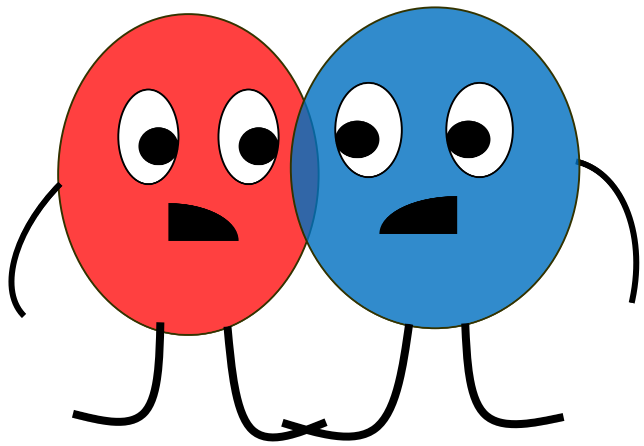
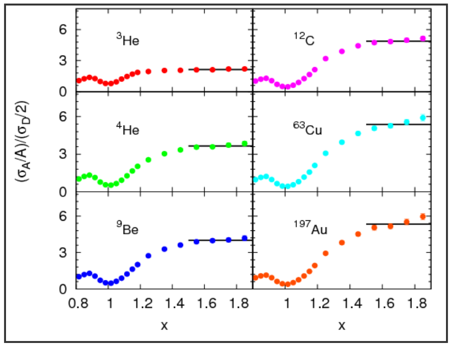
Previously, on Short-Range Correlations Experiments
(a summary of 6 GeV measurements)

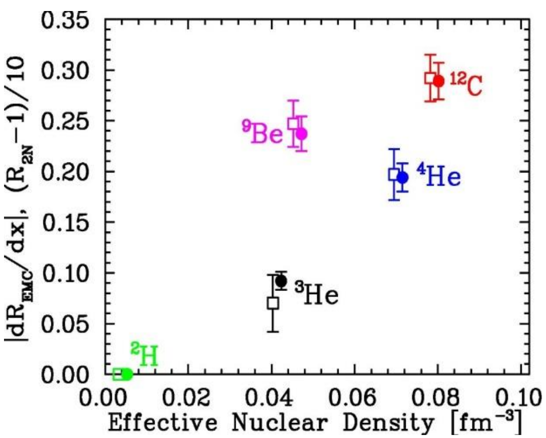


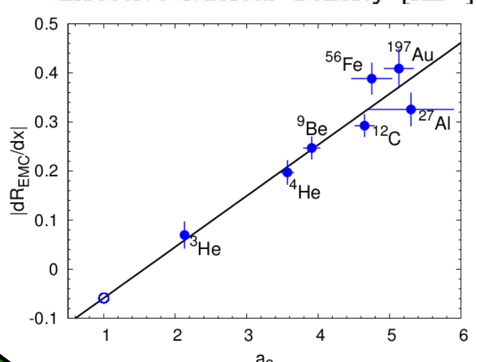
Exposing Novel Quark and Gluon Effects in Nuclei

Nadia Fomin
University of Tennessee
April 19, 2018

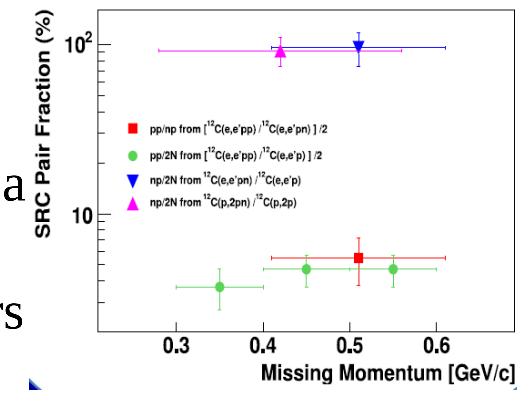
What have we learned from 6GeV era?

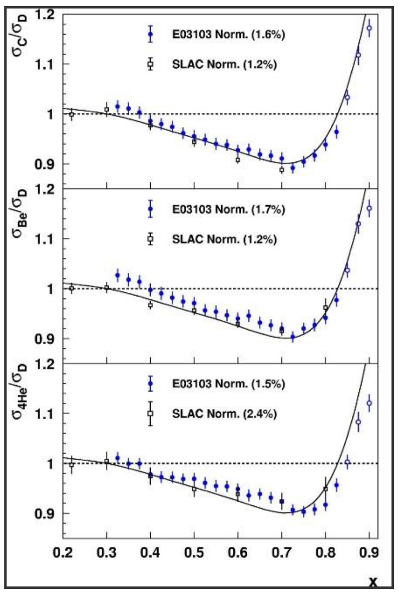






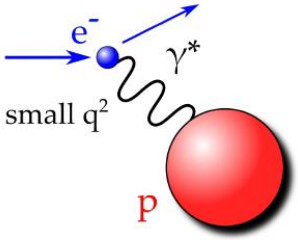
- Scaling of x>1 cross sections relative to the deuteron
  --implies high momentum tail is a result of short-range correlations
- NP dominance of short-range pairs
  --tensor interaction
- No trivial (A or density) dependence for SRC behavior or EMC effect
  --from high-precision light nuclei data
- Suggestive correlation between EMC effect and SRC plateaus

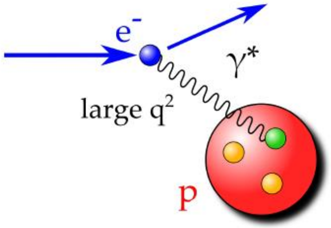




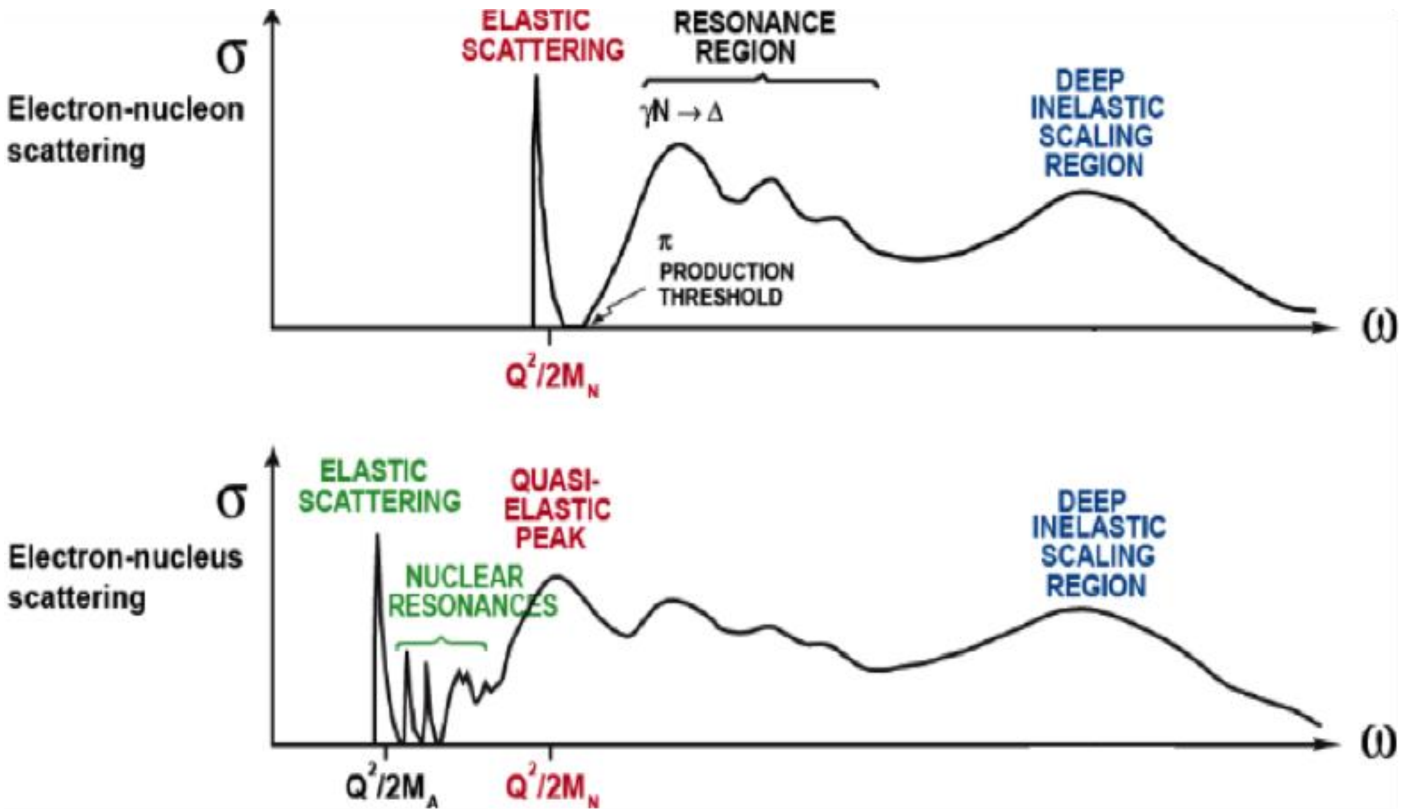
THE END

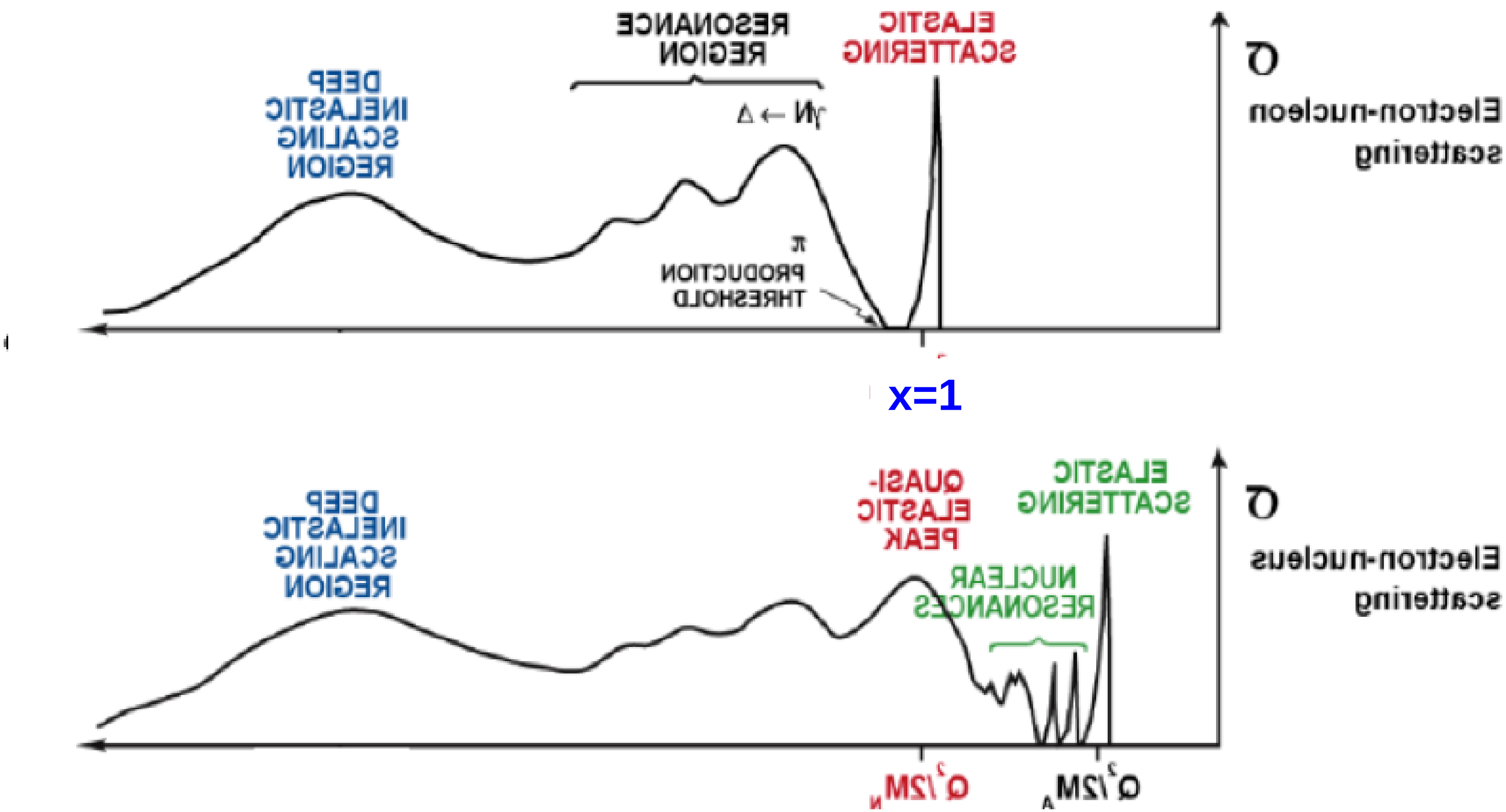
Choosing an Appropriate Microscope





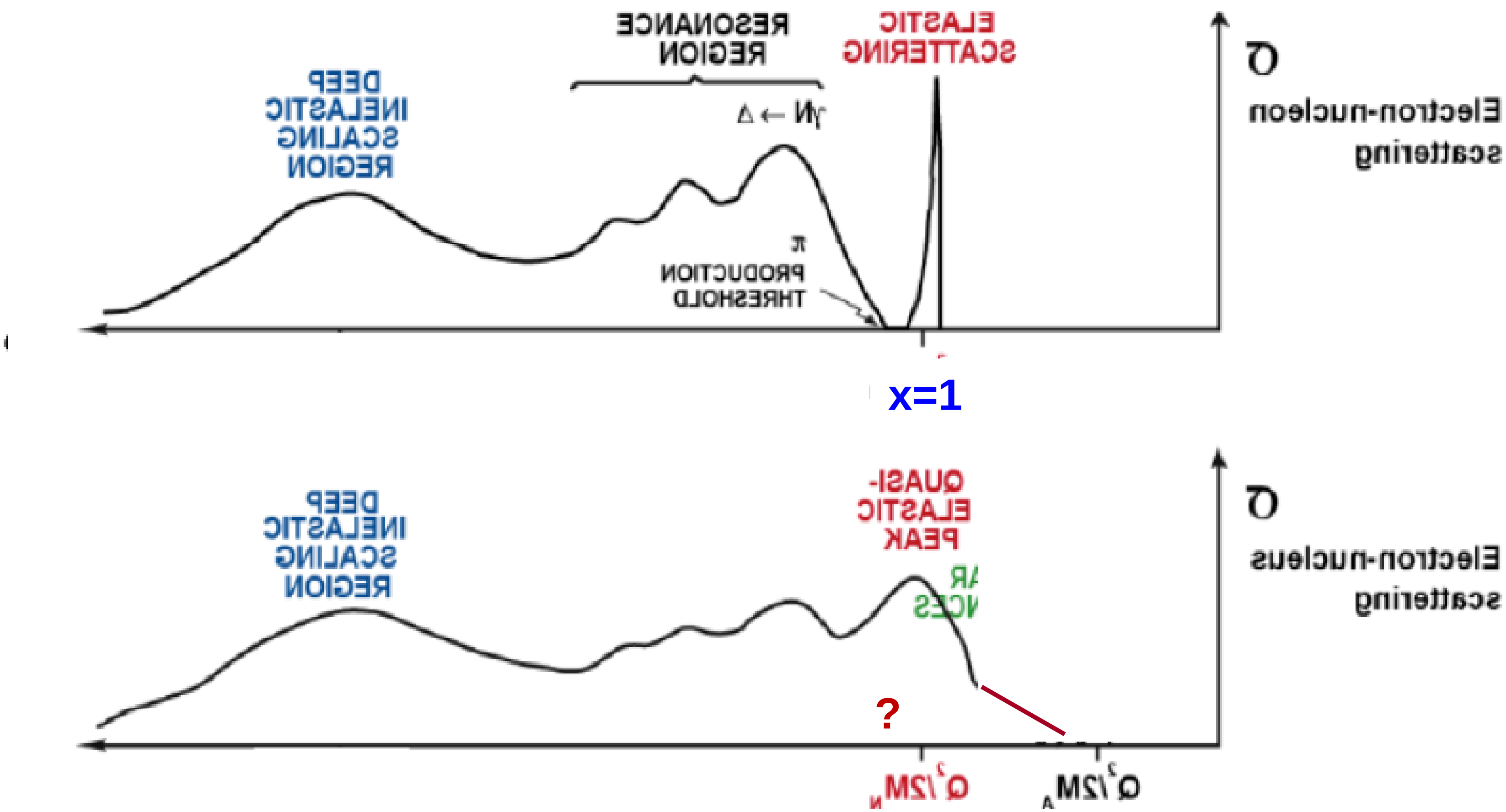
$$\lambda \approx \frac{1}{\vec{q}}$$





1<x<2 is combination of 2-body and 1*-body contributions; 3+ body effect assumed to be small
(*=Fermi-smeared)

Log-ish(x_{Bj})



1<x<2 is combination of 2-body and 1*-body contributions; 3+ body effect assumed to be small
(*=Fermi-smeared)

Log-ish(x_{Bj})

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

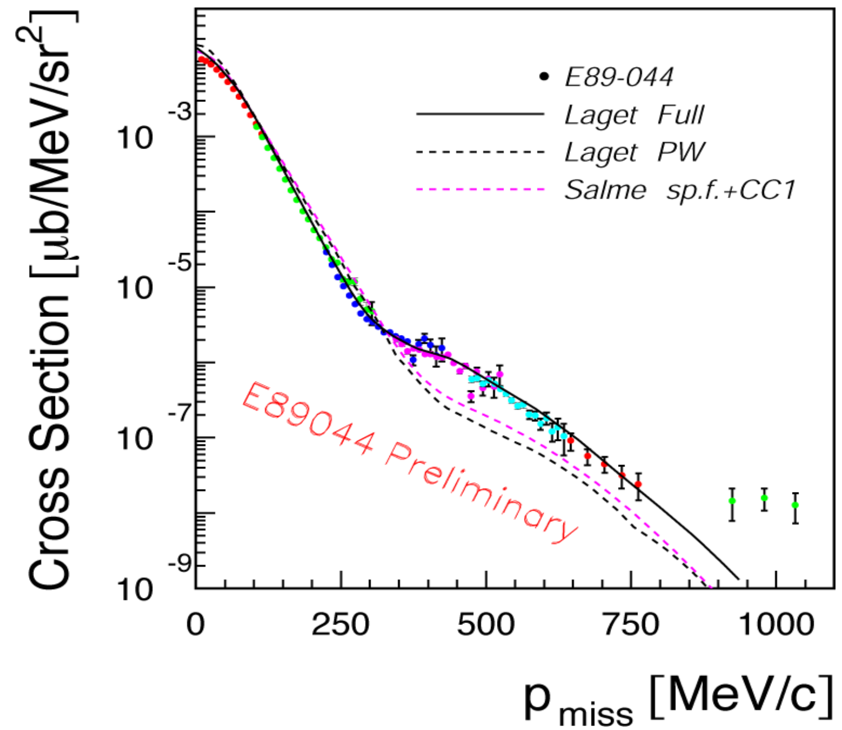
- E89-004: Measure of $^3He(e,e'p)d$
- Measured far into high momentum tail: Cross section is ~5-10x expectation

Difficulty

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

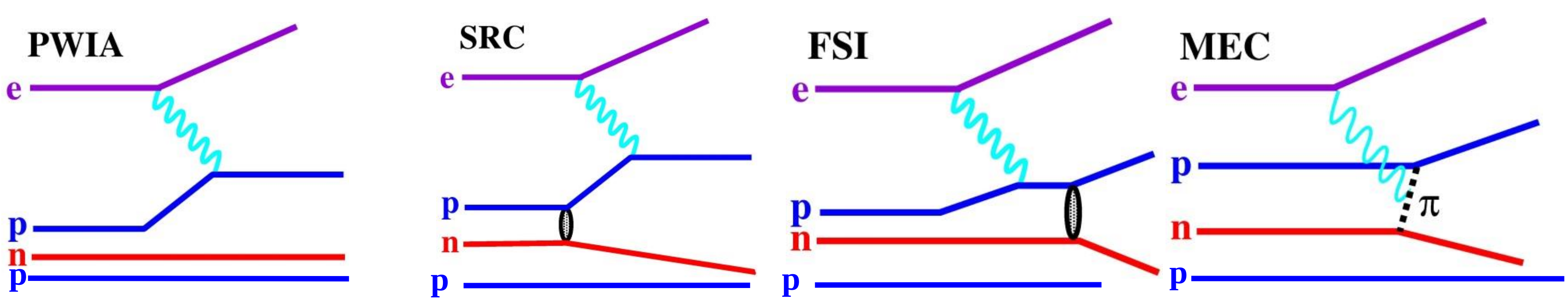
OR

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



"slow" nucleons

"fast" nucleons



A(e,e'p)

