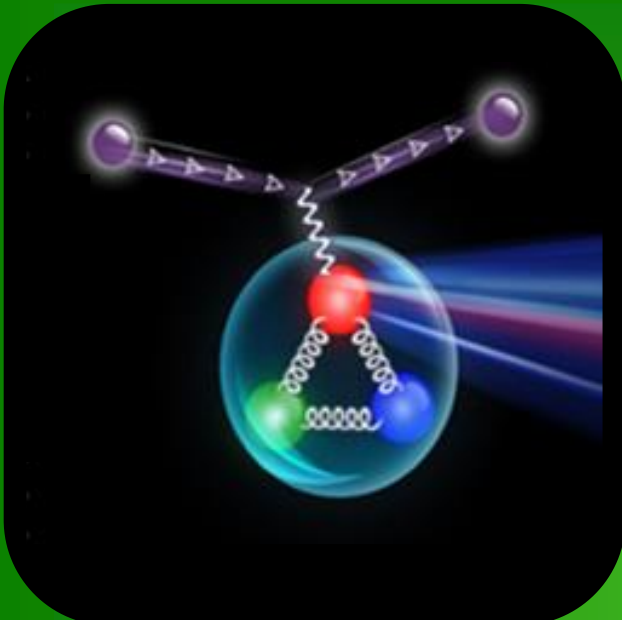


EMC effect
Past, Present, and Future

Nadia Fomin

January 12th , 2018

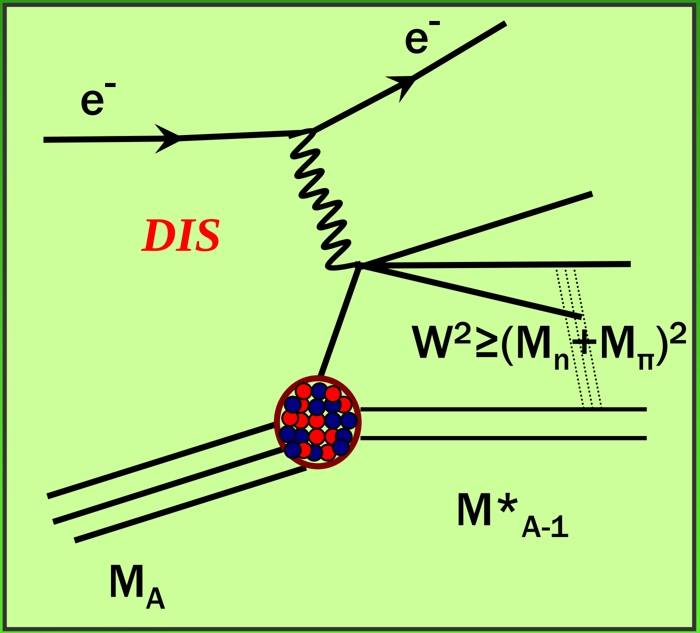
Discovery of the EMC effect

- Goal was a measurement of the lepton-nucleon cross section at high Q^2
  - To achieve statistical precision in a reasonable amount of time, an iron target was used, on the assumption that

