Long Range Outlook for Short-Range Correlations

N. Fomin, O. Hen, J. Kahlbow, D. Nguyen, J. Pybus, N. Rocco, M. Sargsian, **S. N. Santiesteban**, R. Weiss, D. W. Higinbotham, L. Weinstein

Program Advisory Committee (PAC) 53
July 23, 2025

Making the Case for Jefferson Lab

9.3. Two-body correlations in nuclei

The very simplest theoretical picture of a large nucleus treats it as a gas of non-interacting nucleons that move freely through the nuclear volume. Ironically, this overly simple picture is useful because the strong short range repulsion between nucleons keeps them apart, preventing the nucleus from collapsing, guaranteeing that many body forces (involving three or more nucleons) must be small, and clearing the way for the longer range forces to be averaged so that they can be treated as a mean field. From this point of view, any correlations between the nucleons are either a reflection of the strong short range forces, or a signal of the departure from the mean field. In either case, direct observation of correlations is extremely interesting and tells us how the NN force is modified by the nuclear medium, or whether or not there are highly correlated 6-quark states present in nuclei. While this was believed to be an important program, in 1985 it was thought that correlations might show up as the knockout of a pair of nucleons, such as might emerge from a 6-quark bag as suggested by the right-most cartoon in Fig. 2.

What happened? The observations of correlations is one of the most exciting developments to emerge from the Jefferson Lab program but the "best" observation of correlations did not involve a coincidence experiment at all! This was an "inclusive" measurement in which *only* the scattered electron was observed. As shown in Fig. 4, for large Q^2 this cross section depends only on the scaling variable x, and it is easy to show that scattering from a single, free nucleon is possible only if $x \leq 1$. The most direct way to see correlations is therefore to look at processes in which $x > 1$. Under this condition, scattering is *impossible* unless the nucleon is bound in the nucleus. The ratio of the scattering cross section from different nuclei for $x > 1$ will therefore depend in part on the size of the two-body correlations in these nuclei (and, by extension, the ratios for $x > n - 1$ depend on n-body correlations). This fact was predicted before 1985, but sufficiently precise data were unavailable and the accurate observations at Jefferson Lab have opened up this area of study.

As anticipated in 1985, correlations have also been observed in one and two nucleon knock-out experiments. The recent observation of the large ratio of np to pp pairs seen in knockout from ^{12}C can be explained by the dominant role of the tensor part of the NN force.

The Science Driving the 12 GeV Upgrade OF CEBAF

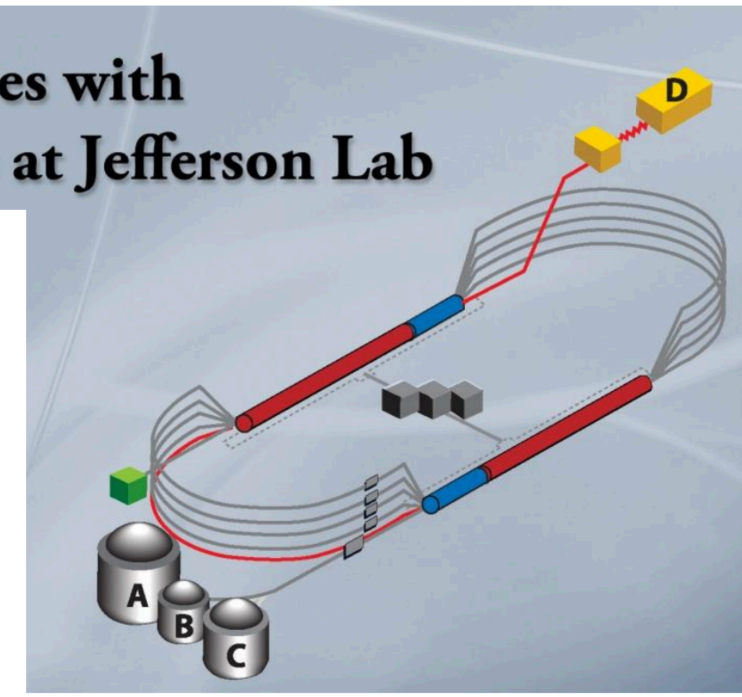
2.D.2 Probing the Limits of the Standard Model of Nuclear Physics: Short-Range Correlations in Nuclei

2001

Observing short-range correlations (SRC) in nuclei has been an important goal of experimental nuclear physics for decades [Be99, Be67]. Not that these correlations are small – calculations of nuclear wavefunctions with realistic NN potentials consistently indicate that in heavy enough nuclei about 25% of the nucleons have momenta above the Fermi surface [Pa97]. This corresponds to about 50% of the kinetic energy being due to SRC. The experimental problem has been the unavailability of the high-momentum-transfer kinematics that could discriminate decisively between the effects of SRC in the initial- and final-state interactions. Though the final-state interactions in nucleon knockout do not disappear at large Q^2, two important simplifications occur which make extraction of the information about the short-range nuclear structure possible. First, in high-energy kinematics a "hidden" conservation law exists – the light-cone momentum fractions of slow nucleons do not change if the ejected nucleon elastically scatters off slow nucleons [Fr97]. Second, the rescatterings of a high-energy nucleon can be described by the generalized Glauber approximation, which takes into account a difference in the space-time picture of proton-nucleus scattering (a proton coming from $-\infty$) and the $A(e, e'p)$ process (a proton is produced inside the nucleus) and also accounts for the nonzero Fermi momenta of rescattered nucleons [Fr97].

Exploring short-range correlations lies at the heart of the physics program at Jefferson Lab

Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab



Recent phenomenological comparisons [4-4] (see ***Figure 4.2***) show that the strength of the EMC effect in different nuclei is linearly related to the short range correlations scale factor, $a_2(A/d)$. This linear relation indicates, but does not prove, that the EMC effect is caused by *local* modifications of nucleon structure occurring when two would-be nucleons make a close encounter and briefly comprise a system of density high enough to be comparable to that of neutron stars. This relationship will be tested and refined at 12 GeV by a series of EMC and SRC experiments covering a wide range of nuclei [4-19, 4-20, 4-24, 4-25]. The deuteron experiment mentioned above [4-18] will increase our understanding of the two-nucleon system that we use as a baseline for both the EMC and SRC measurements.

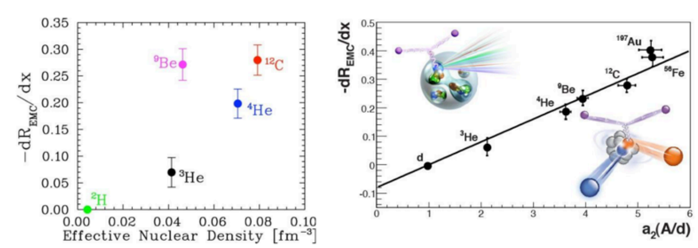


***Figure 4.2:** (left) The strength of the EMC effect (the EMC slope) plotted versus the average nuclear density [4-1]. (right) The strength of the EMC effect plotted versus the SRC scale factors [4-4]. The drawing in the upper left shows deep inelastic electron scattering from a quark in a nucleon. The drawing in the lower right shows electron scattering from a correlated NN pair. (Figure credit: Anna Shneor).*

5.1.2. Short range NN correlations

While mapping out the high missing momentum (P_m) part of the spectral function presents challenges, it is still possible to study SRCs by selecting kinematics where the reaction is dominated by SRC contributions. Nucleons with momenta well above the Fermi momentum are associated with SRCs that are generated by the hard, short-range components of the NN interaction [259, 260, 252, 249, 251, 261]. Because they are generated by two-body interactions, they have a universal structure that comes from the NN interaction, and scattering measurements in kinematics dominated by SRCs allow for studies of the nature and size of SRCs in nuclei. Inclusive scattering at modest Q^2 and $x > 1.4$, where scattering from low-momentum nucleons is kinematically forbidden, provides sensitivity to the relative contribution of SRCs as a function of the mass number A via measurements of the inclusive $A/^2$H cross section ratios. During 6 GeV running, experiments confirmed the initial observation of SRCs [262] and mapped out the A dependence of SRCs in light and heavy nuclei [263, 264]. These data demonstrated that the contribution is sensitive to details of the nuclear structure [265, 266] rather than the previously assumed average nuclear density [267]. In addition, they showed a clear correlation between the contribution of SRCs [264] and the size of the EMC effect [265], discussed further in Sec. 5.3. Measurements of two-nucleon knockout, where both nucleons from the SRC are observed in the final state, showed dominance of np-SRC as well as a dependence of the np/pp SRC ratio as a function of the struck nucleon's momentum (shown in Figure 16. The dominance of np-SRCs was confirmed in additional nuclei using the $A(e, e'p)$ [268] reaction and later through inclusive measurements taking advantage of the *target* isospin structure in measurements of the ^{48}Ca/^{40}Ca cross section ratio [269]. Finally, measurements at $x > 2$ tried to establish the presence of three-nucleon SRCs (3N-SRCs), but low-Q^2 measurements did not observe 3N-SRC dominance [270], while higher-Q^2 data was consistent with 3N-SRC dominance but had extremely limited statistics [264].

Short-Range Correlations (SRCs) at Jefferson Lab

1989	4 GeV Inclusive Scattering Ratios
2002	6 GeV Inclusive Studies in $^{3}He/^{4}He$
2004	CLAS A(e,e'*pp*)/(e,e'pn)
E08-014	6 GeV Inclusive A(e,e) at $x > 1$
E12-06-105	E12-06-105 12 GeV Inclusive A(e,e') at $x > 1$
E12-10-003	D(e,e'*p* at High Missing Momentum
E12-11-112	Inclusive Tritium SRC
E12-11-002	Tagged D(e,e'*p*) High-p
E12-14-011	Tritium (e,e'*p*) at High Momentum
E12-11-107	Tagged SRC with ALERT + CLAS12
E12-19-003	SRC/Color Transparency in Photon-Induced Reactions

Multiple experiments

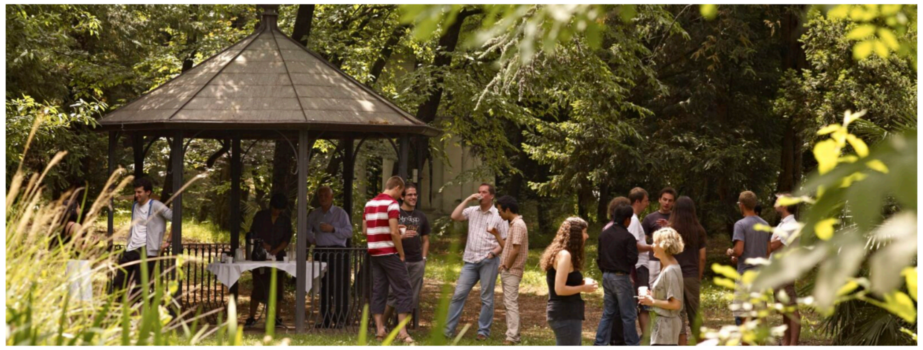
Track record of peer-reviewed experimental results

03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

- 03: Tang PRL, Egiyan PRC
- 04: Niyazov PRL
- 06: Egiyan PRL
- 07: Shneor PRL
- 08: Subedi Science
- 10: Baghdasaryan PRL
- 12: Fomin PRL
- 14: Hen Science, Korover PRL
- 15: Colle PRC
- 18: Ye PRC, Duer Nature, Cohen PRL
- 19: Schmookler Nature, Cruz PLB, Duer PRL
- 20: Schmidt Nature, Cruz PRL, Nguyen PRC
- 21: Patsyuk Nature, Korover PLB
- 22: Li Nature
- 23: Korover PRC
- 25: Li PLB

Inclusive A(e,e’)
Single Nucleon Knockout A(e,e’p|n)
Two-nucleon knock out A(e,e’NN)
Hadronic probes

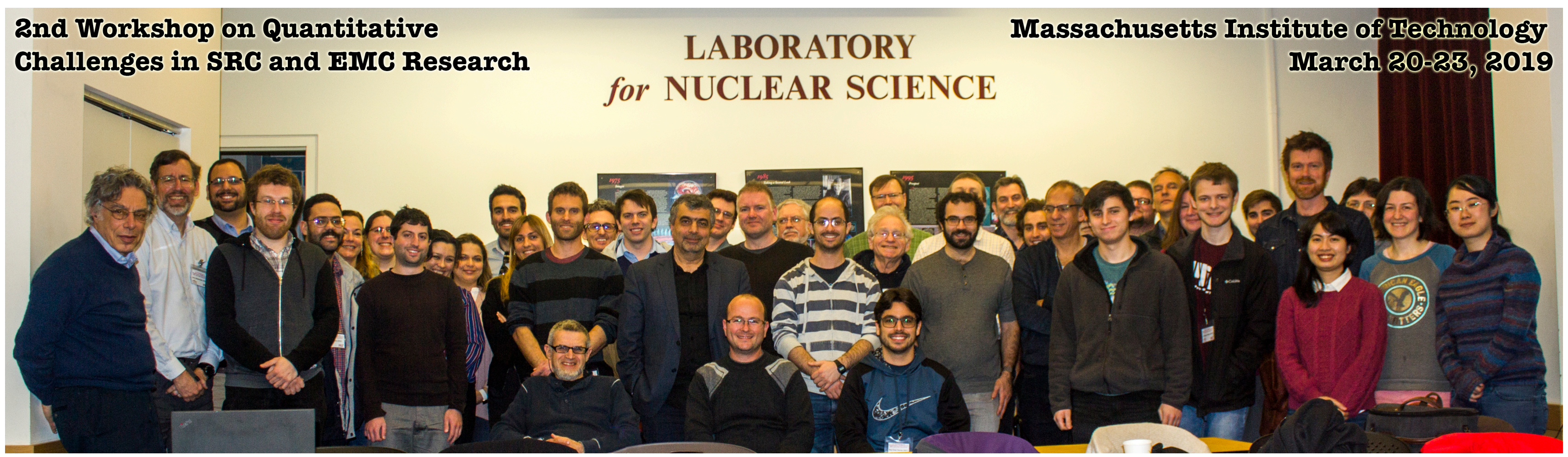
OBSERVATIONS & THEORY IN THE DYNAMICS OF NEUTRON STARS



26 January 2015 — 30 January 2015

LNS Laboratory for Nuclear Science and the EIC^2 EIC Center at Jefferson Lab

3rd Workshop on Quantitative Challenges in EMC and SRC Research



Welcome to the 4th International Workshop on Quantitative Challenges in Short-Range Correlations and the EMC Effect Research held at CEA Paris-Saclay (Orme des Merisiers).

This workshop is supported by

the Espace de Structure Nucléaire Théorique (ESNT)

of the CEA/DRF and CEA/DAM

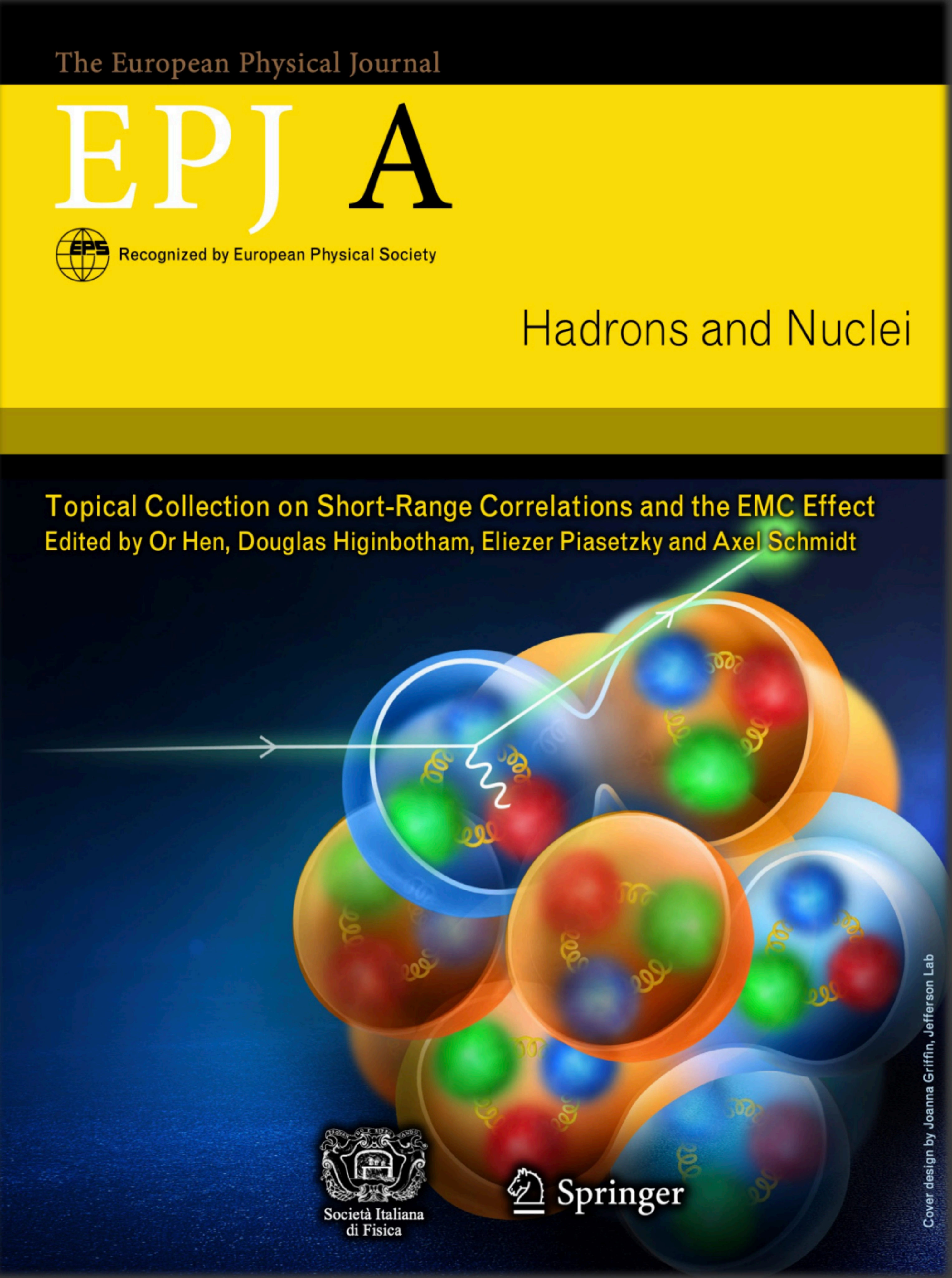
(https://esnt.cea.fr/)

EMMI Workshop
Cold dense nuclear matter:
from short-range nuclear correlations to neutron stars
October 13-16, 2015, Lecture Hall (KBW) GSI Darmstadt

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS — FONDAZIONE BRUNO KESSLER

Short-Distance nuclear structure and PDFs

Numerous topical workshops/conferences



Isospin Structure:

- Phys. Rev. Lett. 122, 172502 (2019)
- Nature 560, 617 (2018)
- Science 346, 614 (2014)
- Phys. Rev. Lett. 113, 022501 (2014)

C.M. Motion:

- Phys. Rev. Lett. 121, 092501 (2018)

Hard-Reaction Dynamics:

- Nature Physics 17, 693 (2021)
- Phys. Lett. B 797, 134792 (2019)
- Phys. Lett. B 722, 63 (2013)

Nuclei / Nuclear Matter Properties:

- Phys. Lett. B 800, 135110 (2020)
- Phys. Lett. B 793, 360 (2019)
- Phys. Lett. B 785, 304 (2018)
- Phys. Rev. C 91, 025803 (2015)

Effective Theory:

- Nature Physics 17, 306 (2021)
- Phys. Lett. B 805, 135429 (2020)
- Phys. Lett. B 791, 242 (2019)

Quantum Numbers, Mass, Asymmetry Dependence:

- Phys. Rev. C 103, L031301 (2023)
- Phys. Lett. B 780, 211 (2018)
- PRC 92, 024604 (2015)
- PRC 92, 045205 (2015)

Why a white-paper? Why now?

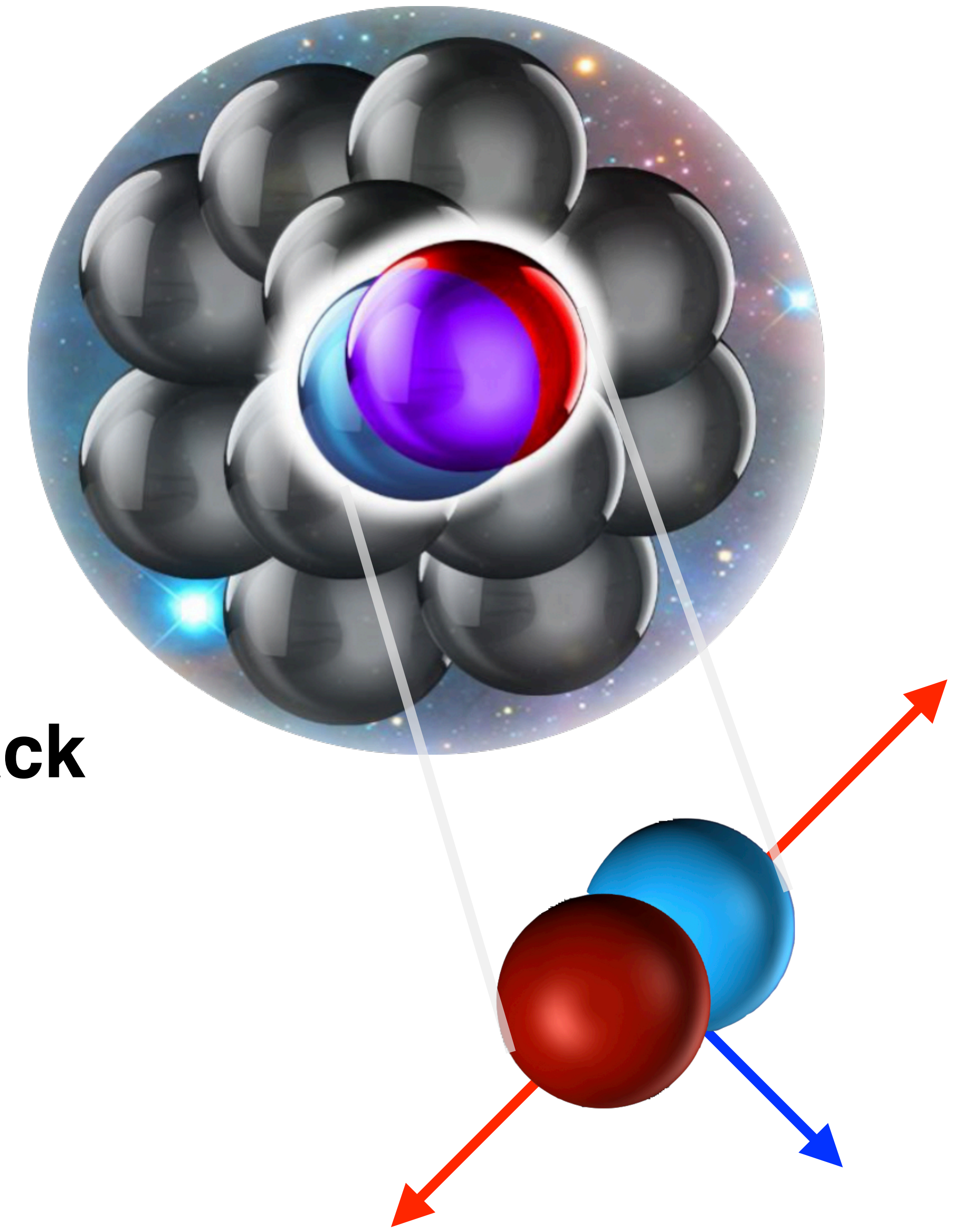
- ✦ Re-evaluate what we hope to understand
- ✦ Identify which aspects of the problem are already well in hand
- ✦ Determine where additional input will be most illuminating
- ✦ Acknowledge that unanswered questions remain

2N SRC pairs

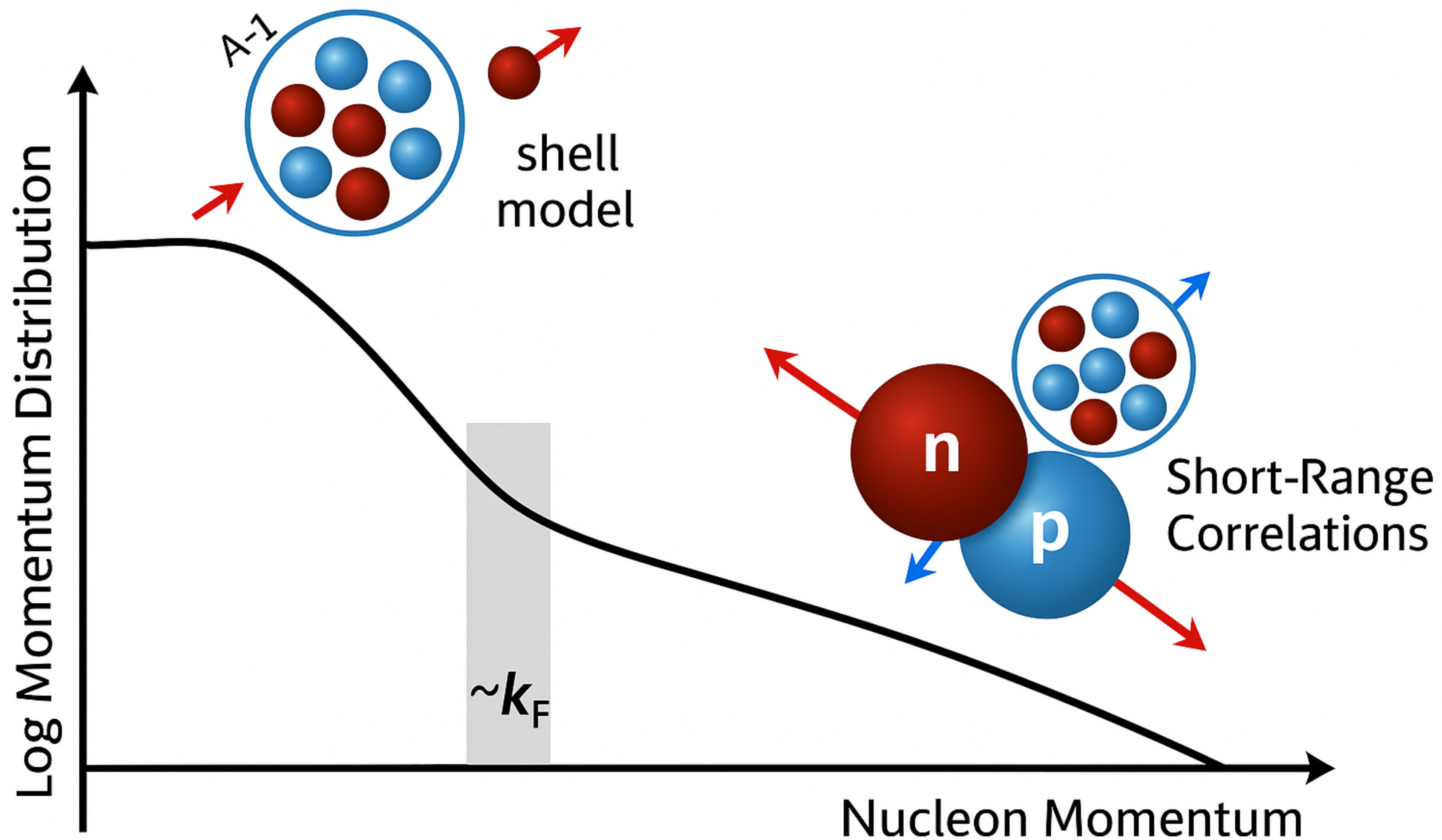
A **nucleon pair forms a short-range correlation** when they are very close together in the nucleus (≲1 fm)

