x>1 and EMC Effect Experiments in Hall C at Jefferson Lab

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CIPANP2025 - Madison, WI

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New Mexico State University

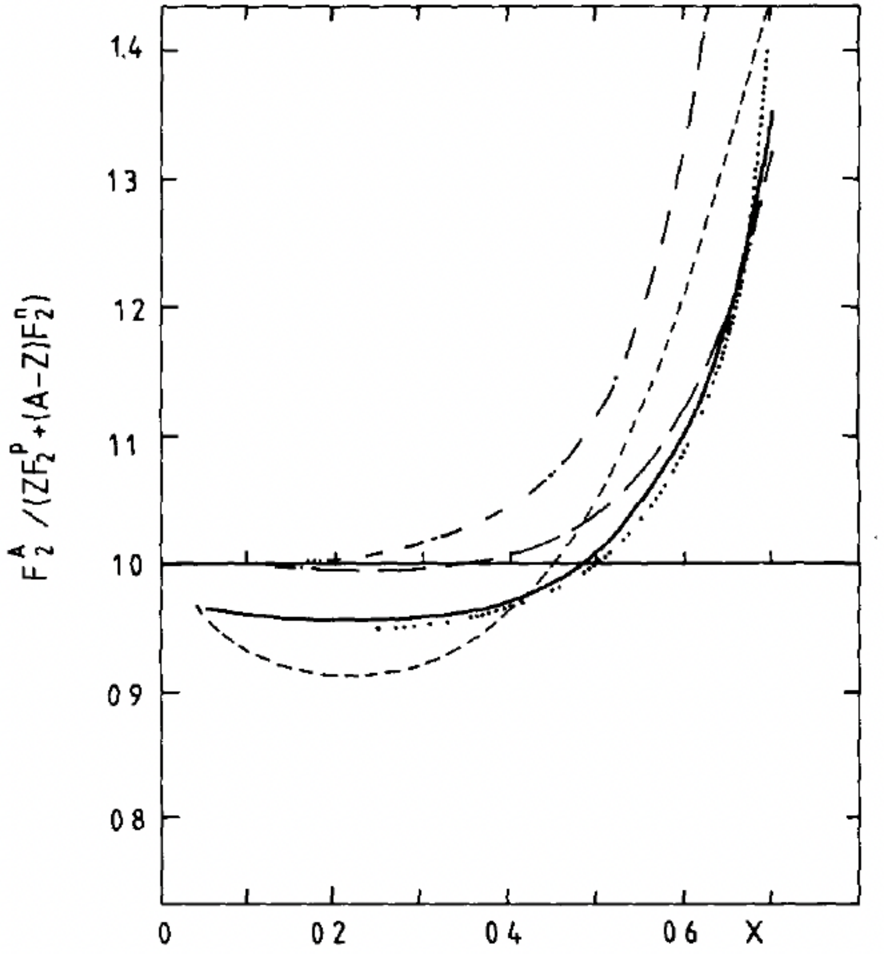
The EMC EFFECT

Discovered by the European Muon Collaboration in 1983

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

- Muon scattering measurements on deuterium and iron
- Internal structure of bound nucleons are different than those of “free” nucleons
- Unexpected considering small nucleon binding energies (and Fermi momenta)
- No universally accepted explanation yet!

J.J. Aubert *et al.*, Phys. Lett. B **123**, 275-278 (1983).



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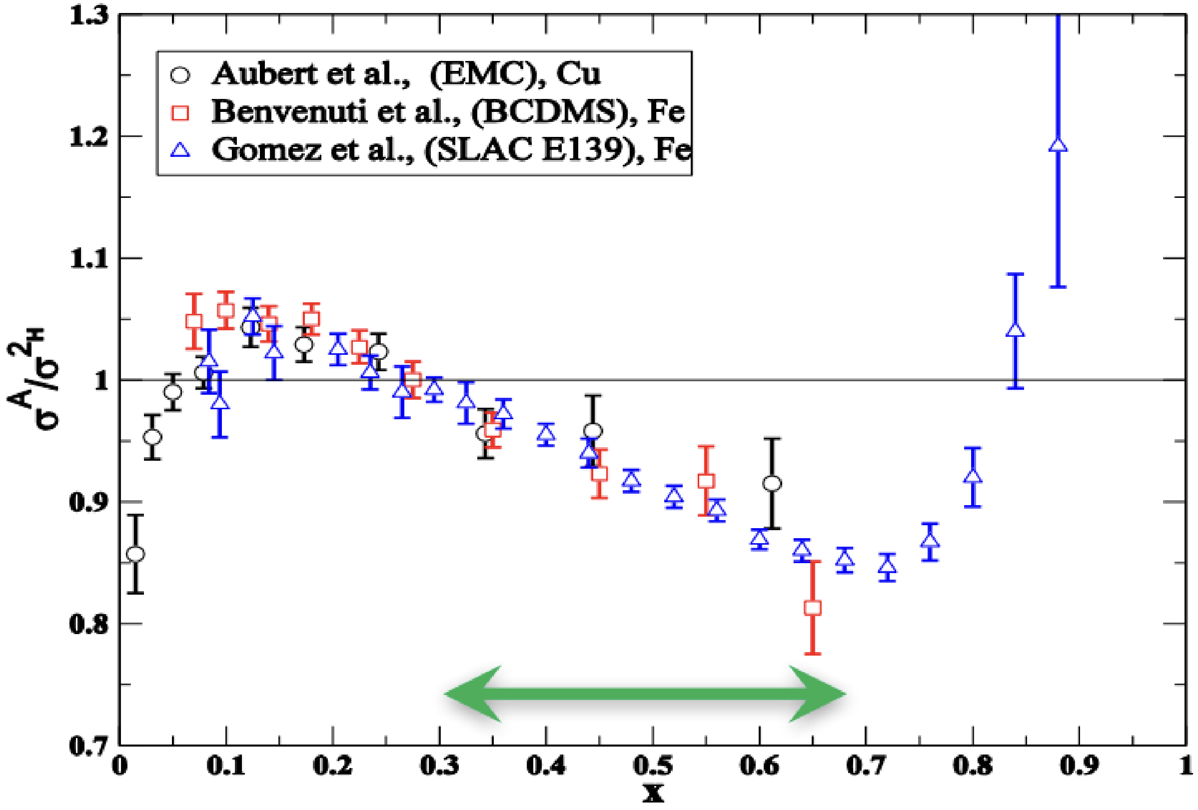
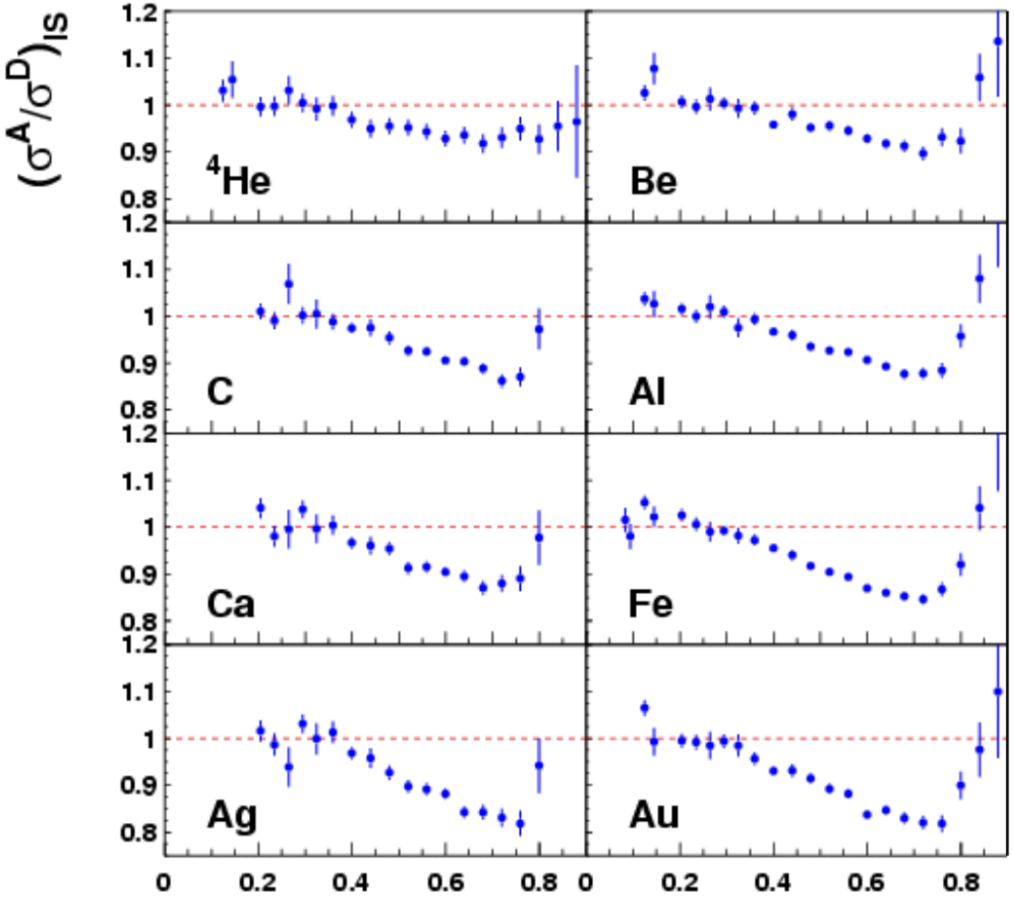


The EMC EFFECT – Previous Measurements

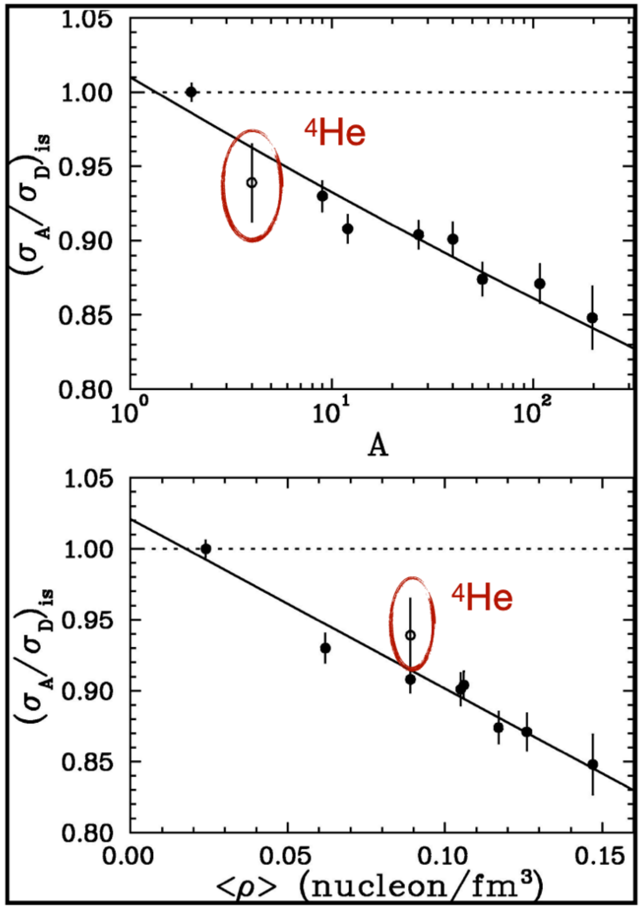
“Nuclear Dependence of the EMC Effect at Fixed x”