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

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

Unfortunately: FSI, MECs overwhelm the high momentum nucleons

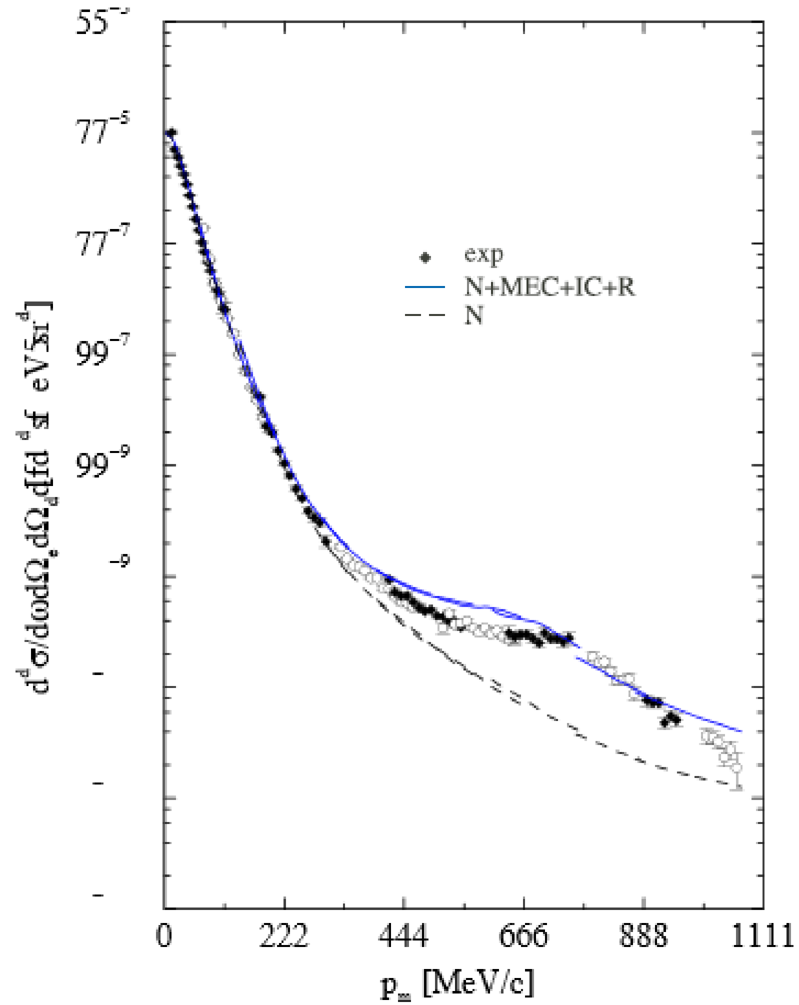


FIG. 1: The experimental D(e,e′p)n cross section as a function of missing momentum measured at MAMI for $Q^2 = 0.33$ $(GeV/c)^2$ [4] compared to calculations [7] with (solid curve) and without (dashed curve) MEC and IC. Both calculations include FSI. The low p_m data have been re-analyzed and used in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

Inclusive Scattering

- Relative measurement
- Reduced FSI
- Test scaling in x and Q^2
- No direct information on isospin structure
  - Only via target isospin structure
- No direct information on momentum distribution for A>2

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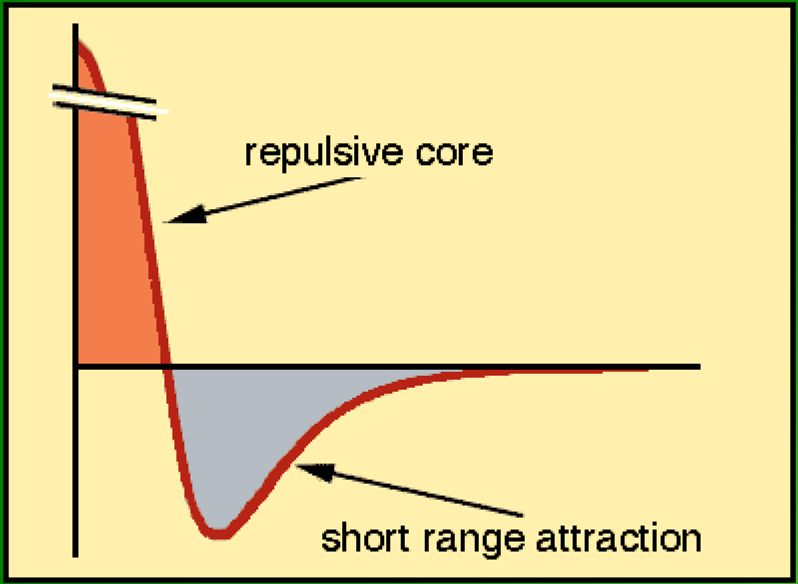
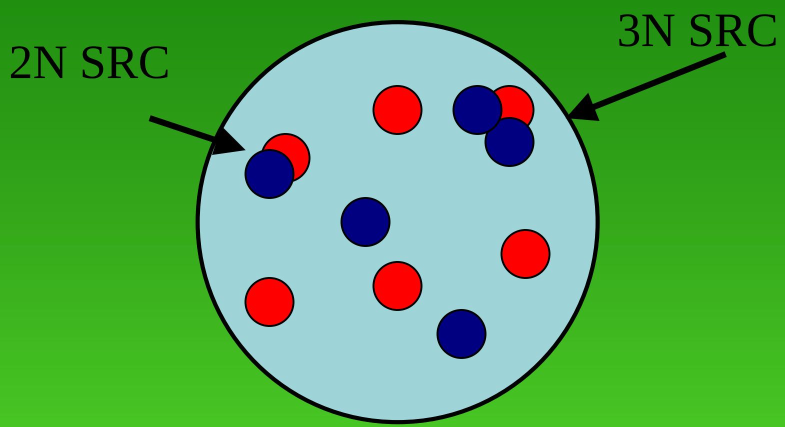
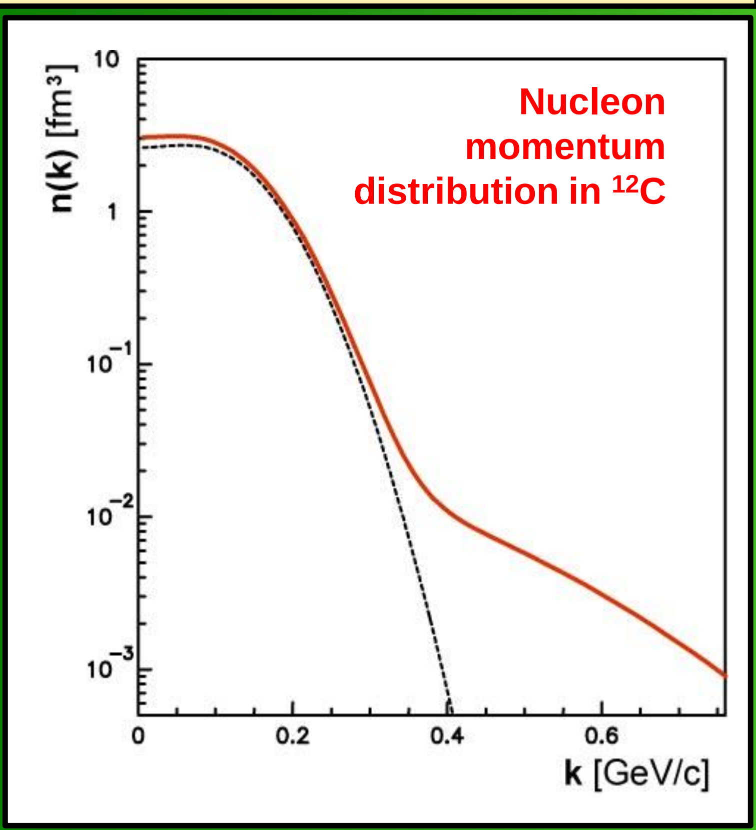
High momentum nucleons

- Short Range Correlations







Try inclusive scattering!
Select kinematics such that the initial nucleon momentum $> k_f$

High momentum nucleons

$$\frac{d\sigma^{QE}}{d\Omega dE'} \propto \int d\vec{k} \int dE \sigma_{ei} S_i(k,E) \delta(Arg)$$

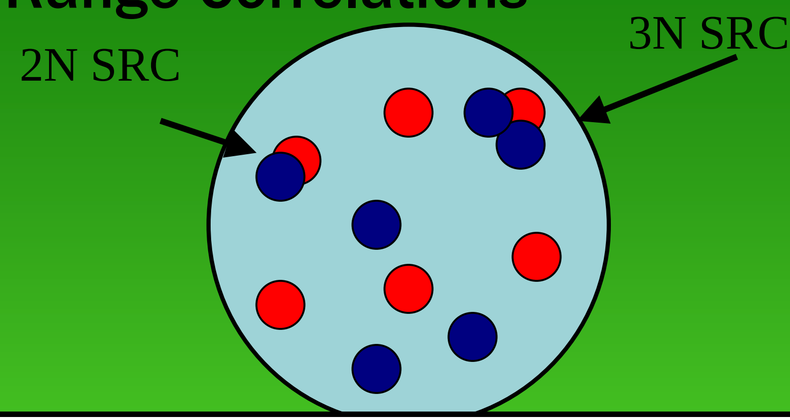
$$Arg = \nu + M_A - \sqrt{M^2 + p^2} - \sqrt{M_{A-1}^{*2} + k^2}$$

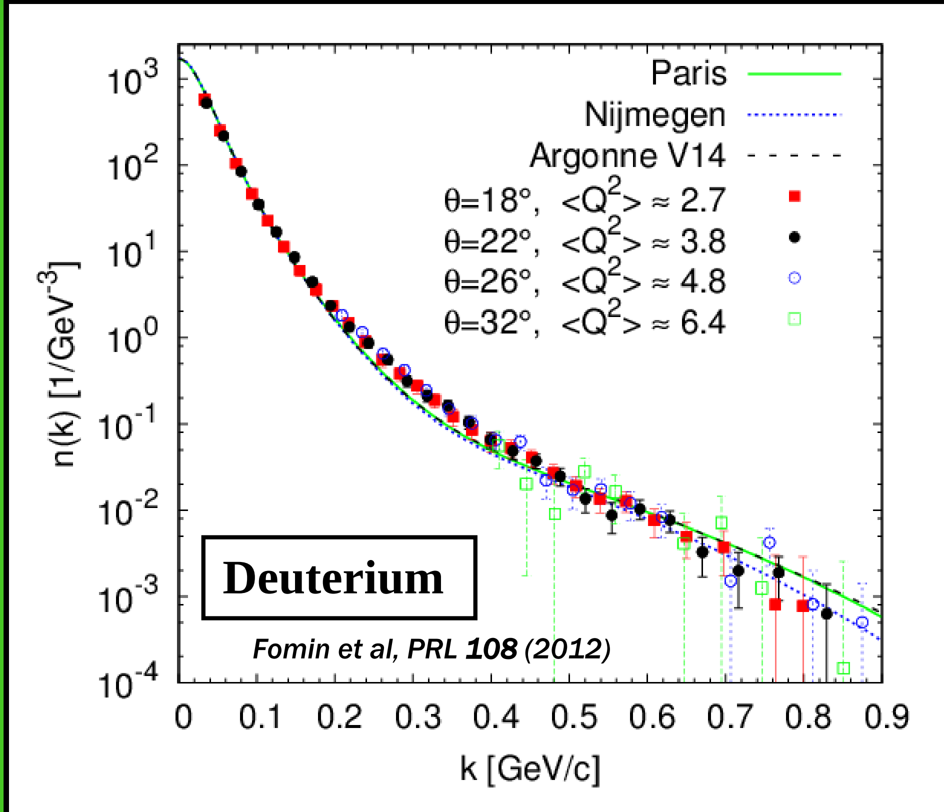
$$F(y,\mathbf{q}) = \frac{d^2\sigma}{d\Omega d\upsilon} \frac{1}{(Z\bar{\sigma}_p + N\bar{\sigma}_n)} \frac{\mathbf{q}}{\sqrt{M^2 + (y+q)^2}}$$

