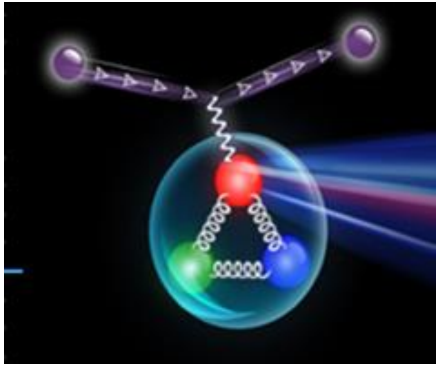
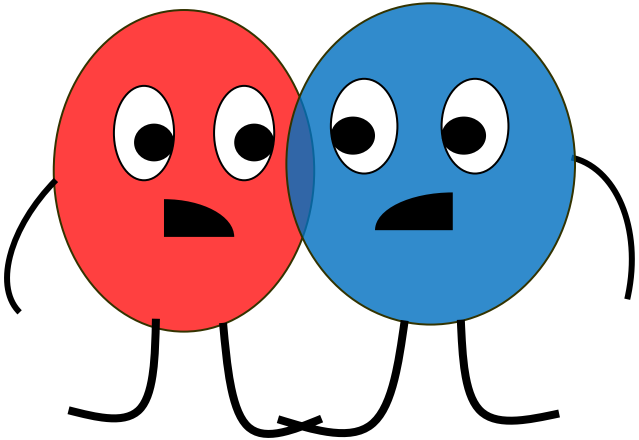
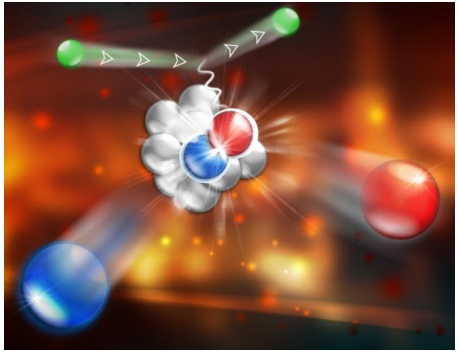
Don’t Stand So Close to Me

A story of short-range nuclear repulsion (…and more)





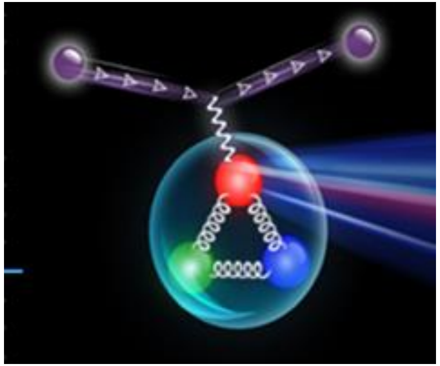


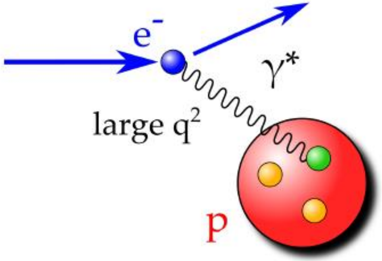
Nadia Fomin

University of Tennessee

September 1, 2022

Just a glance at the EMC effect

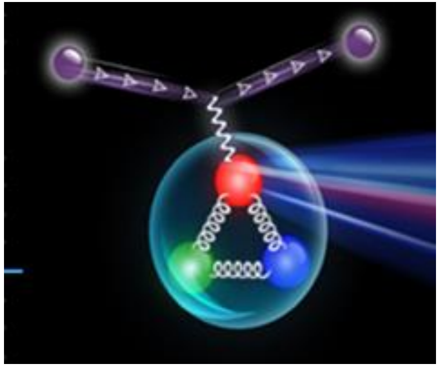


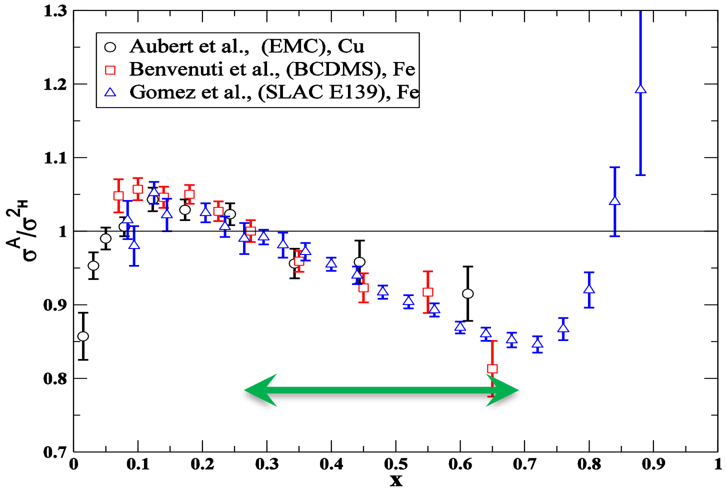


Callan-Gross relation:
$2xF_1(x) = F_2(x)$

$$2F_1(x) = \frac{F_2(x)}{x} = \sum_i e_i^2 q_i(x) = \frac{4}{9}[u(x) + \bar{u}(x)] + \frac{1}{9}[d(x) + \bar{d}(x)] + \frac{1}{9}[s(x) + \bar{s}(x)]$$

Just a glance at the EMC effect

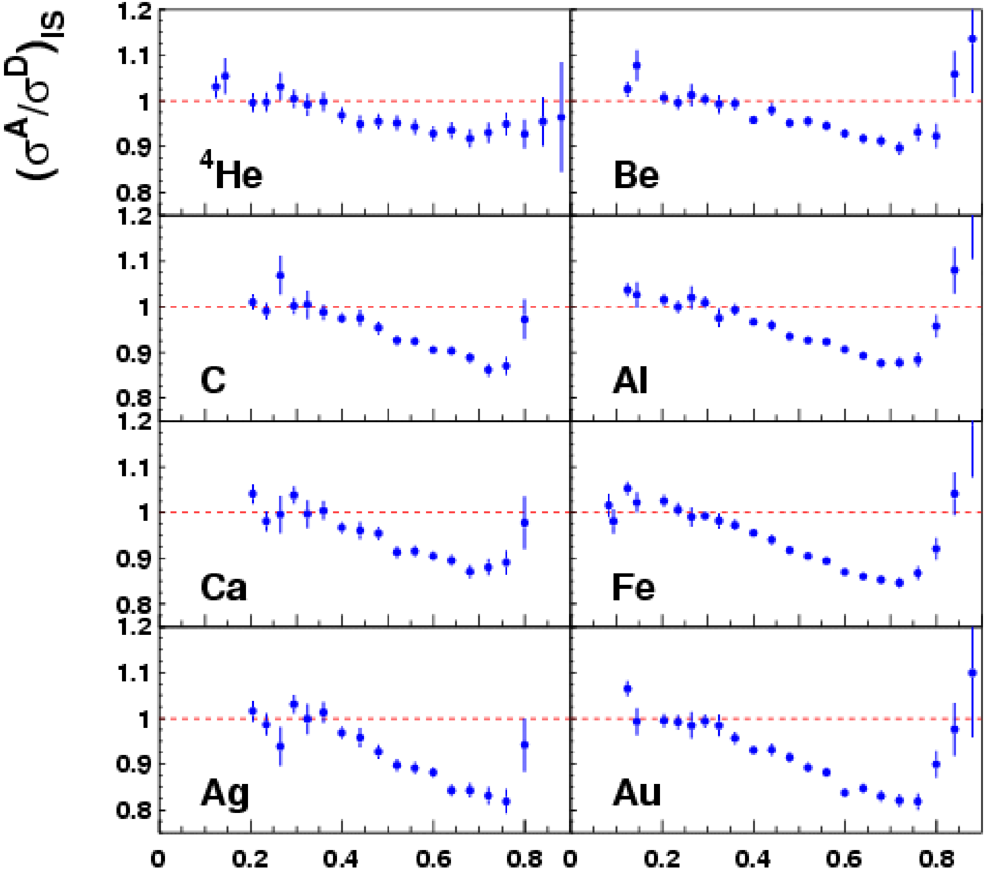


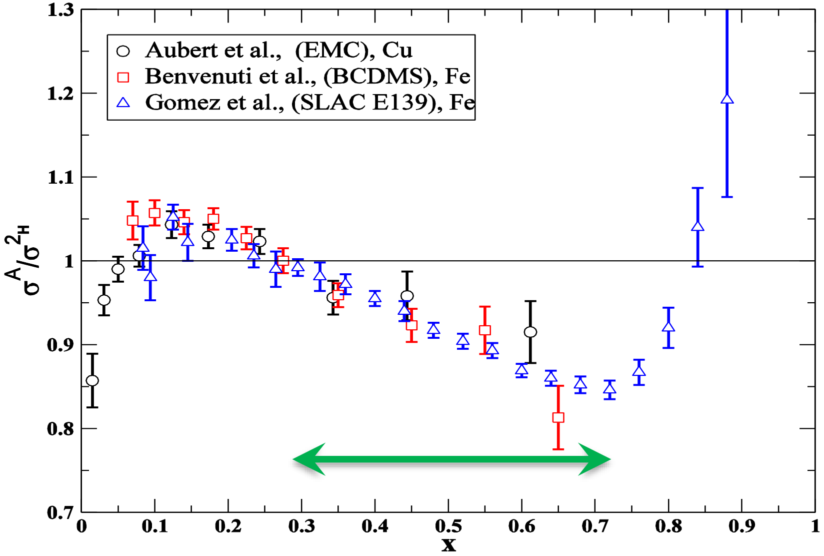


$$2F_1(x) = \frac{F_2(x)}{x} = \sum_i e_i^2 q_i(x) = \frac{4}{9}[u(x) + \bar{u}(x)] + \frac{1}{9}[d(x) + \bar{d}(x)] + \frac{1}{9}[s(x) + \bar{s}(x)]$$

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

The EMC effect

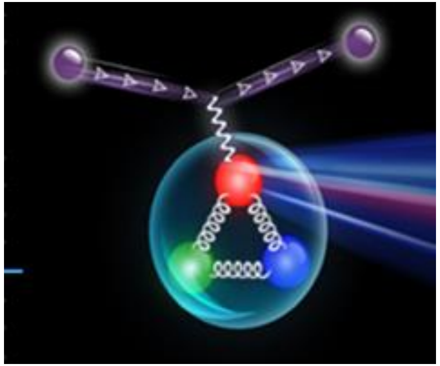


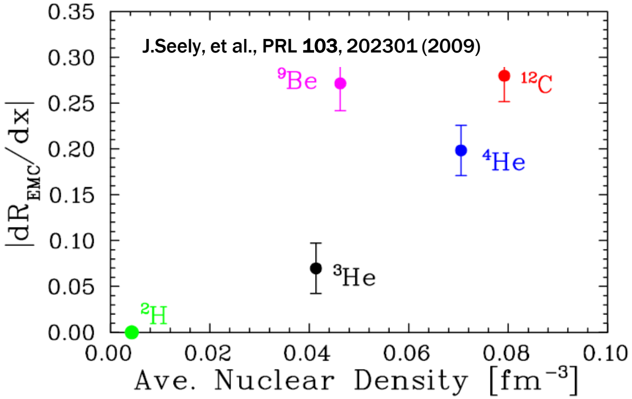


$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

Gomez et al, SLAC E139

Electron Scattering is our microscope

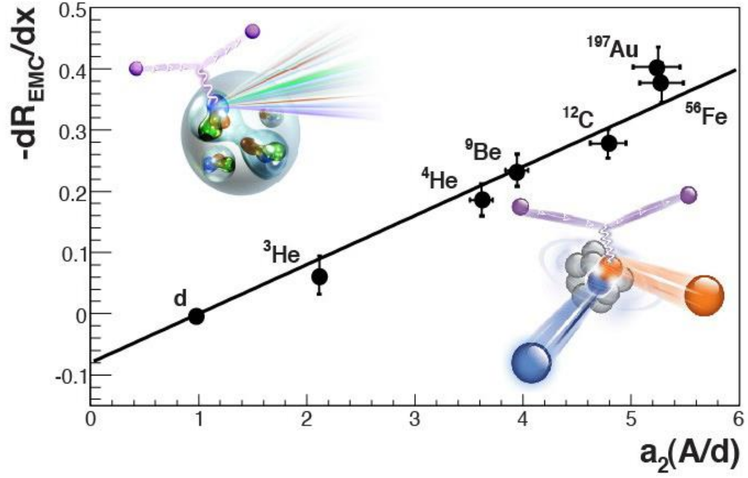




$$2F_1(x) = \frac{F_2(x)}{x} = \sum_i e_i^2 q_i(x) = \frac{4}{9}[u(x) + \bar{u}(x)] + \frac{1}{9}[d(x) + \bar{d}(x)] + \frac{1}{9}[s(x) + \bar{s}(x)]$$