Universal x-dependence

SLAC139

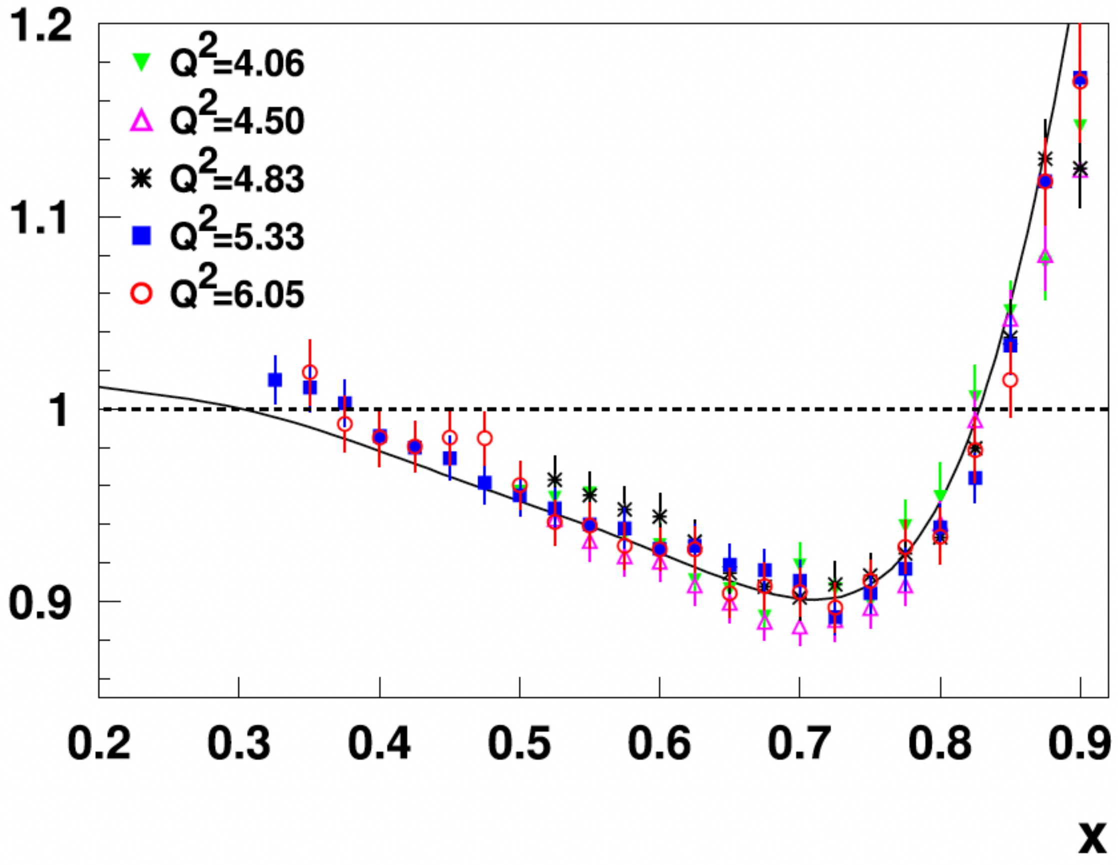
x=0.6

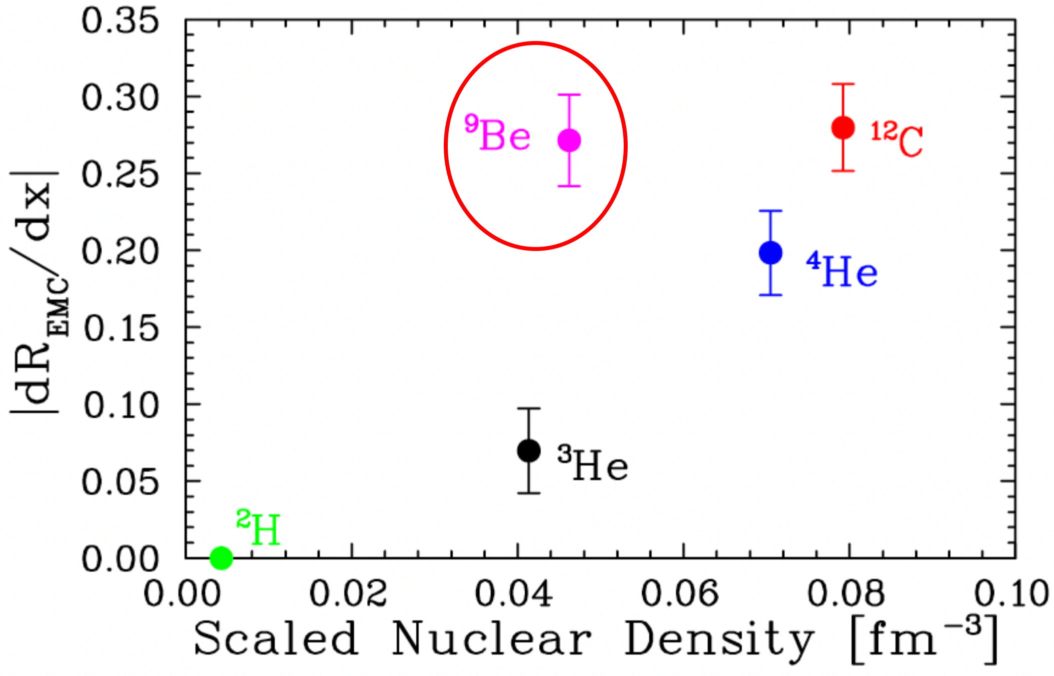


Modification scales with log(A) and average density

The EMC EFFECT – Previous Measurements

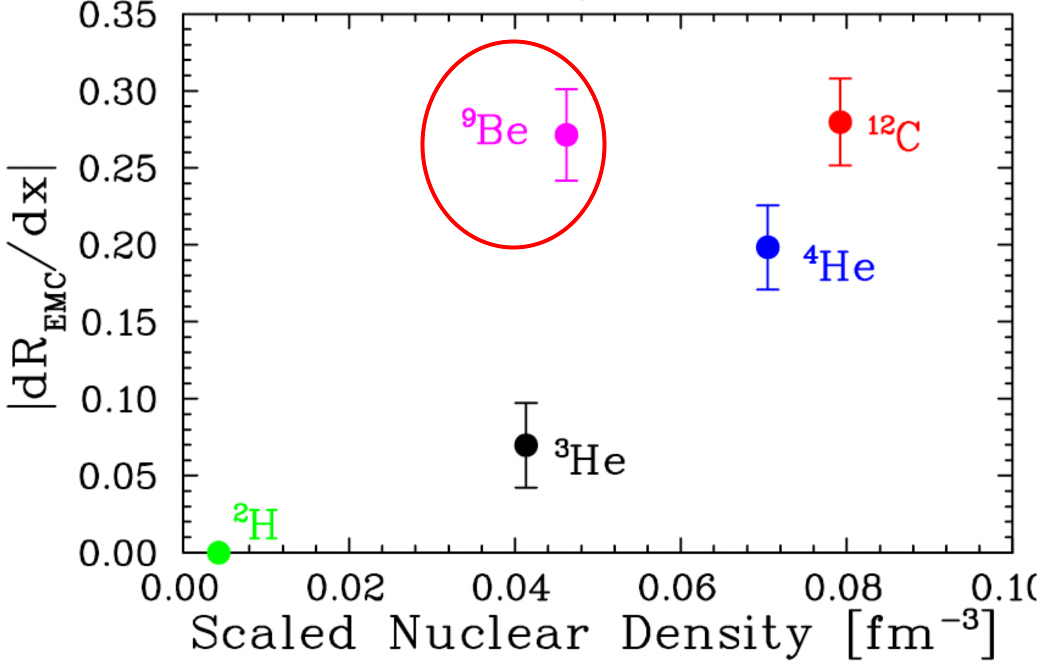
E03-103 (Jefferson Lab Hall C – 6 GeV) : Precision Results on Light Nuclei





The EMC EFFECT – Previous Measurements

E03-103 (Jefferson Lab Hall C – 6 GeV) : Precision Results on Light Nuclei

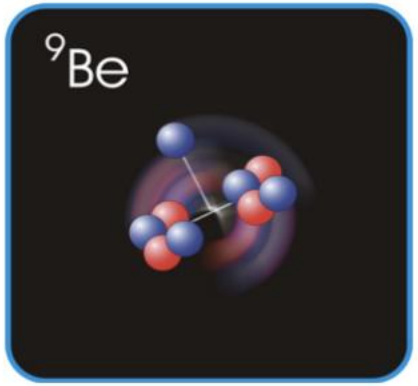


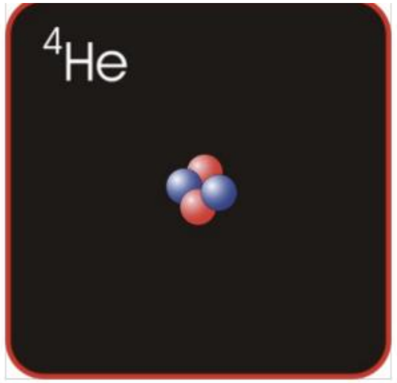
Density determined from *ab initio* few-body calculation
S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)

^{9}Be: larger EMC effect than ^{4}He although lower average density

^{9}Be: 2 dense alpha clusters + one neutron

density seen by the ave. nucleon is much greater than ave. density

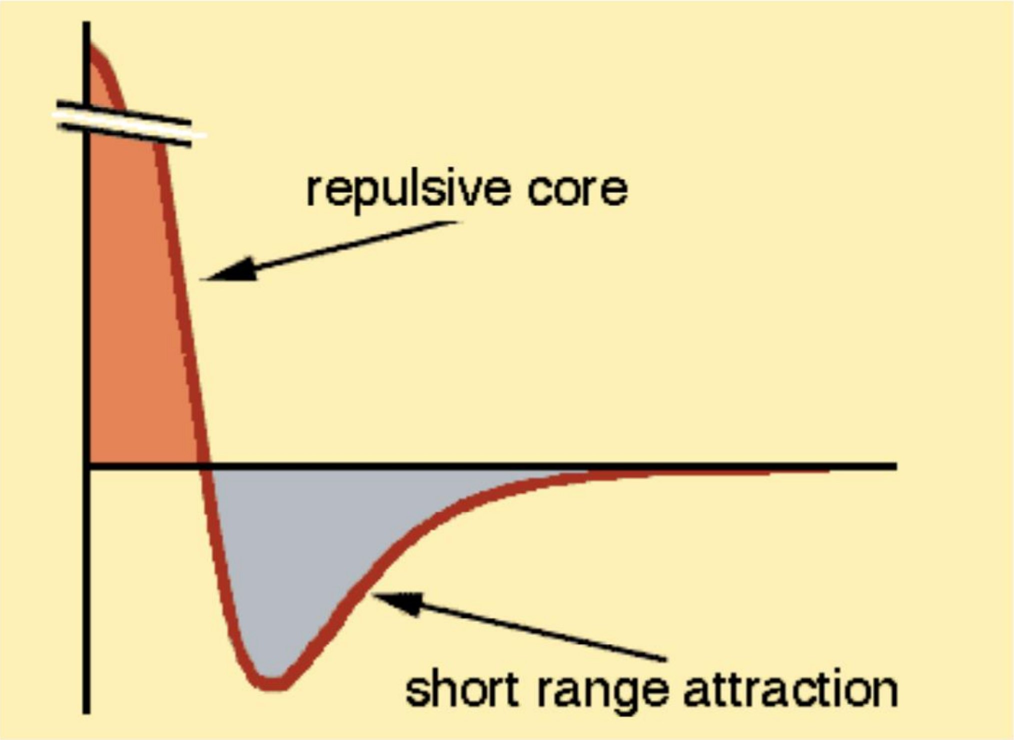




*average nuclear density was scaled by a factor of (A-1)/A to remove the struck nucleon's contribution to the average nuclear density

Short-range Structure of Nuclei

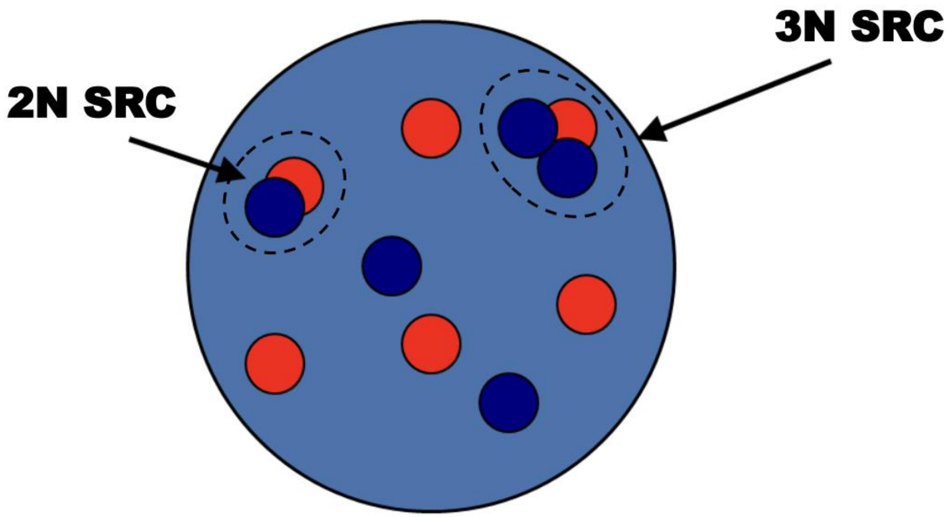
What drives high local density in the nucleus?



The short-distance part of the nucleon-nucleon interaction:

- A hard short-range repulsive core + strong intermediate-range tensor attraction
- Yield high-momentum components in the nucleon momentum distributions in nuclei

Short-range Structure of Nuclei

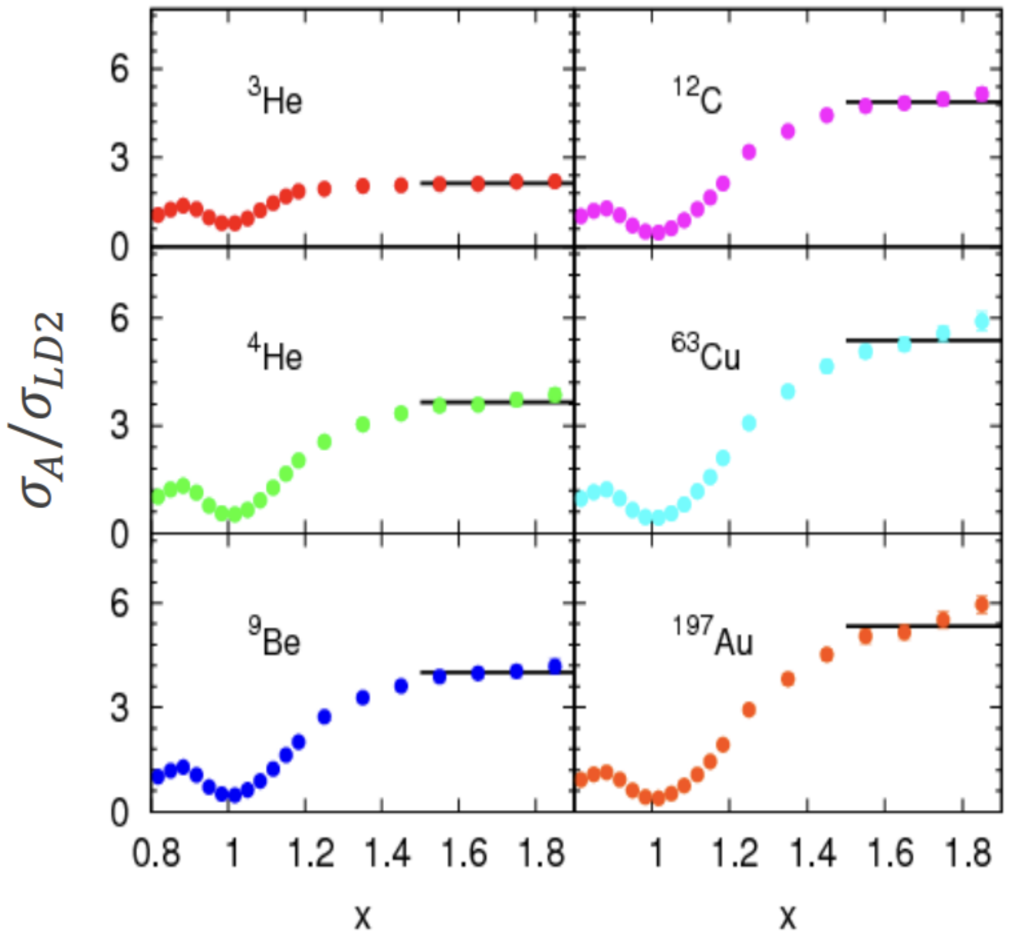


Nuclear structure below fermi energy k_f dominated by mean field

Nuclear structure above fermi energy k_f dominated by 2 (or possibly 3) body physics

