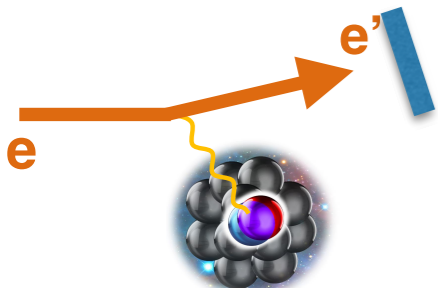


Overview

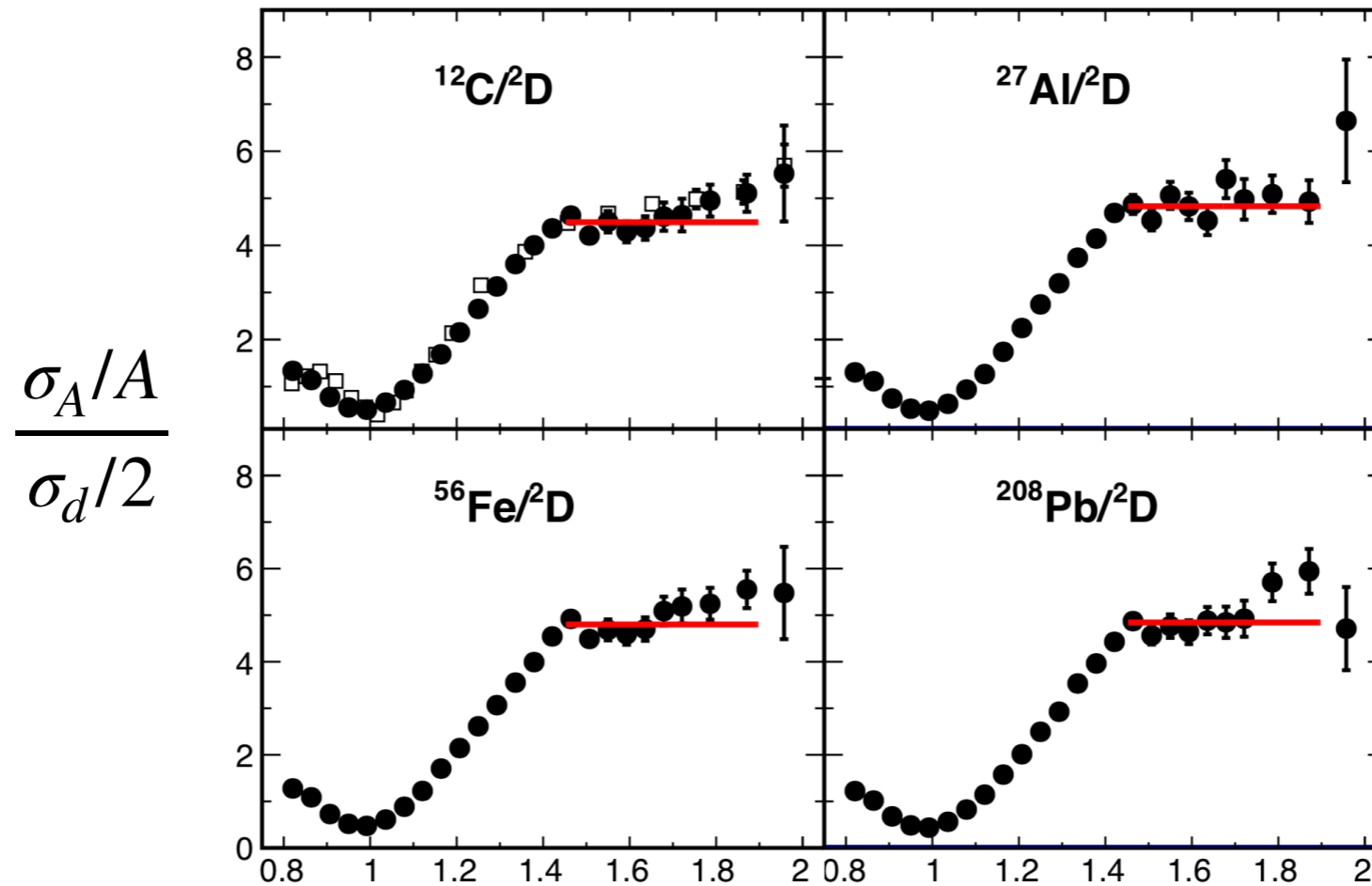
Exclusive SRC Data

Florian Hauenstein
ECT* Workshop
Short-Distance Nuclear Structure and PDFs
07/17/23

Open Questions from Inclusive Measurements



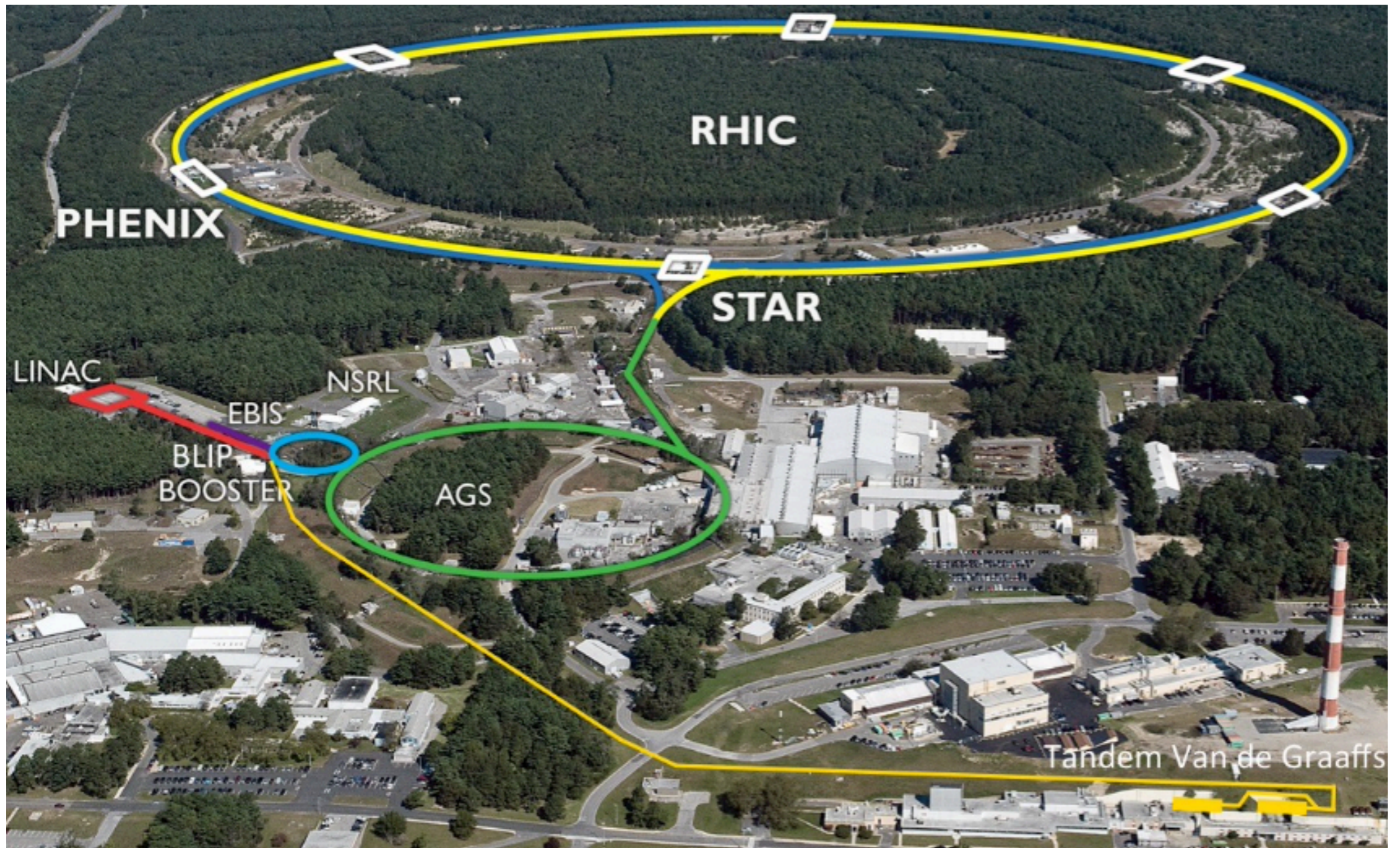
B. Schmookler et al., Nature (2019)



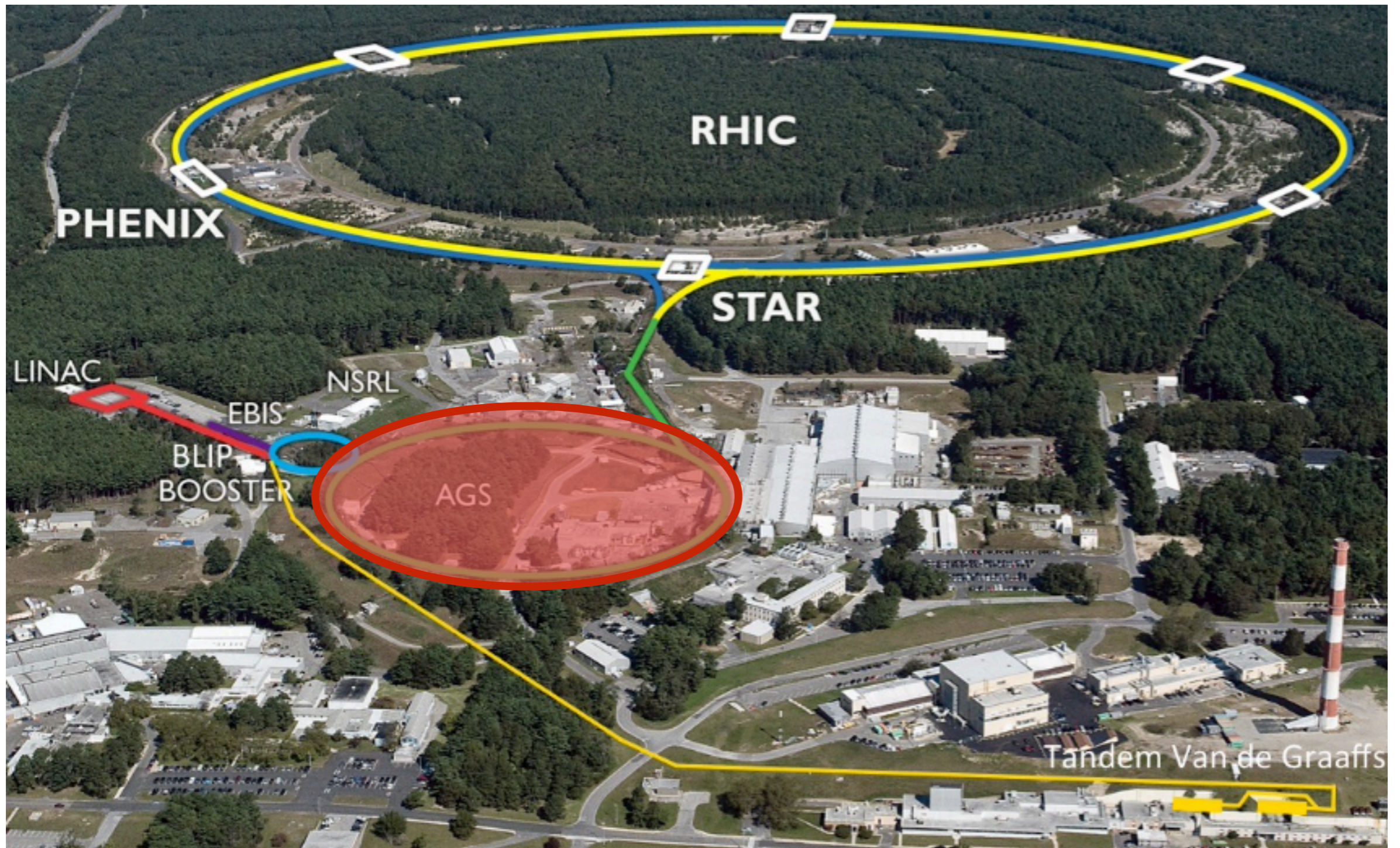
$$x_B = \frac{Q^2}{2m_n\omega}$$

- Which nucleons in a nucleus contribute to SRCs?
- What pairs dominate?
- Learn something about NN interaction?
- Are SRC universal?

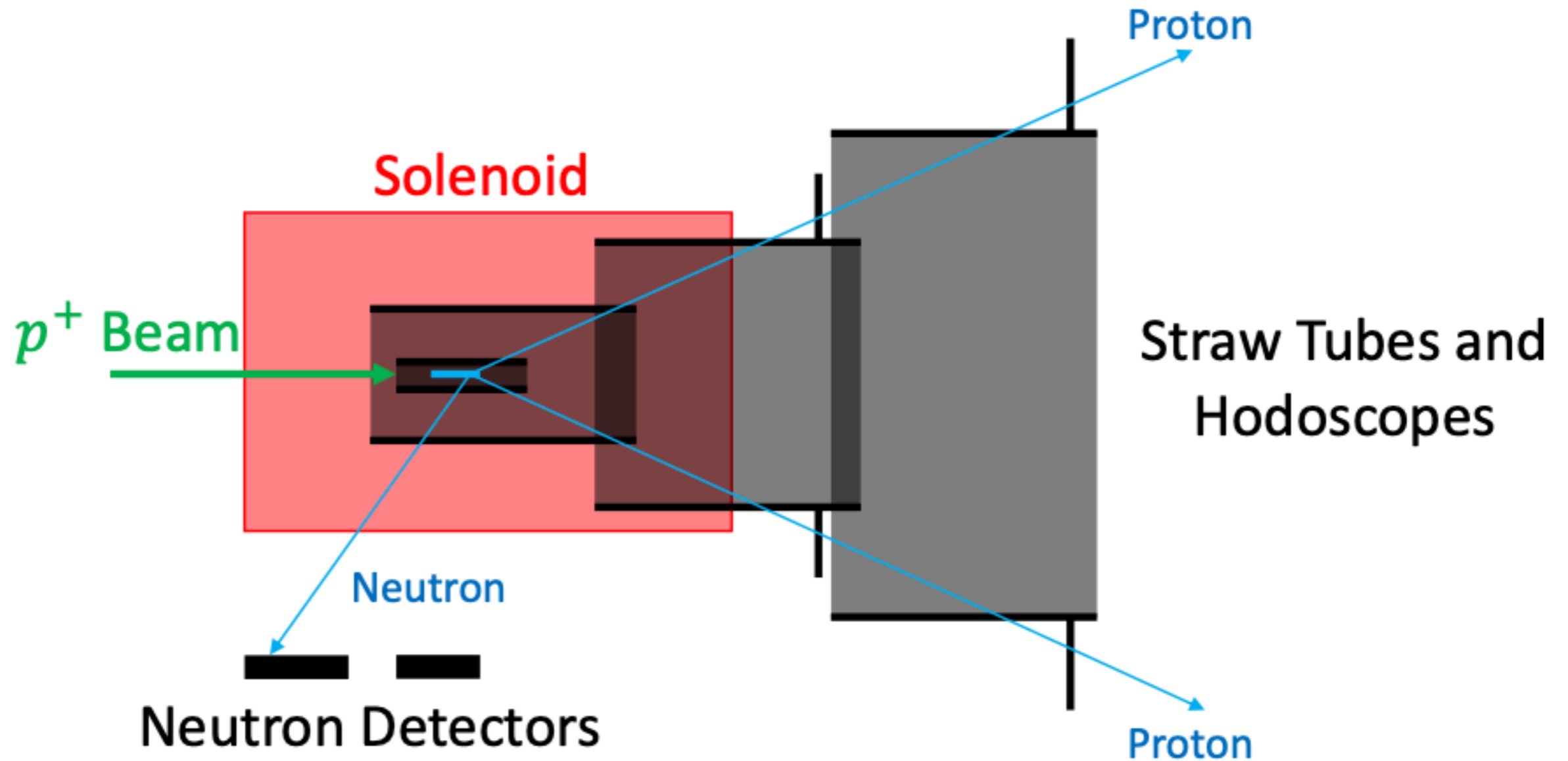
First Exclusive Observation of SRCs



First Exclusive Observation of SRCs



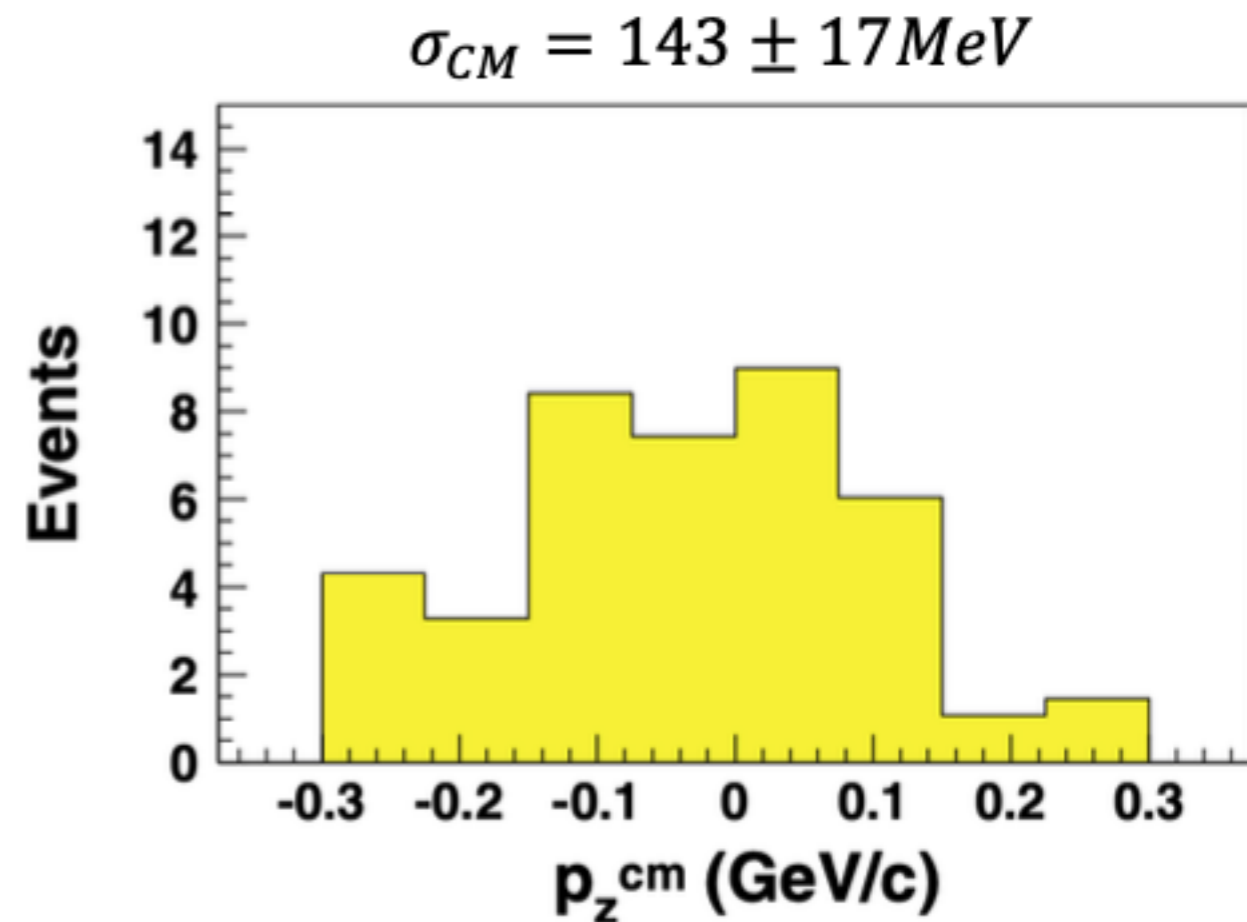
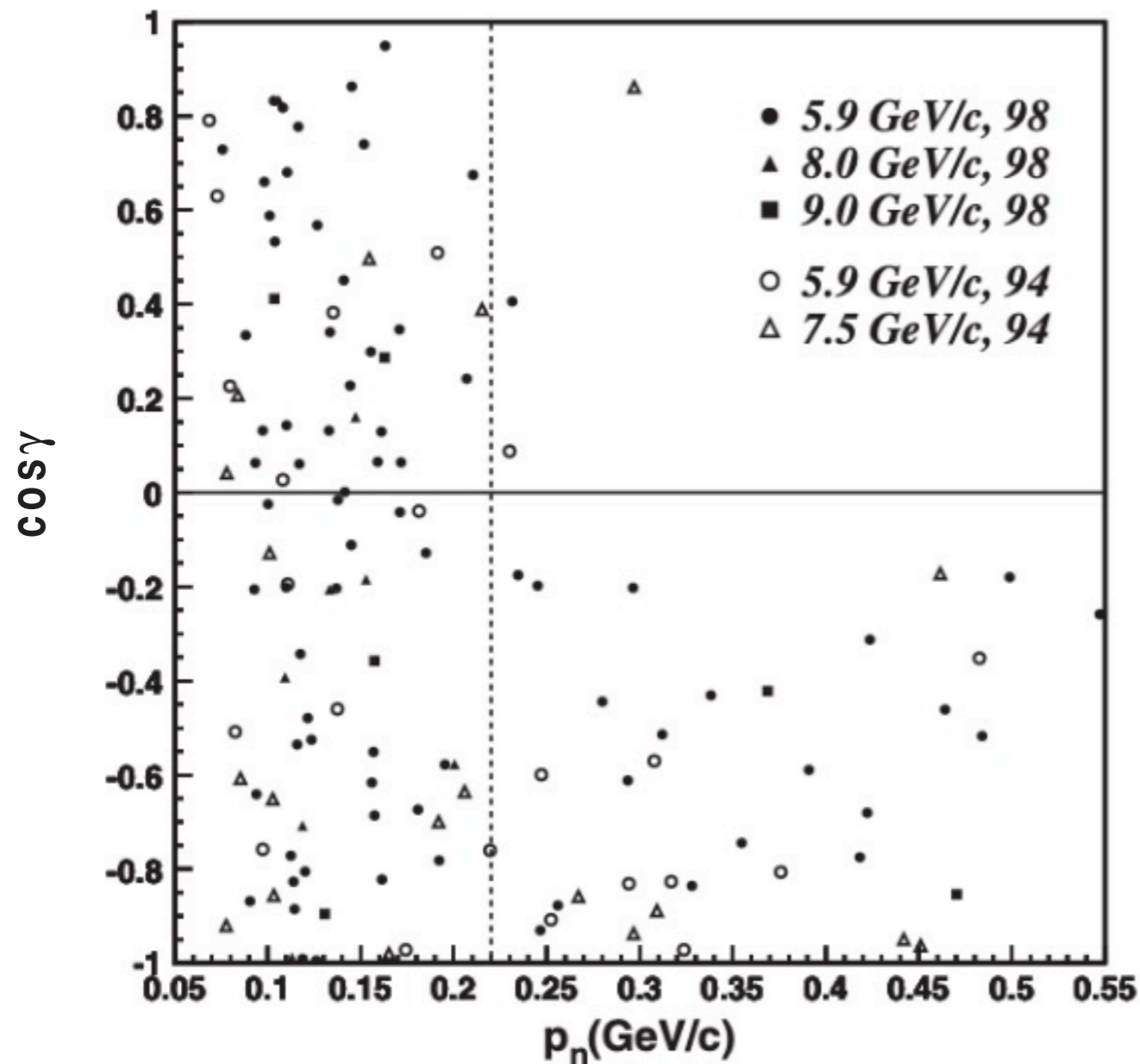
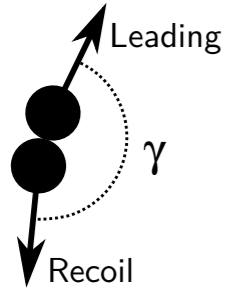
Triple Coincidence Experiment with EVA