$$= 2\pi \int_{|y|}^{\infty} n(k) k dk$$

Ok for A=2

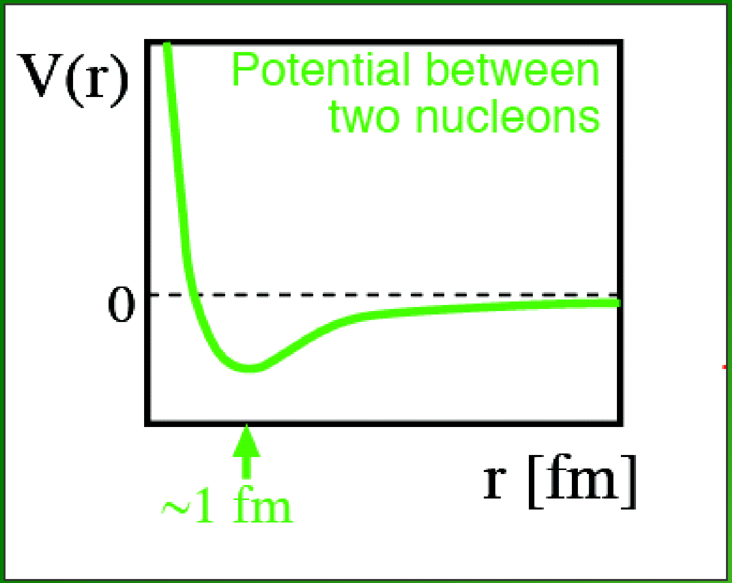
- Short Range Correlations

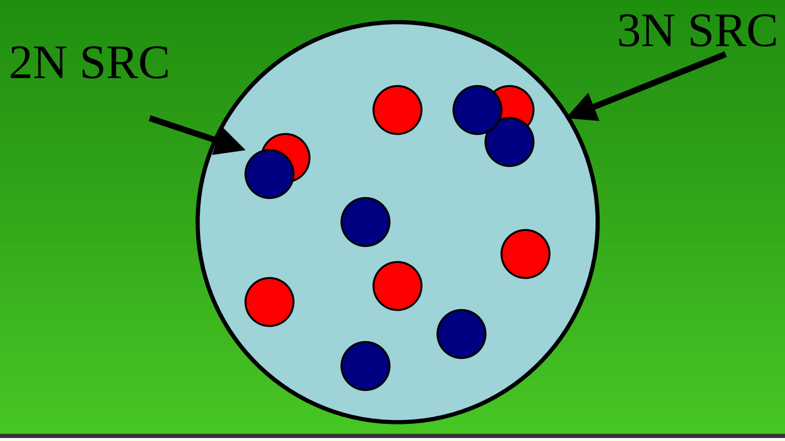


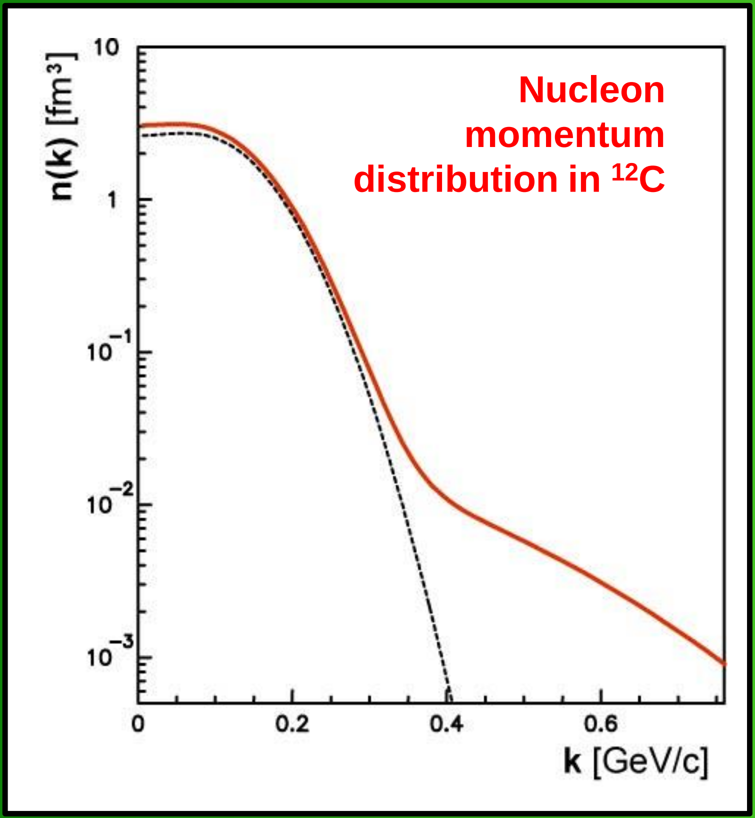


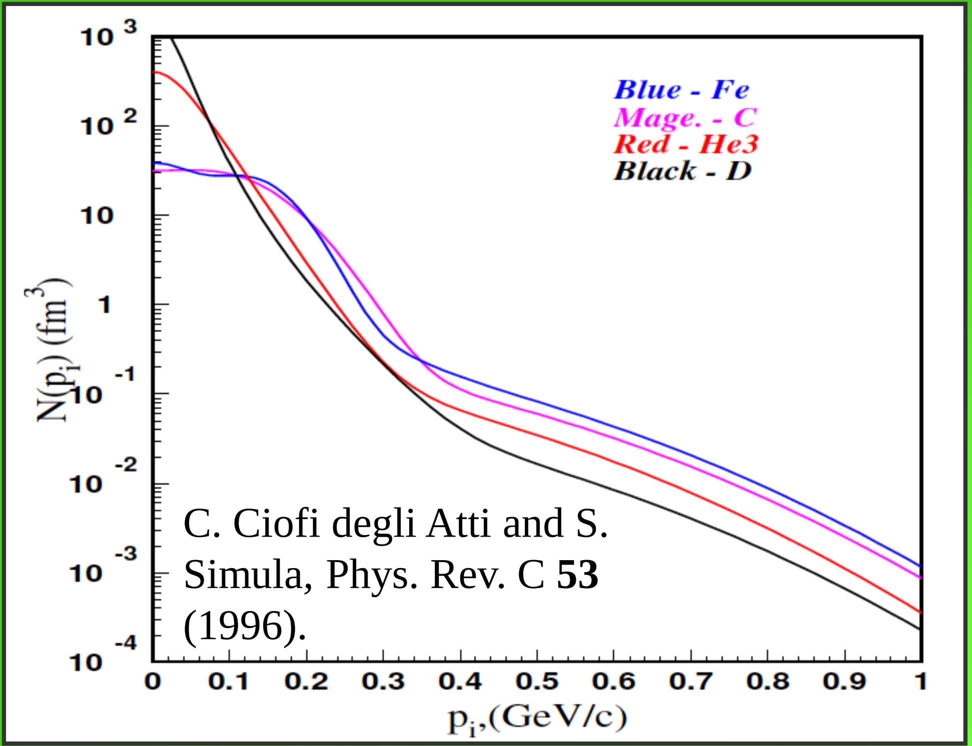
High momentum nucleons

- Short Range Correlations



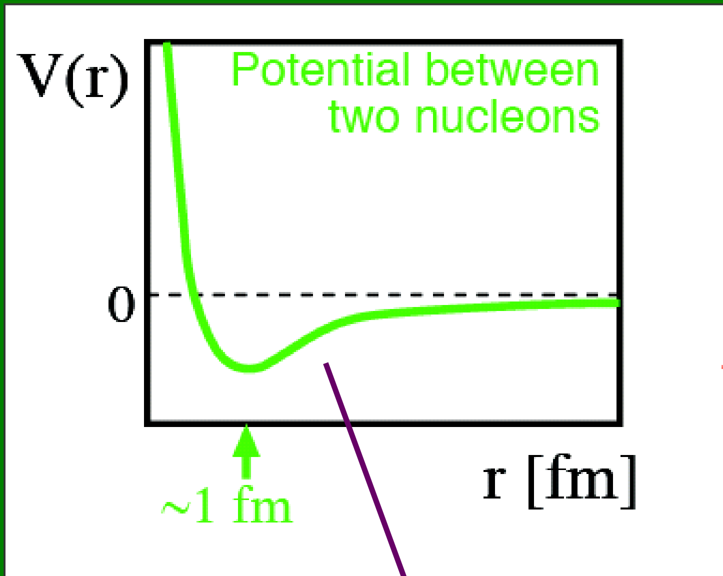


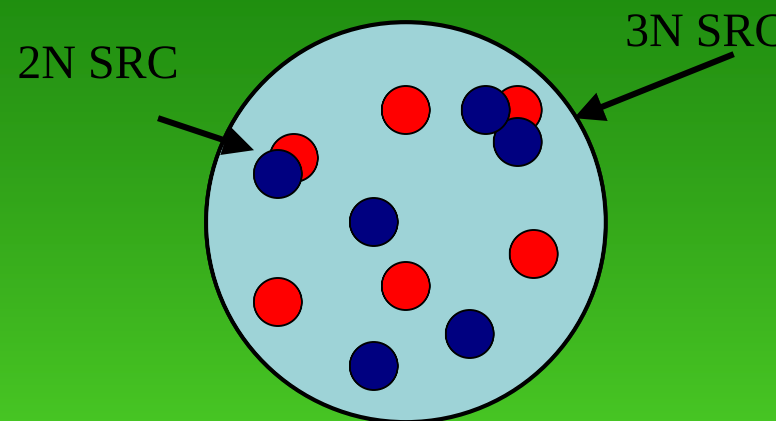


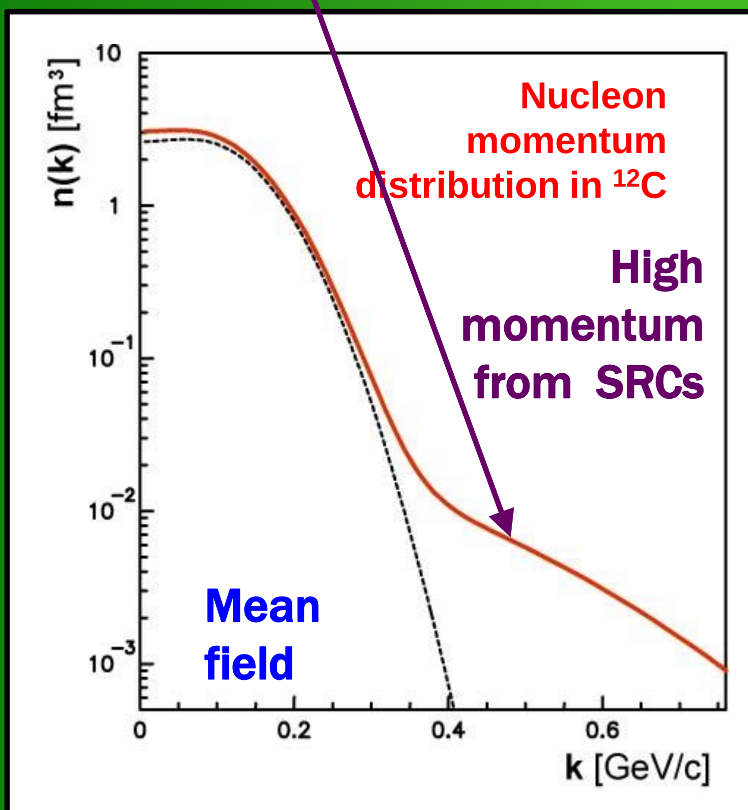


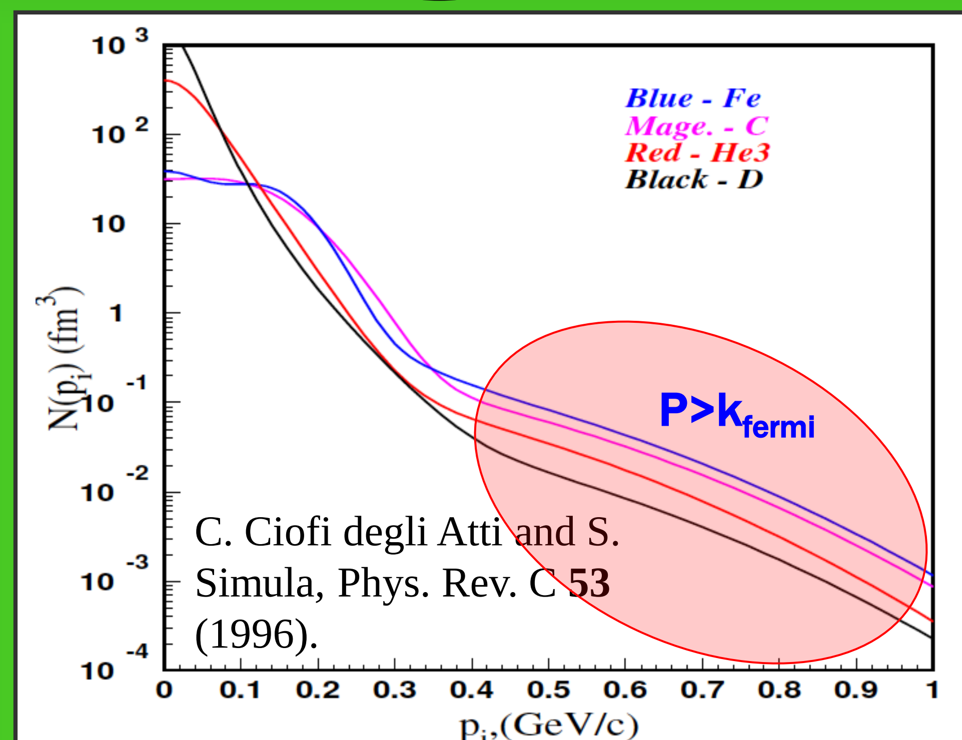
High momentum nucleons

- Short Range Correlations









C. Ciofi degli Atti and S. Simula, Phys. Rev. C **53** (1996).

Short Range Correlations

- To experimentally probe SRCs, must be in the high-momentum region (x>1)

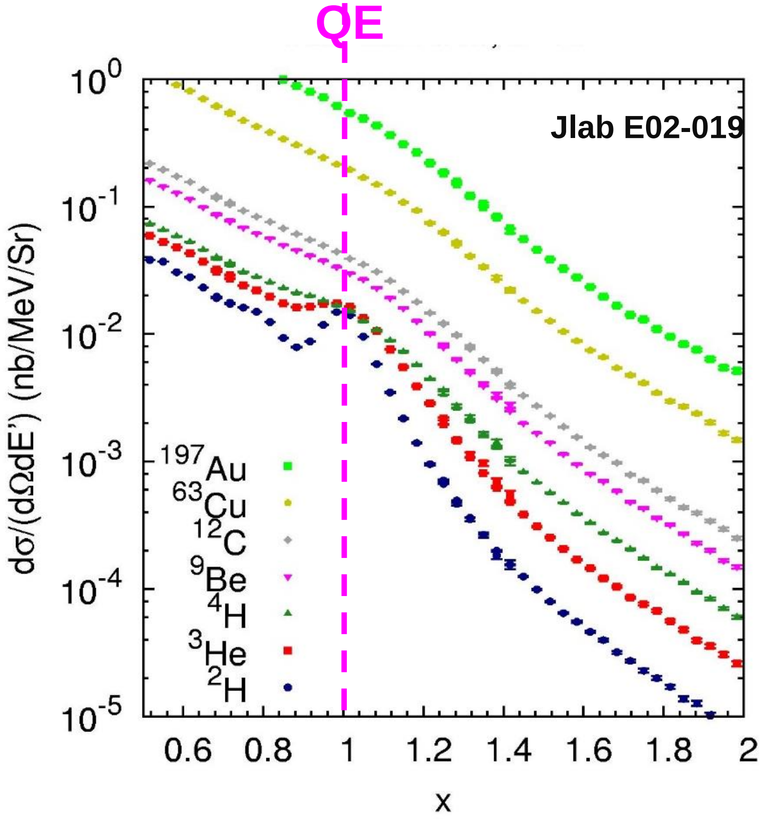
- To measure the relative probability of finding a correlation, ratios of heavy to light nuclei are taken

- In the high momentum region, FSIs are thought to be confined to the SRCs and therefore, cancel in the cross section ratios

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

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

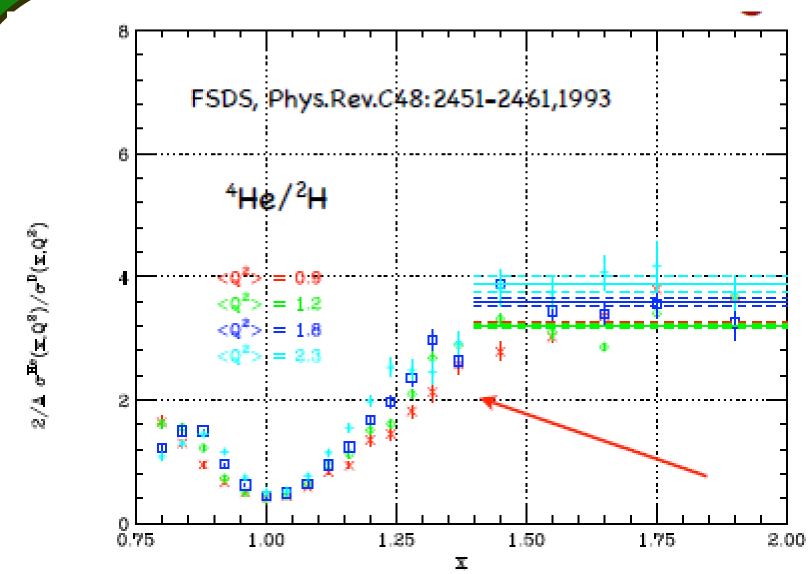
$$\frac{A}{3} a_3(A)\sigma_3(x, Q^2) + ...$$

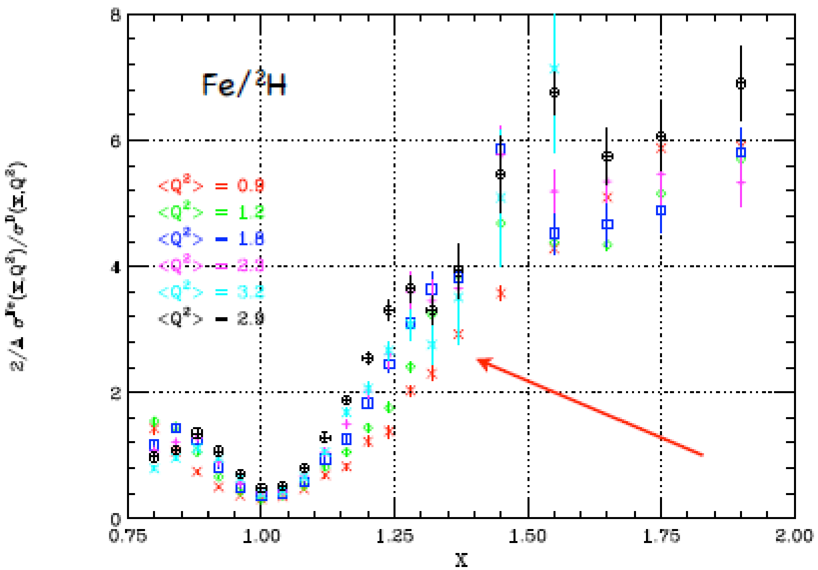


1.4<x<2 => 2 nucleon correlation

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

Before my time





- Moderate Q^2 data from SLAC
- Originally analyzed in the *y*-scaling picture

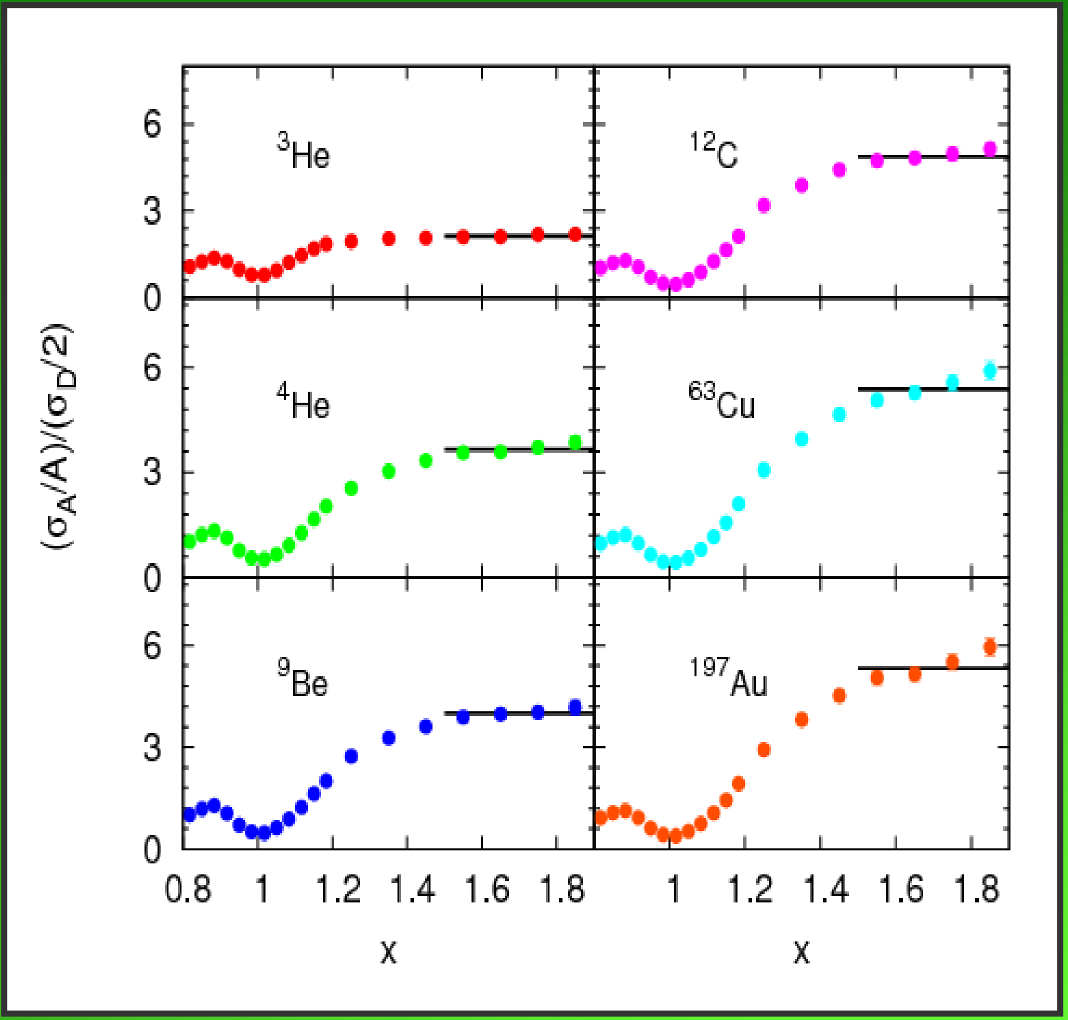
$$\sigma(x, Q^2) = \sum_{j=1}^{A} A \frac{1}{j} a_j(A)\sigma_j(x, Q^2)$$

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

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

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

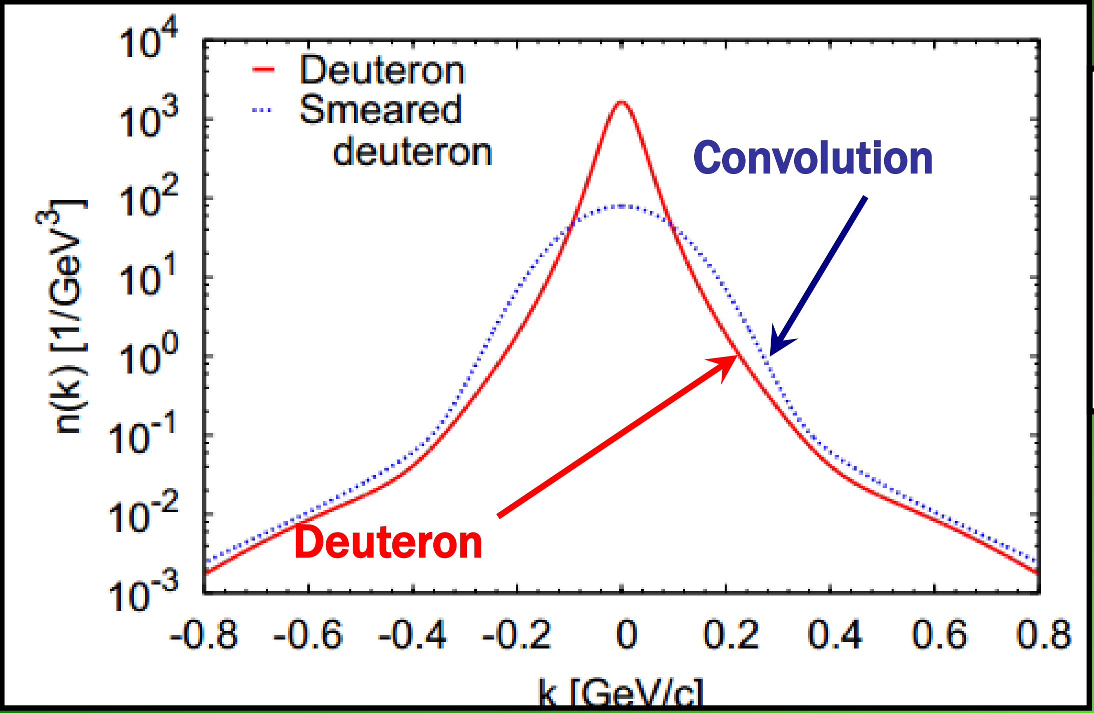


*Fomin et al, PRL **108** (2012)*

Jlab E02-019

<Q^2>=2.7 GeV^2

Note: ($a_2=\sigma_A/\sigma_D$)!= Relative #of SRCs



$n_D^{CONV}(k)$ is the convolution of $n_D(k)$ with the CM motion of correlated pairs in iron

Following prescription from C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53 (1996)

	E02-019	SLAC	CLAS	R_{2N}-ALL	a_2-ALL
^{3}He	1.93±0.10	1.8±0.3	–	1.92±0.09	2.13±0.04
^{4}He	3.02±0.17	2.8±0.4	2.80±0.28	2.94±0.14	3.57±0.09
Be	3.37±0.17	–	–	3.37±0.17	3.91±0.12
C	4.00±0.24	4.2±0.5	3.50±0.35	3.89±0.18	4.65±0.14
Al	–	4.4±0.6	–	4.40±0.60	5.30±0.60
Fe	–	4.3±0.8	3.90±0.37	3.97±0.34	4.75±0.29
Cu	4.33±0.28	–	–	4.33±0.28	5.21±0.20
Au	4.26±0.29	4.0±0.6	–	4.21±0.26	5.13±0.21

