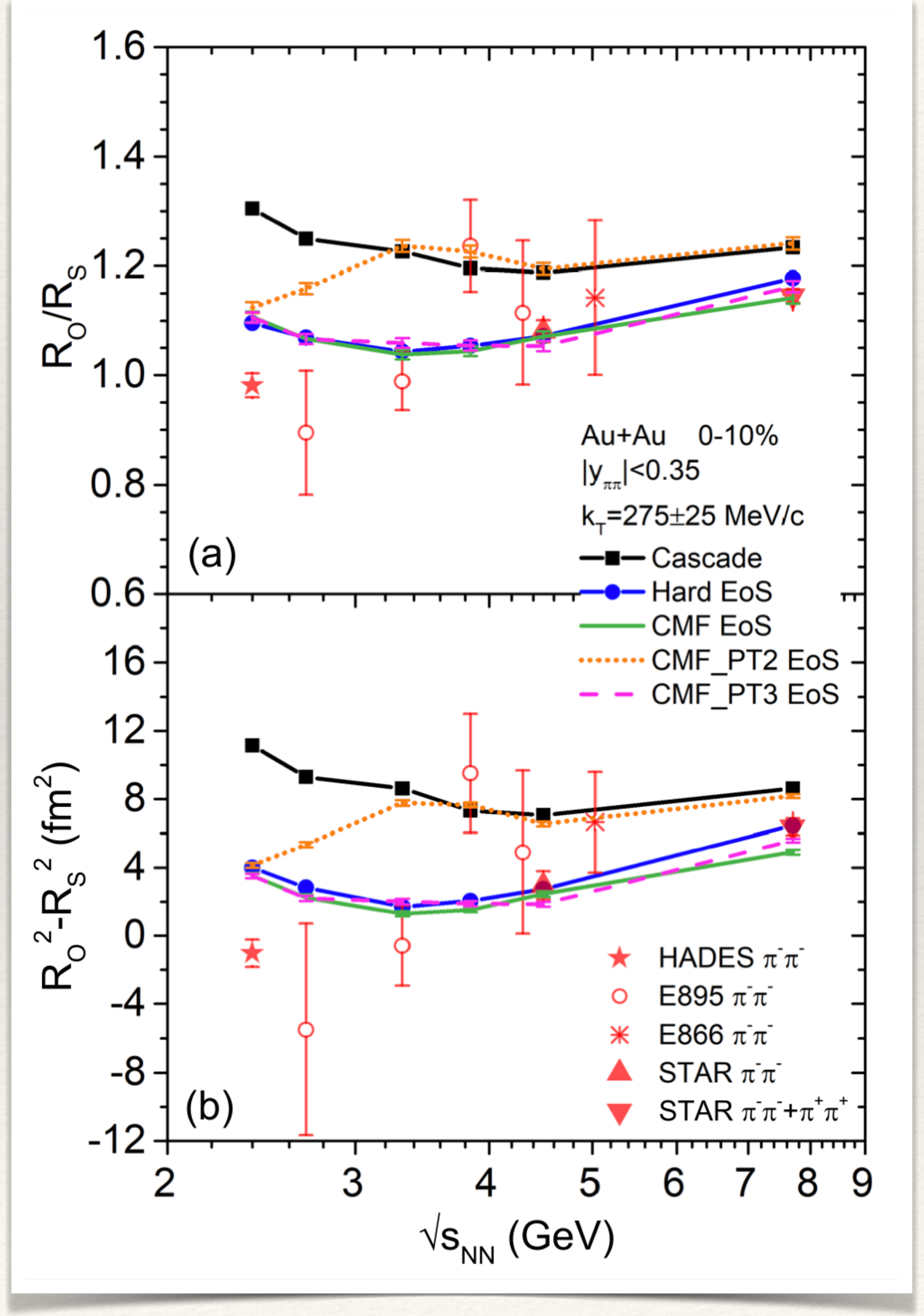


FOPI Collaboration: Eur. Phys. J. A 6, 185–195 (1999)

Proton - proton in EoS studies

Work in progress

With Scott Pratt and Jan Steinheimer



P. Li., J. Steinheimer, et al: arXiv:2209.01413

Pion-pion correlations

Studies performed with UrQMD model + CRAB

What about proton + proton correlations?