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

Enter ^{9}Be

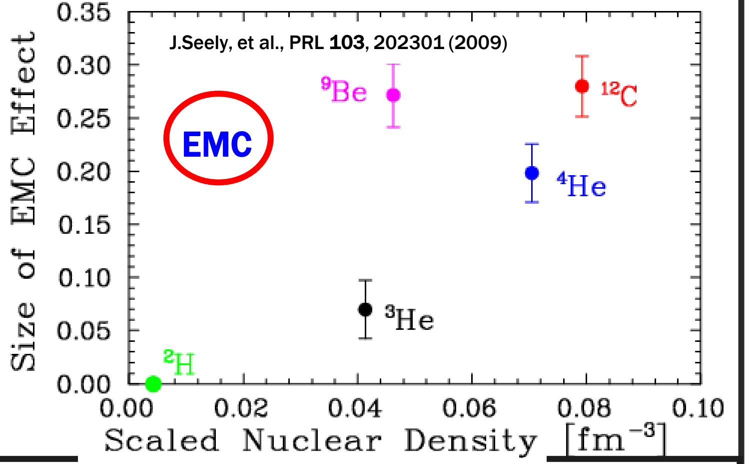


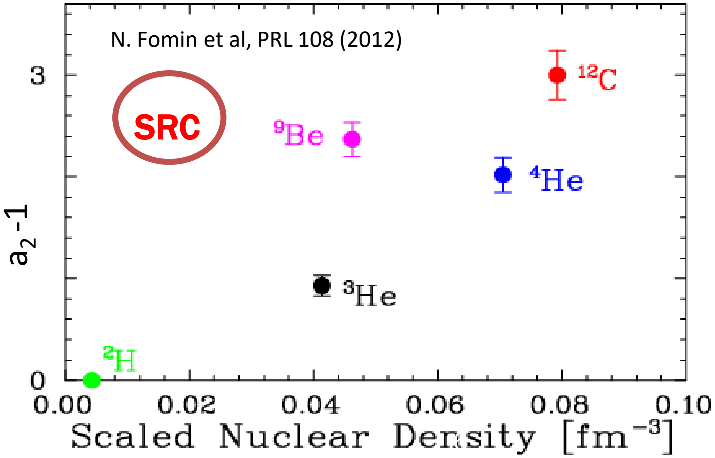
J. Seely, et al., PRL103, 202301 (2009)

N. Fomin, et al., PRL 108, 092052 (2012)

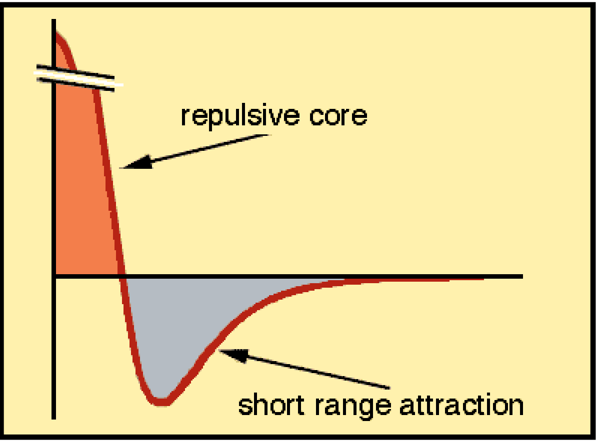
J. Arrington, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86, 065204 (2012)

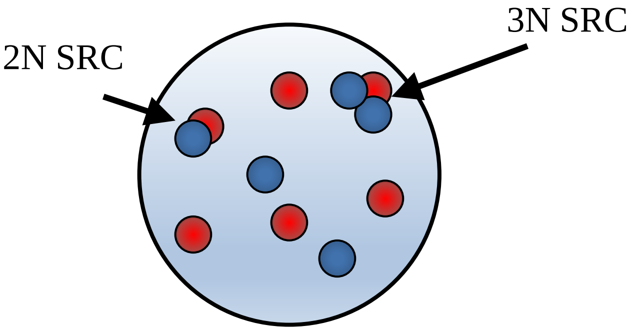
O. Hen, et al, PRC 85, 047301 (2012)
L. Weinstein, et al., PRL 106, 052301 (2011)

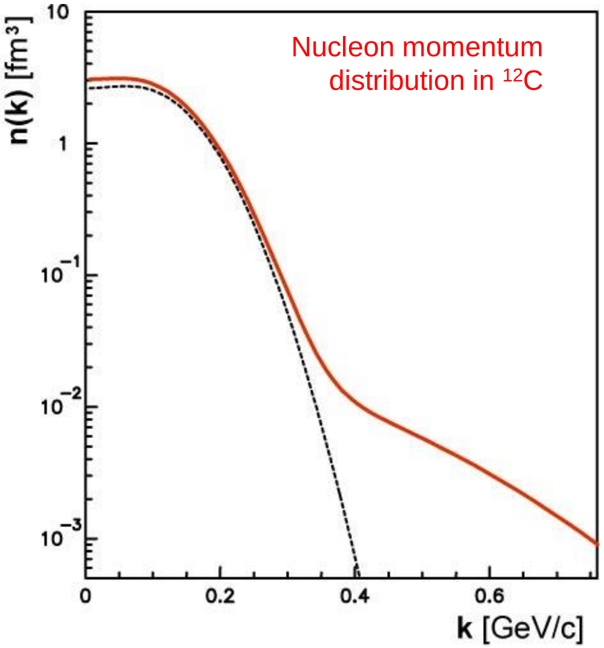




High-Momentum Nucleons ⇔ Short-Range Correlations







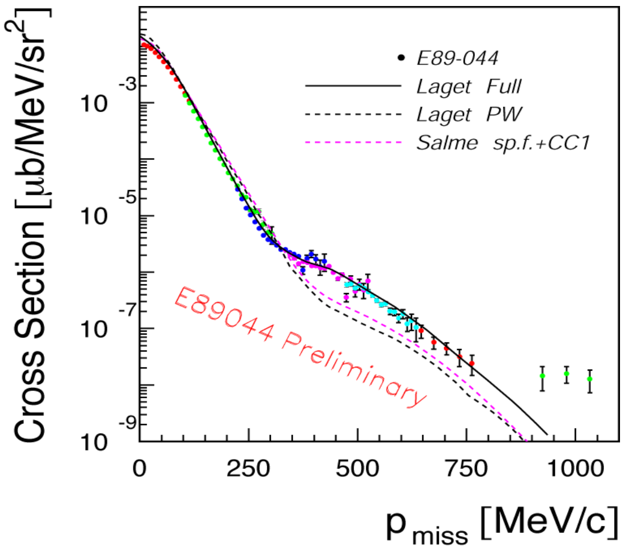
High momentum tails in A(e,e'p)

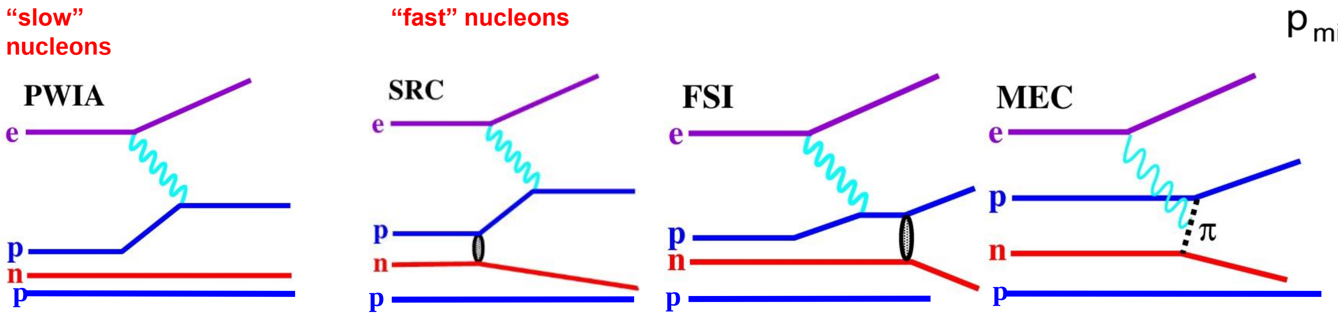
- E89-004: Measure of ^{3}He(e,e'p)d
- Measured far into high momentum tail: Cross section is ~5-10x expectation

Difficulty

- High momentum pair can come from SRC (initial state)

  OR
- Final State Interactions (FSI) and Meson Exchange Contributions (MEC)





A(e,e’p)

^{2}H(e,e’p) Mainz
PRC 78 054001 (2008)

E =0.855 GeV
θ = 45º
E’=0.657 GeV
Q^2=0.33 GeV^2
x=0.88

Unfortunately: FSI, MECs overwhelm the high momentum nucleons

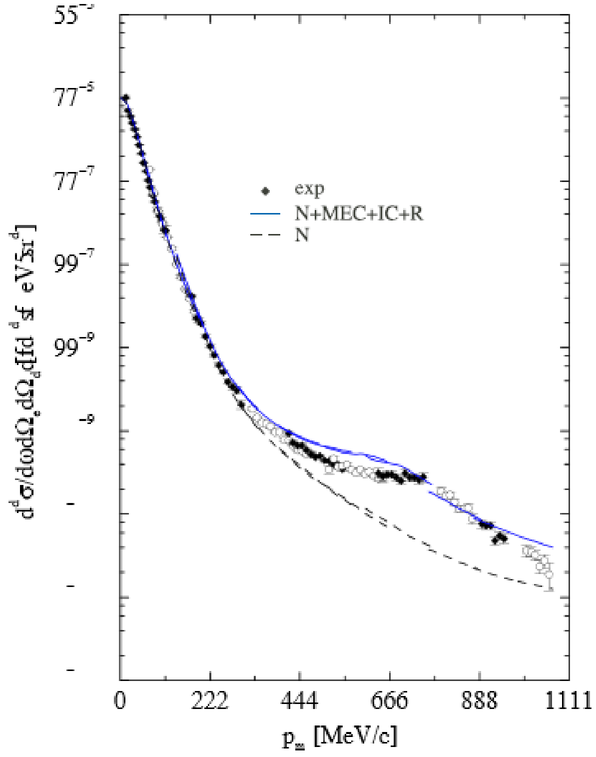
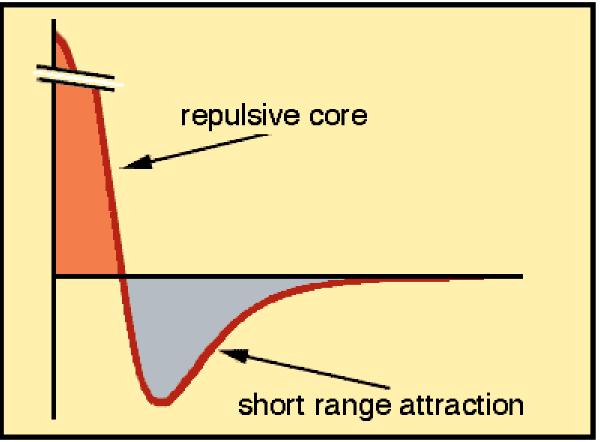
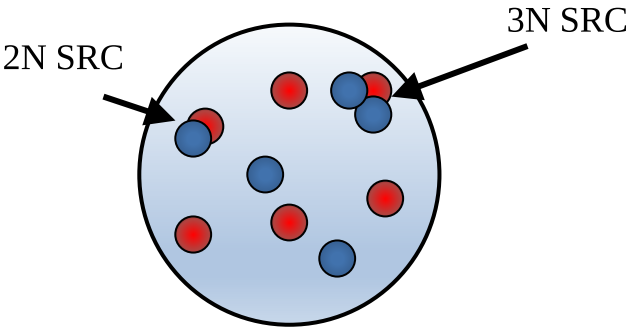
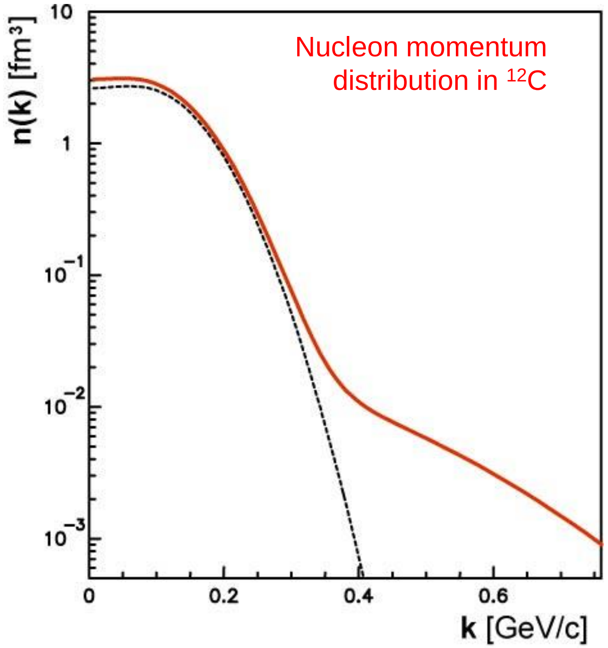


FIG. 1: The experimental D(e,e′p)n cross section as a function of missing momentum measured at MAMI for $Q^2 = 0.33$ $(\mathrm{GeV}/c)^2$ [4] compared to calculations [7] with (solid curve) and without (dashed curve) MEC and IC. Both calculations include FSI. The low p_m data have been re-analyzed and used in this work to determine f_{LT} (color online).