***$a_2=\sigma_A/\sigma_D$** → relative measure of high momentum nucleons*

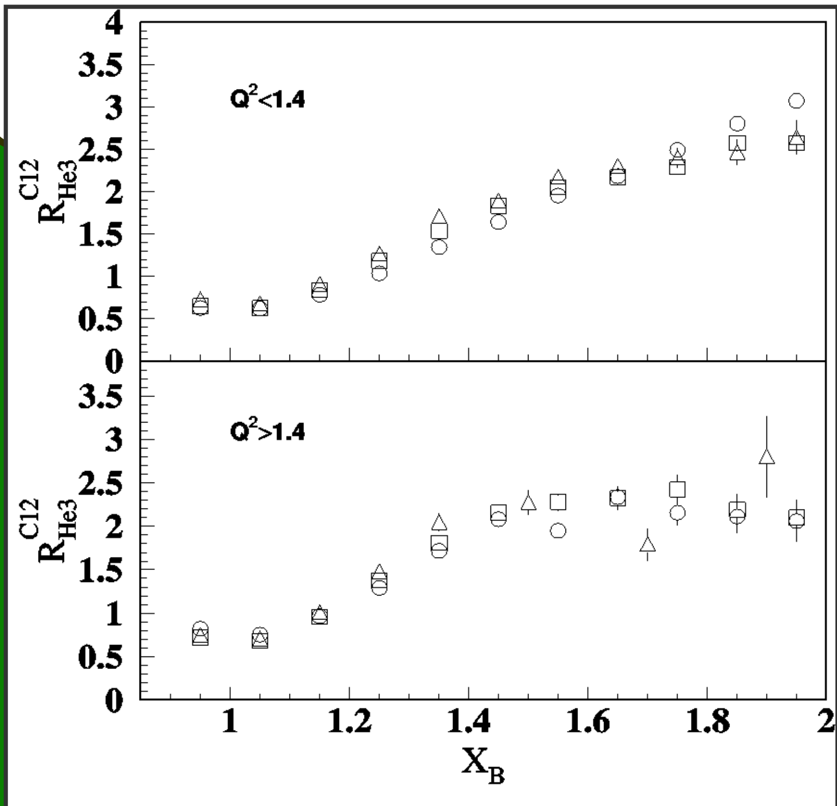
***R_{2n}** → relative measure of correlated pairs*

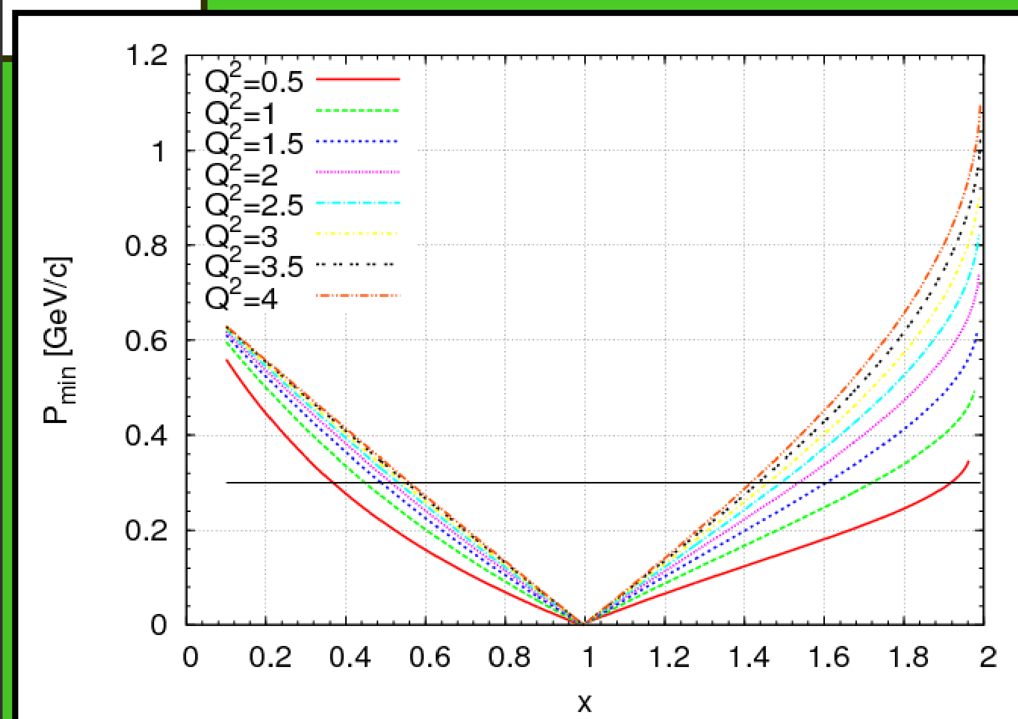
Inclusive Scattering

- Relative measurement
- Reduced FSI
- **Test scaling in x and Q^2**
- No direct information on isospin structure
  - Only via target isospin structure
- No direct information on momentum distribution for A>2

Inclusive Scattering

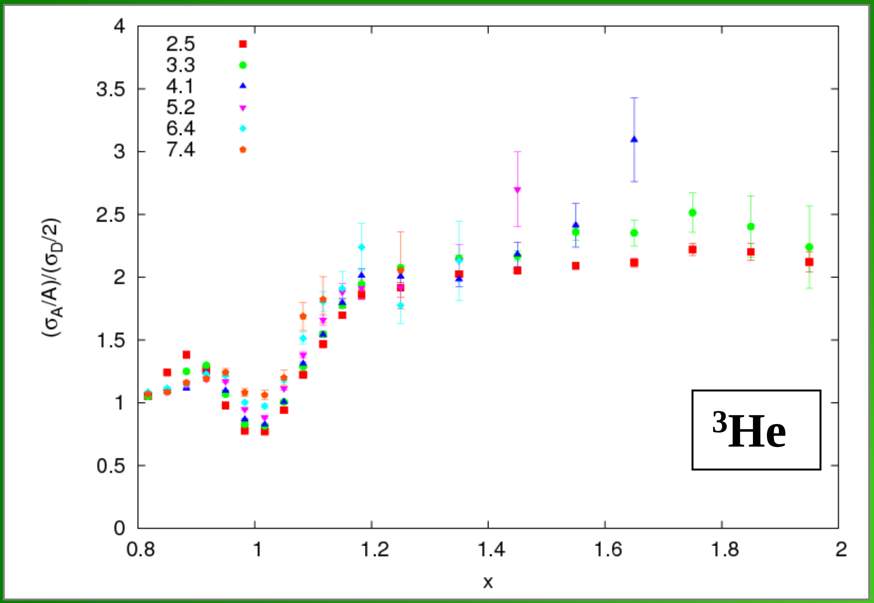
- Relative measurement
- Reduced FSI
- **Test scaling in x and Q^2**
- No direct information on isospin structure
  - Only via target isospin structure
- No direct information on momentum

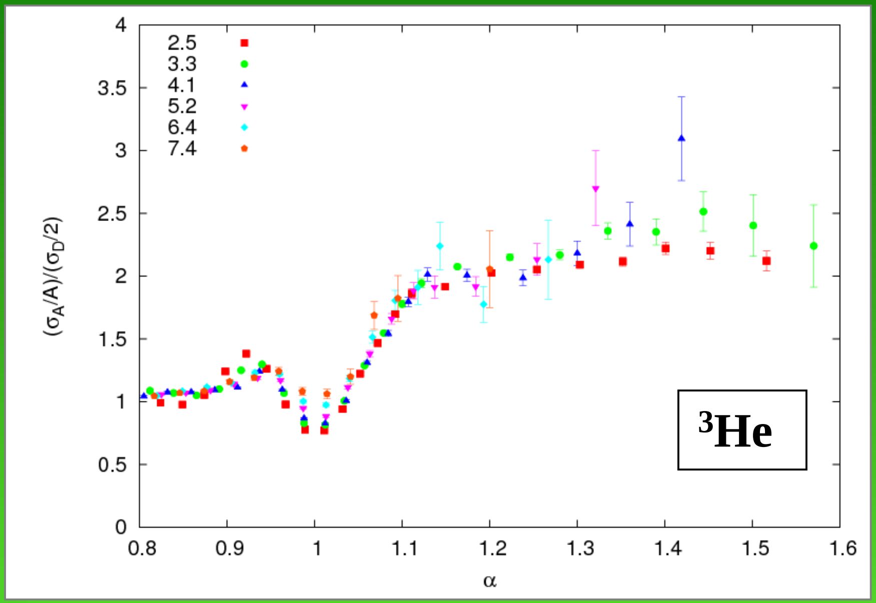


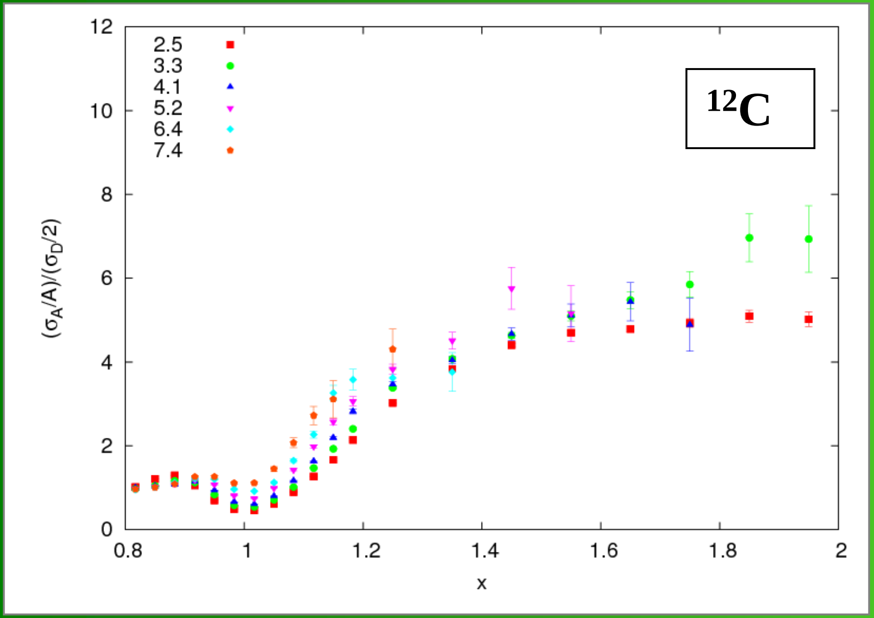


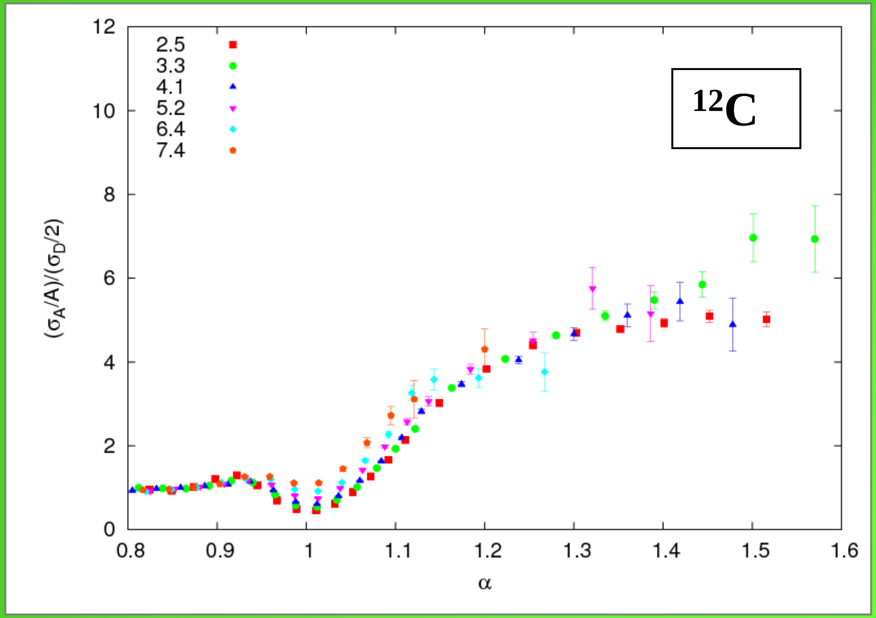
Test scaling in x and Q^2

$$\alpha = 2 - \frac{q^{-} + 2M}{2M}\left(1 + \frac{\sqrt{W^2 - 4M^2}}{W}\right)$$

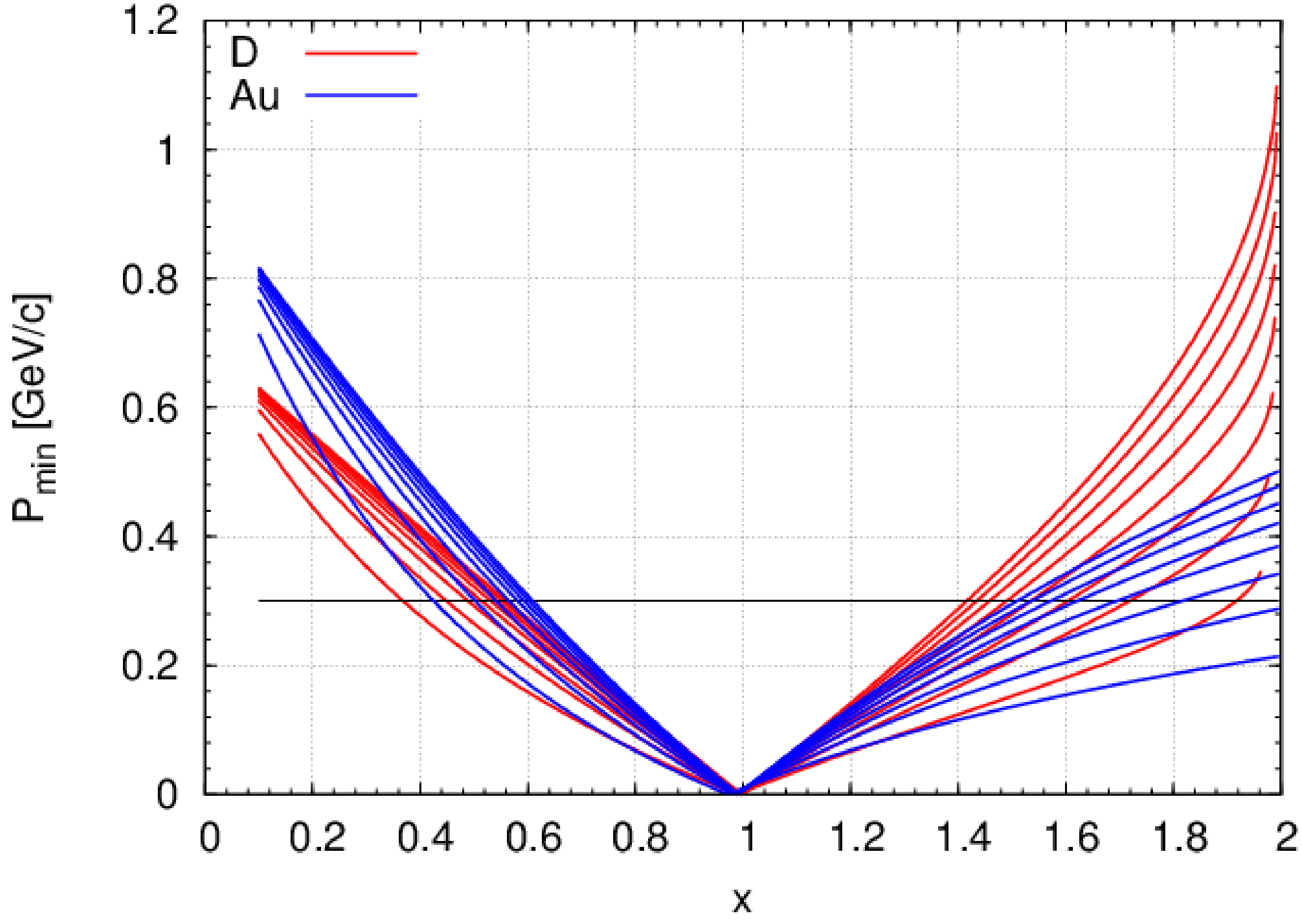








Kinematic cutoff is A-dependent

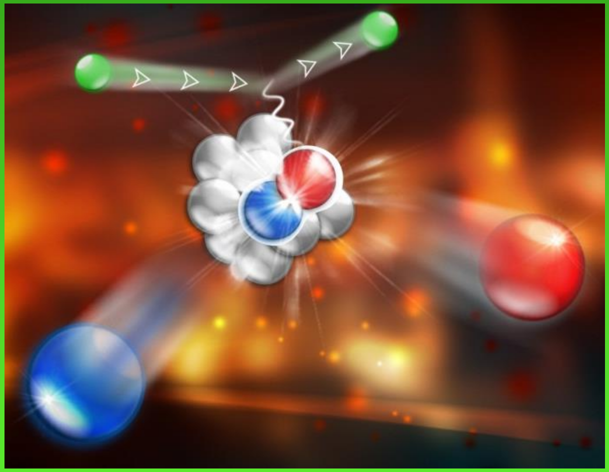


- For heavy nuclei, the minimum momentum changes → heavier recoil system requires less kinetic energy to balance the momentum of the struck nucleon
- Larger fermi momenta for A>2 → MF contribution persists for longer

2N knockout experiments establish NP dominance

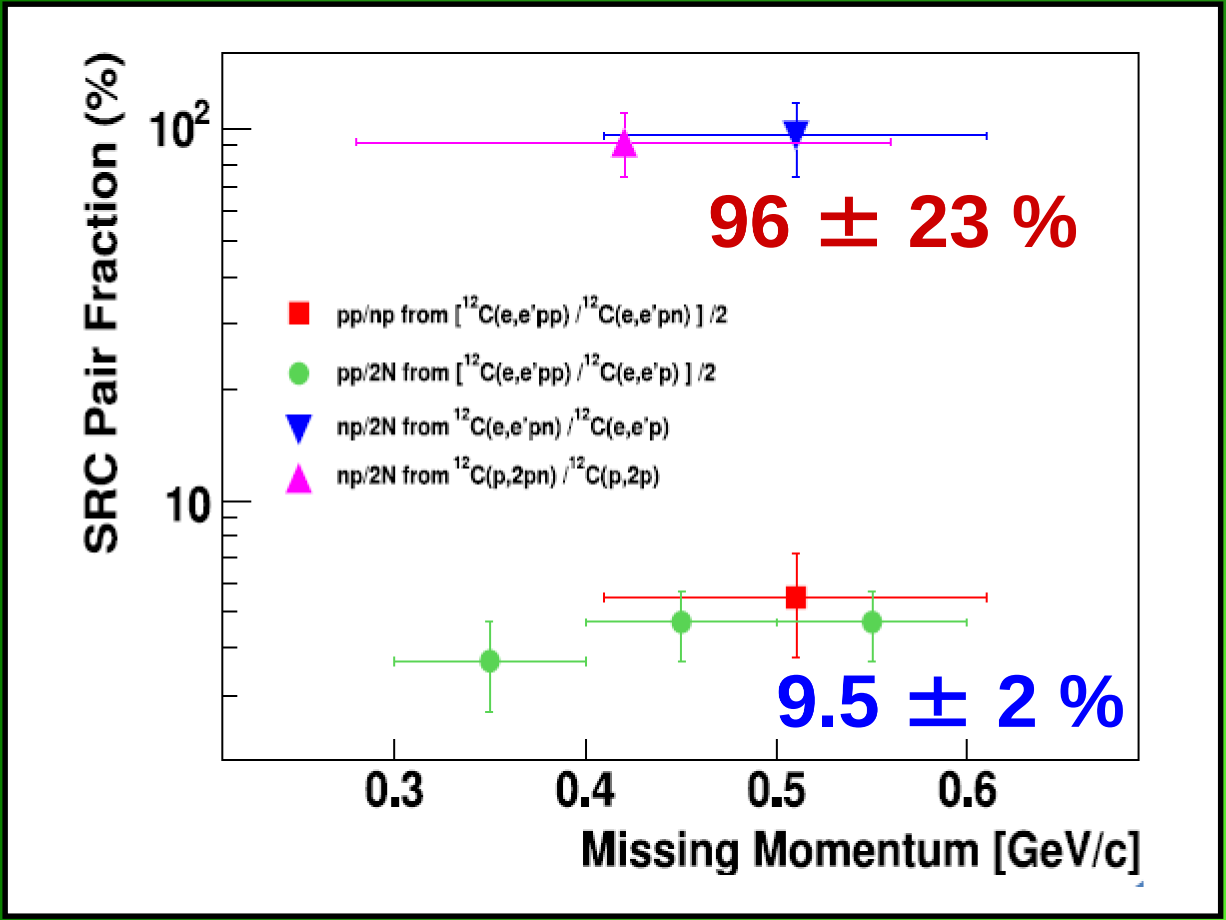
- Knockout high-initial-momentum proton, look for correlated nucleon partner.
- For 300 < P_{miss} < 600 MeV/c all nucleons are part of 2N-SRC pairs: 90% np, 5% pp (nn)

