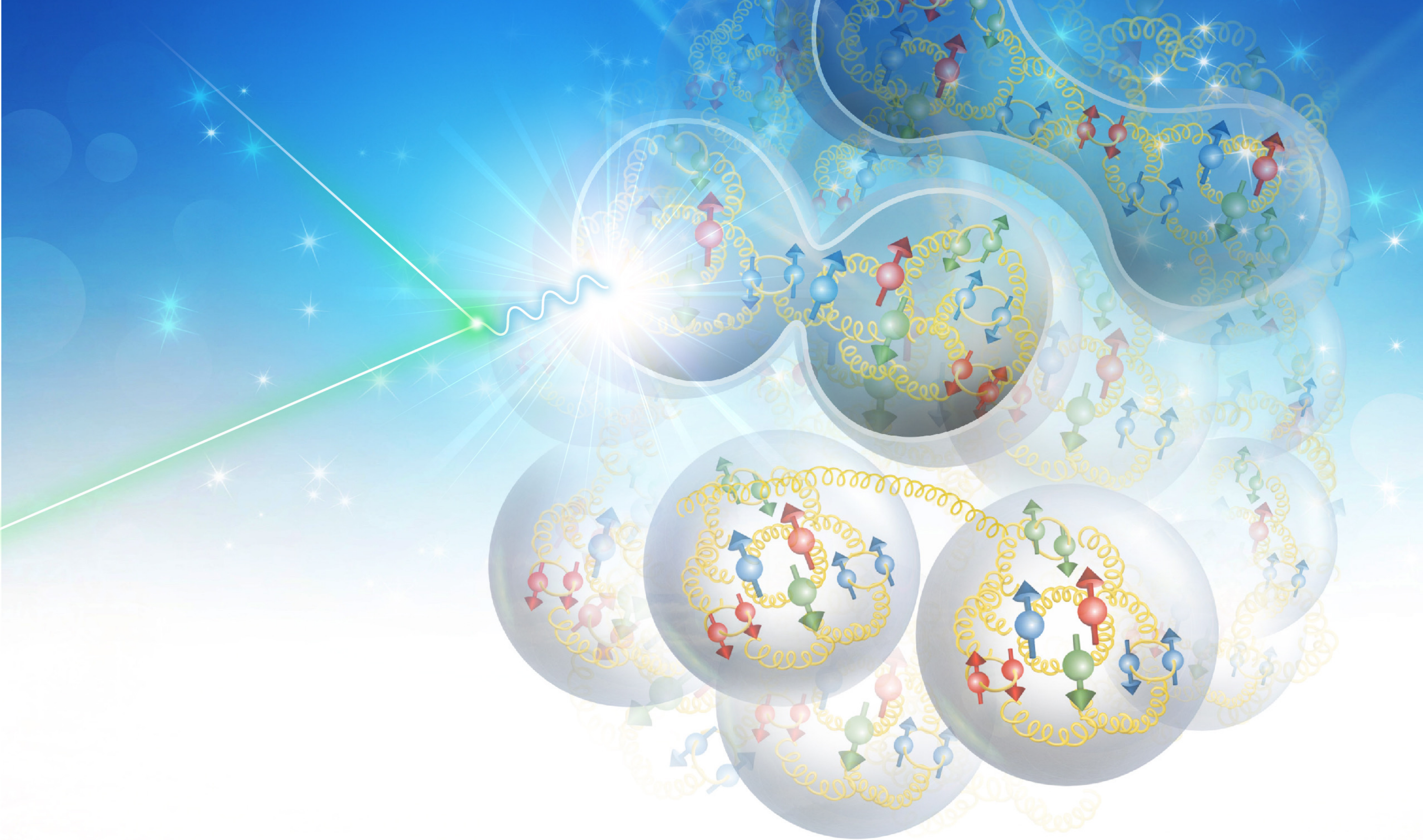


Hampton University Graduate School (HUGs)

June 2022, JLab, Newport News, VA.

What we have learned about SRCs?

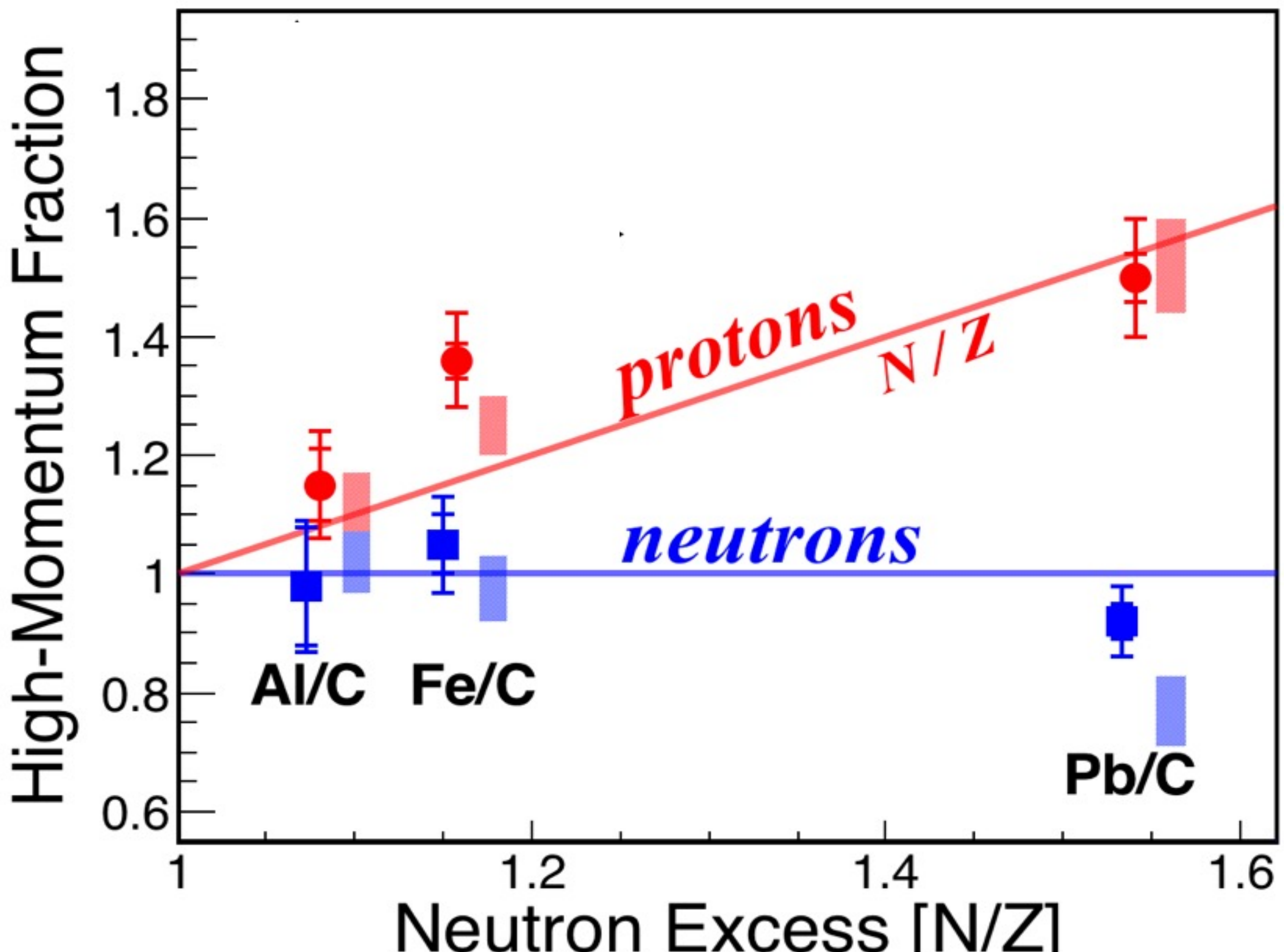
- ❑ SRCs is responsible for high-momentum tail
- ❑ SRCs accounts for ~20% of nucleon
- ❑ SRC pairs are back-to-back with small C.M.
- ❑ np pairs dominate over pp-pairs by ~ x20

  in nuclei from ^{4}He – Pb

What about neutron-rich nuclei?

Proton "speed up" in neutron-rich nuclei

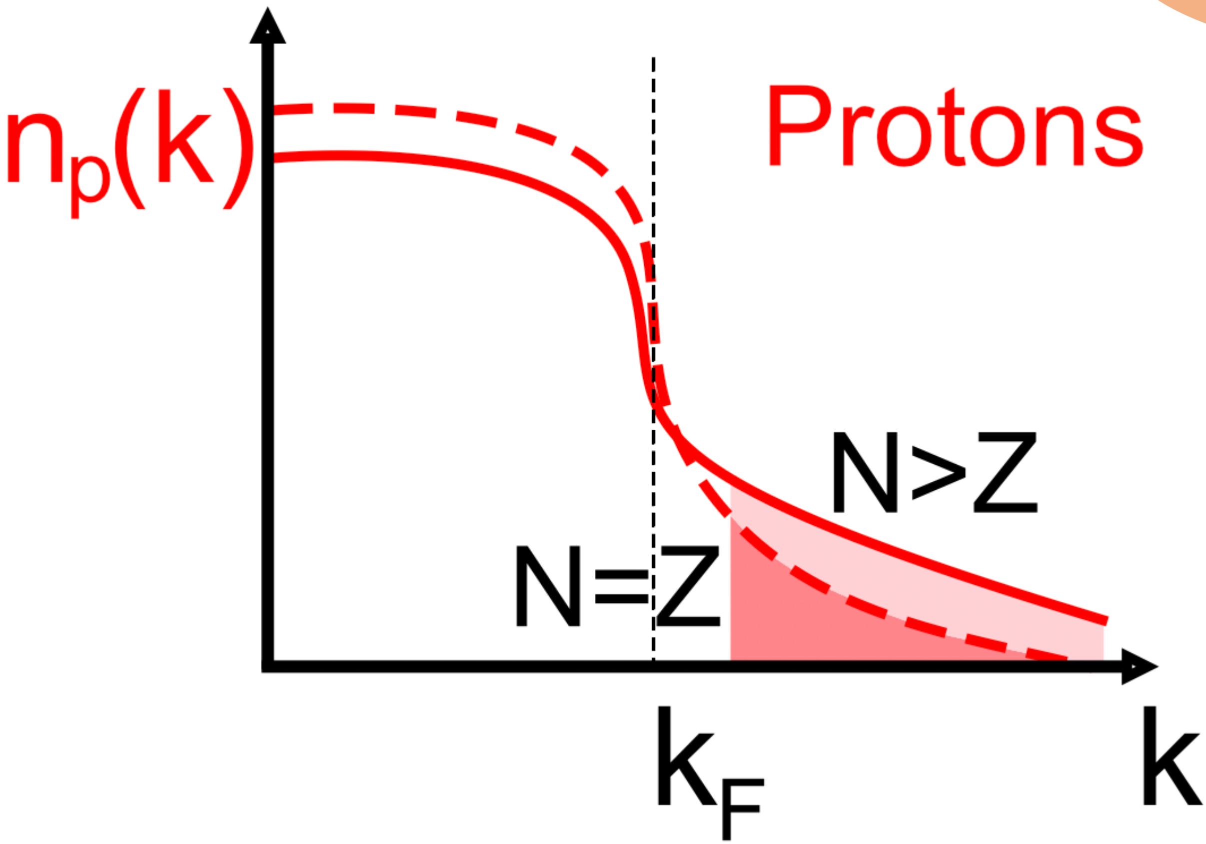
$$\frac{\sigma^A_{SRC}(e,e'N)}{\sigma^A_{MF}(e,e'N)} \Big/ \frac{\sigma^C_{SRC}(e,e'N)}{\sigma^C_{MF}(e,e'N)}$$



Duer et al., Nature (2018)

Protons are more correlated in neutron-rich nuclei

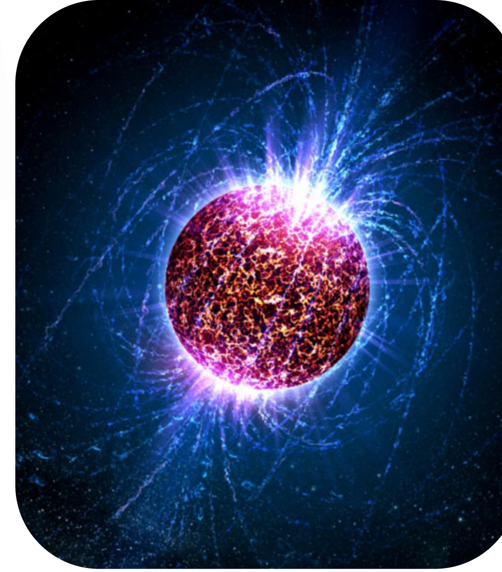
correlate with core protons



Pb/C

Daily Press

Jefferson Lab breaks new ground, from nucleons to neutron stars

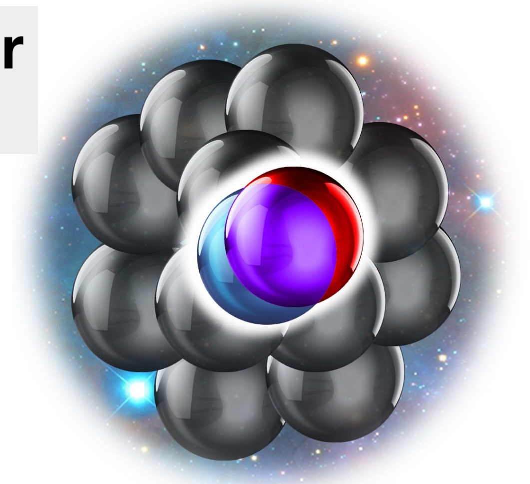


PHYS.ORG

Protons may have an outsize influence on the properties of neutron stars and other neutron-rich objects