Pairs of nucleons with high back-to-back momenta: short range correlated pairs

Measuring 2N Short-range Correlations

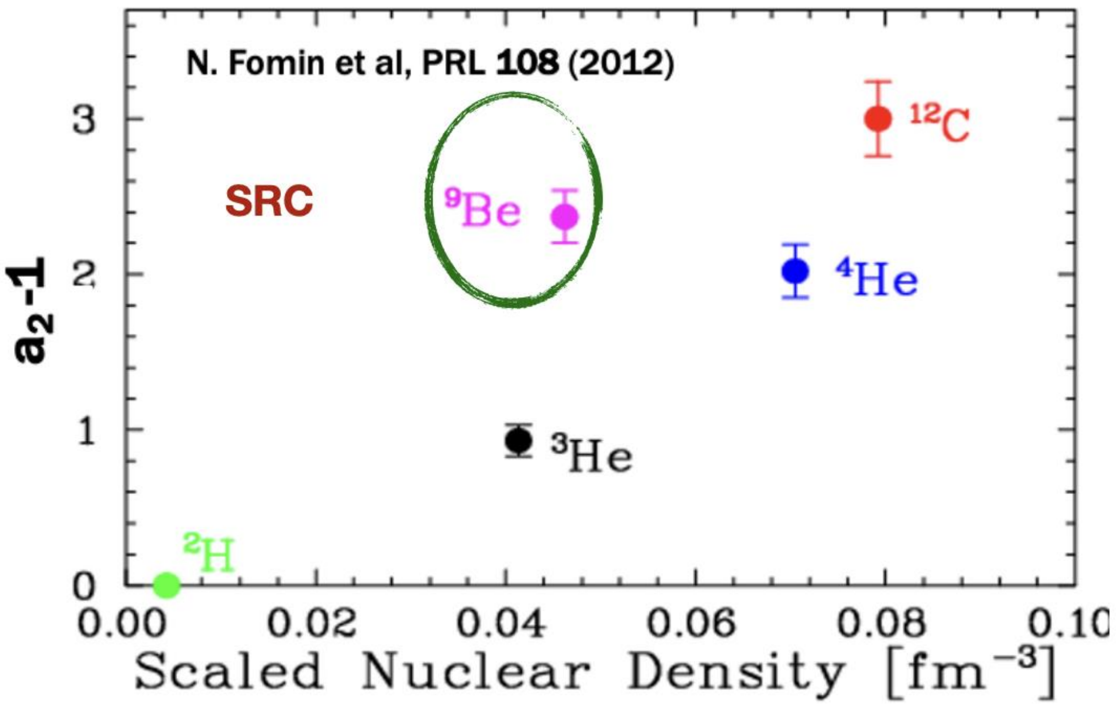


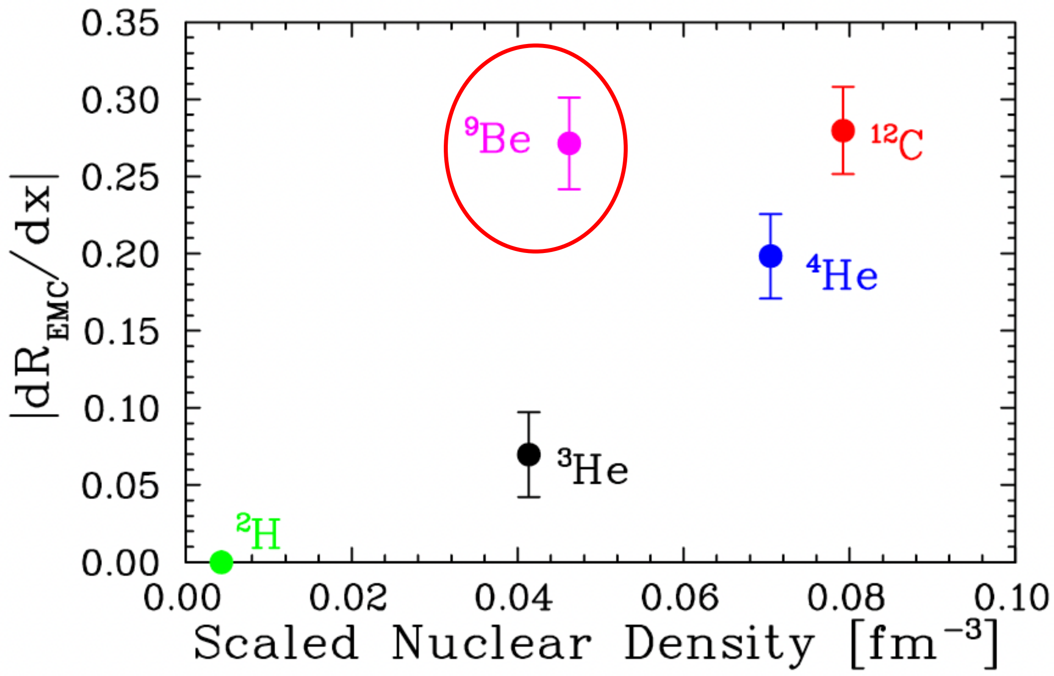
$$\sigma(x, Q^2) = A a_1 \sigma_1(x, Q^2) + \frac{A}{2} a_2 \sigma_2(x, Q^2) + \ldots$$

- To measure the relative probability of finding a correlation, ratios of heavy to light nuclei are taken
- To experimentally probe SRCs, must be in the high-momentum region (x>1): QE scattering
- If the high momentum nucleons in nuclei come from correlated pairs, ratio of A/D should show a plateau.

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

Measuring 2N Short-range Correlations





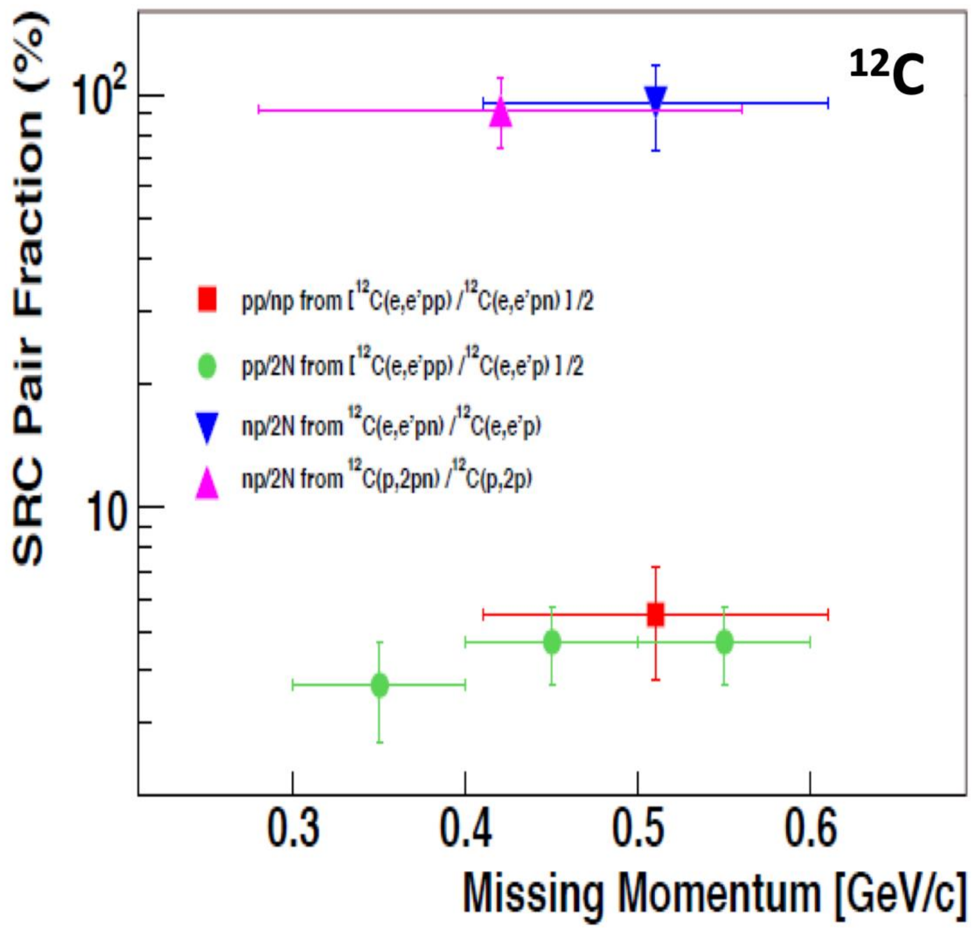
Similar pattern with the SRC measurements in light nuclei

Suggesting a possible connection between the EMC and SRC?

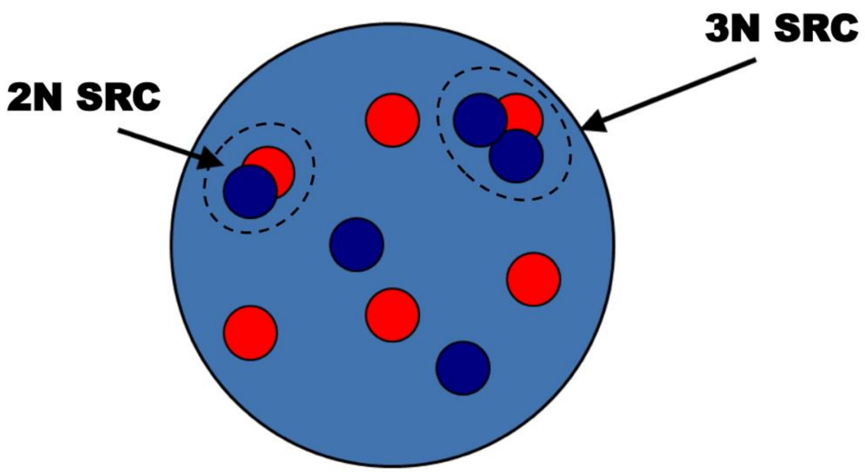
Isospin (Flavor) Dependent EMC EFFECT (?)

- How are the PDFs of the different flavors of quarks modified?
- Can np dominance in SRCs introduce isospin dependence in EMC effect
- A variety of large nuclei with varying N/Z ratios allows for a study of the isospin dependence of the EMC effect

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



3N Short-range Correlations Where do we look at?



$1.4 < x < 2 \Rightarrow 2$ nucleon correlation

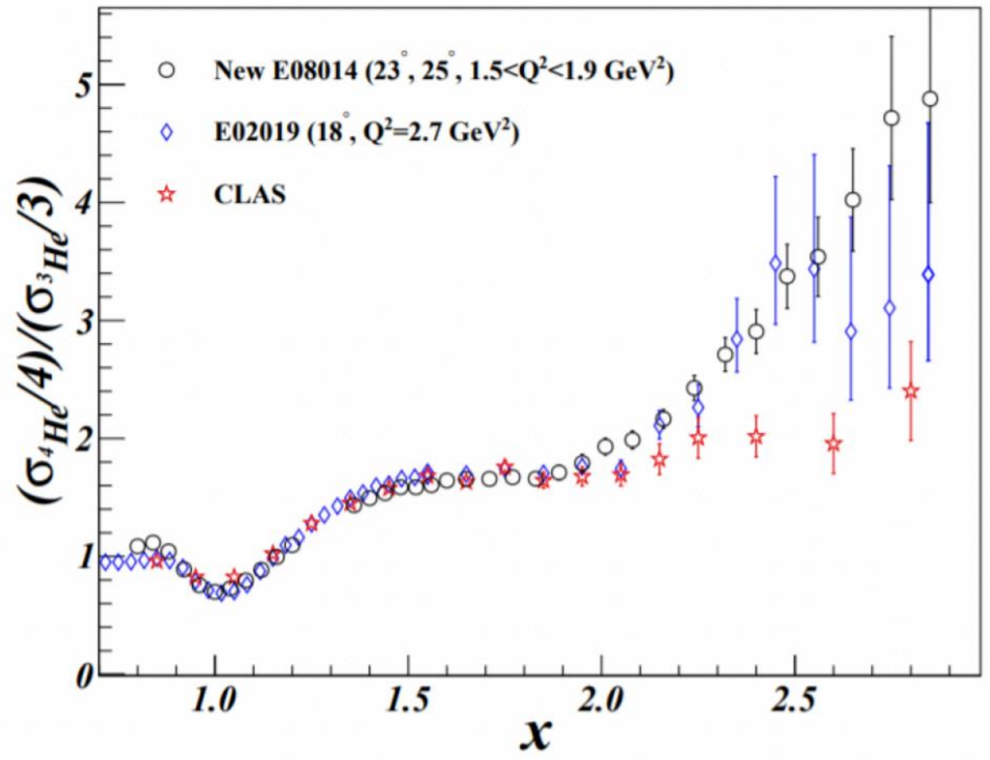
$2.4 < x < 3 \Rightarrow 3$ nucleon correlation