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

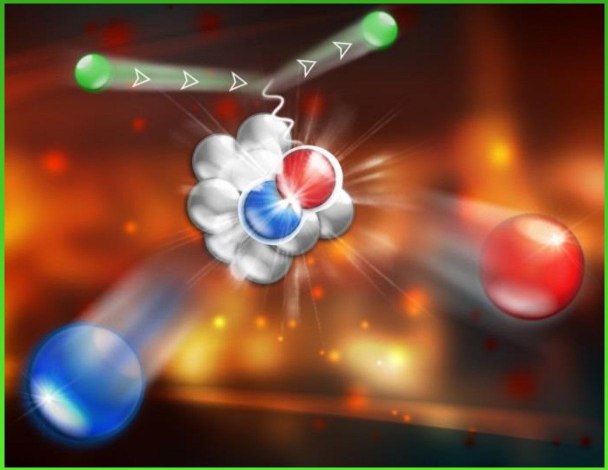


R. Shneor et al., PRL 99, 072501 (2007)

2N knockout experiments establish NP dominance

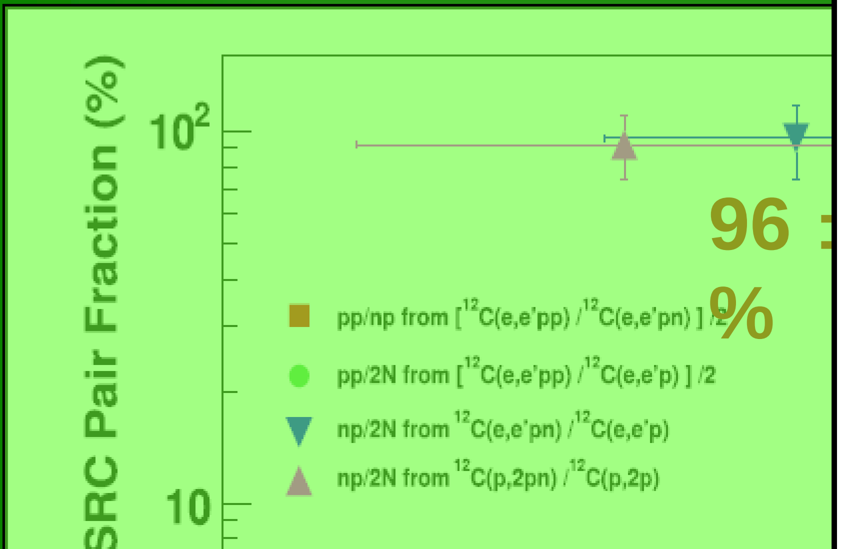


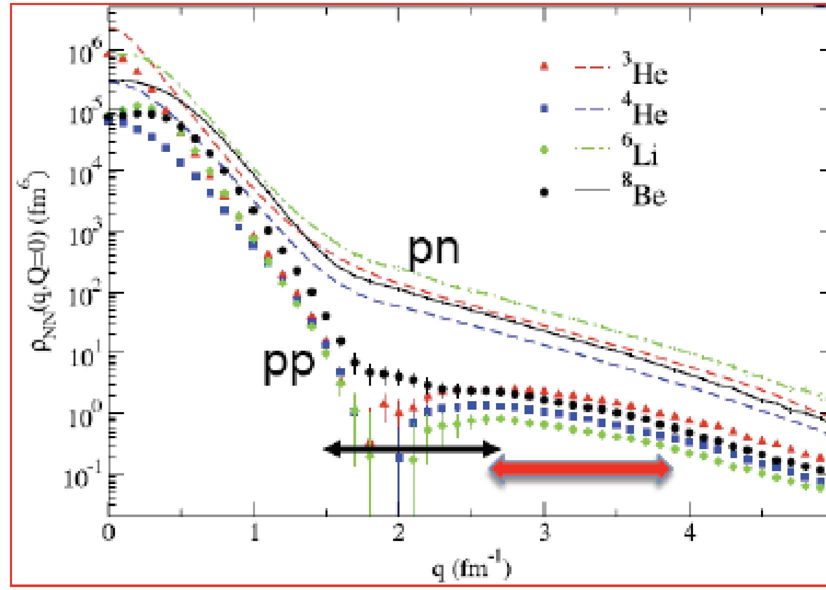
R. Subedi et al., Science 320, 1476 (2008)



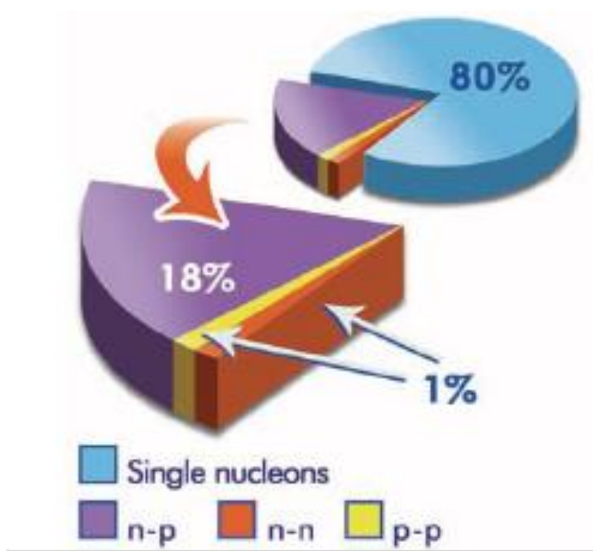
R. Shneor et al., PRL 99, 072501 (2007)

NP dominance





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

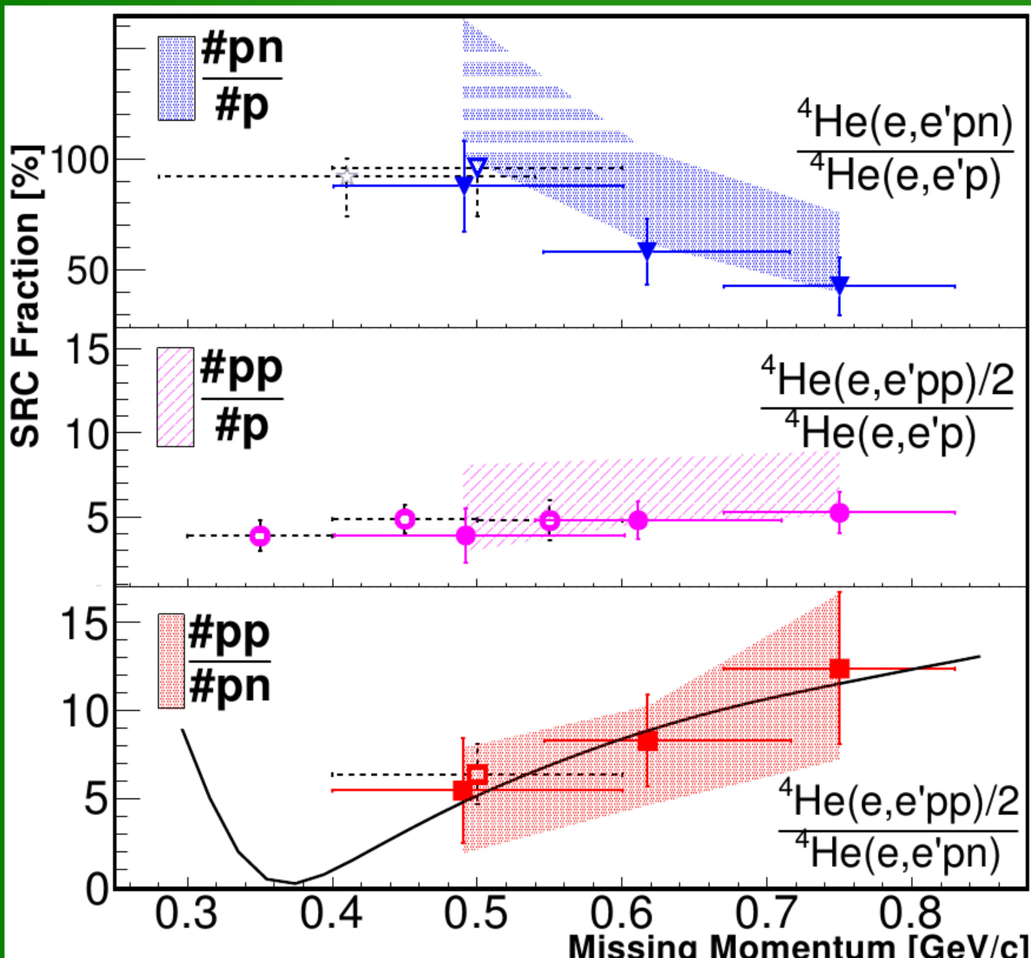


also

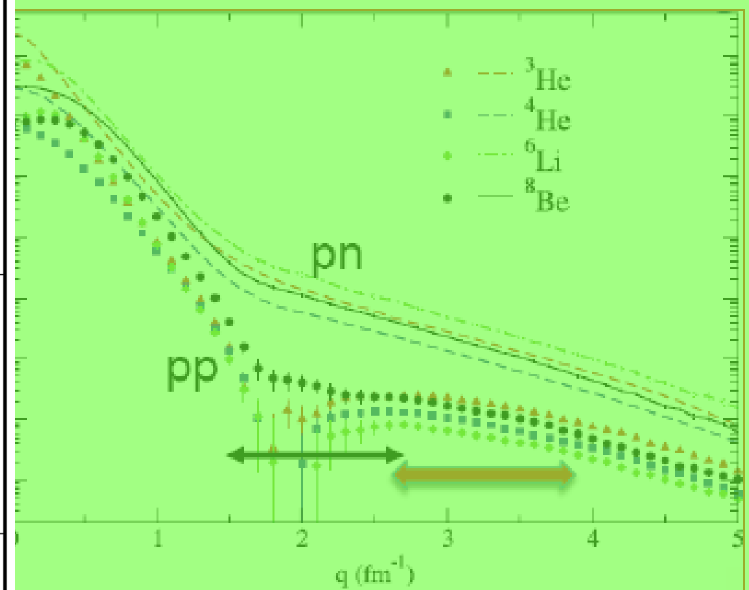
→ Ciofi and Alvioli PRL 100, 162503 (2008)

→Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005)

NP dominance: momentum dependent



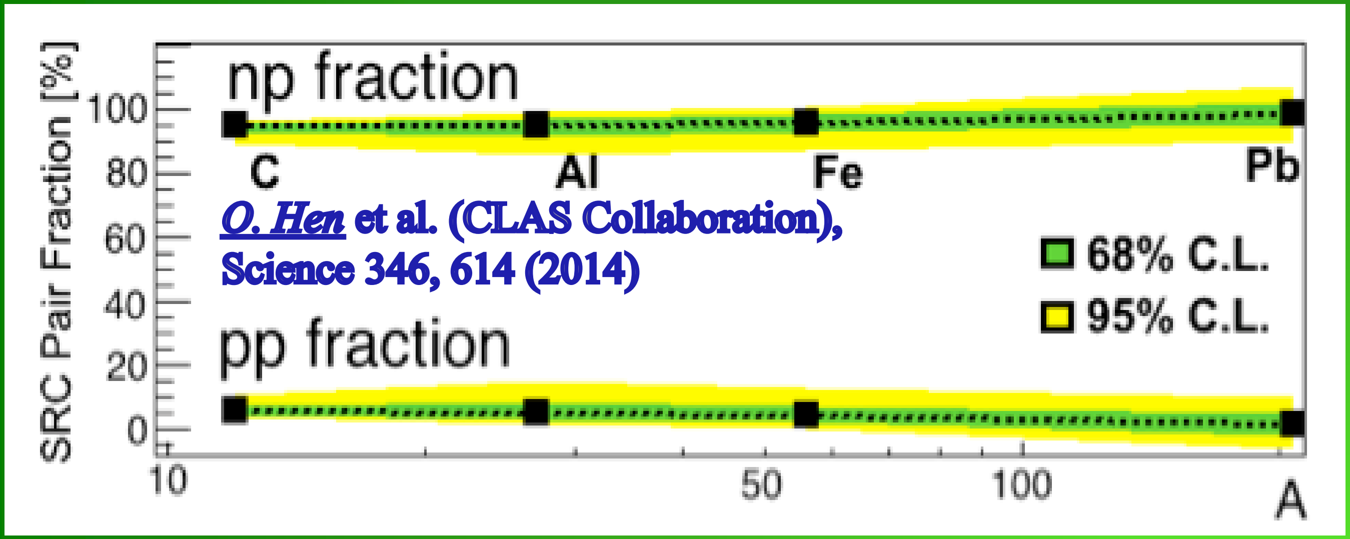
I. Korover et al, PRL 113 (2014) 022501



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

also
→ ...i and Alvioli PRL 100, 162503 (2008)
→Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005)

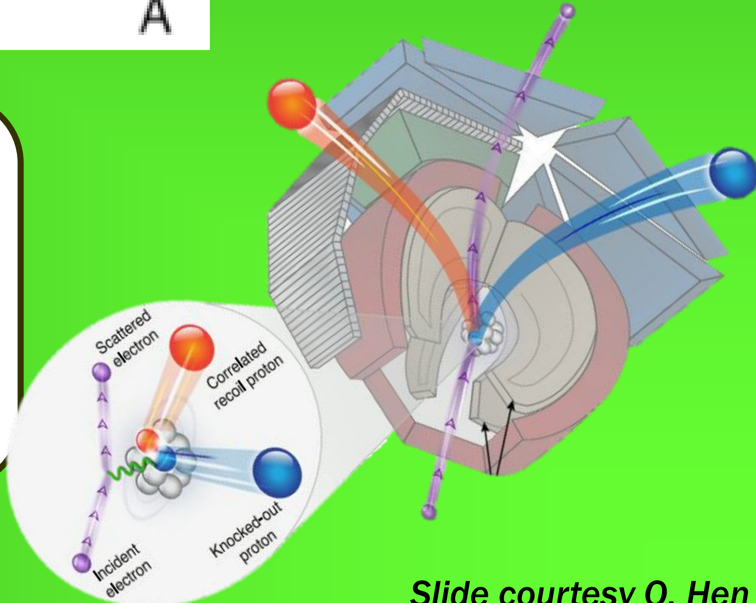
Data mining using CLAS
NP dominance continues for heavy nuclei



Assuming scattering off 2N-SRC pairs:

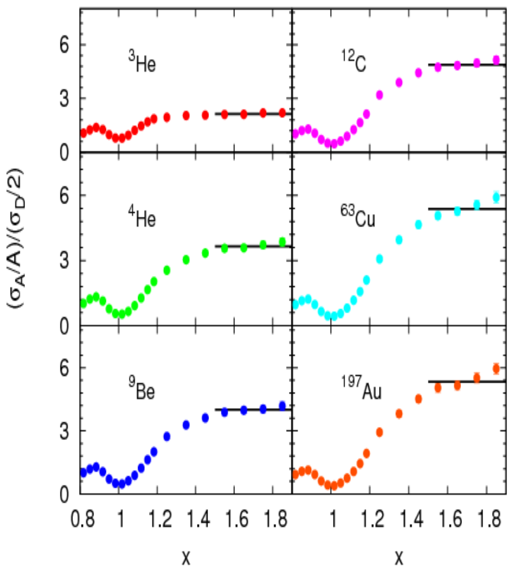
- **(e,e'p) is sensitive to *np* and *pp* pairs**
- **(e,e'pp) is sensitive to *pp* pairs alone**

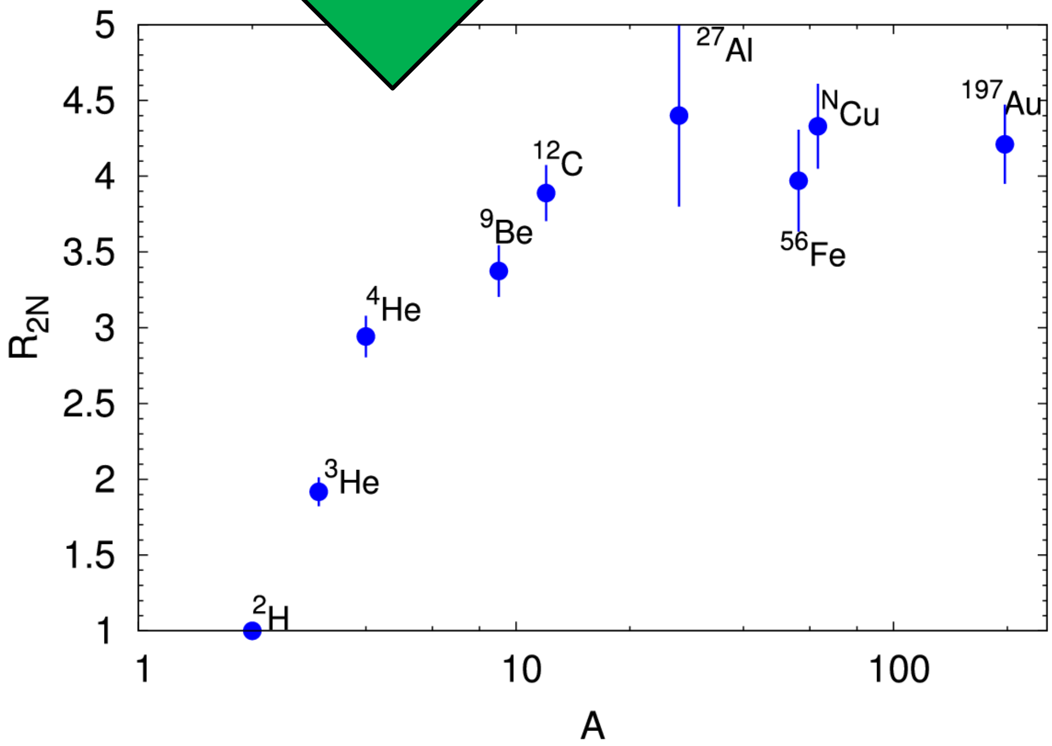
=> (e,e'pp)/(e,e'p) ratio is sensitive to the *np*/*pp* ratio