Space Answers

Protons strongly influence the behaviour of neutron stars



Astronomy Now

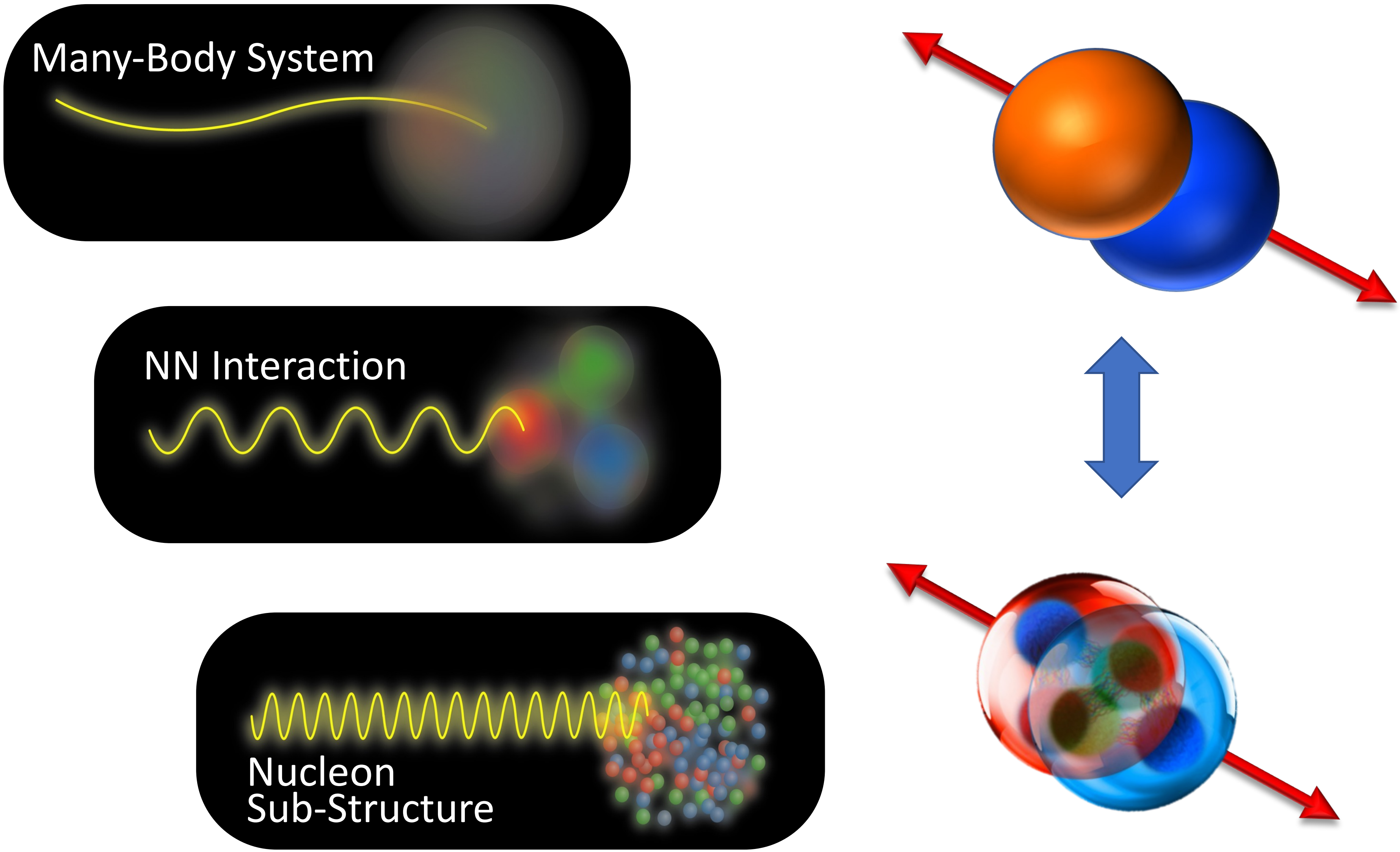
physicsworld

GIZMODO

Surprising Accelerator Finding Could Change the Way We Think About Neutron Stars

Lecture4+5:

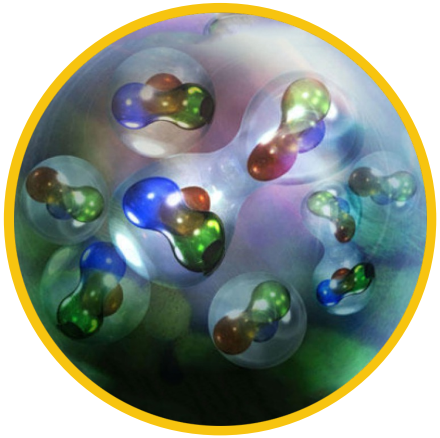
- Nucleon-Nucleon (NN) interactions
  - (e,e'p) measurement on A=3
- Short Range Correlations and EMC effect
- Proton visualization


Many-Body System
NN Interaction
Nucleon
Sub-Structure

Why Nucleon-nucleon interaction?

Crucial for:

- Ab-Initio structure & reaction calculations
- Dense astrophysical objects, e.g. neutron stars
- Any calculation related to nuclear interaction

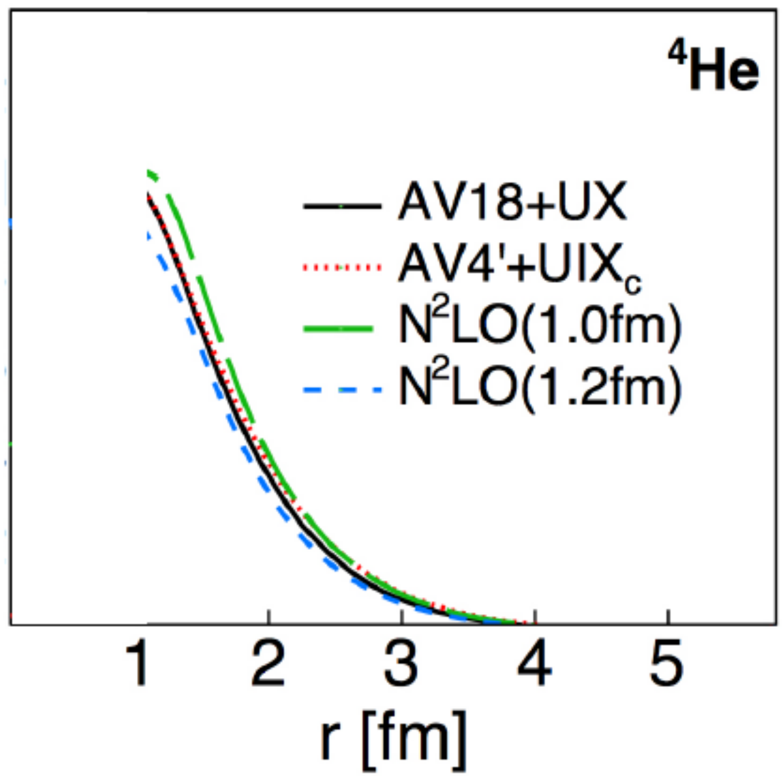


There are many NN potential models…

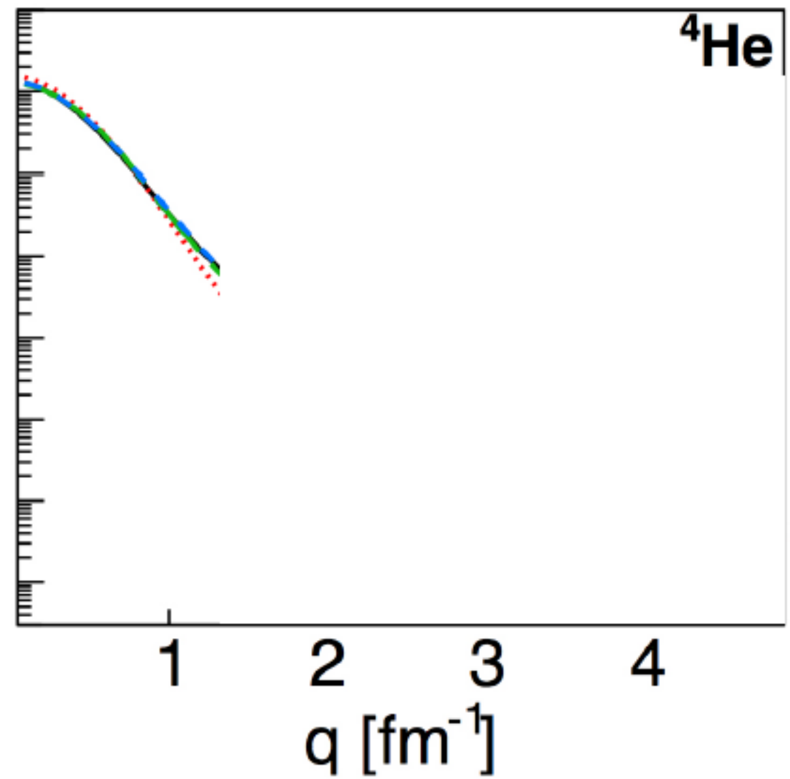
- Hamada-Johnston Potential
- Yale-Group Potential
- Reid68 Potential
- Reid-Day Potential
- Partovi-Lomon Potential
- Paris-Group Potentials
- Stony-Brook Potential
- dTRS Super-Soft-Core Potentials
- Funabashi Potentials
- Urbana-Group Potentials
- Argonne-Group Potentials
  - Argonne V14
  - Argonne V28
  - Argonne V18
- Bonn-Group Potentials
  - Full-Bonn Potential
  - CD-Bonn Potential
- Padua-Group Potential
- Nijmegen-Group Potentials
  - Nijm78 Potential
  - Partial-Wave-Analysis
  - Nijm93
  - NijmI
  - NijmII
  - Reid93 Potential
  - Extended Soft-Core
  - Nijmegen Optical Potentials
- Hamburg-Group Potentials
- Moscow-Group Potentials
- Budapest(IS)-Group Potential
- MIK-Group Potential
- Imaginary Potentials
- QCD-Inspired Potentials
- The Oxford Potential
- The First CHPT NN Potentials
- Sao Paulo-Group CHPT Potentials
- Munich-Group CHPT Potentials
- Idaho-Group CHPT Potentials
- Bochum-Julich-Group CHPT Potentials
  - LO Potentials
  - NLO Potentials
  - NNLO Potentials
  - NNNLO Potentials
- **and more!**

Overall consistent at long-r/ small-k

Probability to find two nucleons with relative distance r



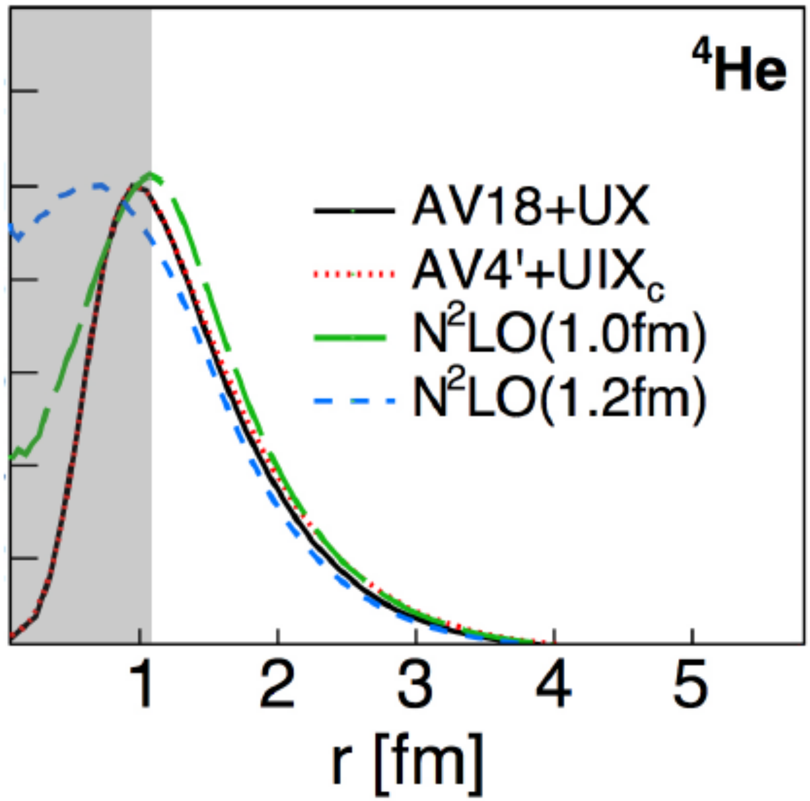
Probability to find two nucleons with relative momentum q.



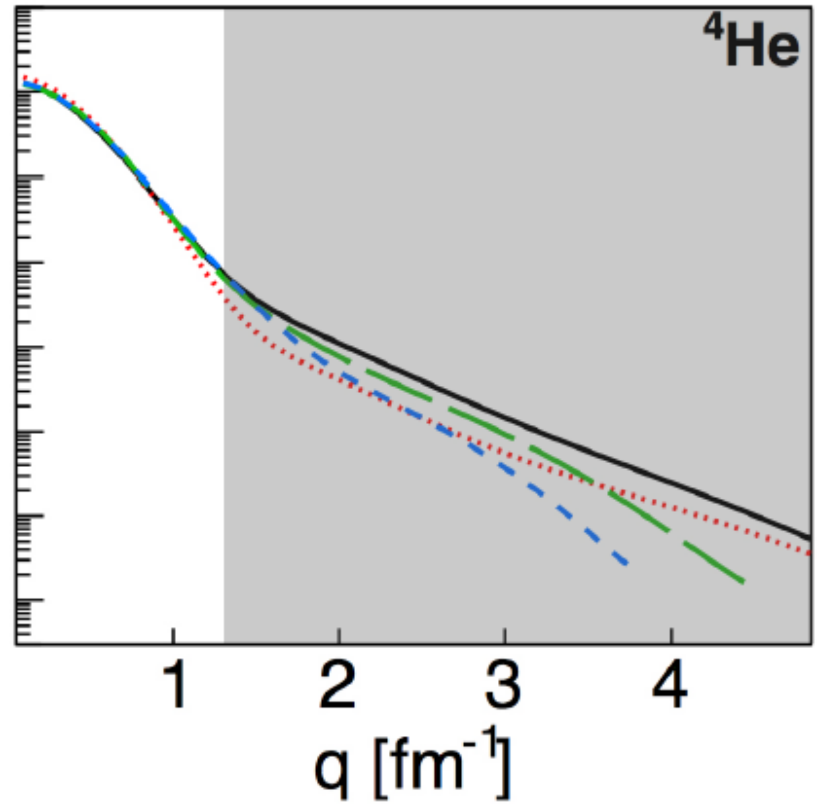
200 MeV/c ≈ 1 fm^{-1}

Large model dependence at small-r/high-k

Probability to find two nucleons with relative distance r



Probability to find two nucleons with relative momentum q.