- Well established 2N SRC presence in 1.4<x<2
- 3N SRCs can lead to a second plateau (A/3He) at x>2
- No experimental observation so far
- Rapid fall off of the mean field contributions → kinematic onset of the 2N SRCs
- 2N-SRCs fall off slowly compared to mean field → kinematic onset of the 3N SRCs
- Kinematic onset is sensitive to the size and nature of the 3N-SRCs (model-dependent)

$$\sigma(x,Q^2) = Aa_1\sigma_1(x,Q^2) + \boxed{\frac{A}{2}a_2\sigma_2(x,Q^2)} + \boxed{\frac{A}{3}a_3\sigma_3(x,Q^2)} + \ldots$$

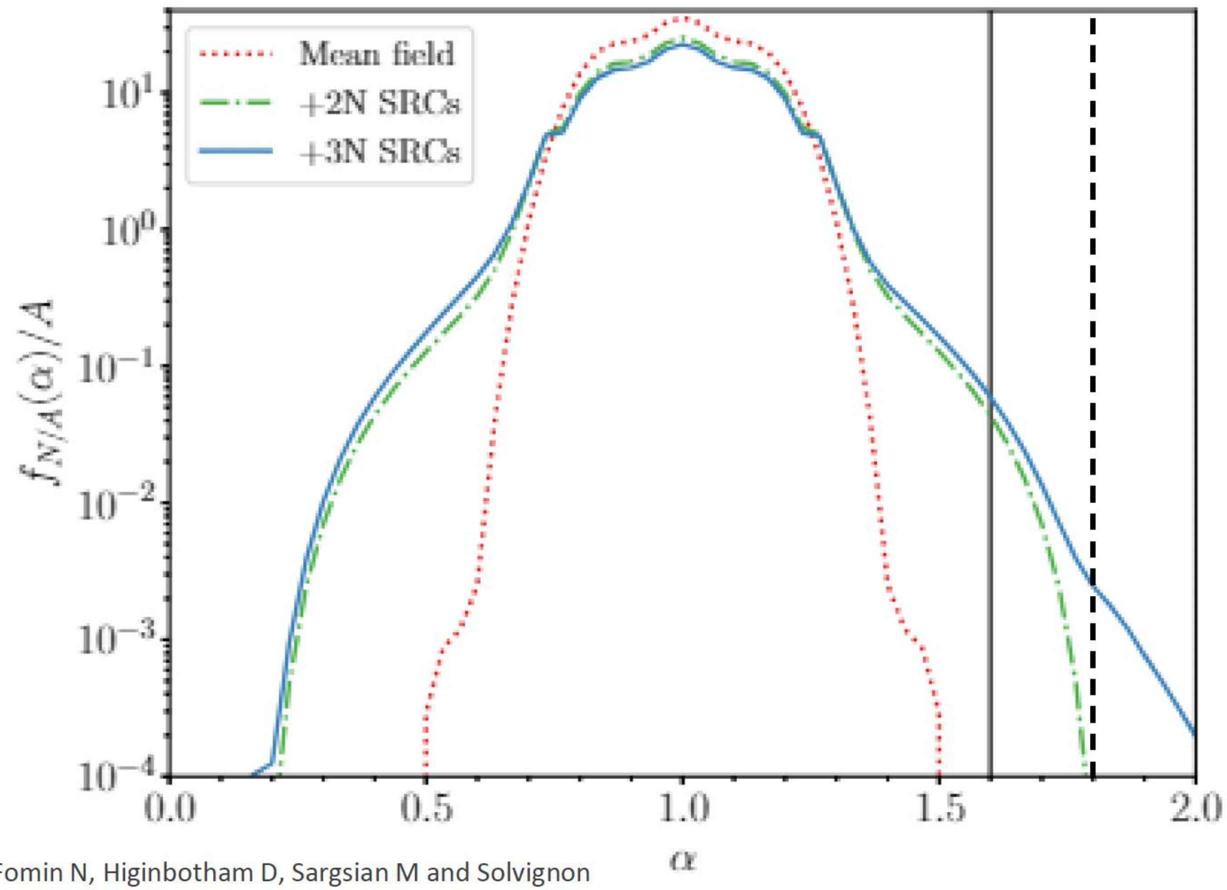
3N Short-range Correlations – Previous Searches

- Jefferson Lab E08-014: longer cryogenic targets for higher statistics
- Overlapped kinematics with CLAS
- Results consistent with Hall C data, disagreed with CLAS results
- No second plateau observed

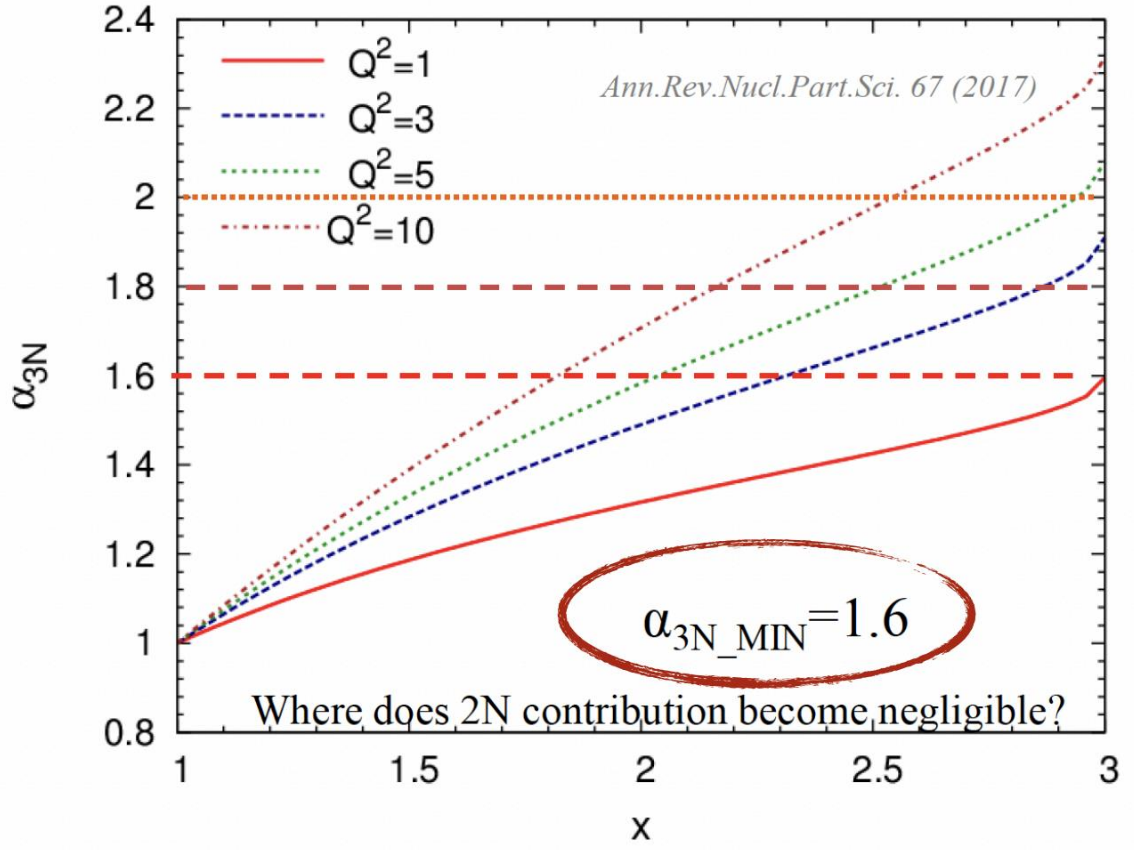


Z. Ye et al, PRC 97 (2018) 6

3N Short-range Correlations – where do we look at?

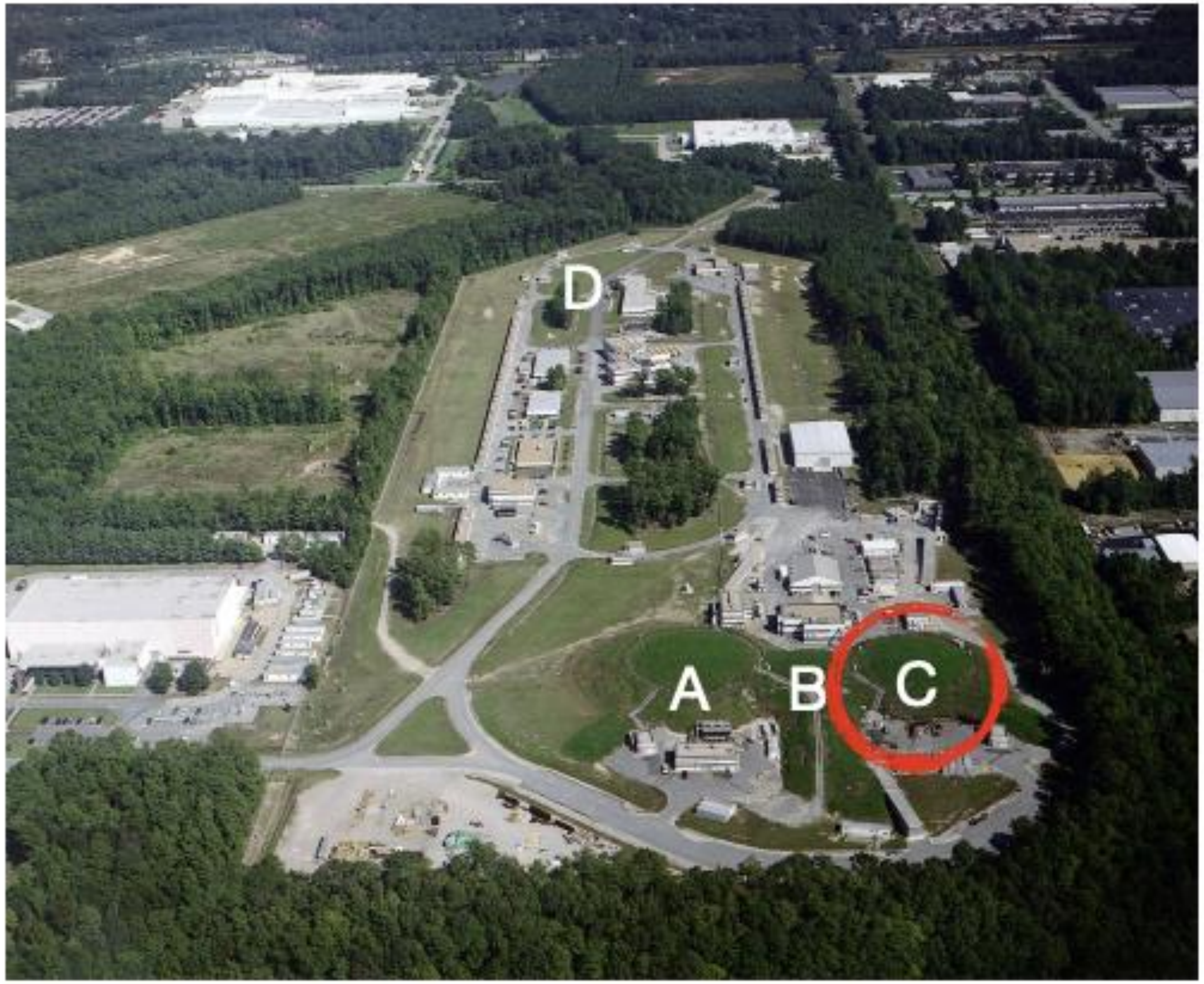


Fomin N, Higinbotham D, Sargsian M and Solvignon P 2017 Ann. Rev. Nucl. Part. Sci. 67 129–159