Slide courtesy O. Hen

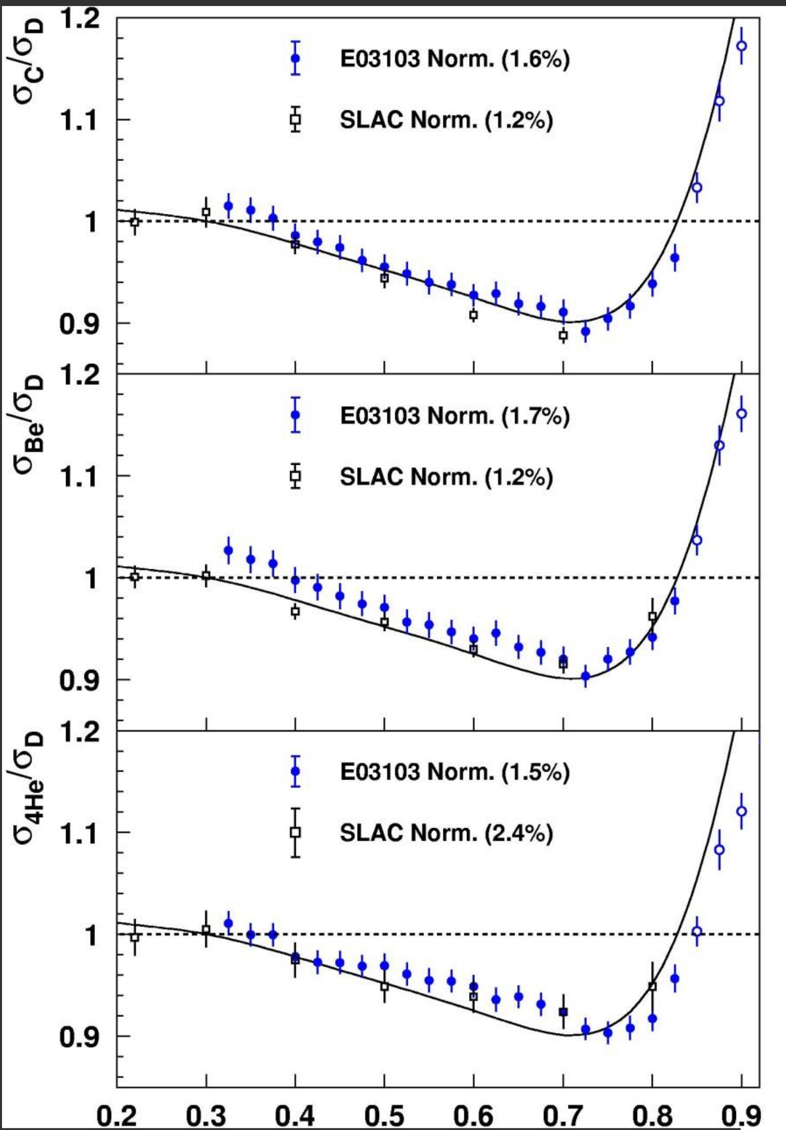
2N correlations





Have not solved the nuclear dependence

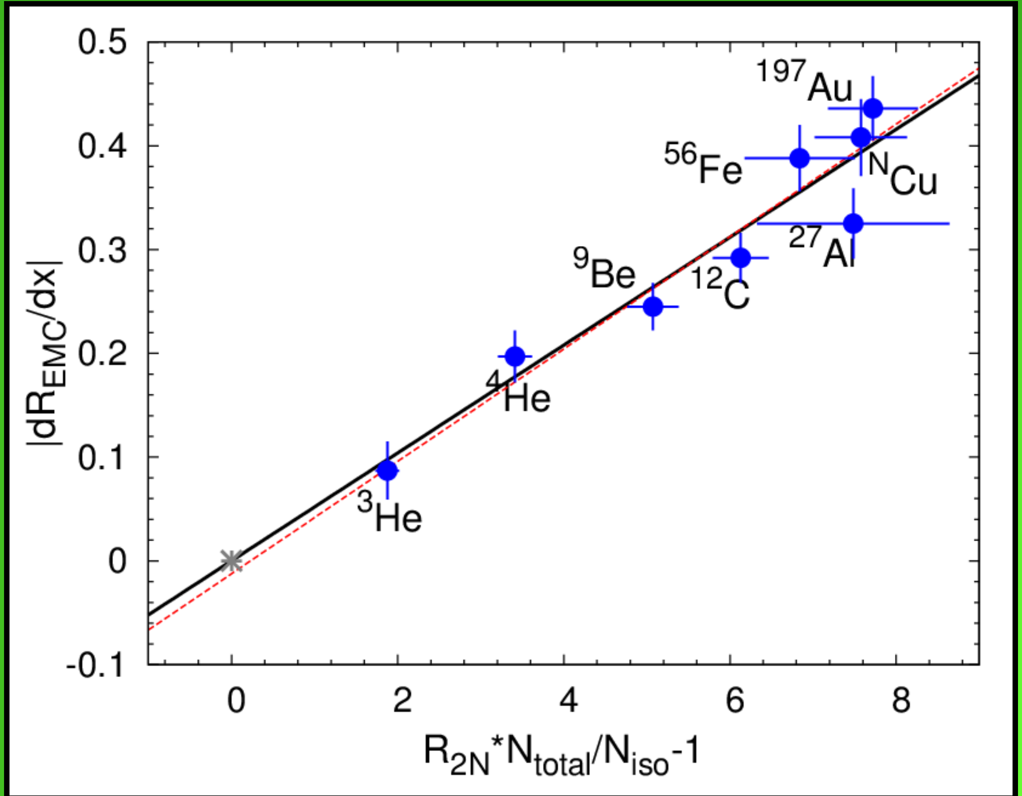
Linear relationship with EMC effect



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

- Fit the slope of the ratios for 0.3<x<0.7:

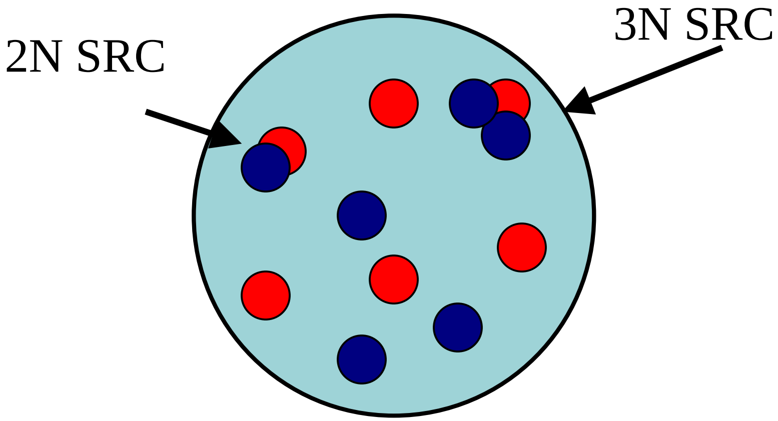
$$\frac{dR_{EMC}}{dx}$$



More nucleons in a correlation

1.4<x<2 => 2 nucleon correlation

2.4<x<3 => 3 nucleon correlation

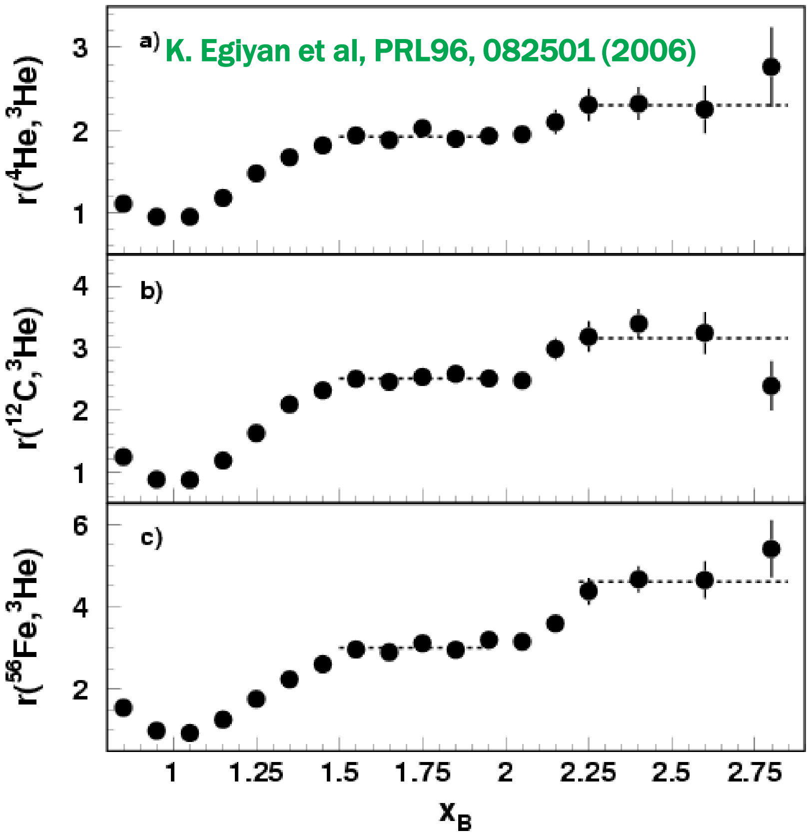


$$\sigma(x, Q^2) = \sum_{j=1}^{A} A \frac{1}{j} a_j(A)\sigma_j(x, Q^2)$$

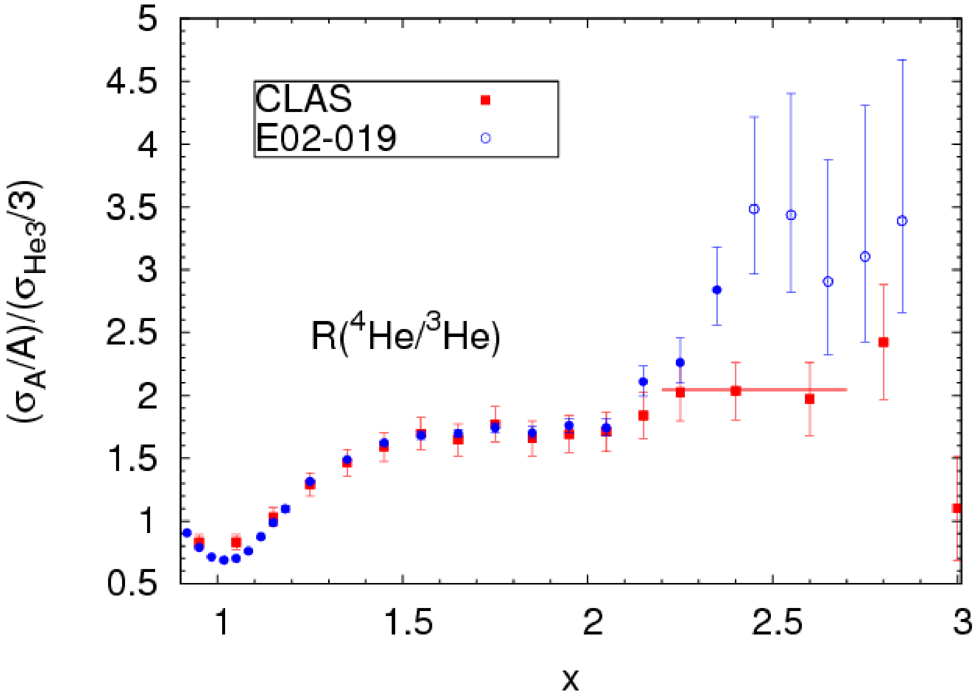
$$= \frac{A}{2} a_2(A)\sigma_2(x, Q^2) +$$

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

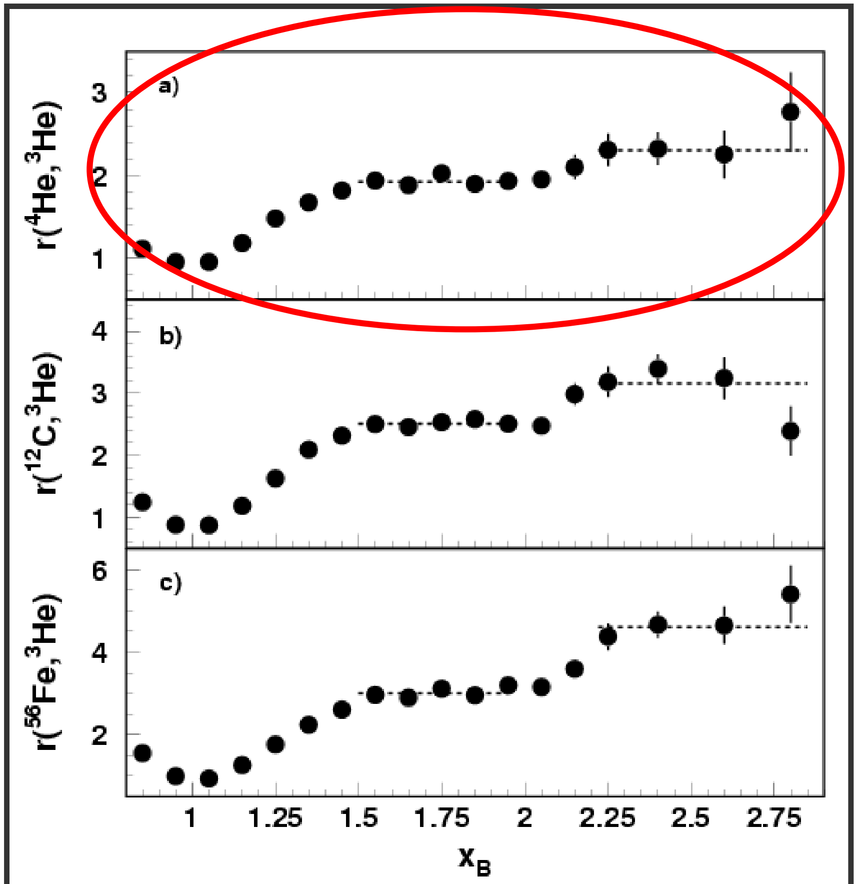
3N correlations (x>2 inclusive scattering)

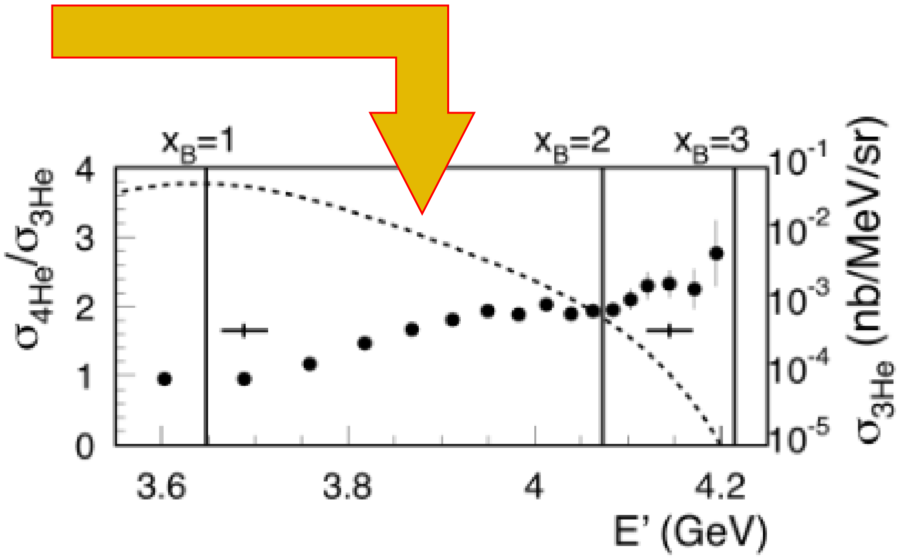


<Q^2> (GeV^2): CLAS: 1.6 E02-019: 2.7



Have we actually seen 3N SRC in ratios?





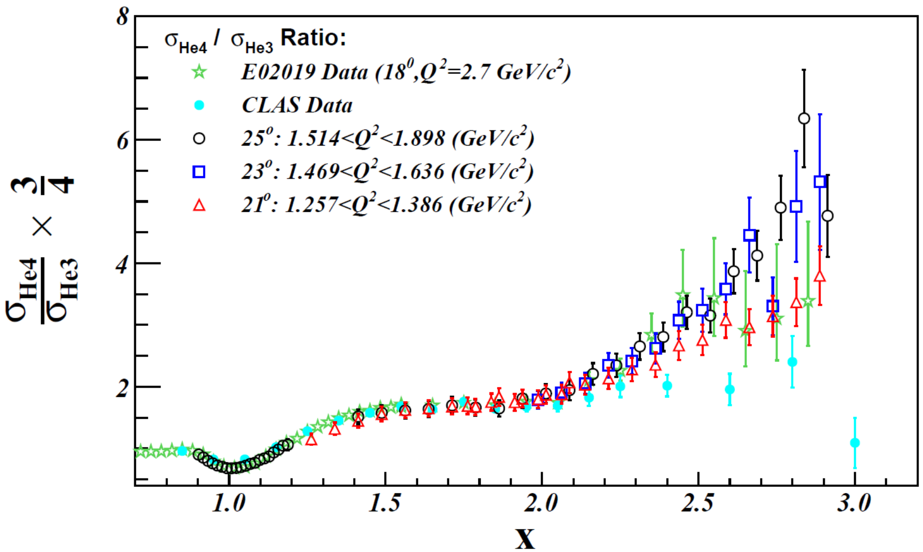
Comment on "Measurement of 2- and 3-nucleon short range correlation probabilities in nuclei"

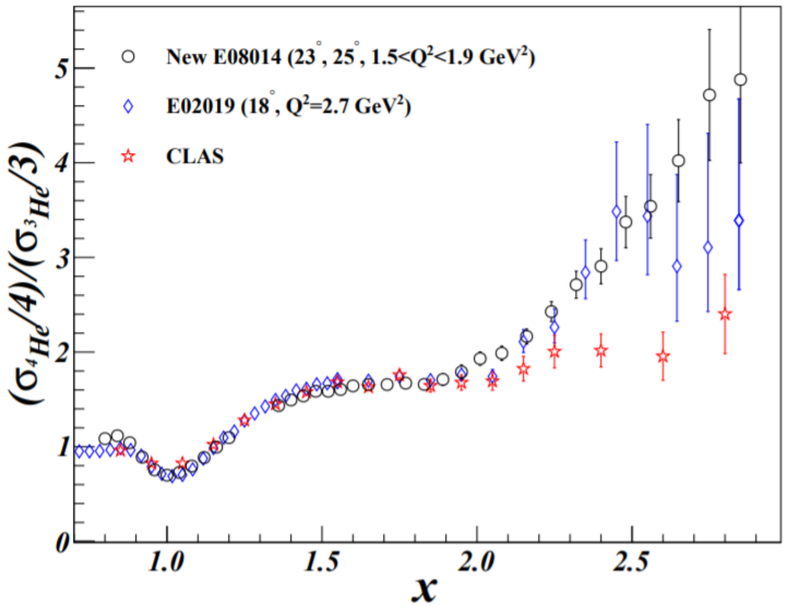
Douglas W. Higinbotham[1] and Or Hen[2]

3N correlations - still looking

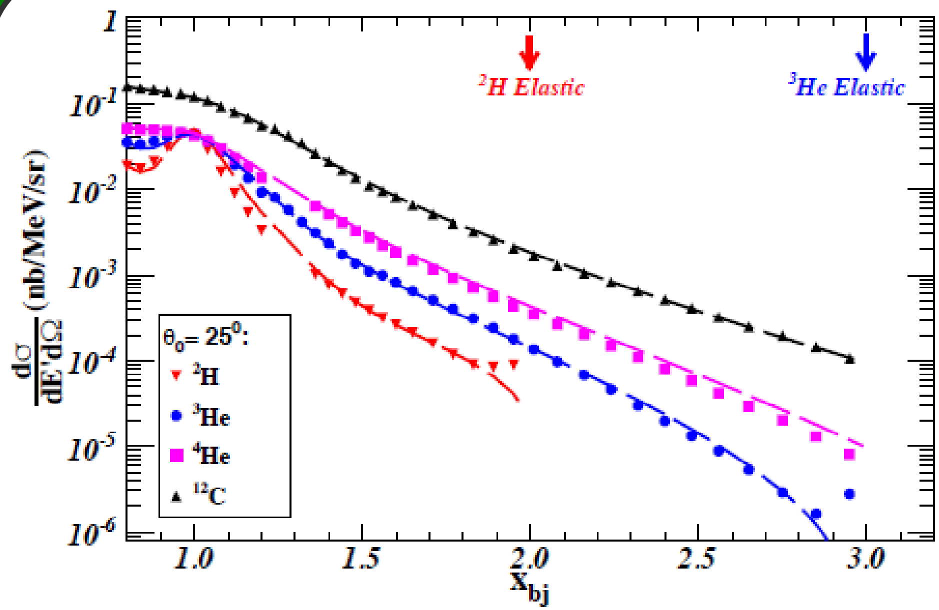
Search for three-nucleon short-range correlations in light nuclei