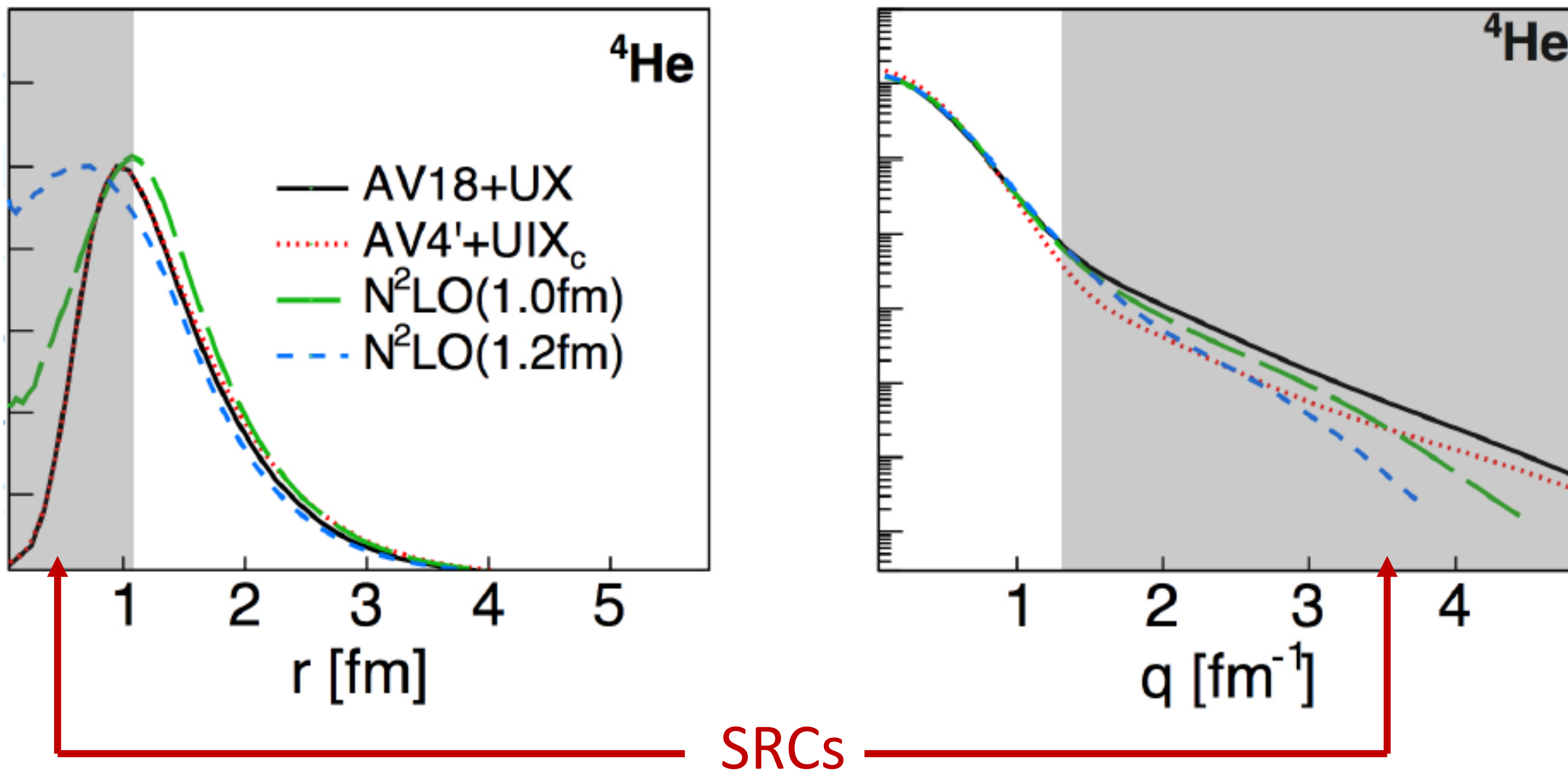
200 MeV/c ≈ 1 fm^{-1}

Need to put these to test

Large model dependence at small-r/high-k

Probability to find two nucleons with relative distance r

Probability to find two nucleons with relative momentum q.

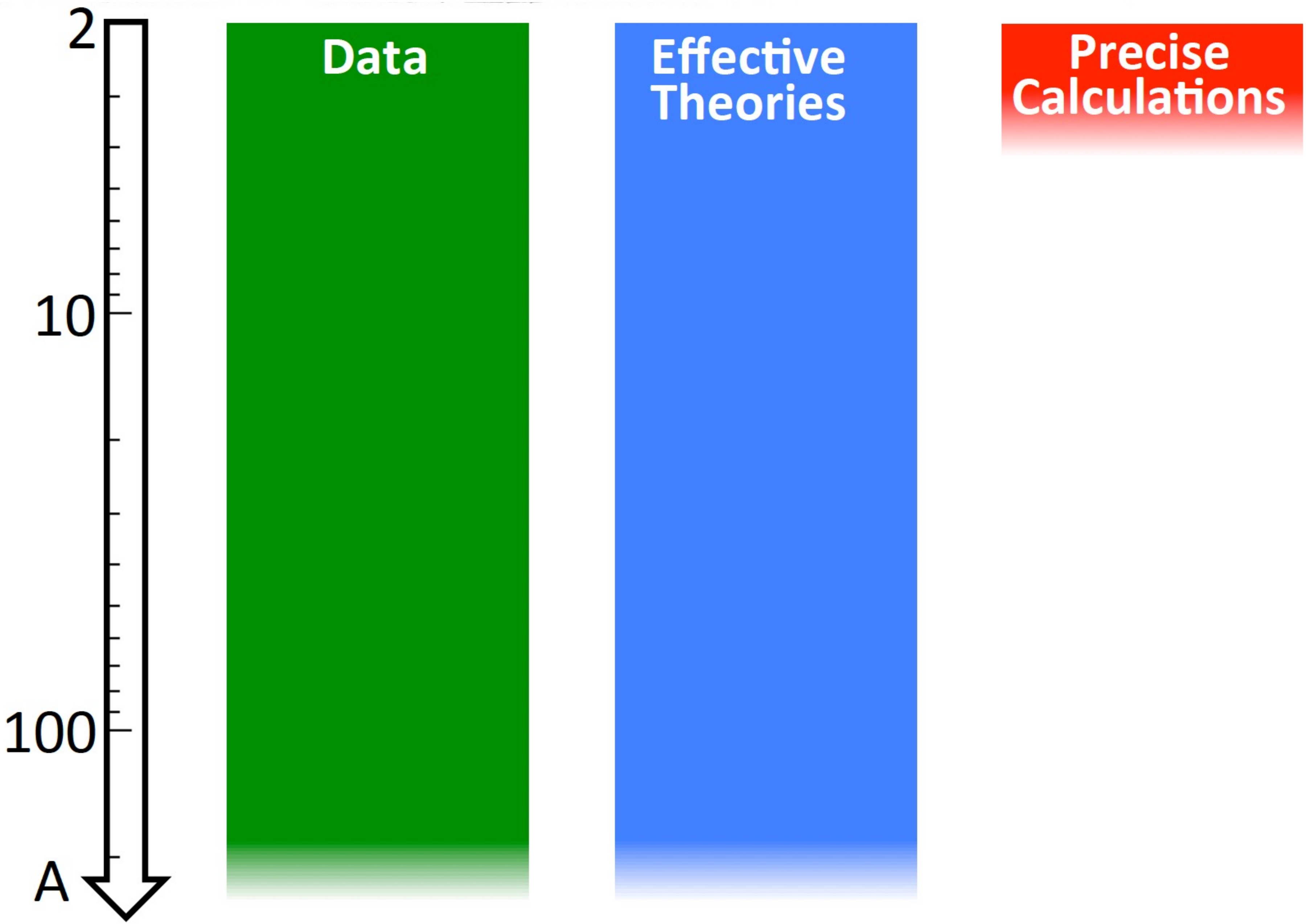


Need to put these to test

Testing Reaction Mechanism & NN models

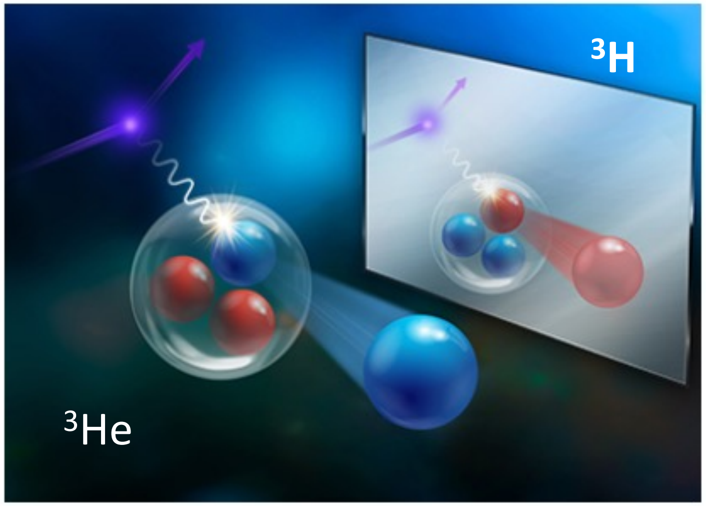
- Measure nucleon-knockout cross-section
- Compare with calculation using different NN interactions and modeling of reaction
- See which one works the best

Light Nuclei: The ideal lab to study NN



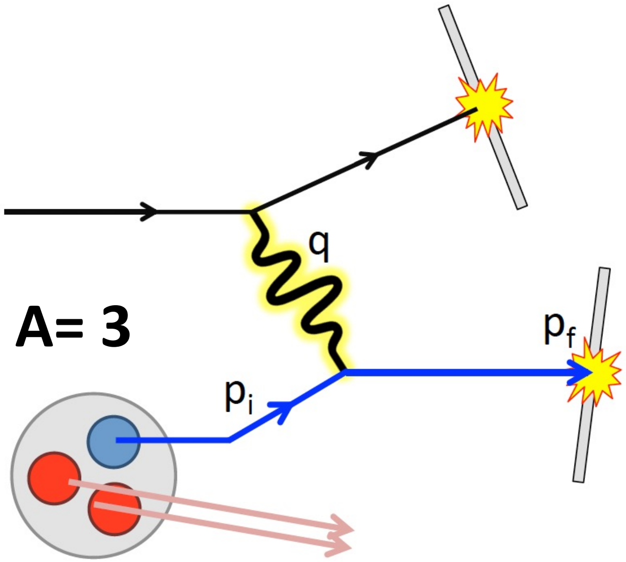
Why A=3 nuclei?

- Exactly calculable
- Mirror nuclei
  - Proton in ^3He = Neutron in ^3H
  - Constraints reaction mechanism
  - Better to study proton in 3H than neutron in 3He



➢ Ideal case: Test and benchmark theory

Quasi-elastic scattering (e,e'p)



- ❑ Missing momentum:

$$\vec{P}_{miss} = \vec{P}_f - \vec{q}$$

- ❑ Plane-Wave Impulse Approximation (PWIA)
  - ❖ Momentum transfer absorber by a single nucleon
  - ❖ Knocked-out nucleon did not re-scatter as it left the nucleus