$$\frac{\sigma_A / A}{\sigma_D / 2} \approx 1$$

meaning

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



$$F_1(x) = \frac{1}{2}\Sigma e_i^2[q_i^{\uparrow}(x) + q_i^{\downarrow}(x)]$$

$$F_1(x) = \frac{1}{2x}F_2(x)$$

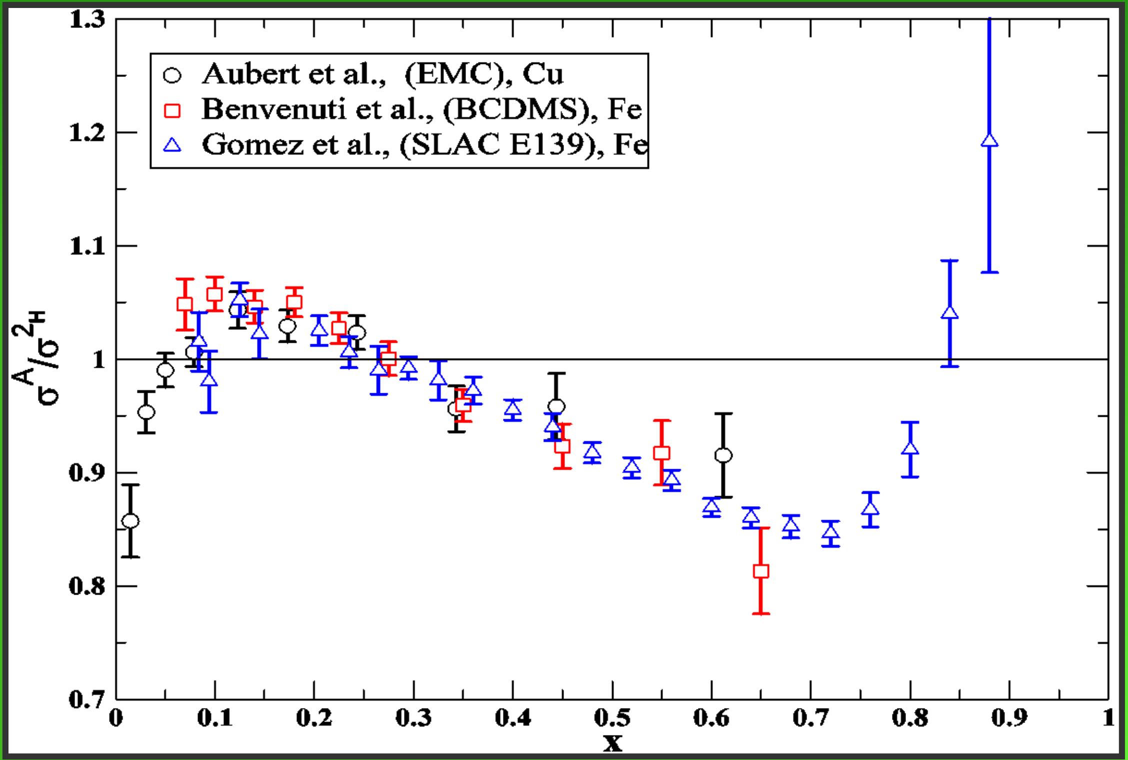
The EMC effect

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

Nuclear dependence of the structure functions discovered 30+ years ago by the European Muon Collaboration (EMC effect)