$$P_{initial} = p_1 + p_2 + p_{beam}$$

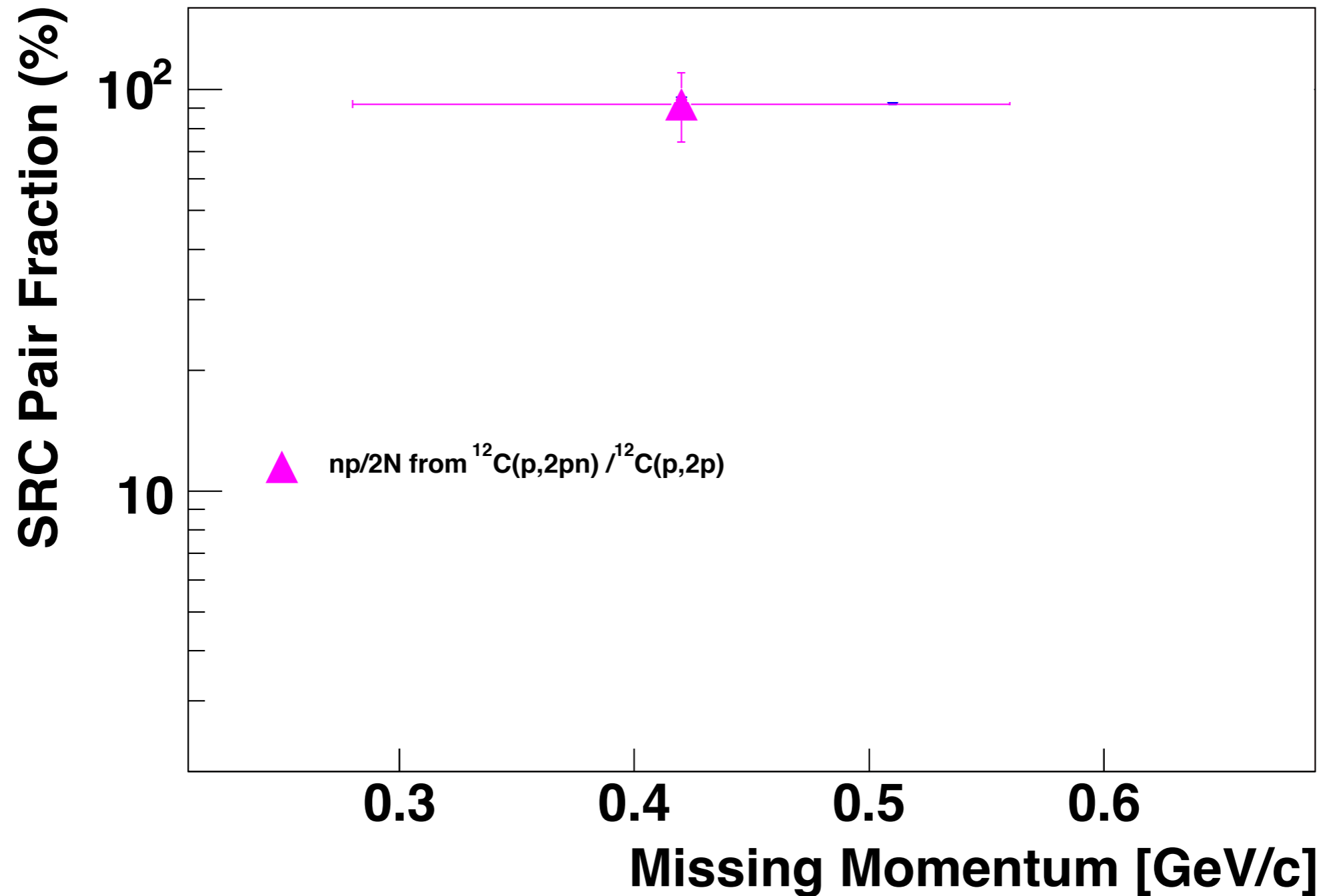
Reaction $^{12}\text{C}(p,2pn)X$

Experimental Evidence of SRC Pair - Correlated Partner



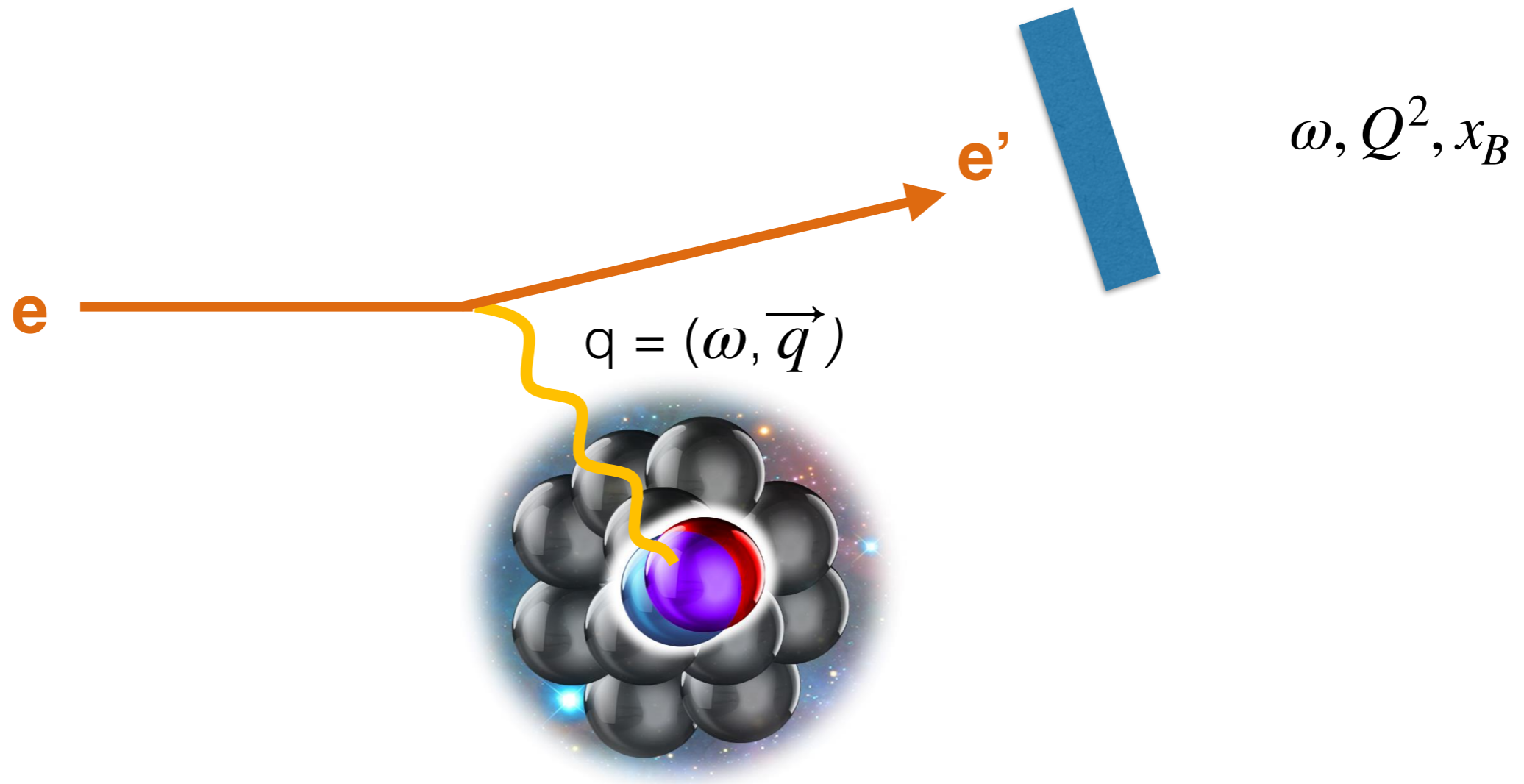
Piassetzky PRL 97 (2006), Aclander, PLB 453 (1999), Tang, PRL 90 (2003)

Evidence of np-dominance



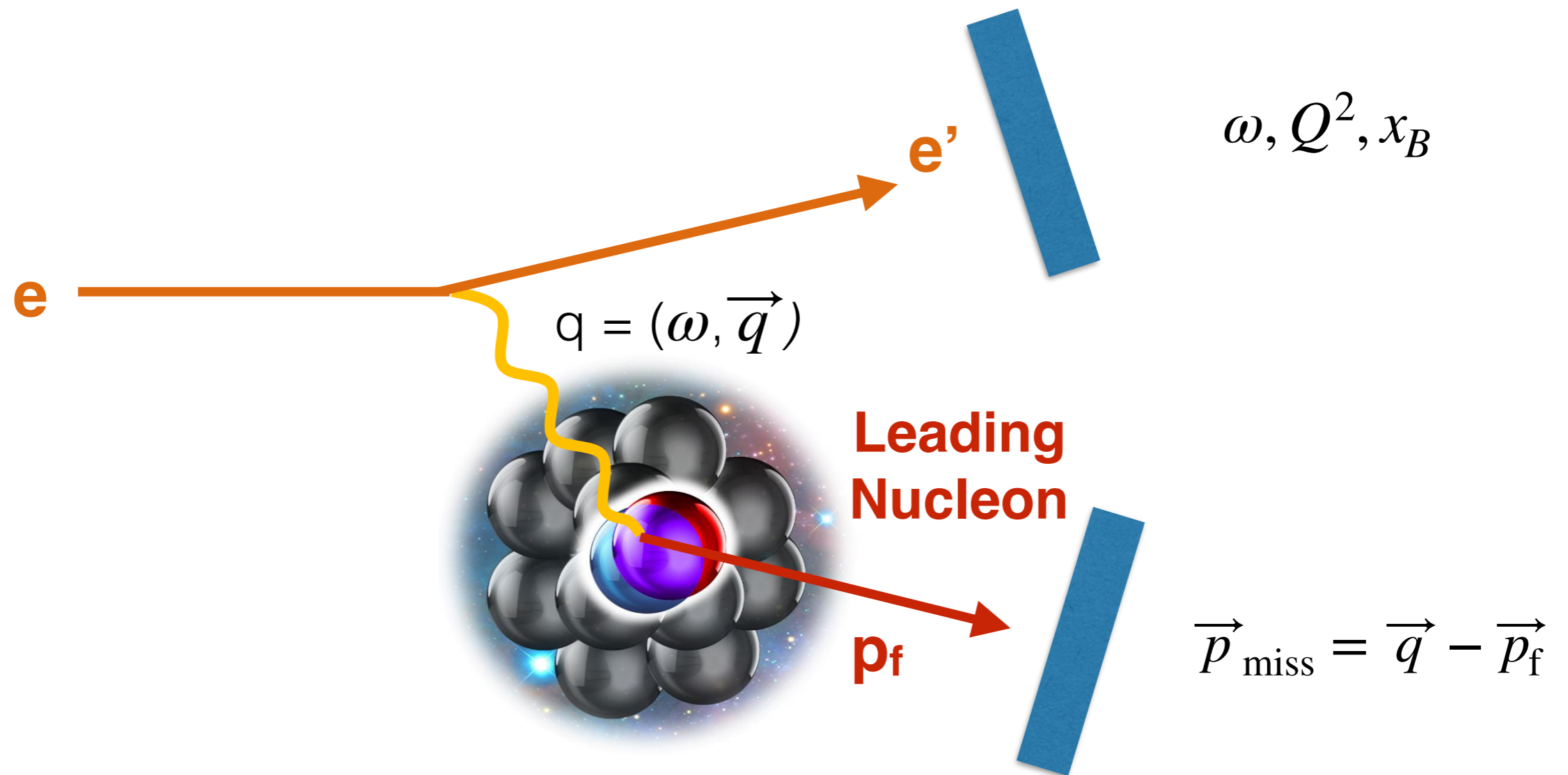
Subedi, Science (2008)

Electron Scattering off SRC pair



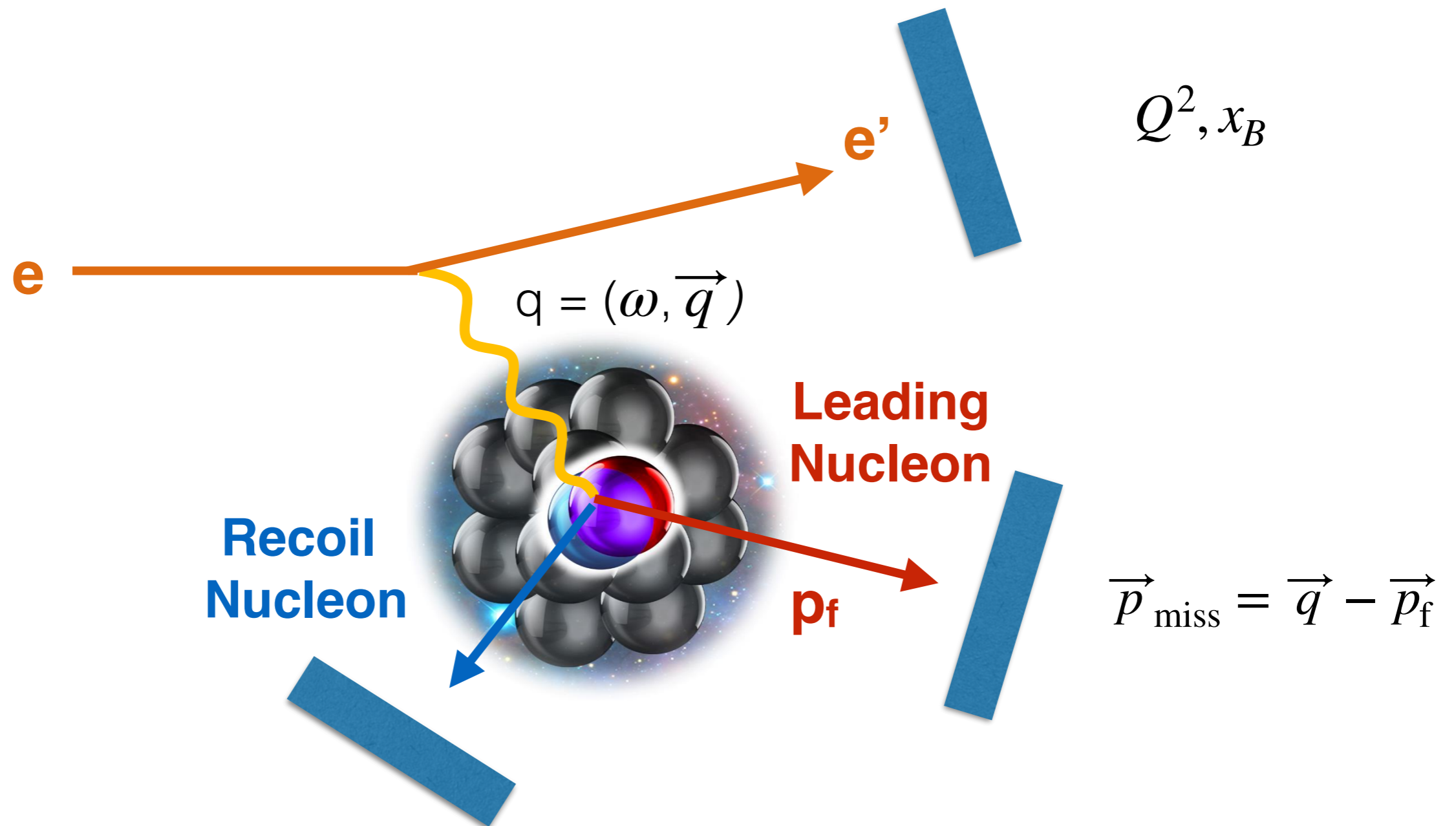
- (e, e') inclusive

Electron Scattering off SRC pair



- (e, e') inclusive
- $(e, e'N)$

Electron Scattering off SRC pair



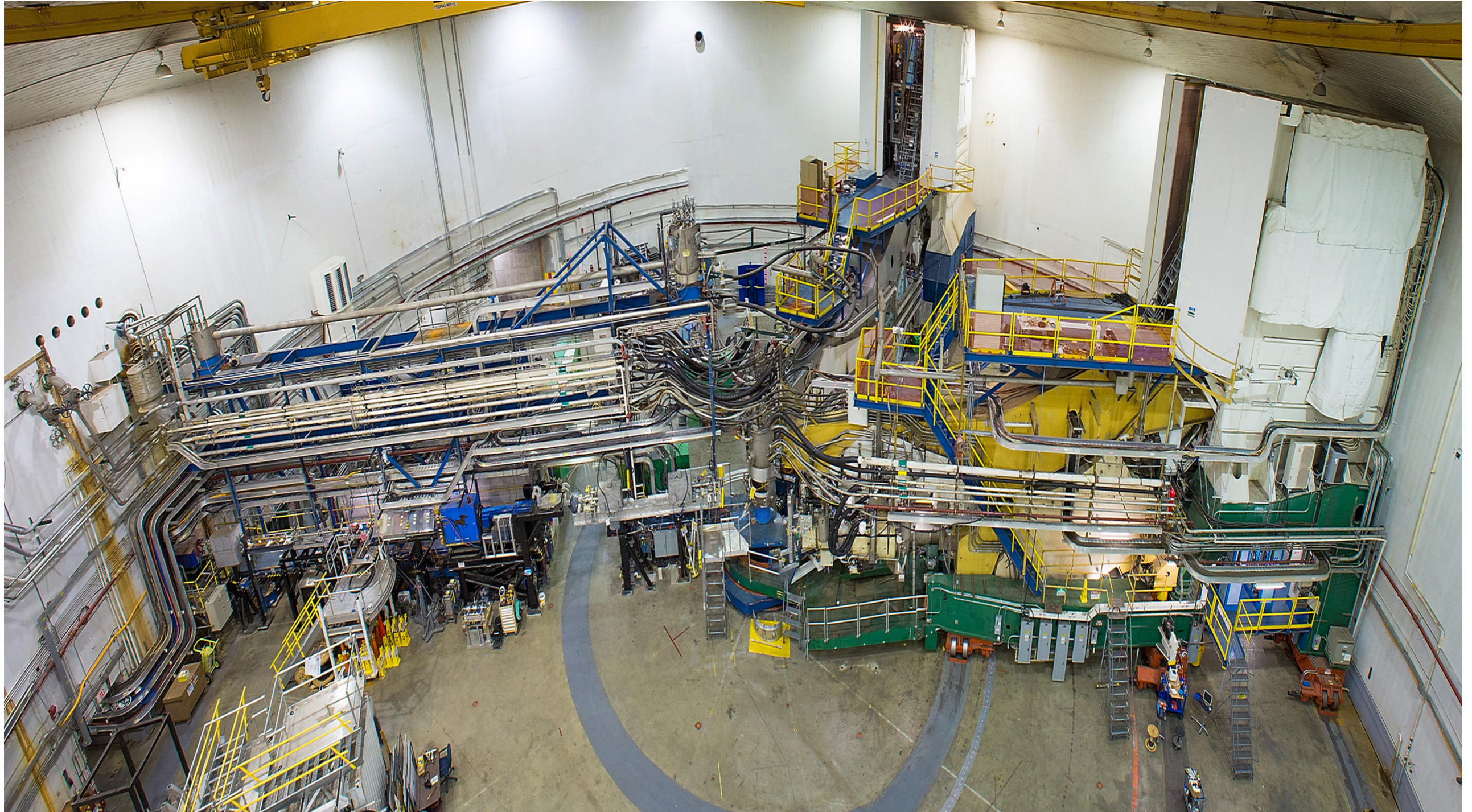
- (e, e') inclusive
- $(e, e'N)$
- $(e, e'NN)$

Jefferson Lab CEBAF Accelerator

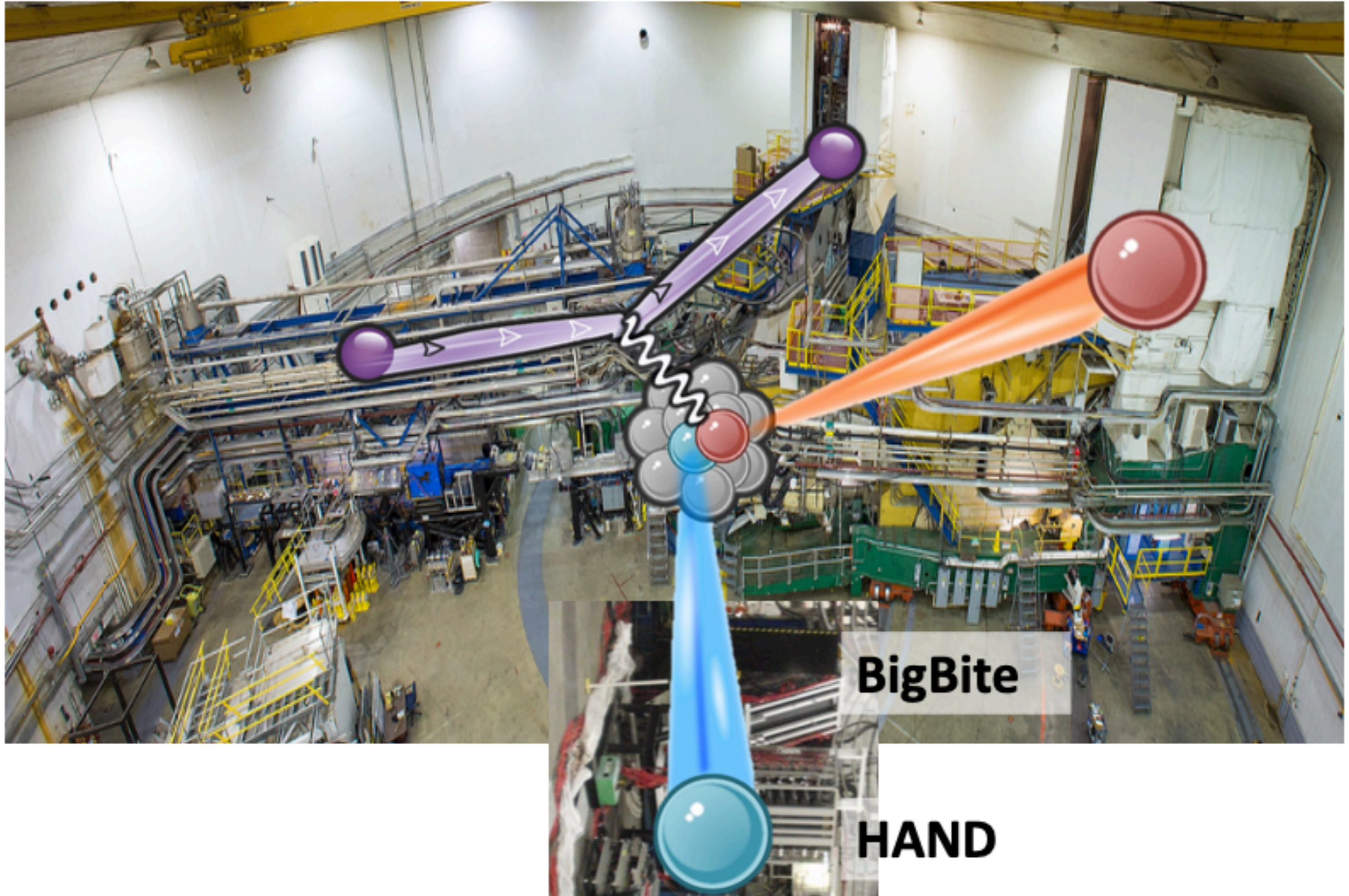
- Located in Newport News, VA
- Electrons up to 11 GeV energy
- 4 experimental halls (A-D)



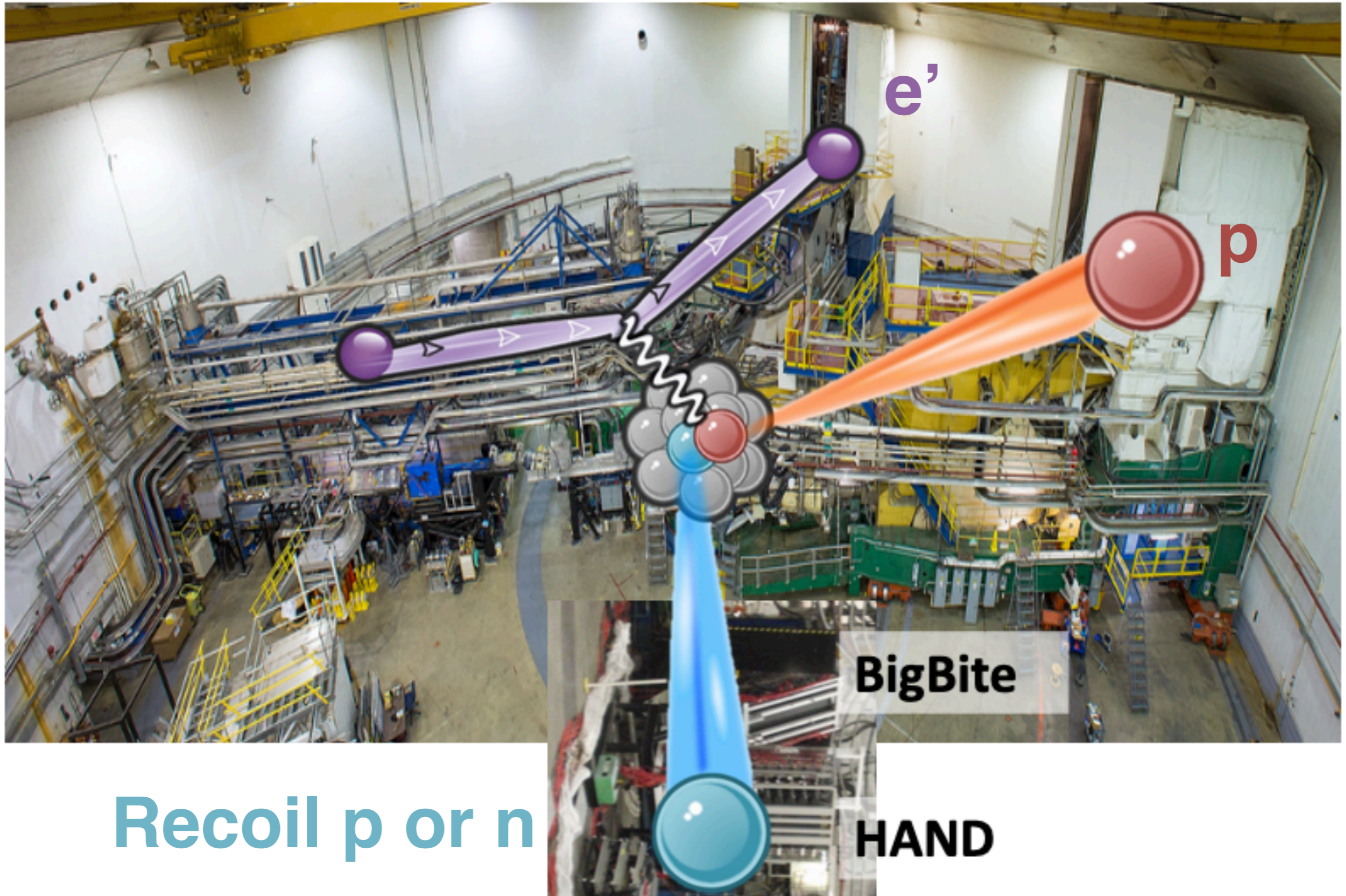
High Resolution Spectrometers in Hall A



Triple Coincidence Experiment

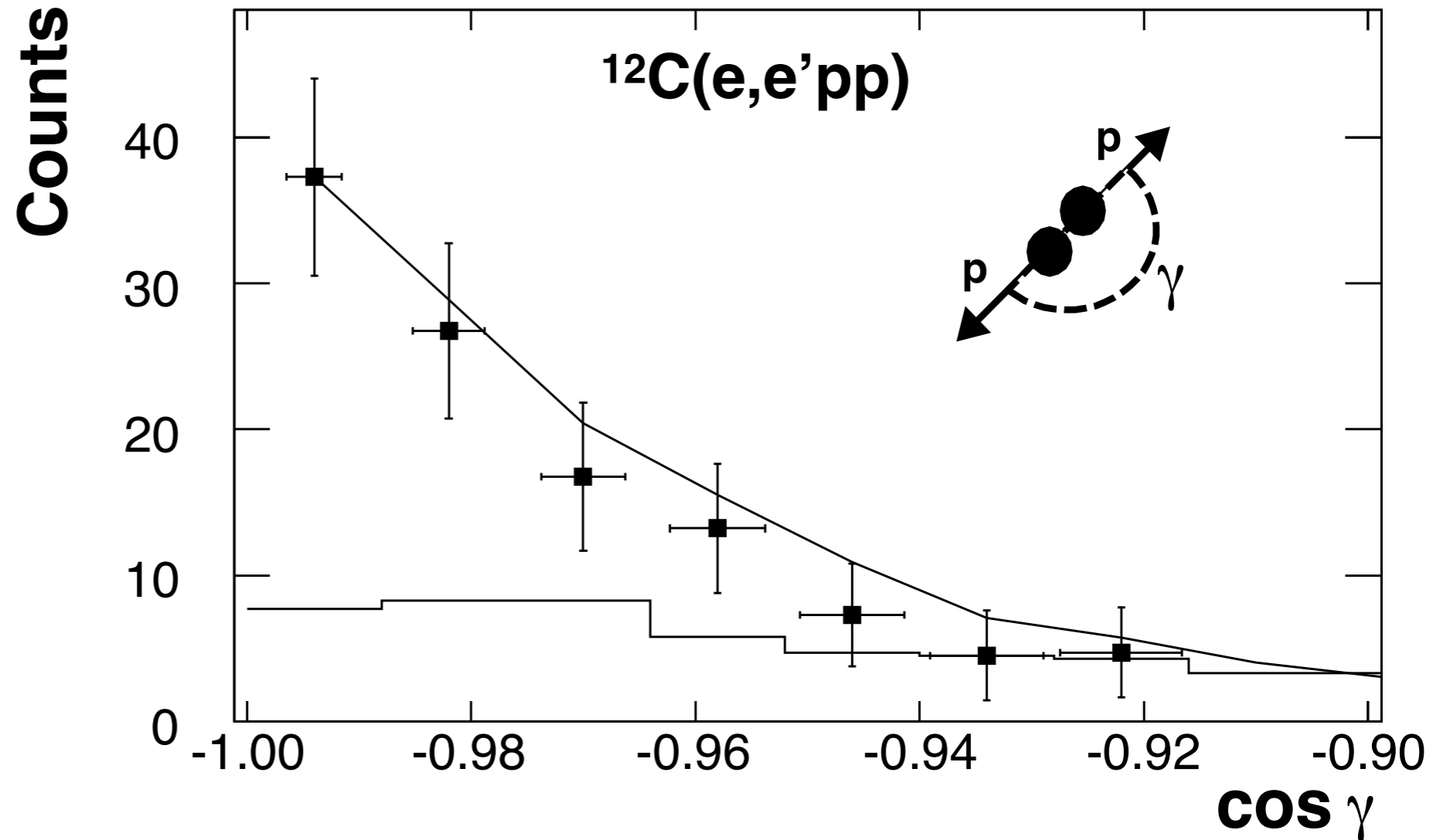
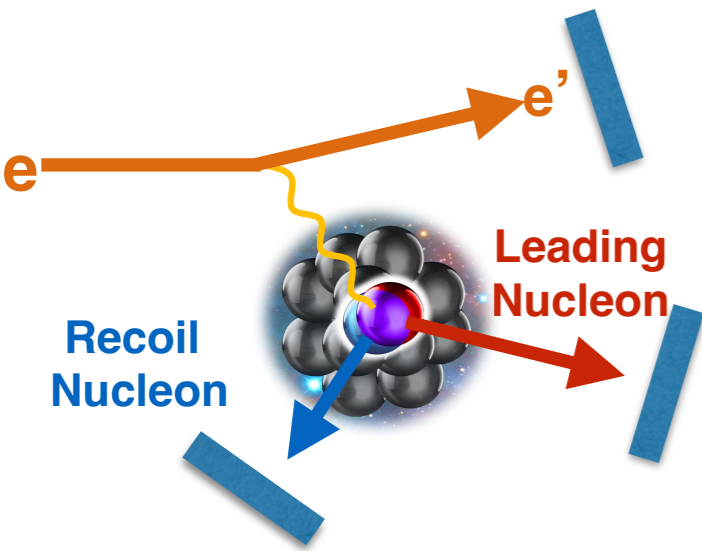