These pairs exhibit **high relative momentum** and **low c.m.** momentum compared with k_f (~300 MeV/c)

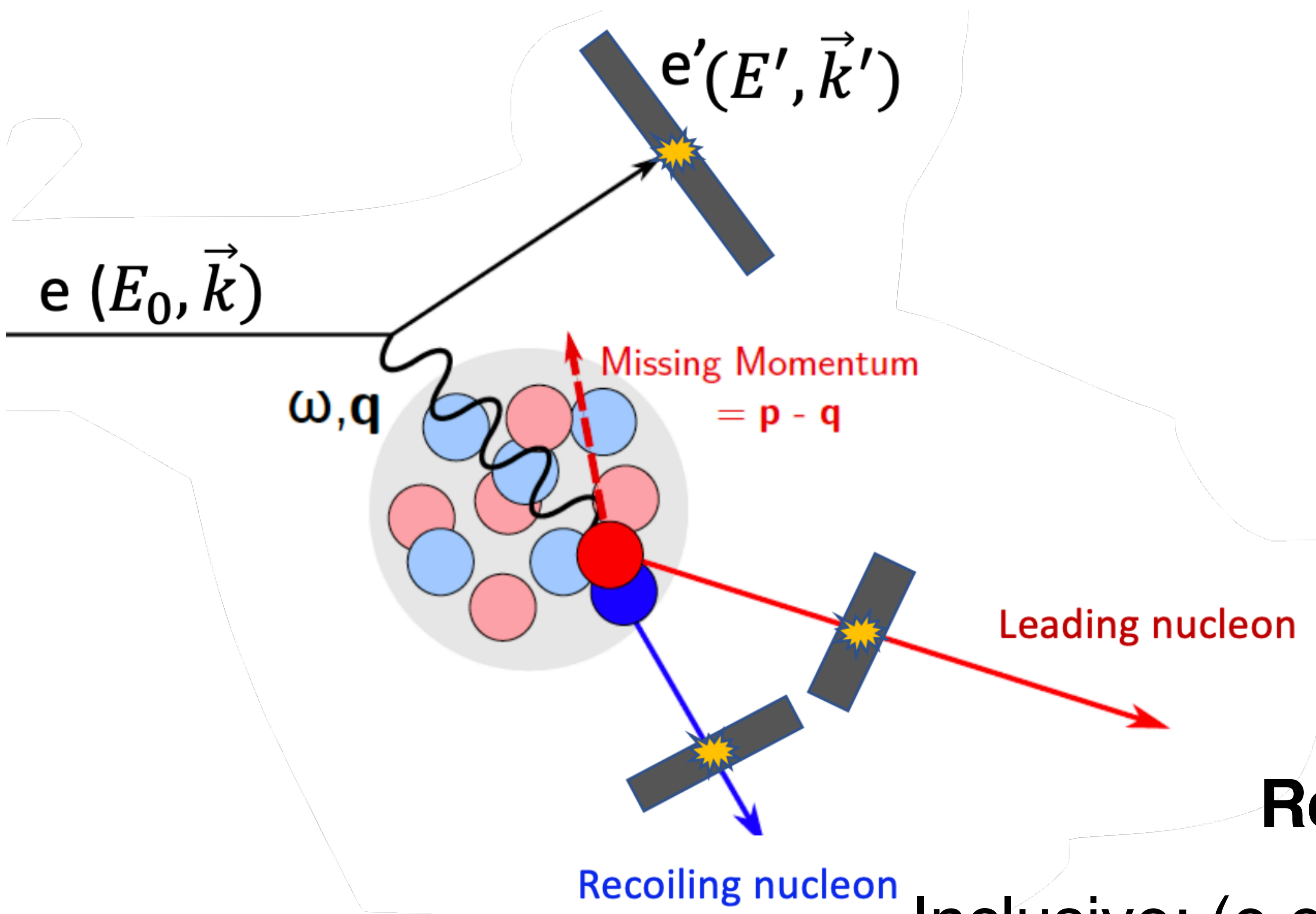
The nucleons in the pair have **back-to-back momenta**, indicating a strong, short-distance interaction



SRCs dominate the **high-momentum tail** of the nuclear momentum distribution



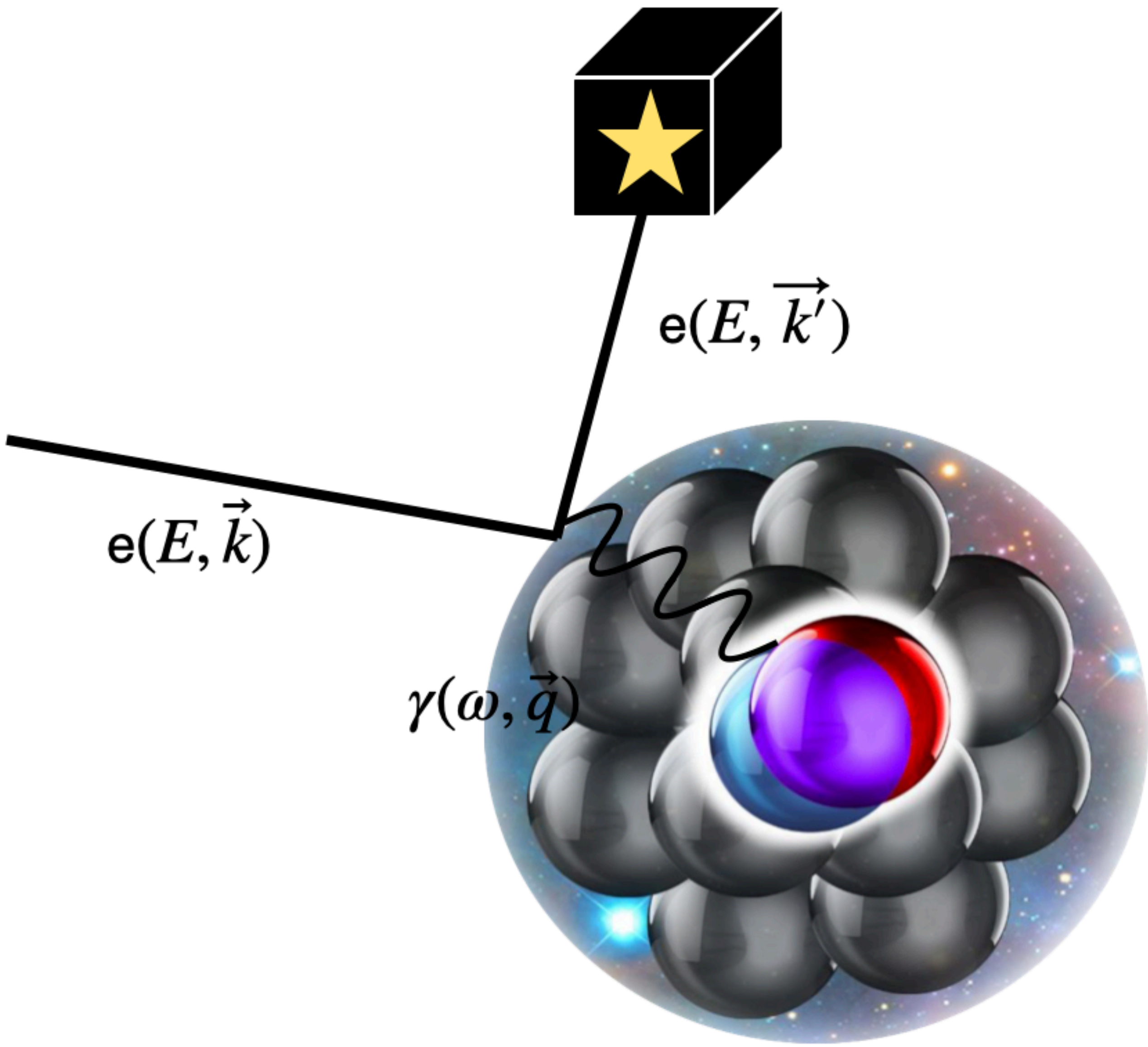
Primary experimental technique: Electron scattering



Reactions:

Inclusive: (e,e')
Single nucleon Knockout: A(e,e'N)
Two nucleon knock out: A(e,e'NN)

Inclusive A(e,e’) results

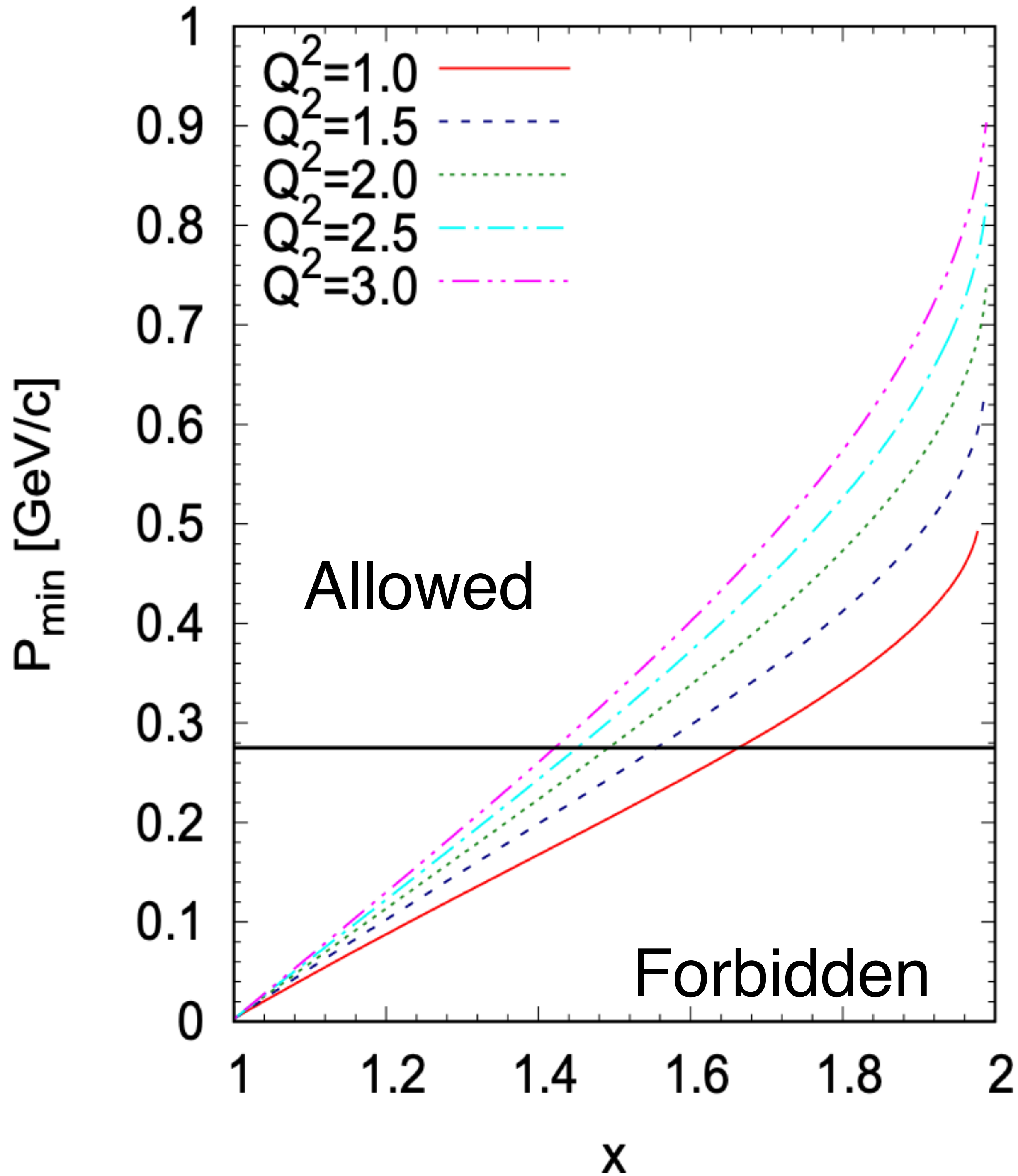


Signature

$$\mathrm{a}_2(A, D) = \frac{2\sigma_A(x, Q^2)}{A\sigma_D(x, Q^2)}$$

Kinematics

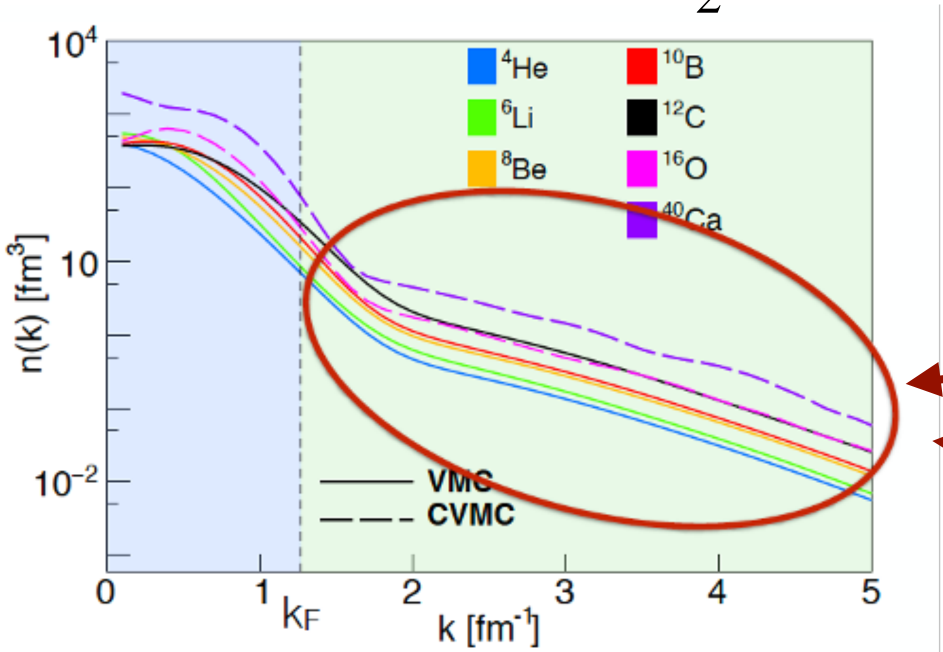
SRC is dominant at high x

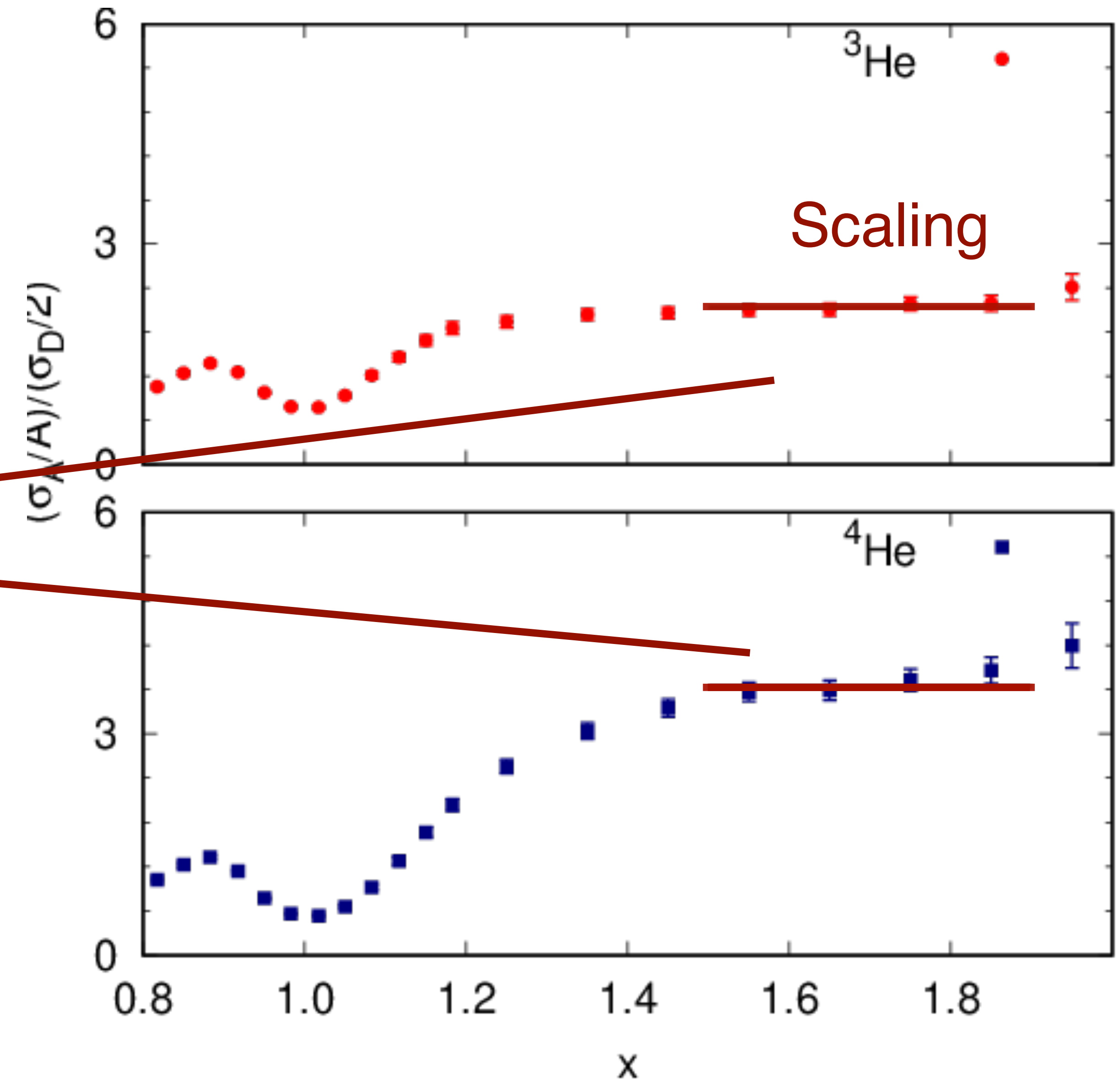


The onset of SRC dominance shifts to lower x as Q^2 increases

Inclusive A(e,e') results

$$\sigma_A(x, Q^2) = \mathrm{a}_2(A, D)\frac{A}{2}\sigma_D(x, Q^2)$$

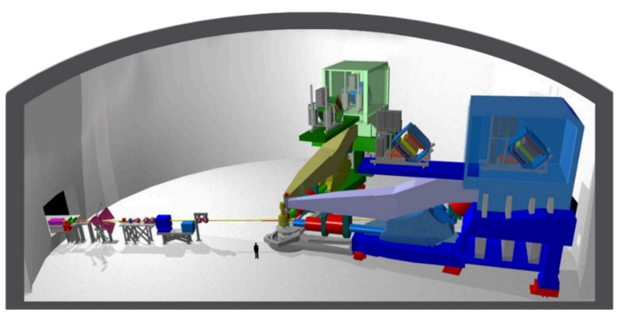




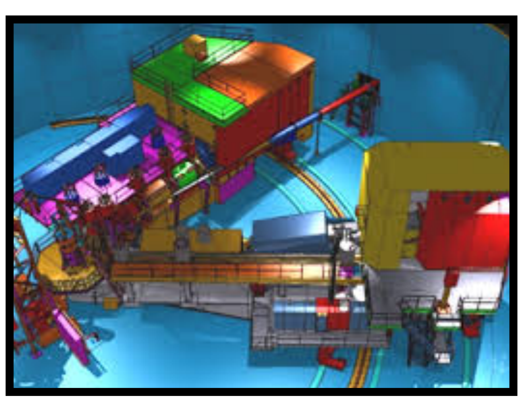
Universal high-momentum tail

S. Li Nature (2022), Schmookler Nature (2019), Fomin PRL (2008), Egiyan PRL (2006), Egiyan PRC (2003),), L. L. Frankfurt, PRC (1993)

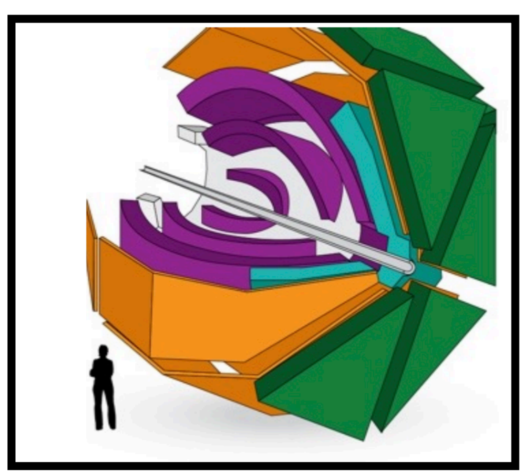
Consistent a_2 measurements:



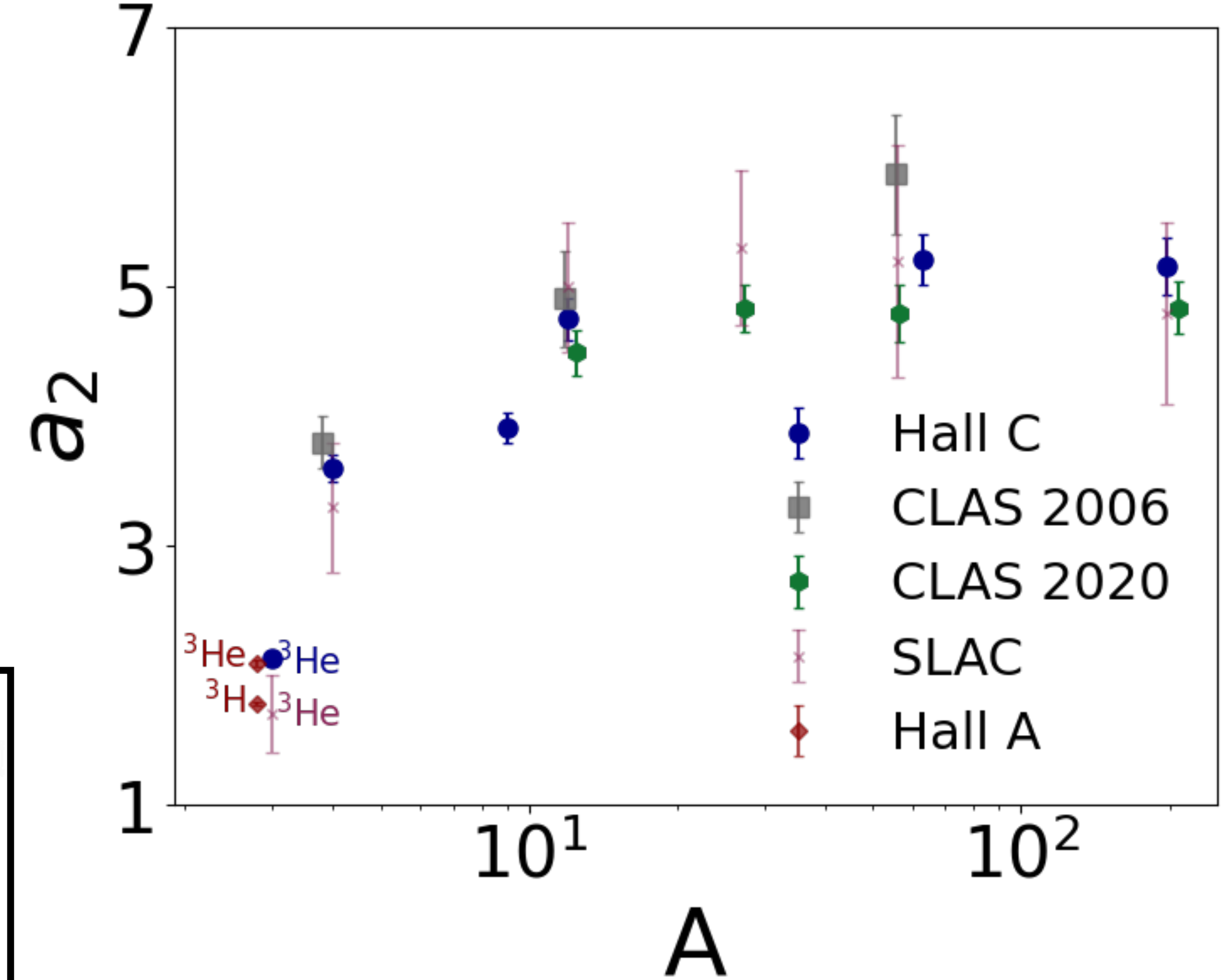
Hall A: HRS



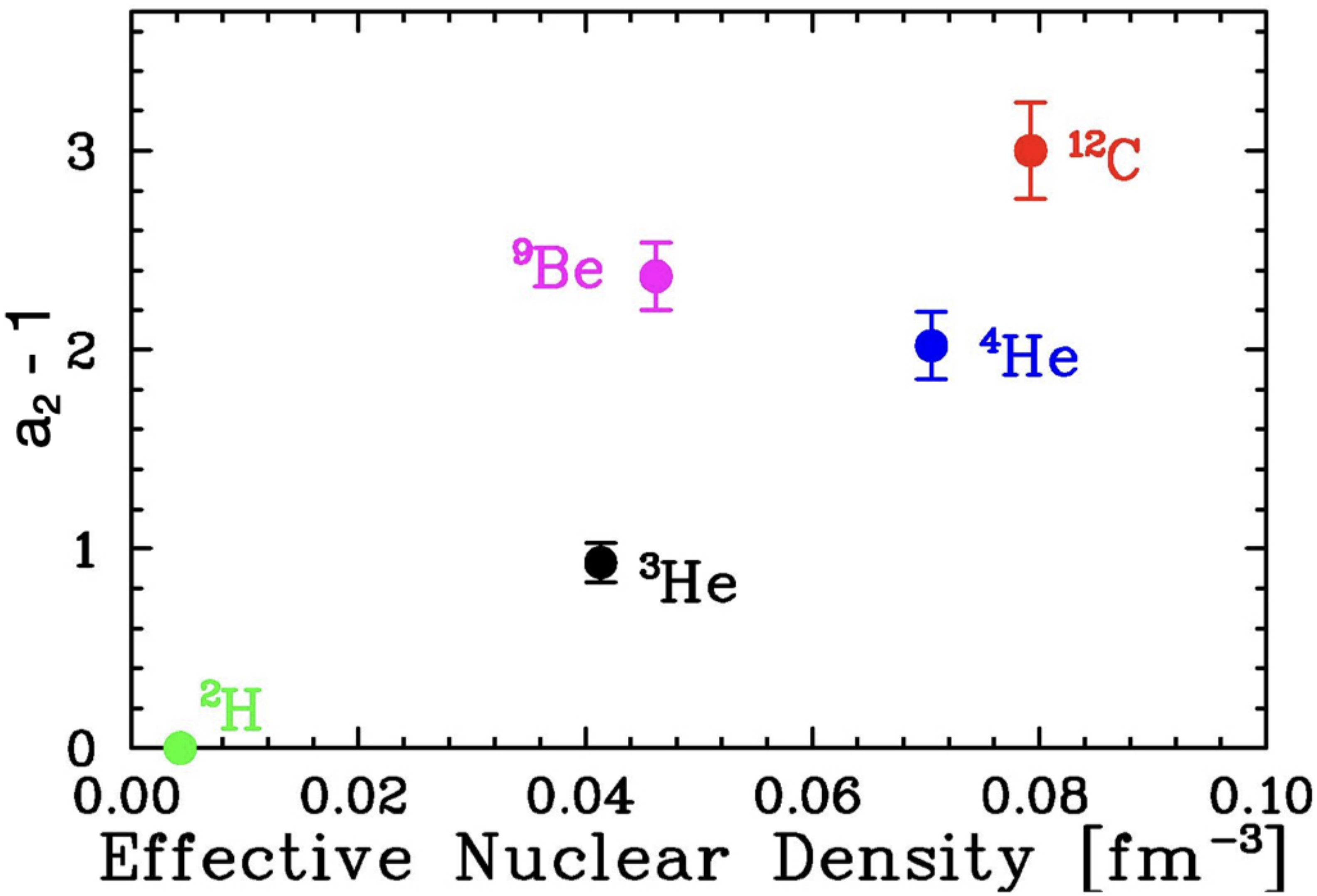
Hall C: HMS, SHMS



Hall B: CLAS, CLAS12

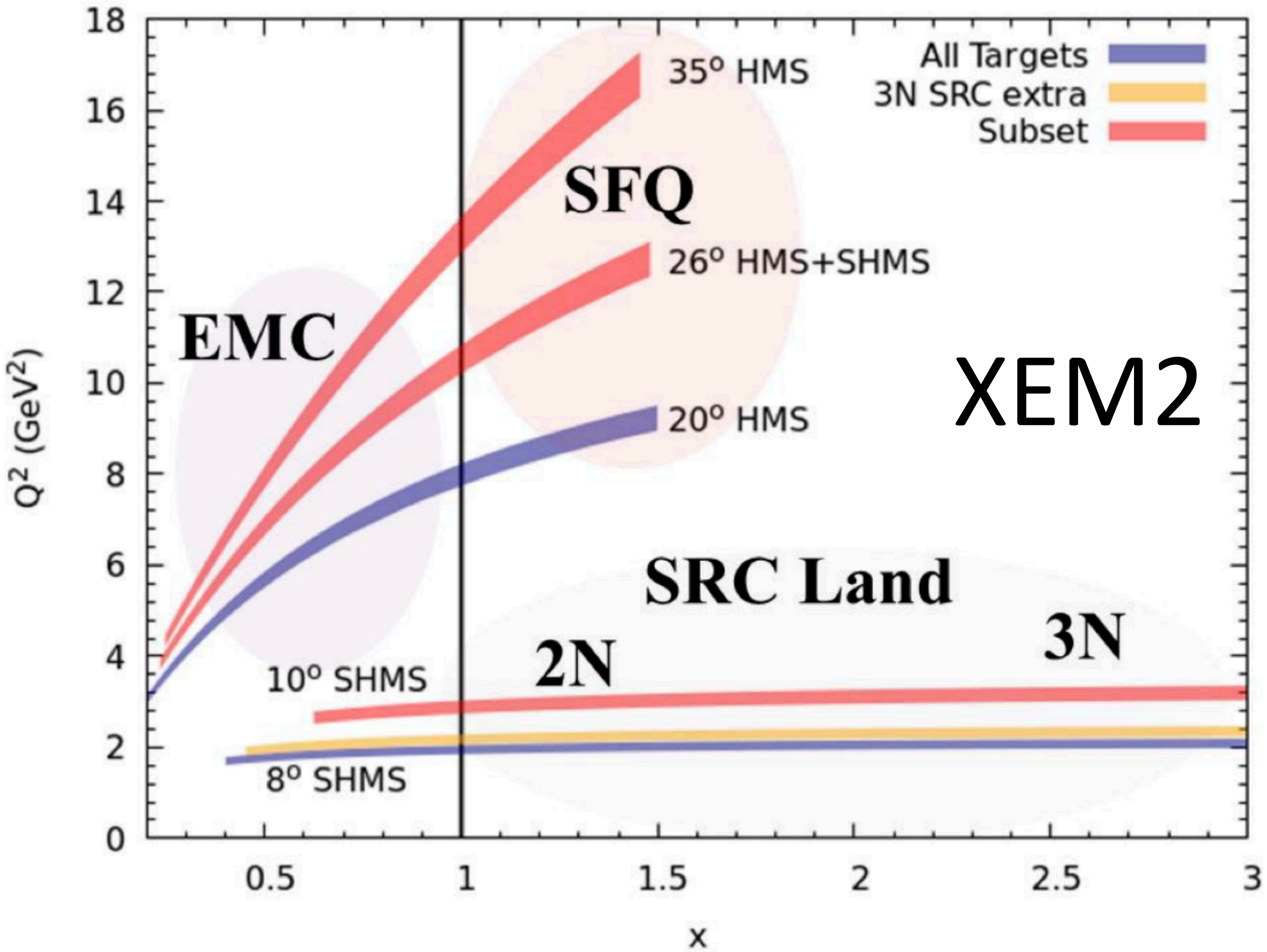


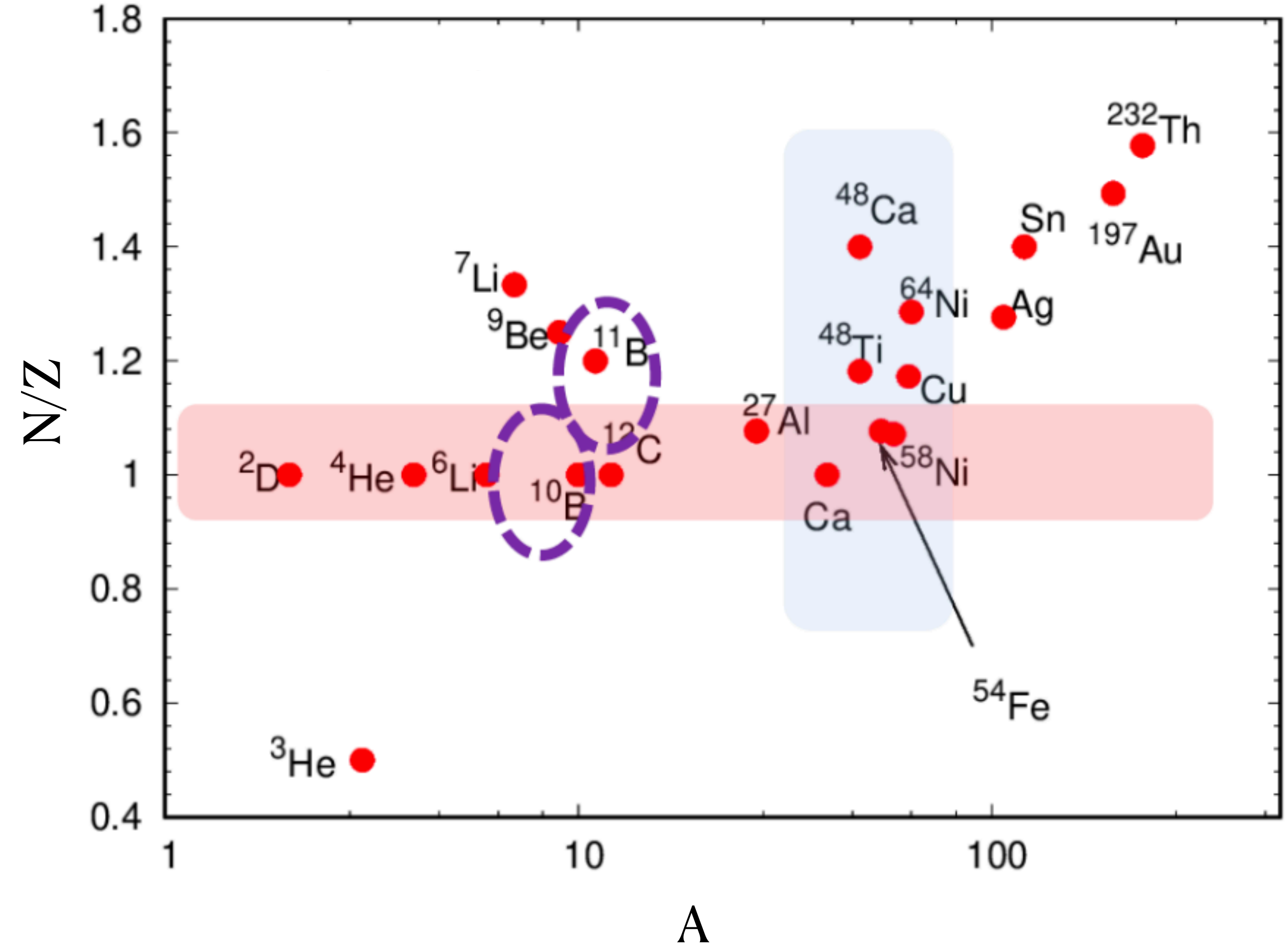
Early studies suggested that the parameter a_2 would scale with the average nuclear density, approximated by $A^{1/3}$



^{9}**Be deviates** significantly from this model

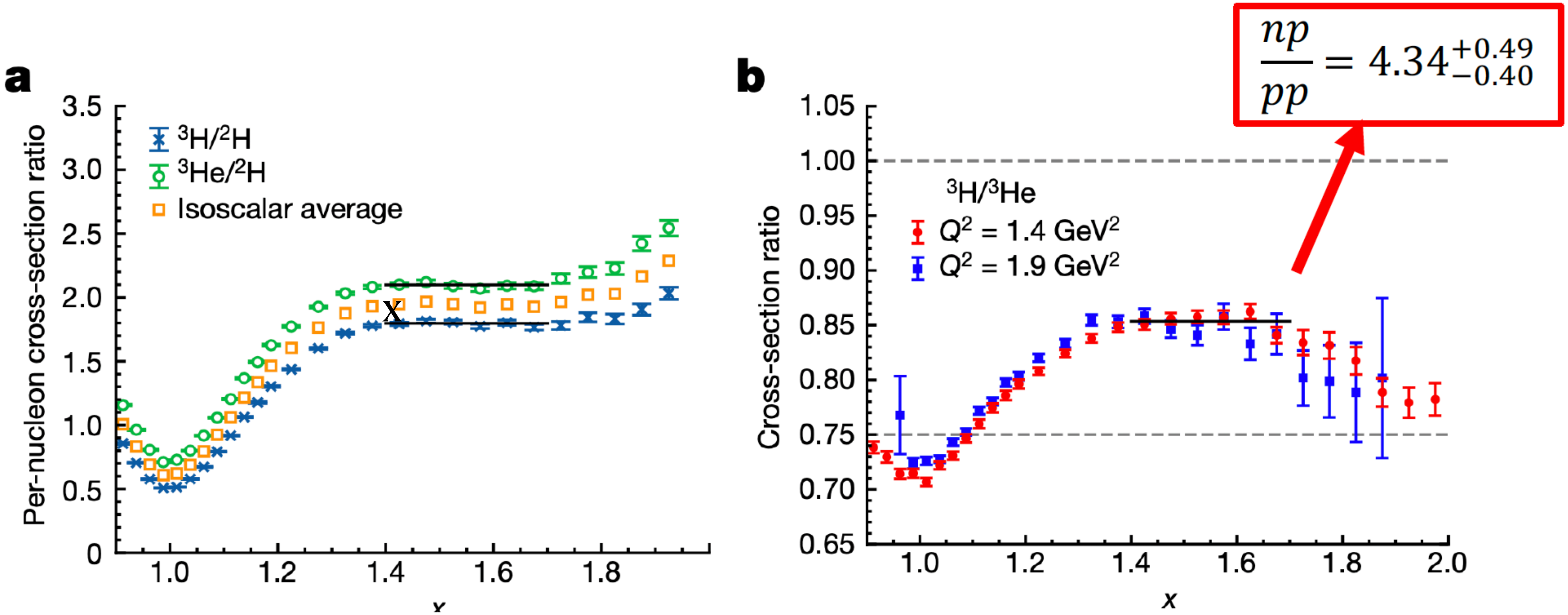
Under analysis





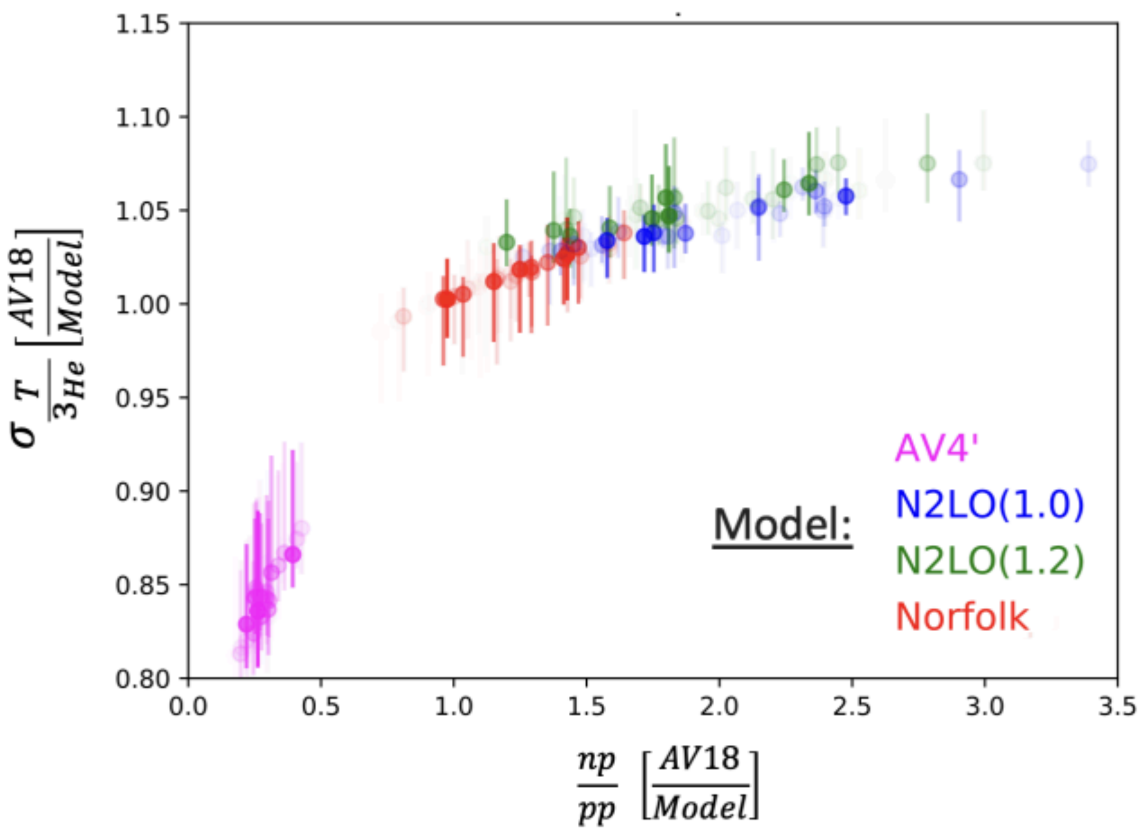
Understanding A and N/Z dependence of a_2
Hall C experiment

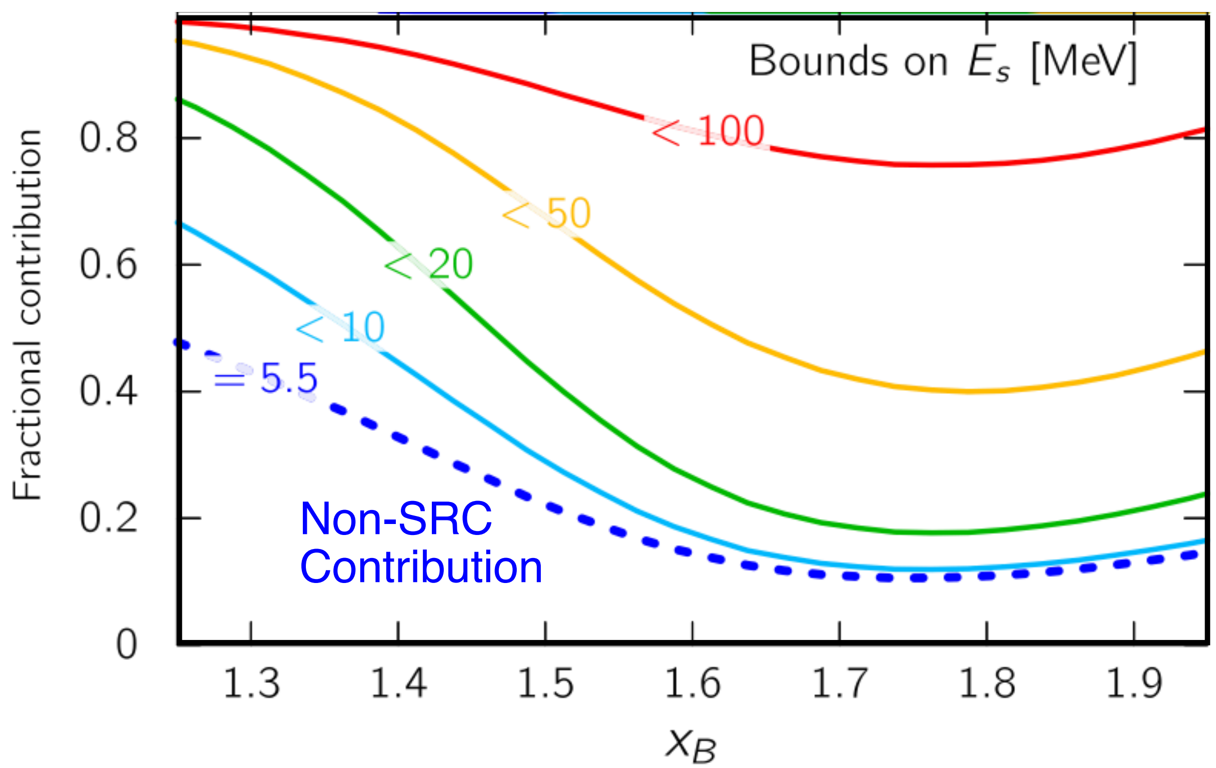
Studies of **isospin dependence** using inclusive measurements



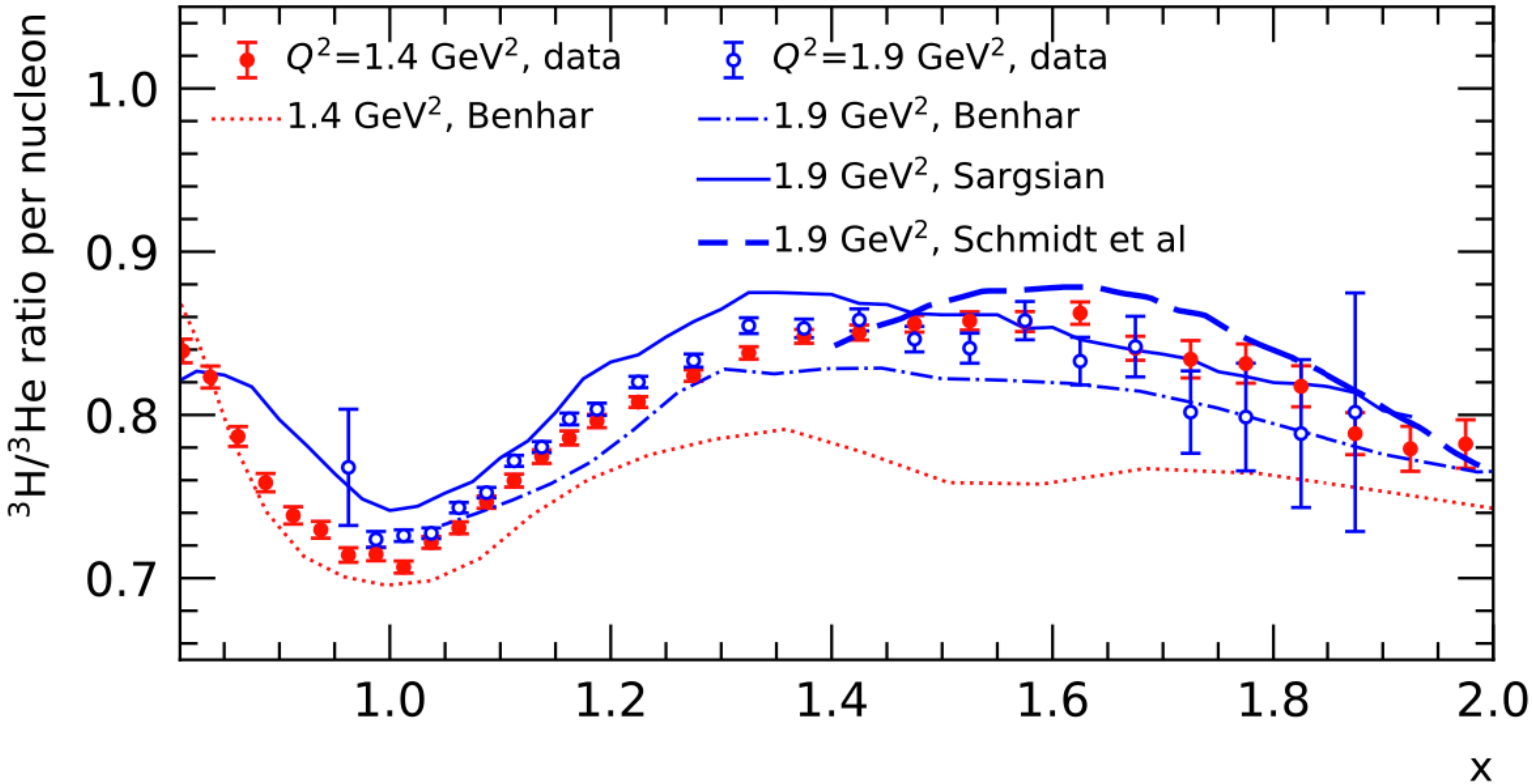
S. Li et al. (Hall A), Nature 609 p. 41 (2022)

Followup studies have shown interpretation challenges associated with the model dependence