Nucleon structure functions are modified by the nuclear medium

Depletion of high-x quarks for A>2 nuclei is not expected or understood



Shadowing

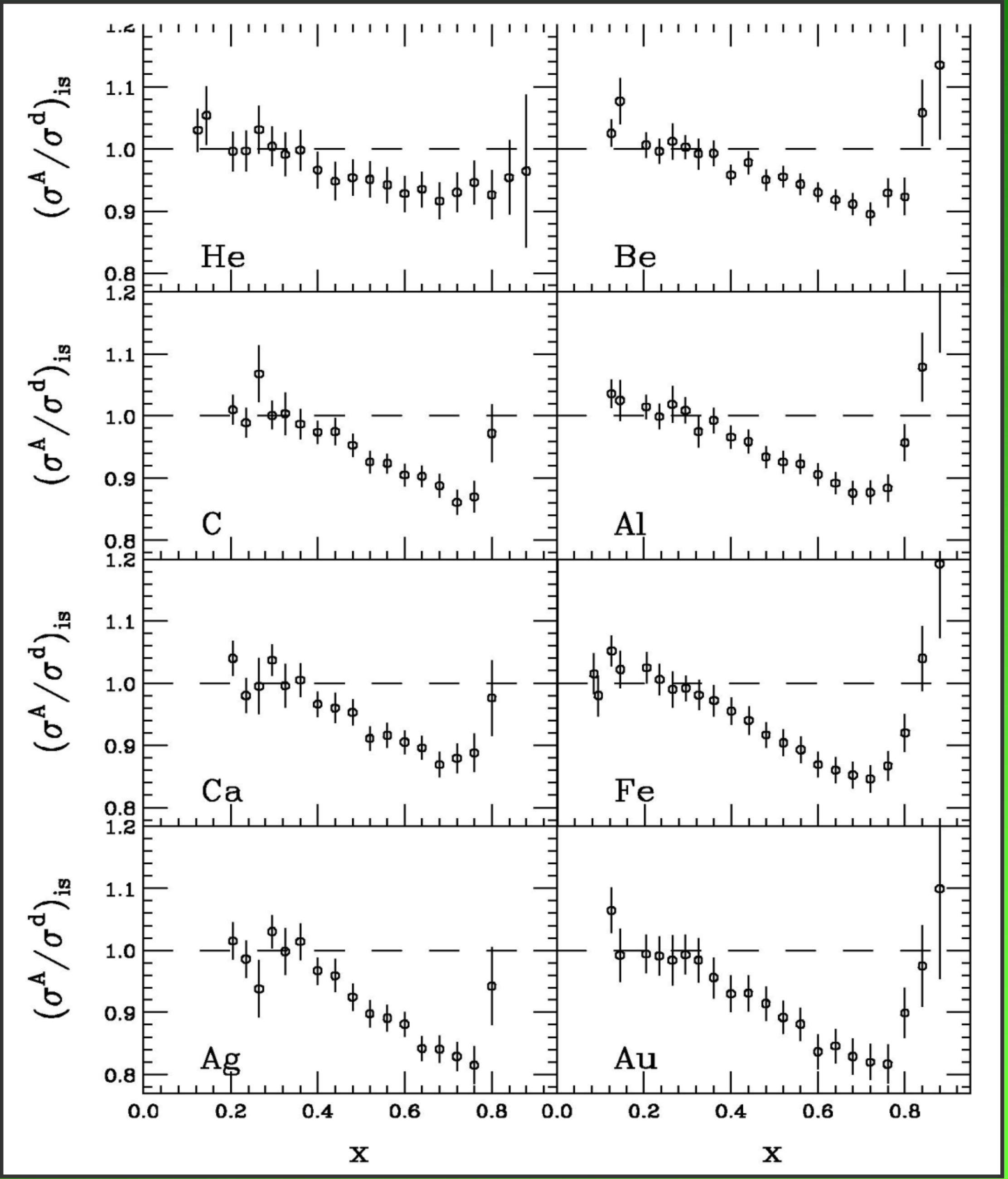
Anti-Shadowing (pion excess)