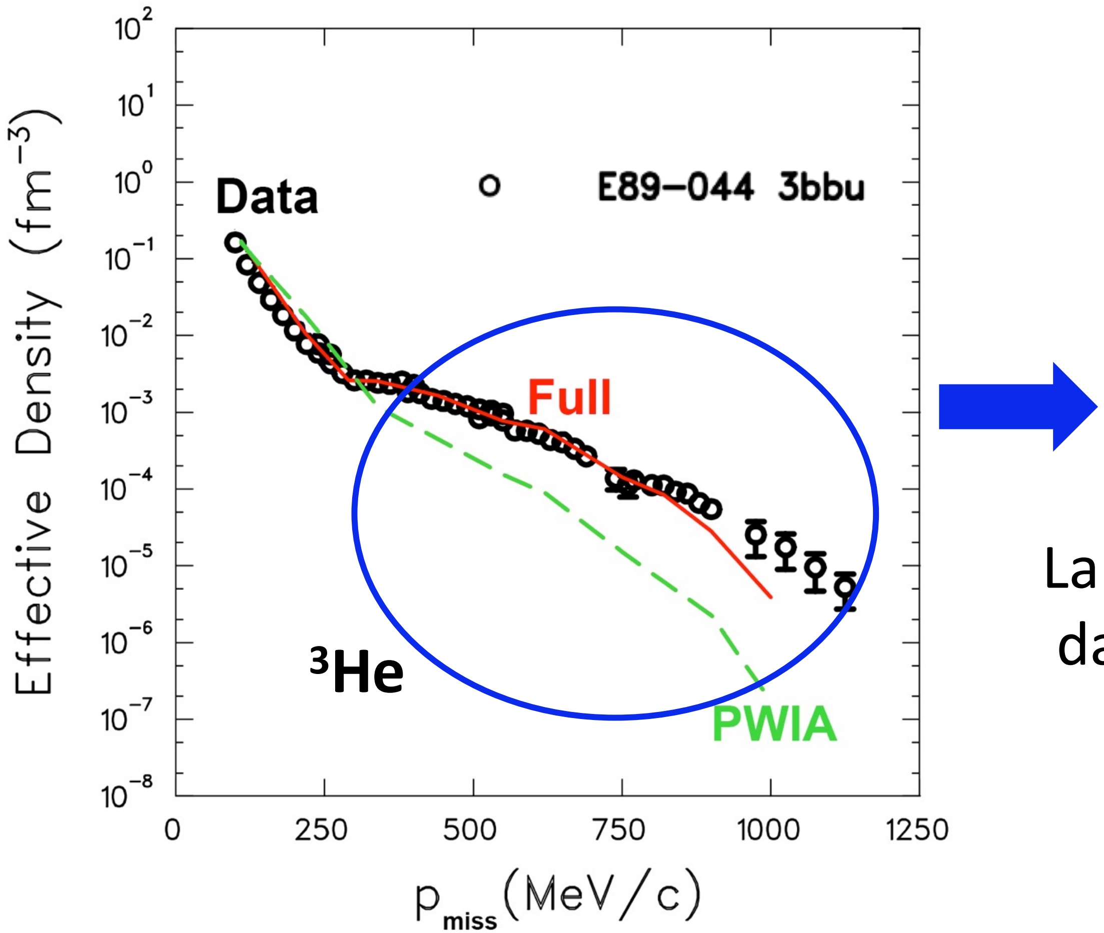
$$\vec{P}_{miss} = \vec{P}_i$$

High Q^2 factorization

$$\sigma = K\,\sigma_{ep}\,S(|\vec{P}_i|, E_i)$$

Previous studies and non-QE mechanisms

F. Benmokhtar et al., PRL (2005)

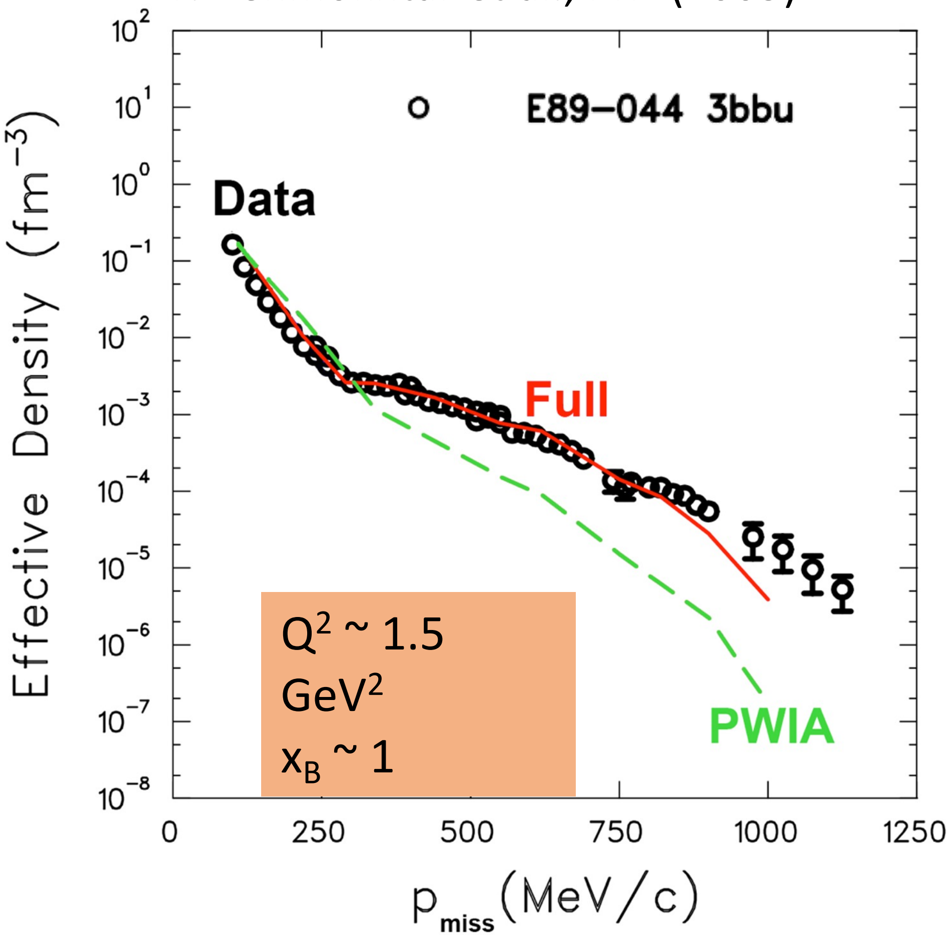


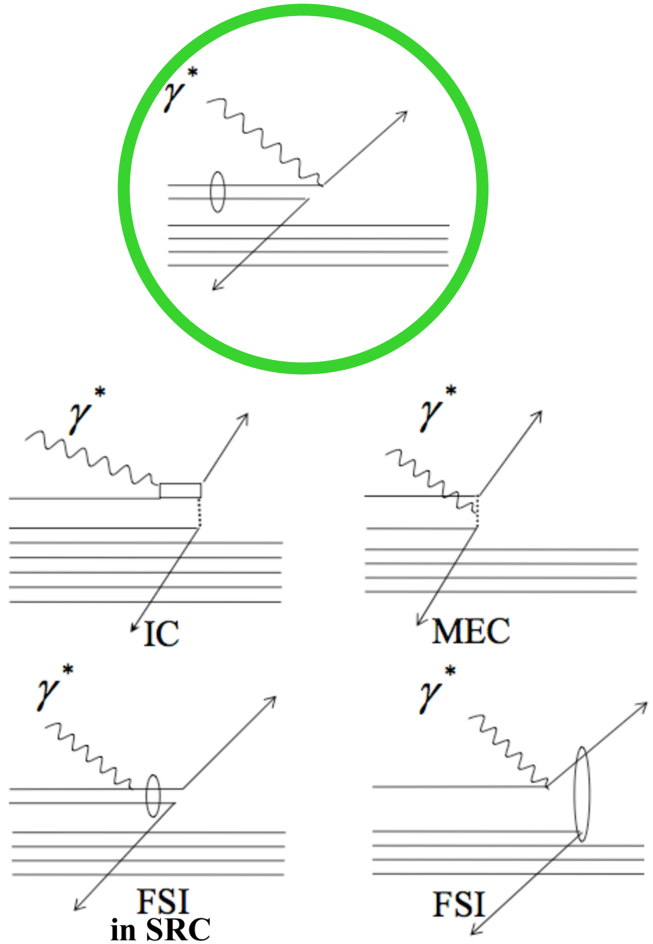
Large differences between data & PWIA

- Data is useful to study reaction mechanism, not nucleon distributions.