A. Schmidt, Phys. Rev. C 109, 054001 (2024)

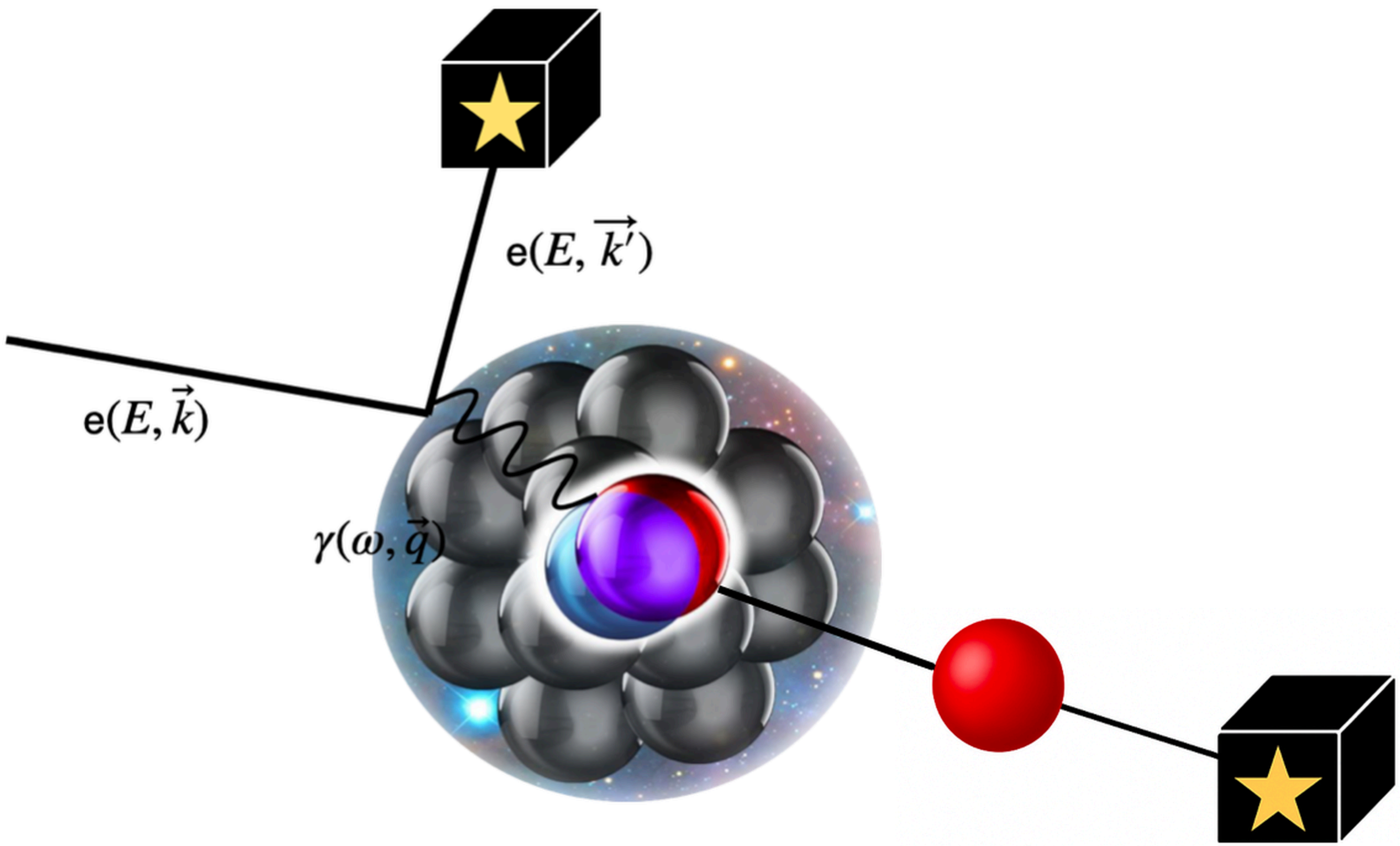


State of the art calculations for high x data for light nuclei
2N-SRC region for light nuclei

Lessons learned inclusive A(e,e')

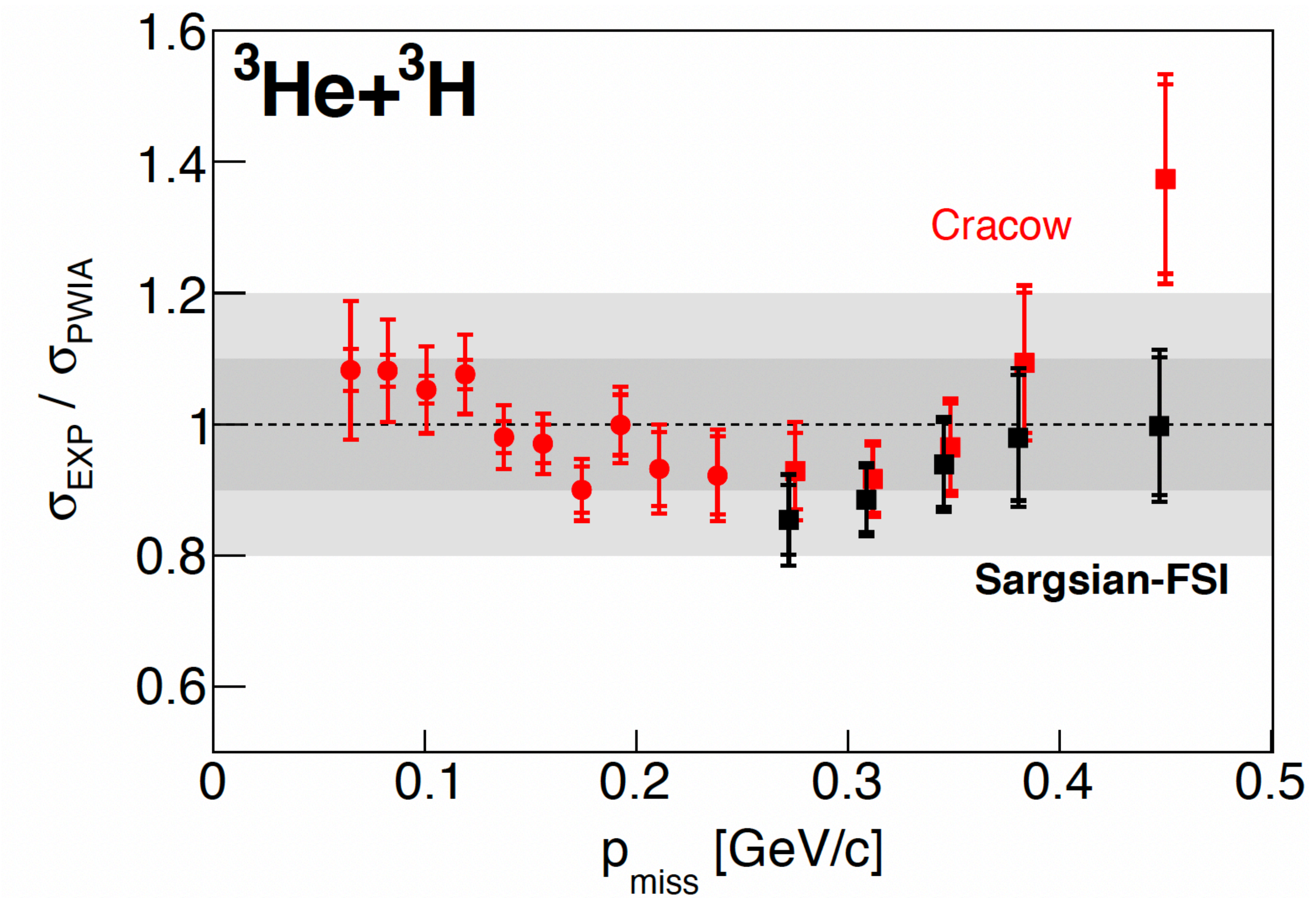
- Shows SRC dominance at $k > k_{fermi}$
- SRC-pair properties are universal across nuclei
- Unprecedented direct comparison to theory in light nuclei!

Single nucleon knockout A(e,e’p|n)



Detecting the struck nucleon

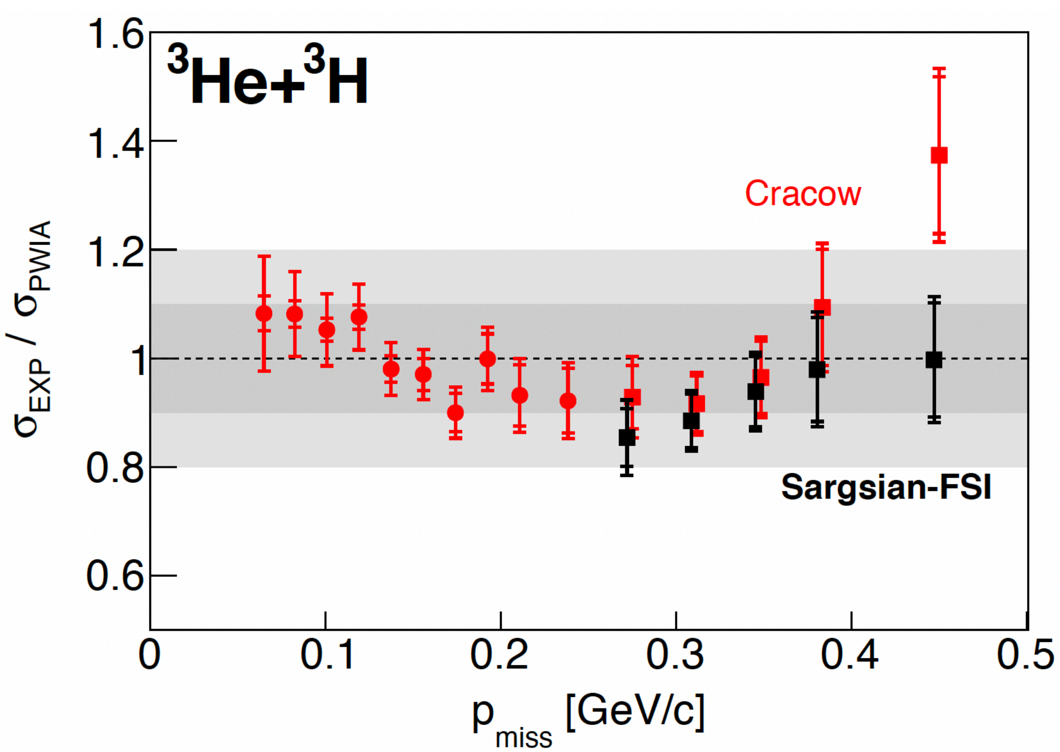
A=3 nuclei: Benchmark systems for testing theory



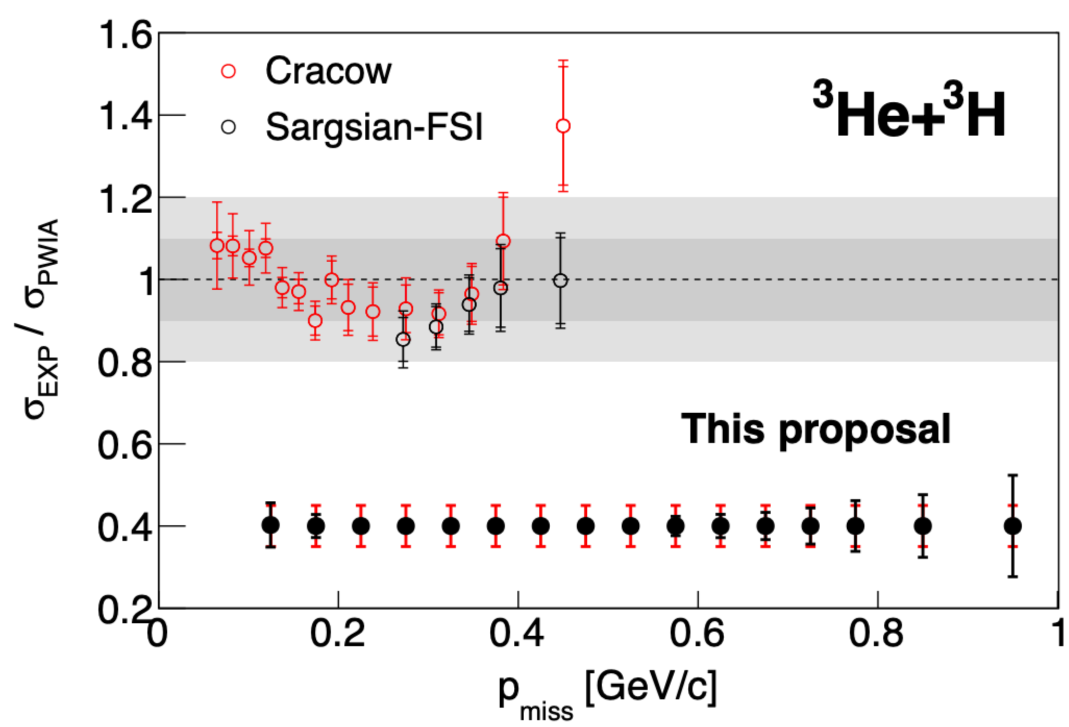
Isoscalar data agrees with full calculation up to 500 MeV/c

R. Cruz-Torres, D. Nguyen, PRL(2020).
R. Cruz-Torres PLB (2019)

A=3 nuclei: Benchmark systems for testing theory



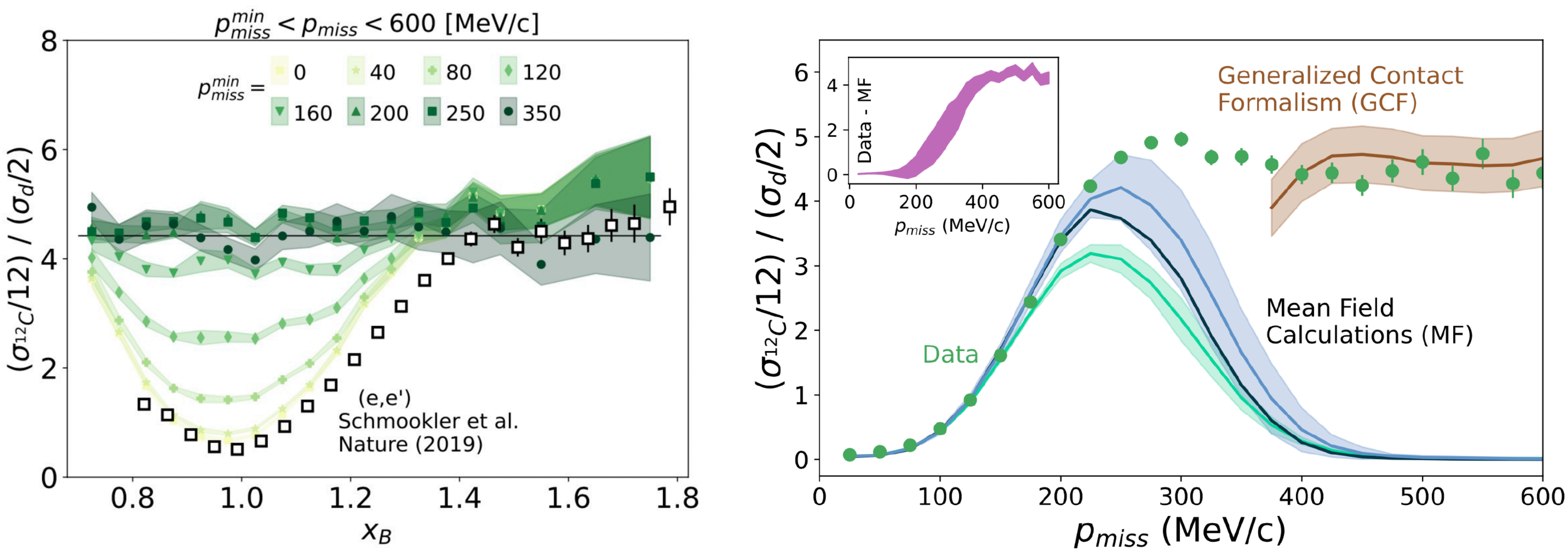
Future approved experiment



R. Cruz-Torres, D. Nguyen, PRL(2020).
R. Cruz-Torres PLB (2019)

Approved CLAS12 experiment

Transition from MF to SRC



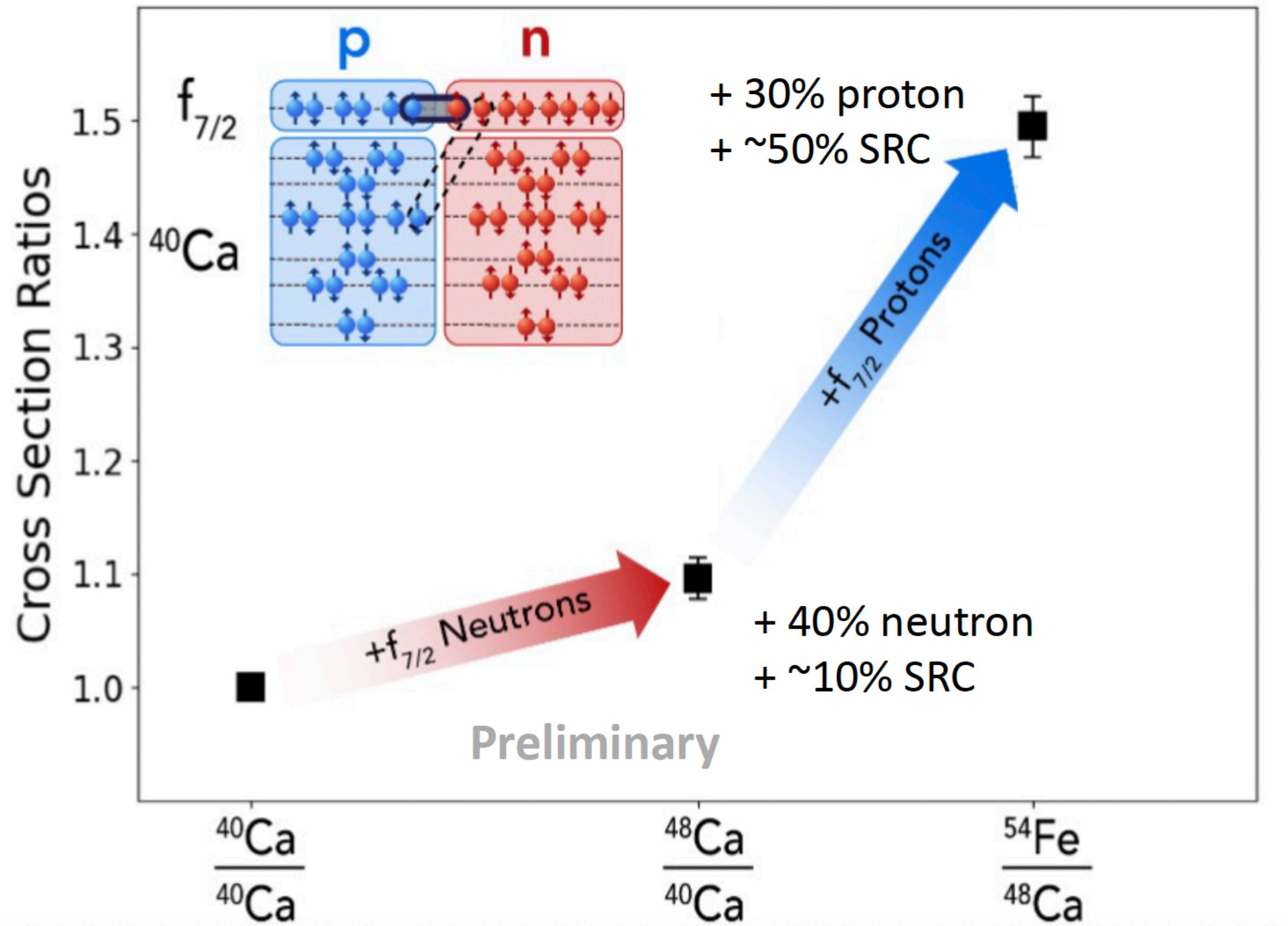
I. Korover, A. Denniston et al. (CLAS), PRC (2023)

- Scaling was observed for 2N SRC $Q^2 \gtrsim 1.5$ GeV^2/c^2
  $250 \gtrsim p_{miss} \gtrsim 600$ MeV/c

- Narrow transition from MF to SRC $250 \gtrsim p_{miss} \gtrsim 350$ MeV/c

Probing pairing mechanisms with ^{40}Ca, ^{48}Ca, ^{54}Fe nuclei

New Hall C data : CaFe (e,e'p)

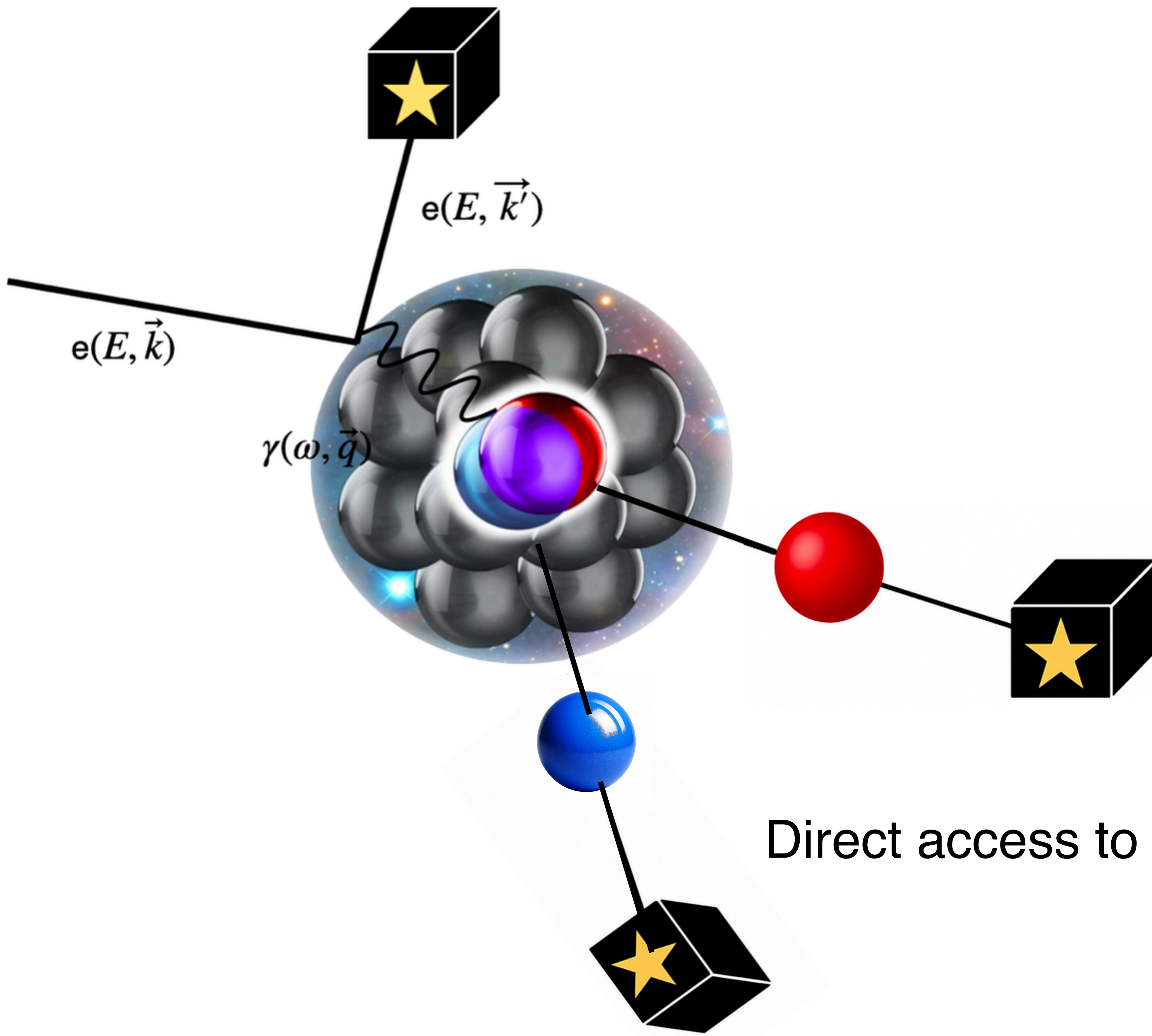


SRC pairing within the same shell

Lessons learned single nucleon knockout A(e,e'p|n)

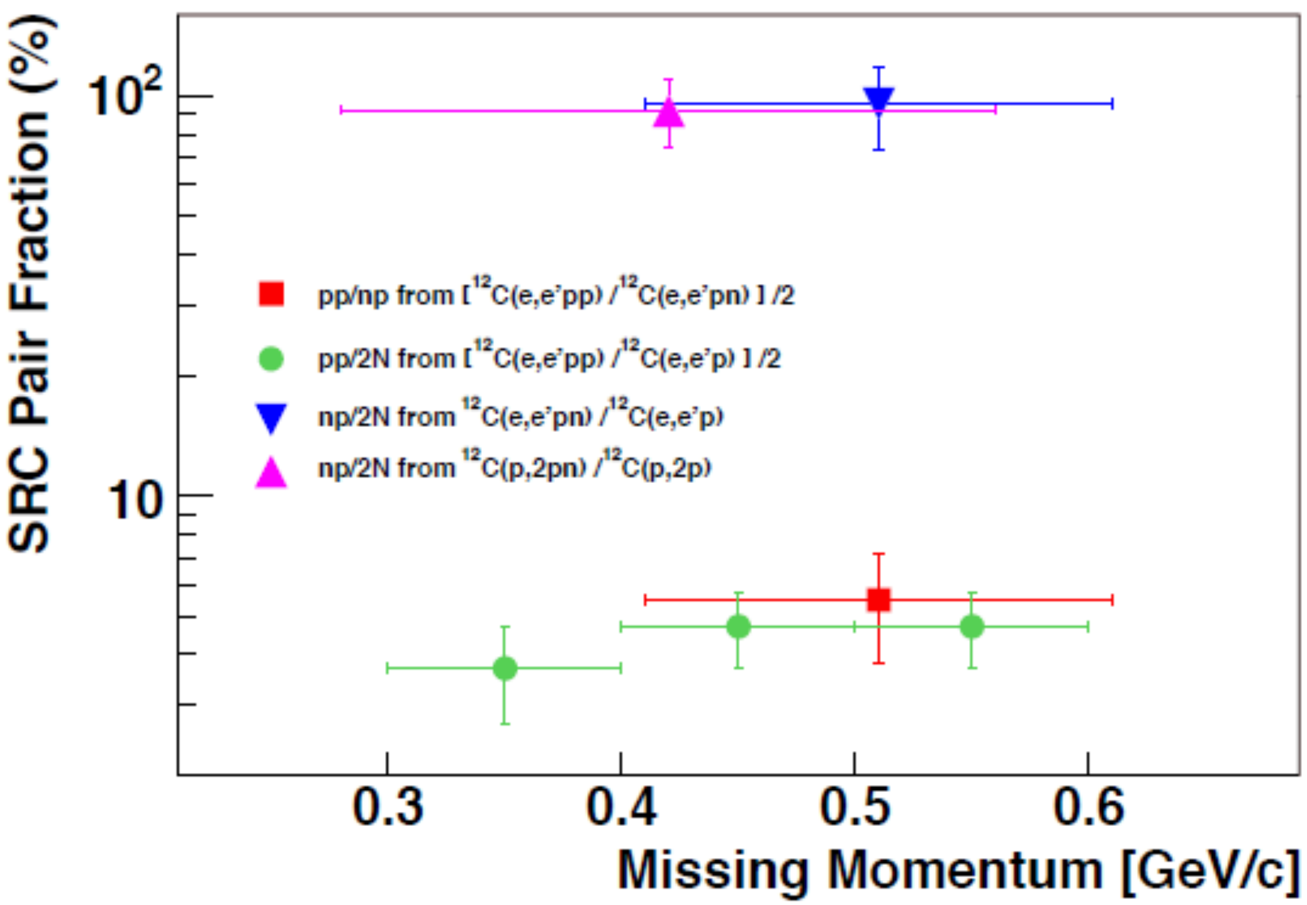
- Direct comparison to theory for light nuclei
- Proportional to abundance of high-momentum of protons and neutron
  - Which nucleons pair (pairing mechanisms)
- Narrow transition region (mean field → SRC)