Idea:

UrQMD

Various EoS

+

CorAl

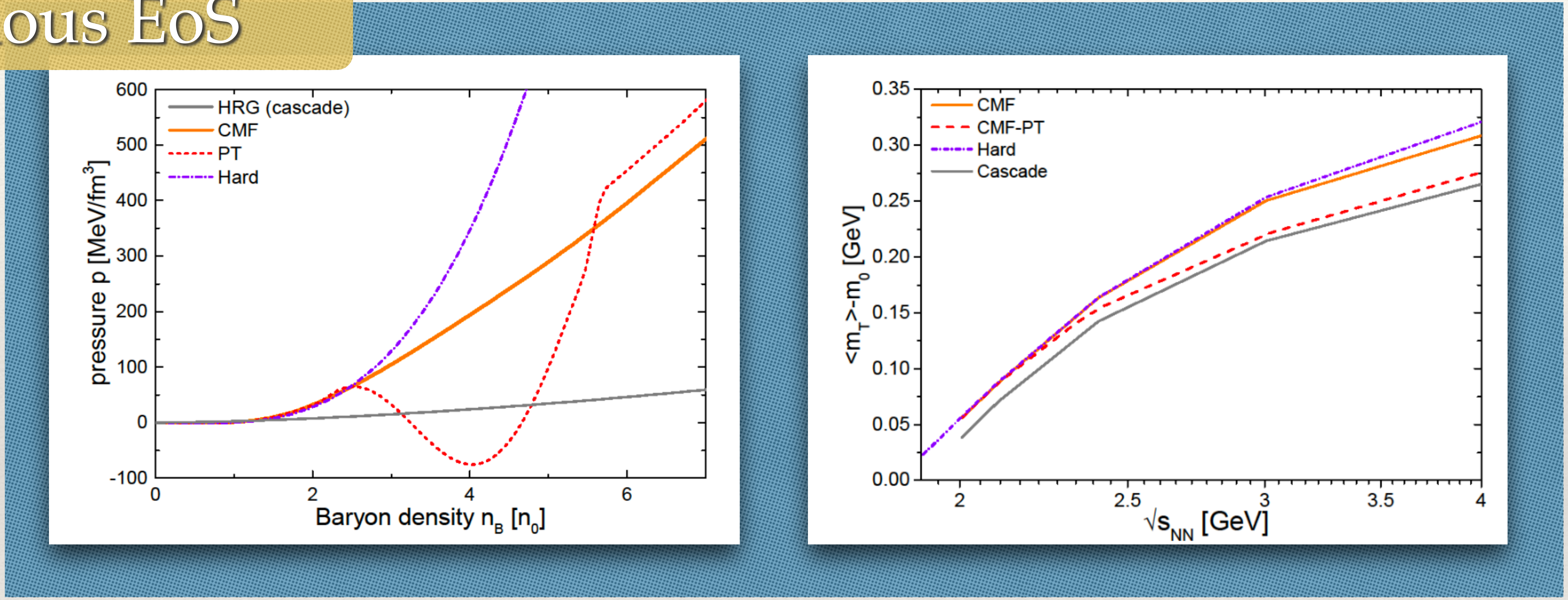
How the p+p correlations differ with EoS within the same model?