Previous studies and non-QE mechanisms

F. Benmokhtar et al., PRL (2005)

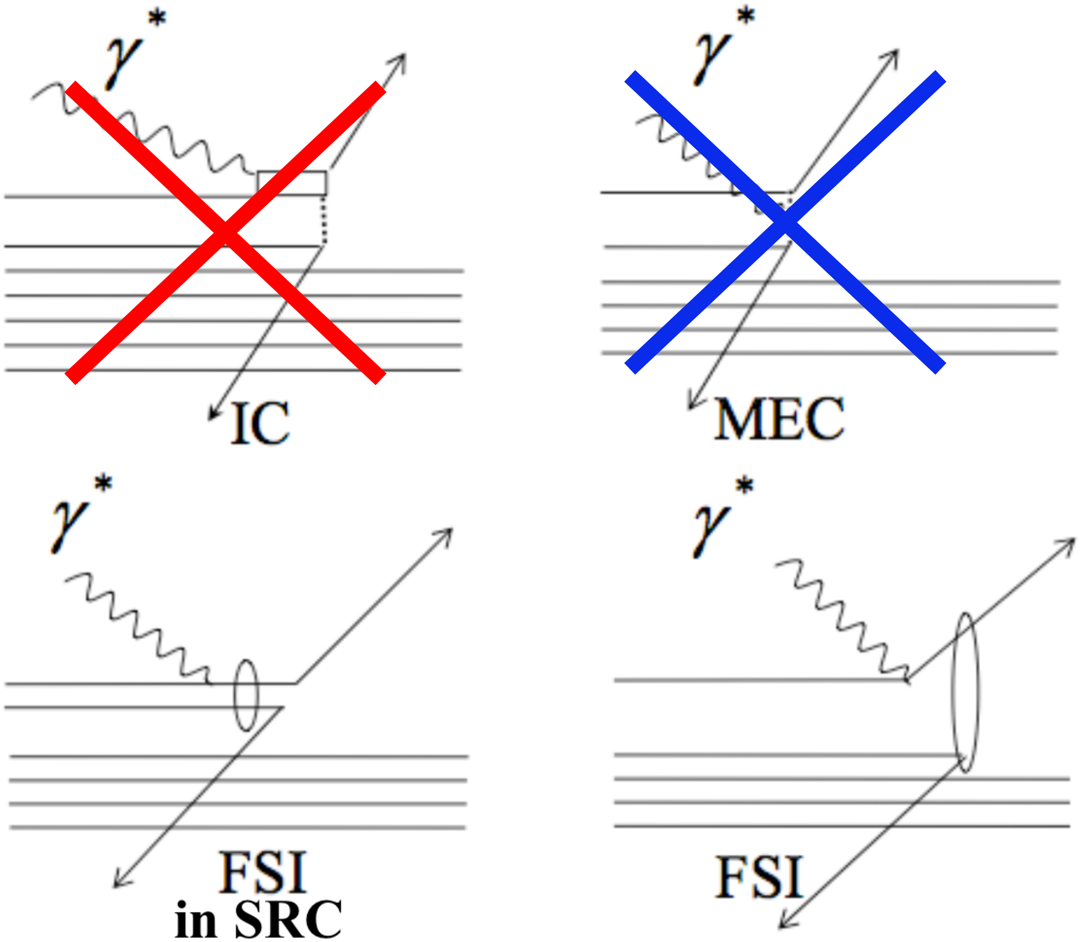




❑Non-QE mechanisms can be minimized using selected kinematic region

Minimizing non-QE mechanisms

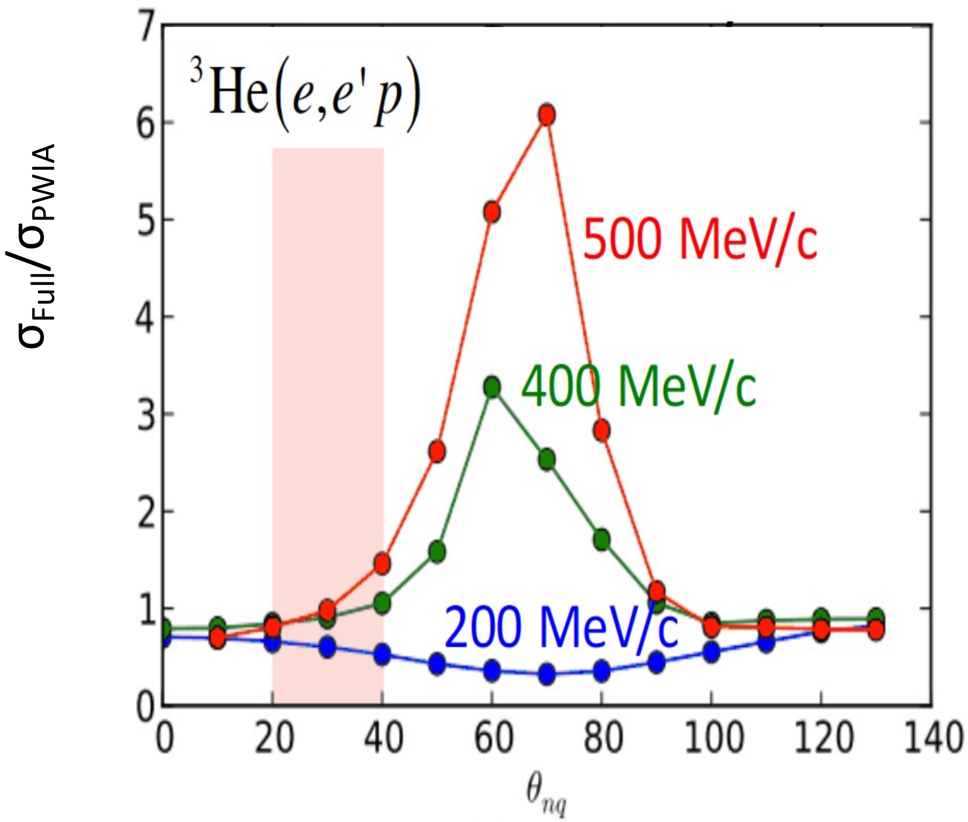
$x_B > 1$

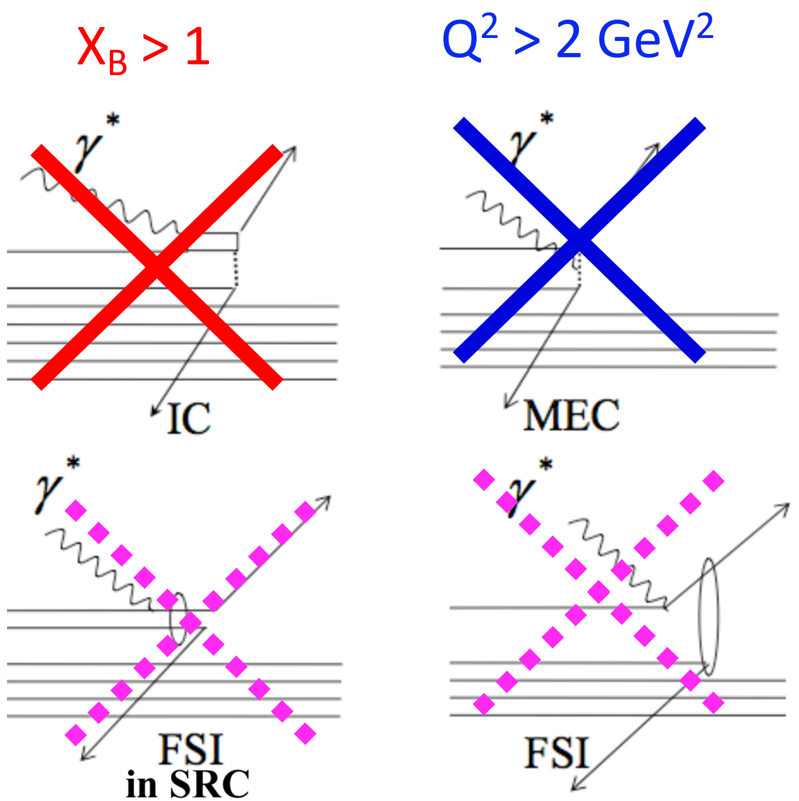


$Q^2 > 2\ GeV^2$

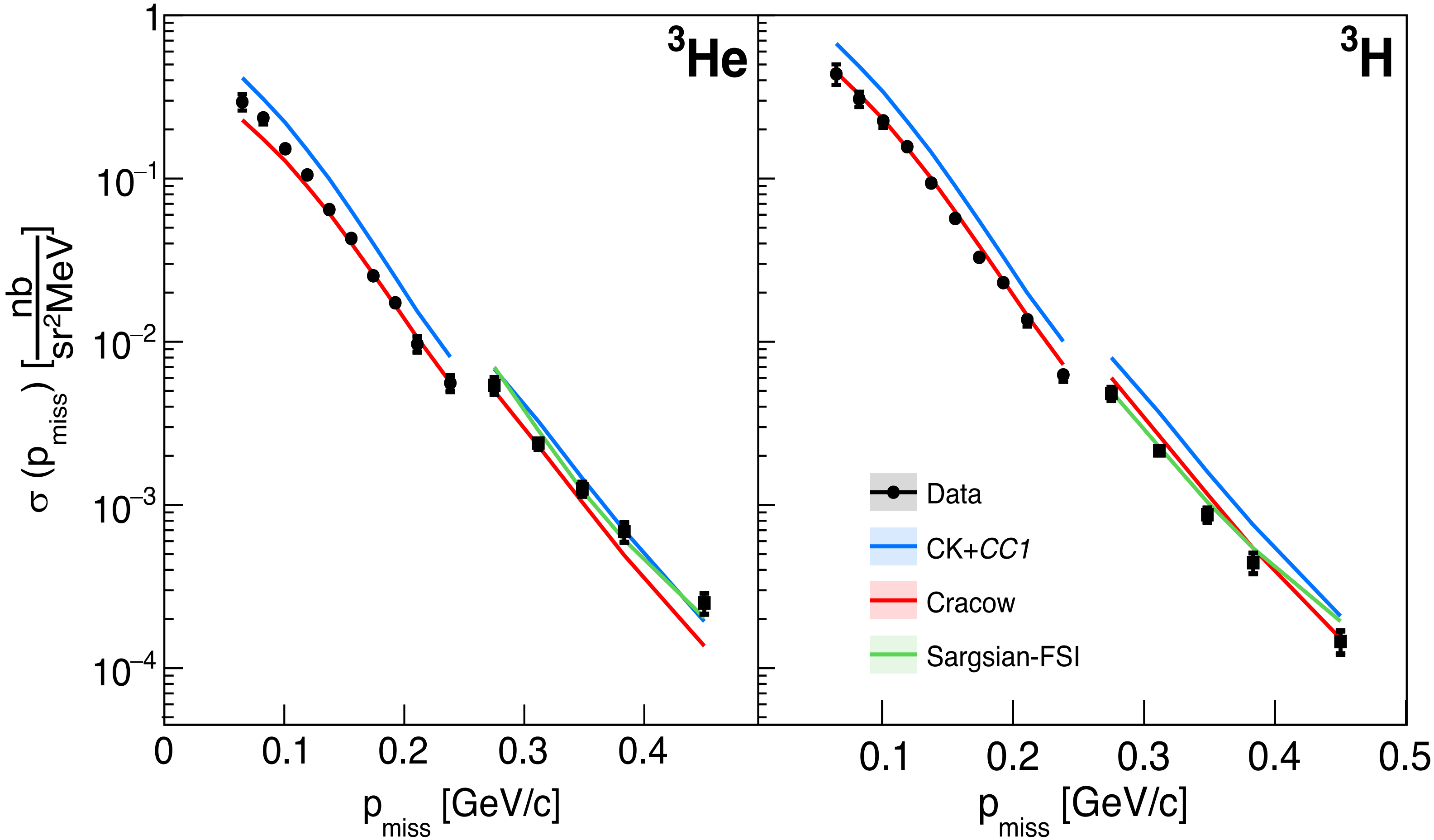
M. M. Sargsian, Int. J. Mod. Phys. E10 (2001)
M. M. Sargsian et al., J. Phys. G29, R1 (2003)

Minimizing non-QE mechanisms



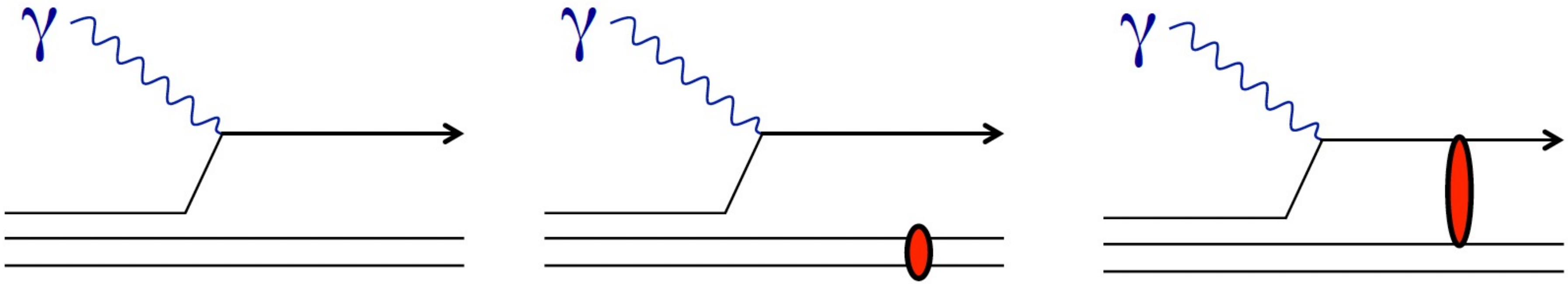


Extracted Absolute cross-section 3-body break up



R. Cruz-Torres*, D. Nguyen* et al., Under PRL review

Compare to different theory calculation



a) PWIA

b) FSI_{23}

c) FSI

Cracow:

- Faddeev-formulation-based
- Continuum interaction between two spectator nucleons (FSI_{23})

CK + *CC1*:

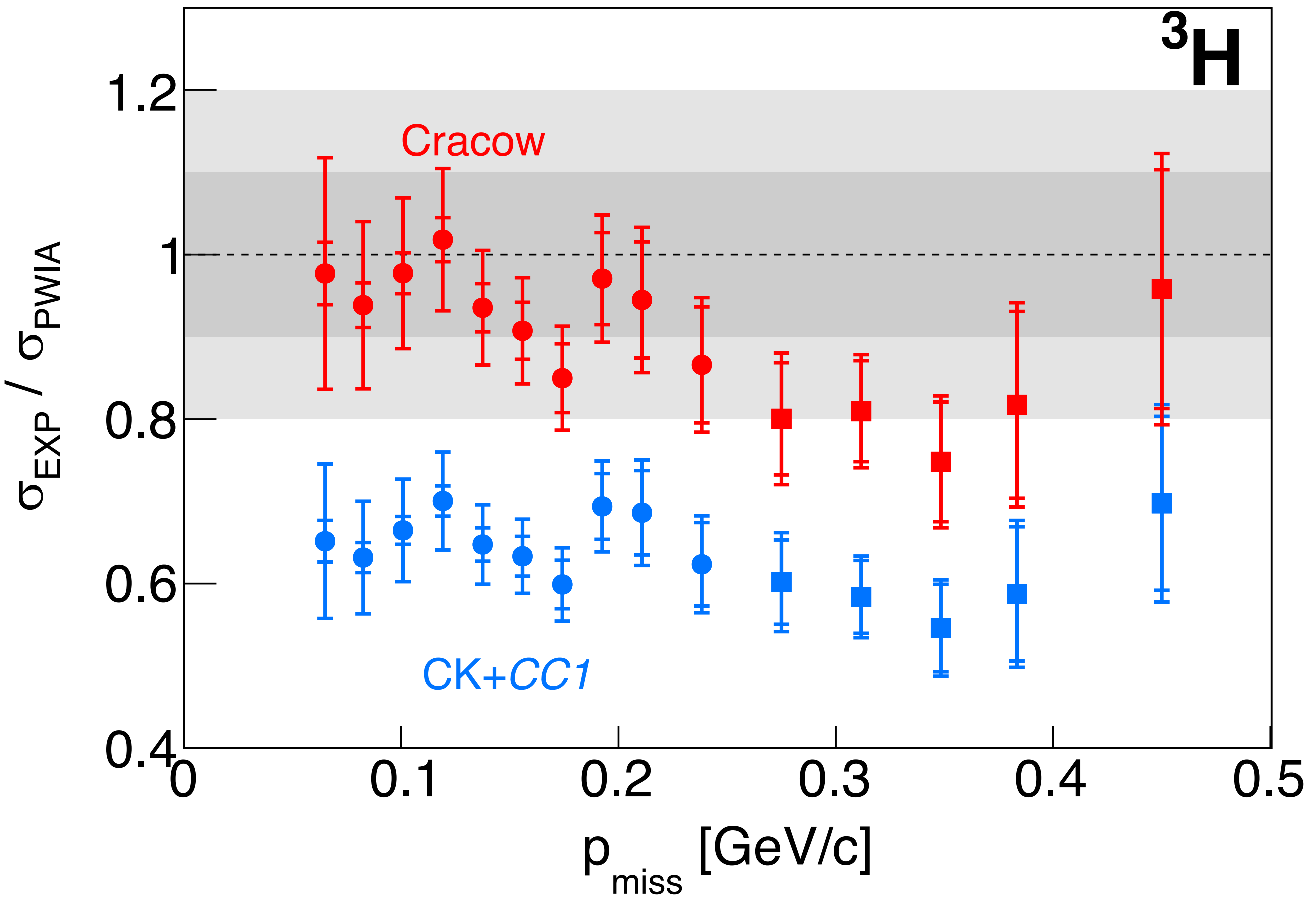
- ^{3}He spectral function of CDA and L.P. Kaptari and electron off-shell nucleon cross-section
- Continuum interaction between two spectator nucleons (FSI_{23})

$$\sigma = \sigma_{ep} \cdot S(p_i, E_i)$$

M. Sargsian (FSI):

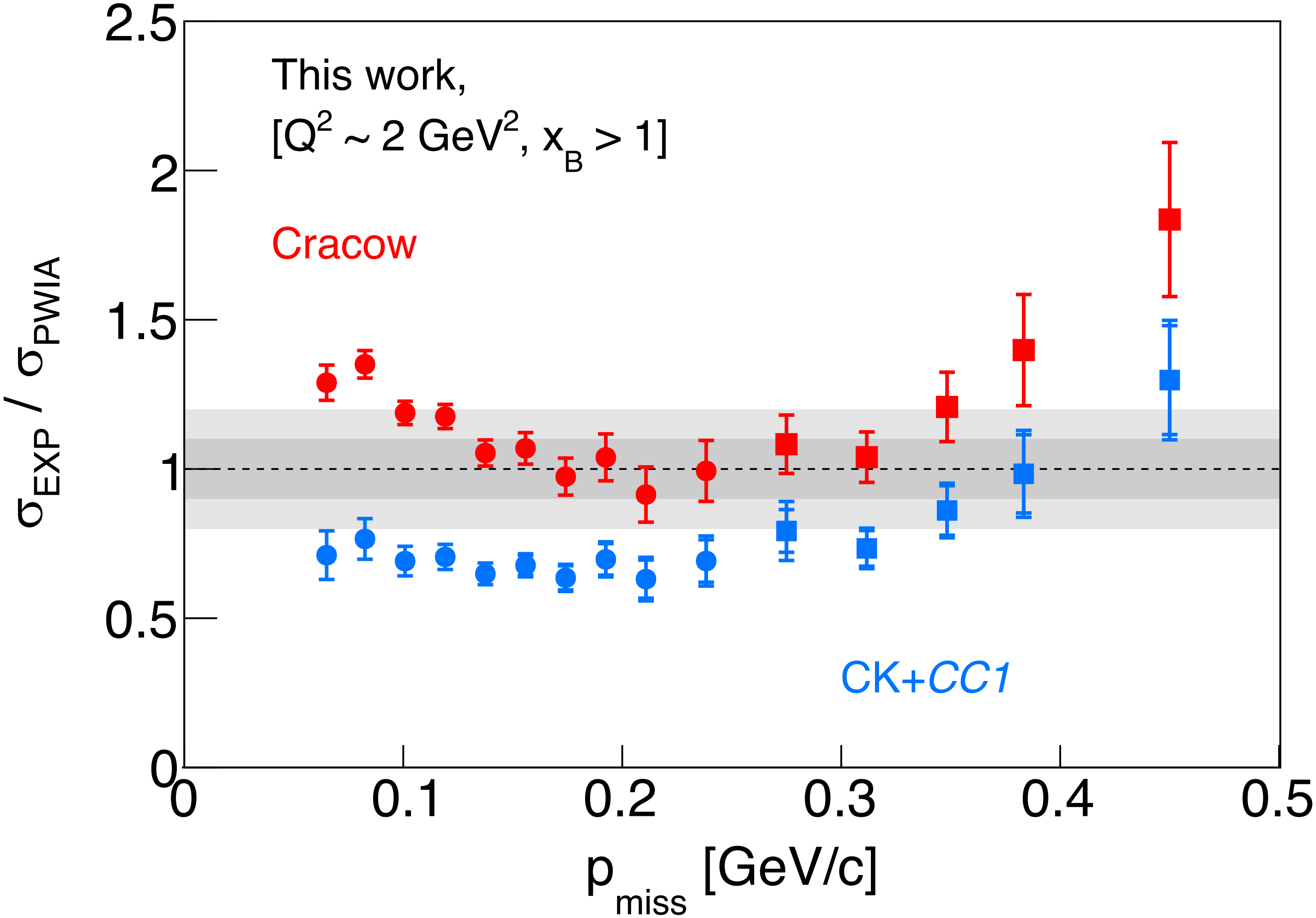
- Generalized Eikonal Approximation based
- NO continuum interaction between two spectator nucleons (FSI_{23}). Only use for high-p_{miss} comparison