High-Momentum Nucleons ⇔ Short-Range Correlations





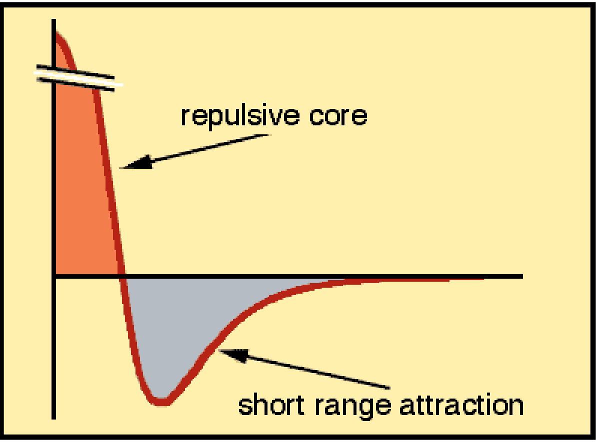


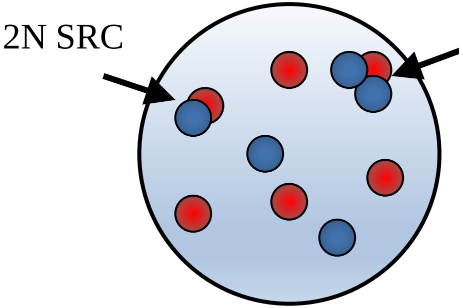
Try inclusive scattering!

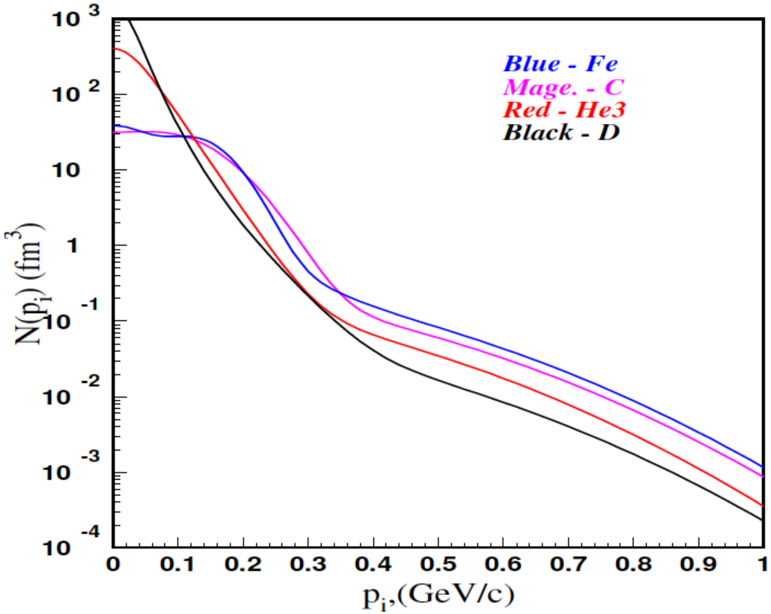
Select kinematics such that the initial nucleon momentum $> k_f$

Do a relative measurement

High-Momentum Nucleons ⇔ Short-Range Correlations







Try inclusive scattering!

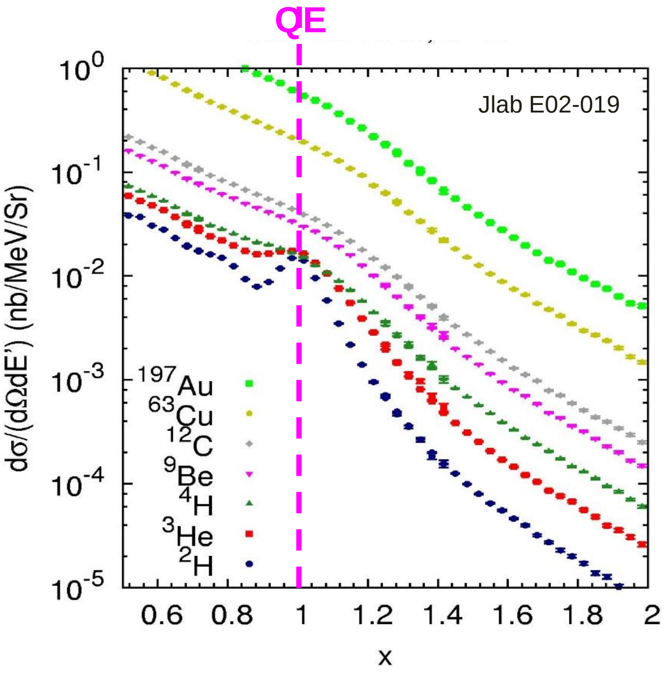
Select kinematics such that the initial nucleon momentum $> k_f$

Do a relative measurement

Short Range Correlations

- To experimentally probe SRCs, must be in the high-momentum region (x>1)
- To measure the relative probability of finding a correlation, ratios of heavy to light nuclei are taken
- In the high momentum region, FSIs are thought to be confined to the SRCs and therefore, cancel in the cross section ratios

$$\sigma(x, Q^2) = \sum_{j=1}^{A} A \frac{1}{j} a_j(A)\sigma_j(x, Q^2)$$
$$= \frac{A}{2} a_2(A)\sigma_2(x, Q^2) +$$
$$\frac{A}{3} a_3(A)\sigma_3(x, Q^2) + ...$$

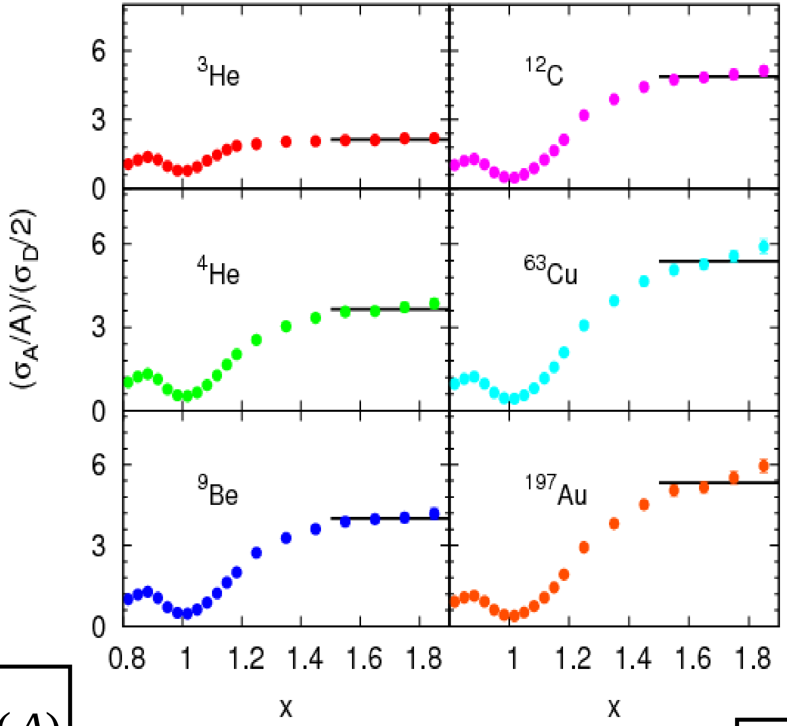


$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A)$$

THE UNIVERSITY OF TENNESSEE KNOXVILLE

E02-019: 2N correlations in A/D ratios

A	θ_e=18°
^{3}He	2.14±0.04
^{4}He	3.66±0.07
Be	4.00±0.08
C	4.88±0.10
Cu	5.37±0.11
Au	5.34±0.11
$\langle Q^2 \rangle$	2.7 GeV^2
x_{min}	1.5



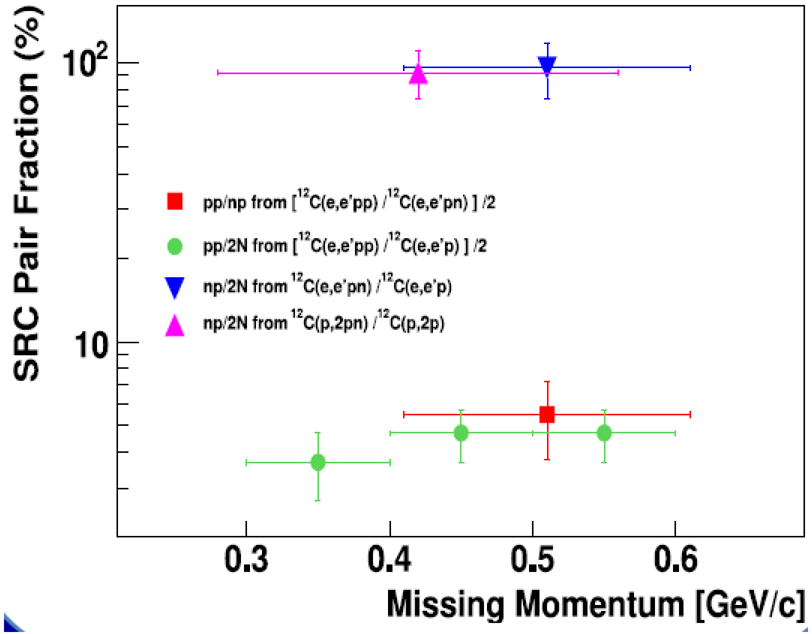
Fomin et al, PRL ***108*** *(2012)*

Jlab E02-019

$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A)$$

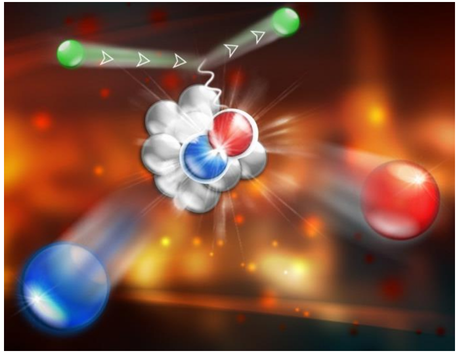
$\langle Q^2 \rangle$=2.7 GeV^2

2N knockout experiments establish NP dominance



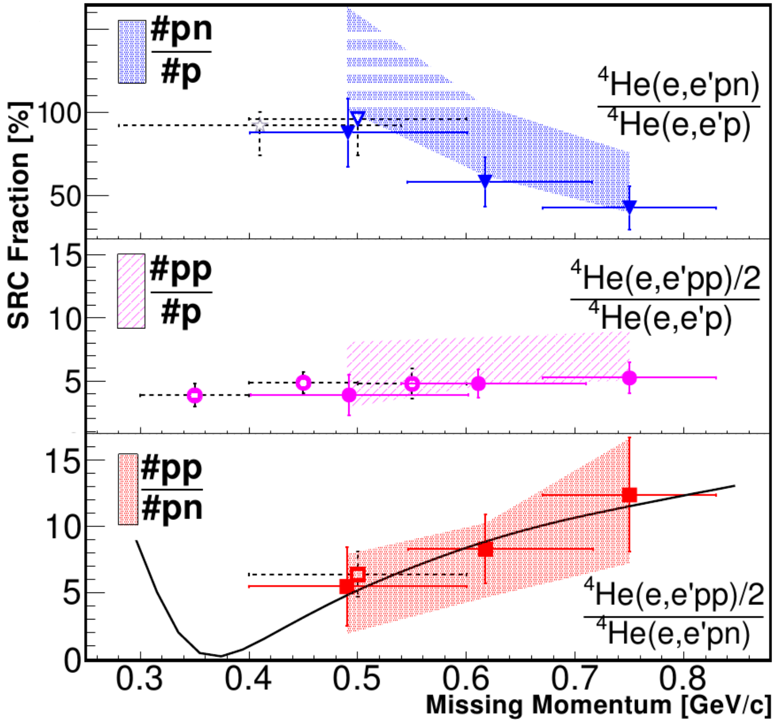
R. Subedi et al., Science 320, 1476 (2008)