Triple Coincidence Experiment



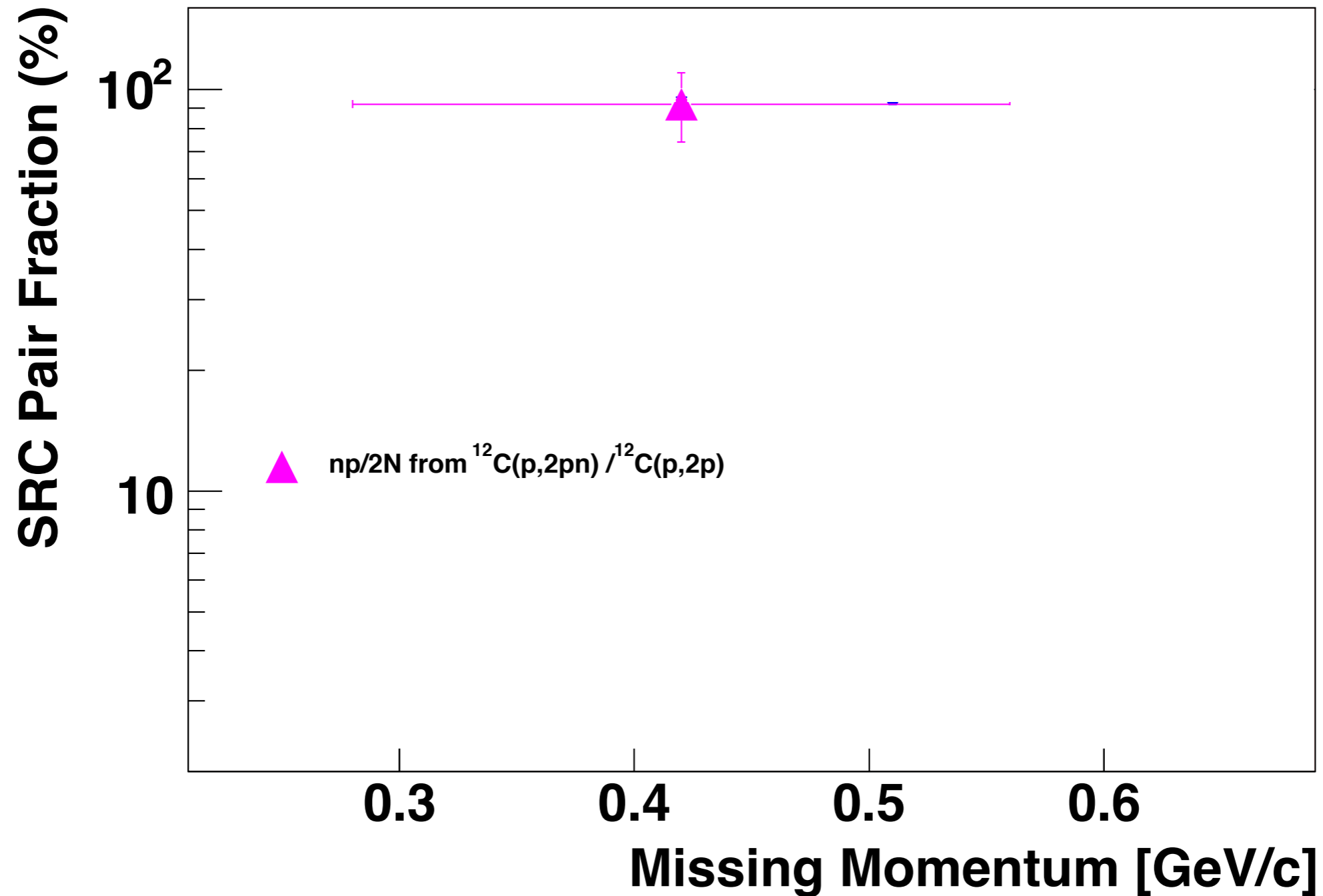
High-Momentum Pair are Back-to-Back

R. Shneor et al., PRL (2007)



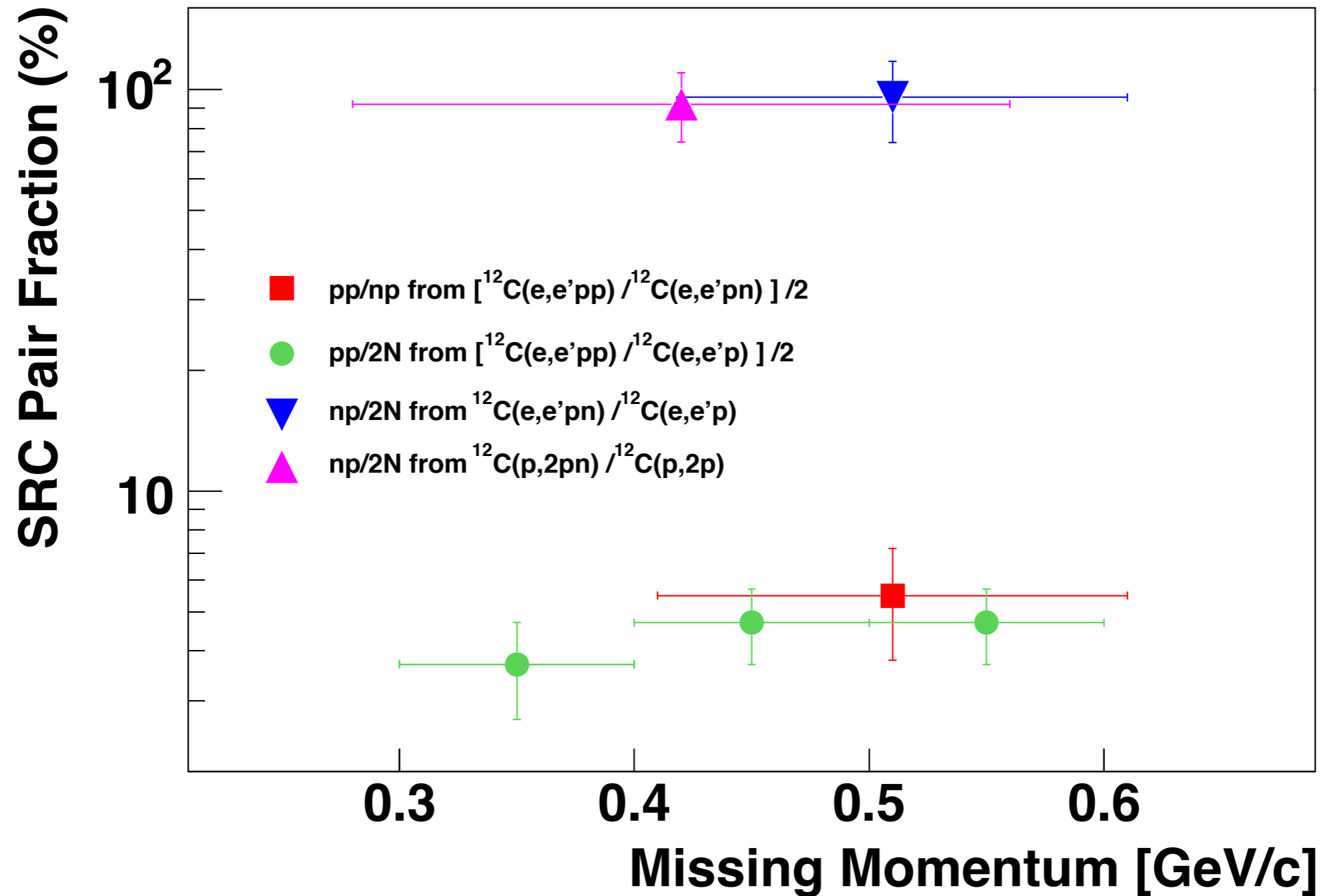
- correlated partner
- recoil anti-parallel to p_{miss} (for $p_{\text{miss}} = 550 \text{ MeV}/c$)

Evidence of np-dominance



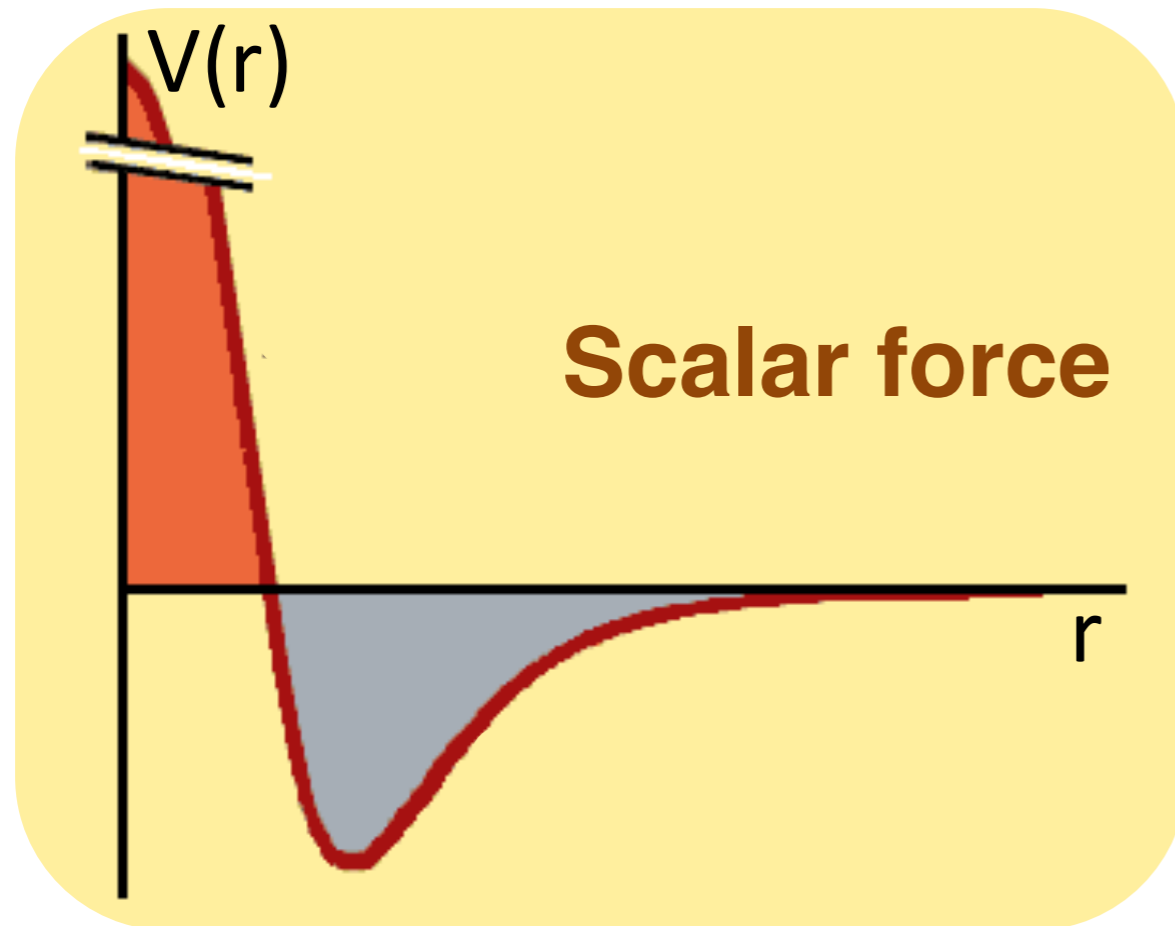
Subedi, Science (2008)

Evidence of np-dominance

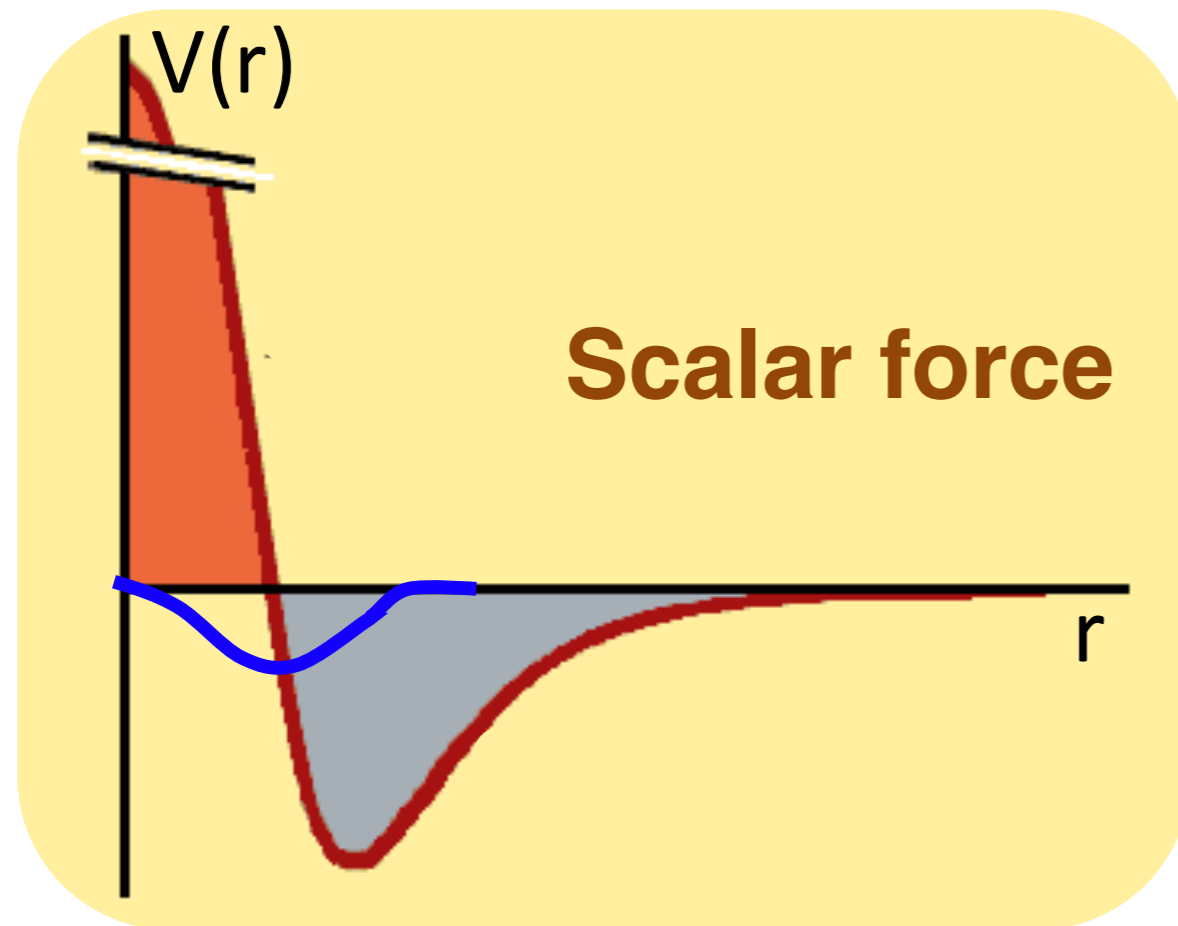


Subedi, Science (2008)

np-Dominance from Tensor Force



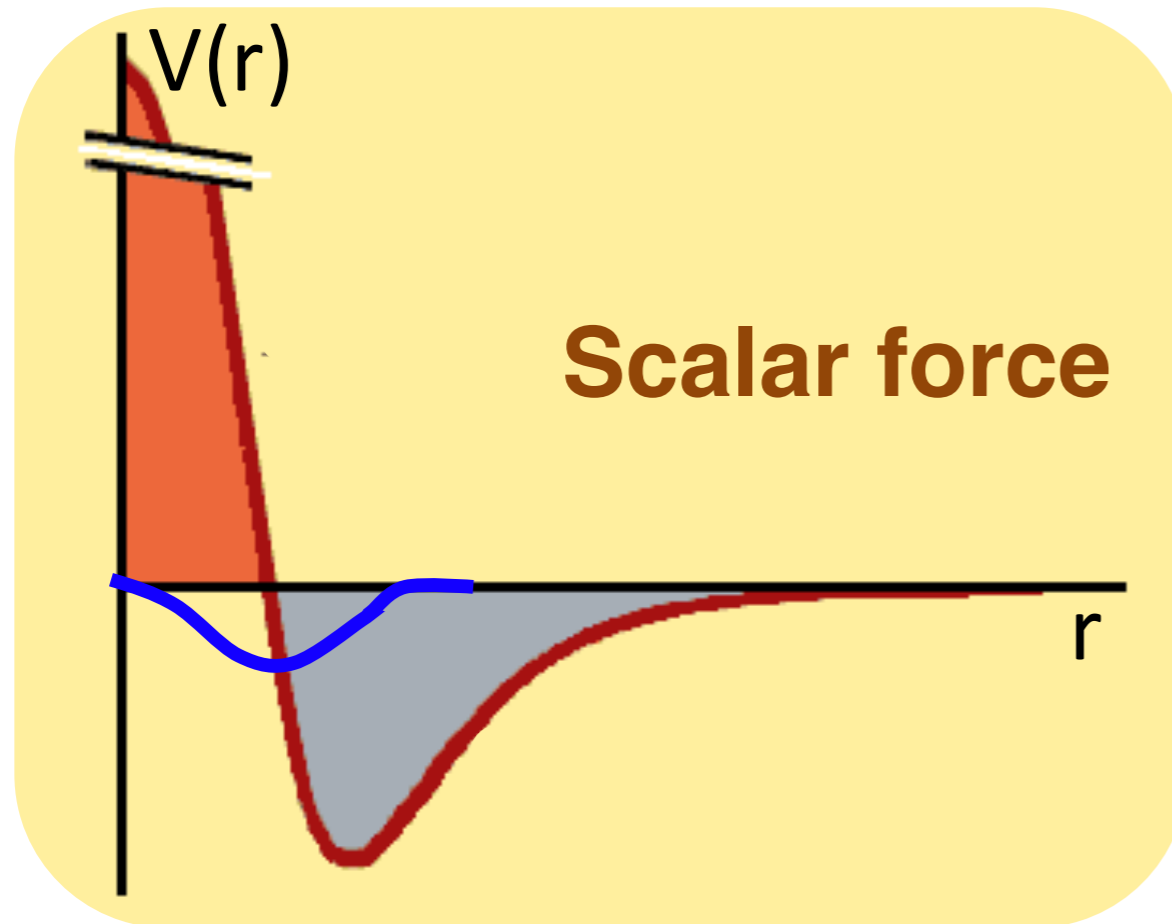
np-Dominance from Tensor Force



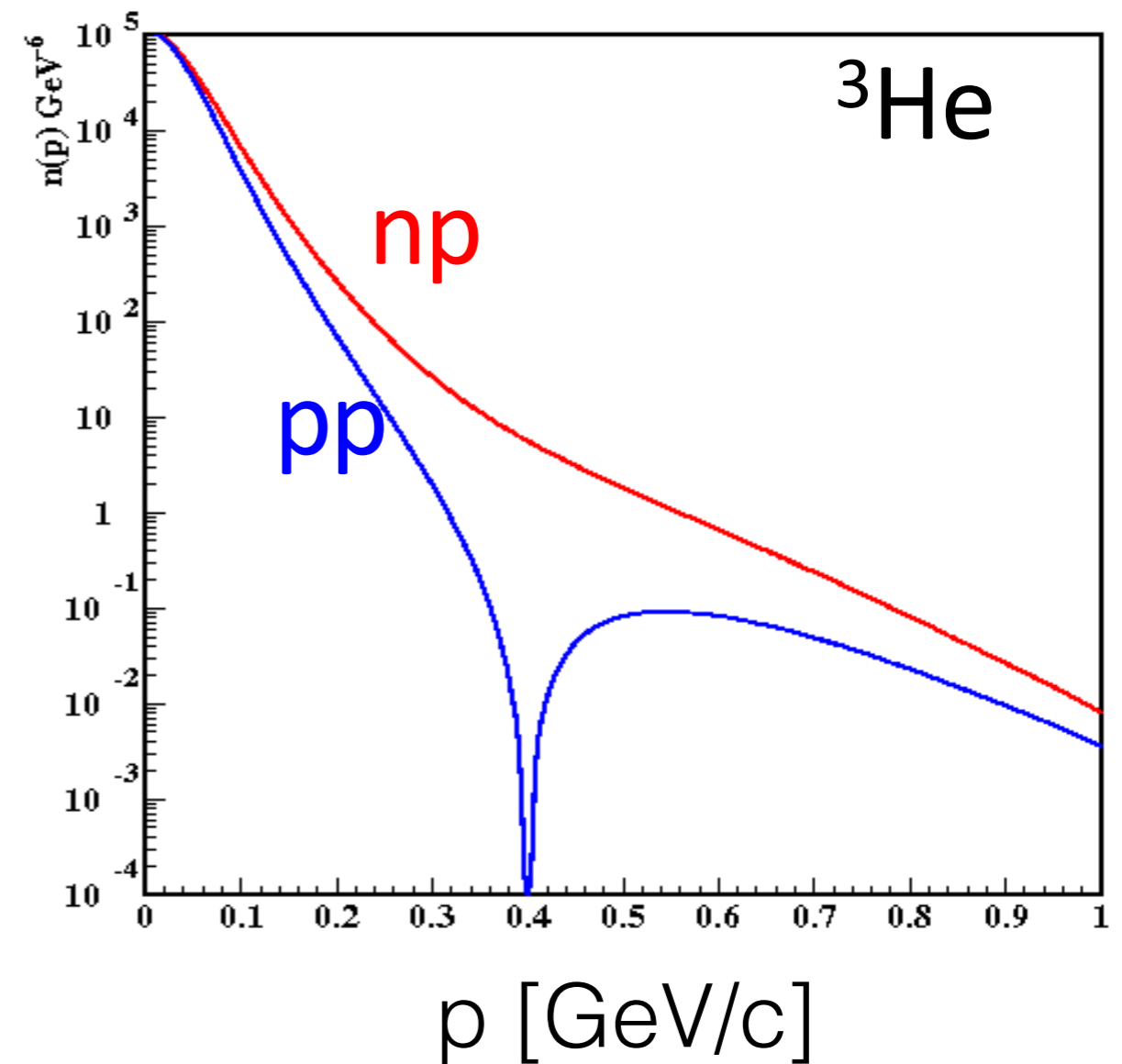
Tensor force
Short-Range attraction

np-Dominance from Tensor Force

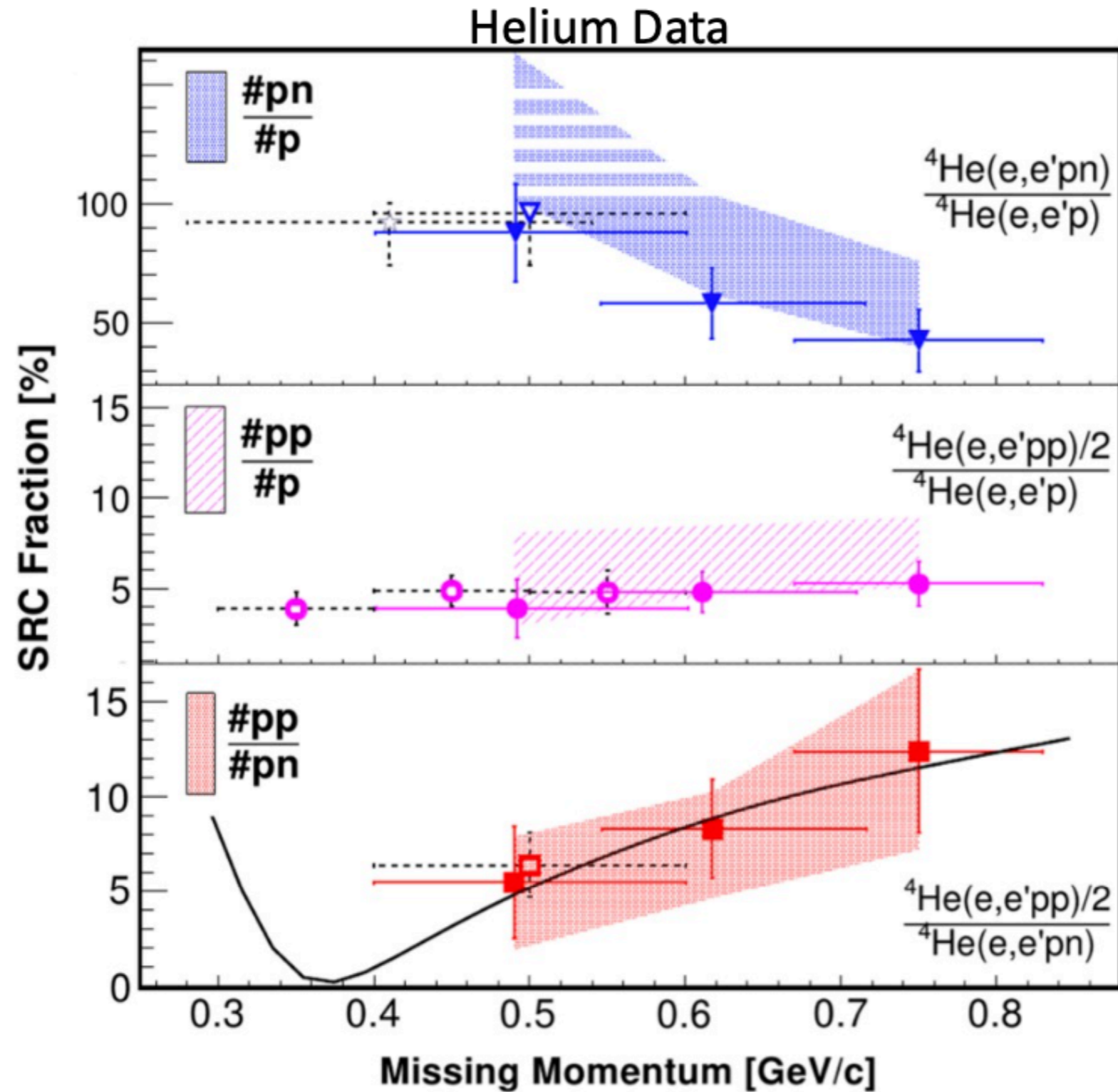
Sargsian et al., PRC (2005)