Proton - proton in EoS studies

Work in progress

With Scott Pratt and Jan Steinheimer

Various EoS



CorAl

Correlation Analysis

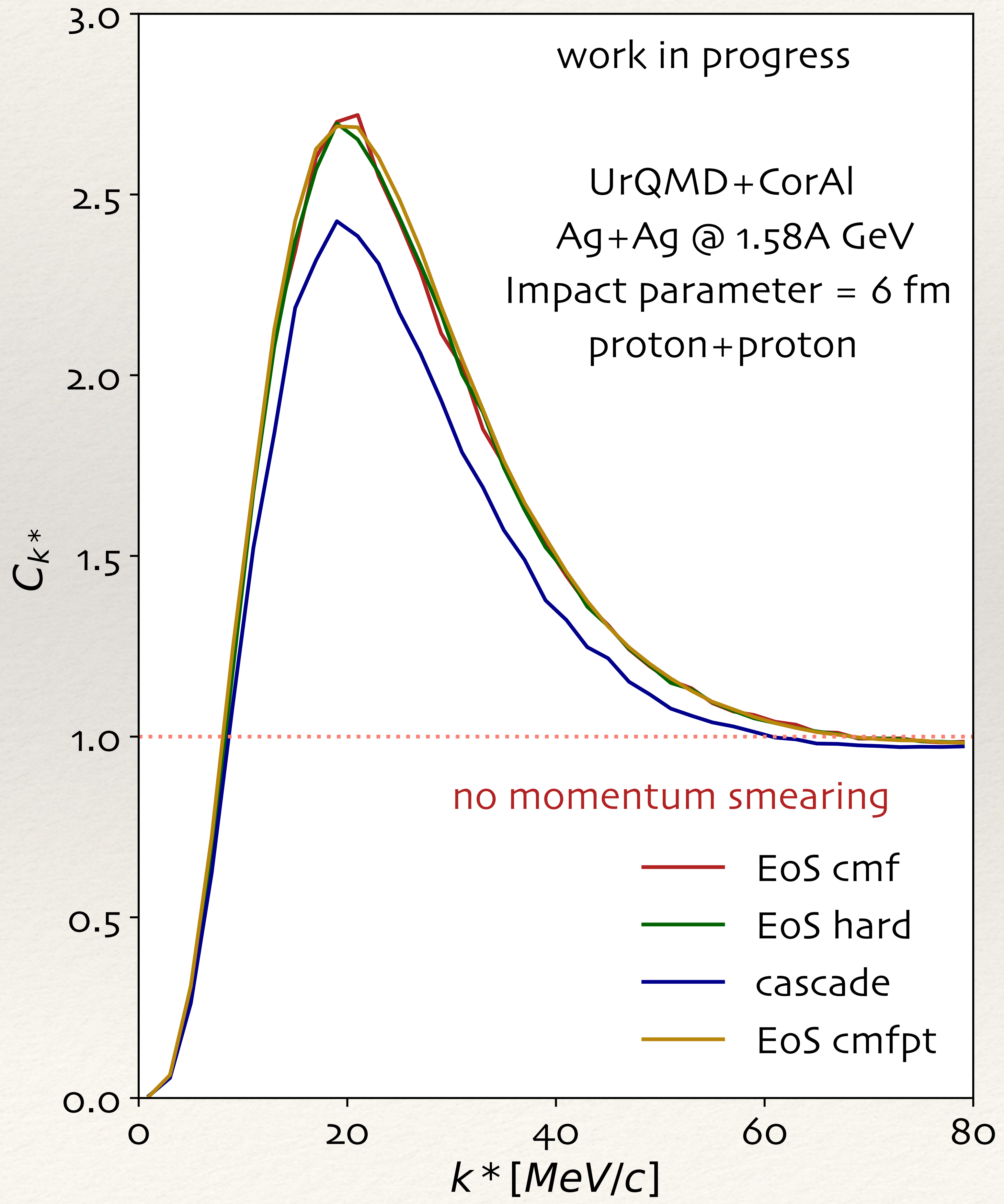
Uses Kooning formula to calculate the wave functions for space-points taken from UrQMD