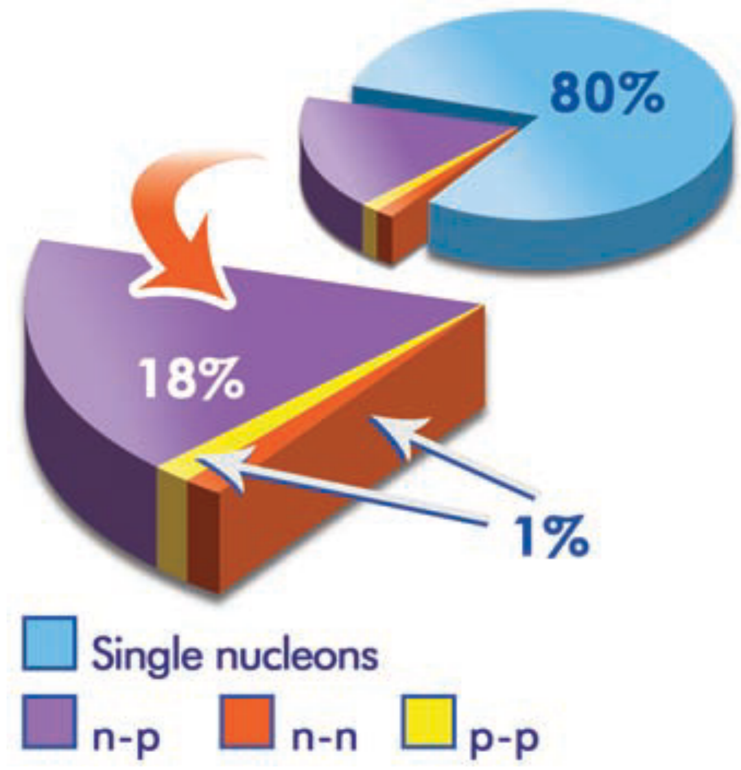
Two-nucleon knock out A(e,e’NN)



Direct access to pair kinematics

Two-nucleon knock out A(e,e'NN) results

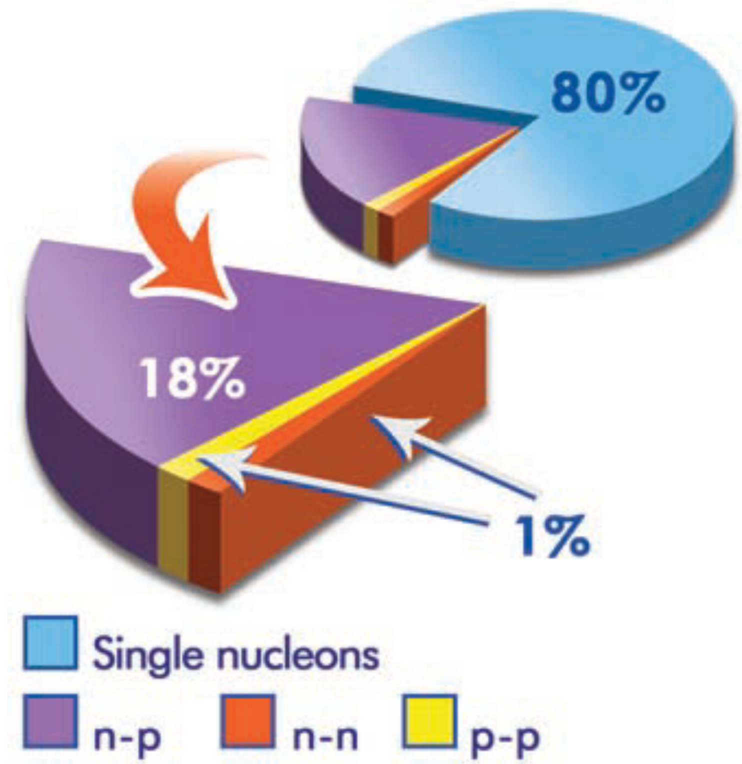




R. Subedi et al, Sc 320, 1476(2008)

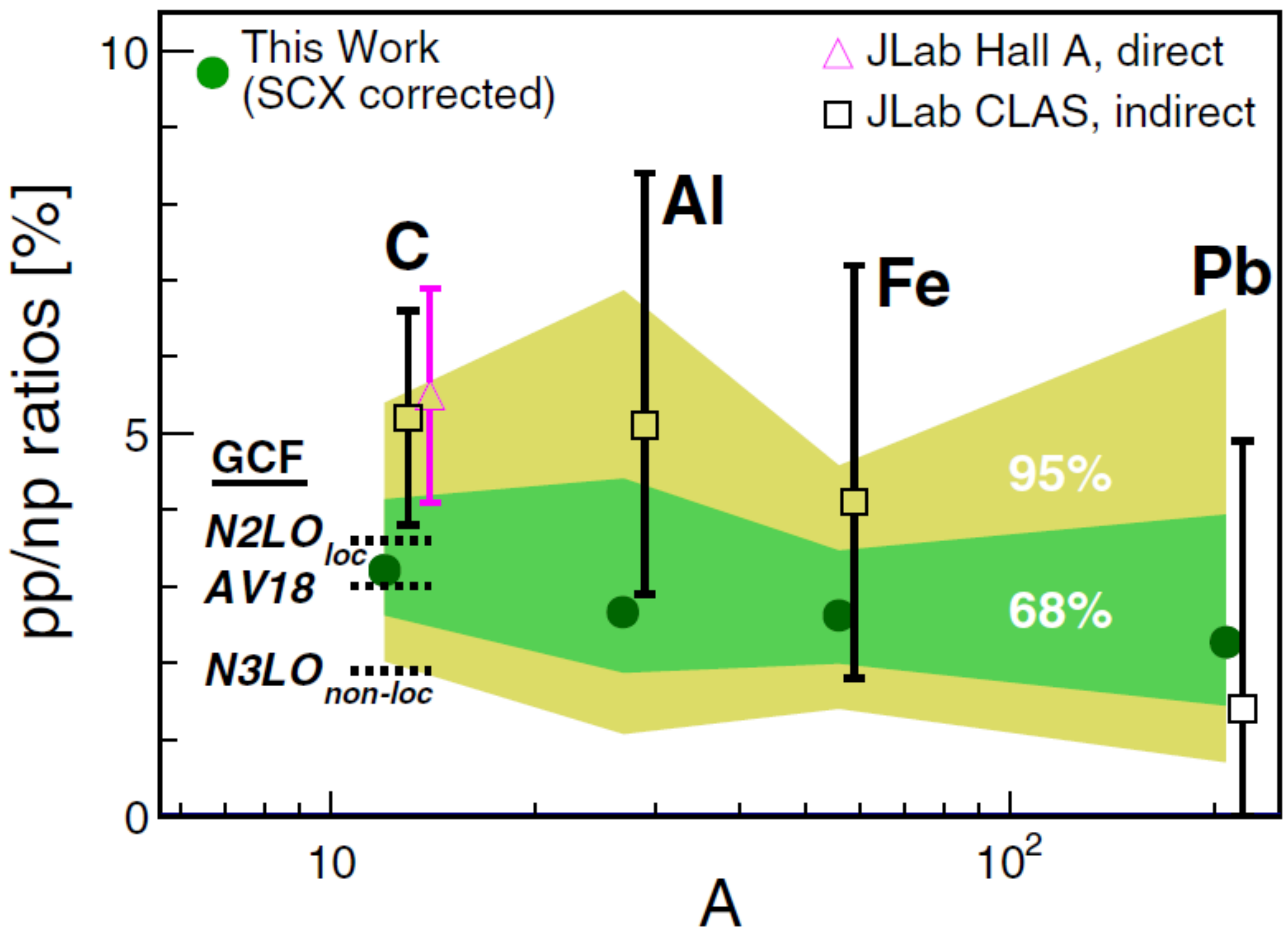
- About 20% of nucleons in medium to heavy nuclei belong to SRC pairs

- Almost all high momentum nucleons ($k > k_f$) belong to an SRC pair
    - predominantly in neutron-proton pairs
    - pair is back-to-back with large relative momentum and smaller center of mass momentum



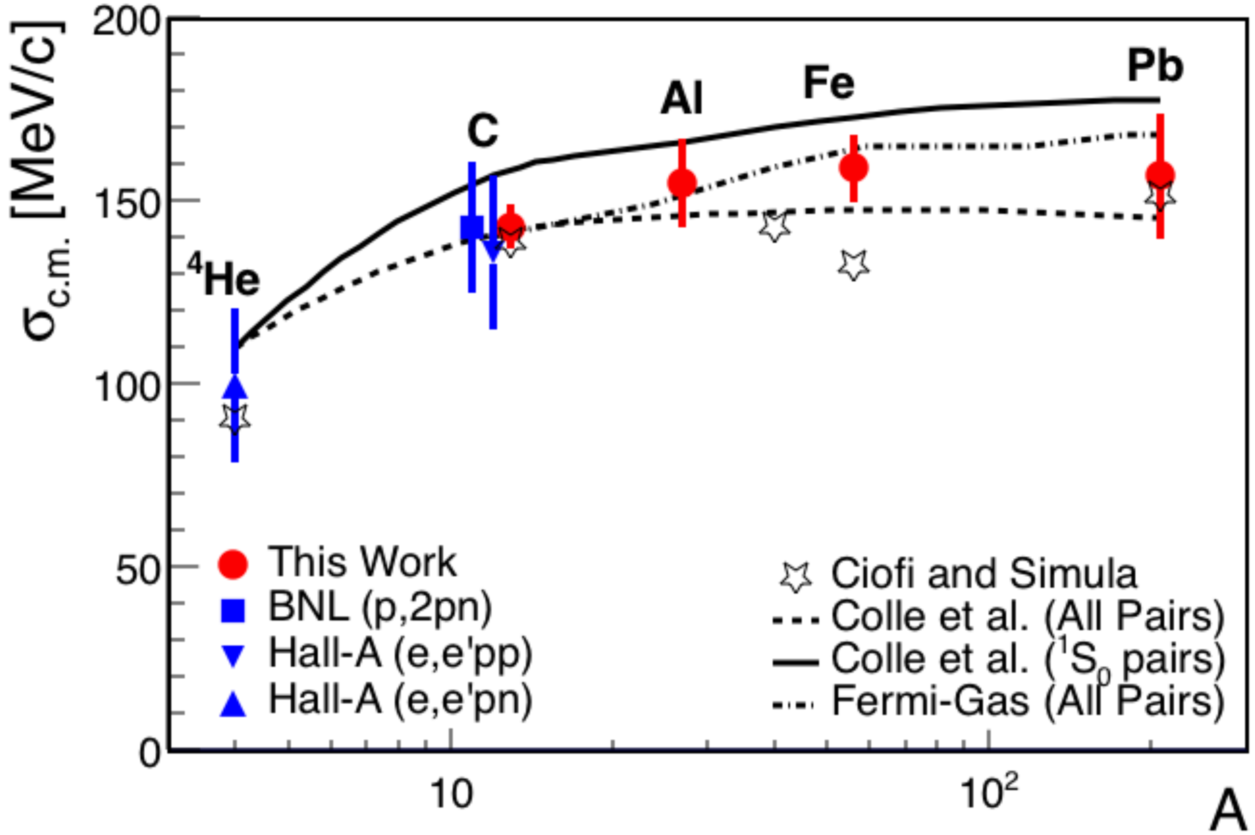
R. Subedi et al, Sc 320, 1476(2008)

SRCs pairs are predominantly np pairs (90% np, 5% each pp and nn)



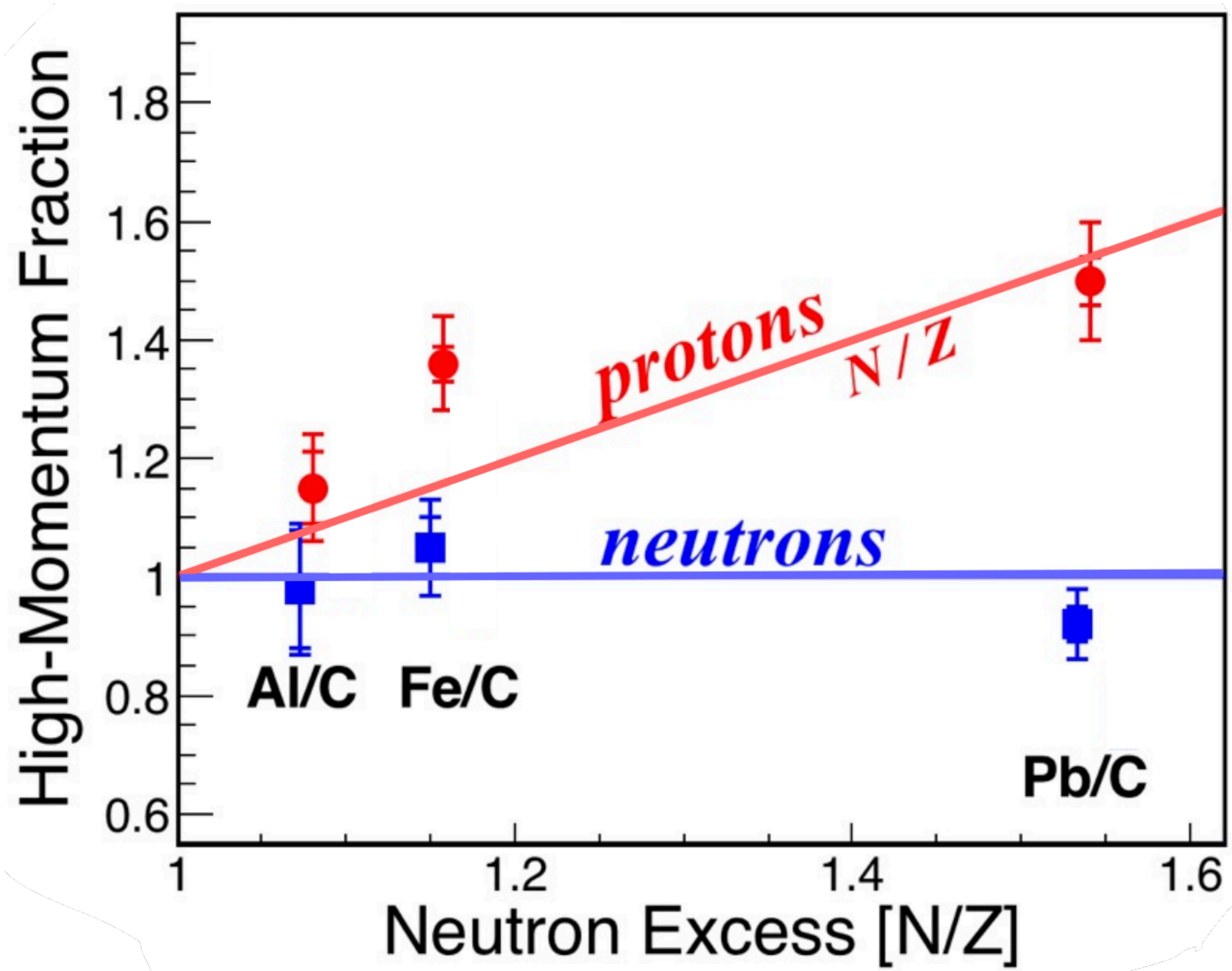
M. Duer et al., Phys. Rev. Lett. 122 (2019)

p_{cm} **distribution** width is consistent with the sum of two MF nucleons



Cohen, Phys. Rev. Lett. 121, 092501 (2018),)

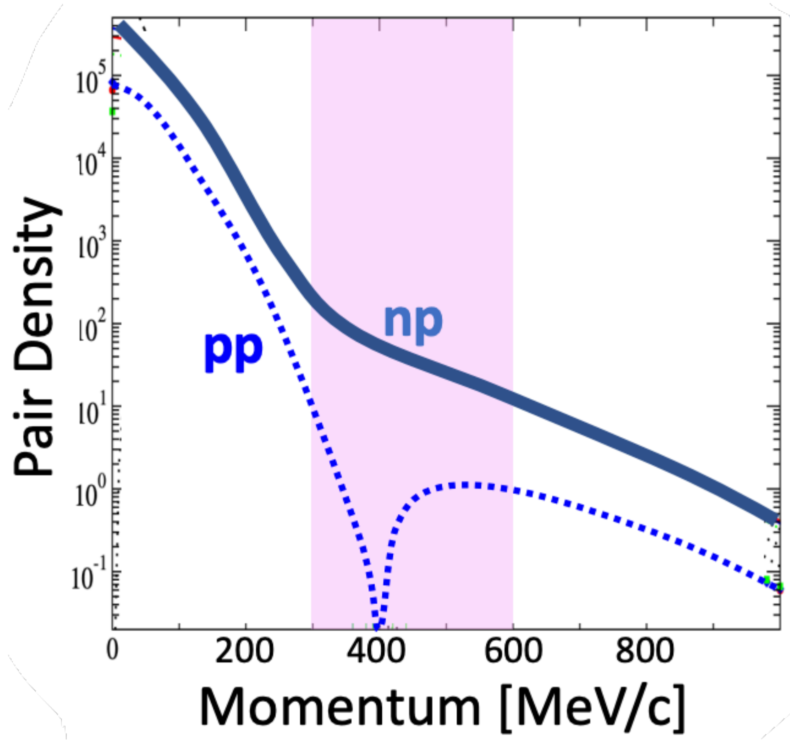
Neutrons saturate Protons grow



Protons 'Speed-Up' In Neutron-Rich Nuclei

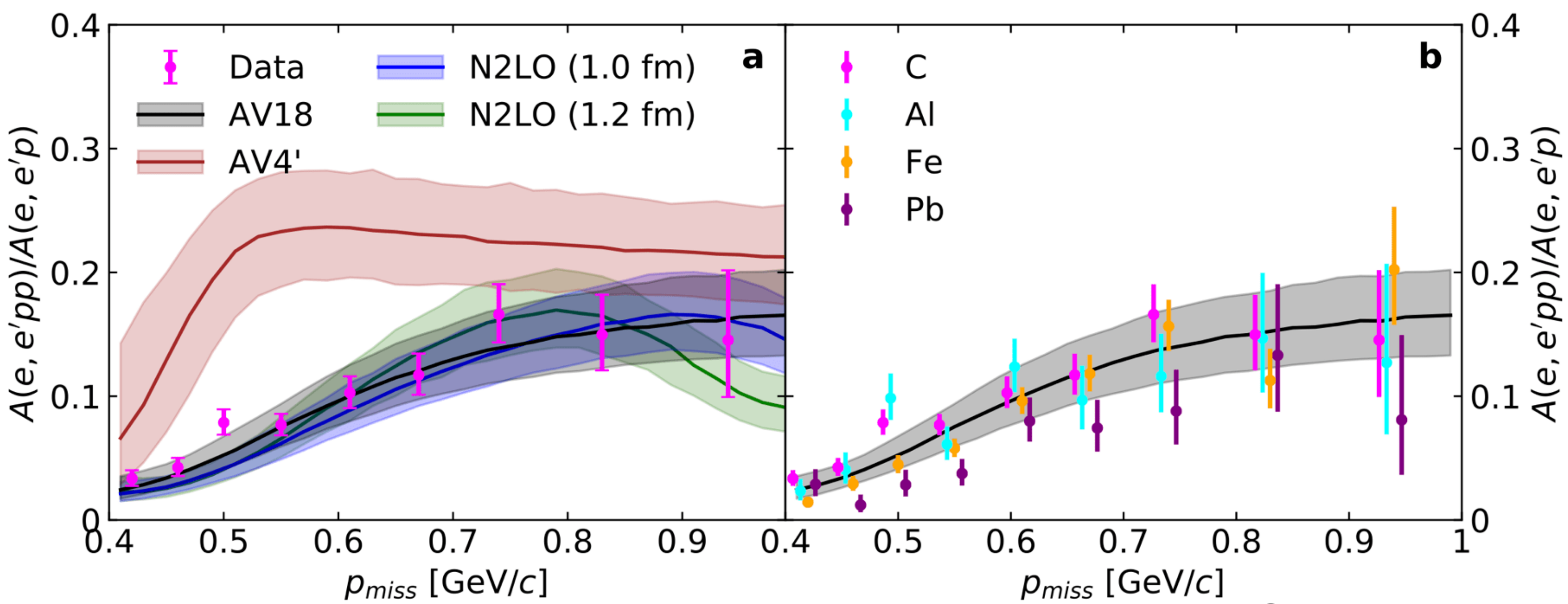
Duer Nature (2018)

Tensor-to-Scalar transition



Theory

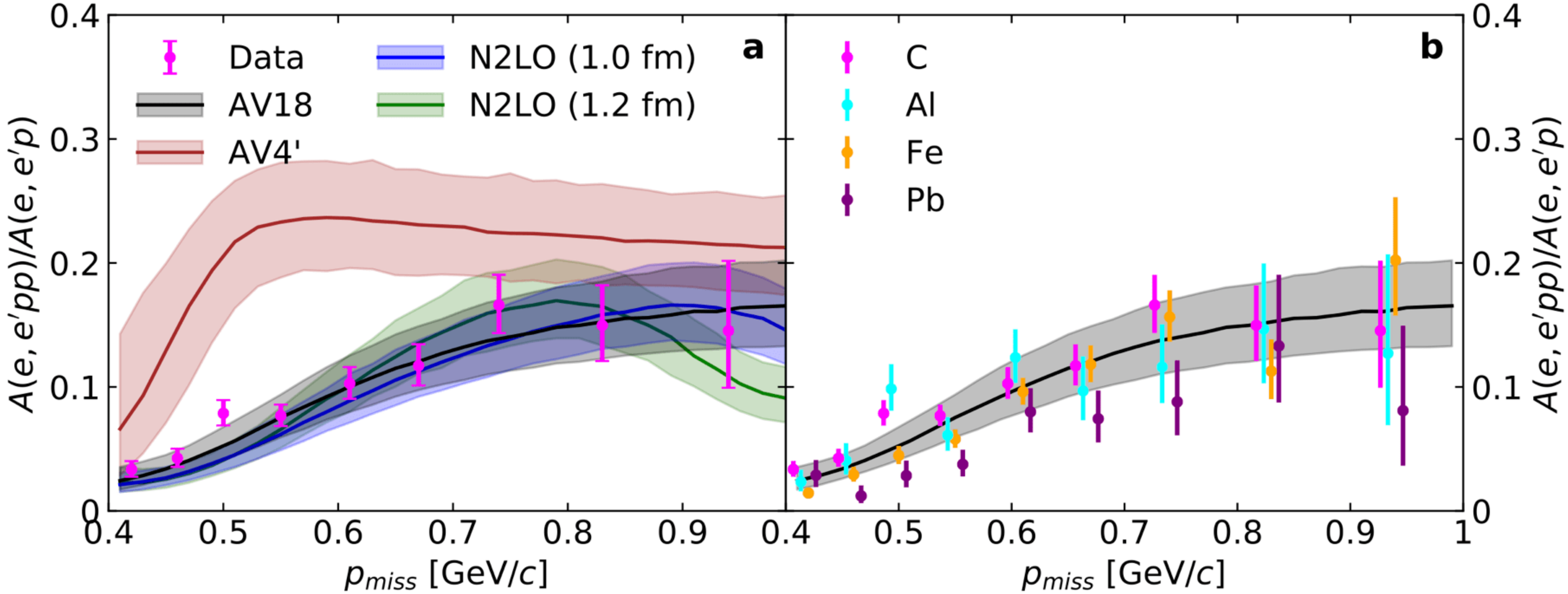
PRL 98, 132501 (2007)