Tensor force
Short-Range attraction

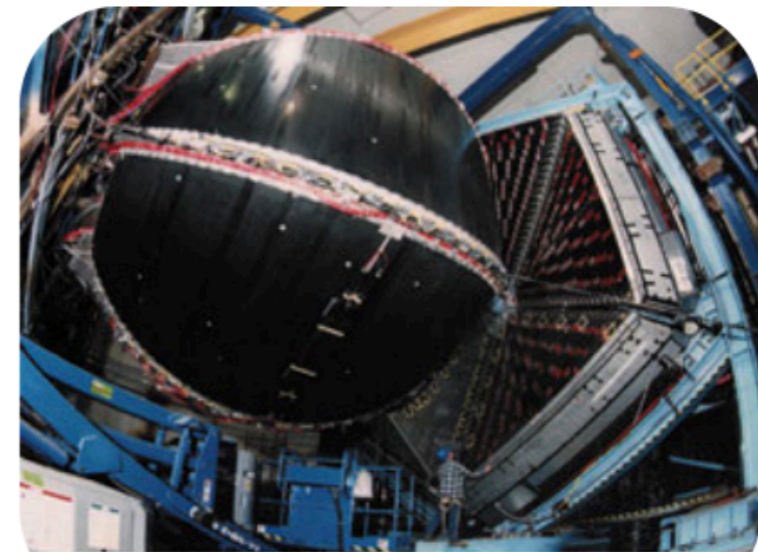
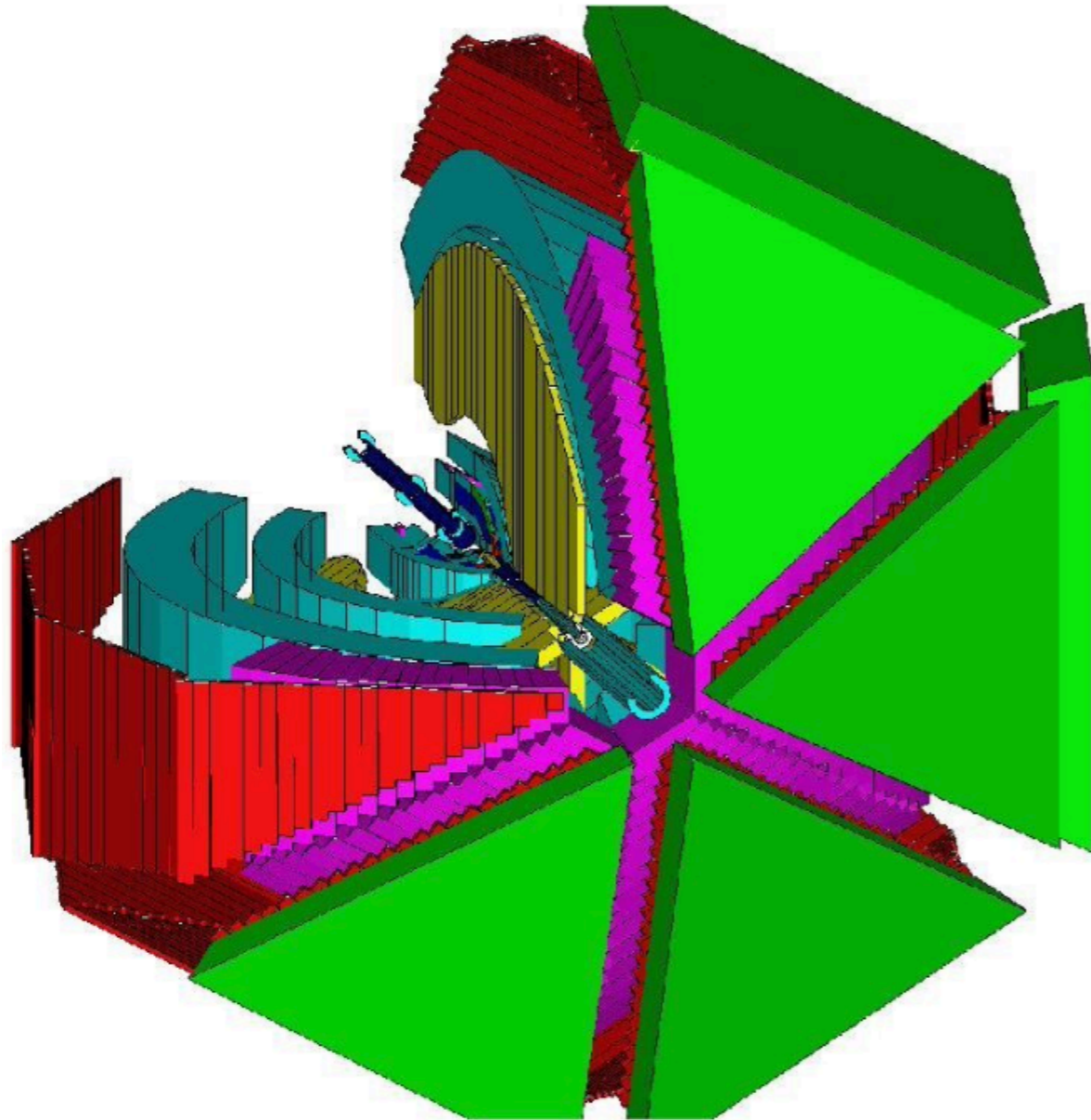


np-dominance Momentum Dependent



Korover, PRL 113 (2014)

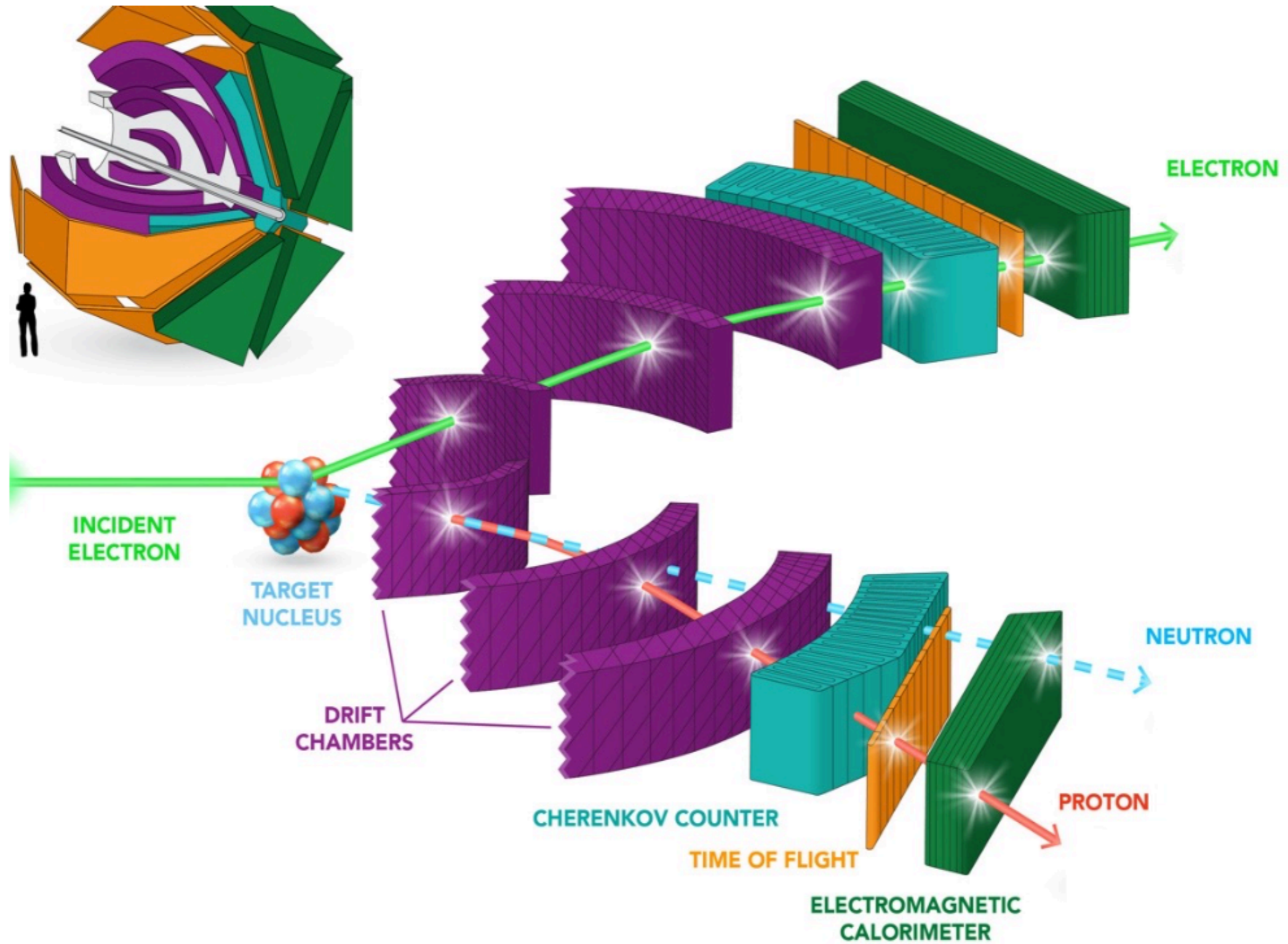
CLAS: CEBAF Large Acceptance Spectrometer



Hall B Large Acceptance Spectrometer

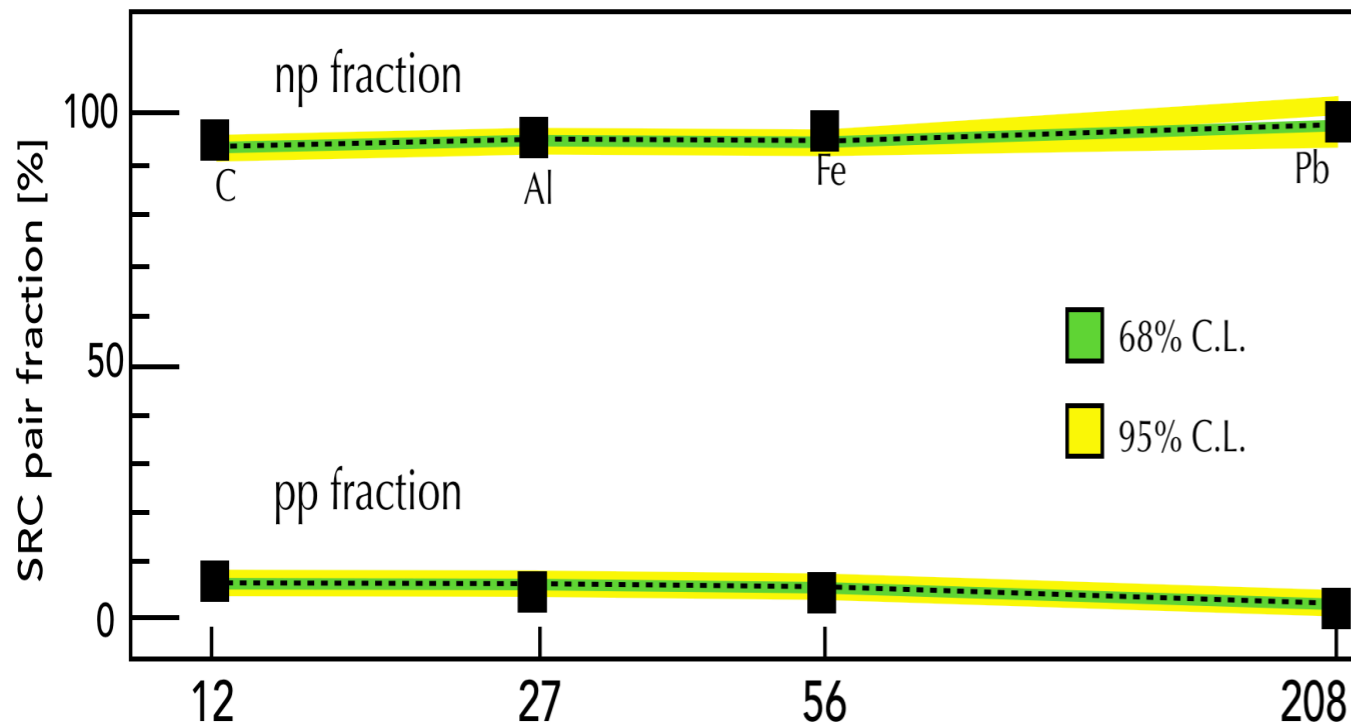
- Open electron trigger
- Large acceptance, multiple nuclear targets

Detect Electron, Protons and Neutrons

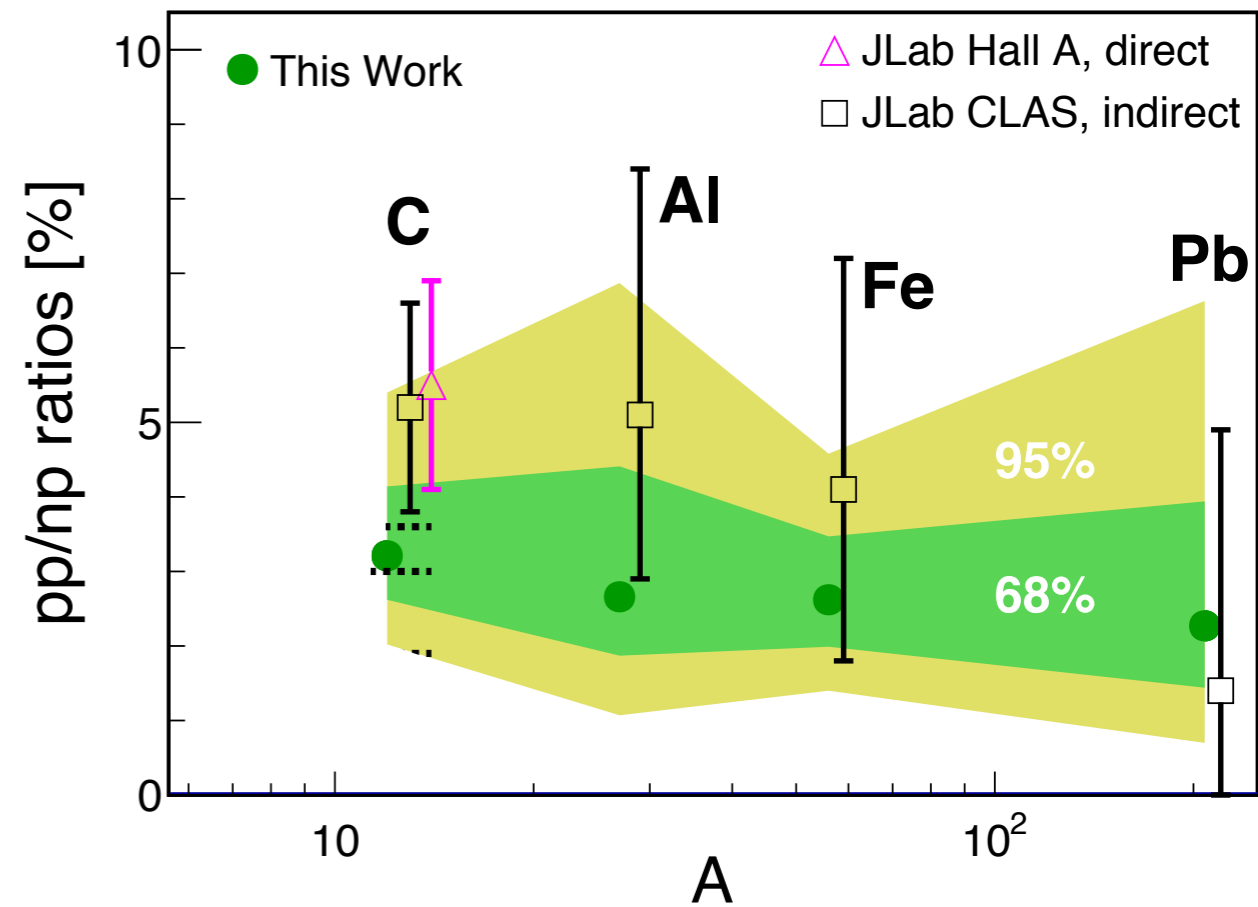


Data Mining of CLAS: Exclusive SRC Results on Heavy Nuclei

Hen et al., Science 346 (2014)



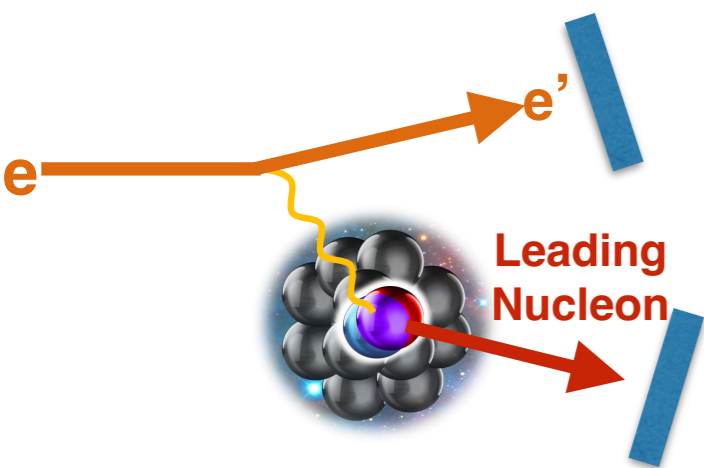
Duer et al., PRL 122 (2019)



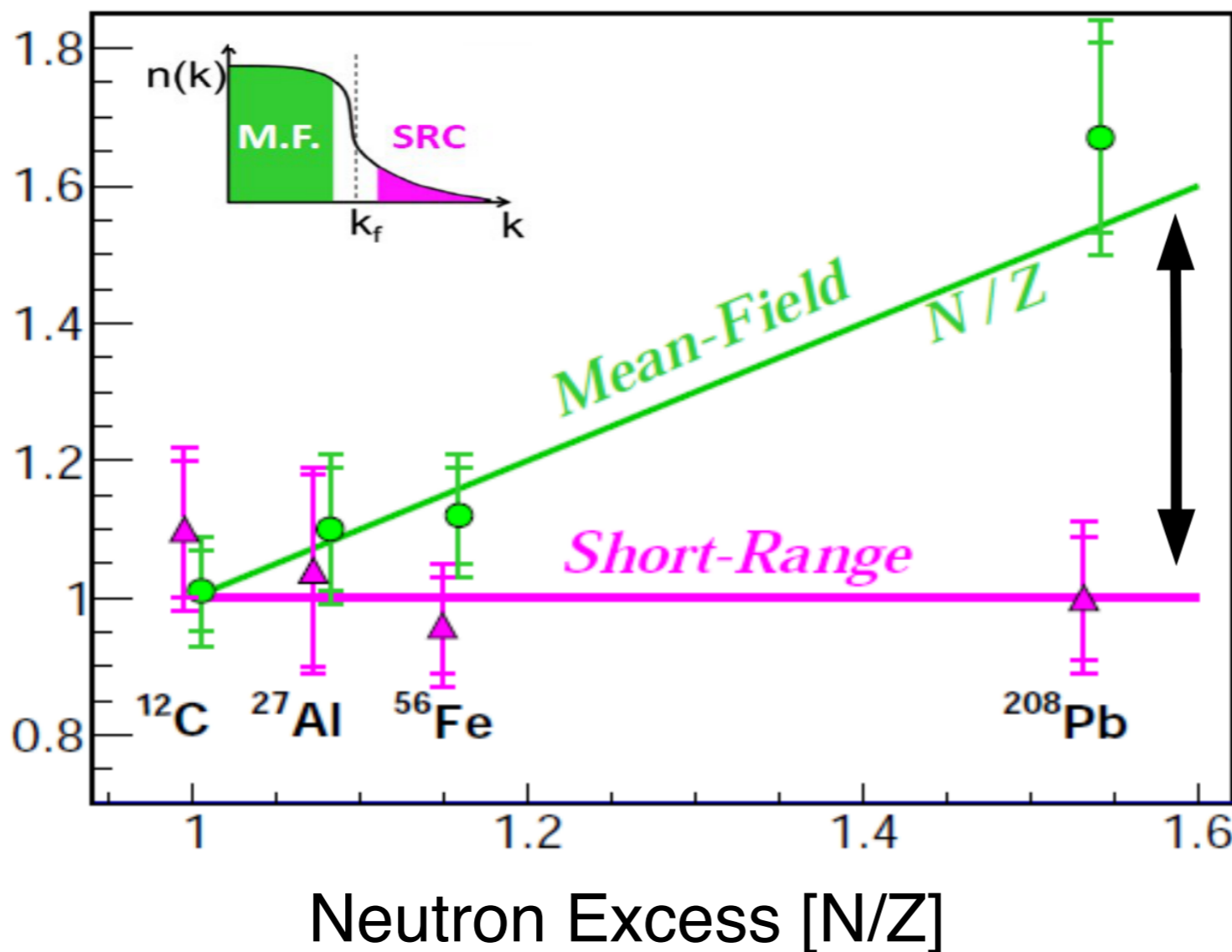
- np-dominance in all nuclei

np-dominance in Single Nucleon Knockout

Duer et al. (CLAS collaboration), Nature 560, 617 (2018)