^{3}H Exp/Cracow & CK+CC1



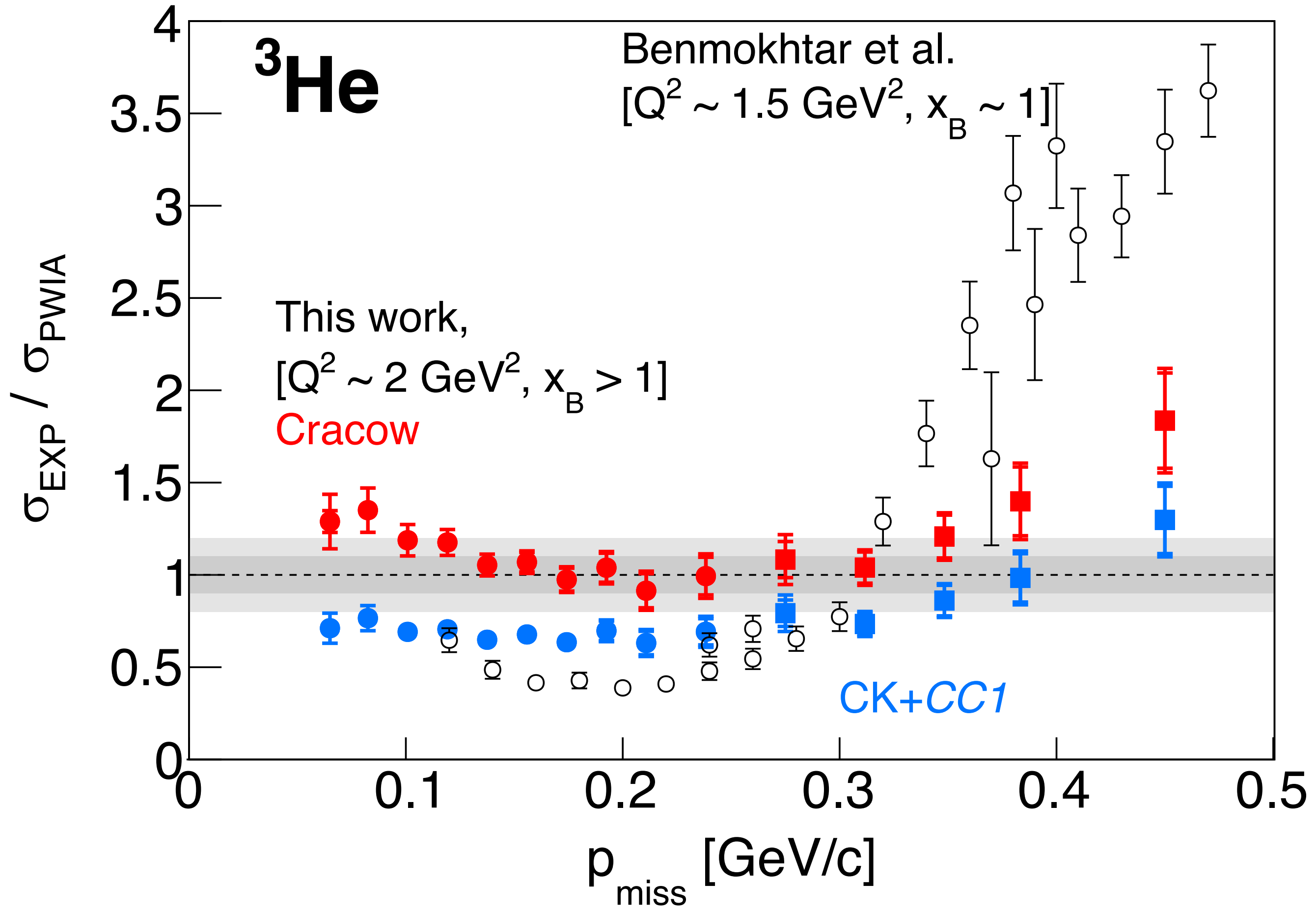
R. Cruz-Torres, **D. Nguyen** et al. PRL editor suggestion (2020)

^{3}He Exp/Cracow & CK+CC1

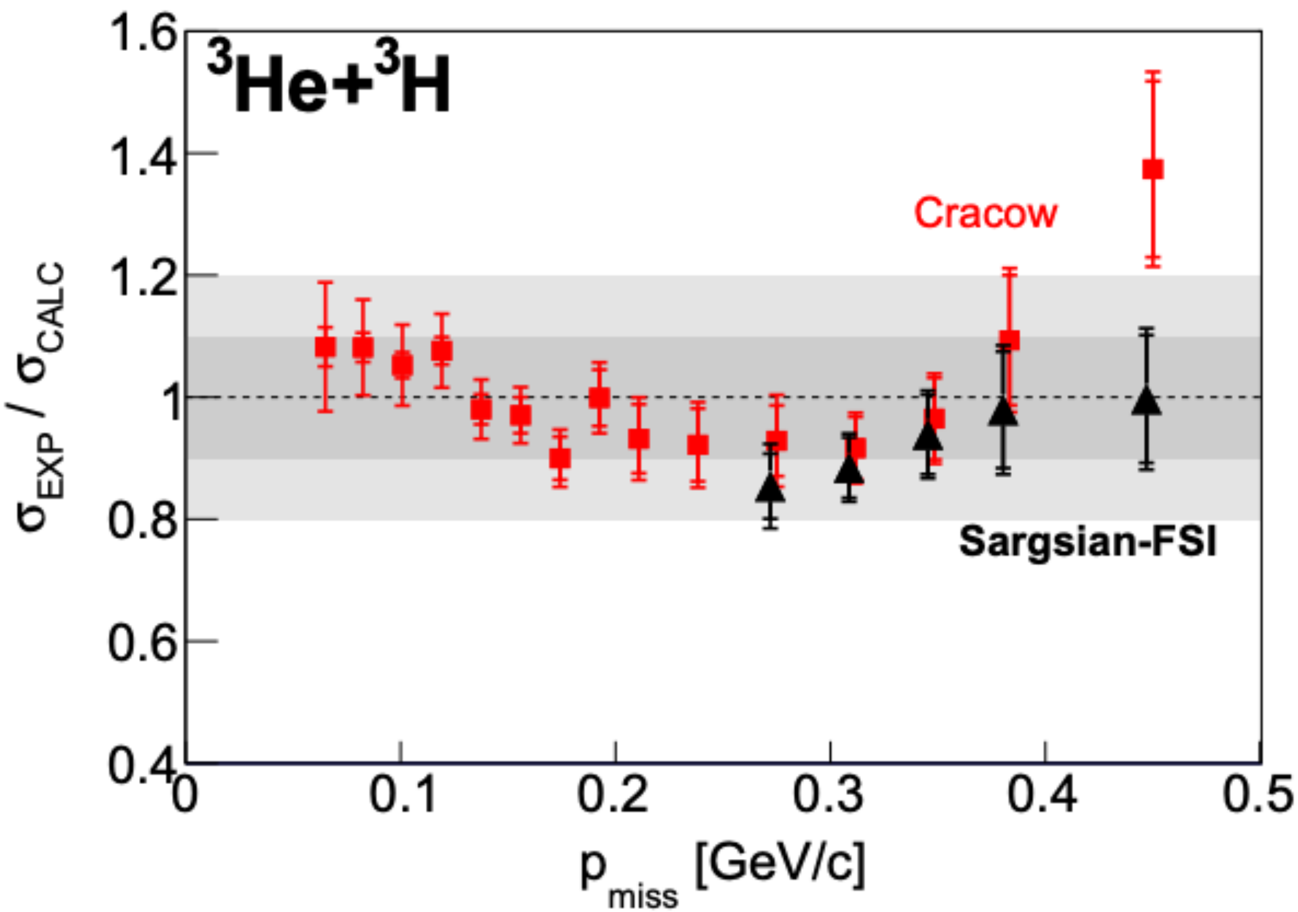


R. Cruz-Torres, **D. Nguyen** et al. PRL editor suggestion (2020)

Much better than previous data!

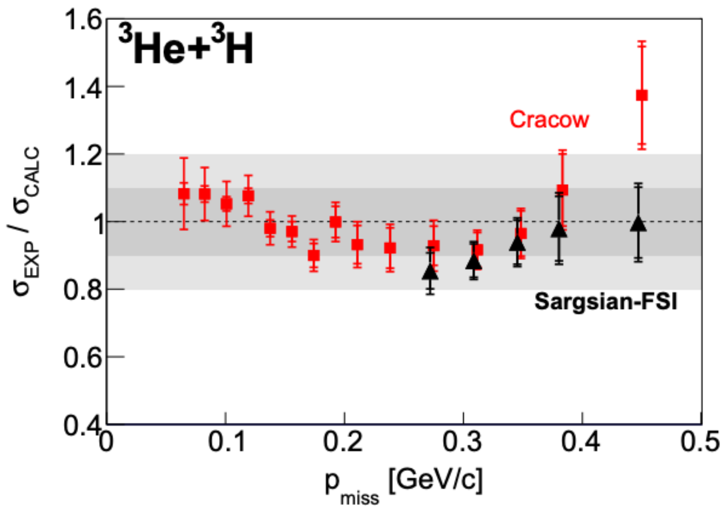


Iso-scalar sum $^3He+^3H$



What we have learned in A= 3:

- ^3H has better agreement to calculation than ^3He
- Data/PWIA ~ 20% at high Pmiss
- Theory describes ^3H+^3He data within 10% up to Pmiss = 500 MeV/c

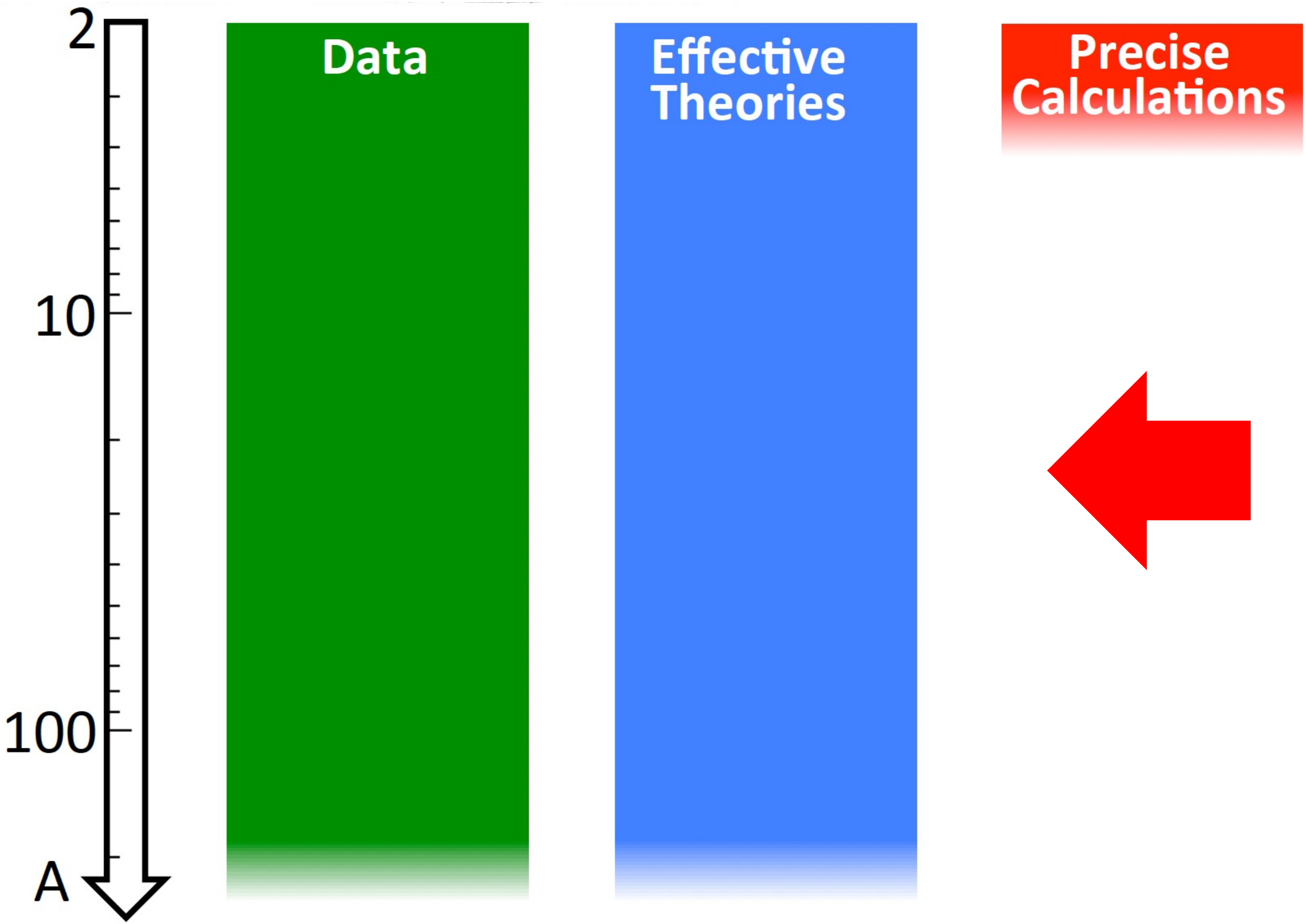


Crucial benchmark for few-body nuclear theory and essential test of theoretical calculation