Experiment

A. Schmidt et al. (CLAS), Nature 578, 540 (2020)

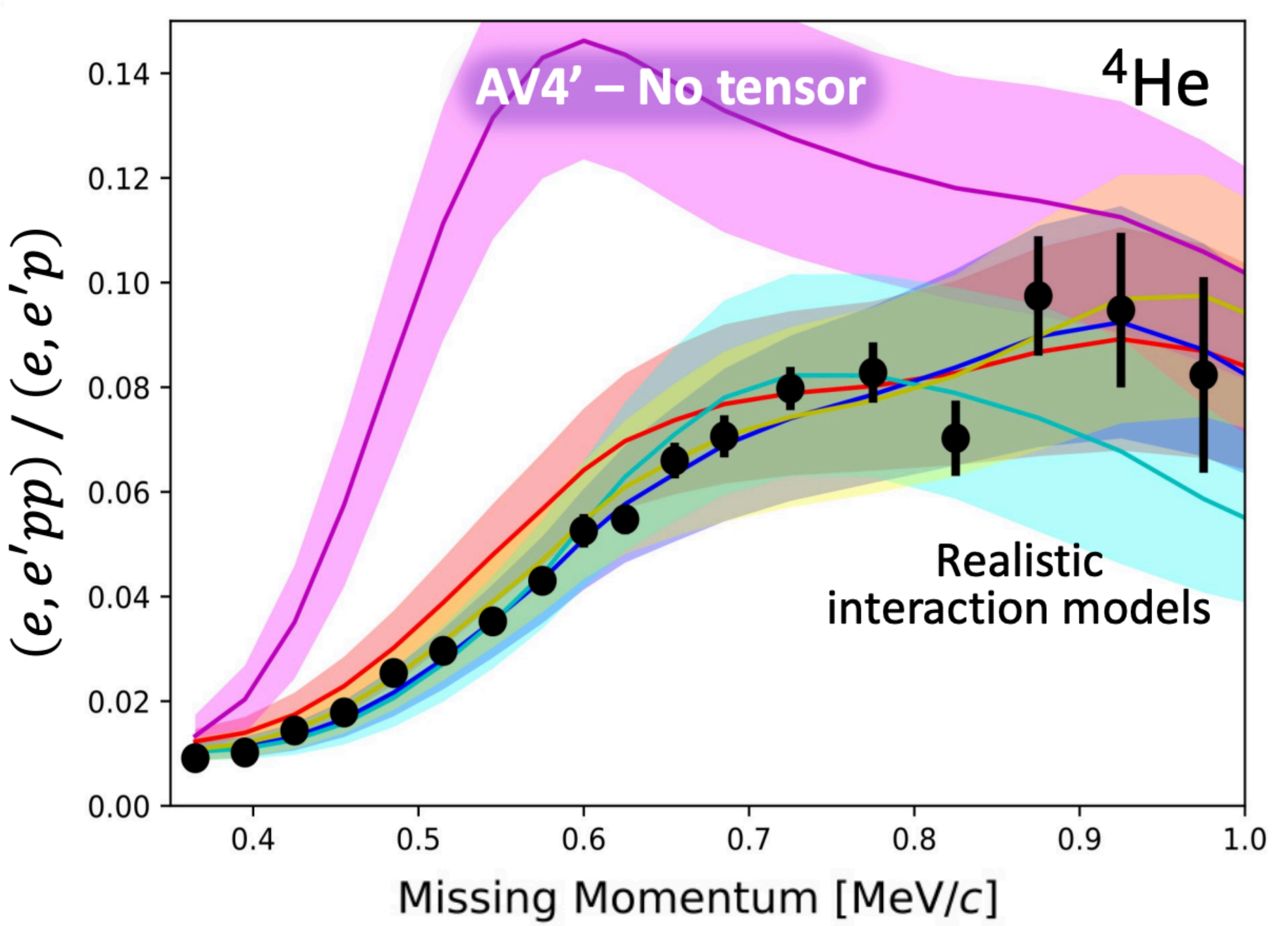
Tensor-to-Scalar transition



A. Schmidt et al. (CLAS), Nature 578, 540 (2020)

- np dominance is due to the tensor force around ~ 400 MeV/c
- np dominance is A-independent
- scalar force dominance as $p_{miss} \rightarrow 1$GeV/c
- p_{miss} distribution is universal

Tensor-to-Scalar transition



Norfolk

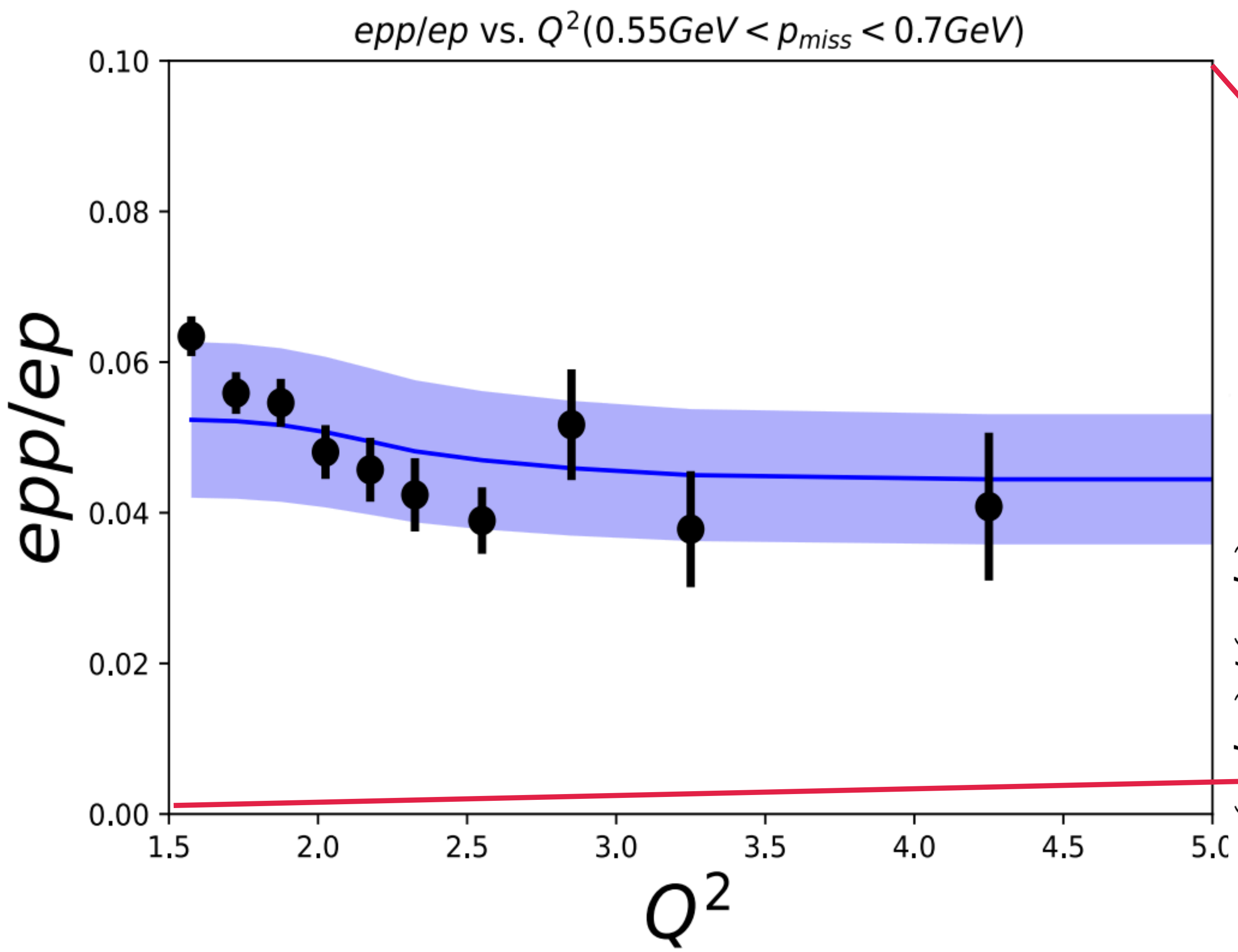
AV18

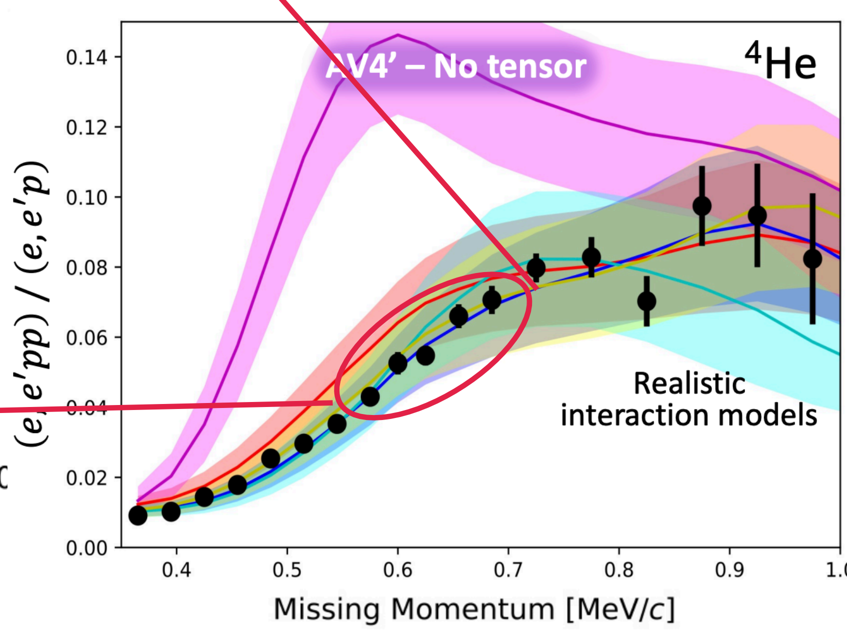
N2LO 1.0 fm

N2LO 1.2 fm

Schmidt and Pybus et al., Nature (2020)
Pybus et al., PLB (2020);
Korover and Pybus et al., PLB (2021)
New high-stat data (2025)

Q^2 Independence Under analysis





SRC properties are Q^2 universal

RGM (CLAS12) under analysis

Figures courtesy of Andrew Denniston

Lessons learned two-nucleon knock out A(e,e’NN)

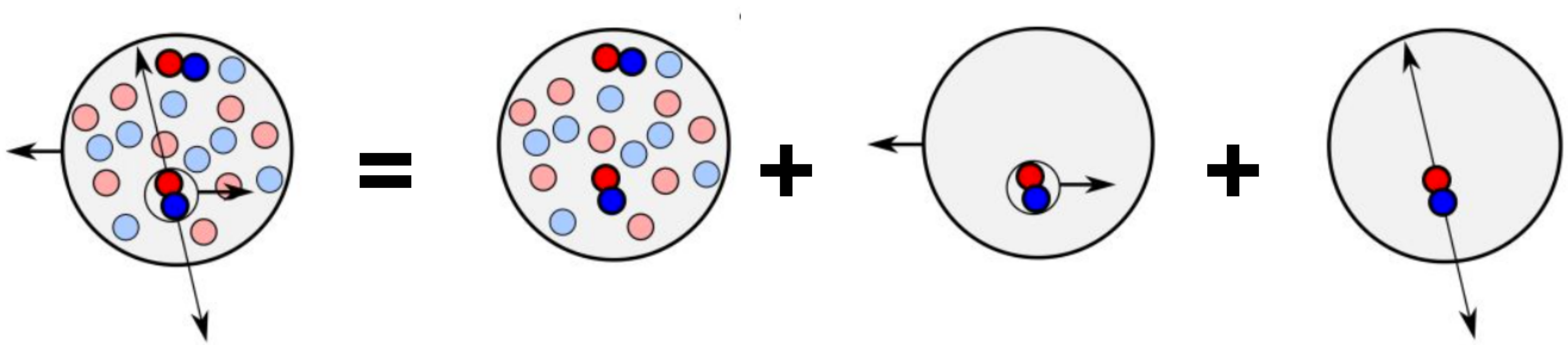
- *pn* pair dominance
- All* high momentum nucleons belong in SRC pairs
- pp/pn ratio increases with missing momentum
  - Tensor → scalar transitions
- Universality and scale separation: nuclear momentum distribution factorizes at short distance (or high momentum) into a two-body NN SRC part and a many-body (A – 2) part

Interpreting SRC Data

==> <u>factorization framework</u>

Elementary eN cross section | Nuclear Contacts | Two-body wave function | Center of mass motion

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



Interpreting SRC Data

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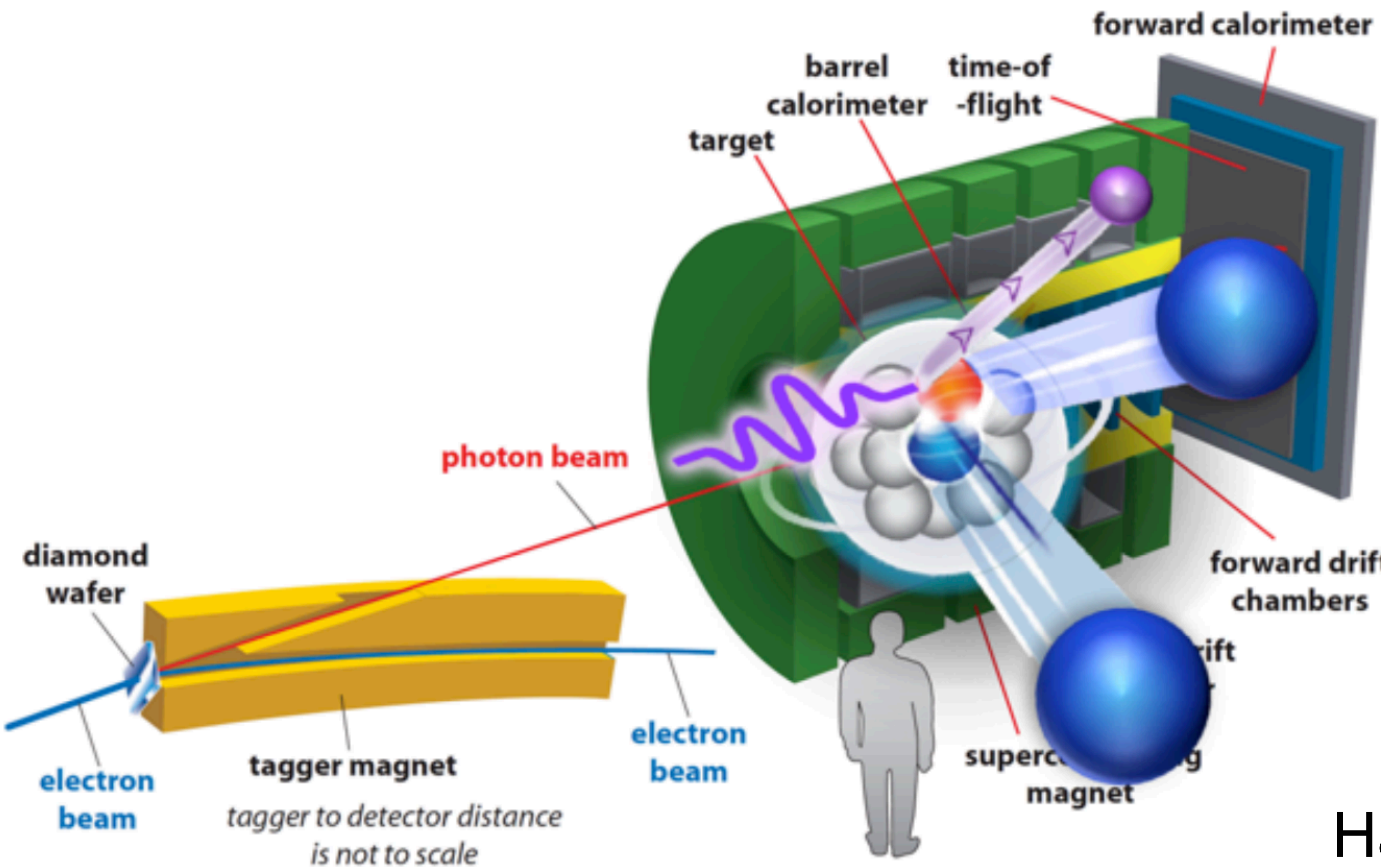
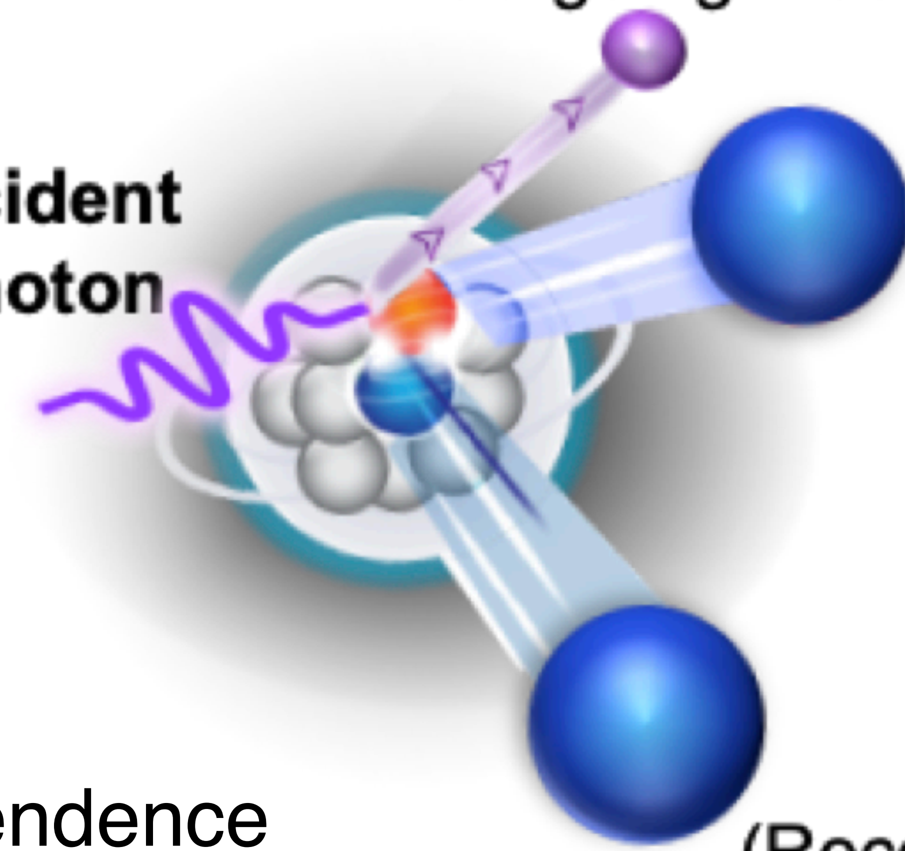
Probe Independence: How Well Do We Understand SRCs?

Studying 2N SRC using photoproduction

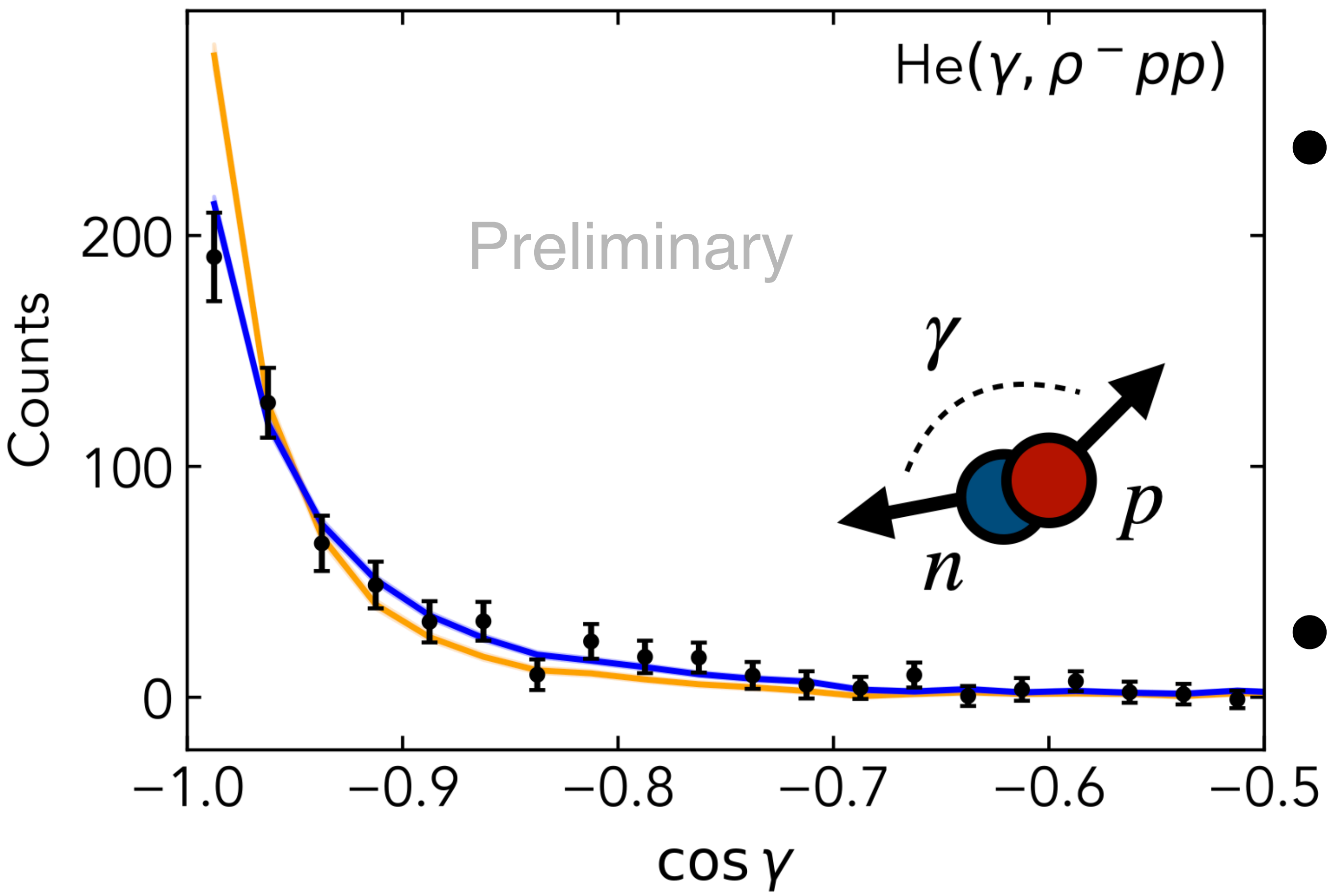


Hall D



- Establish probe-independence
- Explore unique kinematics
- Probe initial-state neutrons

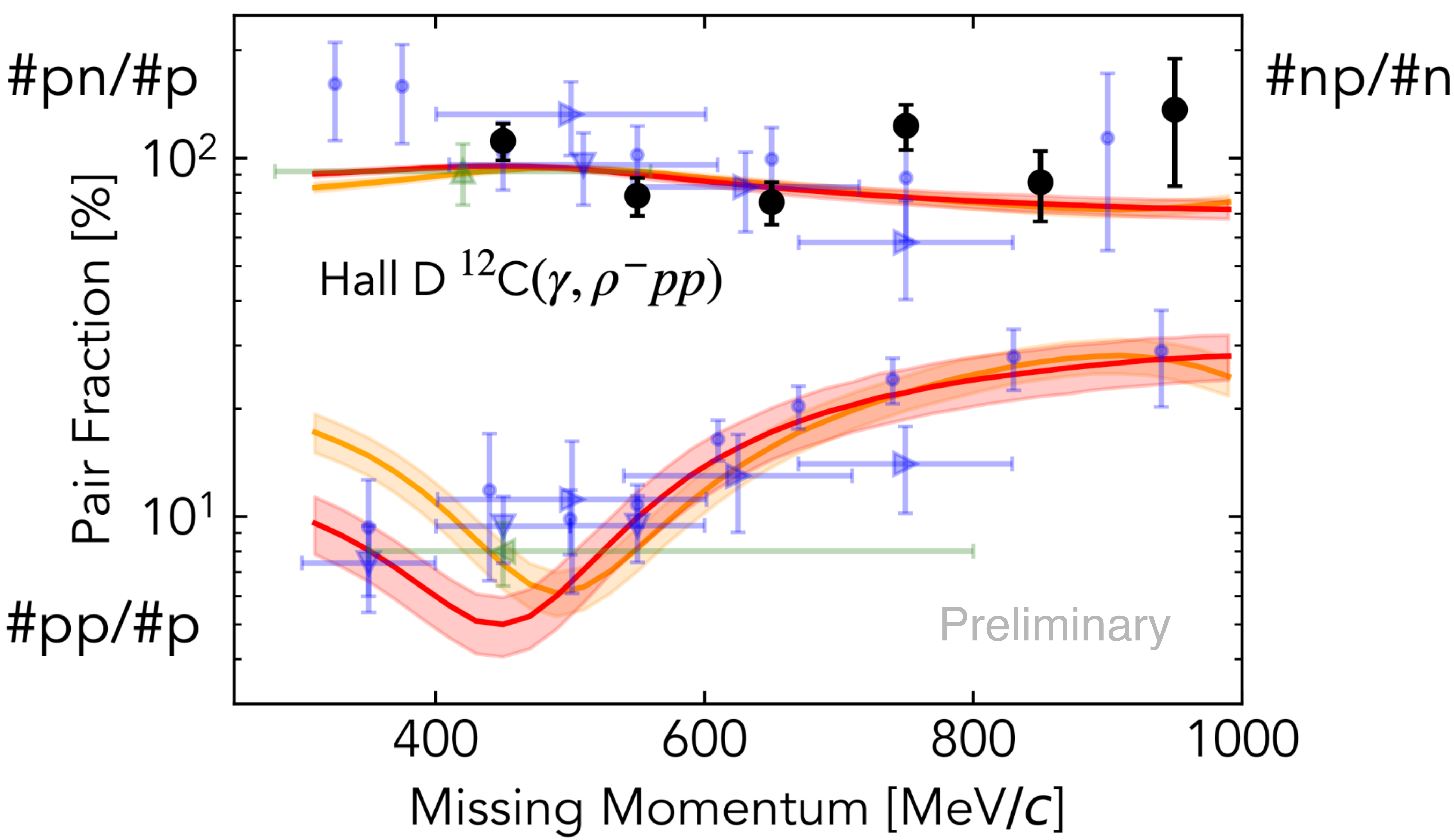
Under Analysis



- First observation of SRC breakup in photoproduction using (γ,ρ^-p) and (γ,ρ^-pp)
- Measures initial-state neutrons using charge-exchange reactions