EMC region

Fermi motion effects

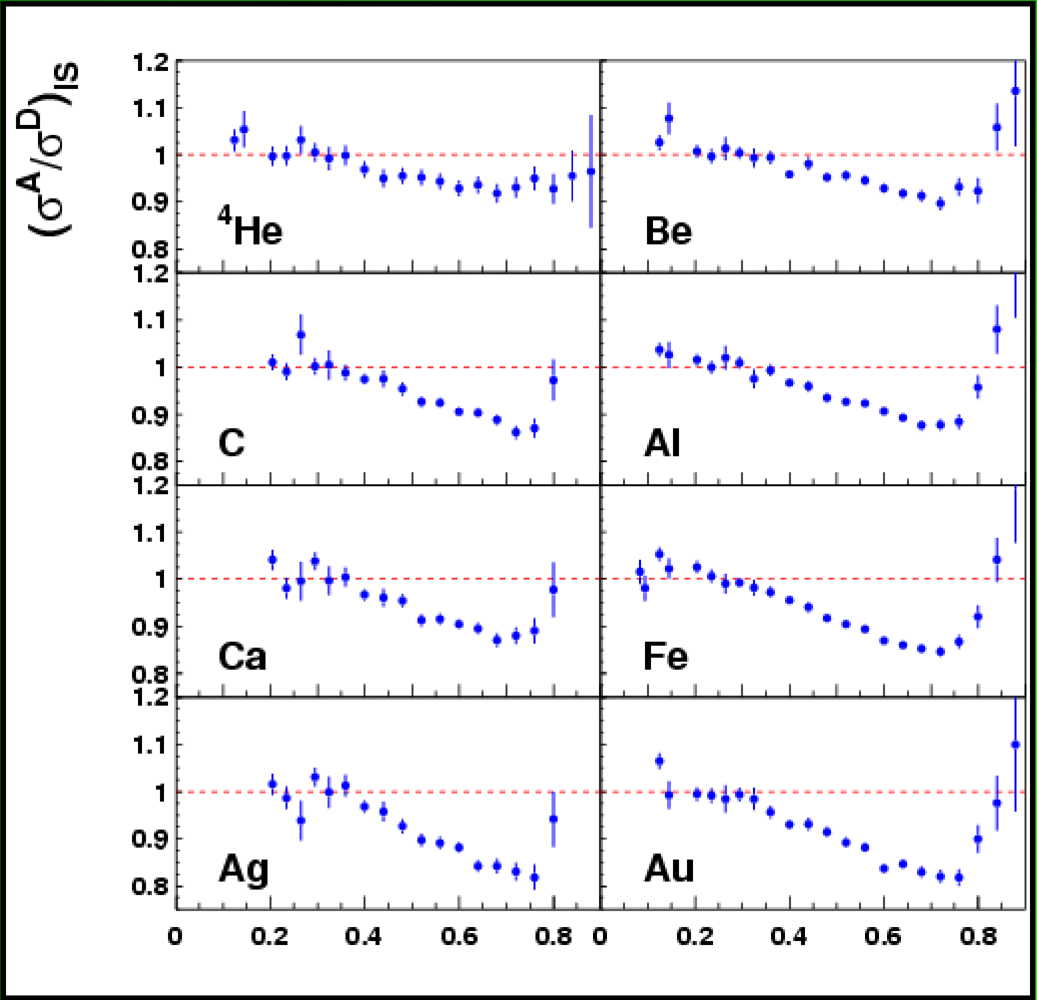
Measurements before 2004

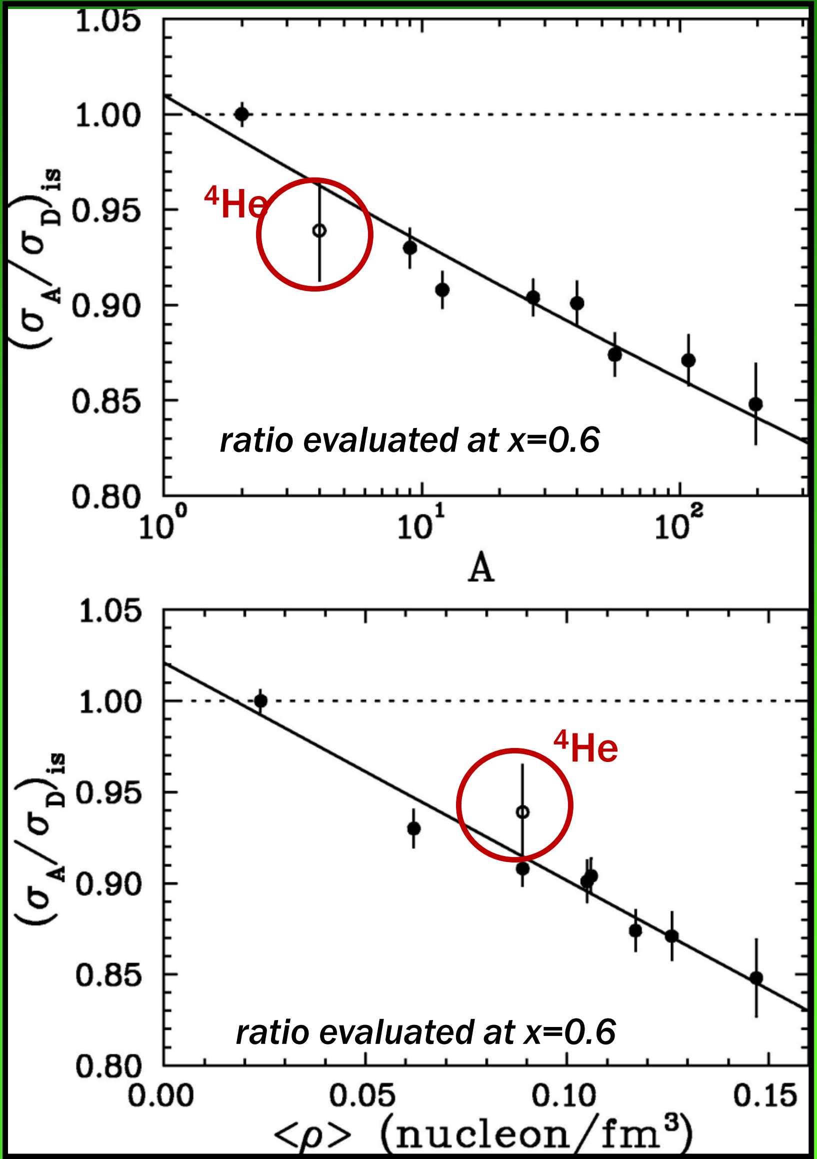
- *NMC* – extraction of F_2^n/F_2^p
- *BCDMS* – 50 < Q^2 < 200 (GeV^2)
- *HERMES* – first measurement on ^3He
- *SLAC E139* – most precise large x data
  - Q^2 independent
  - Universal shape
  - Magnitude approximately scales with density