R. Shneor et al., PRL 99, 072501 (2007)

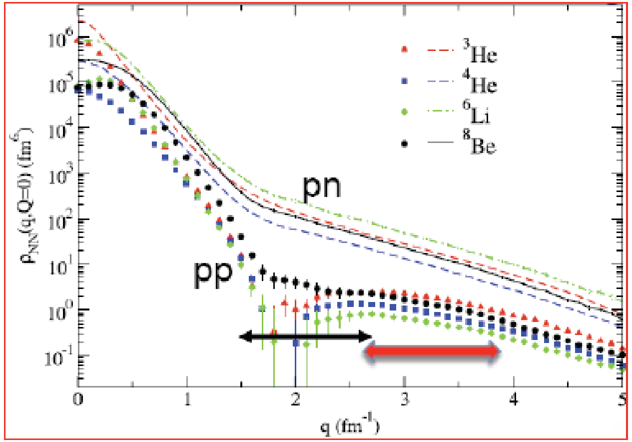


- Knockout high-initial-momentum proton, look for correlated nucleon partner.
- For 300 < P_{miss} < 600 MeV/c all nucleons are part of 2N-SRC pairs: 90% np, 5% pp (nn)

NP dominance: momentum dependent

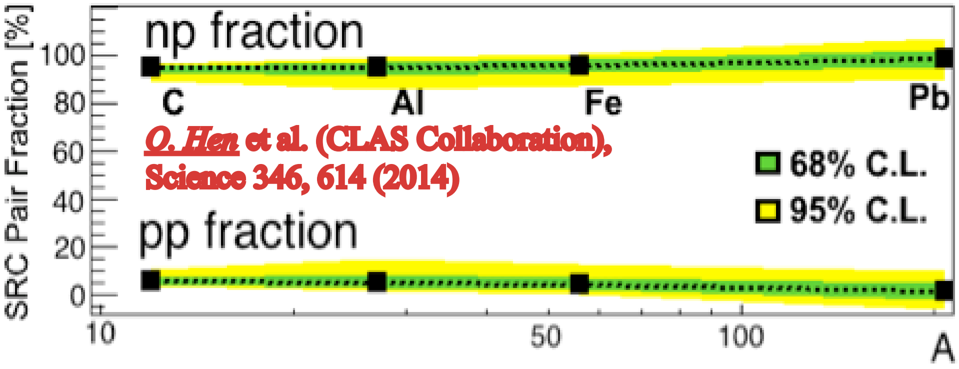


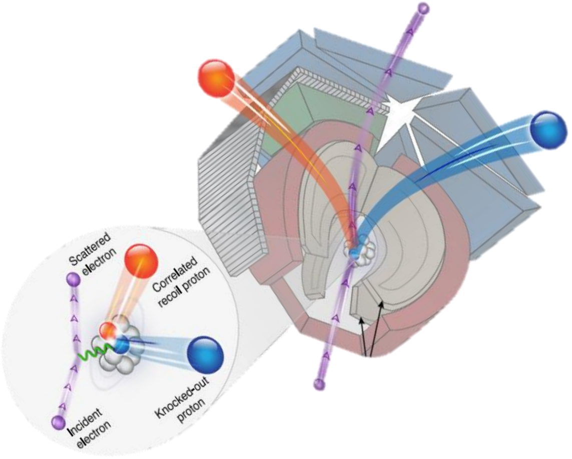
I. Korover et al, PRL 113 (2014) 022501



R. Schiavilla, R. B. Wiringa, S. C. Pieper, J. Carlson, Phys. Rev. Lett. **98** (2007) 132501

Data mining using CLAS
NP dominance continues for heavy nuclei



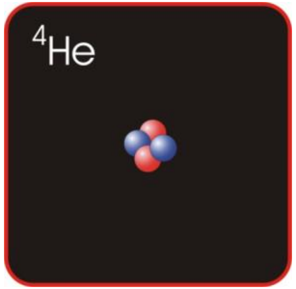


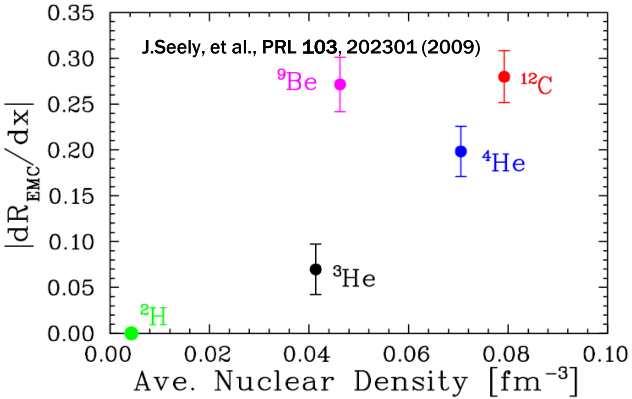
Assuming scattering off 2N-SRC pairs:

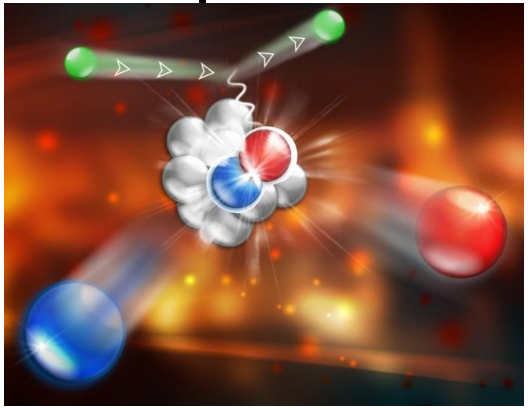
- (e,e'p) is sensitive to *np* and *pp* pairs
- (e,e'pp) is sensitive to *pp* pairs alone

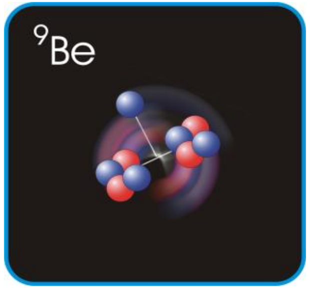
=> (e,e'pp)/(e,e'p) ratio is sensitive to the *np*/*pp* ratio

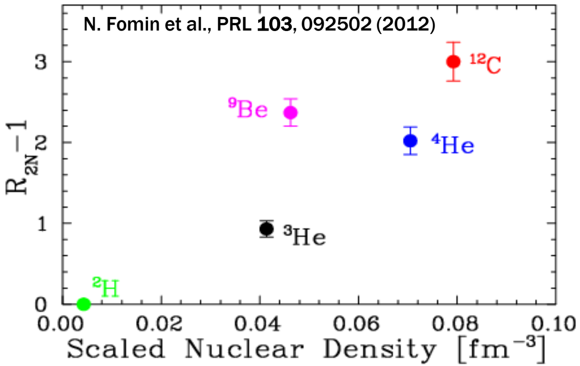
Electron Scattering is our microscope











$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A)$$

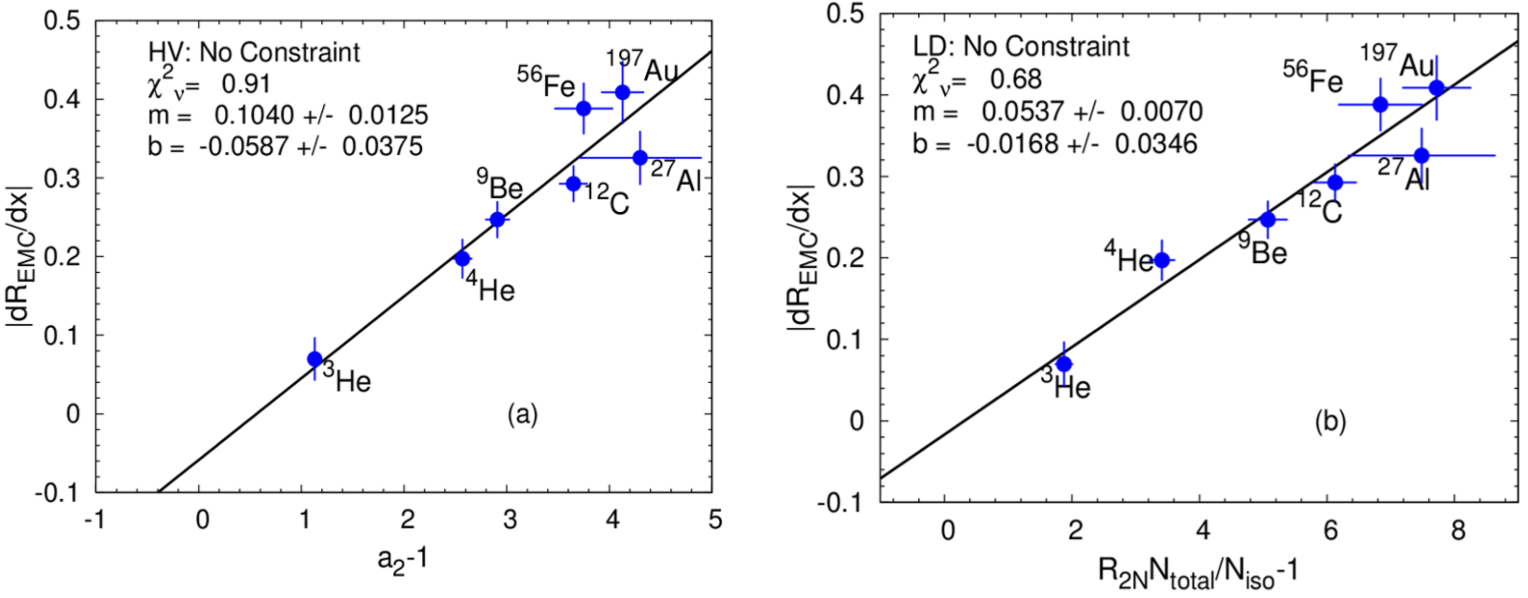
$R_{2N} = a_2$ + CoM correction

Two Hypotheses

1. Both quantities reflect ***virtuality*** of the nucleons (*L. Weinstein et al, PRL 106:052301,2011*)
    - $\boldsymbol{a_2}$ measures the relative high momentum tail – good for testing virtuality
    - dR_{EMC}/dx – relevant quantity

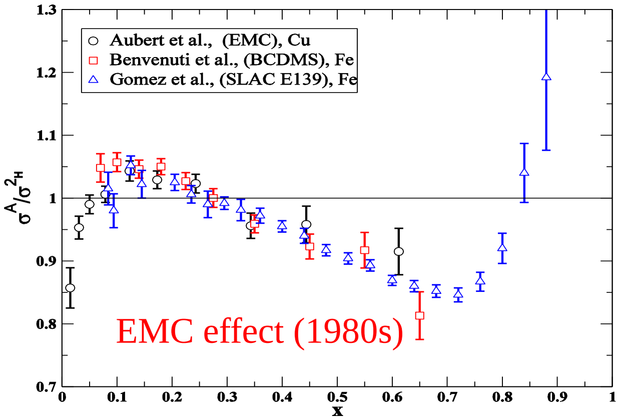
2. EMC effect is driven by ***"local density"*** (JA, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86, 065204 (2012))
    - SRCs are sensitive to high density configurations, but MUST remove the center of mass motion smearing to get $\boldsymbol{R_{2N}}$
      – *measure of correlated pairs relative to the deuteron*
    - EMC effect samples ***all*** the nucleons, whereas $\boldsymbol{R_{2N}}$ is only sensitive to *np* pairs, a subset of all possible NN configurations