$$\frac{\sigma_A(e, e'n)/\sigma_{en}}{\sigma_A(e, e'p)/\sigma_{ep}}$$

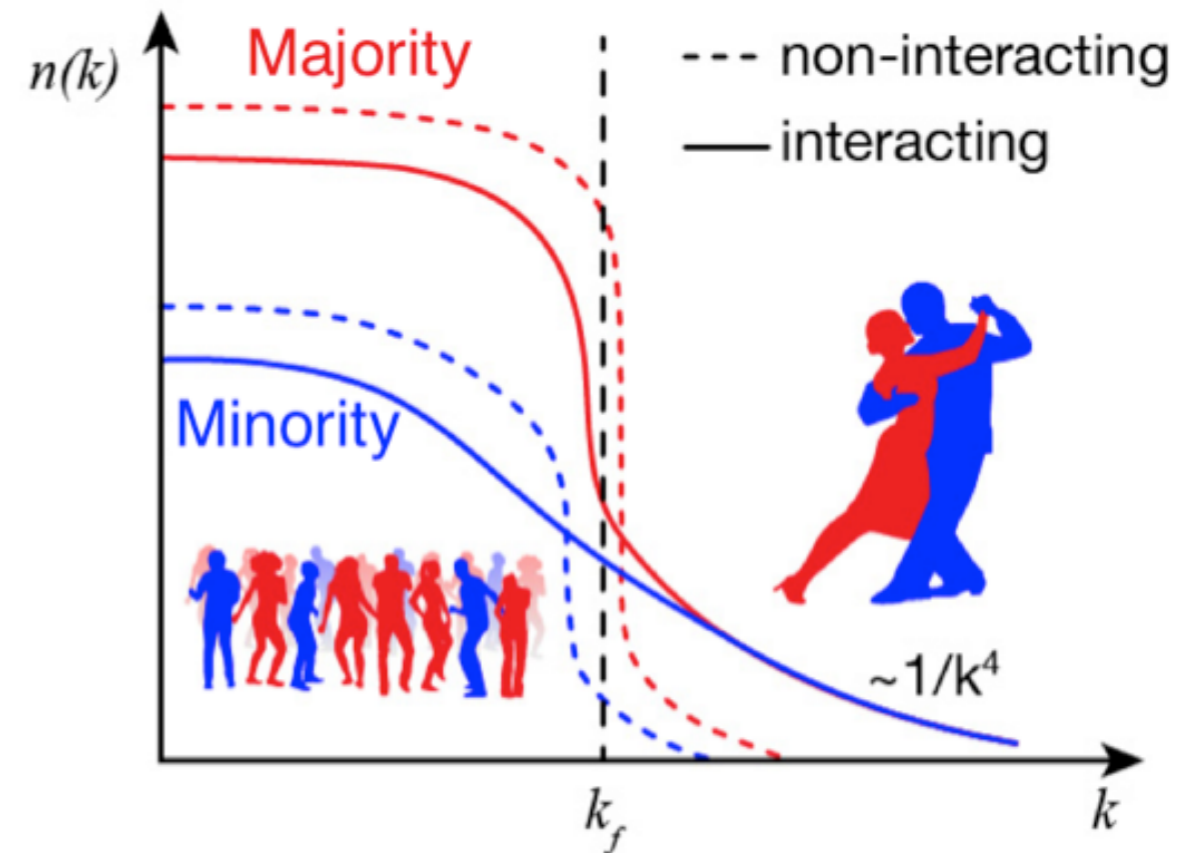
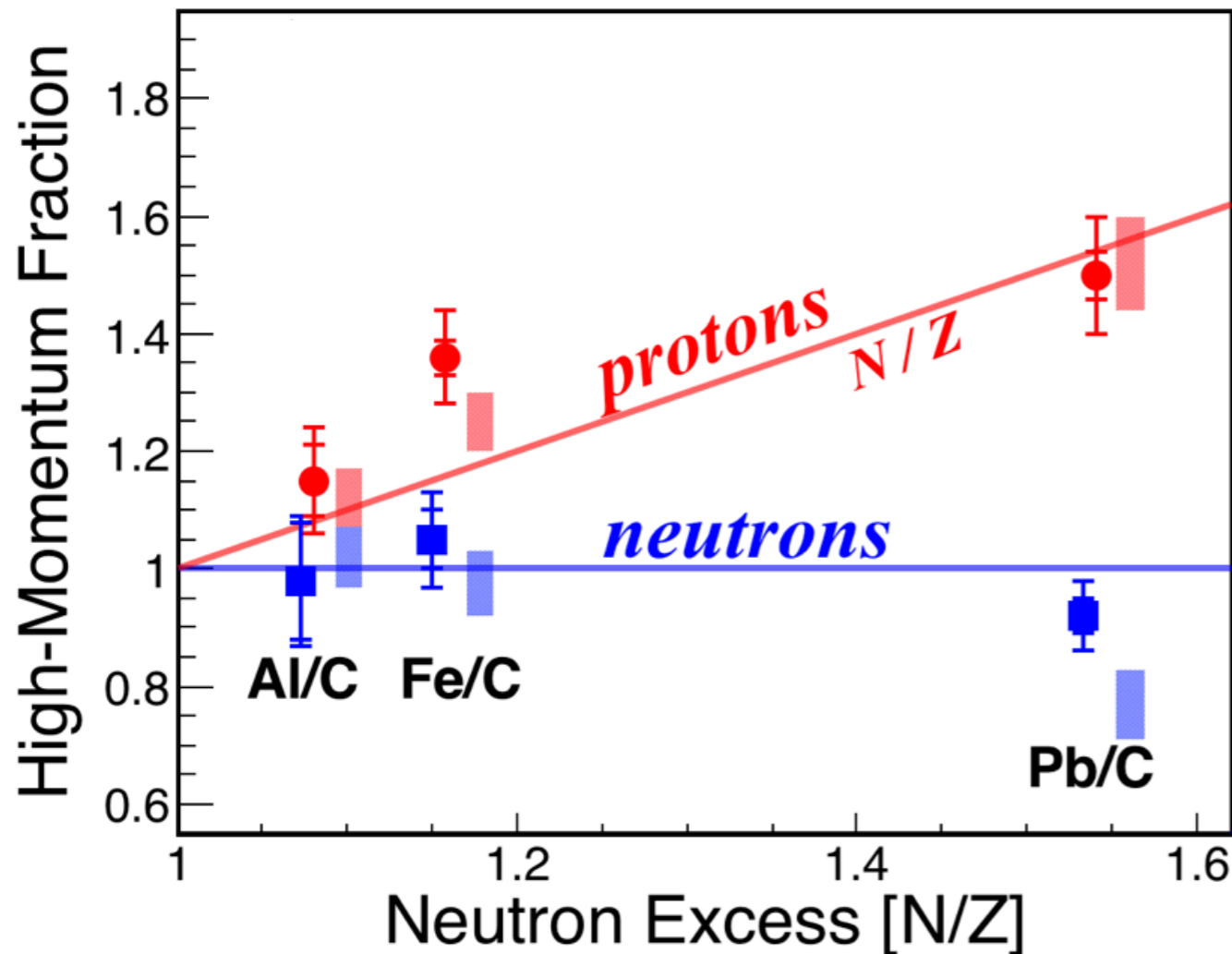


$$\frac{\sigma_A(e, e'n)/\sigma_{en}}{\sigma_A(e, e'p)/\sigma_{ep}} \approx \frac{N\sigma_{en}/\sigma_{en}}{Z\sigma_{en}/\sigma_{en}}$$

$$\frac{\sigma_A(e, e'n)/\sigma_{en}}{\sigma_A(e, e'p)/\sigma_{ep}} \approx \frac{N\sigma_{en}/\sigma_{en}}{N\sigma_{en}/\sigma_{en}}$$

Protons 'speed up' in Neutron-Rich Nuclei

Duer et al. (CLAS collaboration), Nature 560, 617 (2018)

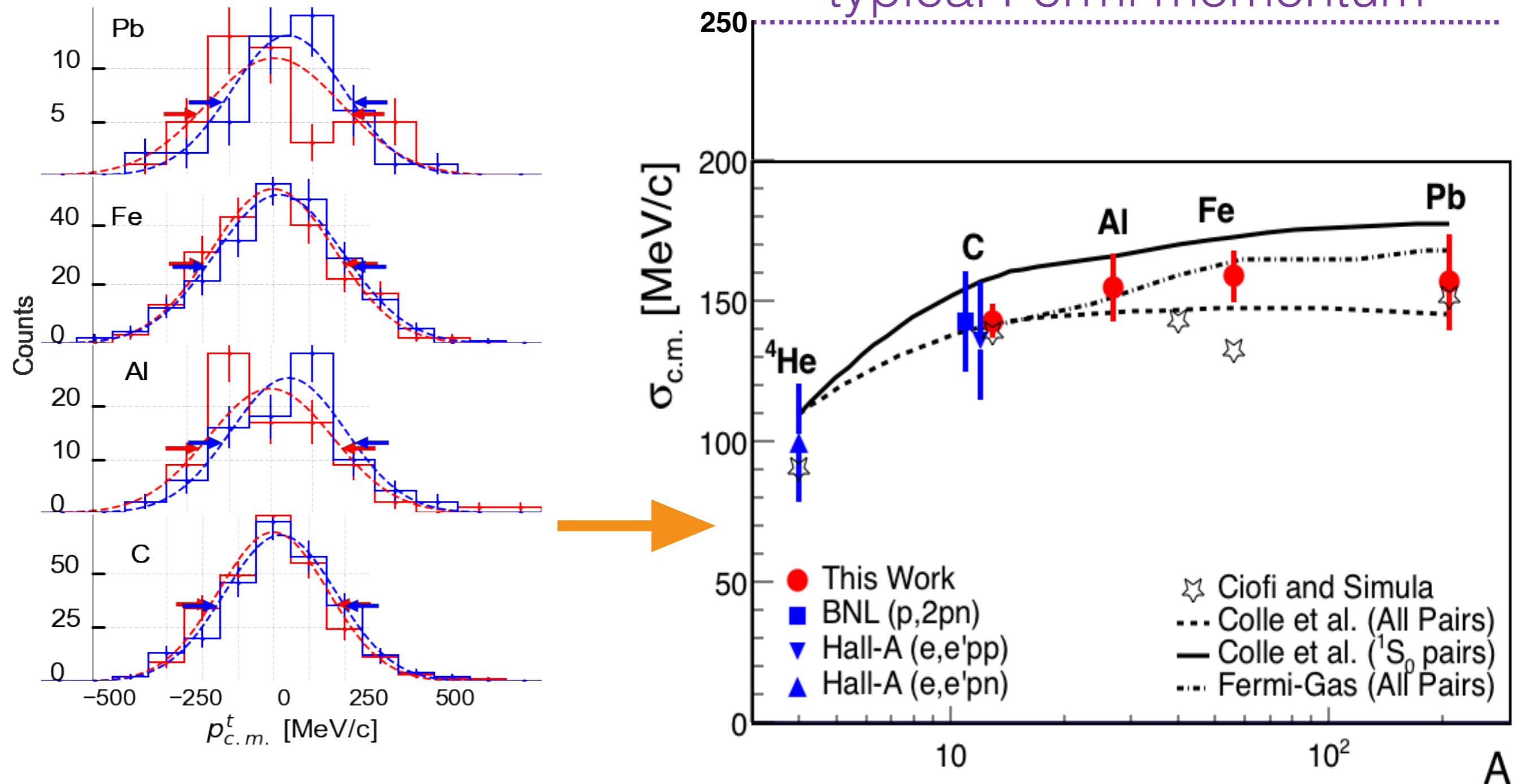


- Minority nucleons faster than majority due to np-dominance

SRC pair - center of mass momentum

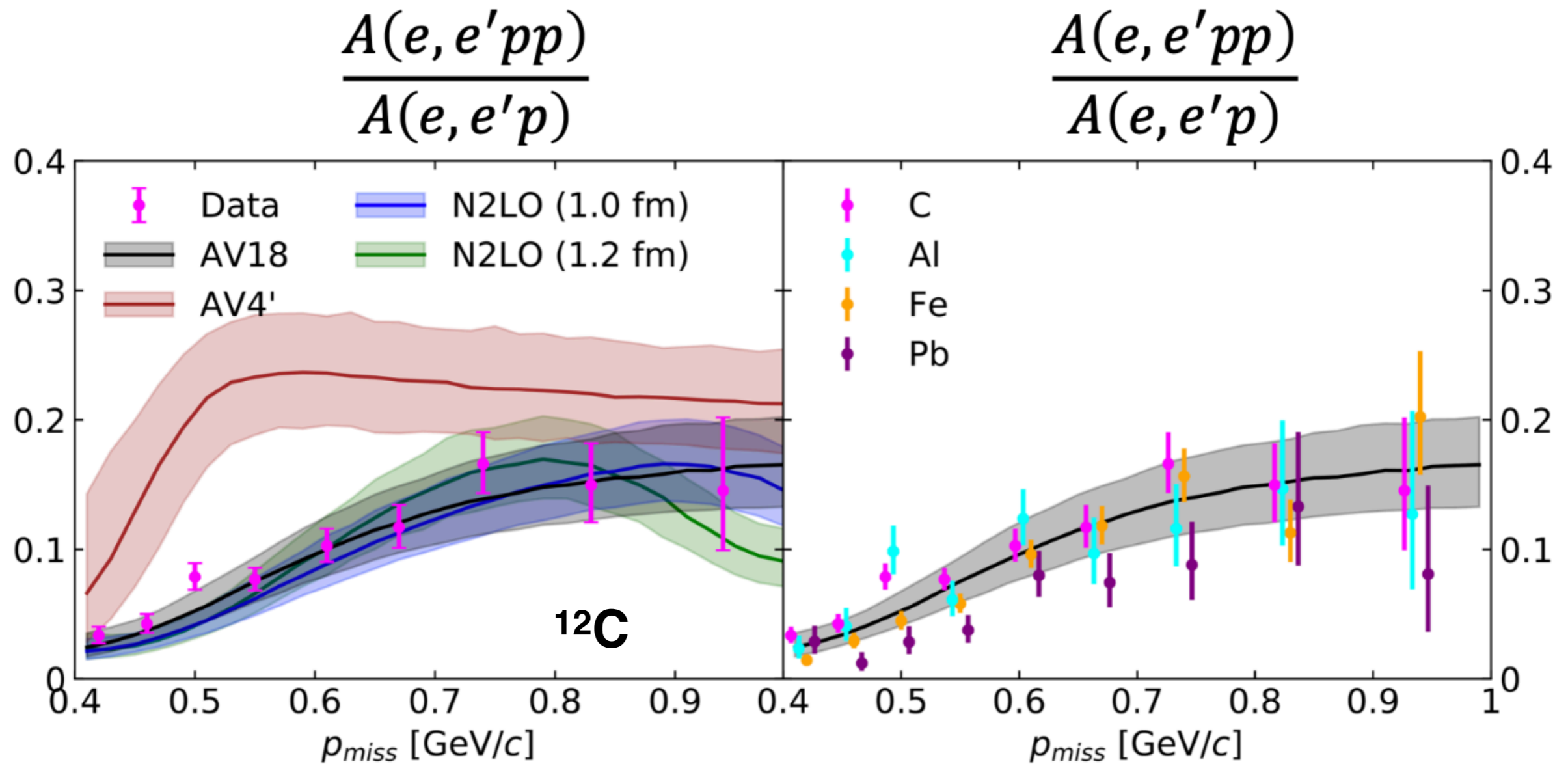
E. Cohen et al.(CLAS collaboration), PRL (2018)

typical Fermi momentum



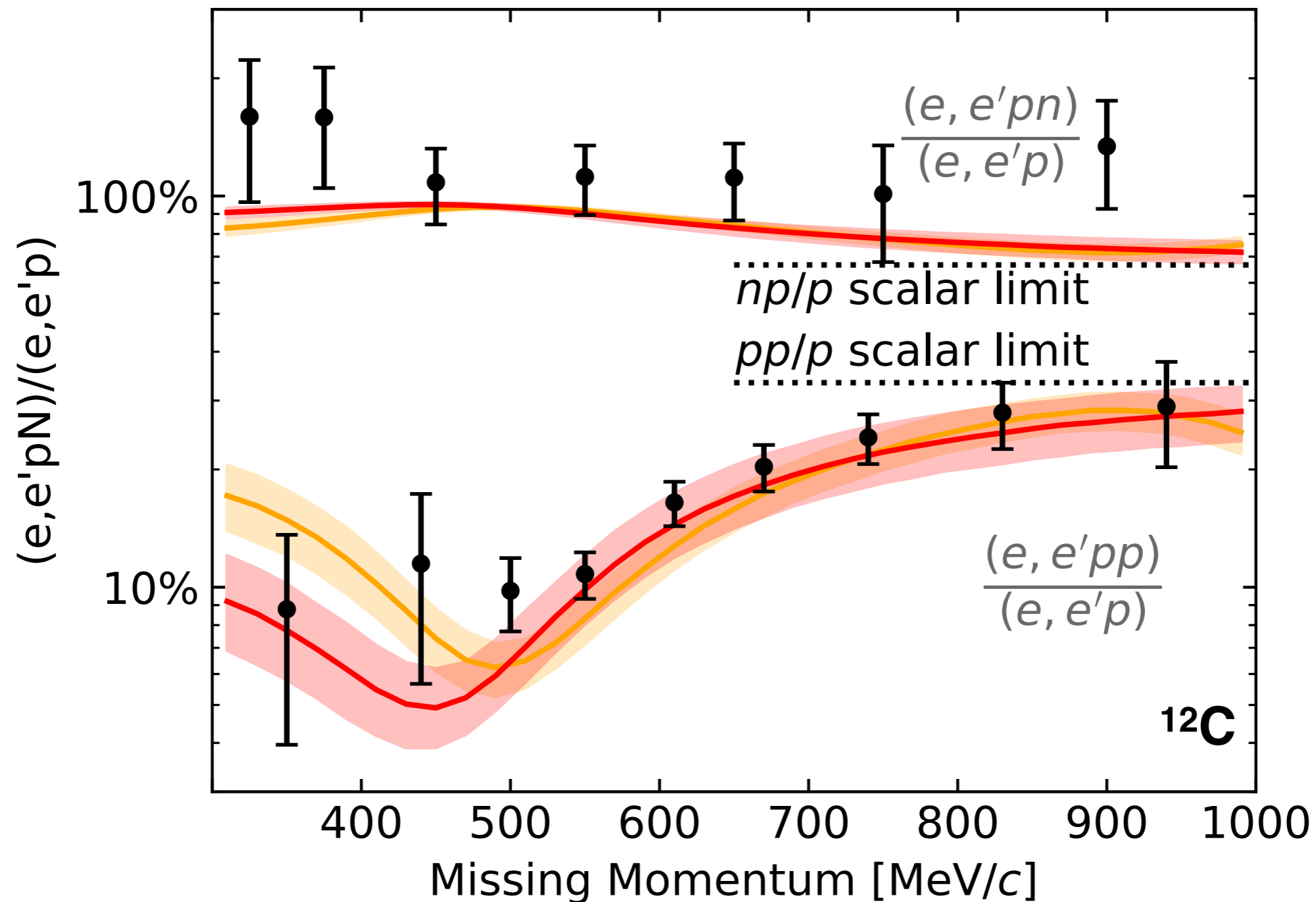
Mapping out NN interaction

Schmidt et al., Nature (2020)



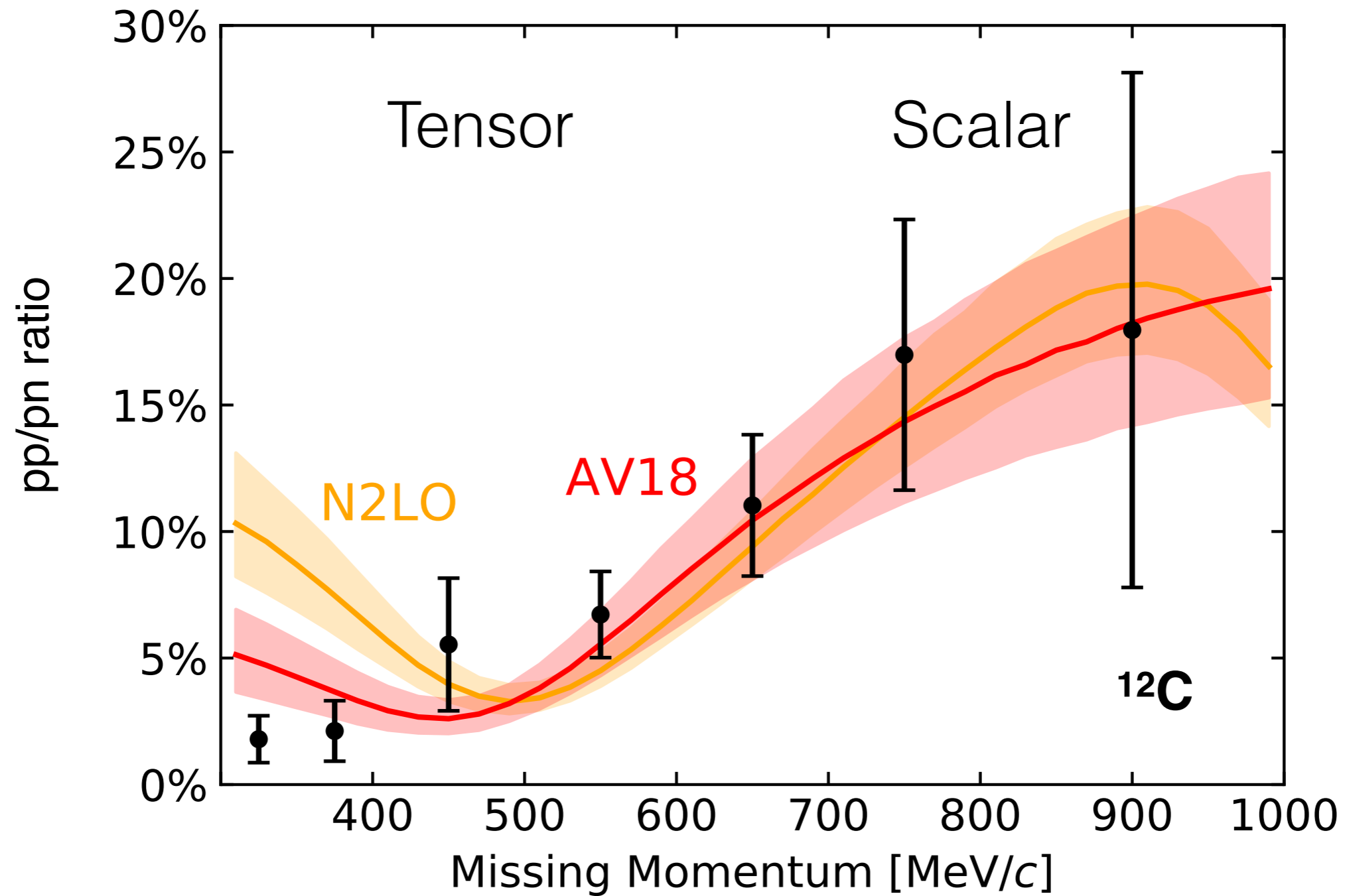
Mapping out NN interaction

Schmidt et al., Nature (2020), Korover et al., PLB (2021)

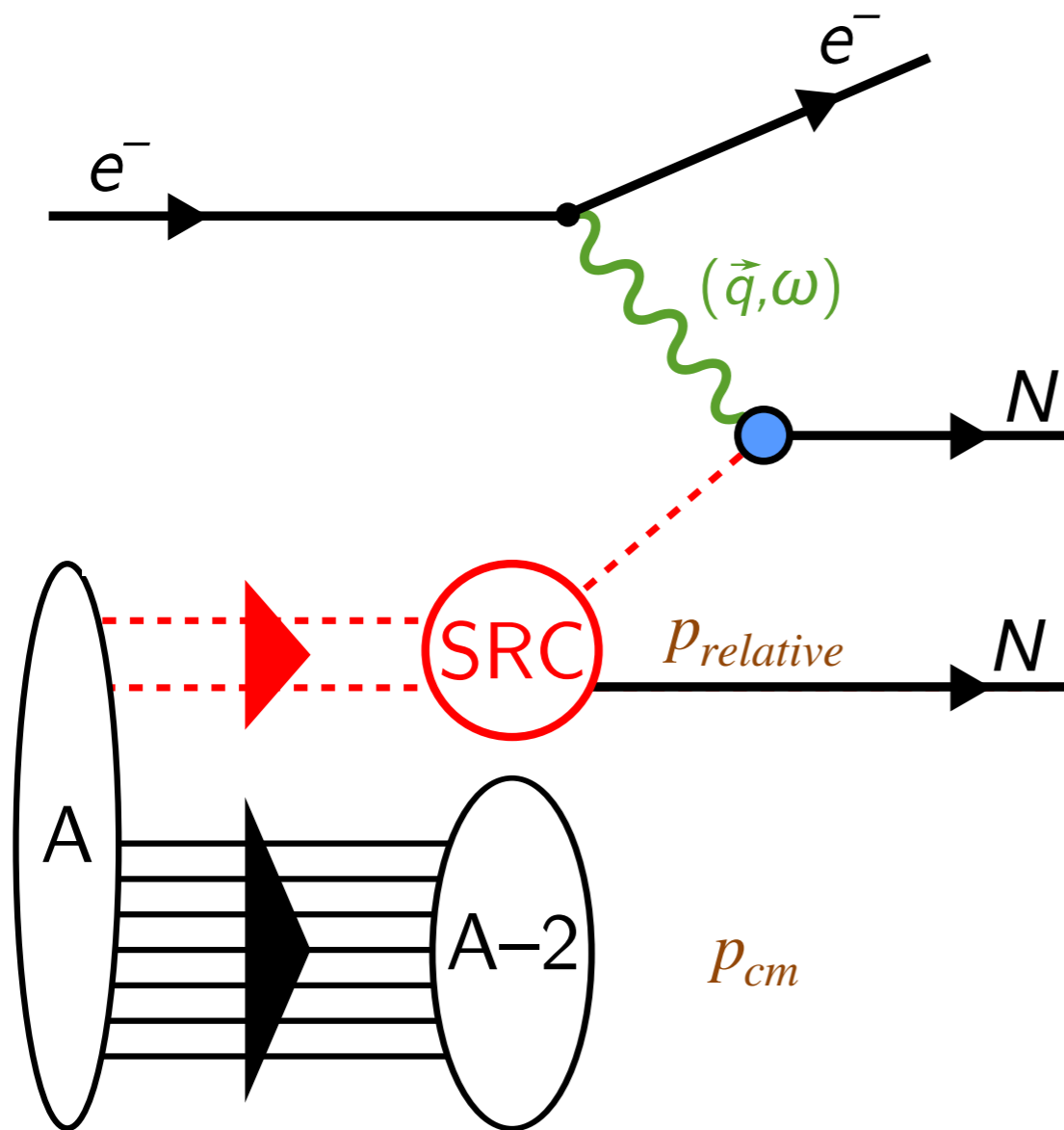


Mapping out NN interaction

Schmidt et al., Nature (2020), Korover et al., PLB (2021)