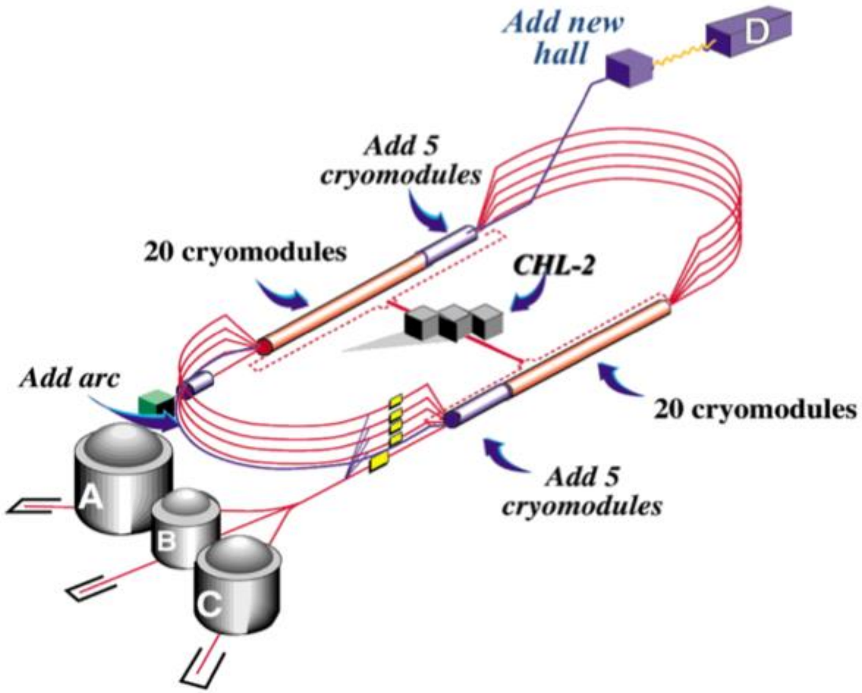


Light cone momentum fraction in a 3N system

XEM2 – Experimental Setup



12 GeV Jefferson Lab



12 GeV Hall C Jefferson Lab

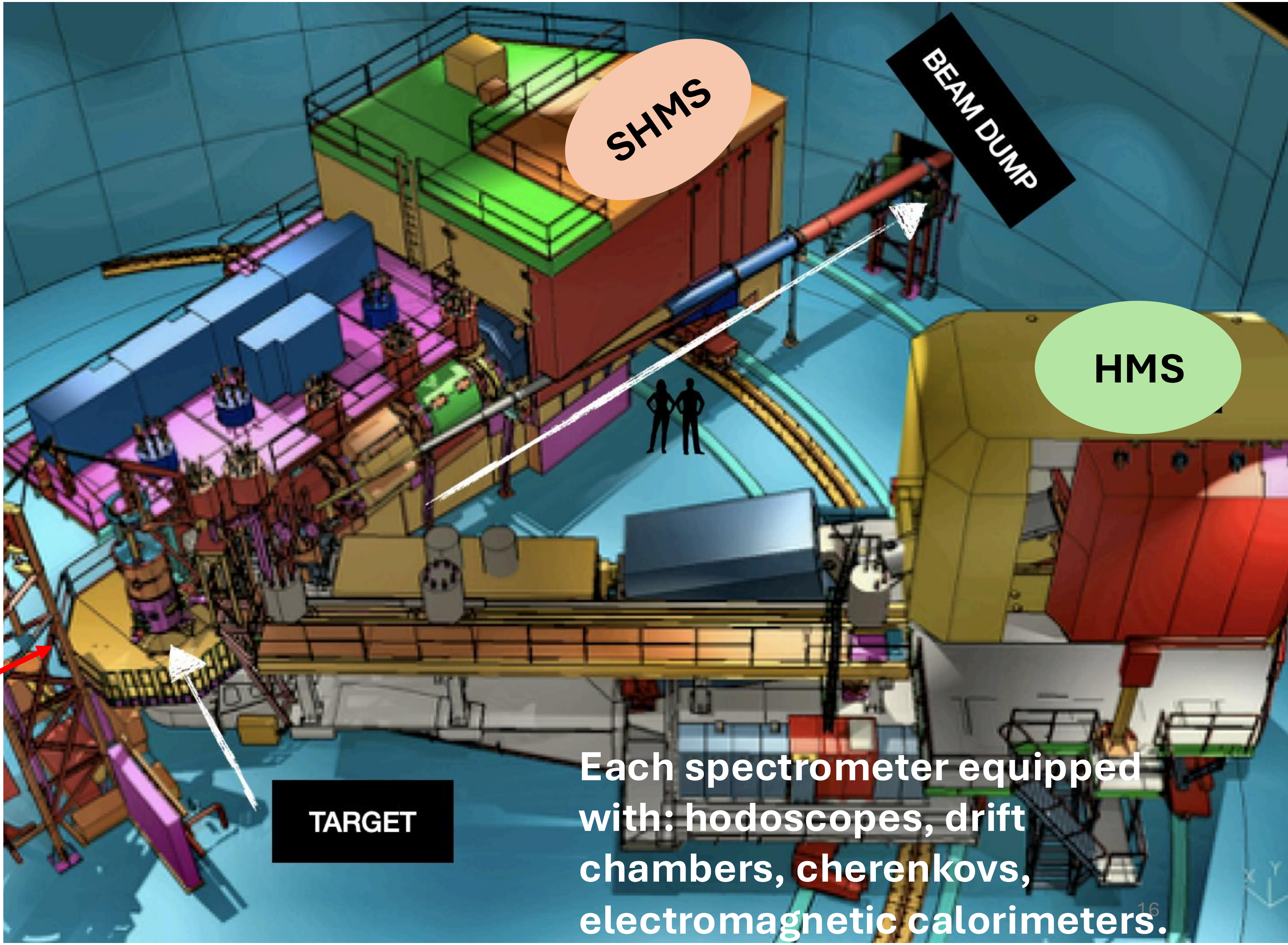
SHMS

SRC measurement

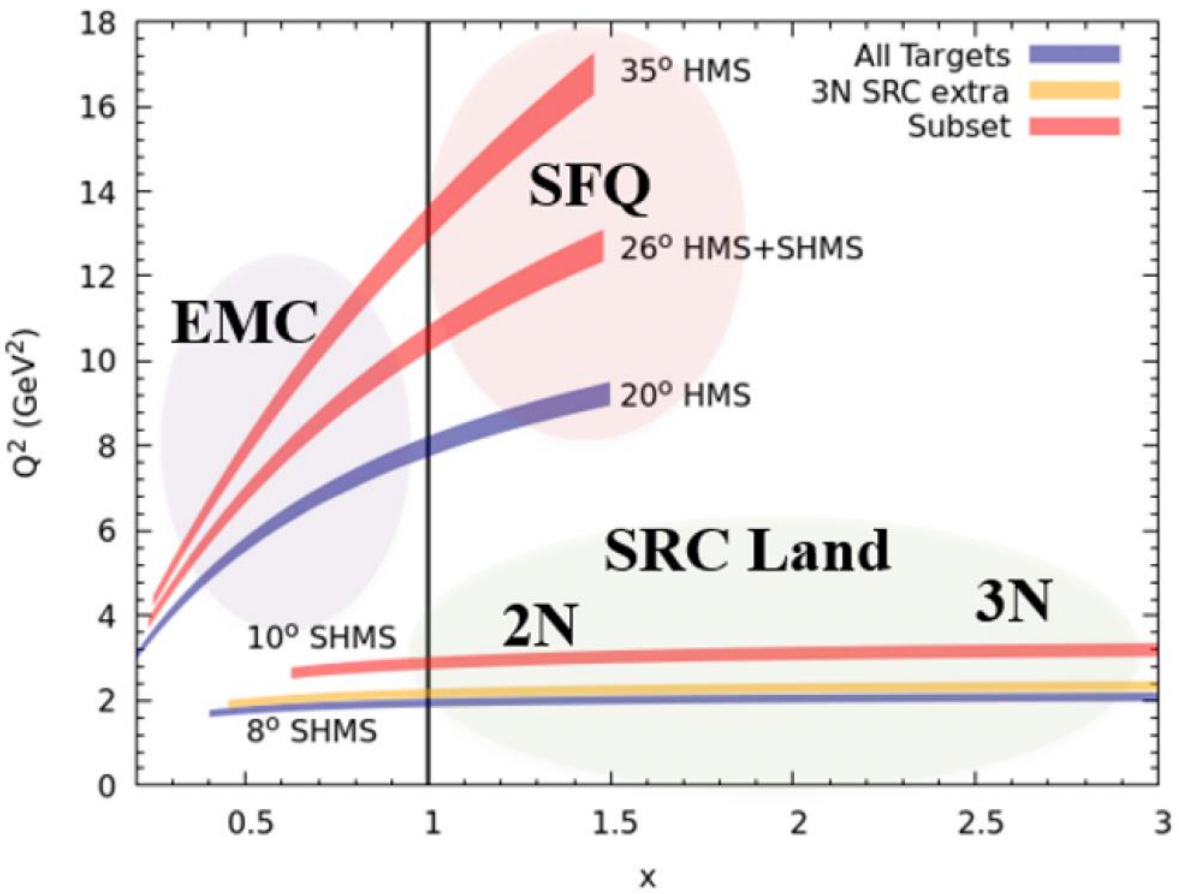
HMS

EMC measurement

10.5 GeV ELECTRON BEAM



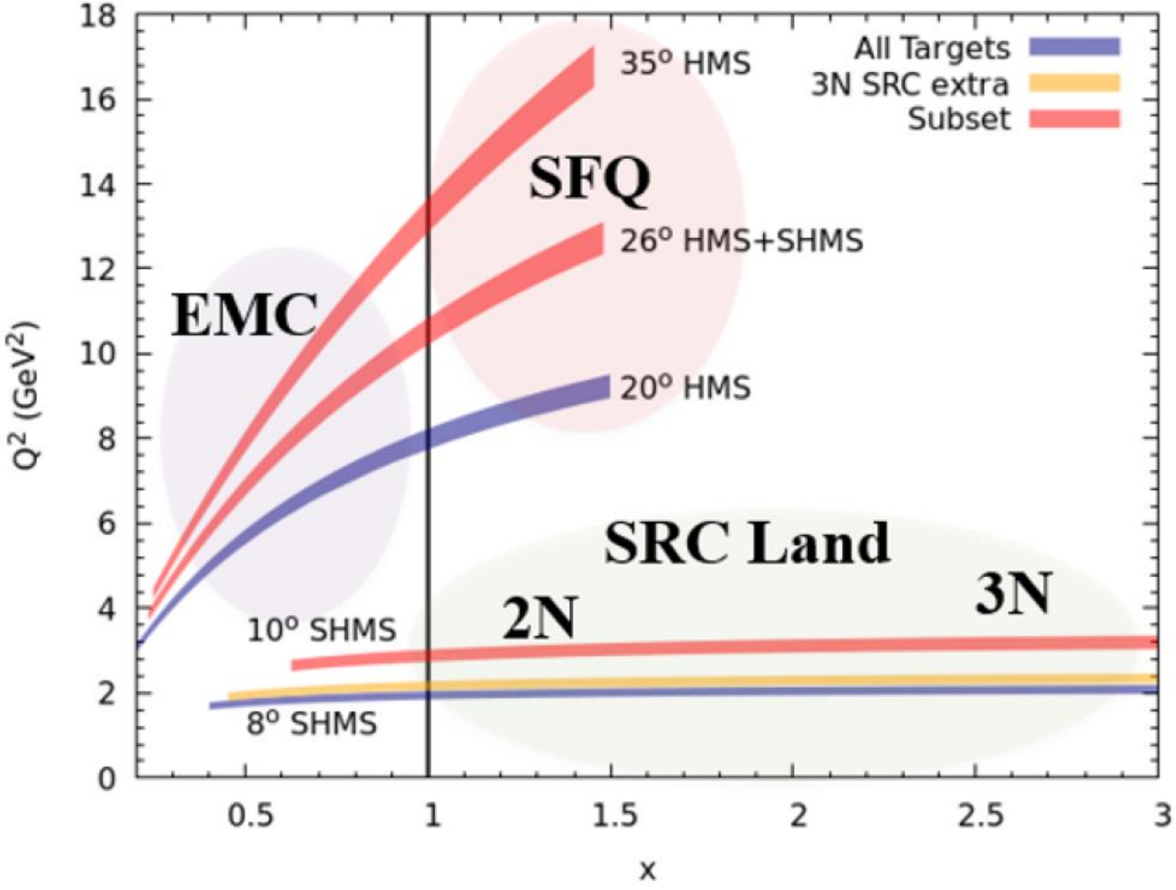
E12-10-008 and E12-06-105 Experiments in Hall C

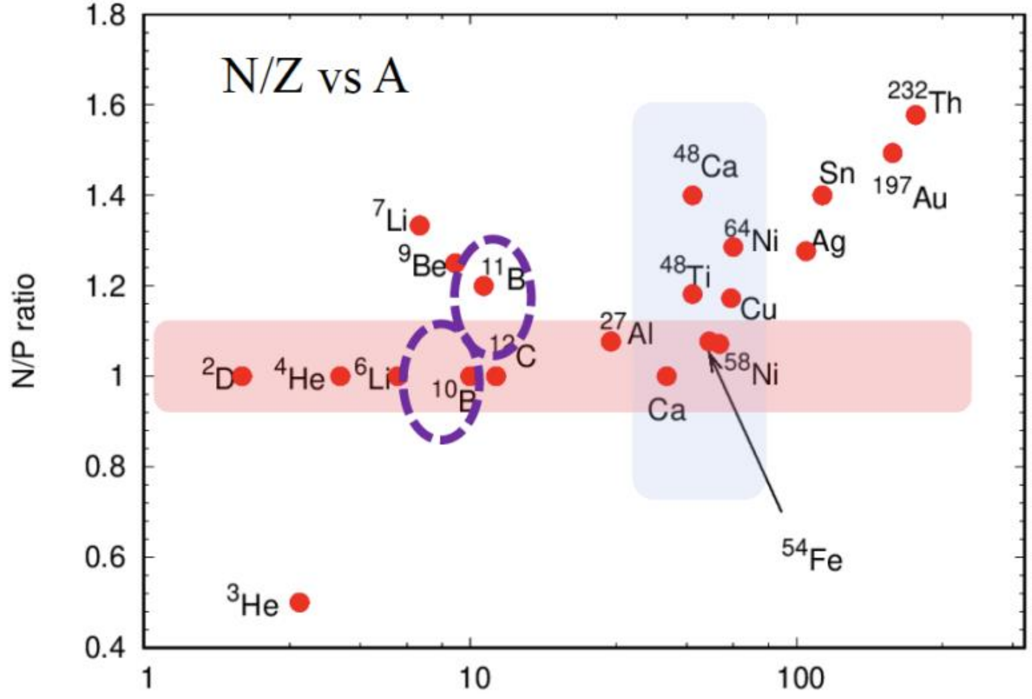


E12-10-008: Detailed Studies of nuclear dependence of F_2 in light nuclei

E12-06-105: Inclusive Scattering from nuclei at x>1 in quasi-elastic and DIS regions

E12-10-008 and E12-06-105 Experiments in Hall C





Ran concurrently!