Local density vs high virtuality



J. Arrington, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86, 065204 (2012)

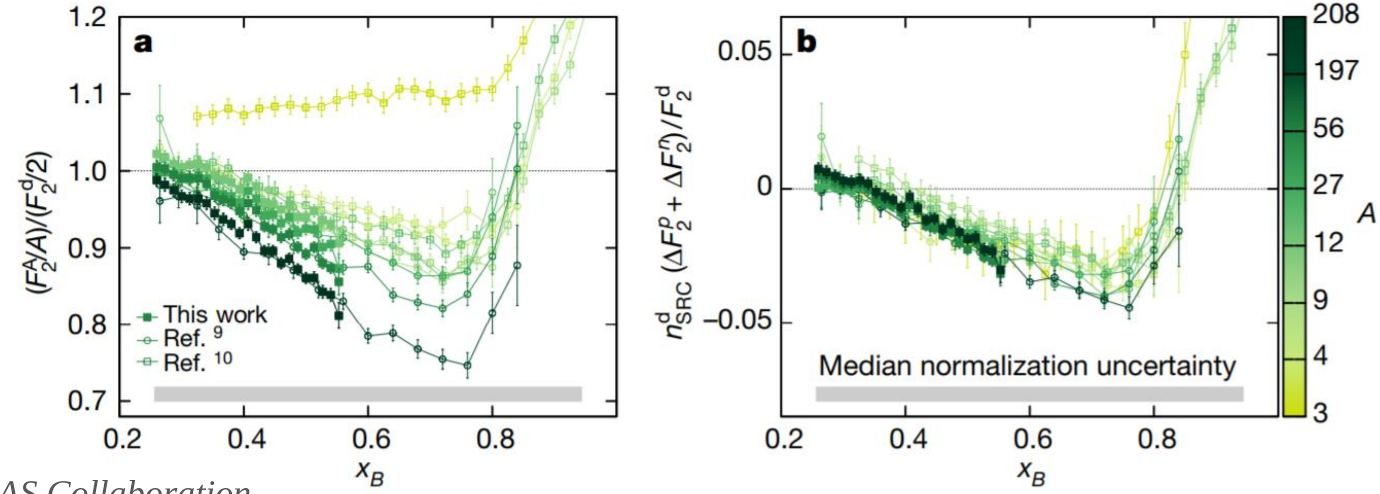
Data show a WEAK preference for LD



While waiting for new data

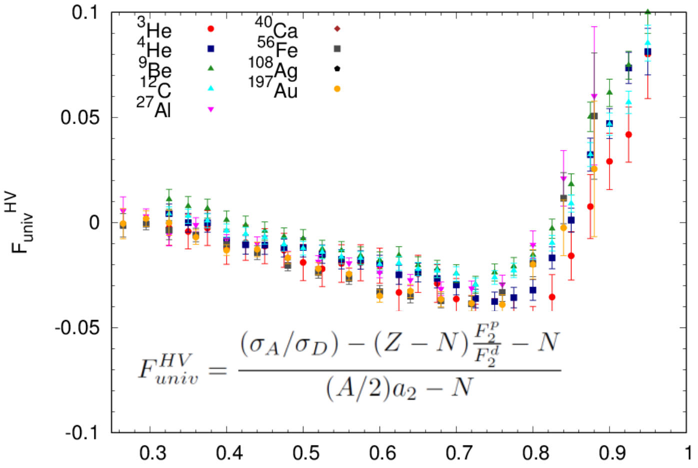
$$F_2^A = (Z - n_{SRC}^A) F_2^p + (N - n_{SRC}^A) F_2^n + n_{SRC}^A (F_2^{p*} + F_2^{n*})$$

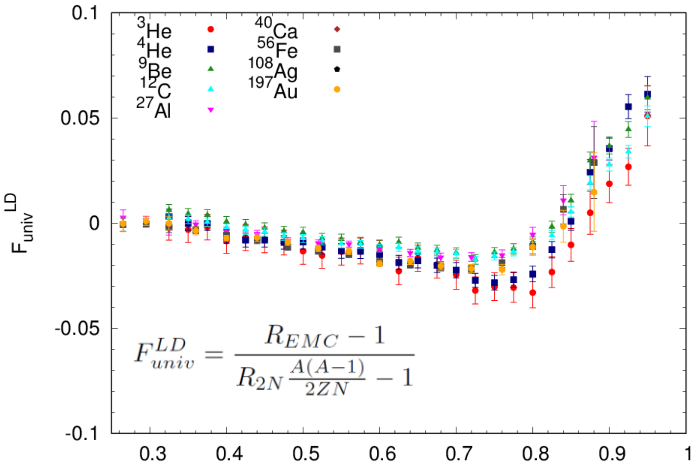
$$= Z F_2^p + N F_2^n + n_{SRC}^A (\Delta F_2^p + \Delta F_2^n)$$



Nature 566, CLAS Collaboration

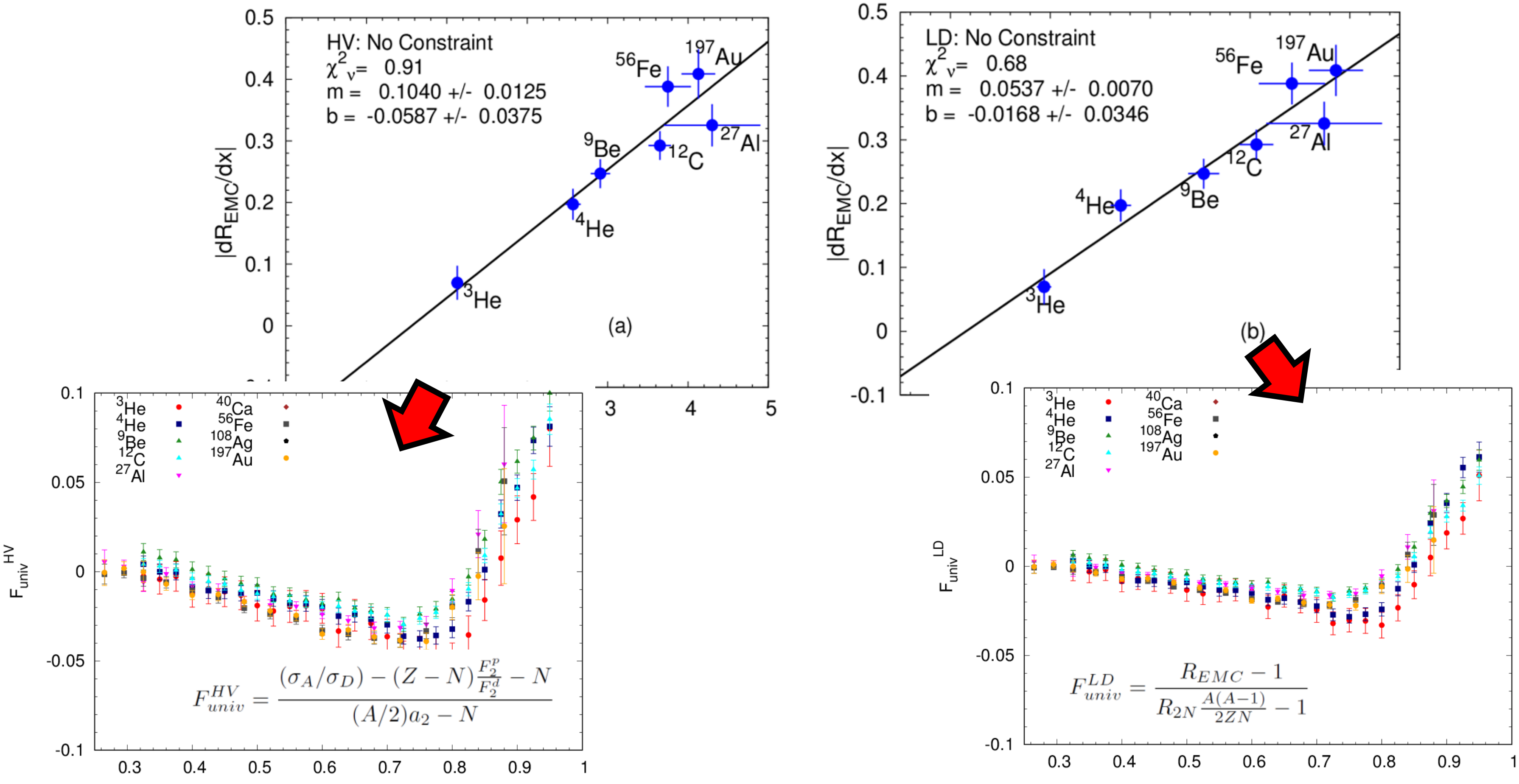
Can other *universal* EMC functions be obtained?





HV picture: np-dominance generates predictable isospin dependence of EMC effect

LD picture: EMC effect from short-distance pairs, assumed to be isospin independent

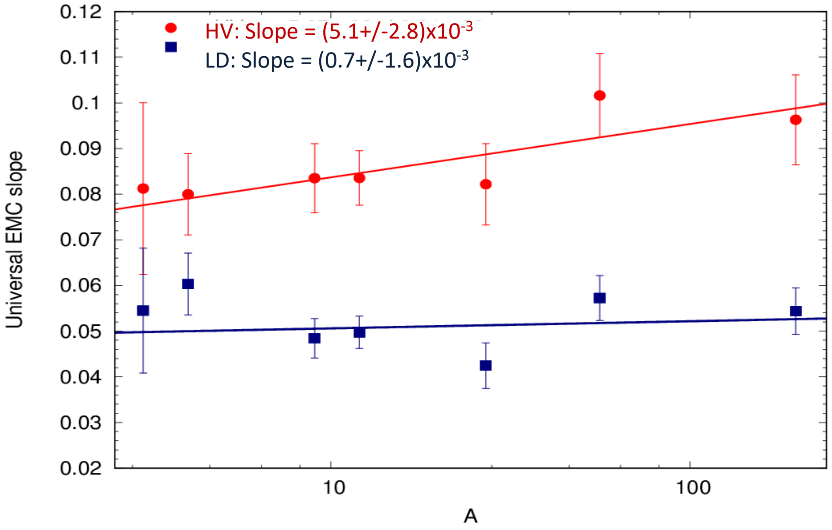

HV: No Constraint
χ^2_ν = 0.91
m = 0.1040 +/- 0.0125
b = -0.0587 +/- 0.0375
|dR_EMC/dx|
(a)
LD: No Constraint
χ^2_ν = 0.68
m = 0.0537 +/- 0.0070
b = -0.0168 +/- 0.0346
(b)
^{3}He ^{4}He ^{9}Be ^{12}C ^{27}Al ^{40}Ca ^{56}Fe ^{108}Ag ^{197}Au
F_{univ}^{HV}
$F_{univ}^{HV} = \frac{(\sigma_A/\sigma_D) - (Z-N)\frac{F_2^p}{F_2^d} - N}{(A/2)a_2 - N}$
F_{univ}^{LD}
$F_{univ}^{LD} = \frac{R_{EMC} - 1}{R_{2N}\frac{A(A-1)}{2ZN} - 1}$

Can other *universal* EMC functions be obtained?

HV picture: EMC effect from np-SRC, generates known isospin dependence

LD picture: Driven by short-distance pairs, assumed to be isospin independent

As in 2012 EMC-SRC test, somewhat better description in isospin-independent LD picture



J. Arrington and N. Fomin Phys. Rev. Lett. 123, 042501 (2019)

Where are we now?

JEFFERSON LAB DEDICATES UPGRADED CEBAF

May 31, 2018

Distinguished guests, staff members, Users and members of the media attend ceremony dedicating the recently upgraded facility.

The Department of Energy and the Thomas Jefferson National Accelerator Facility ushered in a new era of science with a dedication ceremony for the 12 GeV CEBAF Upgrade project on May 2.

"Today marks not only the completion of the construction project, but the beginning of a new era of scientific discovery at Jefferson Lab, a new era of discovery for the scientific community, as well as

Where are we now? Publishing Nature Papers

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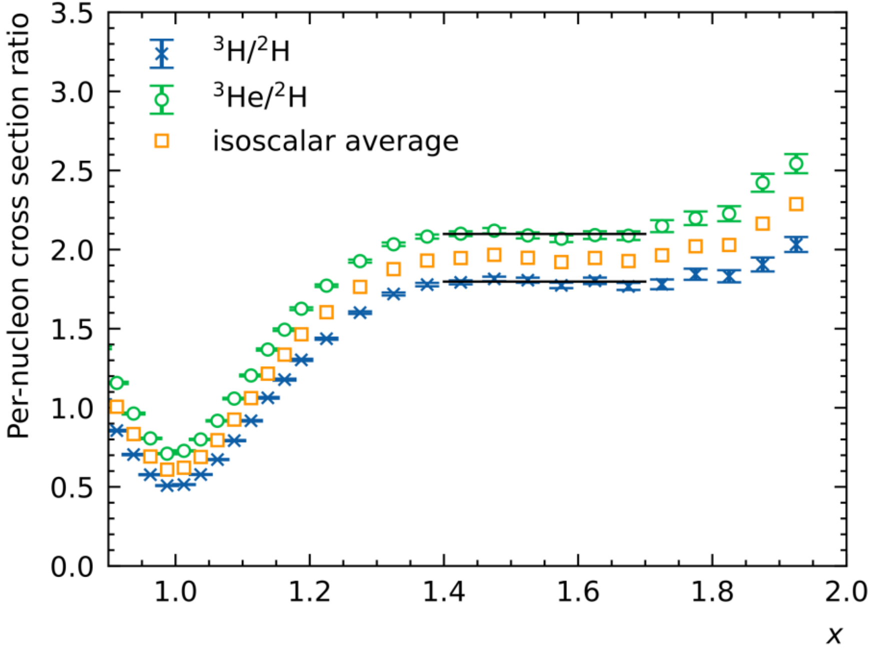
Article | Published: 31 August 2022