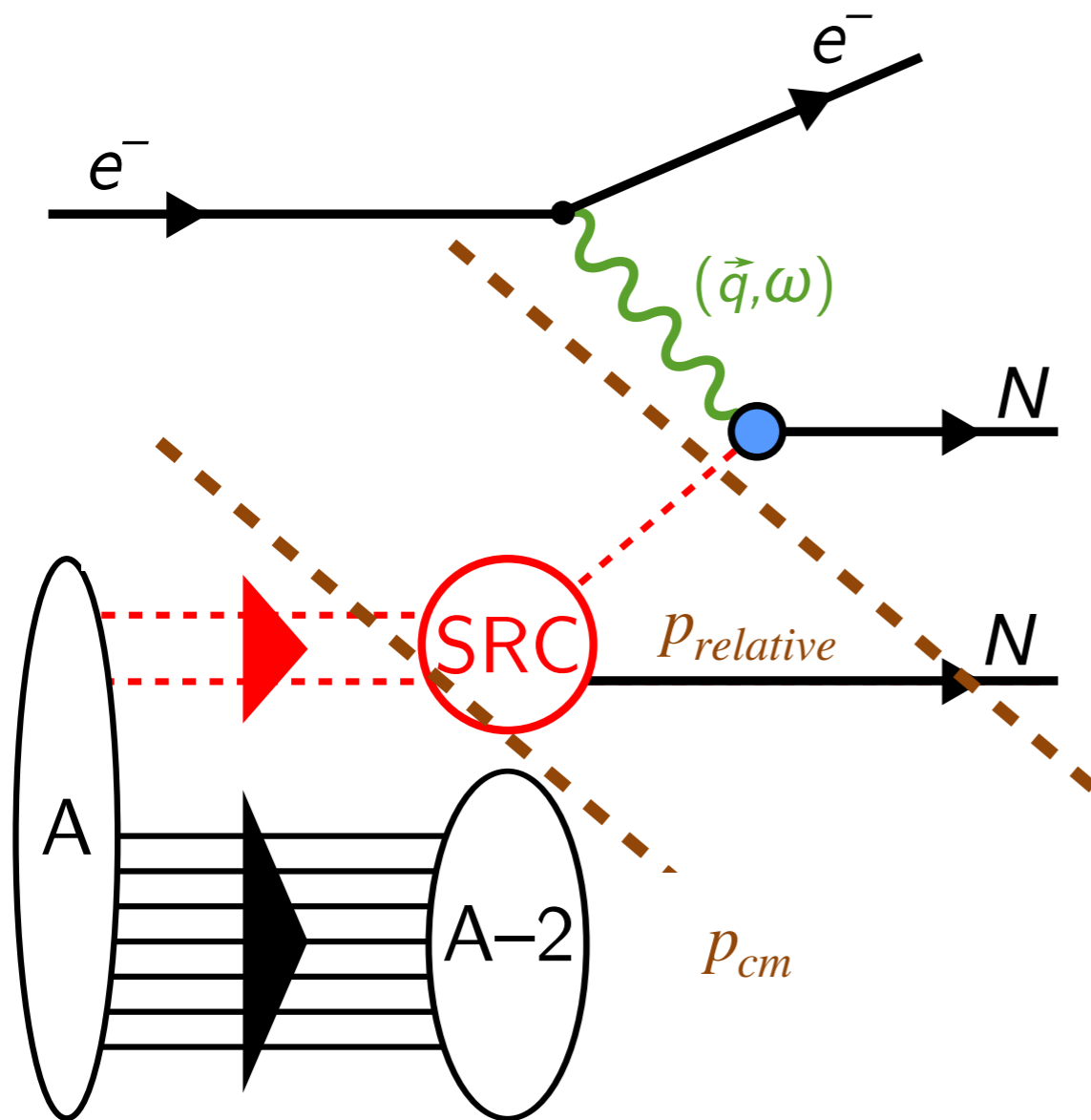


SRC Theory: Generalized Contact Formalism



Weiss PRC 92 (2015), Weiss, PLB 780 (2018), Weiss, PLB 791 (2019), Cruz-Torres, Nature Physics 17, 306 (2021)

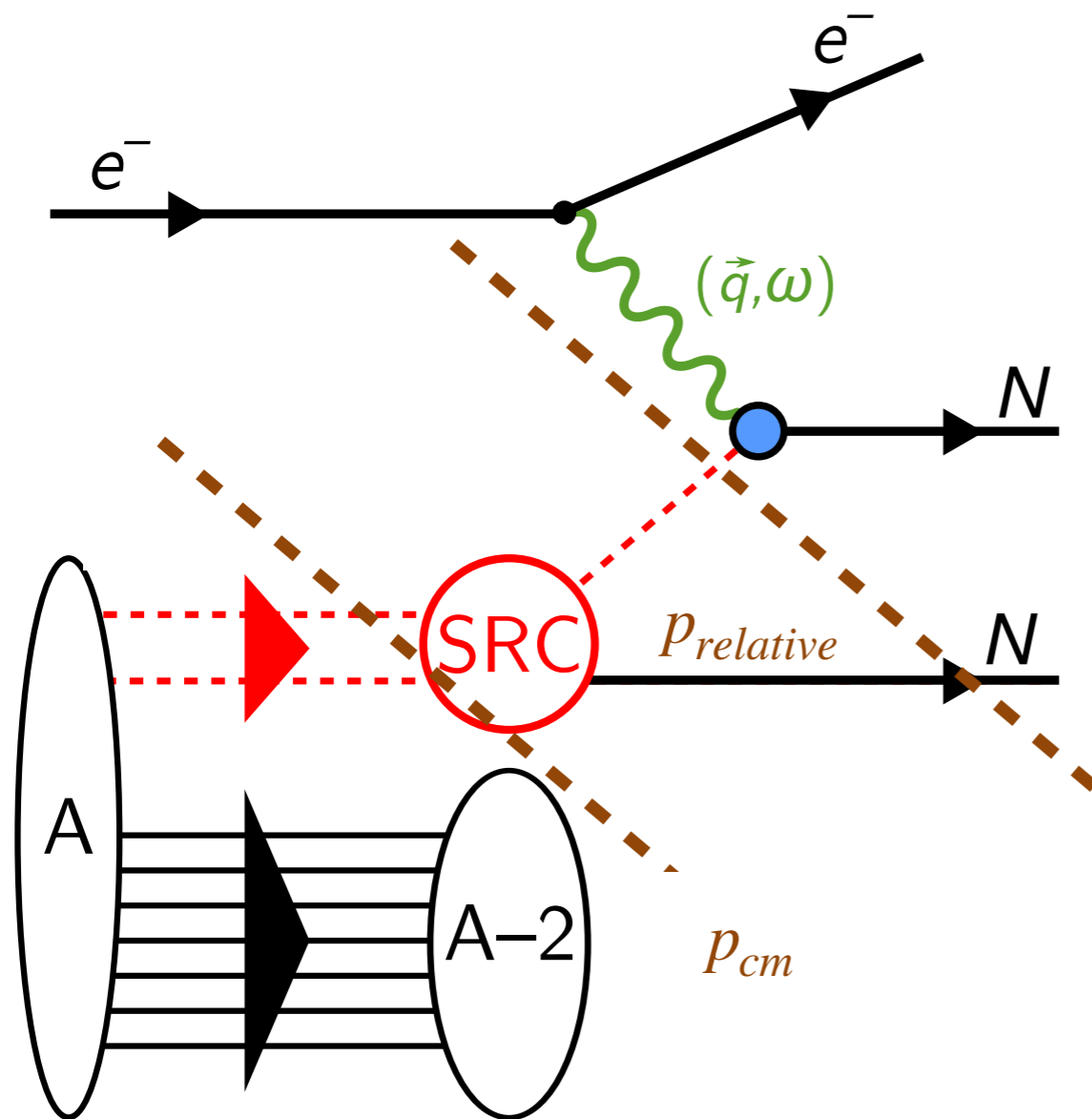
SRC Theory: Generalized Contact Formalism



Scale separation

$$q \gg p_{rel} \gg p_{cm}$$

SRC Theory: Generalized Contact Formalism



Scale separation

$$q \gg p_{rel} \gg p_{cm}$$



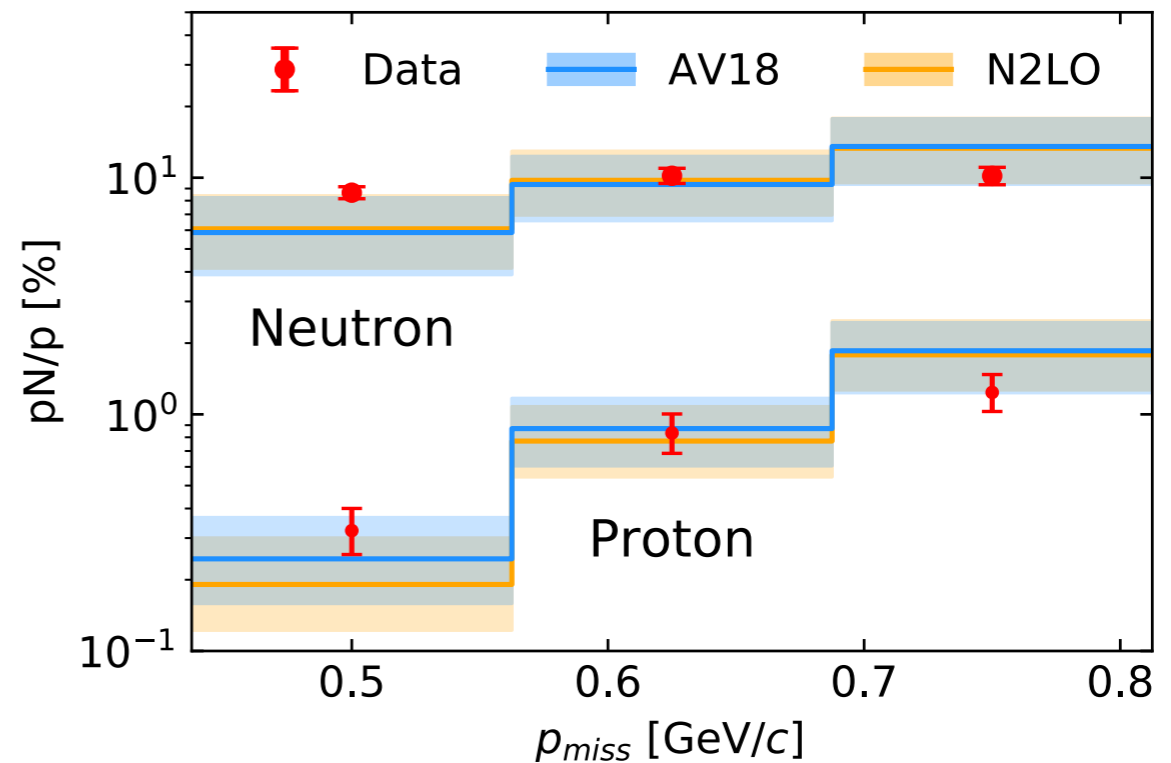
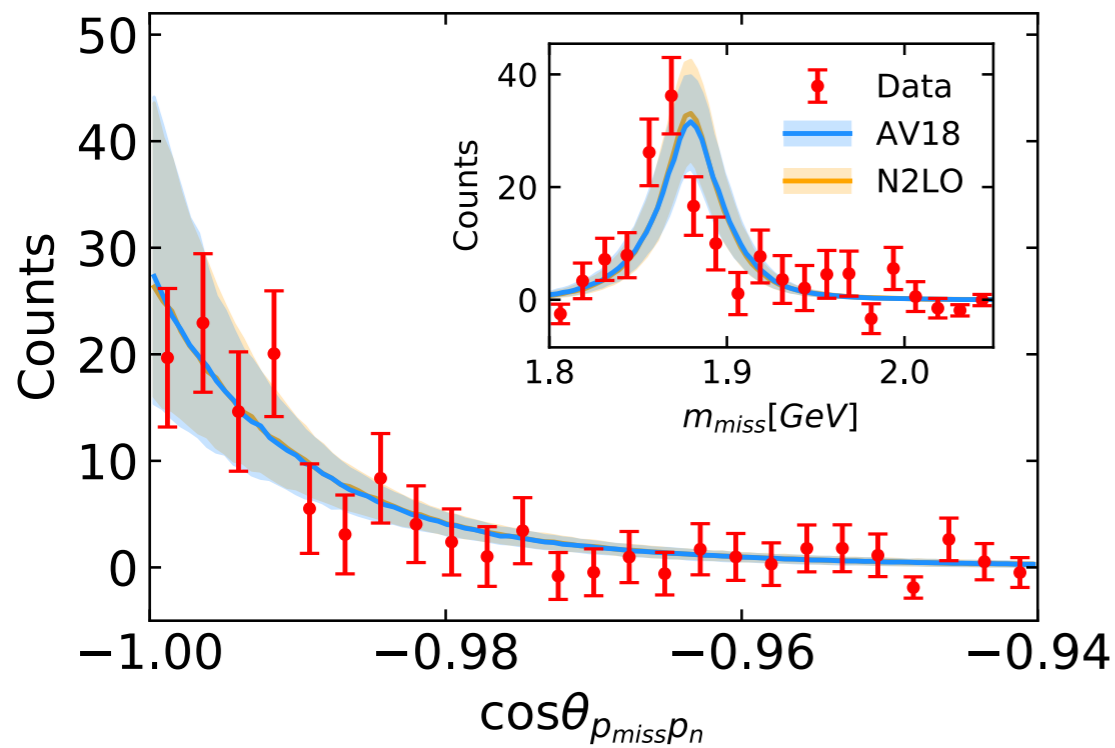
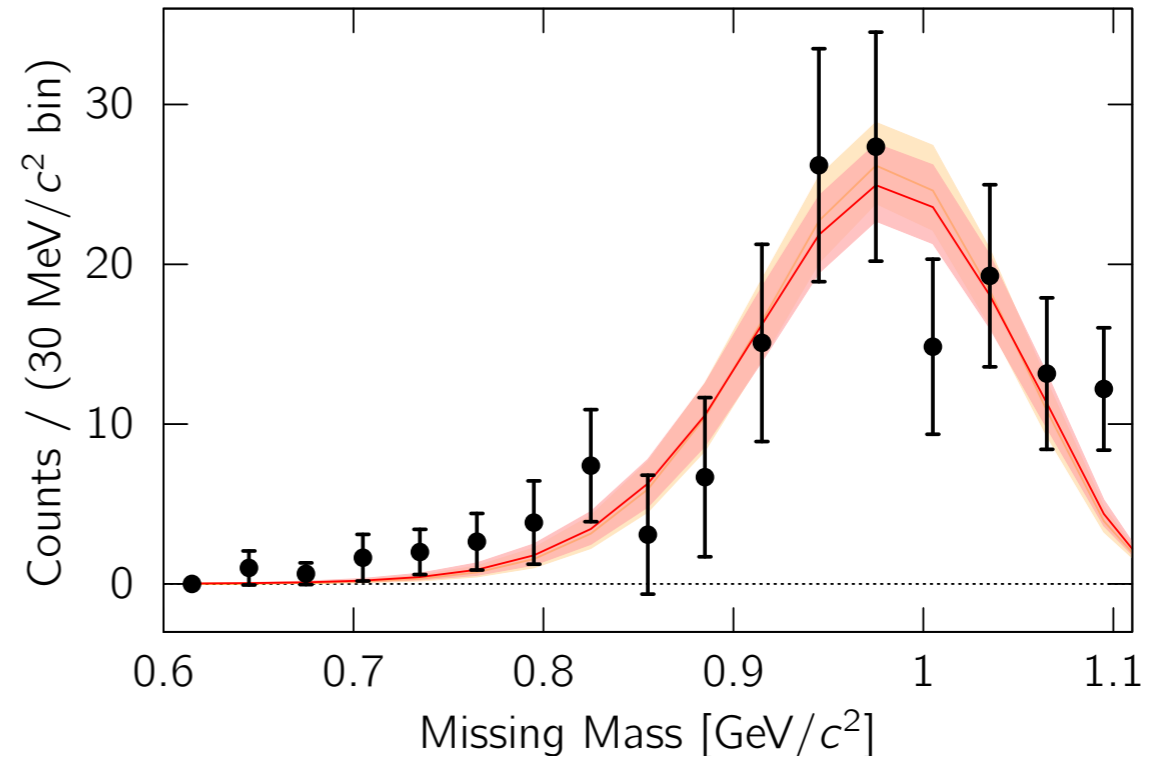
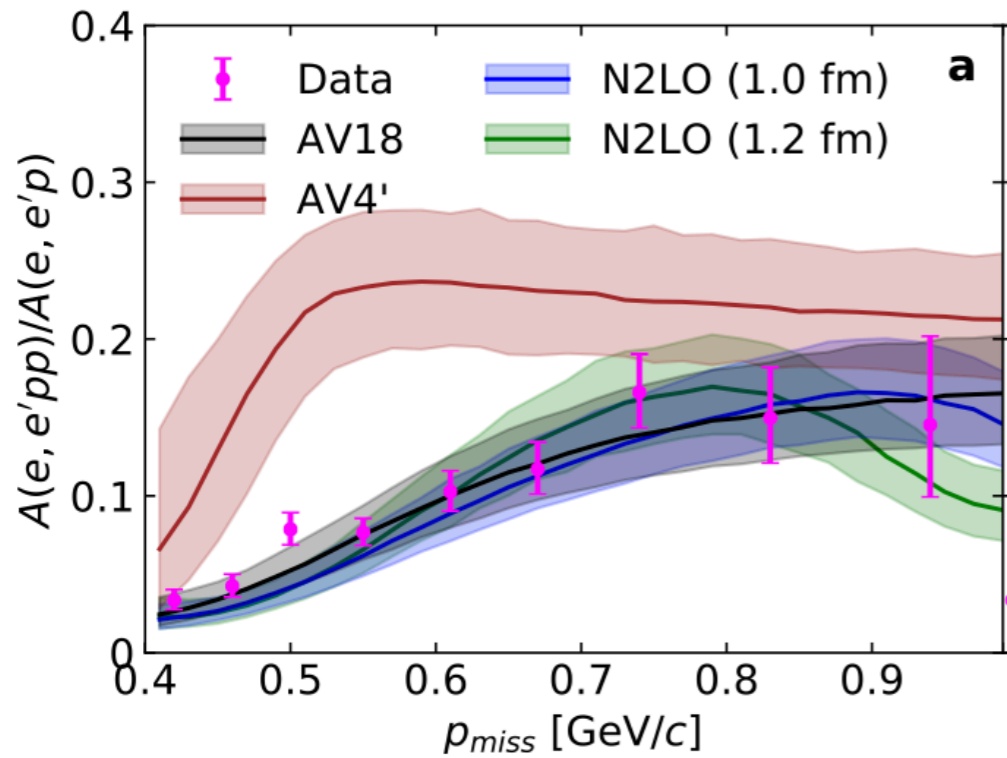
Factorization of many-body wave function



$$\sigma = \sigma_{eN}(q) \sum_{NN} |\phi(p_{relative})|^2 C_A^{NN} n(p_{cm})$$

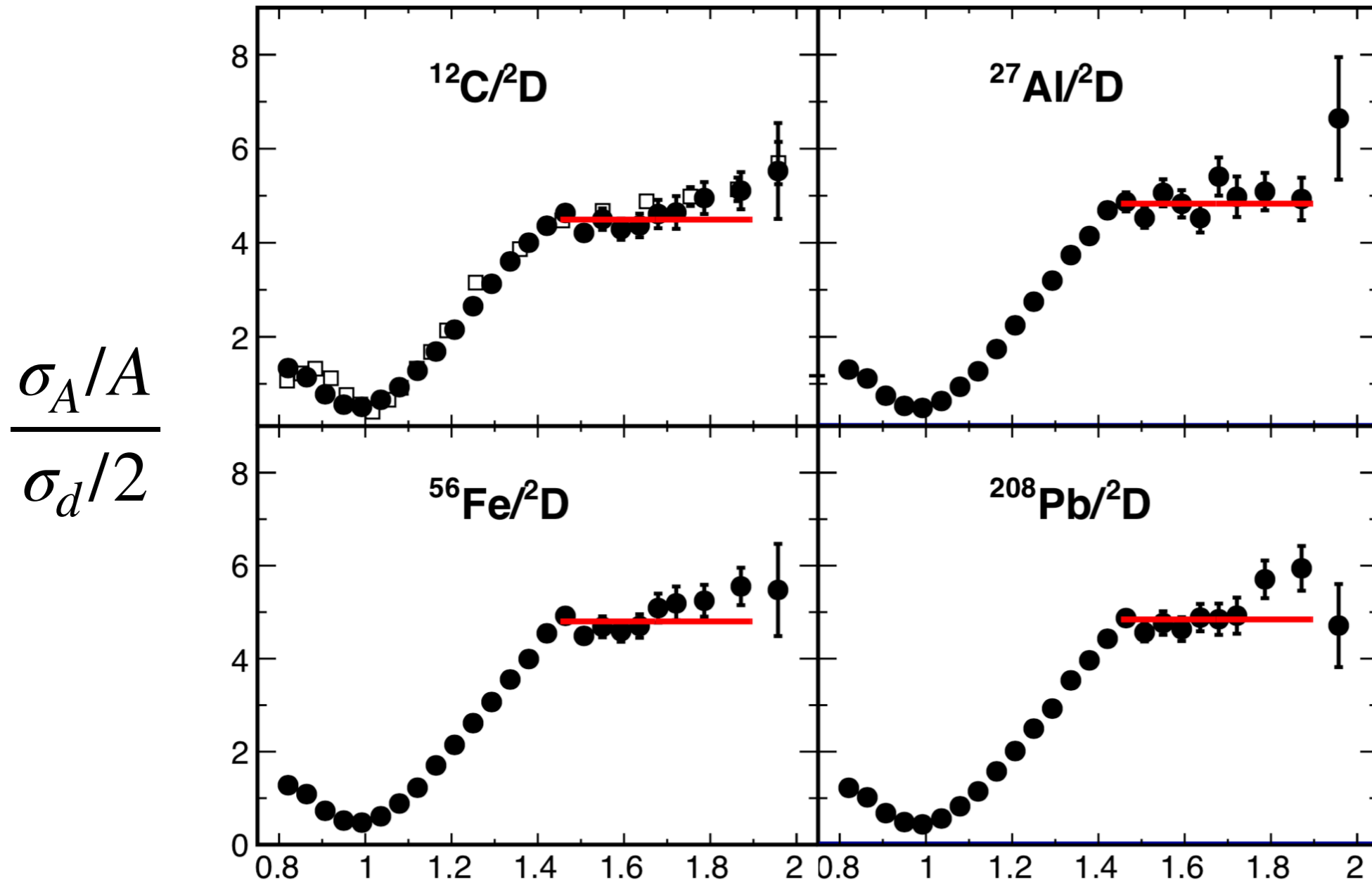
Generalized Contact Formalism works very well

Schmidt, Nature 578, 540544 (2020), Korover, PLB 820, 136523 (2021), Pybus, PLB 805, 135429 (2020)



Open Questions from Inclusive Measurements

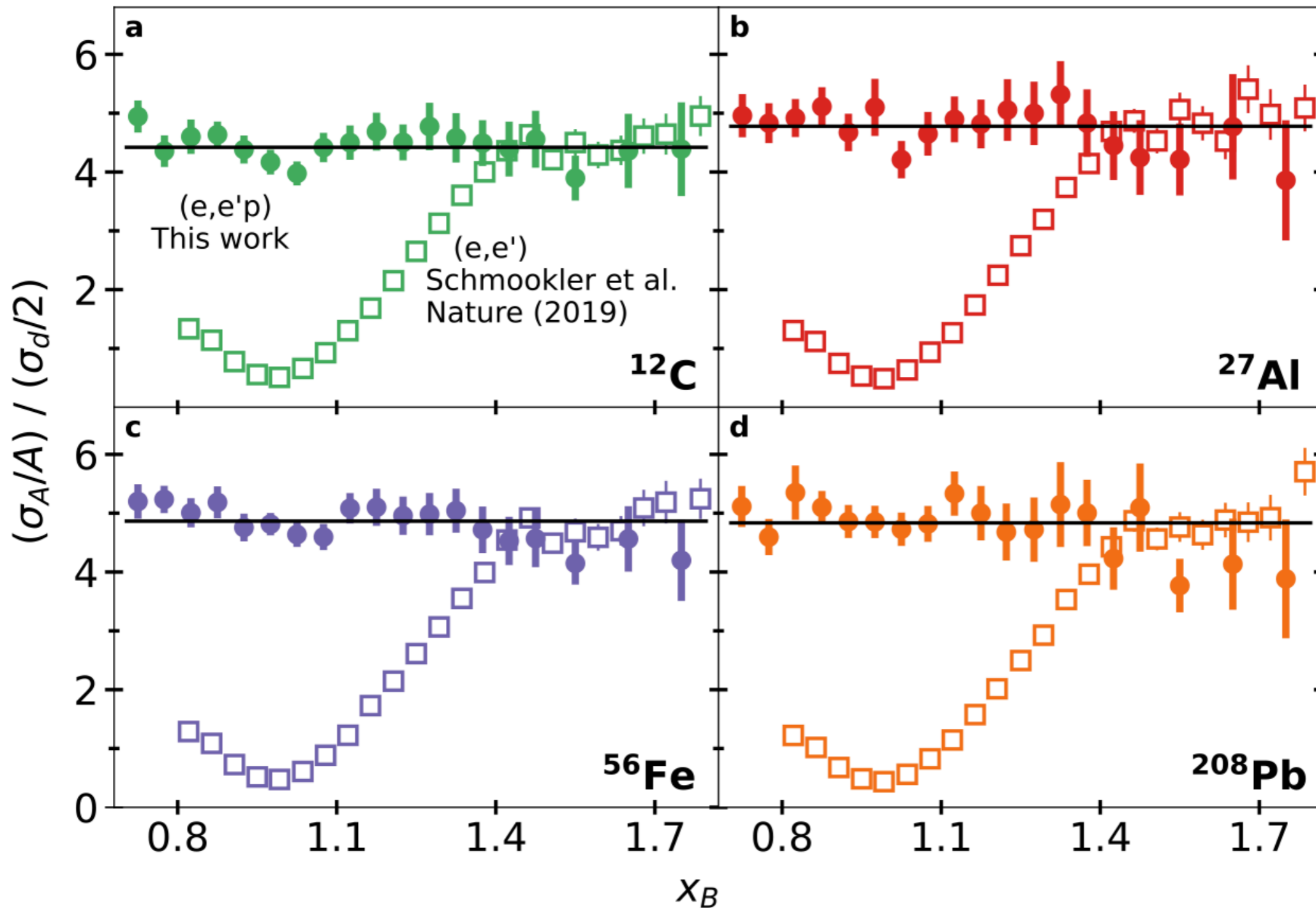
B. Schmookler et al., Nature (2019)



$$x_B = \frac{Q^2}{2m_n\omega}$$

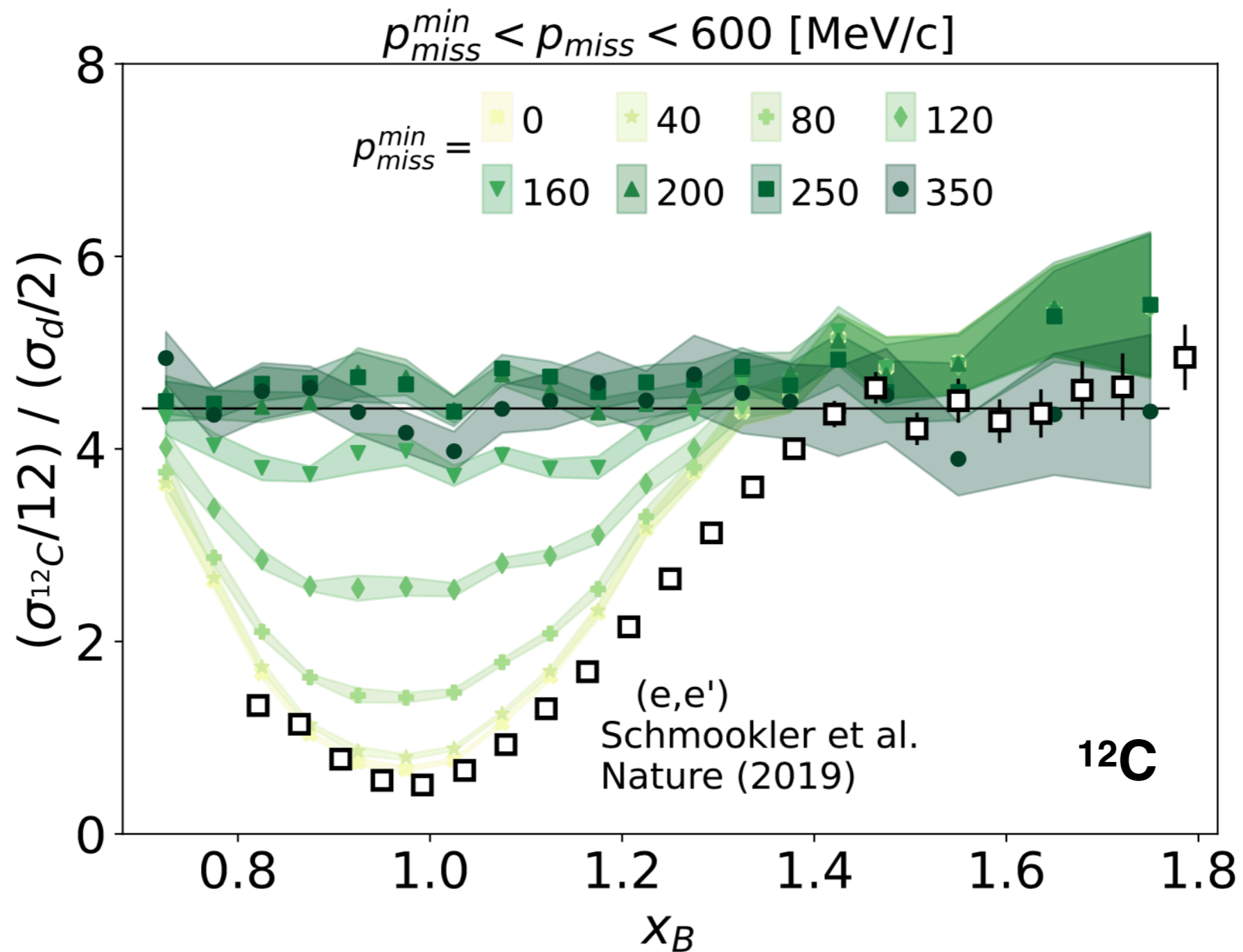
Consistent Scaling in Inclusive and Exclusive