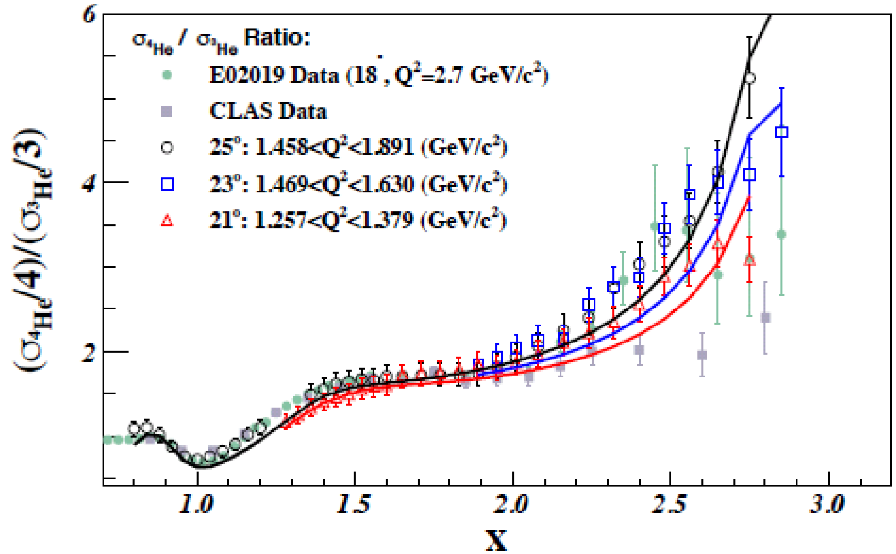
Z. Ye,[1,2,3] P. Solvignon,[4,5,*] D. Nguyen,[2] P. Aguilera,[6] Z. Ahmed,[7] H. Albataineh,[8] K. Allada,[5] B. Anderson,[9] D. Anez,[10] K. Aniol,[11] J. Annand,[12] J. Arrington,[1] T. Averett,[13] H. Baghdasaryan,[2] X. Bai,[14] A. Beck,[15] S. Beck,[15] V. Bellini,[16] F. Benmokhtar,[17] A. Camsonne,[5] C. Chen,[18] J.-P. Chen,[5] K. Chirapatpimol,[2] E. Cisbani,[19] M. M. Dalton,[2,5] A. Daniel,[20] D. Day,[2] W. Deconinck,[21] M. Defurne,[22] D. Flay,[23] N. Fomin,[24] M. Friend,[25] S. Frullani,[19] E. Fuchey,[23] F. Garibaldi,[19] D. Gaskell,[5] S. Gilad,[21] R. Gilman,[26] S. Glamazdin,[27] C. Gu,[2] P. Guèye,[18] C. Hanretty,[2] J.-O. Hansen,[5] M. Hashemi Shabestari,[2] O. Hen,[28] D. W. Higinbotham,[5] M. Huang,[3] S. Iqbal,[11] G. Jin,[2] N. Kalantarians,[2] H. Kang,[29] A. Kelleher,[21] I. Korover,[28] J. LeRose,[5] J. Leckey,[30] R. Lindgren,[2] E. Long,[9] J. Mammei,[31] D. J. Margaziotis,[11] P. Markowitz,[32] D. Meekins,[5] Z. Meziani,[23] R. Michaels,[5] M. Mihovilovic,[33] N. Muangma,[21] C. Munoz Camacho,[34] B. Norum,[2] Nuruzzaman,[35] K. Pan,[21] S. Phillips,[4] E. Piasetzky,[28] I. Pomerantz,[28,36] M. Posik,[23] V. Punjabi,[37] X. Qian,[3] Y. Qiang,[5] X. Qiu,[38] P. E. Reimer,[1] A. Rakhman,[7] S. Riordan,[2,39] G. Ron,[40] O. Rondon-Aramayo,[2] A. Saha,[5,*] L. Selvy,[9] A. Shahinyan,[41] R. Shneor,[28] S. Sirca,[42,33] K. Slifer,[4] N. Sparveris,[23] R. Subedi,[2] V. Sulkosky,[21] D. Wang,[2] J. W. Watson,[9] L. B. Weinstein,[8] B. Wojtsekhowski,[5] S. A. Wood,[5] I. Yaron,[28] X. Zhan,[1] J. Zhang,[5] Y. W. Zhang,[26] B. Zhao,[13] X. Zheng,[2] P. Zhu,[43] and R. Zielinski[4]
(The Jefferson Lab Hall A Collaboration)

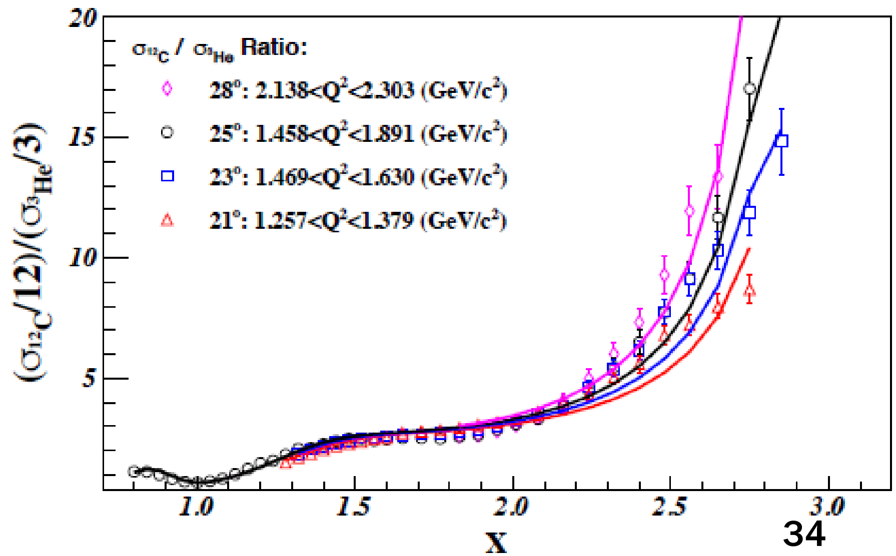




Can we see a second plateau?





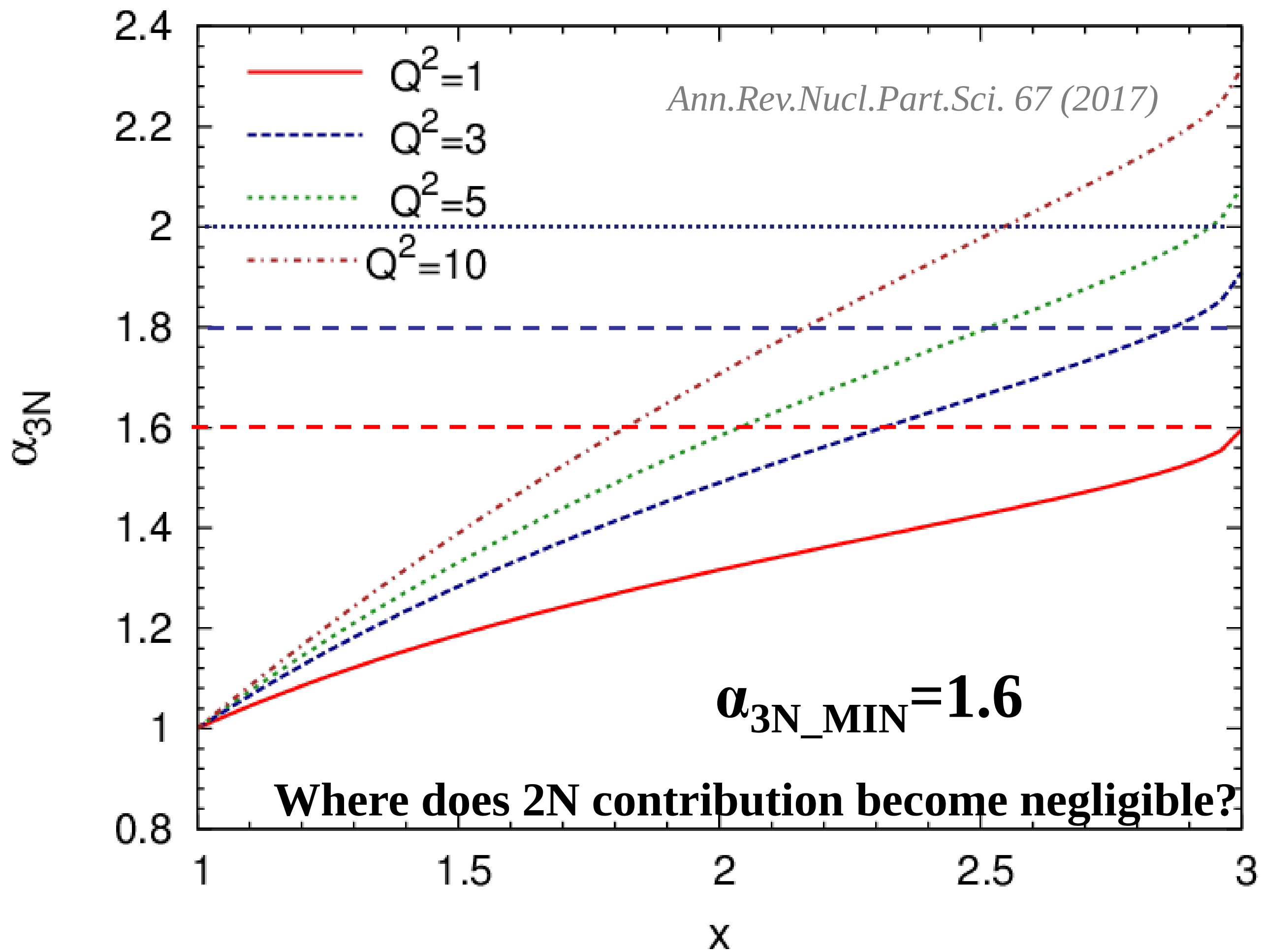


Deuteron: smeared SRC similar to 2H (A/D is ~flat) until x>1.8

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

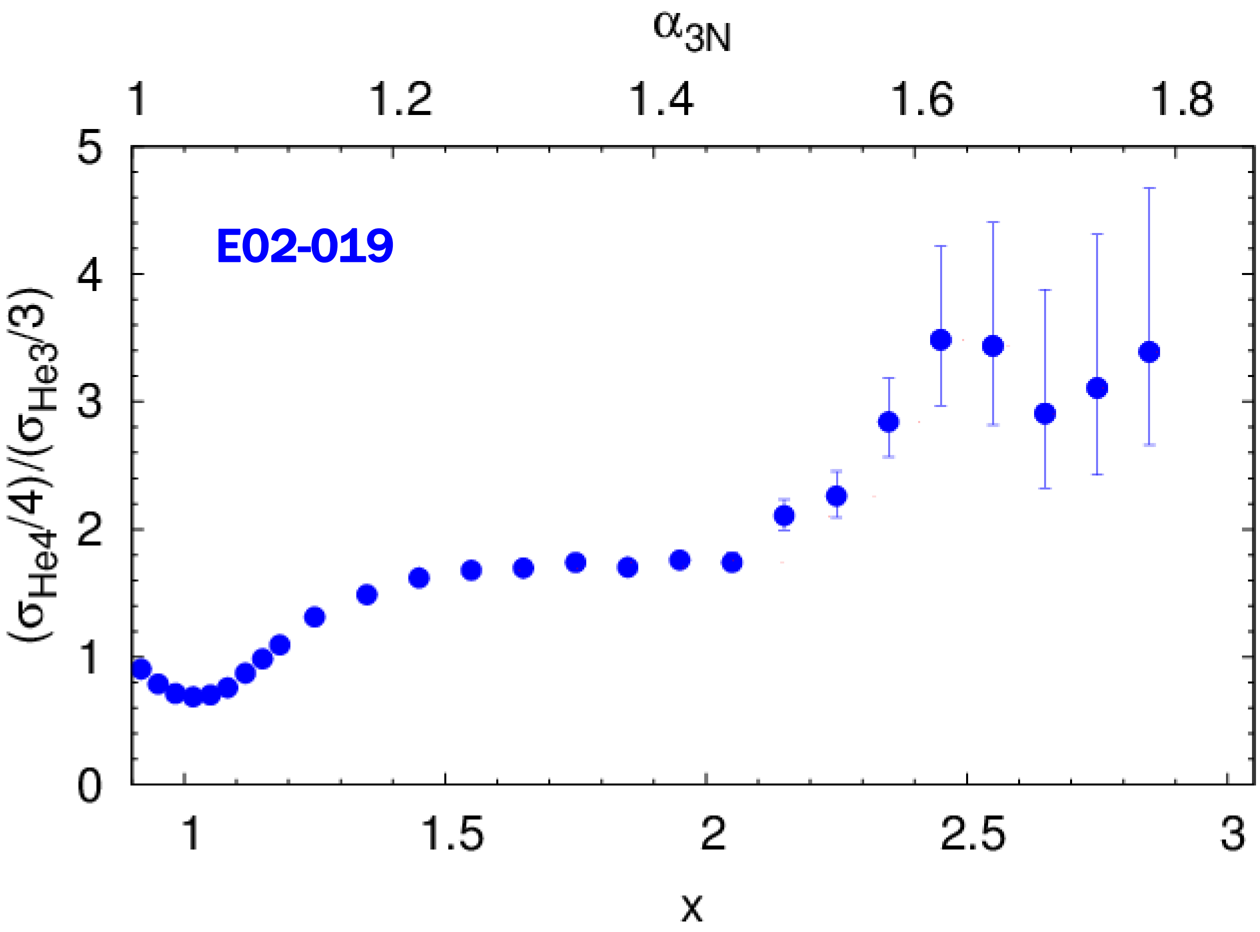

I WAS TOLD THERE WOULD BE
3N SRC PLATEAUS
imgflip.com

3N correlations – are we there yet?



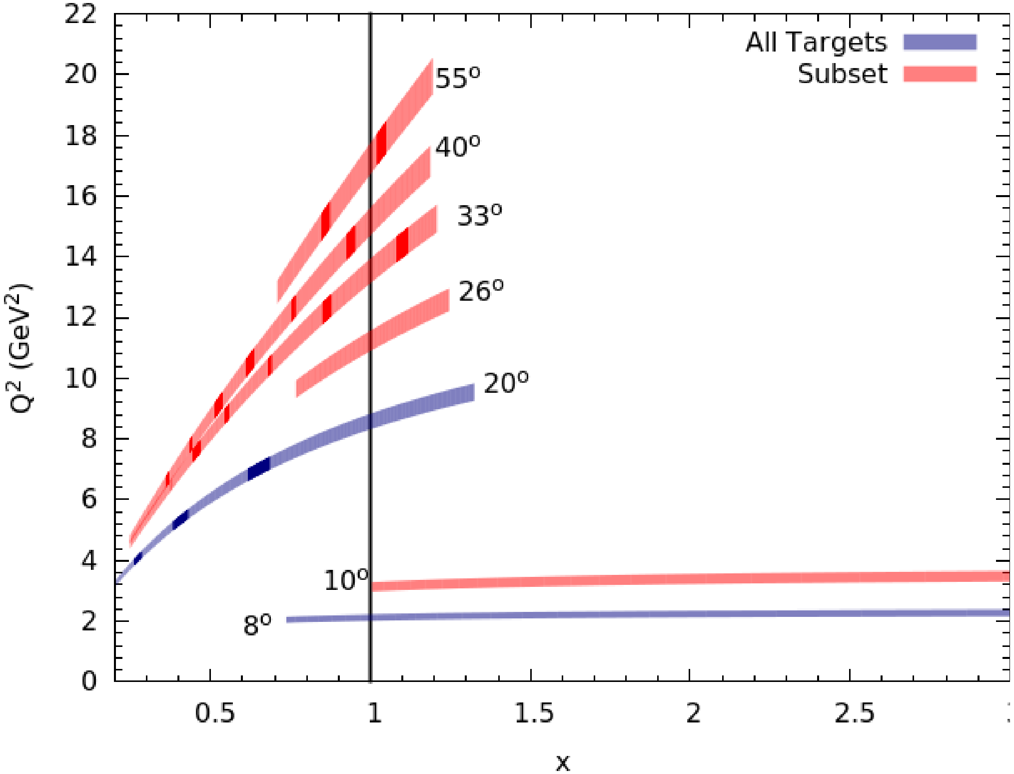
α_i represents the light-cone momentum fraction of 3N SRCs carried by the correlated nucleon *i*

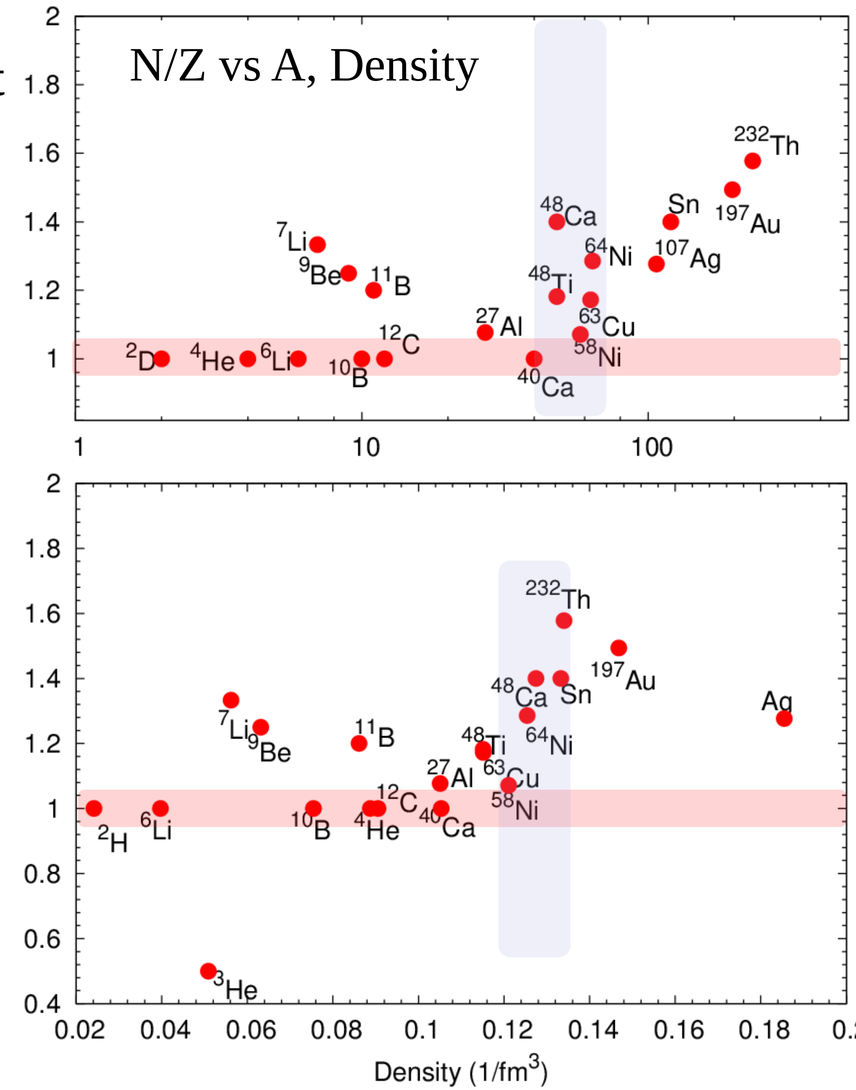
We were so close



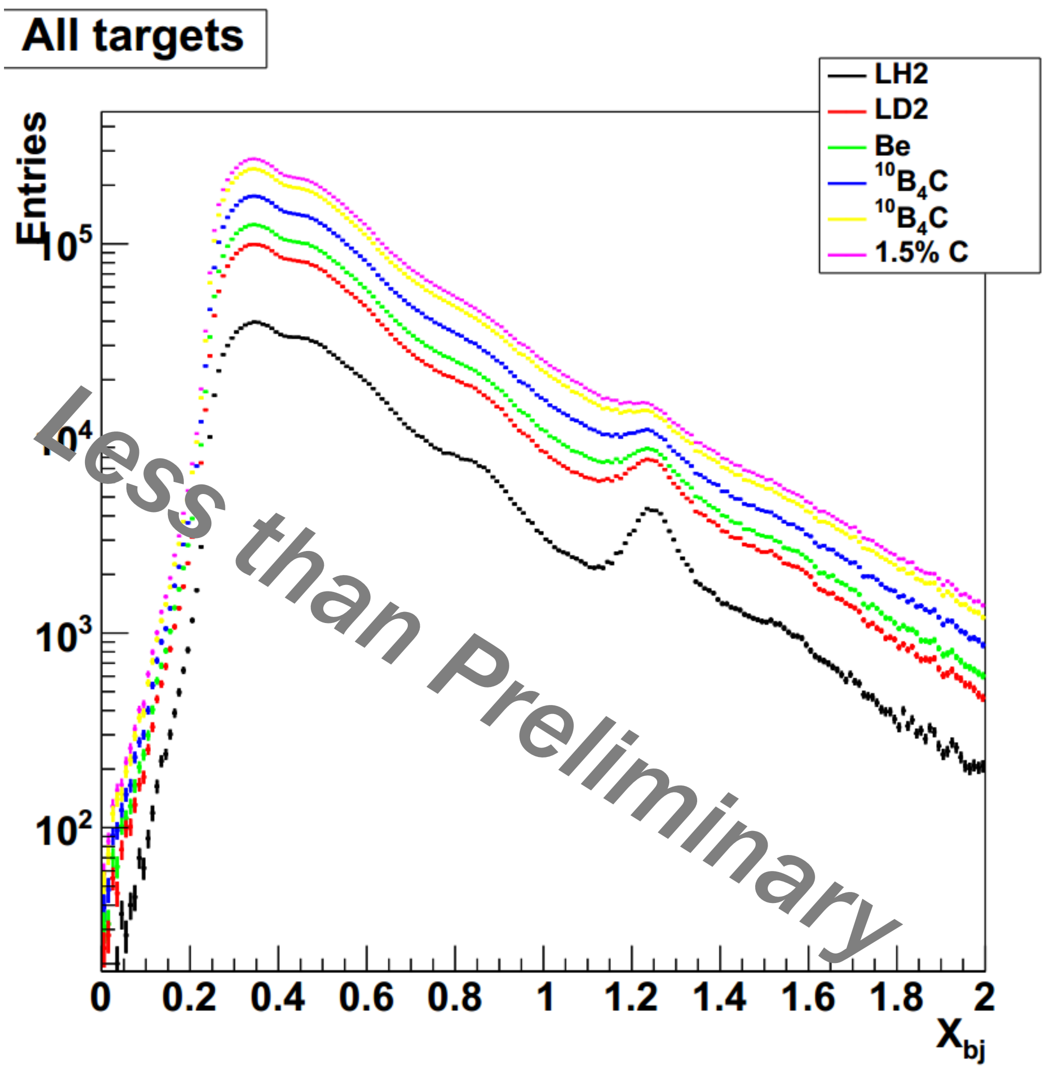
3N correlation measurements – Hall C (soon?)