Revealing the short-range structure of the mirror nuclei ^{3}H and ^{3}He

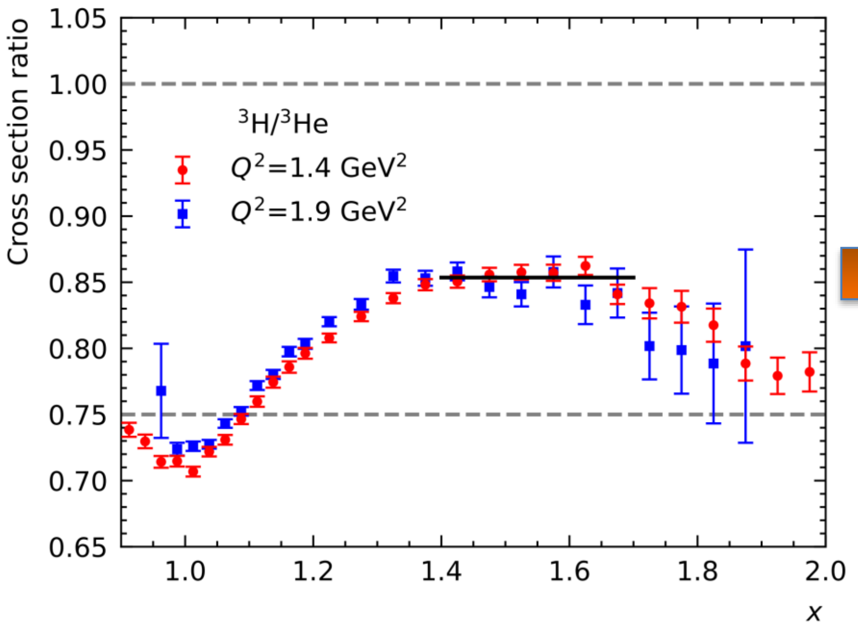
S. Li, R. Cruz-Torres, N. Santiesteban, Z. H. Ye, D. Abrams, S. Alsalmi, D. Androic, K. Aniol, J. Arring

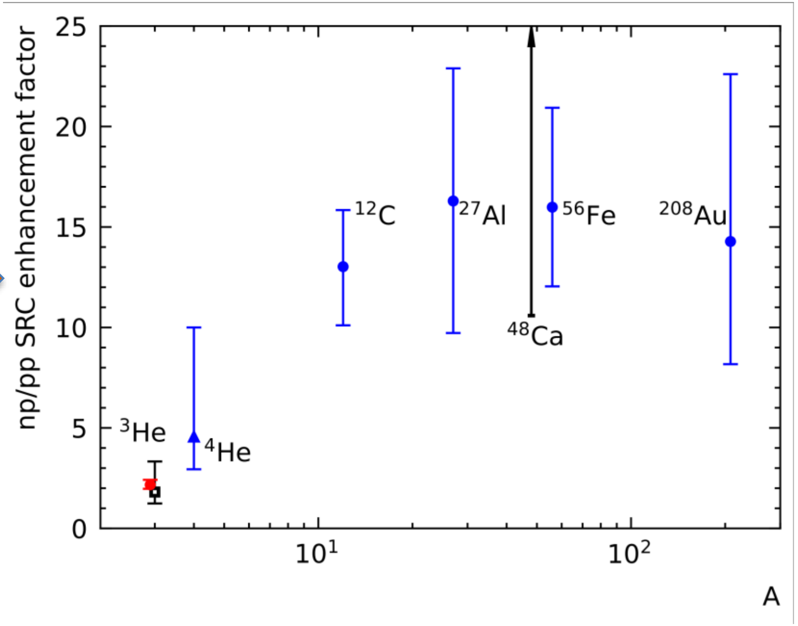


Inclusive measurement on A=3 nuclei

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

Where are we now? Publishing Nature Papers



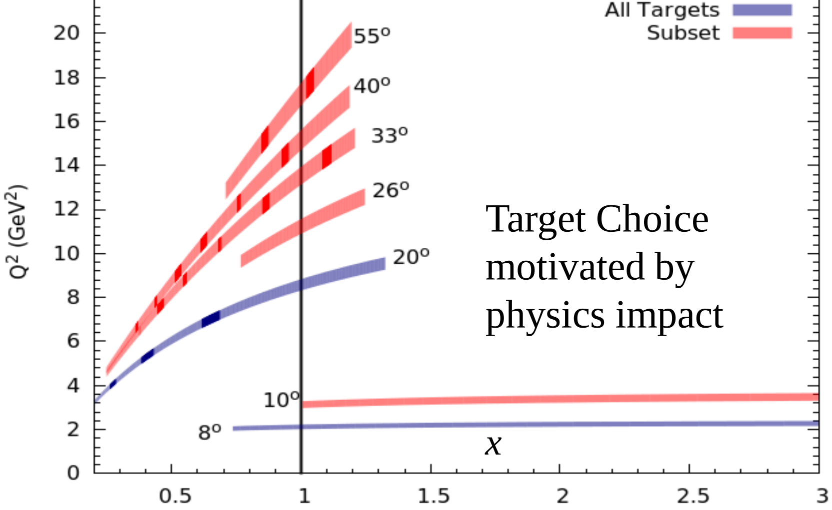


Inclusive measurement on A=3 nuclei

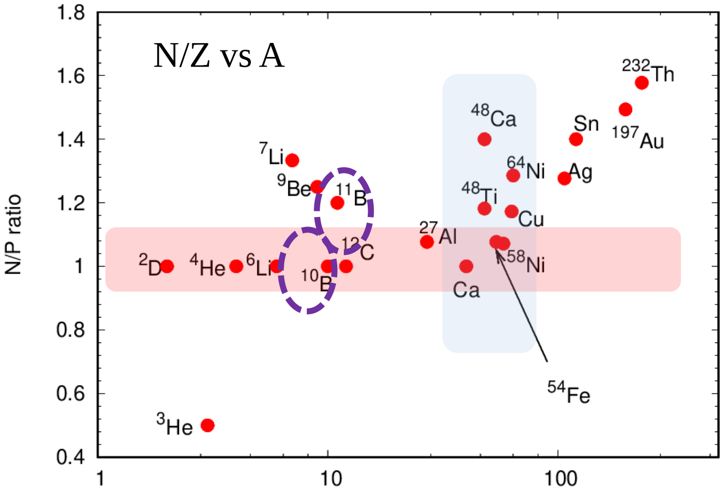
S. Li, et al., Nature 609, 41 (2022)

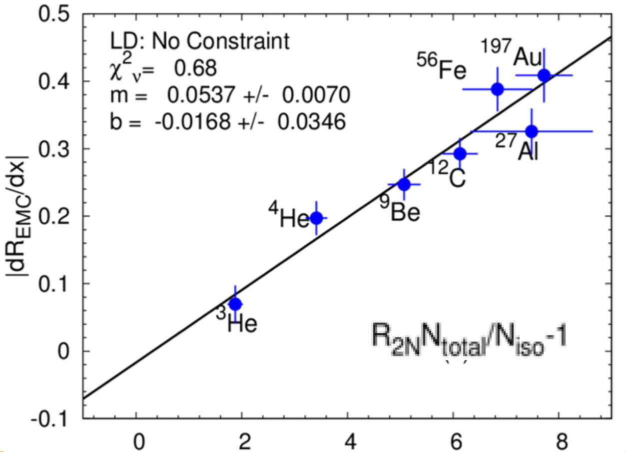
E12-10-008: J. Arrington, A Daniel, NF, D. Gaskell: Detailed Studies of the nuclear dependence of F_2 in light nuclei

E12-06-105: J. Arrington, D. Day, NF, P. Solvignon: Inclusive Scattering from Nuclei at x>1 in the quasielastic and deeply inelastic regimes



Target Choice motivated by physics impact

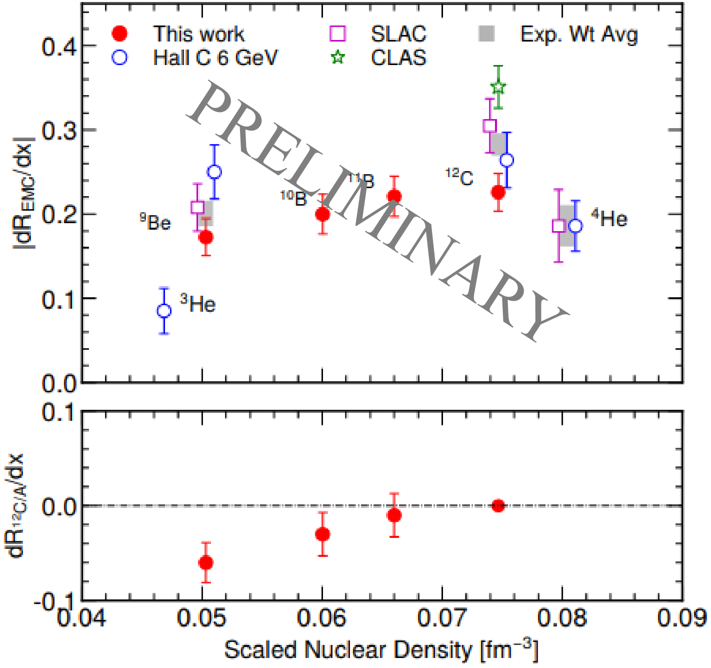




First paper from commissioning data submitted to PRL

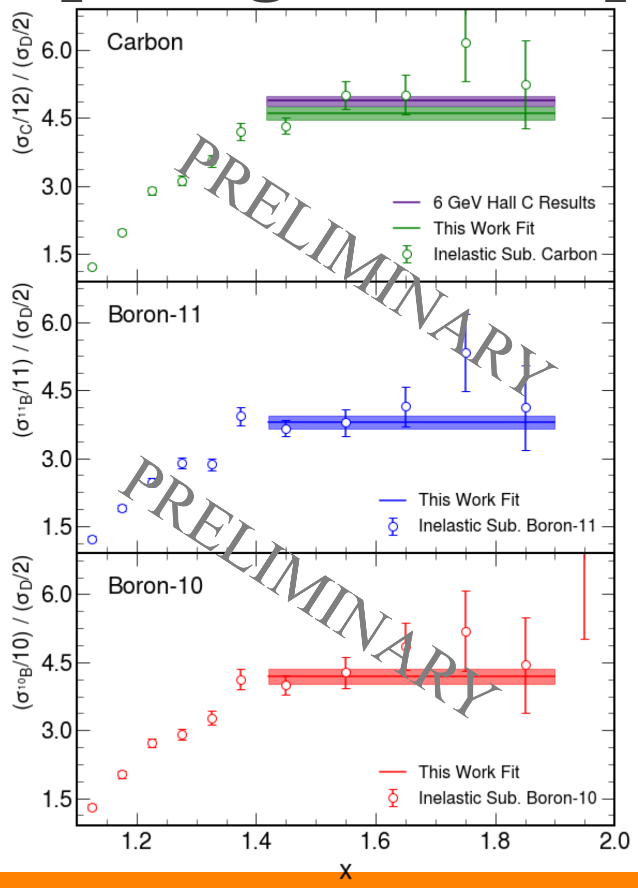
First Measurement of the EMC Effect in ^{10}B and ^{11}B

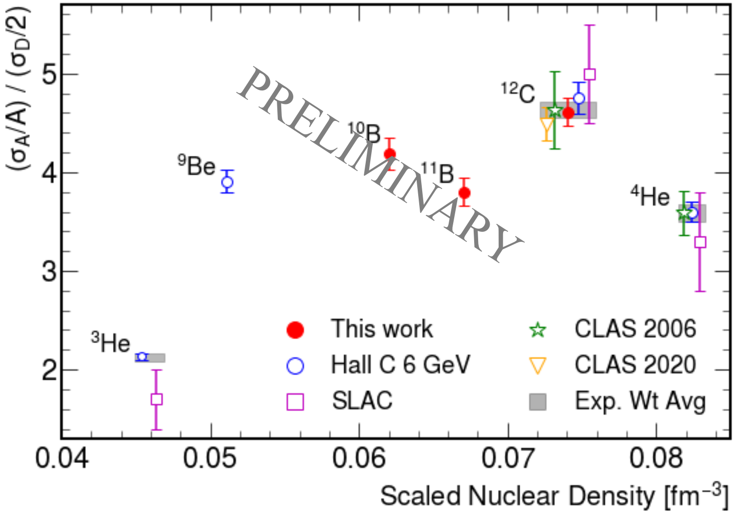
A. Karki,[1] D. Biswas,[2,*] F. A. Gonzalez,[3] W. Henry,[4] C. Morean,[5] A. Nadeeshani,[2] A. Sun,[6] D. Abrams,[7] Z. Ahmed,[8] B. Aljawrneh,[9,†] S. Alsalmi,[10] R. Ambrose,[8] D. Androic,[11] W. Armstrong,[12] J. Arrington,[13] A. Asaturyan,[14] K. Assumin-Gyimah,[1] C. Ayerbe Gayoso,[15,1] A. Bandari,[15] J. Bane,[5] J. Barrow,[5] S. Basnet,[8] V. Berdnikov,[16] H. Bhatt,[1] D. Bhetuwal,[1] W. U. Boeglin,[17] P. Bosted,[15] E. Brash,[18] M. H. S. Bukhari,[19] H. Chen,[7] J. P. Chen,[4] M. Chen,[7] M. E. Christy,[2] S. Covrig,[4] K. Craycraft,[5] S. Danagoulian,[9] D. Day,[7] M. Diefenthaler,[4] M. Dlamini,[20] J. Dunne,[1] B. Duran,[21] D. Dutta,[1] C. Elliott,[5] R. Ent,[4] H. Fenker,[4] N. Fomin,[5] E. Fuchey,[22] D. Gaskell,[4] T. N. Gautam,[2] J. O. Hansen,[4] F. Hauenstein,[23] A. V. Hernandez,[16] T. Horn,[16] G. M. Huber,[8] M. K. Jones,[4] S. Joosten,[12] M. L. Kabir,[1] N. Kalantarians,[24] C. Keppel,[4] A. Khanal,[17] P. M. King,[20] E. Kinney,[25] H. S. Ko,[26] M. Kohl,[2] N. Lashley-Colthirst,[2] S. Li,[27] W. B. Li,[15] A. H. Liyanage,[2] D. Mack,[4] S. Malace,[4] P. Markowitz,[17] J. Matter,[7] D. Meekins,[4] R. Michaels,[4] A. Mkrtchyan,[14] H. Mkrtchyan,[14] S. Nanda,[1] D. Nguyen,[7] G. Niculescu,[28] I. Niculescu,[28] Nuruzzaman,[29] B. Pandey,[2] S. Park,[3] E. Pooser,[4] A. J. R. Puckett,[22] M. Rehfuss,[21] J. Reinhold,[17] N. Santiesteban,[27] B. Sawatzky,[4] G. R. Smith,[4] H. Szumila-Vance,[4] A. S. Tadepalli,[29] V. Tadevosyan,[14] R. Trotta,[16] S. A. Wood,[4] C. Yero,[17] and J. Zhang[3,‡]
(for the Hall C Collaboration)