Korover (CLAS), PRC 107, L061301 (2023)



Consistent Scaling in Inclusive and Exclusive

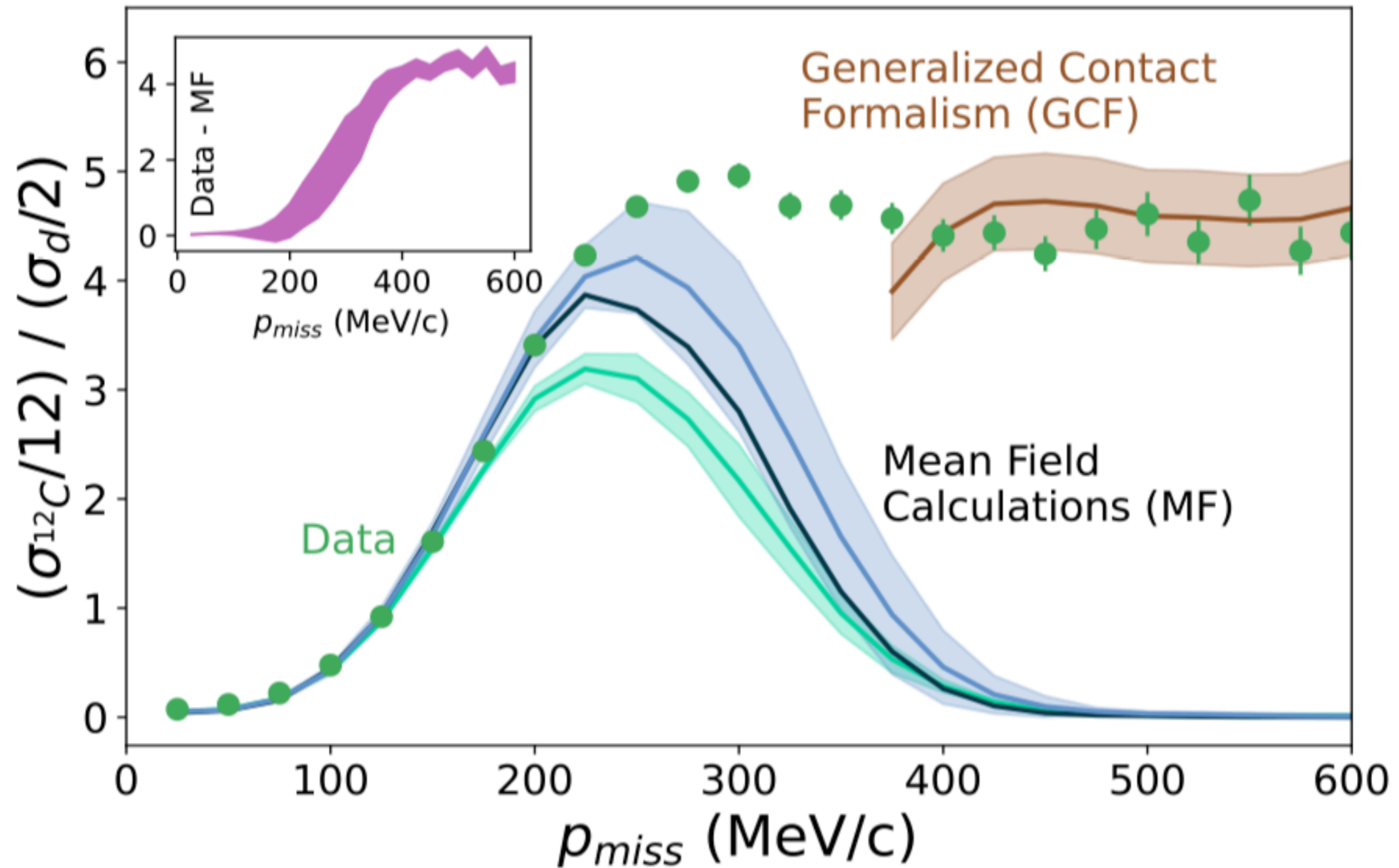
Korover (CLAS), PRC 107, L061301 (2023)



- Scaling for minimum p_{miss} above Fermi momentum

First Time Study of Transition from Mean-field to SRC Domain

Korover (CLAS), PRC 107, L061301 (2023)



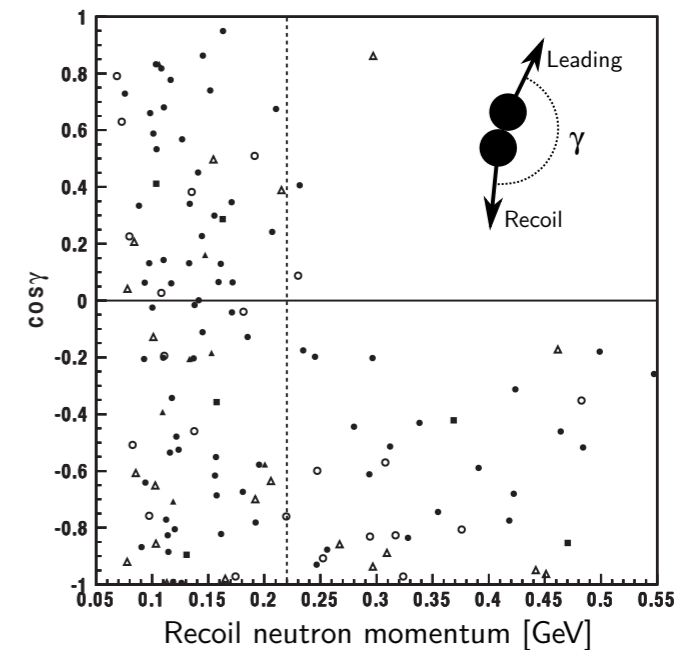
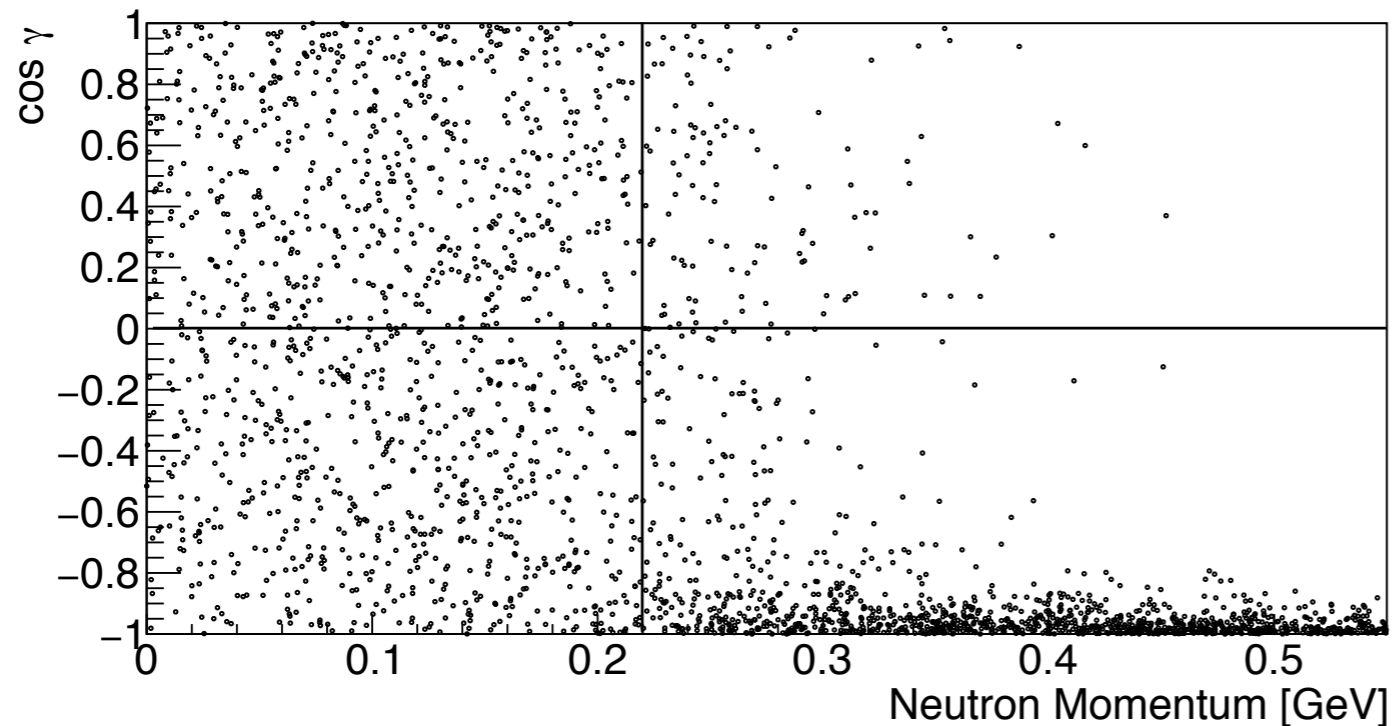
- Residual mean-field contributions above k_F

Summary

- Various exclusive measurements
- What we learned:
 - np-dominance of SRC pairs
 - probing of NN interaction
 - SRC center of mass motion
 - transition from mean-field to SRC domain
 - universality of SRCs (see Justin's talk)
- Theoretical approach - Generalized Contact Formalism
 - Factorization of wave function
 - Works very well to describe and predict data

What Comes Next

- High-statistics data on various nuclei with CLAS12 (see Justin's talk)
 - x100 more than CLAS
 - measurement of nn pairs possible
- Studies of pairing with CaFe in Hall-C (see Carlos' talk)
- Photon probes (see Justin's talk)
- Inverse kinematic measurements (see Thursday - Julian Kahlbow)
- Jlab Proposal this year for CLAS12+ALERT detector: Full exclusive SRC study with ${}^4\text{He}(e,e'pds)n$



- Tagged SRC at EIC (Z. Tu et al., PLB 811 (2020), Hauenstein et al, PRC 105 (2022))

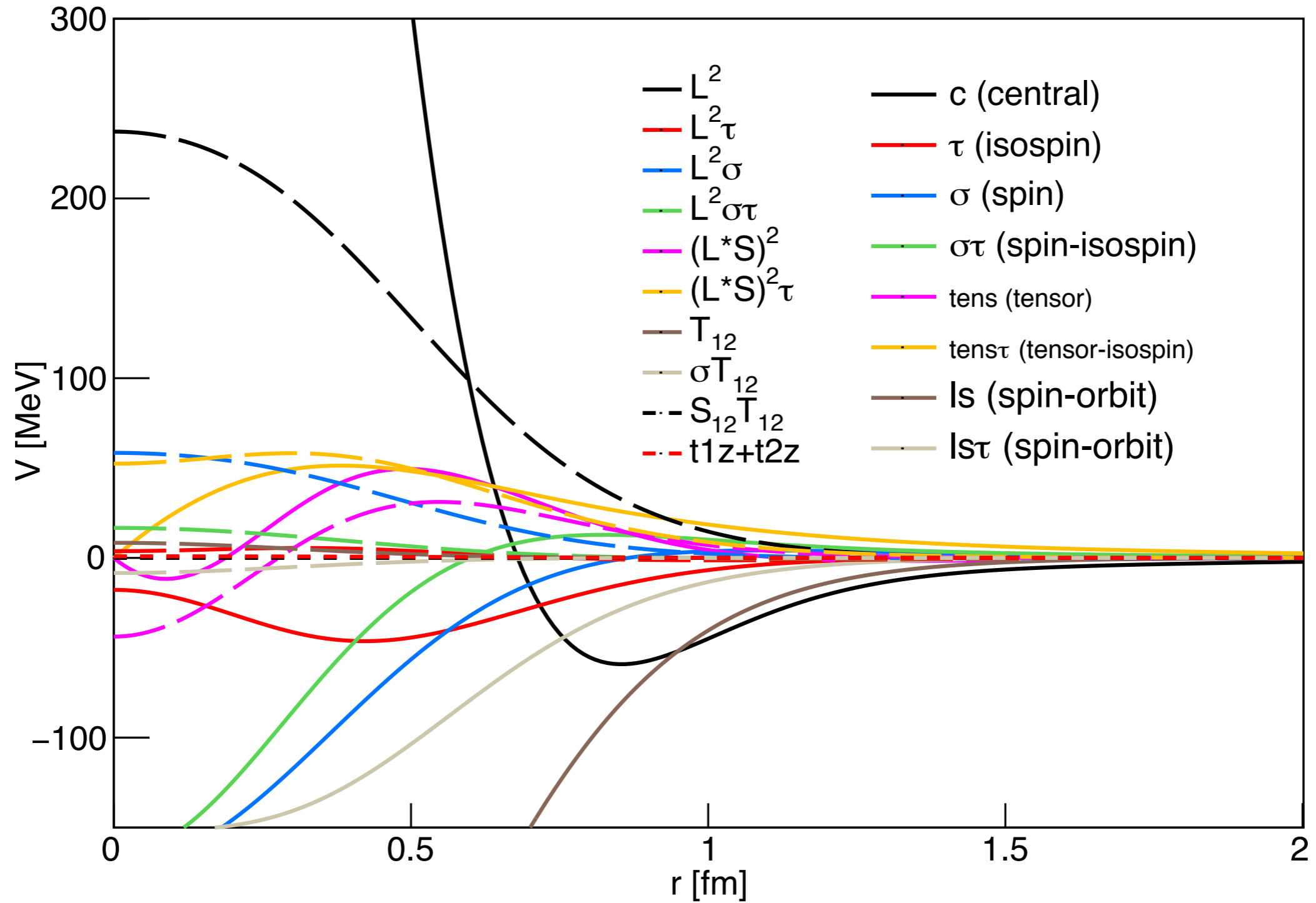
Apologies if I forgot someone or something important.

**Thank you to everyone who conducted and analysed all
this exclusive SRC measurement**

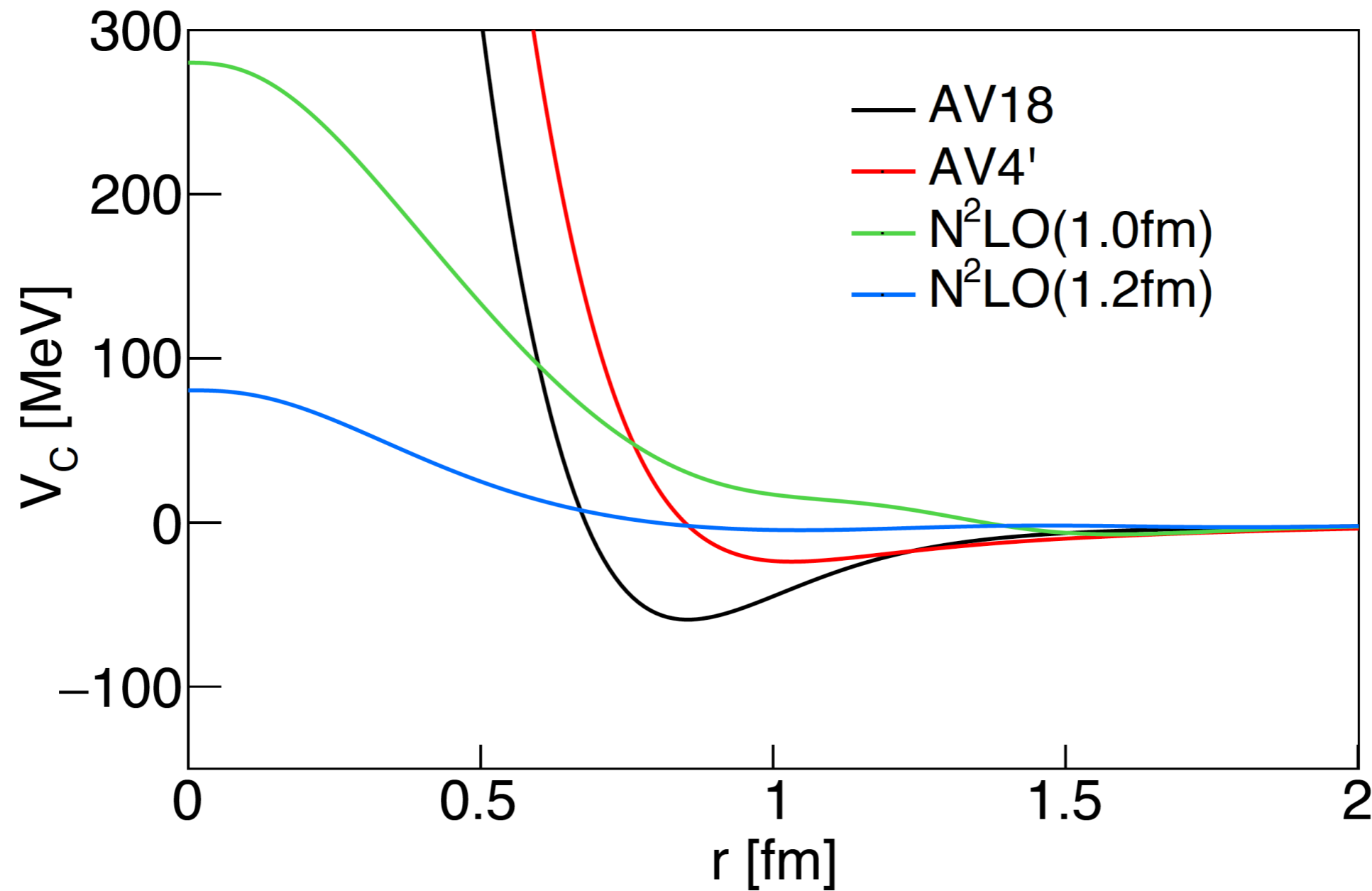
Questions?