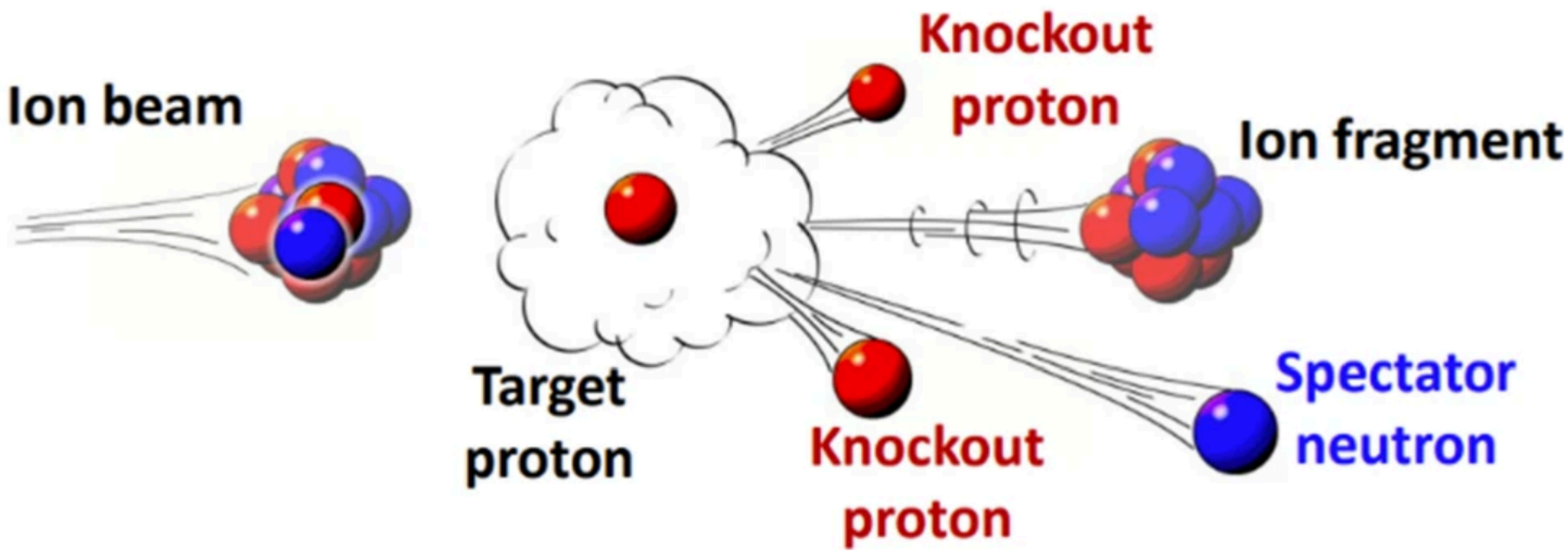
Figures courtesy of Jackson Pybus

Consistent with electron- and hadron-scattering results



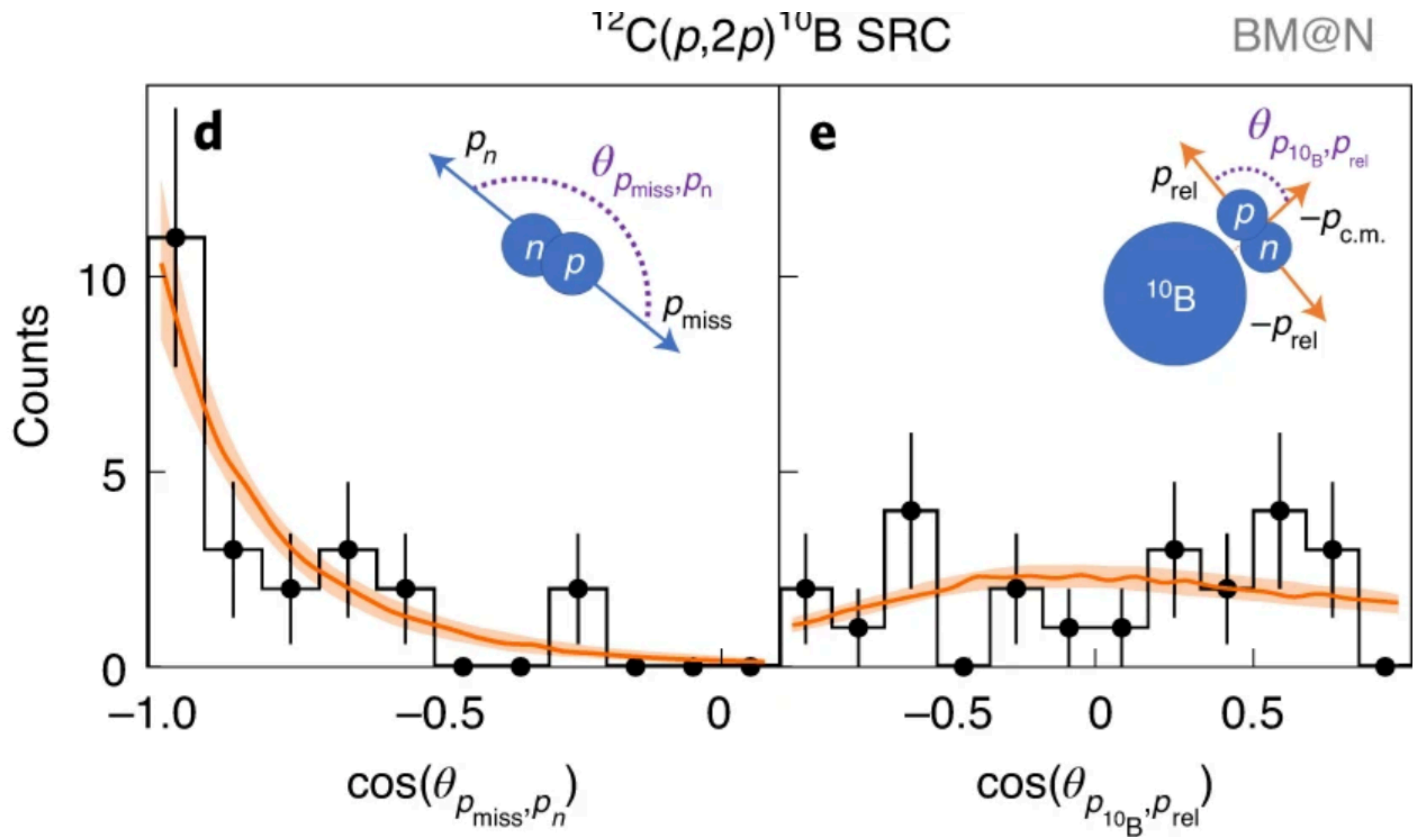
Figures courtesy of Jackson Pybus

Studying 2N SRC using hadronic probes



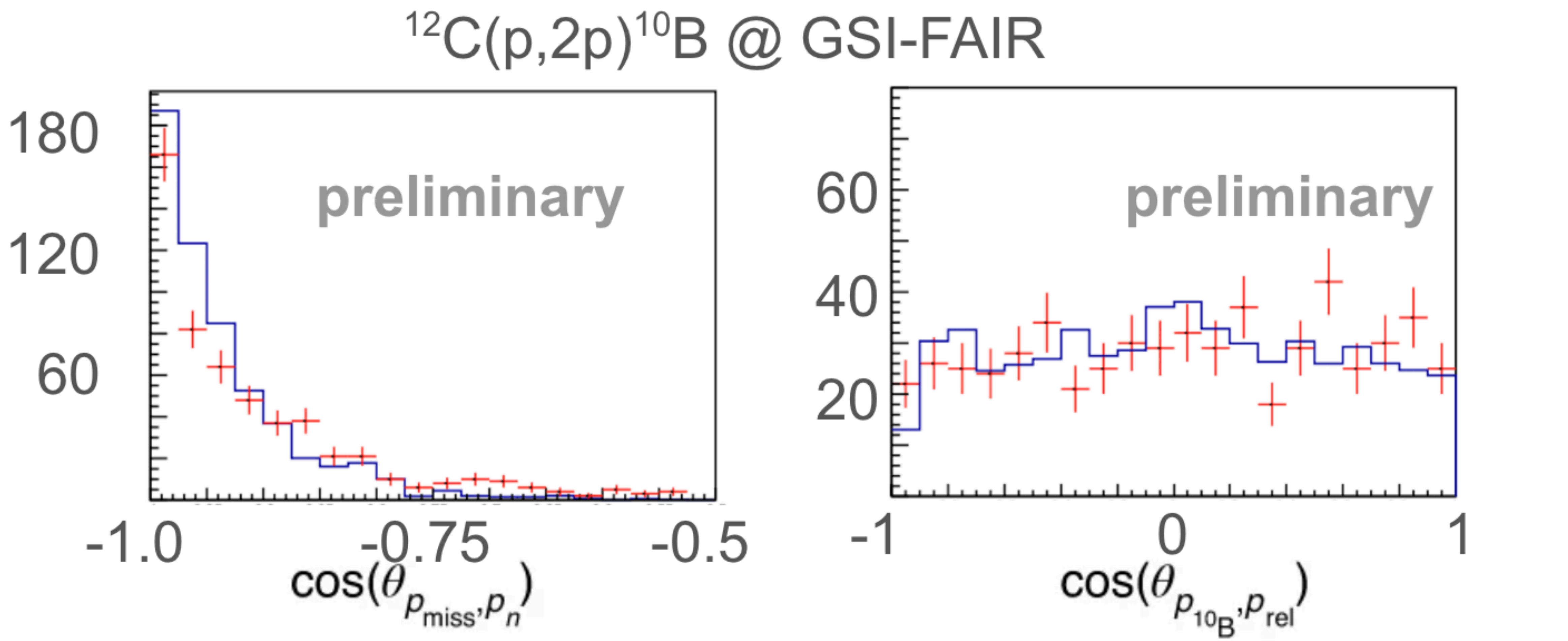
JINR and GSI-FAIR

Successful SRC identification



M. Patsyuk et al., Nat. Phys. 17 (2021)

Clear SRC Factorization



Back-to-back SRC pairs

SRC / A-2 system factorization

Confirmed *pn* dominance, low p_{cm}
indication for factorization A-2 vs pairs

Figures courtesy of Julian Kahlnbow

Open Questions

Quantitative era of 2N SRC

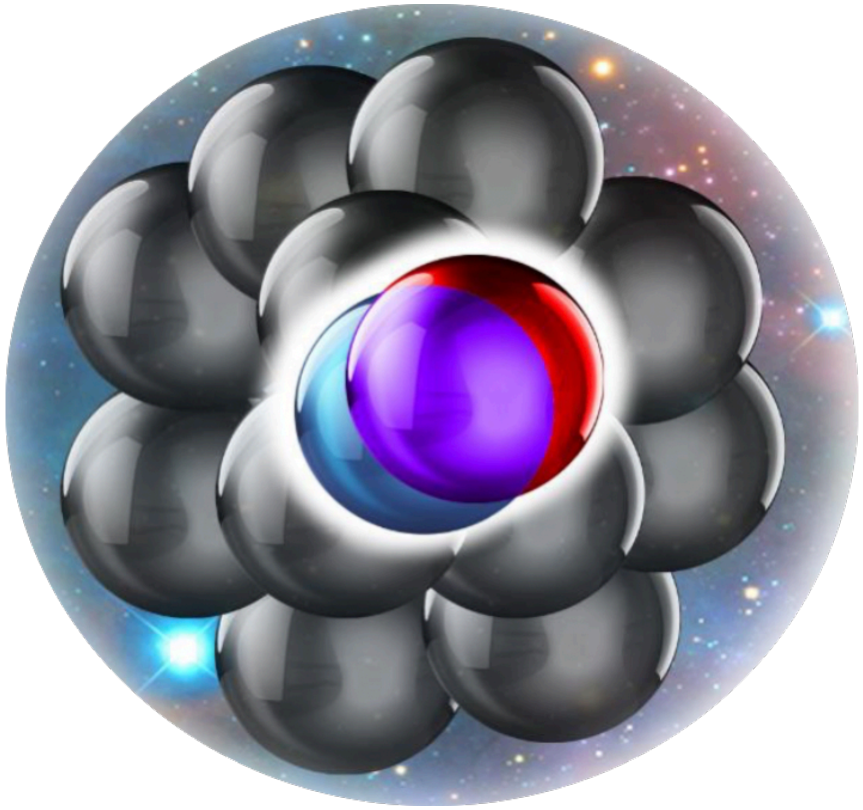
- Scale dependence (Q^2)
  All observables

- Probe independence (e, p, γ)
  Confirm factorization

- Pairing mechanisms

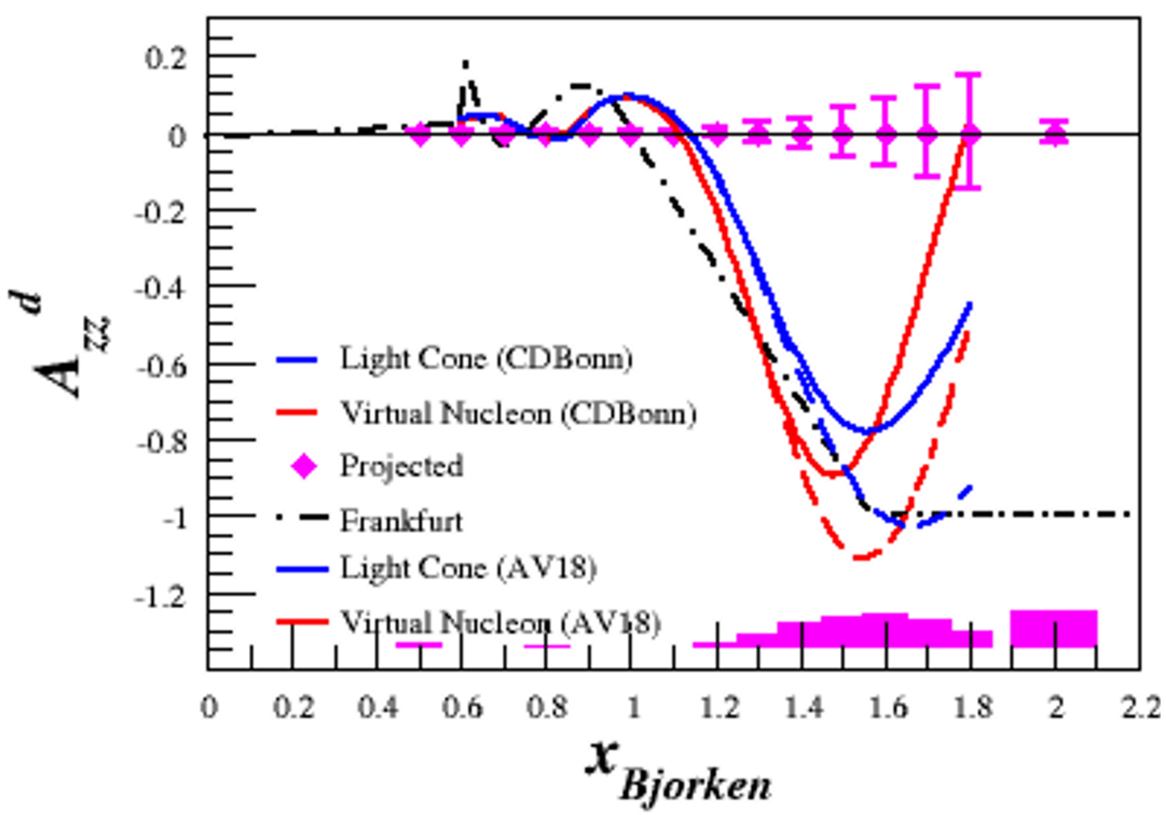
- Precision of interpretation in terms of ground state properties (theory)

- Neutron rich systems



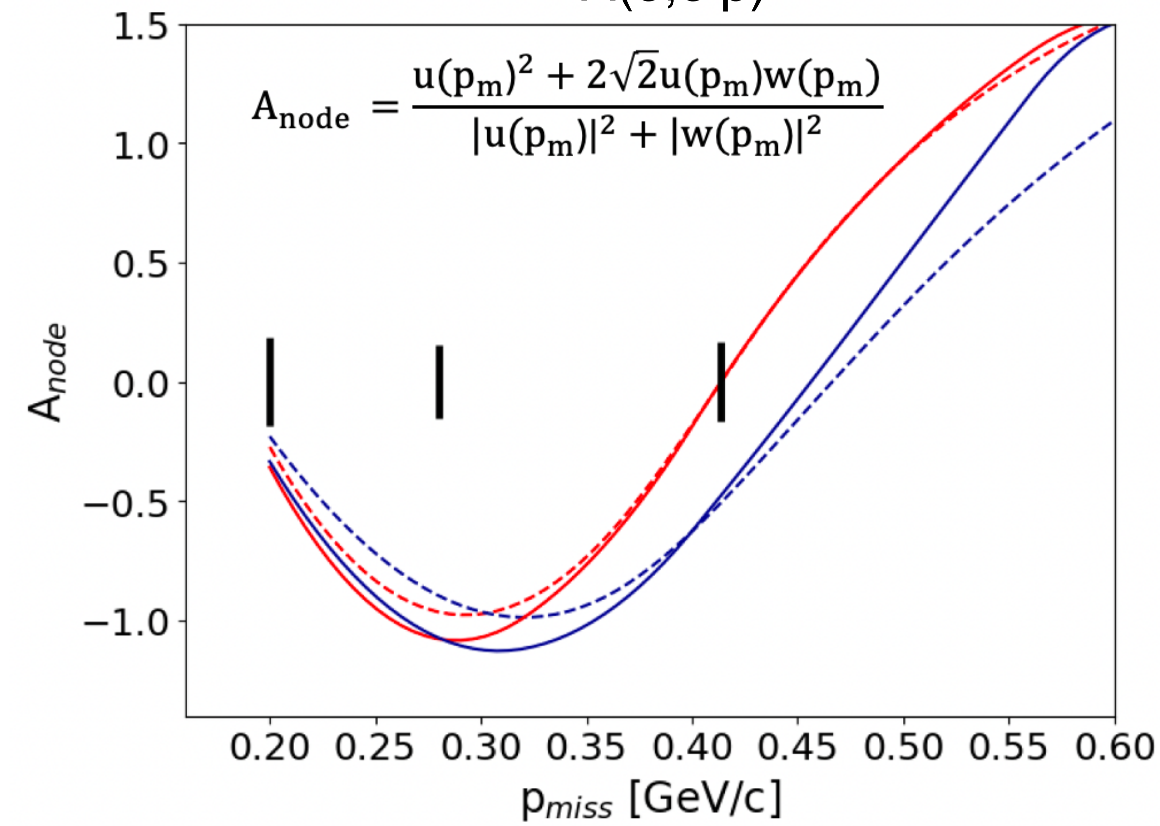
New observables: Using tensor polarized deuteron

A(e,e')



Approved experiment

A(e,e'p)



LOI

Further understanding of NN potentials

Measurement of the repulsive strength of the nuclear core ever done in electro-nuclear processes

Open Questions

Discovery era of 3N SRC

- (e,e') high Q^2 , x>2
  existence of a second plateau

- 3N KO (e,e'ppN)
  Extraction of triplet characteristics

Theory guidance

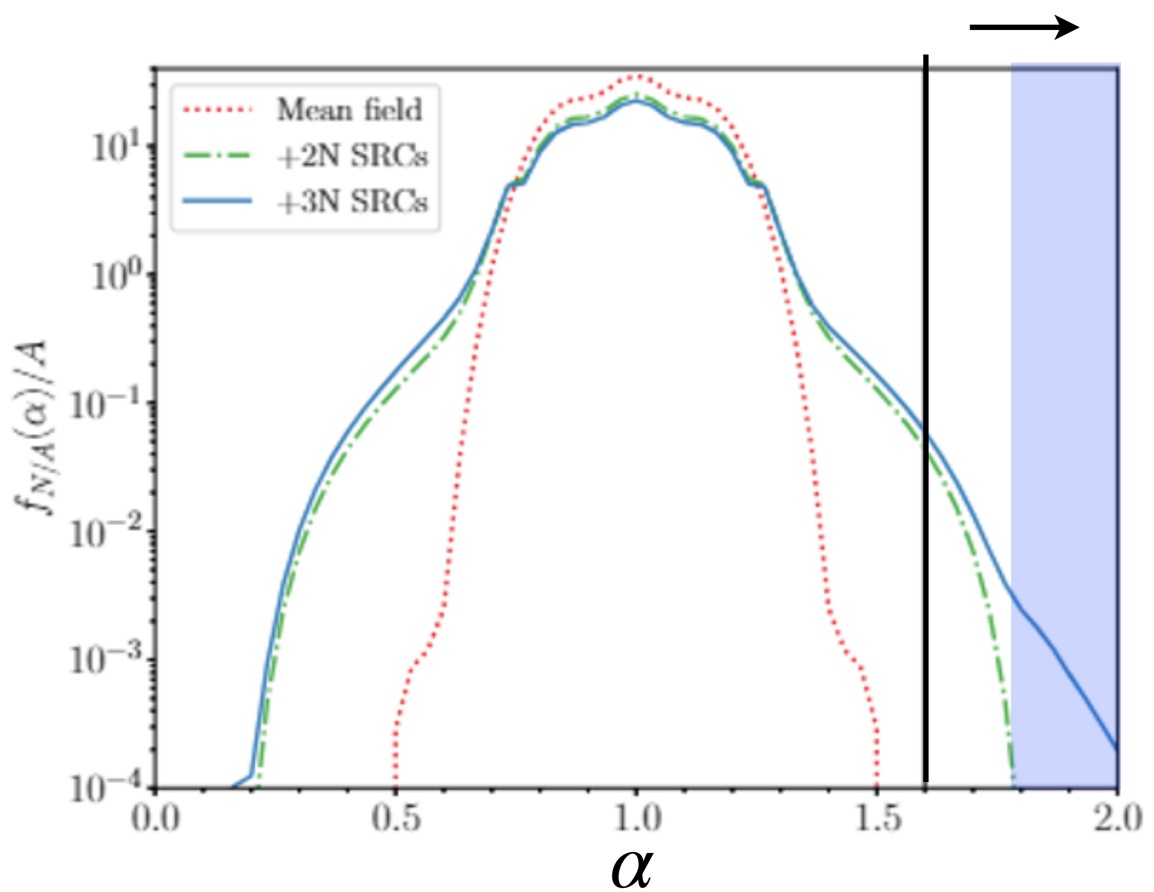
- Kinematics
- Ground state
- Factorization
- Phenomenology

Discovering 3N SRC

Inclusive worked for 2N SRC

Light cone momentum fraction in a 3N system

$$\alpha_{3N} = 3 - \frac{q_- + 3m_N}{2m_N}\left[1 + \frac{m_S^2 - m_N^2}{W_{3N}^2} + \sqrt{\left(1 - \frac{(m_S^2 + m_N^2)^2}{W_{3N}^2}\right)\left(1 - \frac{(m_S^2 - m_N^2)^2}{W_{3N}^2}\right)}\right]$$