Details in next talk (J. Arrington)

Preparing 2N SRC publication as well





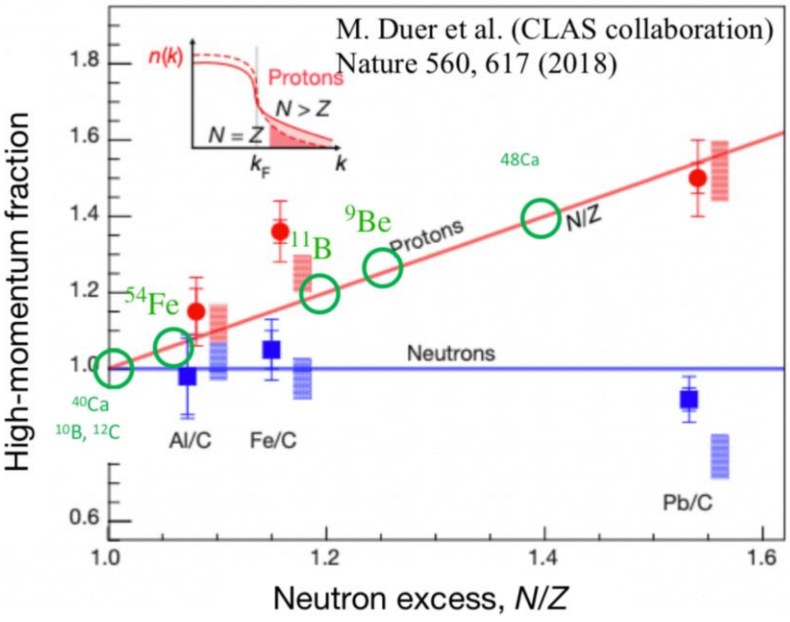
Analysis by Casey Morean (UTK)

More Upcoming SRC Searches

CaFe Experiment in Hall C at JLab

- Studying SRC pairing
  - effect of different orbits
  - dependence on A and N/Z
- Test of *ab-initio* calculations

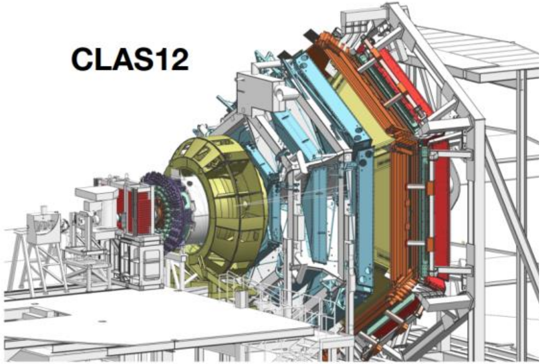
- Observables
  - cross sections
  - single ratios - SRC/MF
  - double ratios (SRC/MF)_A1 / (SRC/MF)_A1



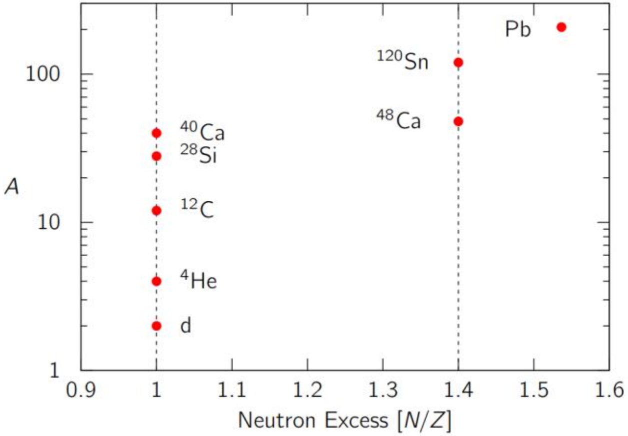
- A(e,e'p) measurement at different kinematics (8 days)
  - mean field (MF)
  - SRC pairs
- Various targets (^{40}Ca - ^{48}Ca - ^{54}Fe, ^{9}Be - ^{10}B - ^{11}B - ^{12}C, d)

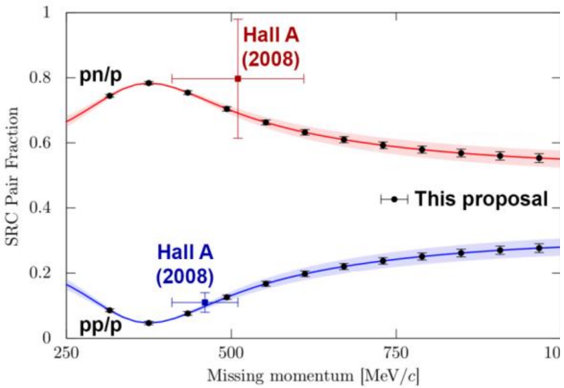
Run Group M in Hall B at Jlab

- 4.4 and 6.6 beam energy
- Several targets
- Various reaction channels
- Measurement of *nn*-pairs possible
- Run in 2021

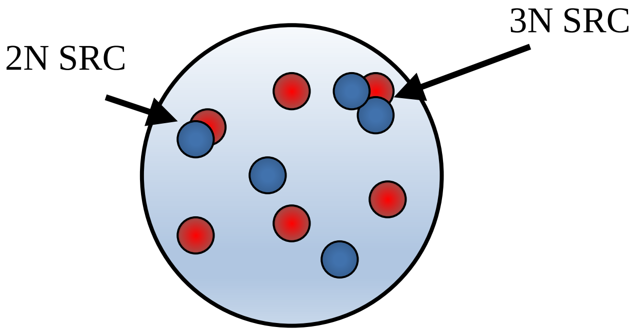


1. NN Interaction & Nuclear wave-function [^{2}H, ^{4}He]
2. Many-body systems & nuclear asymmetry [^{40}Ca, ^{48}Ca, ^{120}Sn]
   - Decouple N/Z vs A; nn vs pp
3. 3N-SRC observation [^{4}He, ^{12}C, ^{40}Ca]
   - First Observation of A dependence
4. Reaction Mechanisms [^{4}He, ^{12}C, ^{40}Ca, ^{48}Ca, ^{120}Sn]
   - Q^2, A dependence





More nucleons in a correlation



1.4 < x < 2 => 2 nucleon correlation

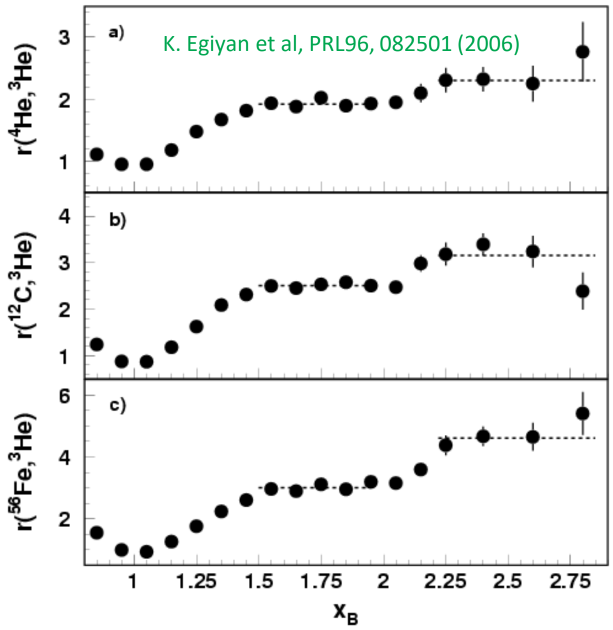
2.4 < x < 3 => 3 nucleon correlation

$$\sigma(x, Q^2) = \sum_{j=1}^{A} A \frac{1}{j} a_j(A) \sigma_j(x, Q^2)$$

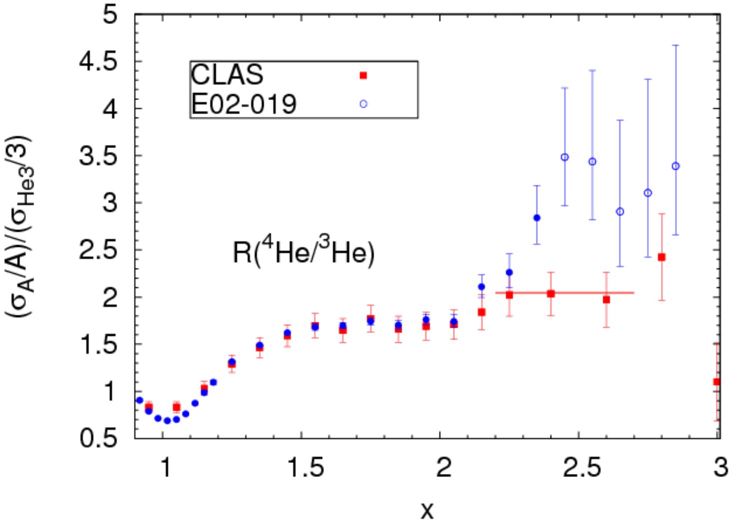
$$= \frac{A}{2} a_2(A) \sigma_2(x, Q^2) +$$

$$\frac{A}{3} a_3(A) \sigma_3(x, Q^2) + \ldots.$$

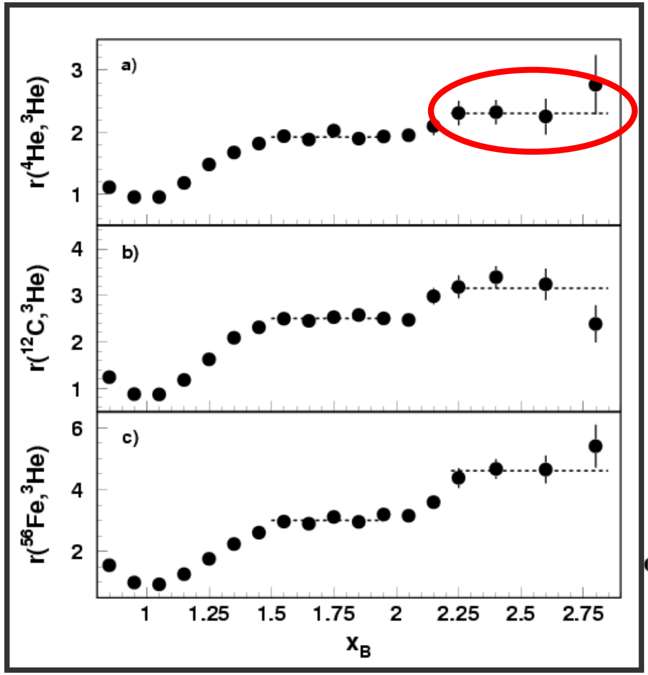
3N correlations (x>2 inclusive scattering)

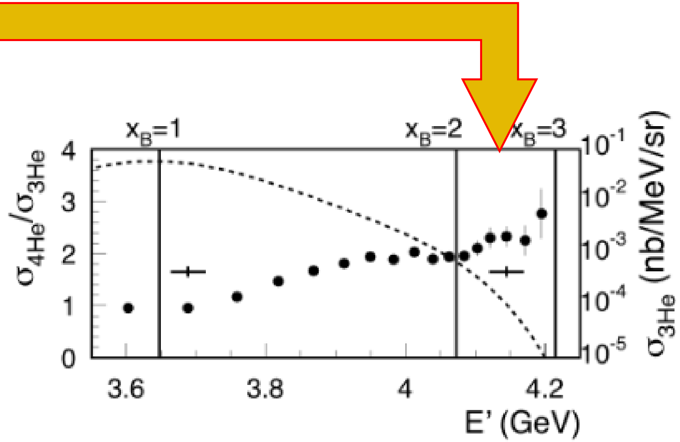


<Q^2> (GeV^2): *CLAS: 1.6* *E02-019: 2.7*



Have we actually seen 3N SRC in ratios?