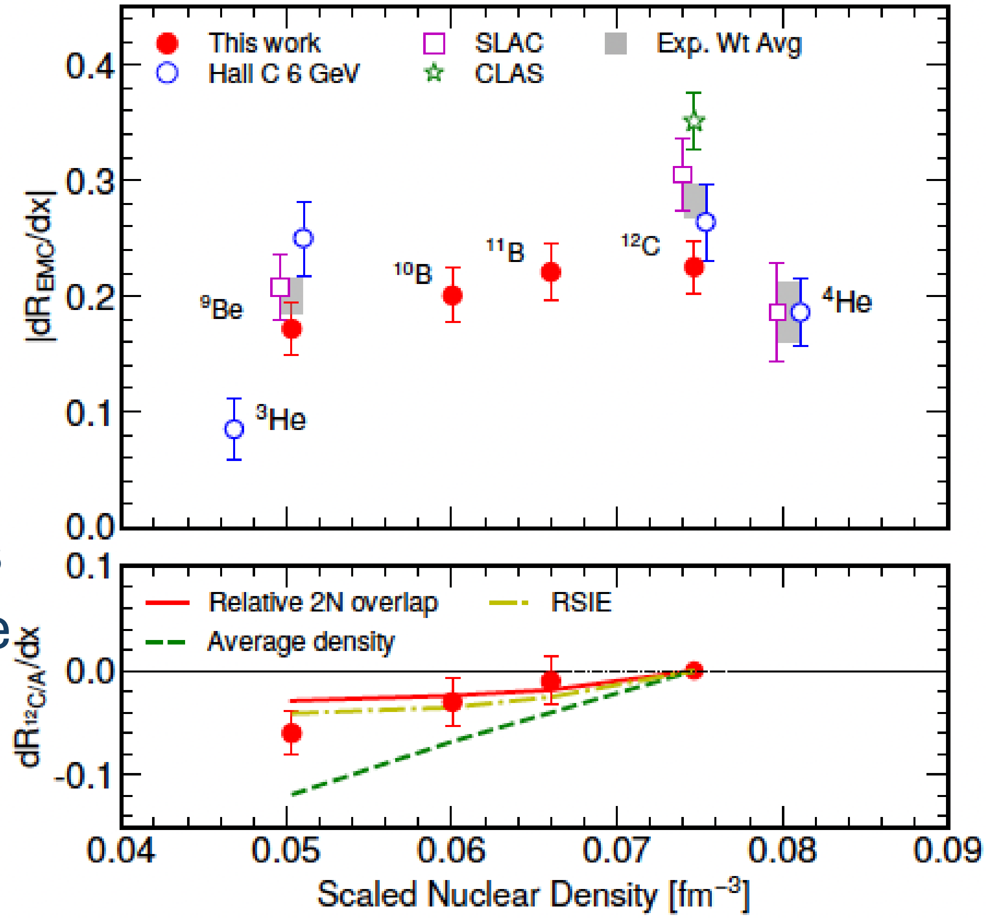
E12-10-008 (EMC Effect) – Commissioning data

- Part of the data taken during spring 2018 concurrently with E12-10-002 experiment (commissioning of the SHMS spectrometer)
- Inclusive electron scattering off Hydrogen, deuterium, ^{12}C, ^{9}Be, Boron isotopes (^{10}B, ^{11}B)
- 10.6 GeV unpolarized electron beam
- Data taken at a single Q^2 (21 degrees angle)
  - ➢ Additional data taken at different angles with ^{12}C target for the Q^2 dependence studies.

E12-10-008 (EMC Effect) – Commissioning data

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)

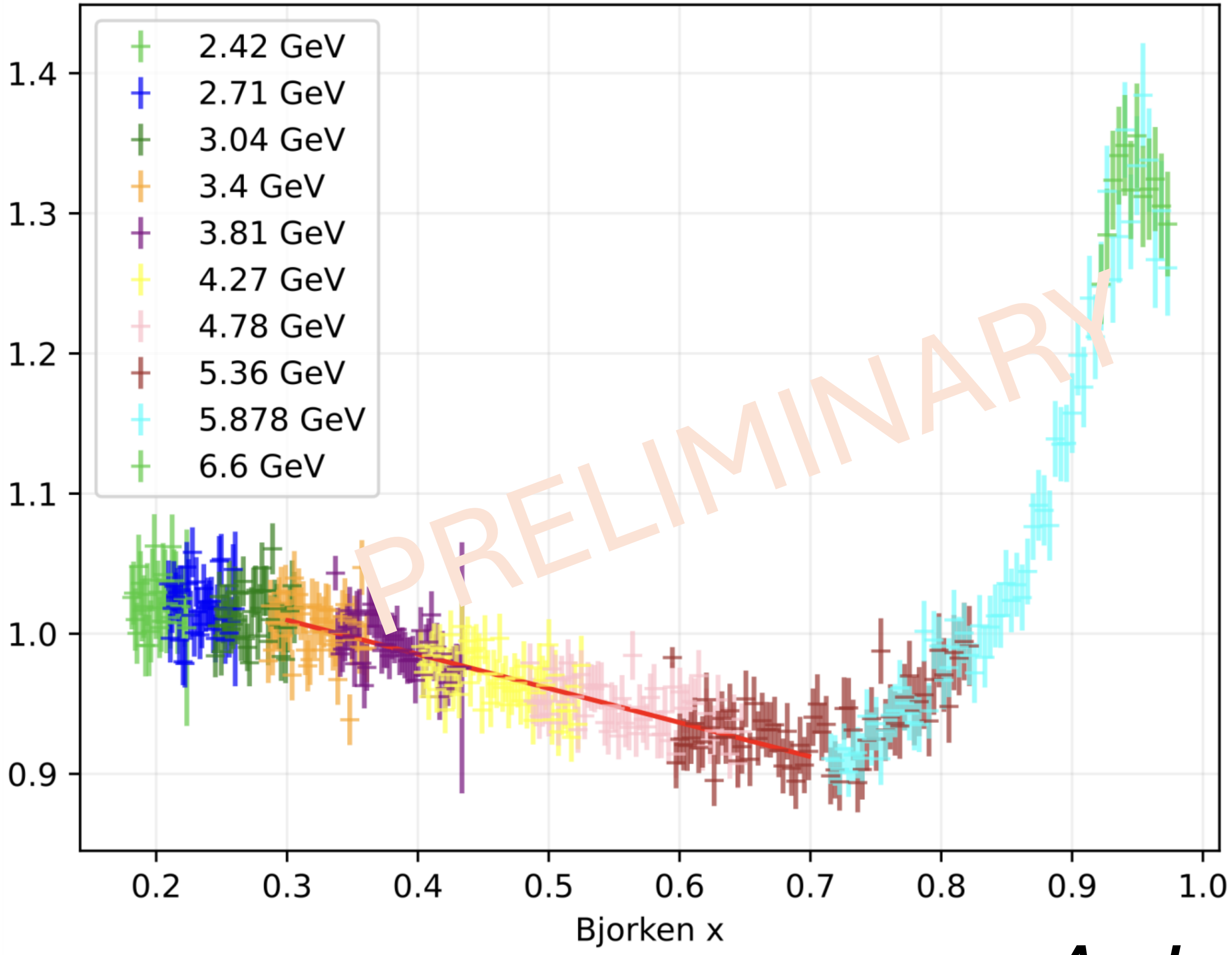


A. Karki et al. First Measurement of the EMC Effect in ^{10}B and ^{11}B. Phys. Rev. C (2023)

- The size of the EMC effect for the boron isotopes is similar to that for ^{4}He, ^{9}Be, and ^{12}C (supportive of local density approach)
- The , ^{9}Be, and ^{12}C results were systematically smaller than previous measurements by about 2% with a significance of 2 σ.

E12-10-008 (EMC Effect) – Phase II

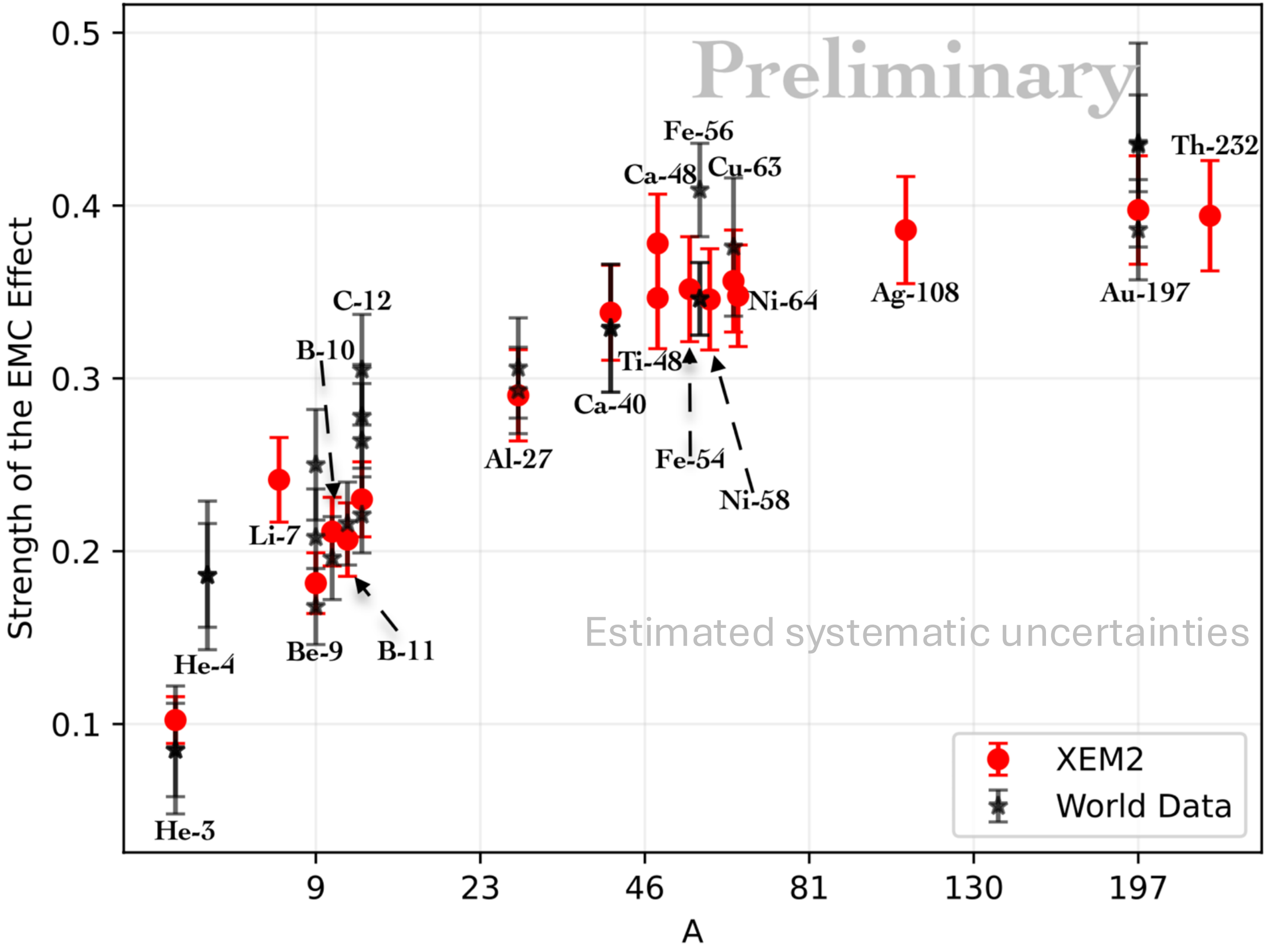
$$\frac{\sigma_C/12}{\sigma_D/2}$$



Representative xsec ratio plot for 12C only

Analysis by Abhyuday Sharda (UTK)

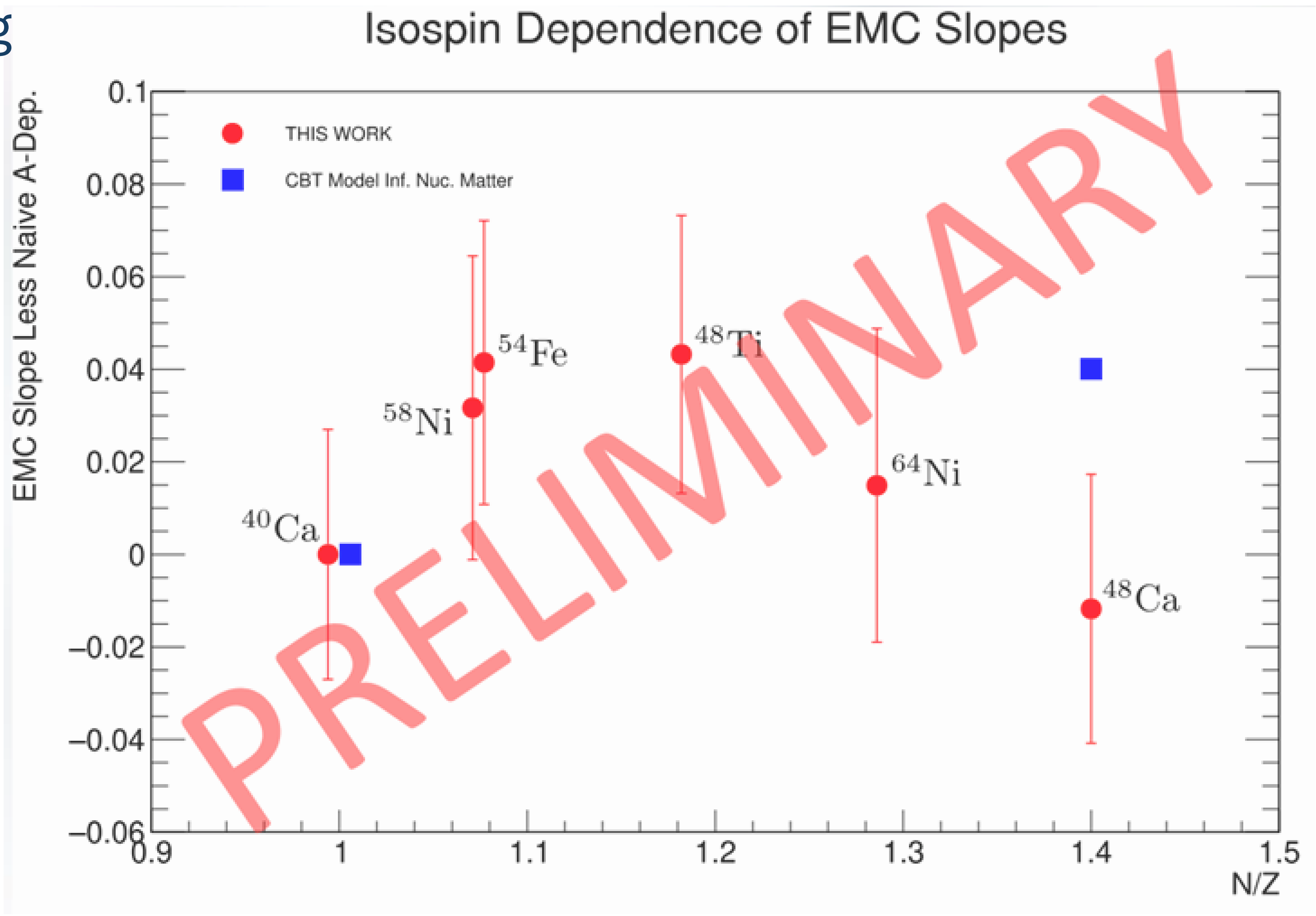
E12-10-008 (EMC Effect) – Phase II



Analysis by Abhyuday Sharda (UTK)