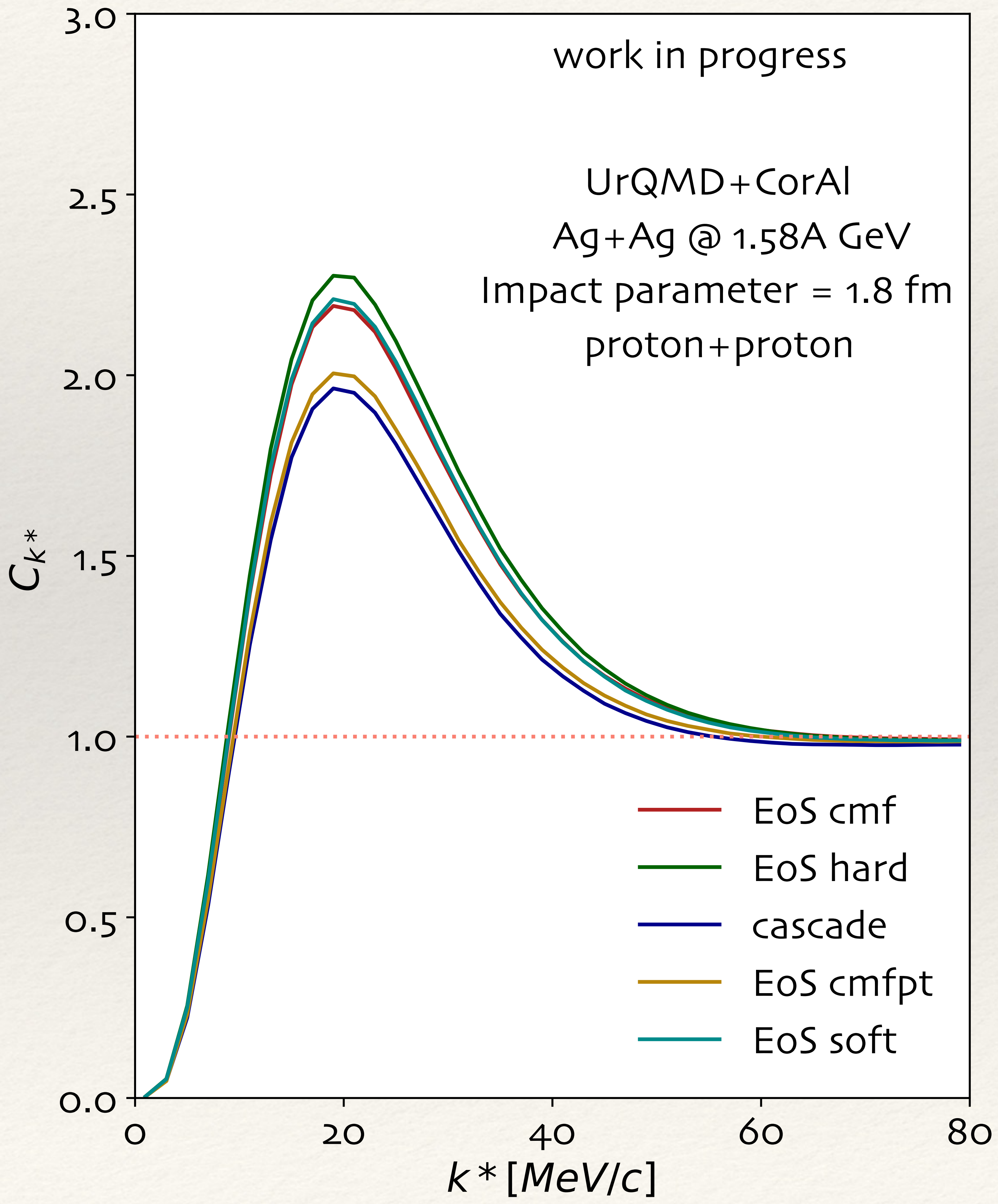
P. Li., J. Steinheimer, et al: arXiv:2209.01413

Proton - proton in EoS studies

Work in progress

With Scott Pratt and Jan Steinheimer





EoS:

SOFTER vs STIFFER

Shorter emission duration

Longer emission duration

Higher flow

Lower flow

Visible changes of EoS in pp CF

The higher baryon density the more vital differences

Summary and Outlook

1. First initial *(no smearing)* radius of proton and deuteron source extracted: *possibly* similar, what would indicate the thermal production mechanism of light nuclei. - Getting closer to solving the snowball puzzle!
2. Comparisons between proton - triton vs proton - Helium-3:
   - Visible differences in SI and Coulomb
   - Presence of excited states ^{4}He and unbound ground state ^{4}Li
3. UrQMD+CorAl: proton+proton correlations relevantly sensitive to changes of EoS

---

1. Comparisons of thermal and coalescence models + CorAl to proton-cluster correlations
2. Further investigation of EOS with UrQMD+CorAl

THANK YOU!

Back up

Detector effect corrections

Double ratio method

Expectation:

1)

The simulated „raw" CF
do ***not*** *include any correlations*

2)

Simulations +HGeant
include detector effects

3)