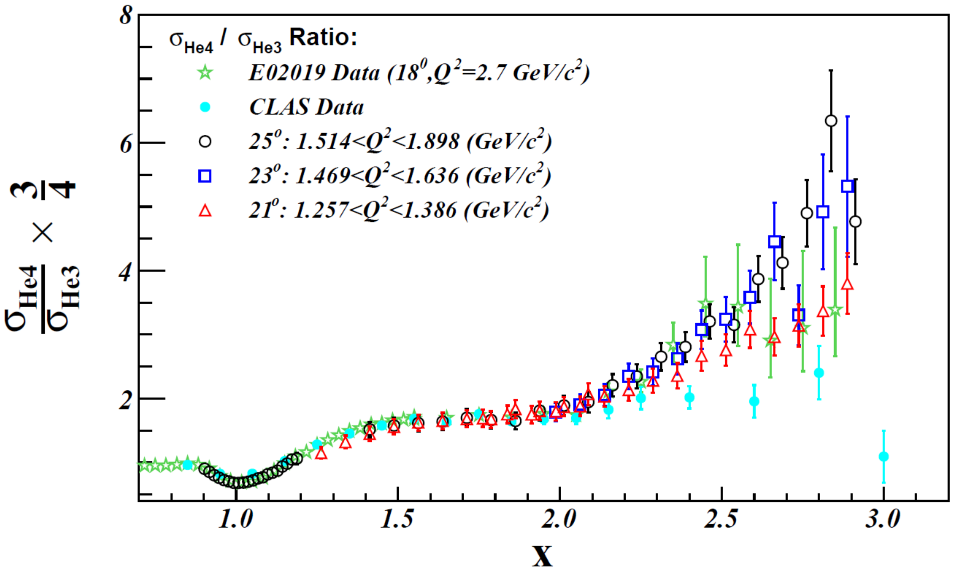


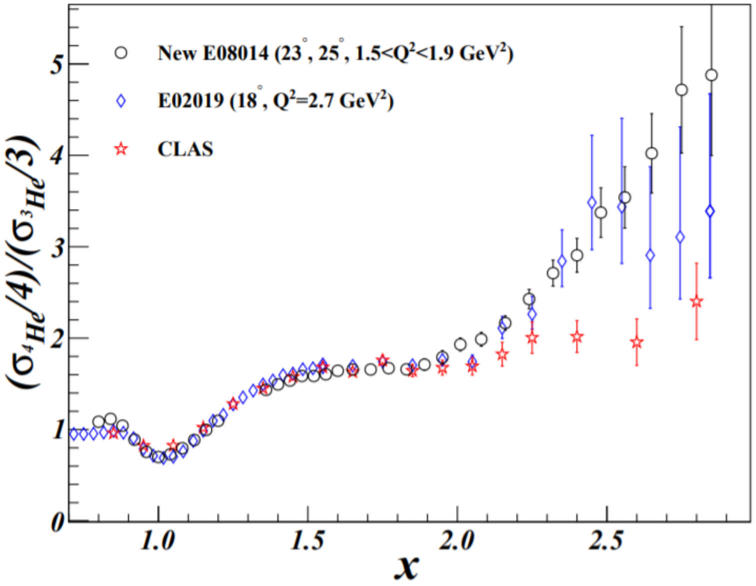
omment on "Measurement of 2- and 3-nucleon short range correlation probabilities in nuclei"

Douglas W. Higinbotham[1] and Or Hen[2]

[1]*Jefferson Lab, Newport News, VA 23606, USA*
[2]*Tel Aviv University, Tel Aviv, Israel*

3N correlations - still looking





Z. Ye et al, PRC 97 (2018) 6

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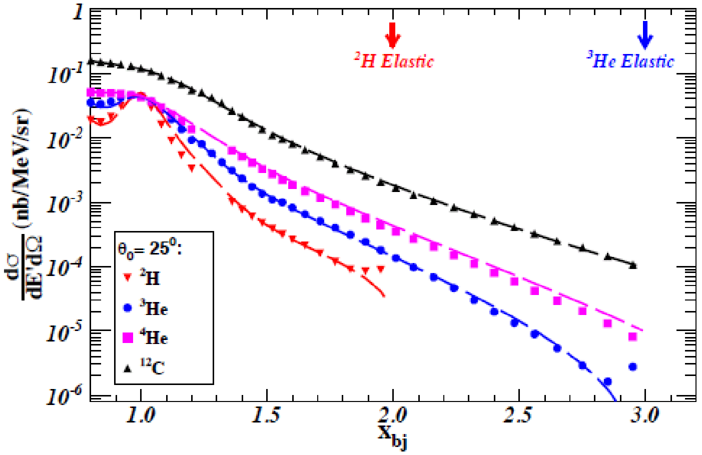
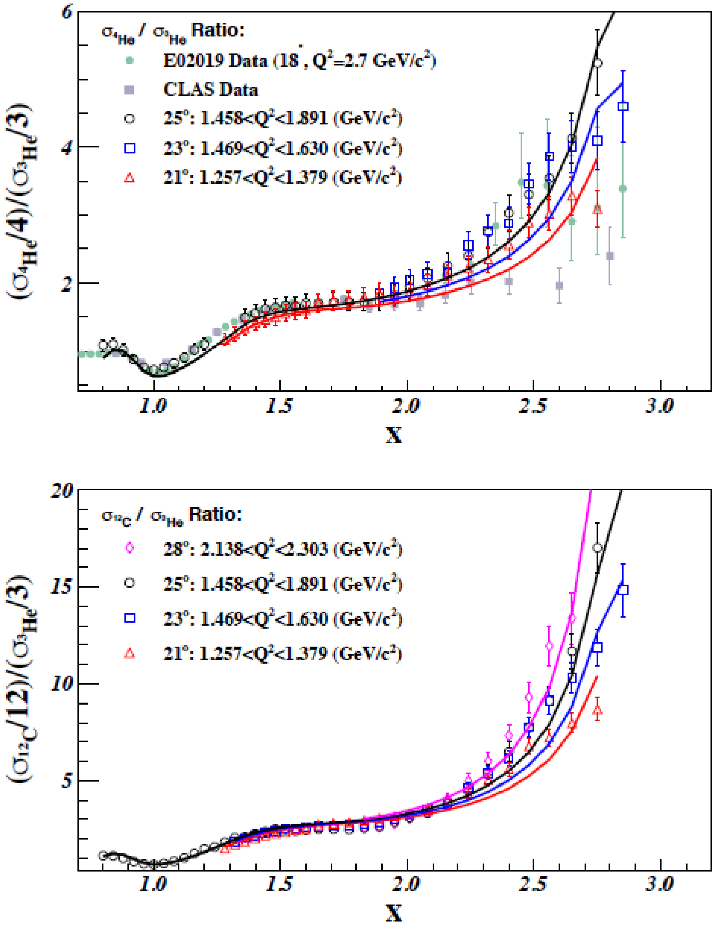
Can we see a second plateau?



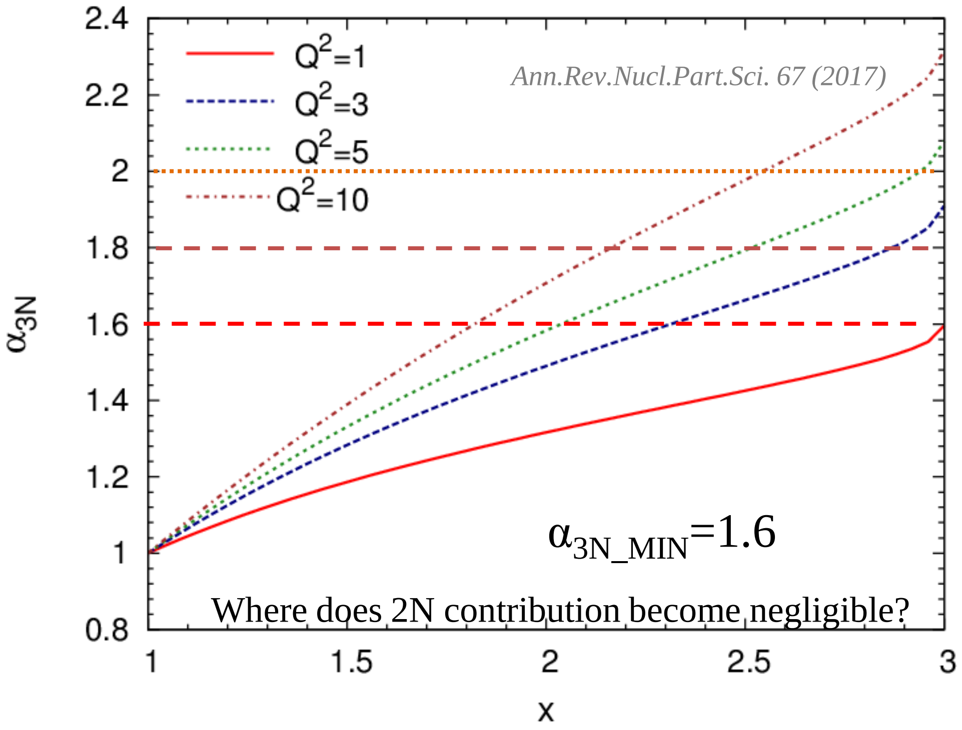


Deuteron: smeared SRC similar to 2H (A/D is ~flat) until x>1.8

3He: cross section of stationary 3N-SRC begins to fall off closer to x=2.6. Sets in EARLIER at high Q^2

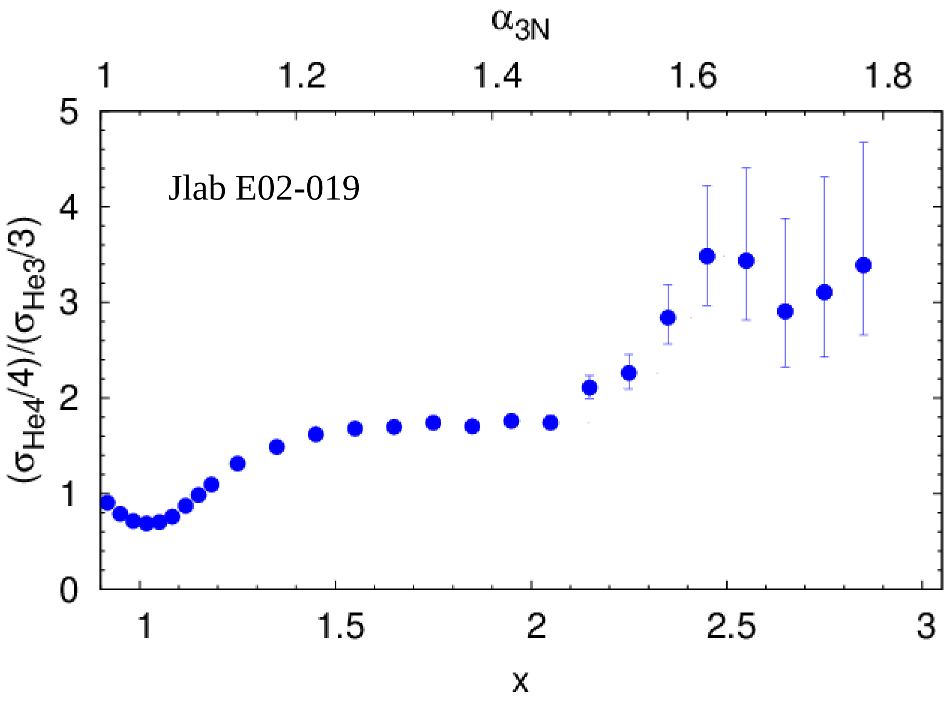

I WAS TOLD THERE WOULD BE
3N SRC PLATEAUS
imgflip.com

3N correlations – are we there yet?



α_i represents the light-cone momentum fraction of 3N SRCs carried by the correlated nucleon *i*

We were so close



Summary

- Studies of SRCs continue at Jlab in the 12 GeV era
  - Tantalizing connection between 2N SRCs and EMC effect seen in 6 GeV data
- First observation of 3N SRC existence is yet to come
- New results in the next few years!
- This work was supported by DOE Award DE-SC0013615