R. Cruz-Torres, D. Nguyen et al. PRL editor suggestion (2020)

Path forward
To
Study heavier nuclei

Light Nuclei: The ideal lab to study NN



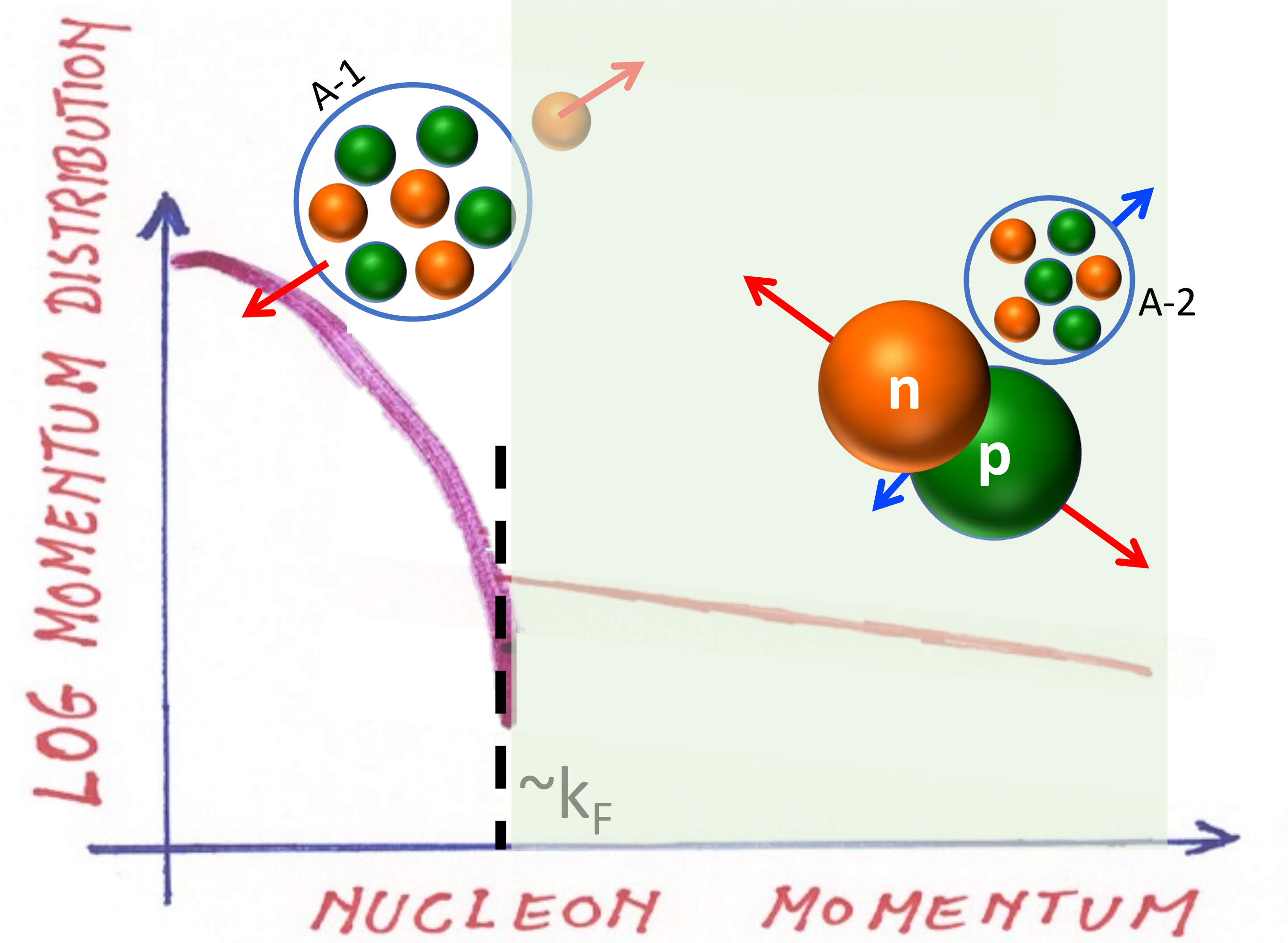
Why effective theories for SRCs?

- Complicated NN interaction & large nuclear density
- Mean-field theories don’t include SRCs
- Ab-initio calculations are limited to light nuclei

Need an effective theory that describes SRC

The Generalized Contact Formalism (GCF)

High-Momenta ⟺ SRCs

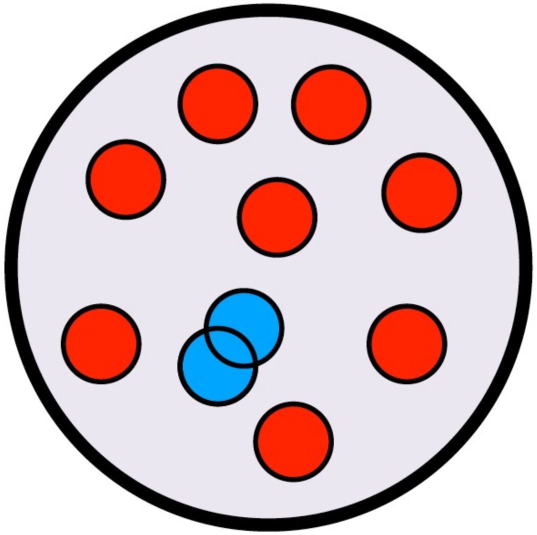


Factorization in nuclear systems

Scale separation at the short distance

⬇

Factorization of the nuclear wave function



$$\Psi \xrightarrow{r_{ij} \to 0} \varphi(r_{ij}) \times A_{ij}(R_{ij}, \{r\}_{k \neq ij})$$

Many two body wave function

Two-body Wave function

A-2 Residual system

Two-body densities in GCF

$$\rho_A^{NN,\alpha}(r,R) = C_A^{NN,\alpha}(R) \times |\varphi_{NN}^{\alpha}(r)|^2$$

Two-body densities in GCF

$$\rho_A^{NN,\alpha}(r,R) = C_A^{NN,\alpha}(R) \times |\varphi_{NN}^{\alpha}(r)|^2$$

Many-body density

<u>Contacts</u>

(nucleus dependent)

2-body density

(universal)

Two-body densities in GCF

$$\rho_A^{NN,\alpha}(r,R) = C_A^{NN,\alpha}(R) \times |\varphi_{NN}^{\alpha}(r)|^2$$

$$\rho_A^{NN,\alpha}(q,Q) = C_A^{NN,\alpha}(Q) \times |\varphi_{NN}^{\alpha}(q)|^2$$

Many-body density

Contacts

(nucleus dependent)

2-body density

(universal)

Integrating over R and Q

$$\rho_A^{NN,\alpha}(r) = \int d\vec{R}\, \rho_A^{NN,\alpha}(r, R)$$

$$\rho_A^{NN,\alpha}(q) = \int d\vec{Q}\, \rho_A^{NN,\alpha}(q, Q)$$

$$\rho_A^{NN,\alpha}(r, R) = C_A^{NN,\alpha}(R) \times |\varphi_{NN}^{\alpha}(r)|^2$$

$$\rho_A^{NN,\alpha}(q, Q) = C_A^{NN,\alpha}(Q) \times |\varphi_{NN}^{\alpha}(q)|^2$$

Short-r Two-body densities in GCF

$$\rho_A^{NN,\alpha}(r) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(r)|^2$$

Nuclear 2-body coordinate density

scaling constants called **Contacts**

(nucleus dependent)

zero-energy solution of 2-body Schrödinger equation

(universal)

High-k Two-body density in the GCF

$$\rho_A^{NN,\alpha}(r) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(r)|^2$$

$$\rho_A^{NN,\alpha}(q) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(q)|^2$$

Nuclear 2-body momentum density

scaling constants called **Contacts**

(nucleus dependent)

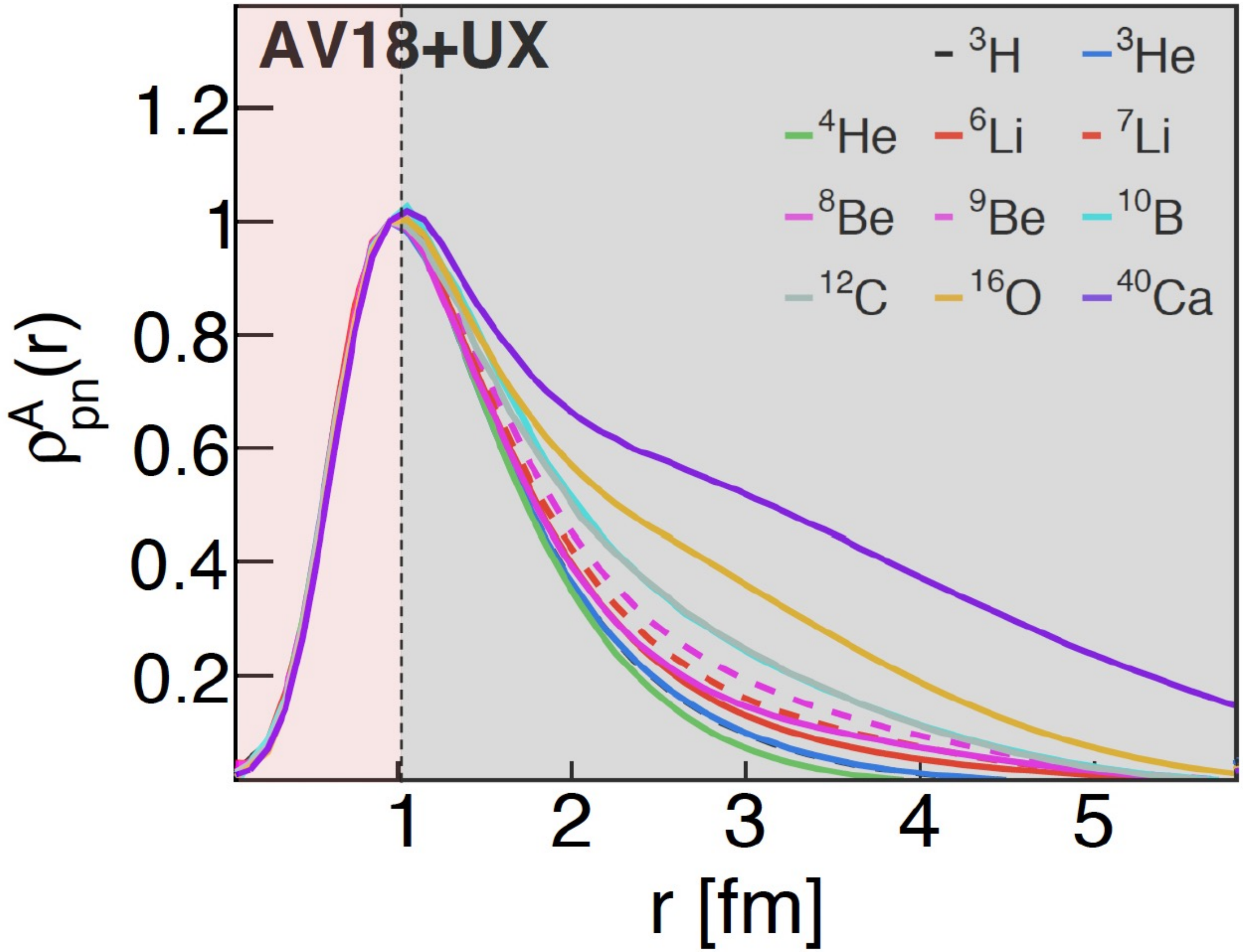
zero-energy solution of 2-body Schrödinger equation

(universal)

Small-r Universality and GCF

$$\rho_A^{NN,\alpha}(r) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(r)|^2$$

Many-body   Constant   Pair

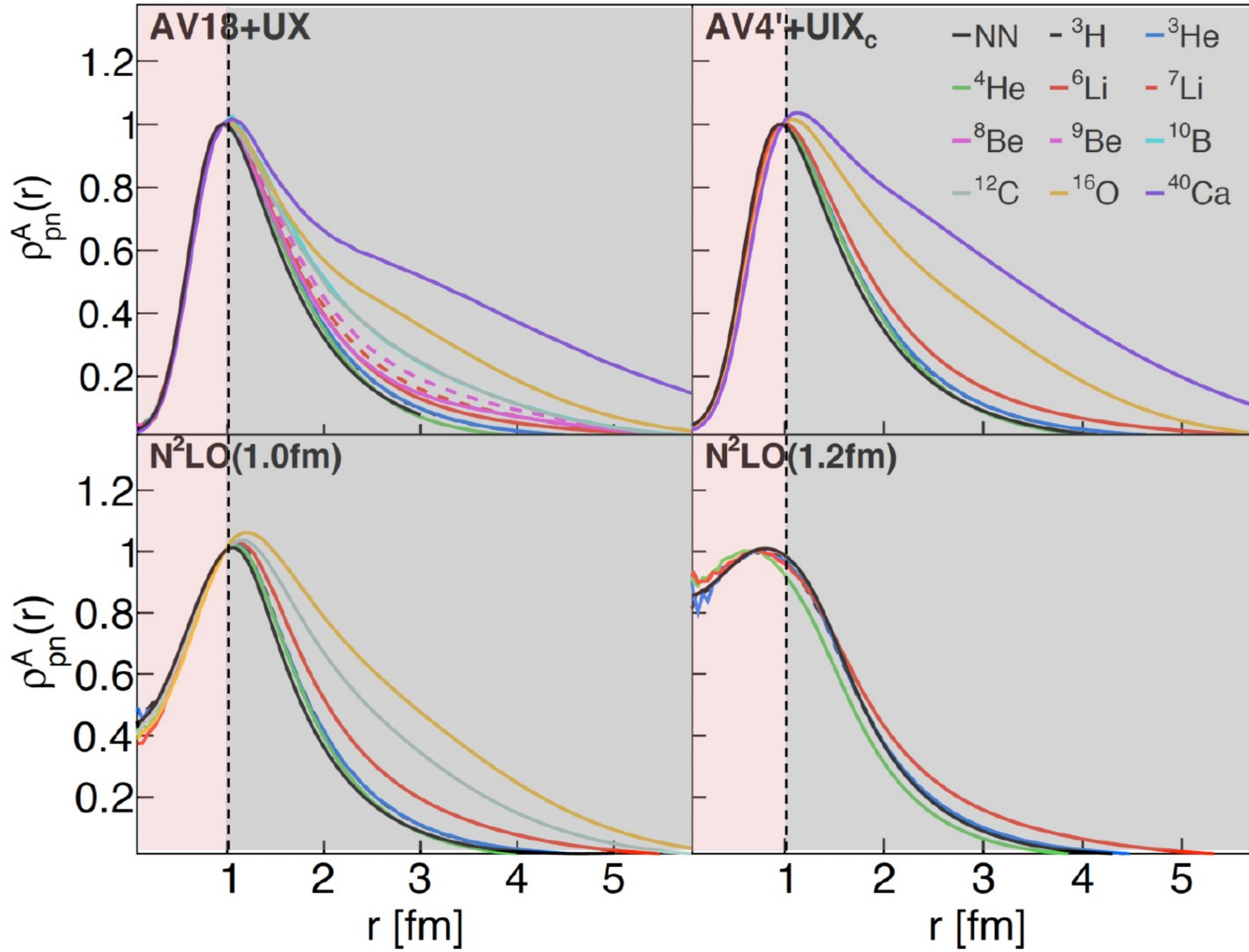


Small-r Universality and GCF

$$\rho_A^{NN,\alpha}(r) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(r)|^2$$