Backup slides

AV18 potential



Scalar part of NN potentials

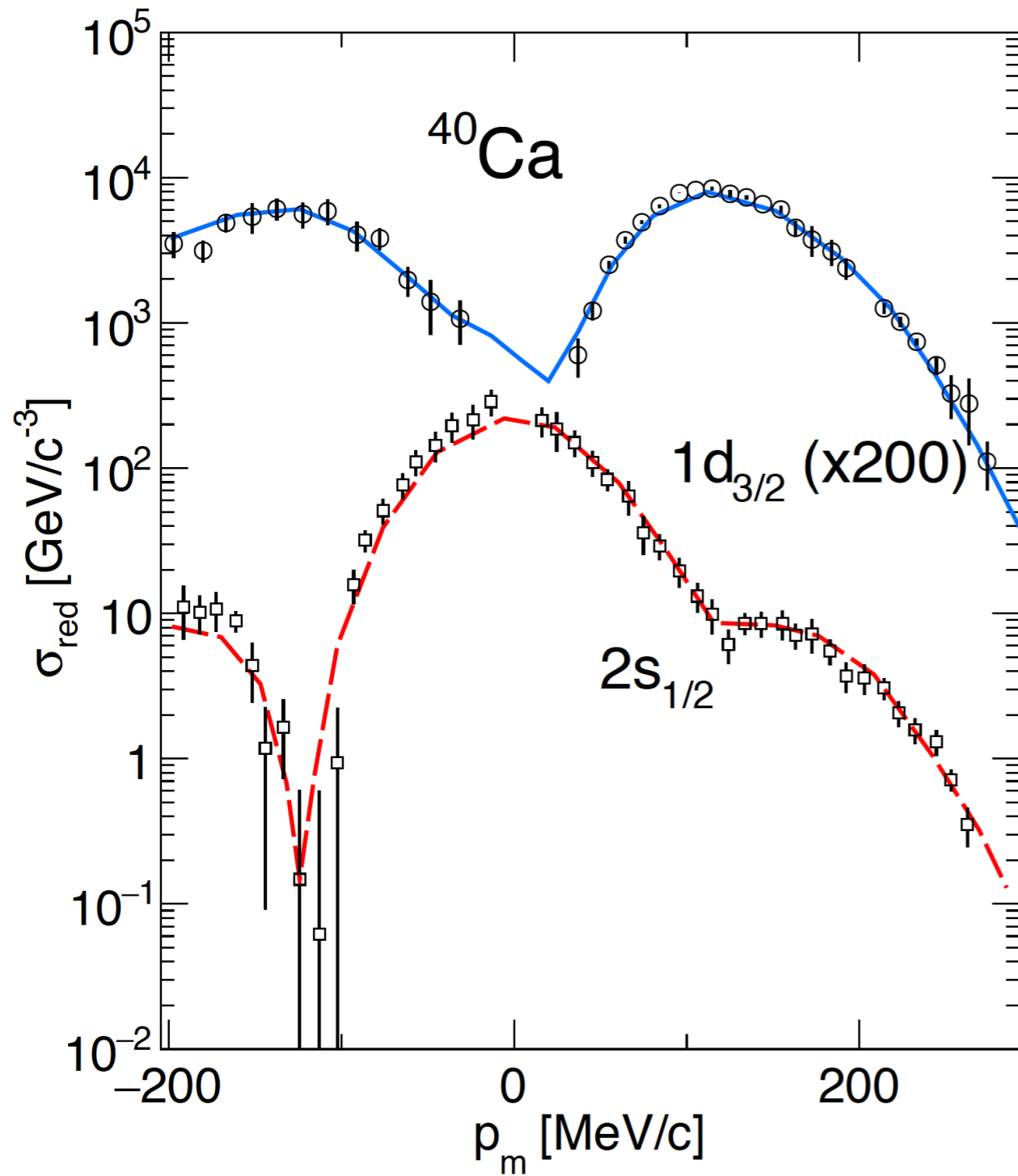


Short-range
Repulsive core



$r \rightarrow \infty$
 $V \rightarrow 0$

(e,e'p) scattering off nucleon shells

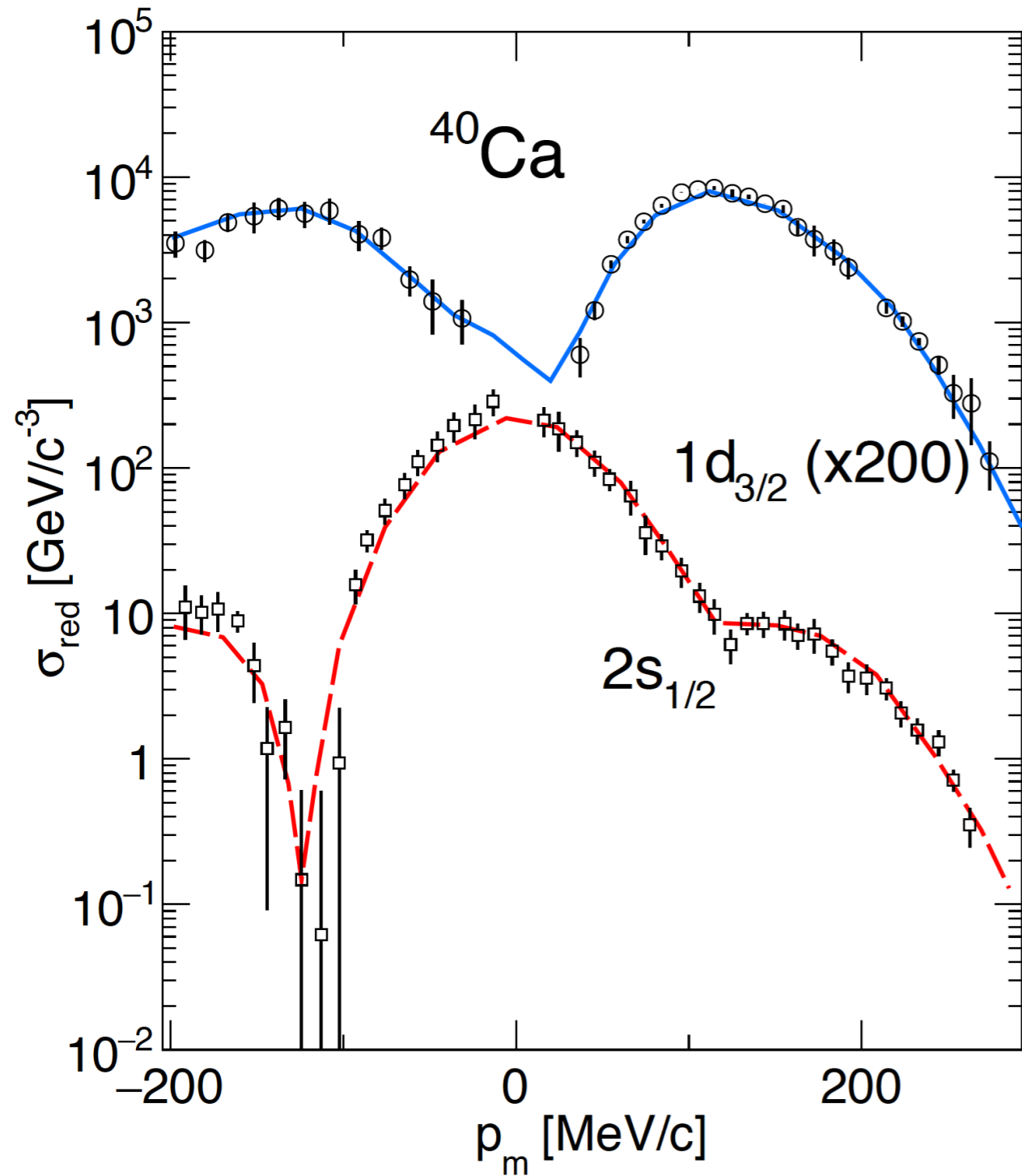


Model comparison

- shape well described
- **but: normalization**

L. Lapikas, Nuclear Phys. A553, 297c (1993)

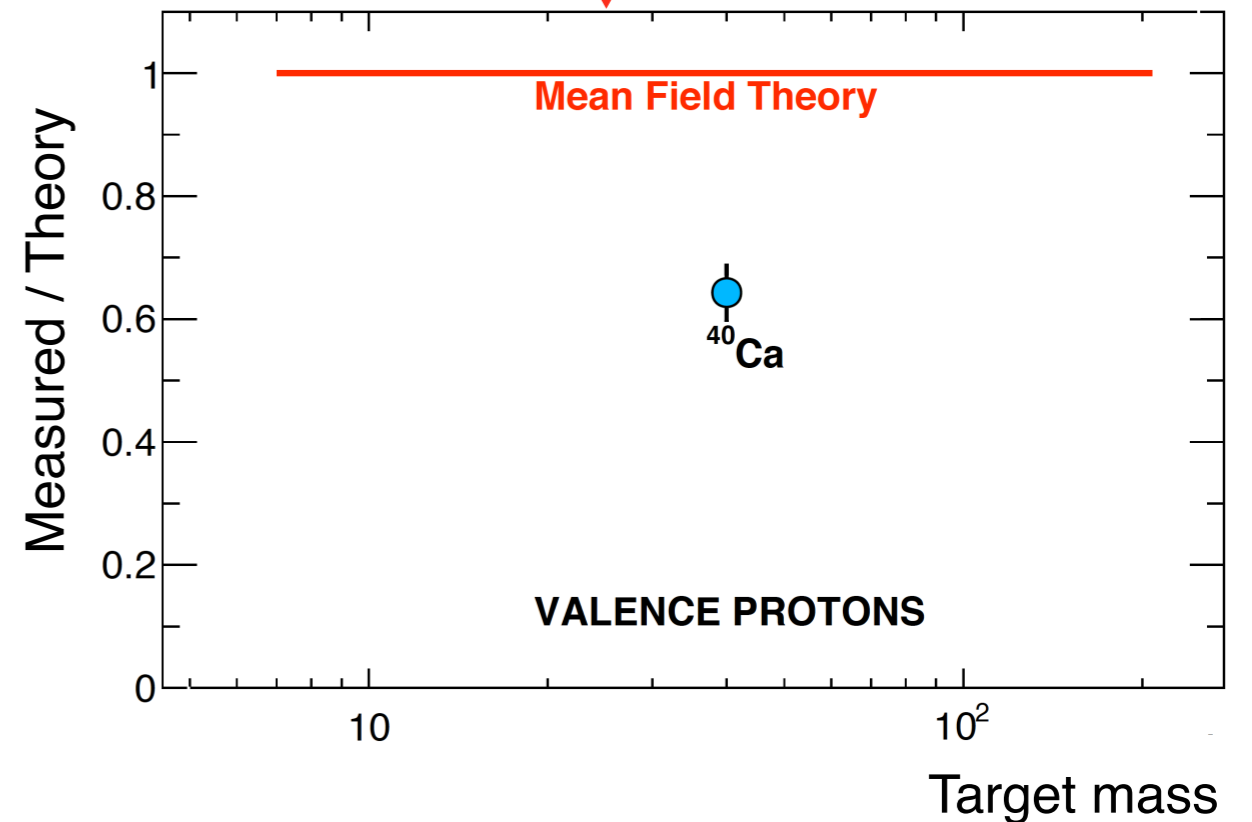
(e,e'p) scattering off nucleon shells



L. Lapikas, Nuclear Phys. A553, 297c (1993)

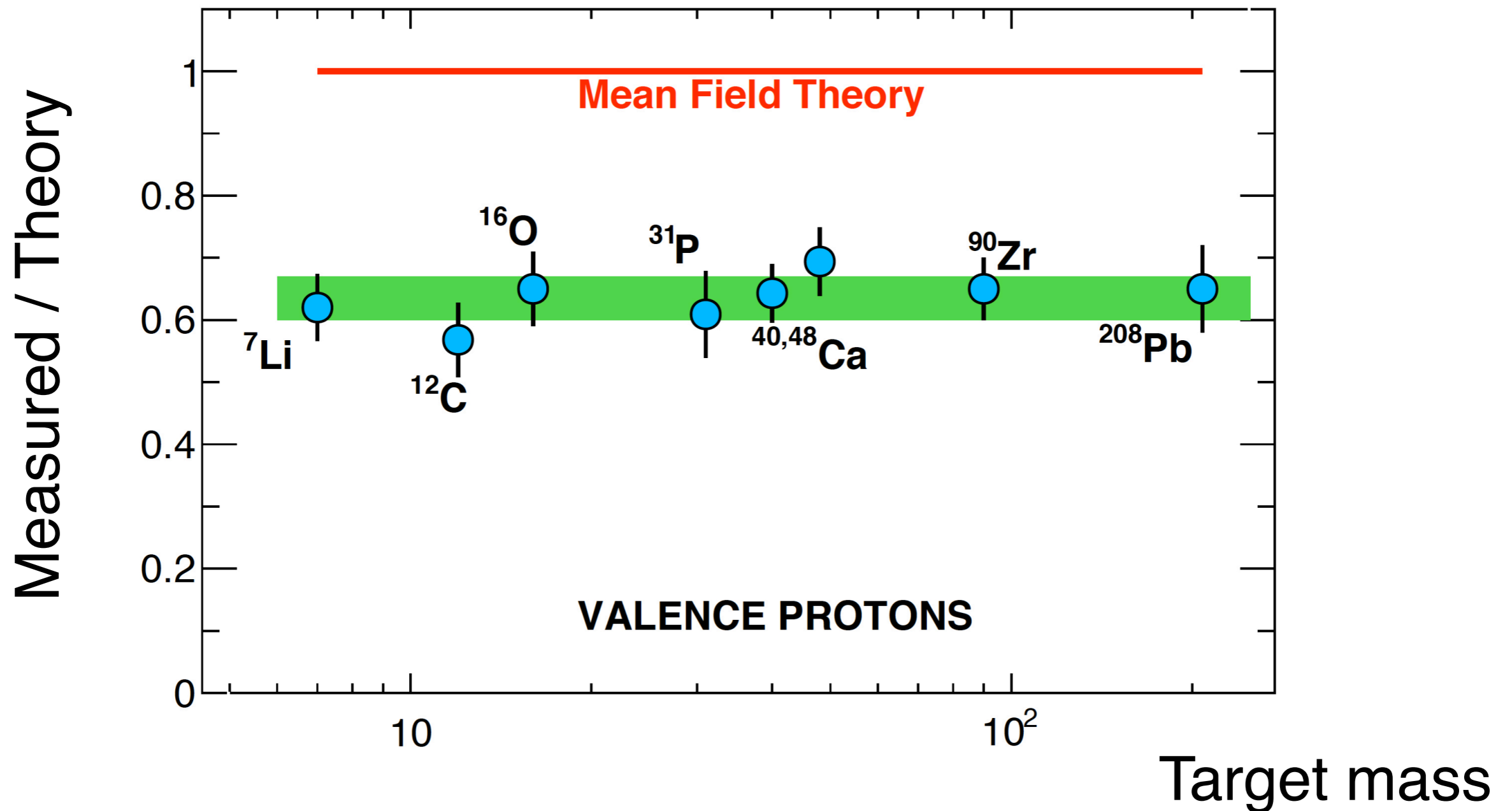
Model comparison

- shape well described
- **but: normalization**



Something is missing

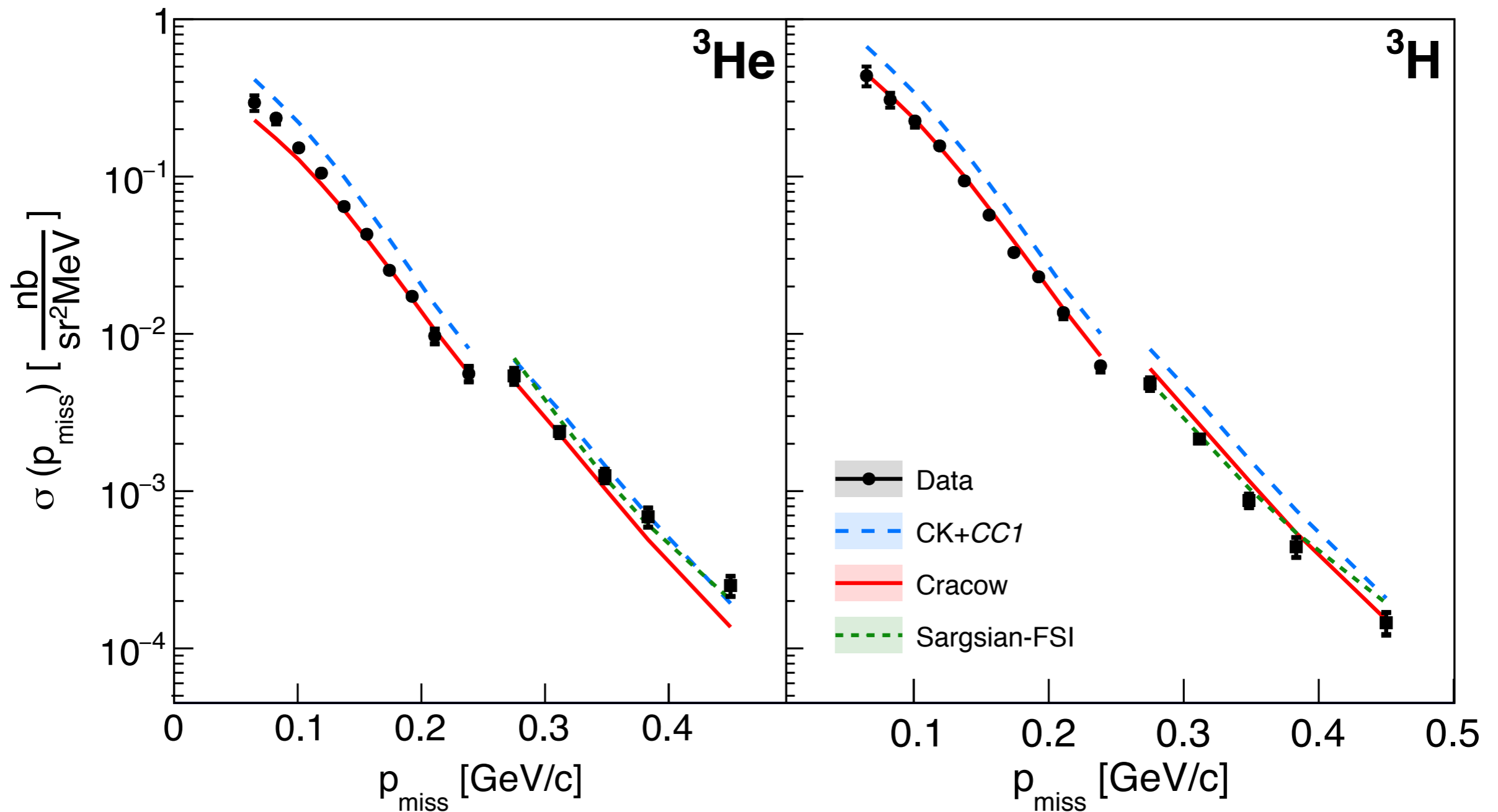
L. Lapikas, Nuclear Phys. A553, 297c (1993)



—> Mean-field not sufficient —> NN potentials

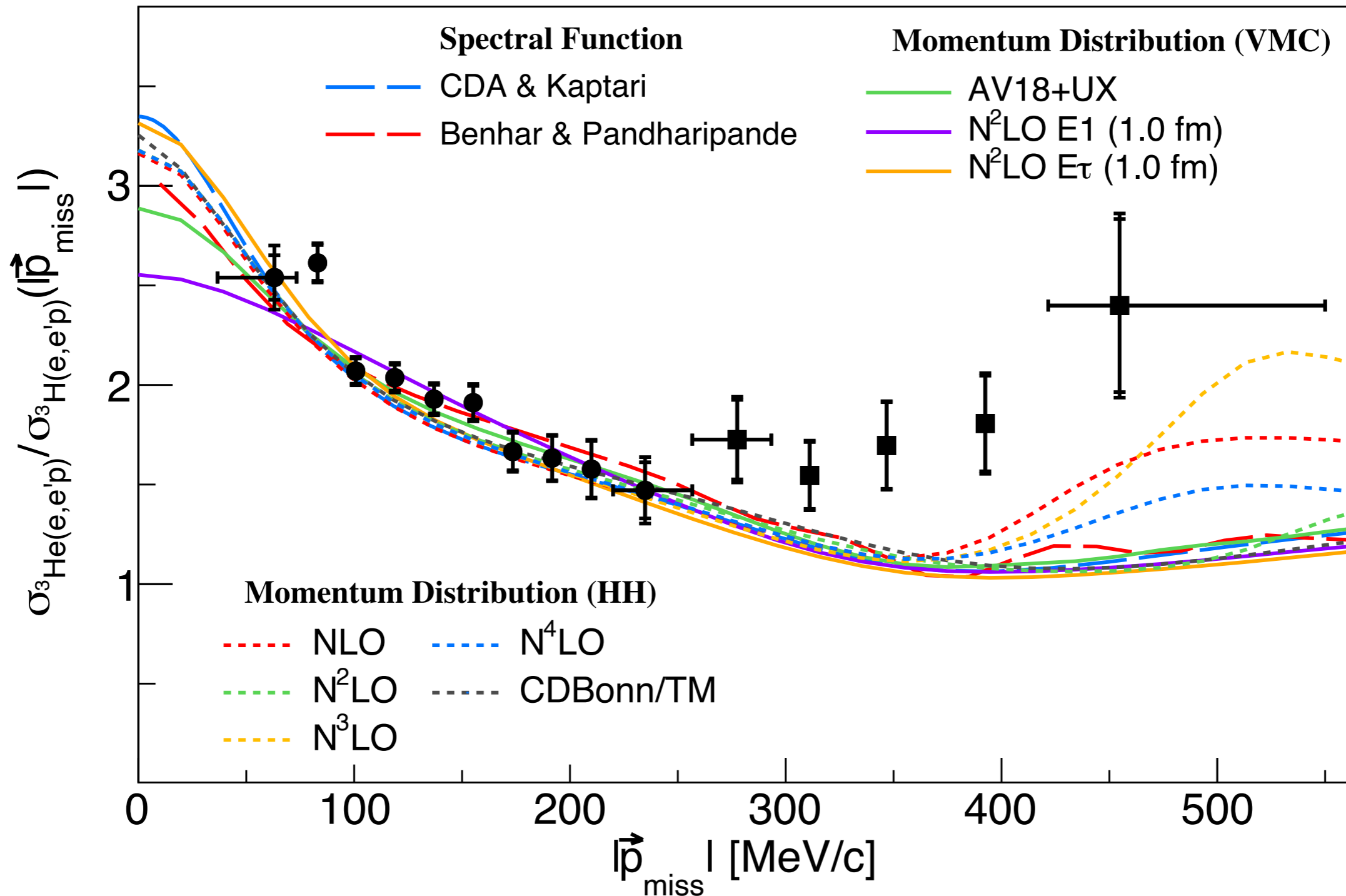
^3He and ^3H Total Cross Sections

Cruz-Torres, Nguyen, **Hauenstein** et al, PRL124, 212501 (2020)



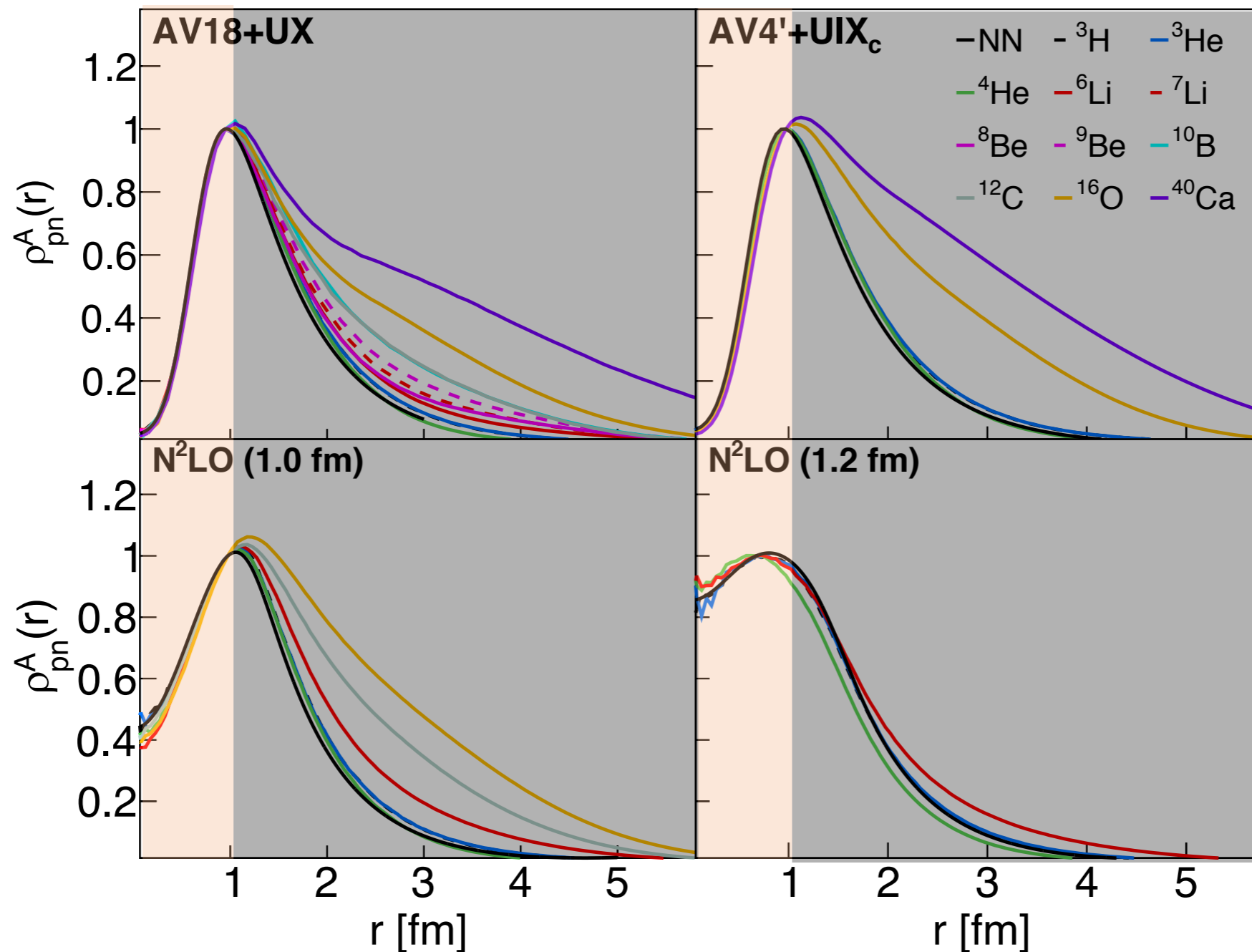
Results

Cruz-Torres et al. (HallA Tritium collaboration), Phys. Lett. B 797, 134890 (2019)



SRC pair distribution r-space

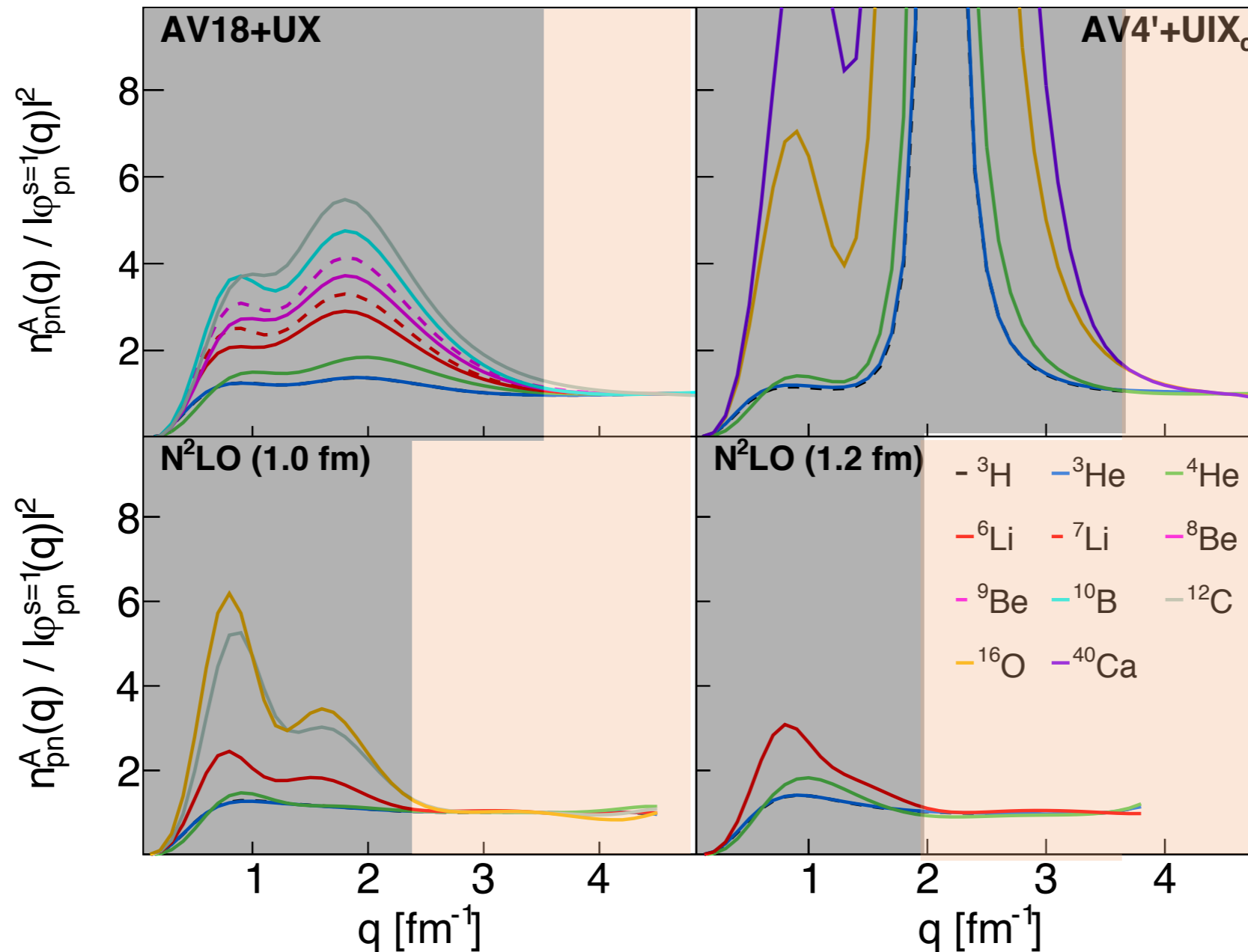
R. Cruz-Torres et al., arXiv:1907.03658 (2019)



$$\rho_A^{NN,\alpha}(r) = C_A^{NN,\alpha} \times |\varphi_{NN}^\alpha(r)|^2 \quad \longrightarrow \text{Contact Formalism}$$

SRC pair distribution k-space

R. Cruz-Torres et al., arXiv:1907.03658 (2019)



$$n_A^{NN,\alpha}(q) = C_A^{NN,\alpha} \times |\varphi_{NN}^\alpha(q)|^2 \quad \longrightarrow \text{Contact Formalism}$$