Looking at the region where 3N is dominant

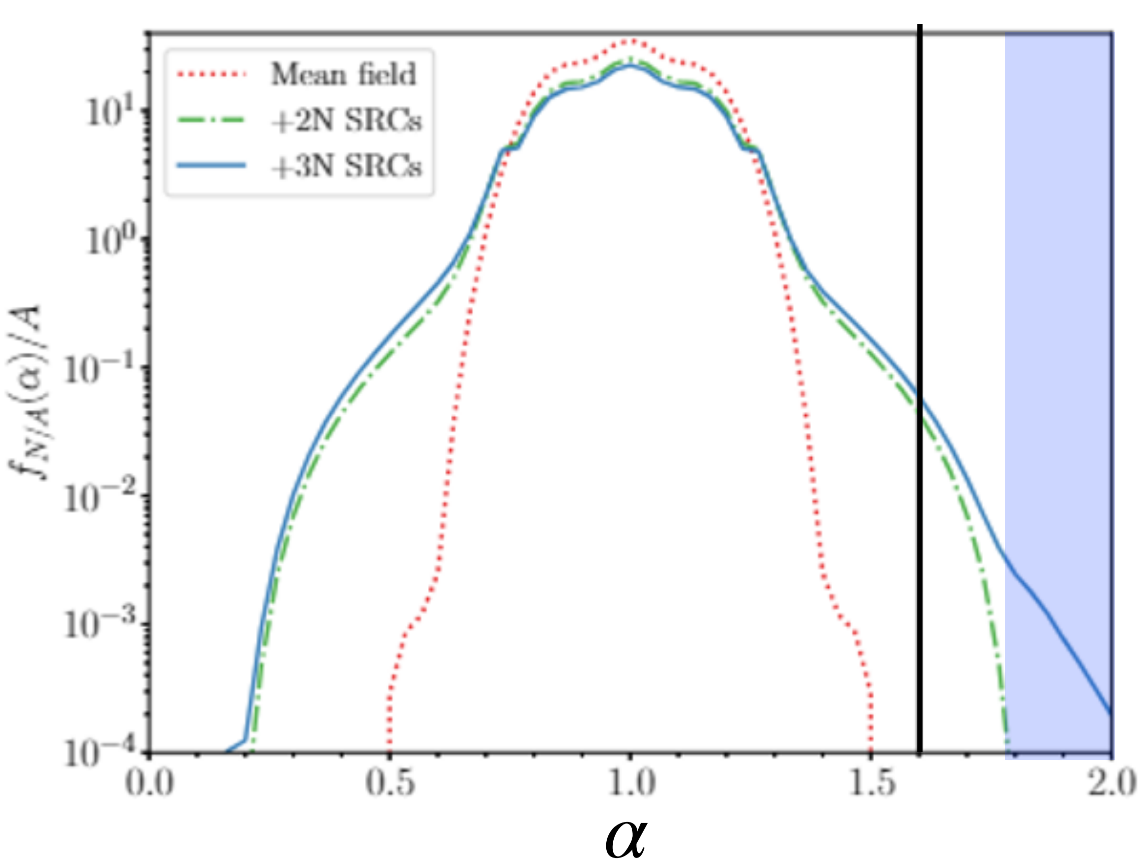
Completely dominant

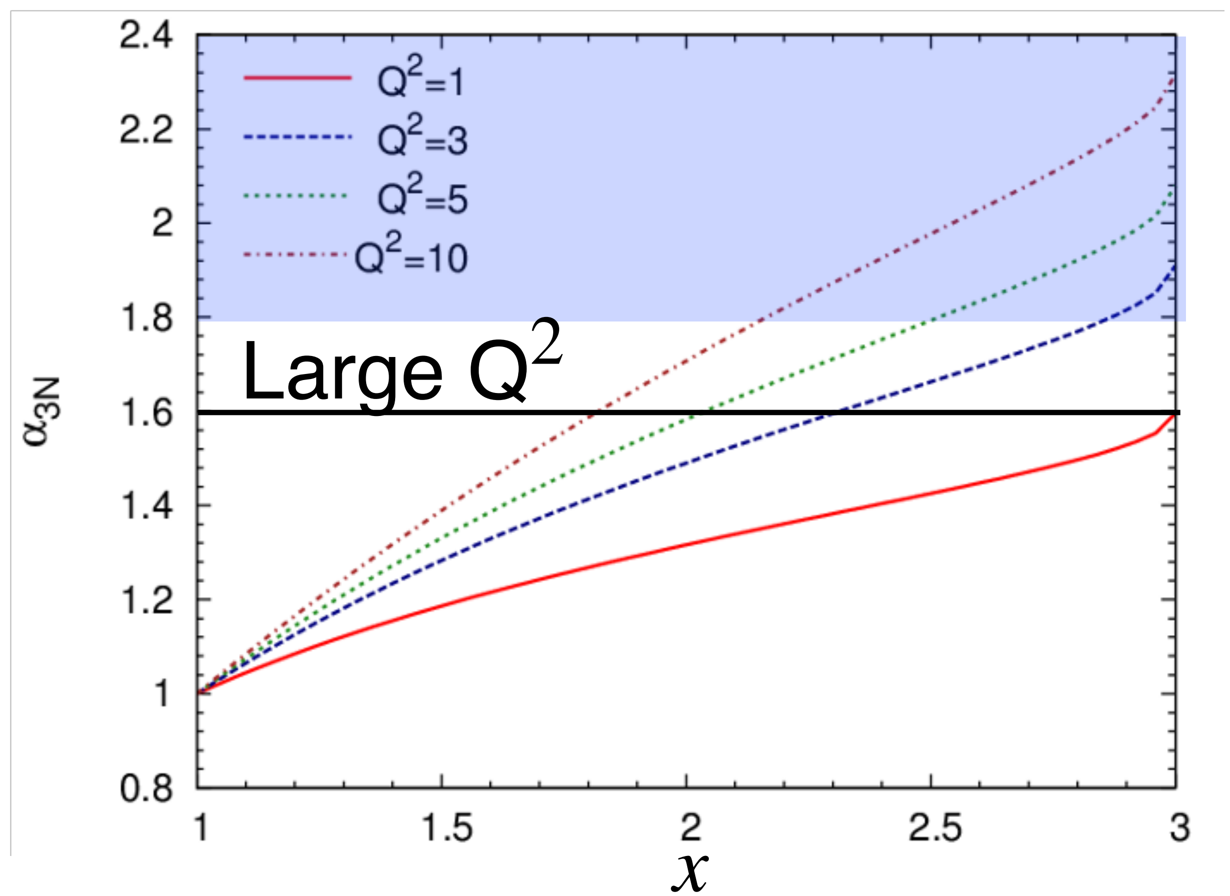
Discovering 3N SRC

Inclusive worked for 2N SRC

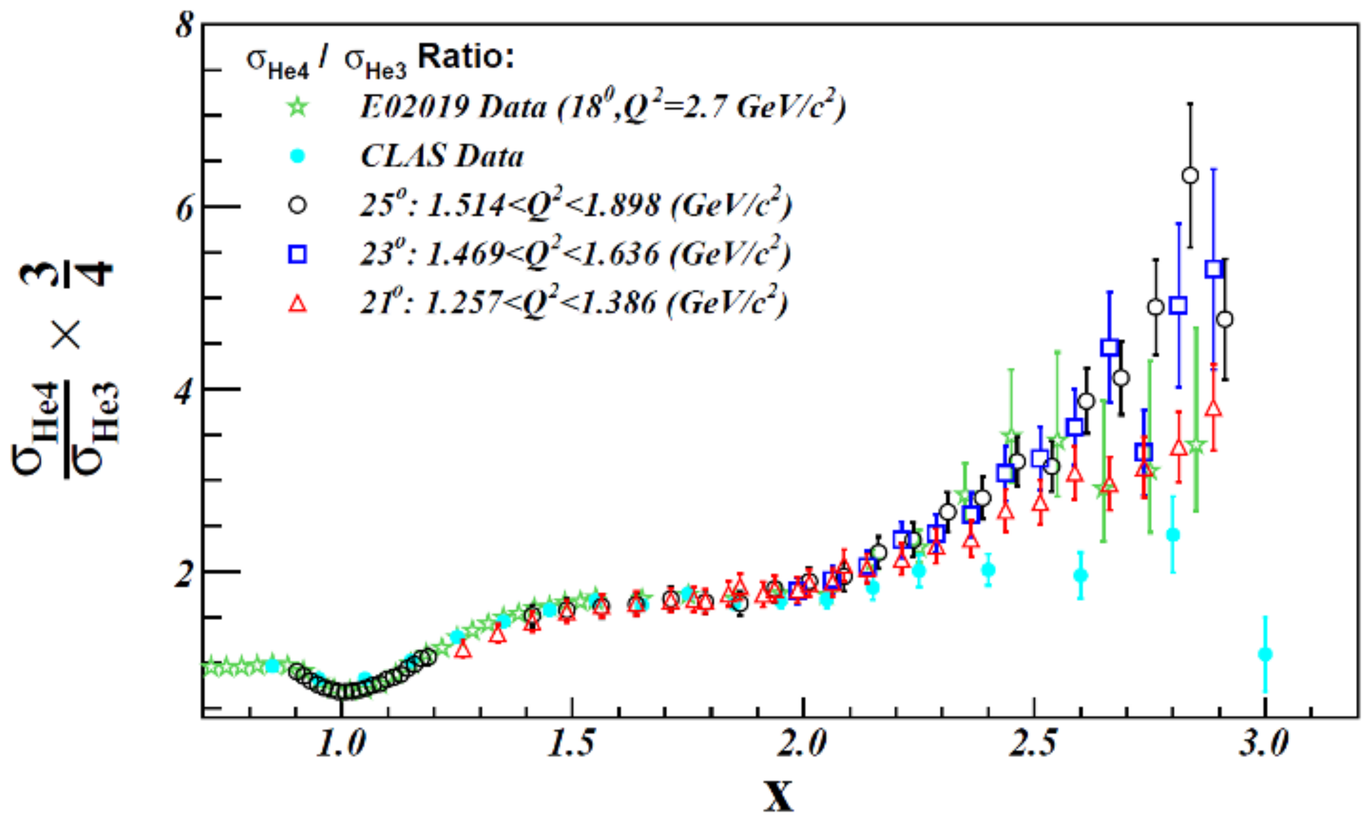
Light cone momentum fraction in a 3N system

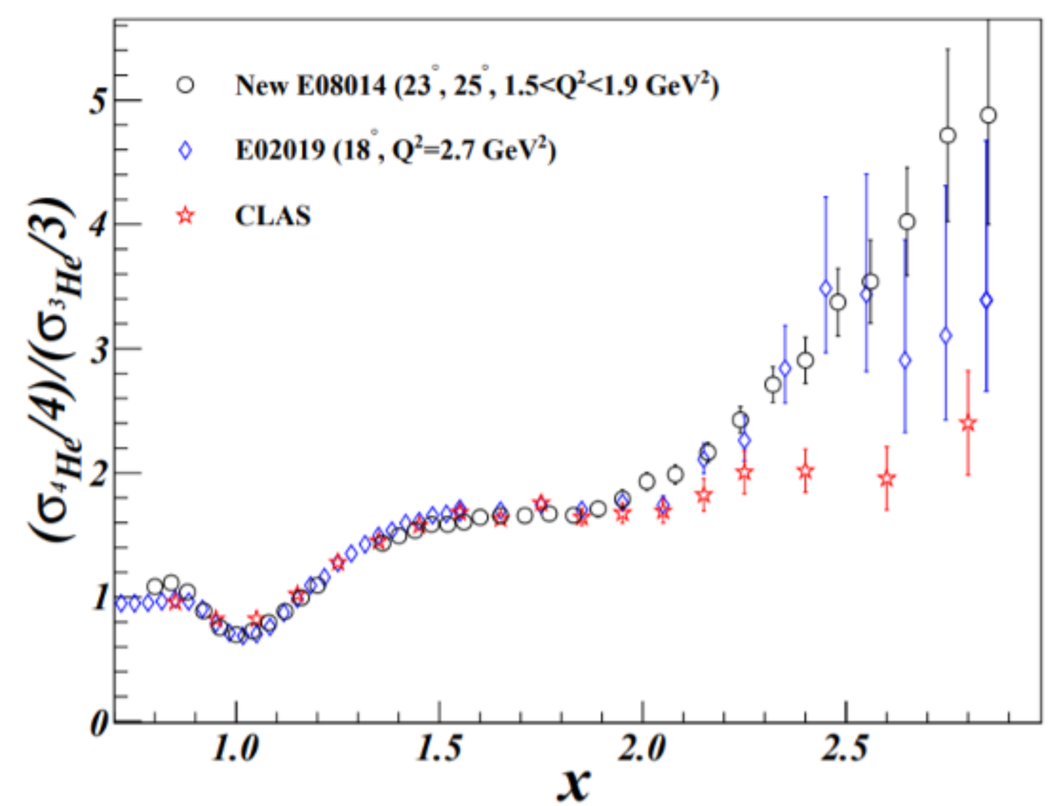
$$\alpha_{3N} = 3 - \frac{q_- + 3m_N}{2m_N}\left[1 + \frac{m_S^2 - m_N^2}{W_{3N}^2} + \sqrt{\left(1 - \frac{(m_S^2 + m_N^2)^2}{W_{3N}^2}\right)\left(1 - \frac{(m_S^2 - m_N^2)^2}{W_{3N}^2}\right)}\right]$$



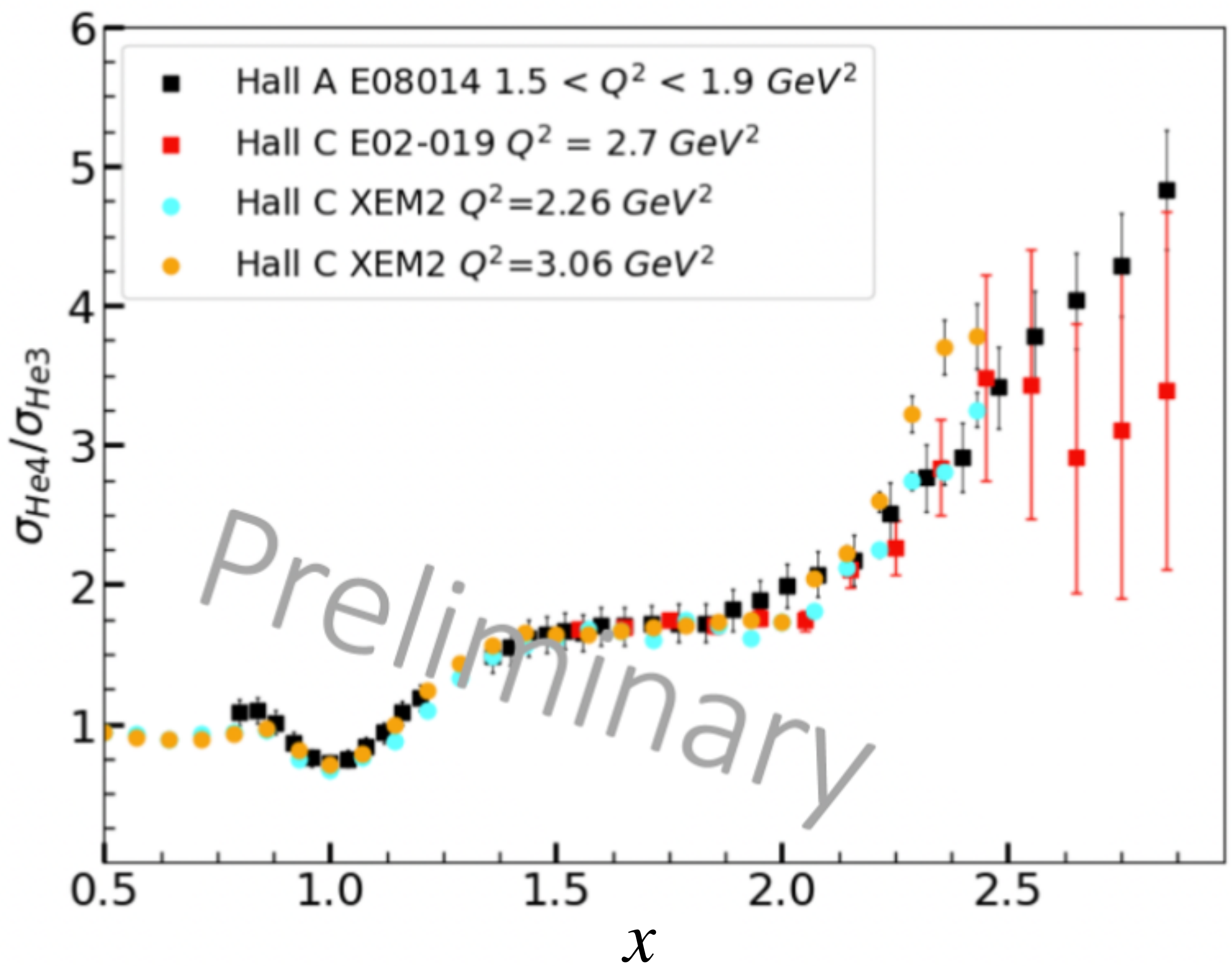


Previous data not at the quite at the right kinematics (low Q^2)

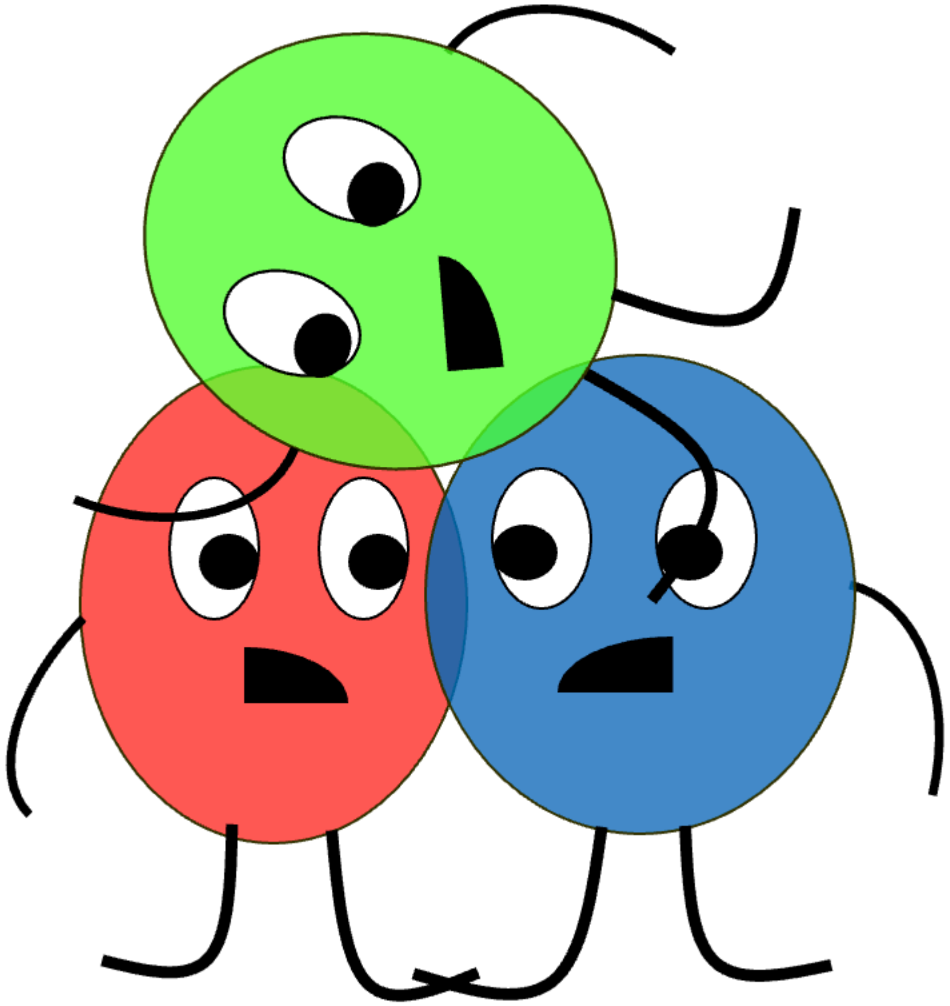




Under analysis (XEM2) just at the threshold where 3N SRC are dominant

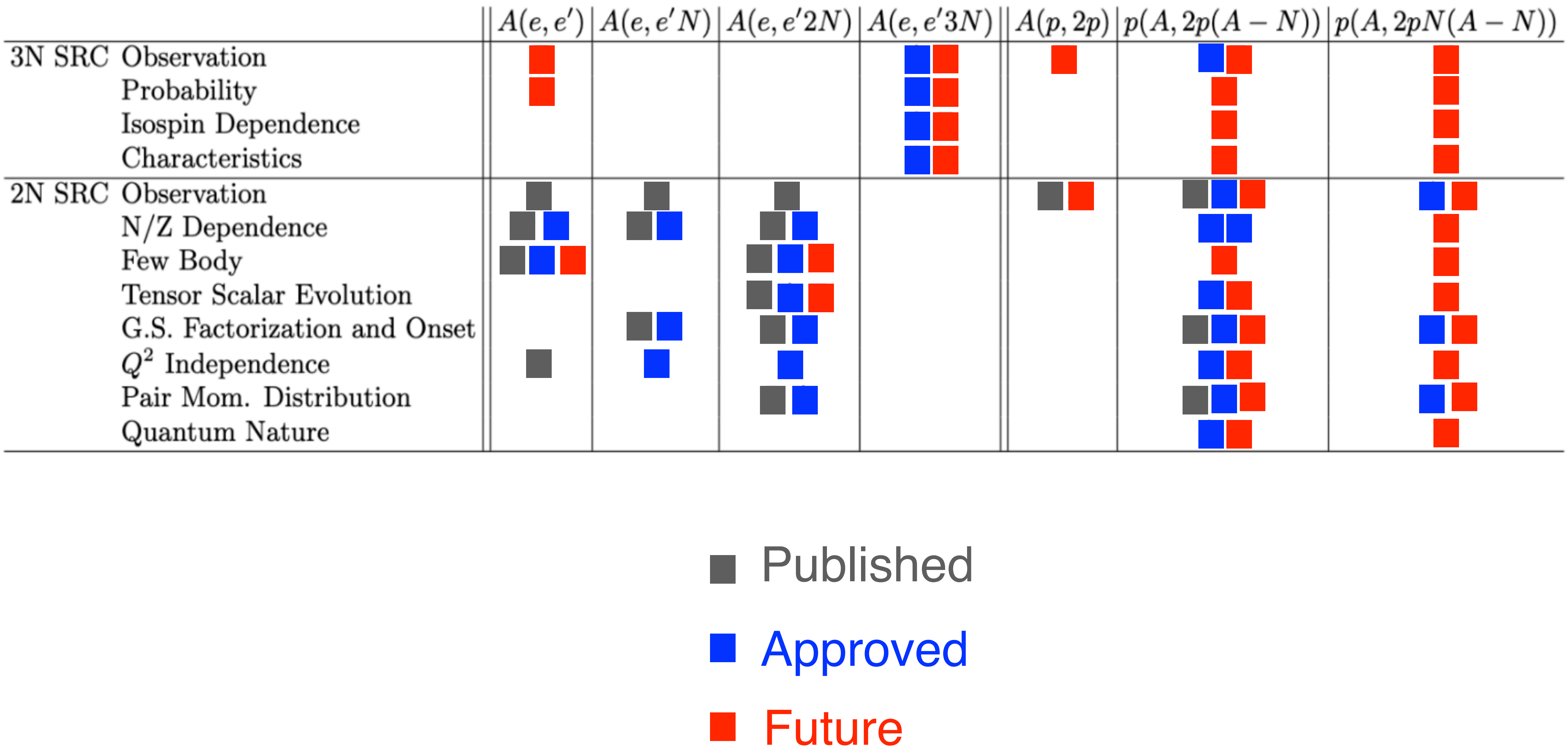


Authors working in the exciting
$x \gtrsim 2.5$ data points
Not yet in the plot



We need more 3N SRC dedicated measurements

Overview

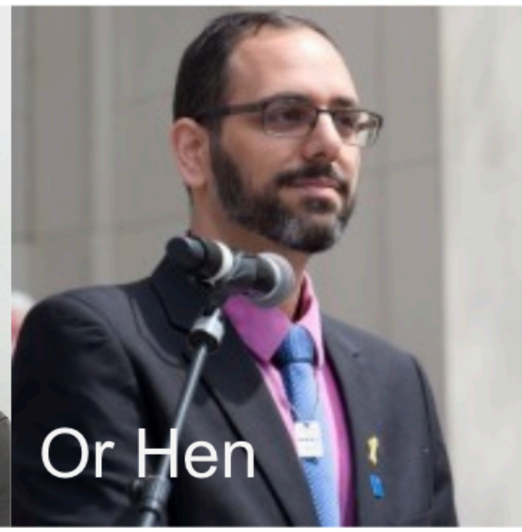

$A(e,e')$
$A(e,e'N)$
$A(e,e'2N)$
$A(e,e'3N)$
$A(p,2p)$
$p(A,2p(A-N))$
$p(A,2pN(A-N))$
3N SRC Observation
Probability
Isospin Dependence
Characteristics
2N SRC Observation
N/Z Dependence
Few Body
Tensor Scalar Evolution
G.S. Factorization and Onset
Q^2 Independence
Pair Mom. Distribution
Quantum Nature
Published
Approved
Future

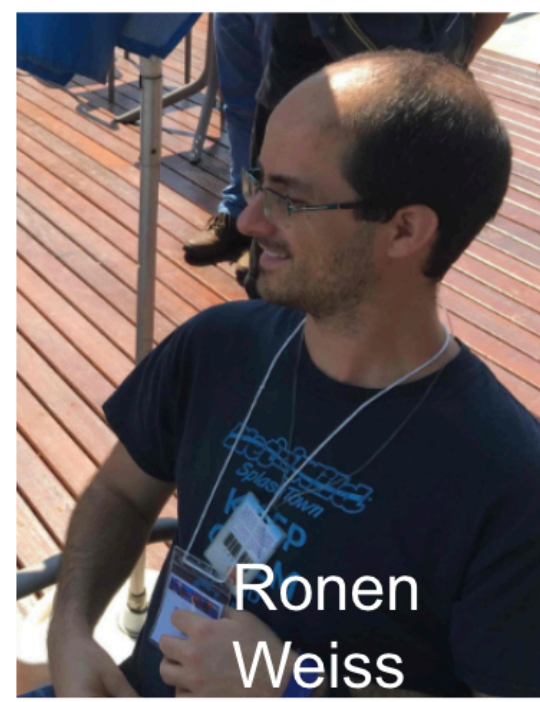
Overview

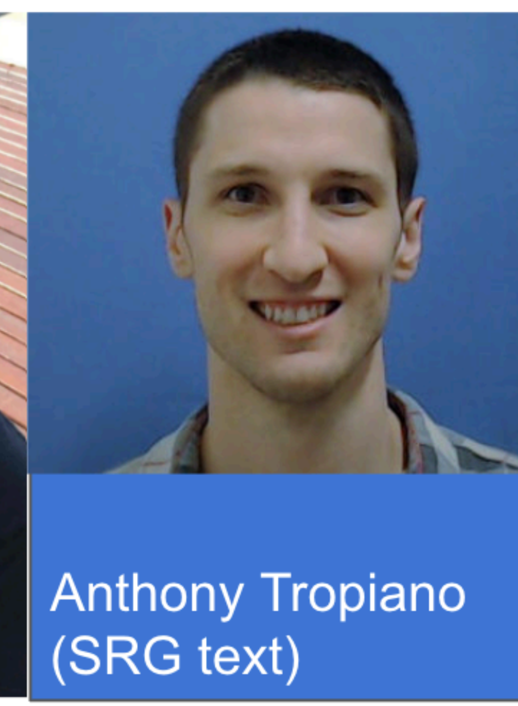
		$A(e,e')$	$A(e,e'N)$	$A(e,e'2N)$	$A(e,e'3N)$
3N SRC	Observation	■			■
	Probability	■			■
	Isospin Dependence				■
	Characteristics				■
2N SRC	Observation				
	N/Z Dependence				
	Few Body	■		■	
	Tensor Scalar Evolution			■	
	G.S. Factorization and Onset				
	Q^2 Independence				
	Pair Mom. Distribution				
	Quantum Nature				

■ Future with electron scattering

SRC white paper group







SRC white paper group

+ Large Community that participated in our While-Paper Forum, provided feedback, and signed on the paper!

Thank You!

GSI

JINR

TEL AVIV UNIVERSITY

Jefferson Lab

THE UNIVERSITY OF TENNESSEE KNOXVILLE

OLD DOMINION UNIVERSITY

清華大学
Tsinghua University

BERKELEY LAB

GW UNIVERSITY WASHINGTON DC

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

THE CATHOLIC UNIVERSITY OF AMERICA

Massachusetts Institute of Technology

FIU

University of New Hampshire

TECHNISCHE UNIVERSITÄT DARMSTADT

Exciting times ahead!

cea