Many-body Constant Pair

$$C_A^{NN,\alpha} = \frac{\rho_A^{NN,\alpha}(r)}{|\varphi_{NN}^{\alpha}(r)|^2}$$

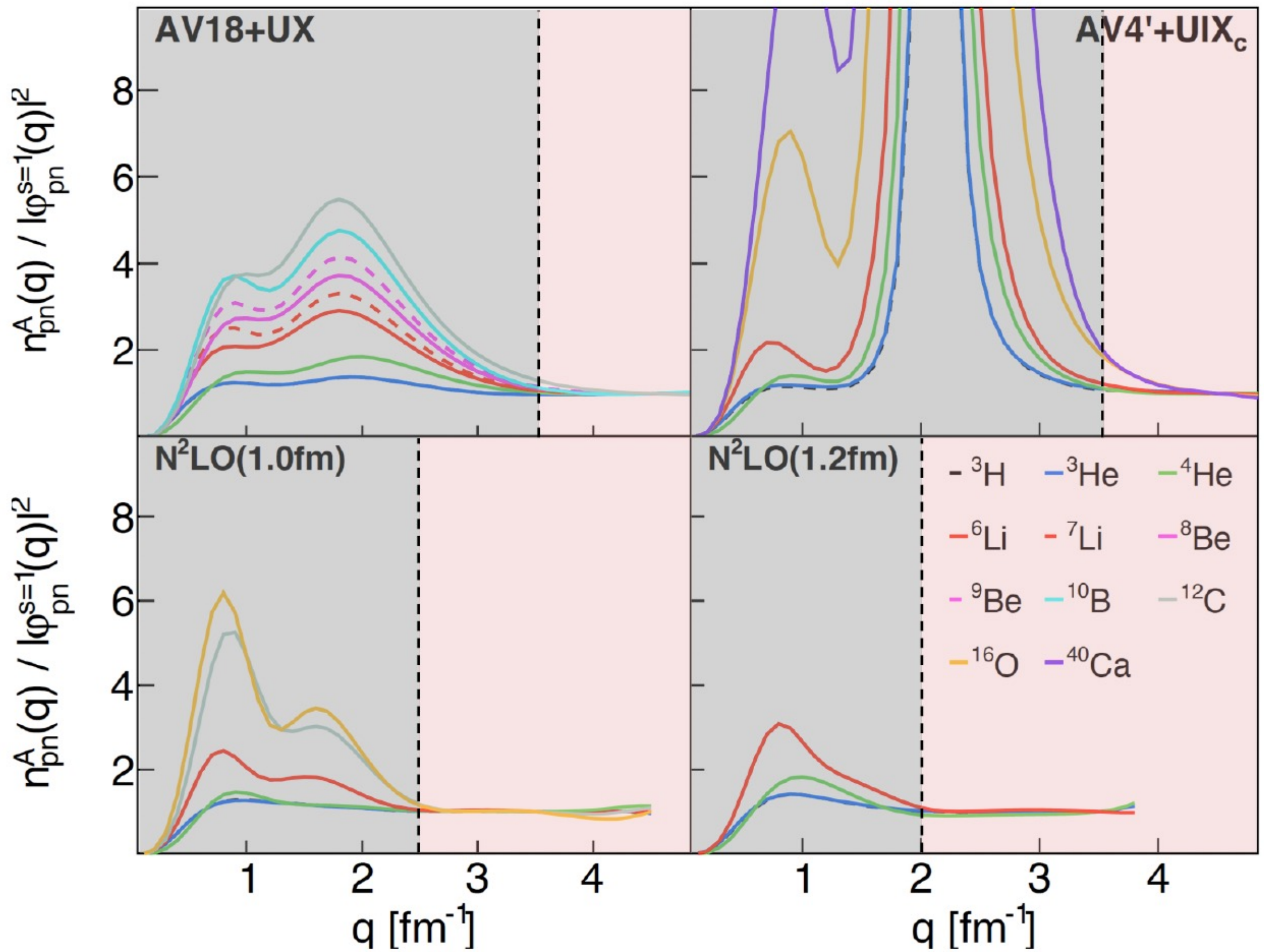


Cruz Torres and Lonardoni et al., Nature Physics (2020)

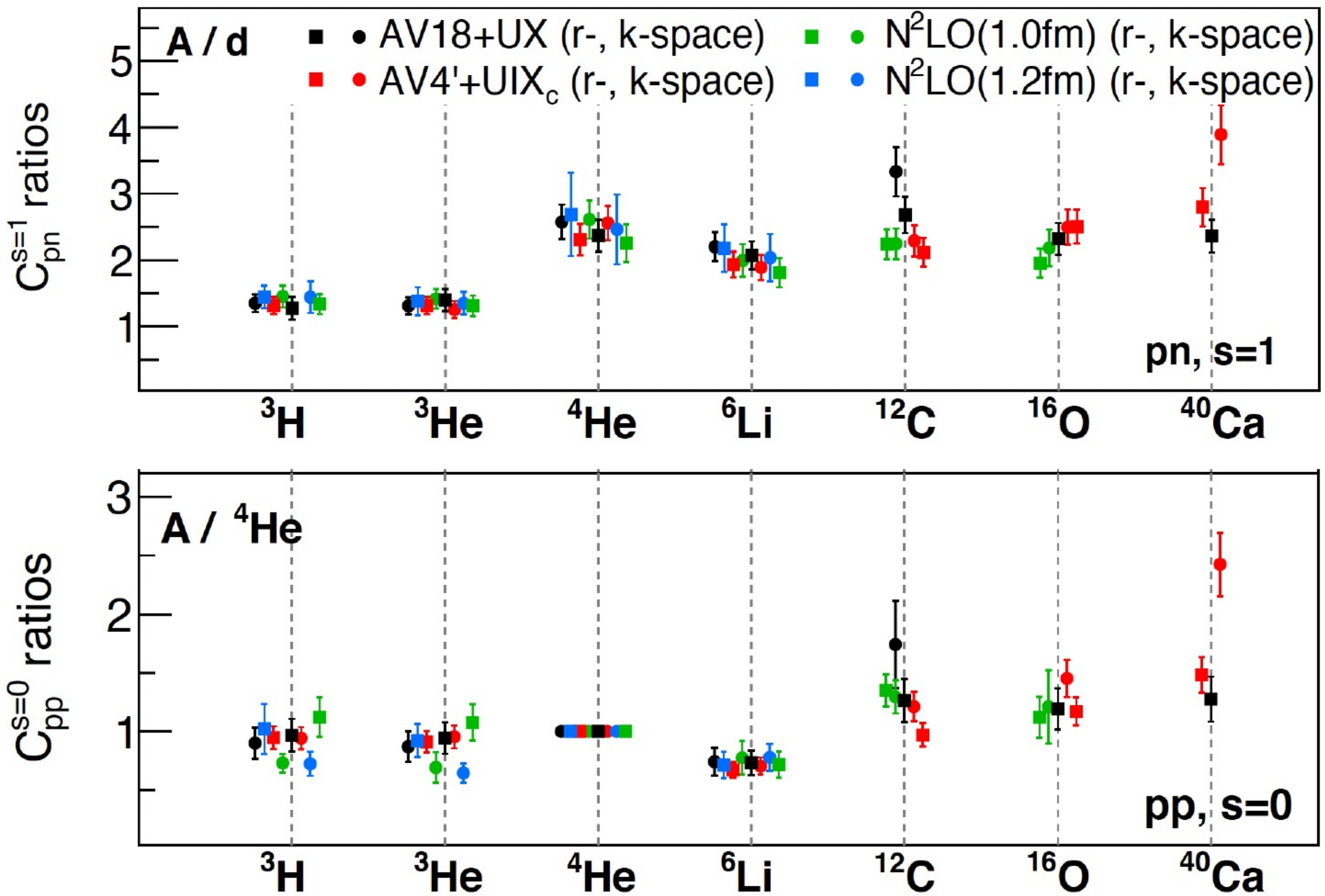
High-k universality and the GCF

$$\rho_A^{NN,\alpha}(q) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(q)|^2$$

$$C_A^{NN,\alpha} = \frac{\rho_A^{NN,\alpha}(q)}{|\varphi_{NN}^{\alpha}(q)|^2}$$

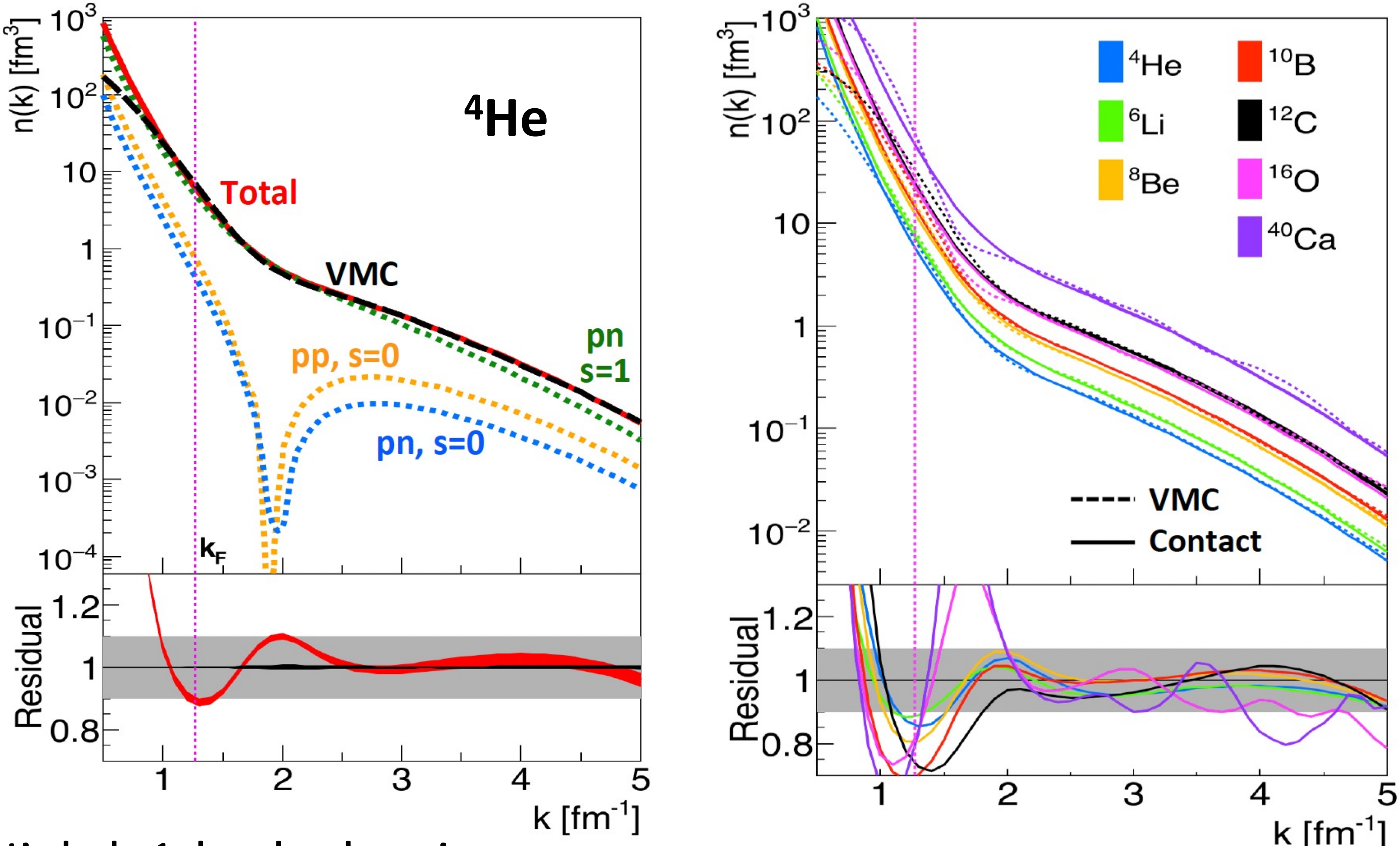


A/D: small-r and high-k scaling are Identical



Weiss, Phys. Lett. B (2018); Cruz Torres, Phys. Lett B (2018); Weiss Phys. Lett B (2019).
+ many works by Claudio Ciofi; Jan Ryckebusch; Frankfurt Strikman; …

GCF: can produce the high-k



High-k 1-body density

$$n(k) = 2C_{pp}^{s=0}\left|\tilde{\varphi}_{pp}^{s=0}(k)\right|^2 + C_{pn}^{s=0}\left|\tilde{\varphi}_{pn}^{s=0}(k)\right|^2 + C_{pn}^{s=1}\left|\tilde{\varphi}_{pn}^{s=1}(k)\right|^2$$

Take-away message

- ❑A=3 cross-section is well described by the current theory calculation up to 500 MeV/C

- ❑ Understanding the complex NN interaction is a challenge and a priority of nuclear physics

- ❑GCF allows us to study NN interaction at short distances and high momentum