Target Choice motivated by physics impact



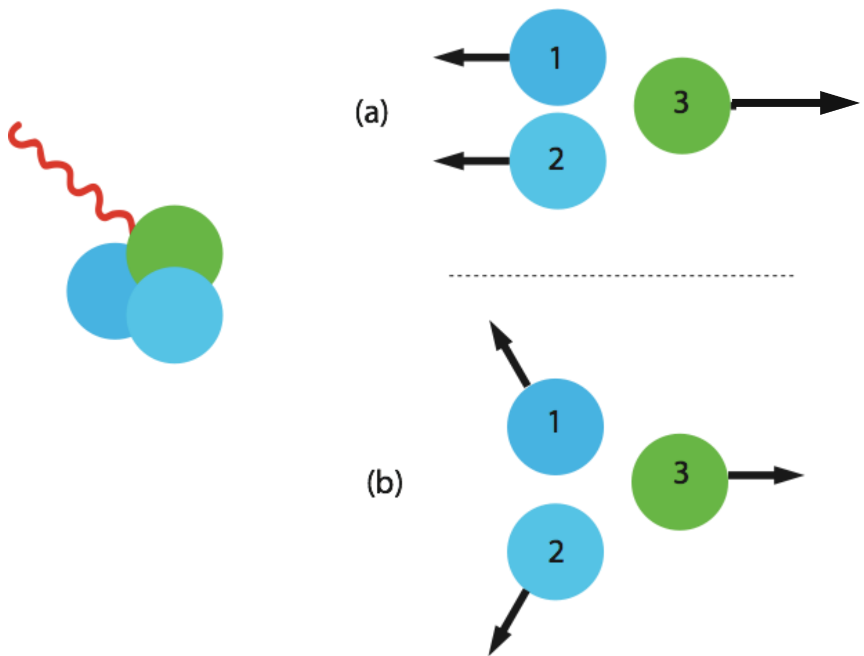


Earlier this spring in Hall C



It's happening!
3N correlation measurements – $^3H/^3He$

Momentum-isospin correlations for 3N-SRCs



"Linear configuration"

$p_3 = p_1 + p_2$

extremely large momentum

"Star configuration"

$p_1 = p_2 = p_3$

(a) yields $R(^3He/^3H) \approx 1.4$ if configuration is isospin-independent, as does (b)

(a) yields $R(^3He/^3H) \approx 3.0$ if nucleon #3 is always the doubly-occurring nucleon

(a) yields $R(^3He/^3H) \approx 0.3$ if nucleon #3 is always the singly-occurring nucleon

R≠1.4 implies isospin dependence AND non-symmetric momentum sharing

The experiment formerly known as CaFe

Goals are to extract the

• ratios of high to low momentum protons in each of D, C, ^{40}Ca, ^{48}Ca, and ^{54}Fe,

• ratios of high-momentum protons in heavier nuclei to deuterium and in ^{40}Ca to C, ^{40}Ca to ^{48}Ca and in ^{54}Fe to ^{48}Ca

• double ratios of high to low momentum protons in heavier nuclei to deuterium, ^{40}Ca to C, ^{40}Ca relative to ^{48}Ca, and in ^{54}Fe relative to ^{48}Ca.

"We will need to correct each of these ratios for the effects of final state interactions"

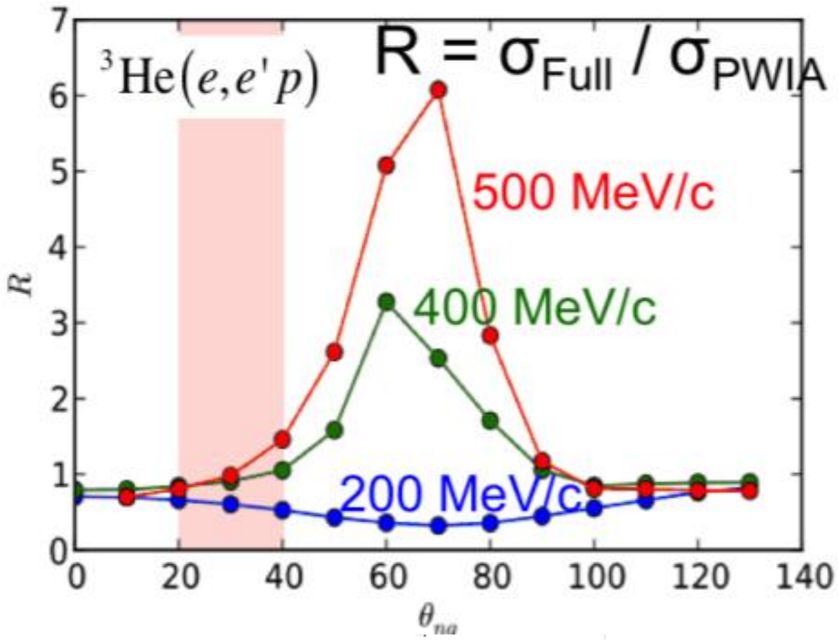
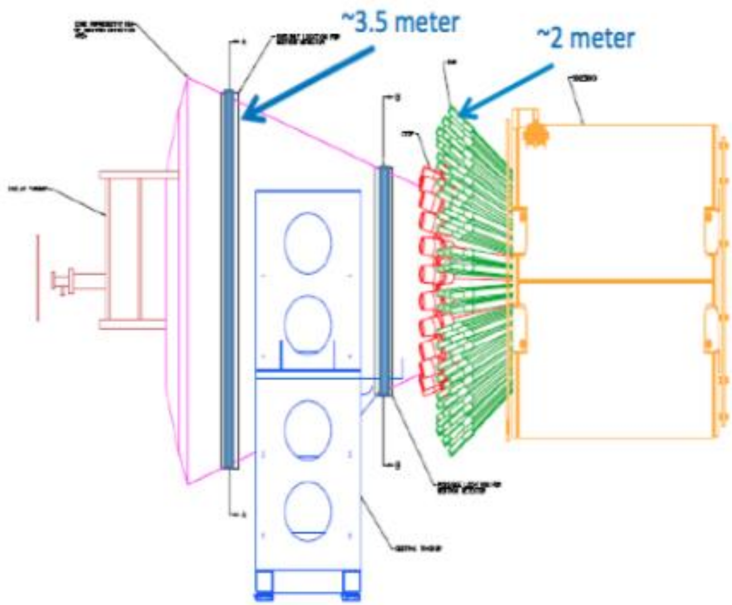


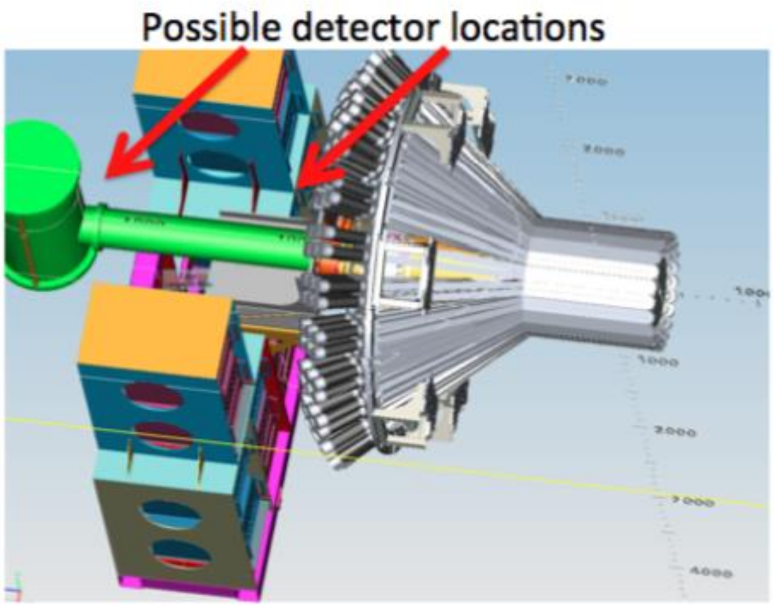
FIG. 8: The calculated ^{3}He$(e,e'p)$ ratio of the cross section which includes rescattering of the struck nucleon (FSI) to the PWIA cross section for $p_{miss} = 0.2$ (blue), 0.4 (green), and 0.5 (red) GeV/c as a function of θ_{rq}, the angle between the recoil momentum and $\vec{q}$ in the laboratory frame [45].

In Medium Proton Structure Functions, SRC, and the EMC effect: E12-11-003A

- Structure Functions of bound protons in deuterium as a function of their initial momentum

- "Tagging" the deep inelastic scattering on the deuteron with high momentum recoiling neutrons emitted at large angle relative to the momentum transfer

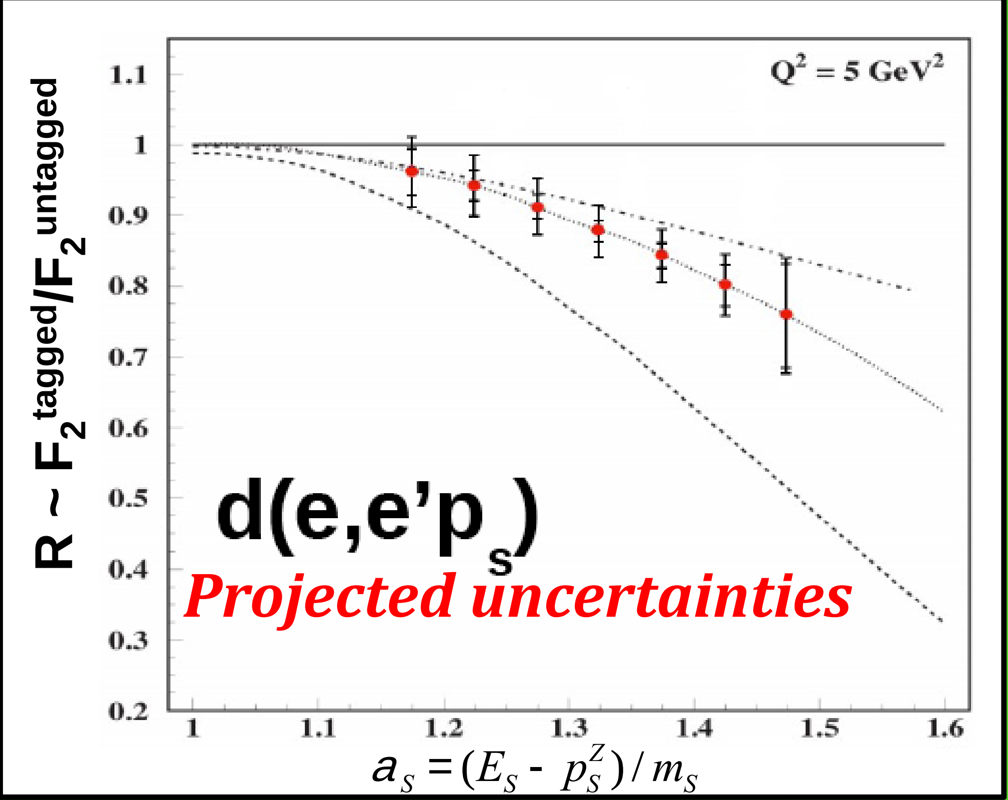


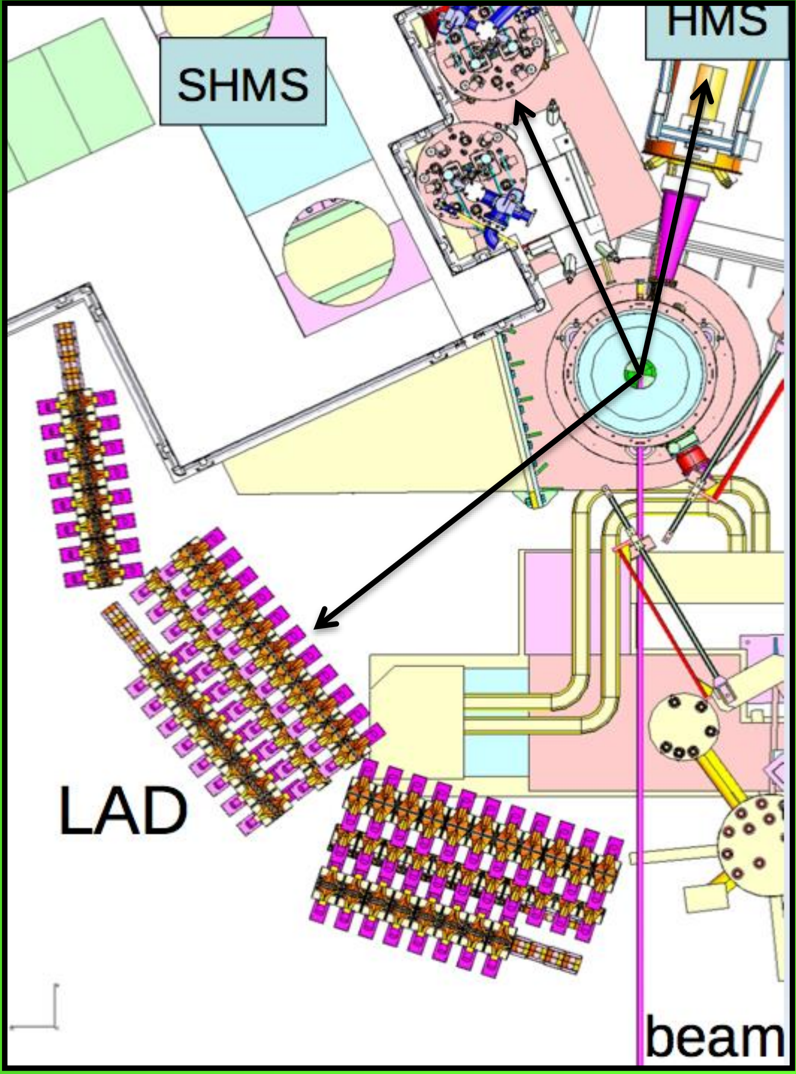


In-Medium Nucleon Structure Functions

[E11-107: O. Hen, L.B. Weinstein, S. Gilad, S.A. Wood]

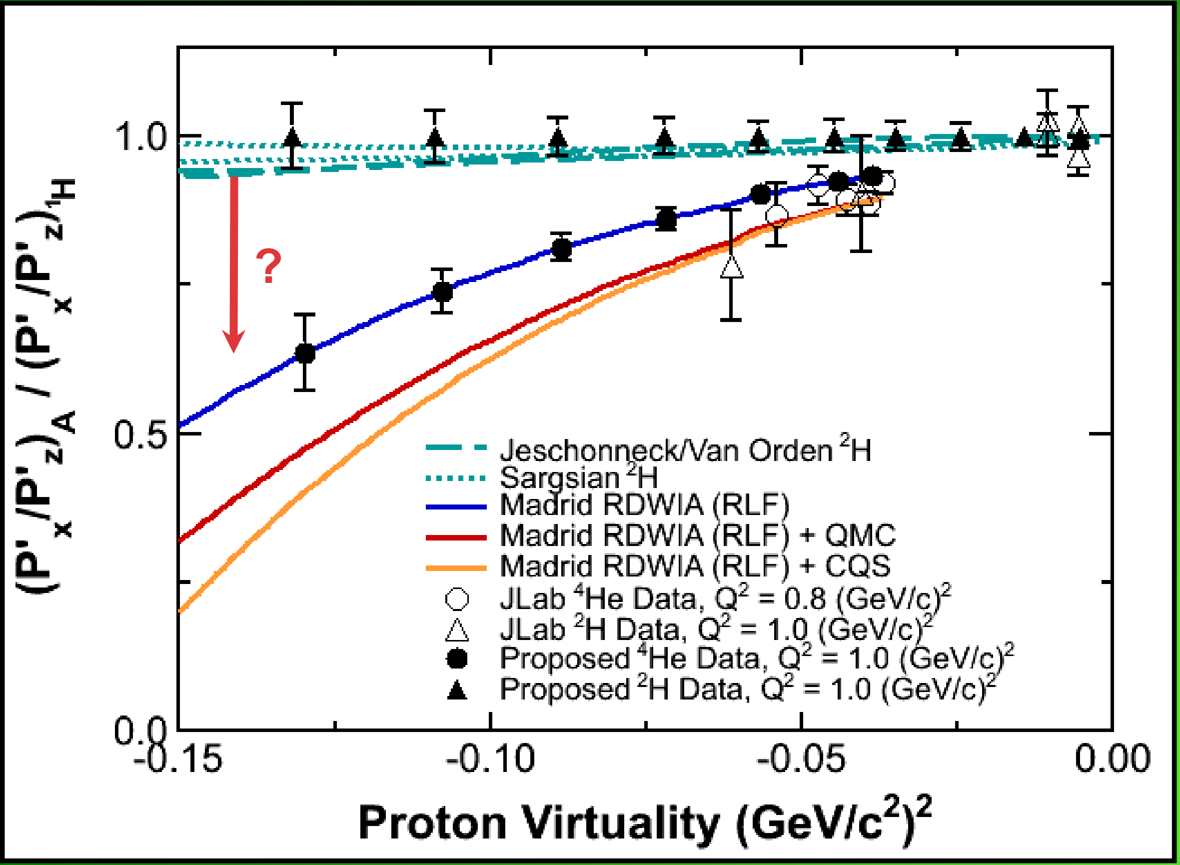
- **DIS scattering from nucleon in deuterium**
- **Tag high-momentum struck nucleons by detecting backward "spectator" nucleon in Large-Angle Detector**





In-Medium Nucleon Form Factors

[E11-002: E. Brash, G. M. Huber, R. Ransom, S. Strauch]



- **Compare proton knock-out from dense and thin nuclei: *^{4}He(e,e′p)^{3}H* and *^{2}H(e,e′p)n***
- **Modern, rigorous ^{2}H(e,e'p)n calculations show reaction-dynamics effects and FSI will change the ratio at most 8%**
- **QMC model predicts 30% deviation from free nucleon at large virtuality**

S. Jeschonnek and J.W. Van Orden, Phys. Rev. C 81, 014008 (2010) and Phys. Rev. C 78, 014007 (2008); M.M. Sargsian, Phys. Rev. C82, 014612 (2010)

Summary

- SRCs and EMC effect have been under the microscope for many decades – 6GeV era at Jlab has yielded interesting data
- 12 GeV experiments continue the search
- Upcoming and current experiments in Halls A/C
  - → Study short range correlations in ^{3}He/^{3}H
  - → Map out nuclear dependencies of clustering
  - → Study how quark distributions are modified in nuclei over free nucleons
- New results in the next few years!