E12-10-008 (EMC Effect) – Phase II

- A variety of large nuclei with varying N/Z ratios allows for a study of the isospin dependence of the EMC effect
- Assumption: EMC effect for nuclei with mass numbers in the range $40 \leqslant A \leqslant 64$ scales only with isospin and A.
- A dependence is removed to “isolate” the isospin dependence
- Similar EMC slopes for 40Ca and 48Ca
- No significant isospin dependence but more studies needed



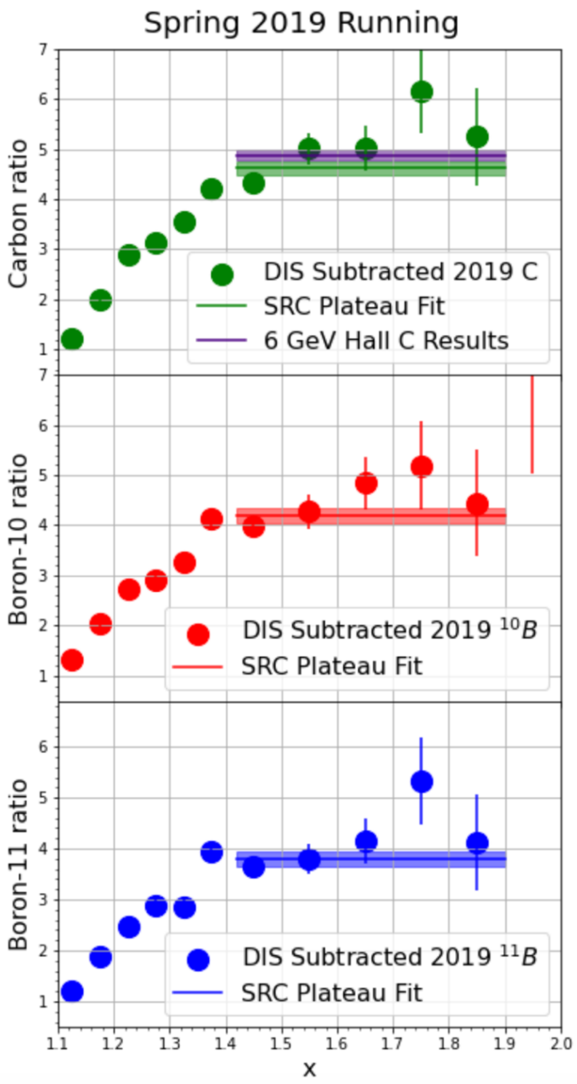
Cameron Cotton (UVA) thesis

E12-10-005 (x>1) – Commissioning data

2018	
Central Momentum	9.8 GeV
Q^2	2.08
Angles	8.02
Elements	H, D, C, Al, ^{9}Be, ^{10}B, ^{11}B

2019	
Central Momentum	9.8 GeV
Q^2	4.46
Angle	13.10
Elements	H, D, C, Al, ^{10}B, ^{11}B

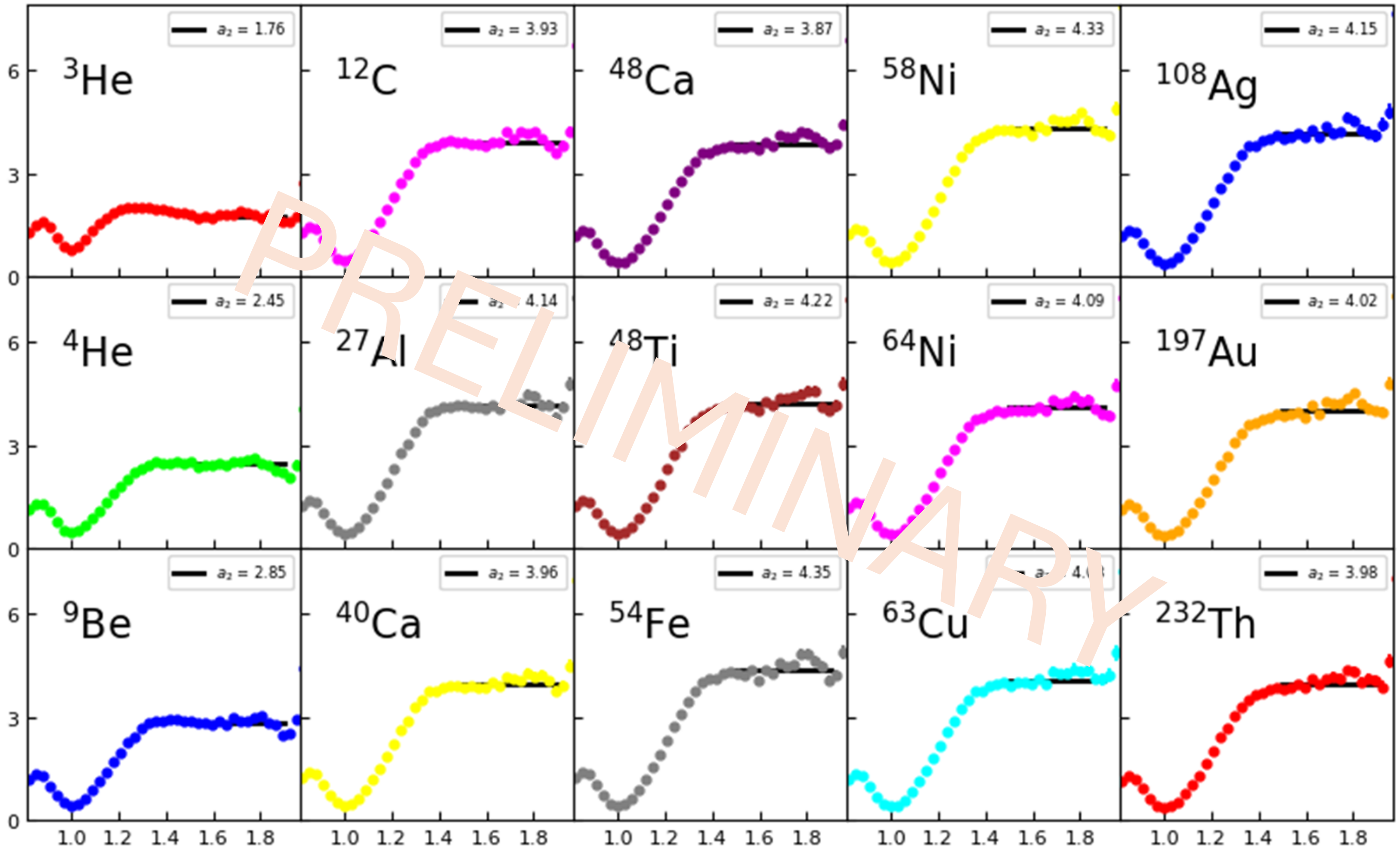
*Boron targets are boron carbide



Casey Morean (UTK) thesis

E12-10-005 (x>1) – Phase II

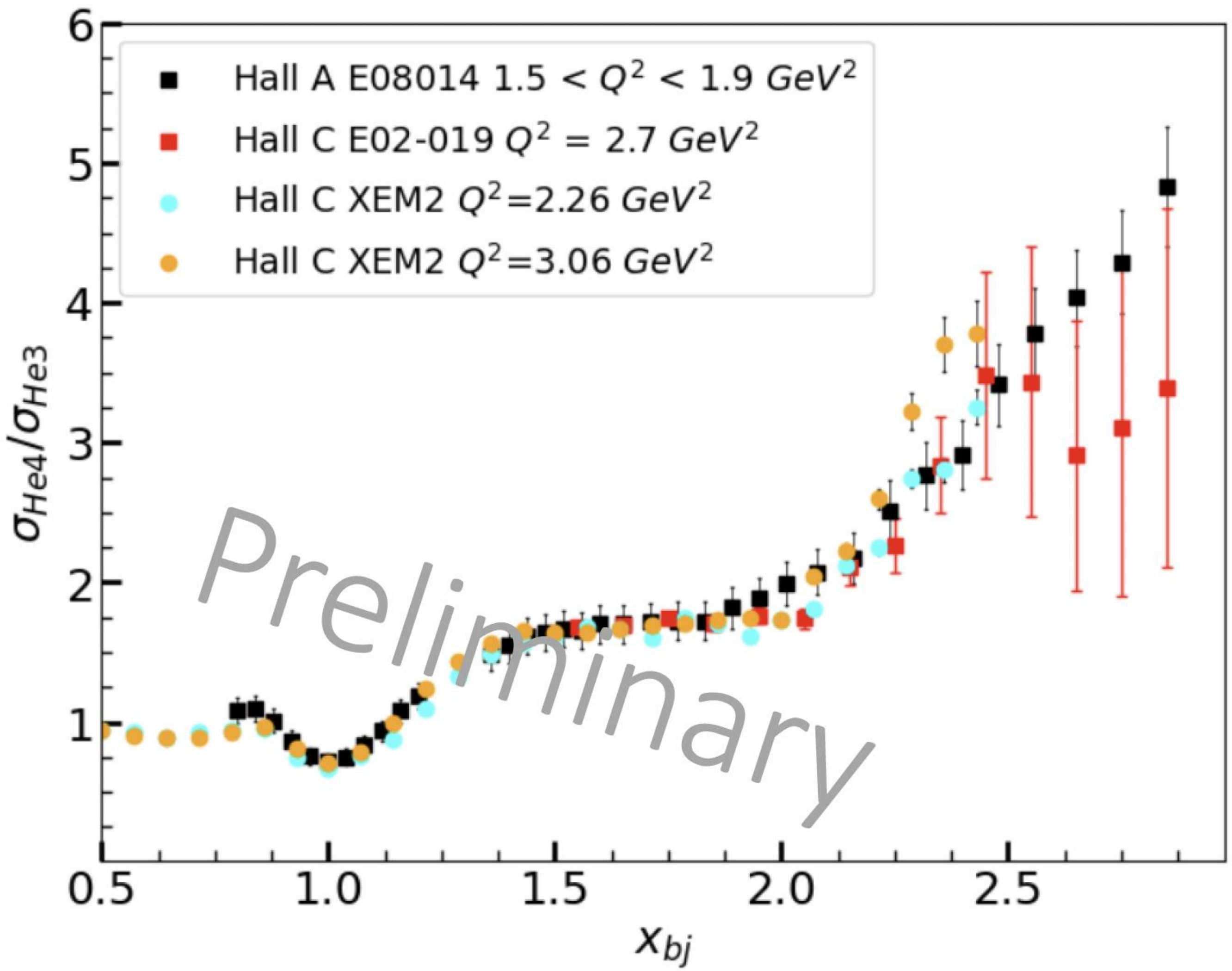
- 2N-SRC region
- E = 10.5 GeV
- Angle = 8^o
- Q^2 = [1.91 – 2.05] GeV^2
- x_{bj}= [0.8 – 2.0]



Analysis by Jordan O'Kronley (UTK) and Ramon Ogaz (UTK)

E12-10-005 (x>1) – Phase II

- Ongoing analysis for the 3N SRC ratios
- XEM2 data in the 2N region compares well to the previous measurements



Analysis by Jordan O'Kronley (UTK)

Conclusion

- XEM2 performed inclusive measurements of the DIS and QE cross sections off several nuclei to study the nuclear dependence of the EMC effect and SRCs
- Wealth of data to the EMC world data with new nuclei
- If observed, the first experimental evidence for the 3N SRCs
- XEM2 data taking is complete
- One PRC publication and 2 PhD theses
- Plenty of data analysis is underway!