$$\frac{\text{Experiment}}{\text{Simulations +HGeant}}$$

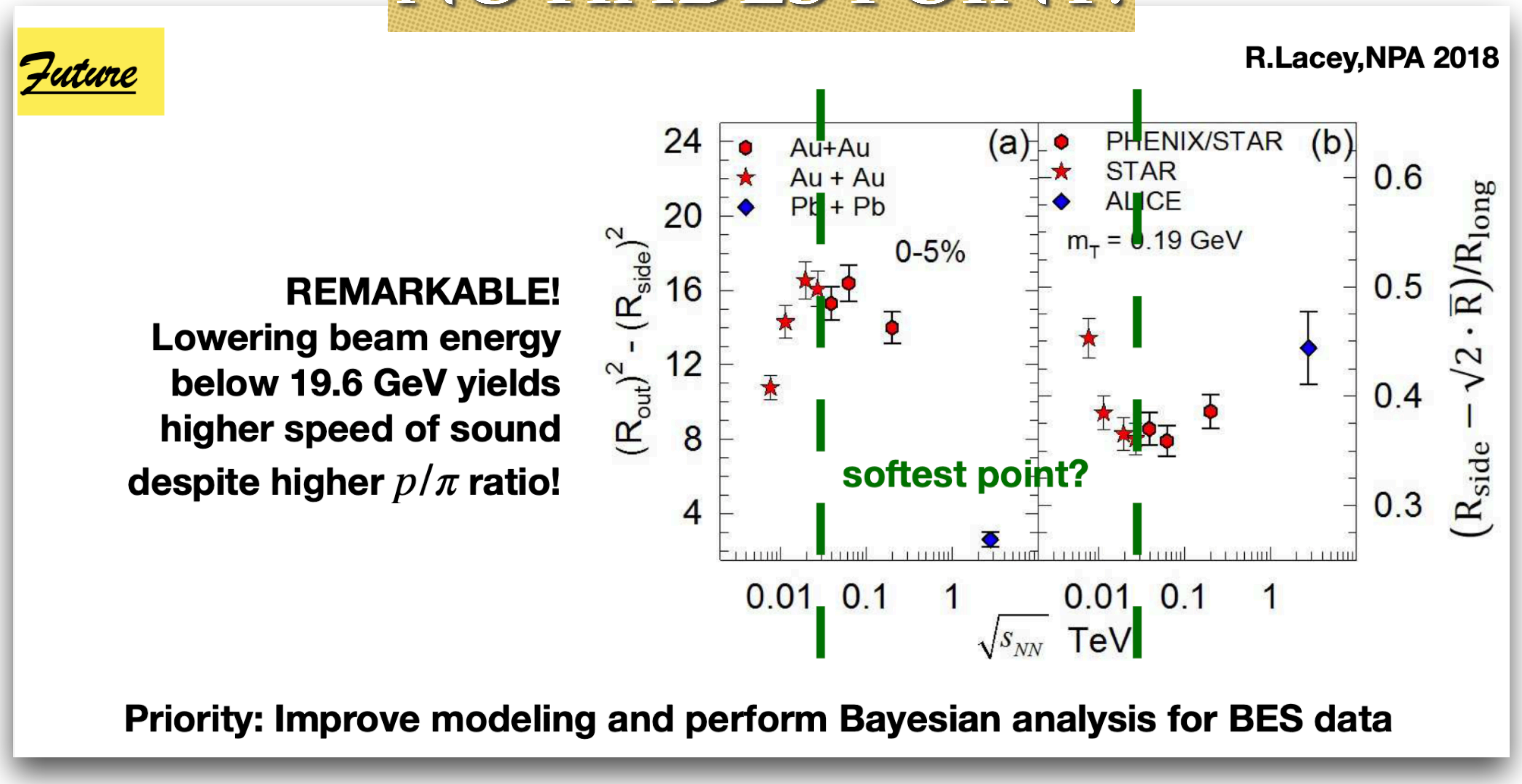
Only Femto Correlations left!

EoS with HBT

Source: S.Pratt, J. Vredevoogd: Phys.Rev.C78:054906,2008

Scott Pratt lecture at GSI: *„Foundation of femtoscopy”*

NO HADES POINT!



Future

R.Lacey,NPA 2018

REMARKABLE!
Lowering beam energy below 19.6 GeV yields higher speed of sound despite higher p/π ratio!

Priority: Improve modeling and perform Bayesian analysis for BES data

Stiff EoS:

- Rapid expansions: emission at earlier times, more confined to a brief burst
- Mean emission reduced: R_{long} smaller (less time to expand in long direction before the emission)
- Increased suddenness - shorter R_{out} to R_{side} as long-live emission causes the earlier-emitted particles to move ahead of the later-emitted ones along the out direction

Soft EoS:

- Higher entropy
- For fixed spectra, entropy grows with volume ~ $R_{out}R_{side}R_{long}$
- Longer relative R_{long} and R_{out} to R_{side}

Critical Point

Bulk viscosity huge in vicinity of T_c, system struggles to maintain equilibrium

- Lowers pressure
- Increase entropy

Larger source dimensions

Shear viscosity important mostly at early times, when velocity gradients are big and highly anisotropic

Enhancement in the transverse components of energy tensor which accelerates the transverse expansion resulting in smaller values of R_{long} and R_{out} to R_{side}