Acknowledgement

Spokespeople:
John Arrington (LBL), Nadia Fomin (UTK) & Dave Gaskell (JLab)

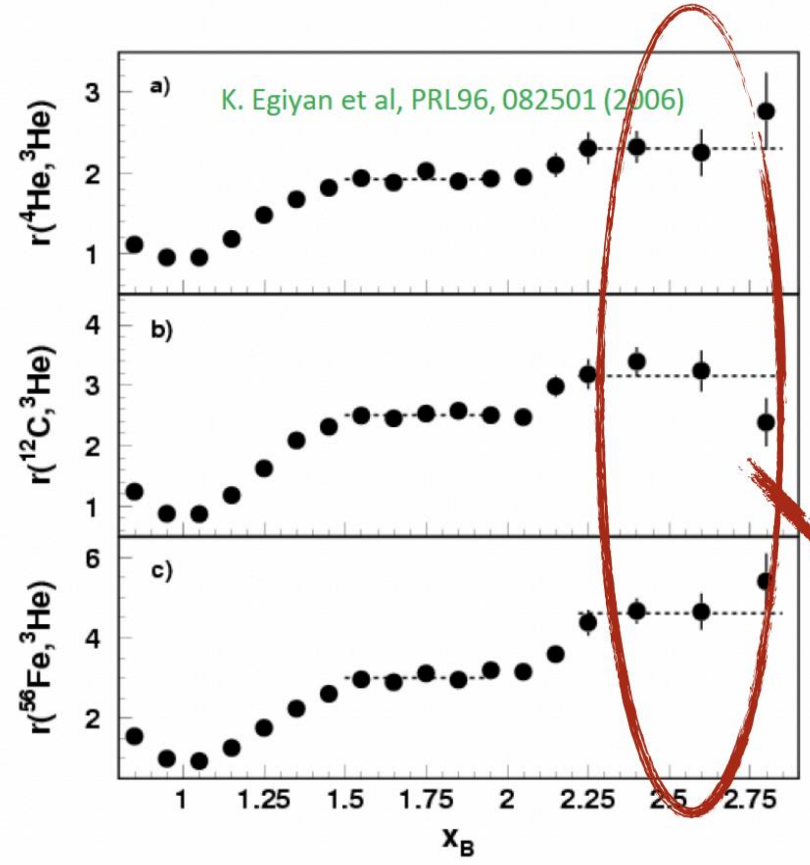
Graduate Students:
Cameron Cotton (UVA), Abishek Karki* (MSU), Casey Morean* (UTK), Jordan O'Kronley (UTK), Ramon Ogaz (UTK), Abhyuday Sharda (UTK), Sebastian Vasquez (UCR), Zoe Wolters (UNH)

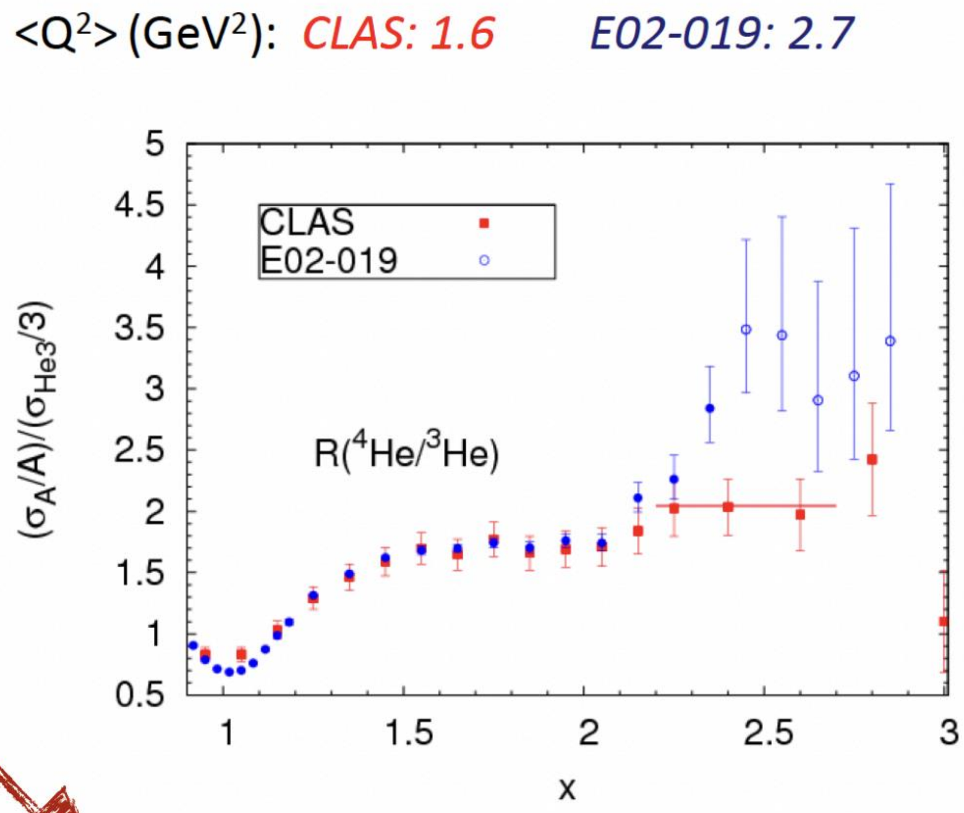
* = Graduated

Other Collaborators:
Miguel Arratia (UCR), Dipangkar Dutta (MSU), Shujie Li (LBL), Dien Nguyen (UTK),
Nathaly Santiesteban (UNH), Xiaochao Zheng (UVA), Burcu Duran (NMSU), Tyler Hague (JLab)

BACK UP

3N Short-range Correlations – Previous Searches



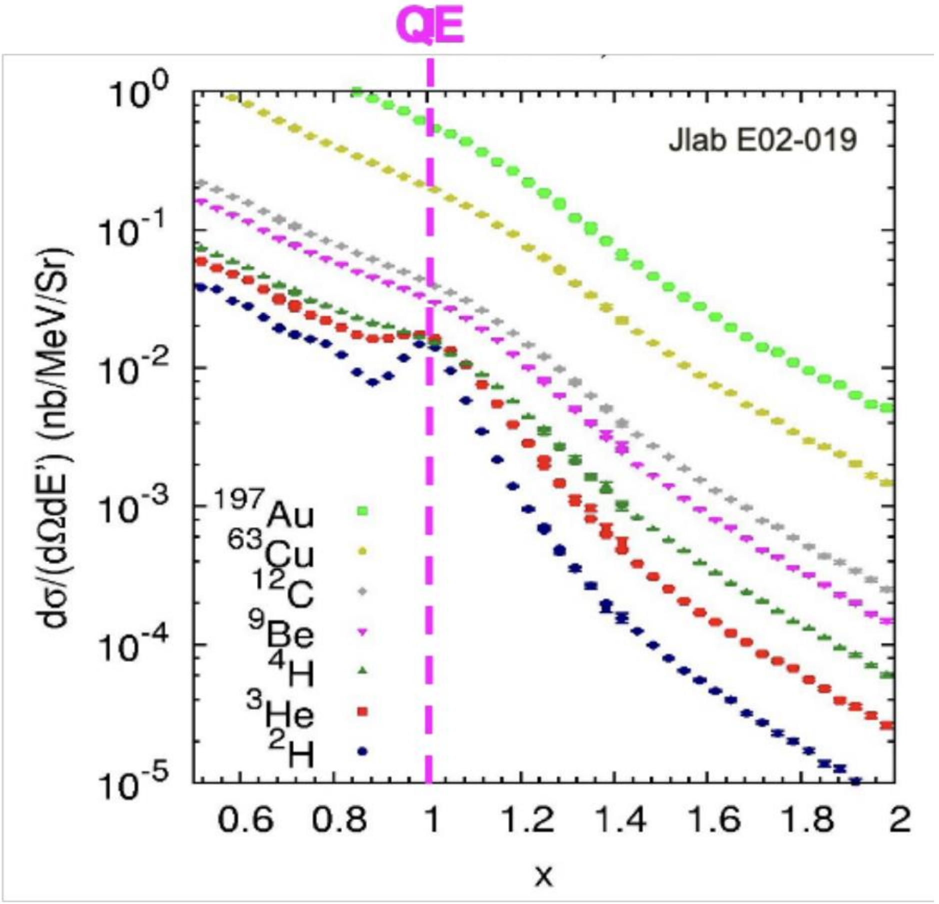


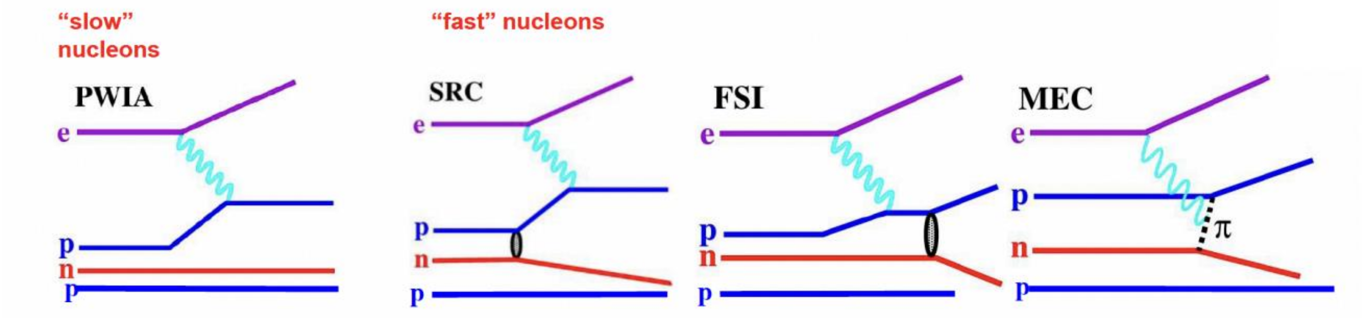
Comment on "Measurement of Two- and Three-Nucleon Short-Range Correlation Probabilities in Nuclei"

Douglas W. Higinbotham and Or Hen
Phys. Rev. Lett. **114**, 169201 – Published 24 April 2015

Artifact of bin migration associated with 1% momentum resolution in CLAS detector

- ➡ To measure the relative probability of finding a correlation, ratios of heavy to light nuclei are taken
- ➡ To experimentally probe SRCs, must be in the high-momentum region (x>1): QE scattering
- ➡ If the high momentum nucleons in nuclei come from correlated pairs, ratio of A/D should show a plateau.
- ➡ FSIs are thought to be confined to the SRCs so cancel in the cross section ratios





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

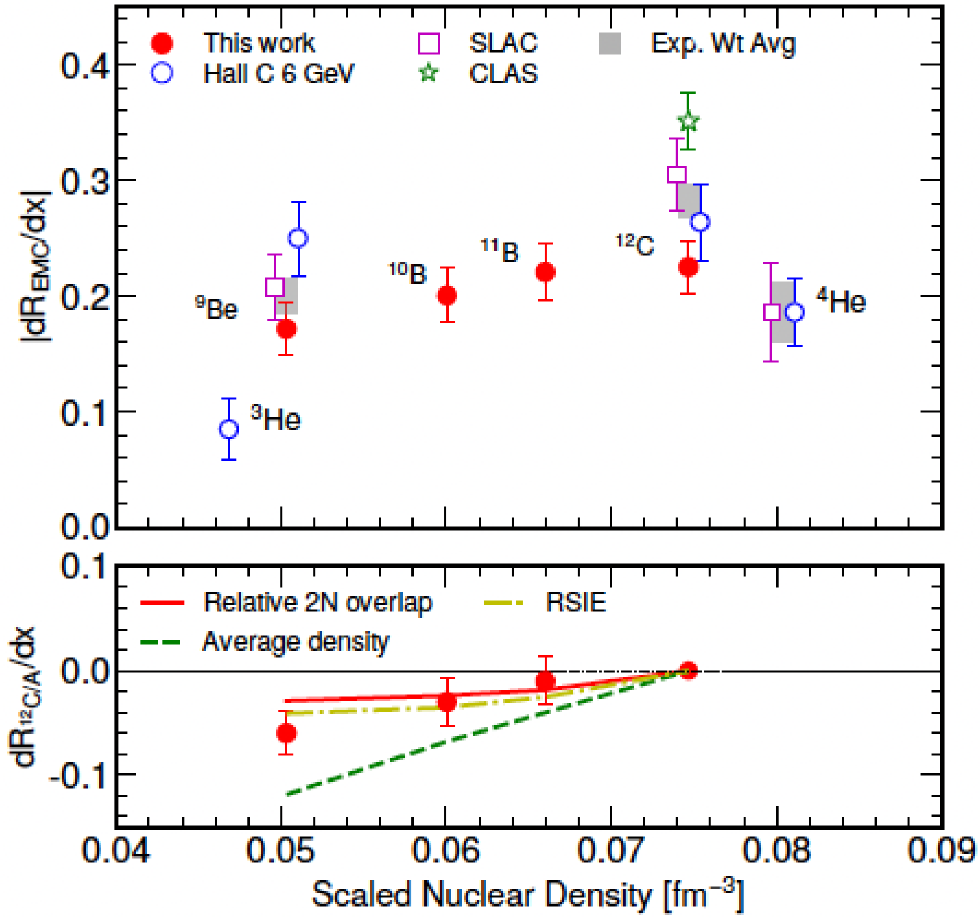
E12-10-008 (EMC Effect) – Commissioning data

9Be: 6 GeV Hall C data and the results from this work are both in agreement with the SLAC E139 results, but are in some disagreement with each other

Larger systematic effects from the cross section model used in the radiative corrections for 6 GeV data might be the reason

6 GeV Hall C results agree with those from this experiment for carbon, although the latter are in some tension with the SLAC E139 and CLAS ratios

systematic difference in the CLAS results can be attributed to differences in the approximations used in determination of the radiative corrections



A. Karki et al. First Measurement of the EMC Effect in ^{10}B and ^{11}B. Phys. Rev. C (2023)