Nuclear Dependence of the EMC effect

- → *Quark distributions are modified in nuclei*
- → *Modification scales with A*





Models of the EMC effect

Nucleon structure is modified *in the nuclear medium*

- Dynamical rescaling
- Nucleon 'swelling'
- Multiquark clusters (6q, 9q 'bags')

or

Nuclear structure is modified *due to hadronic effects*

- More detailed binding calculations
  - Fermi motion + binding
  - N-N correlations
- Nuclear pions

Models of the EMC effect

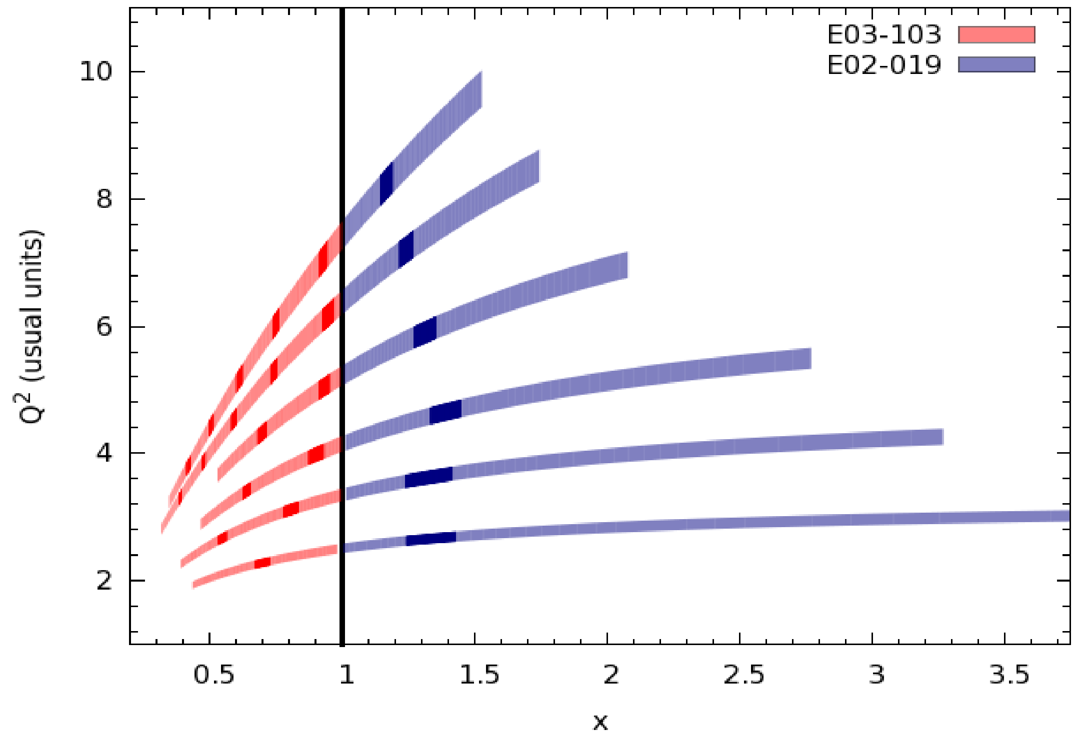
1. **“Conventional”** nuclear physics based explanations (convolution calculations)
   - Fermi motion alone clearly not sufficient
   - Early attempts to combine Fermi motion effects and binding were fairly simplistic
   - Even more sophisticated approaches (spectral function) fail unless one includes something more, e.g. “**nuclear pions**”

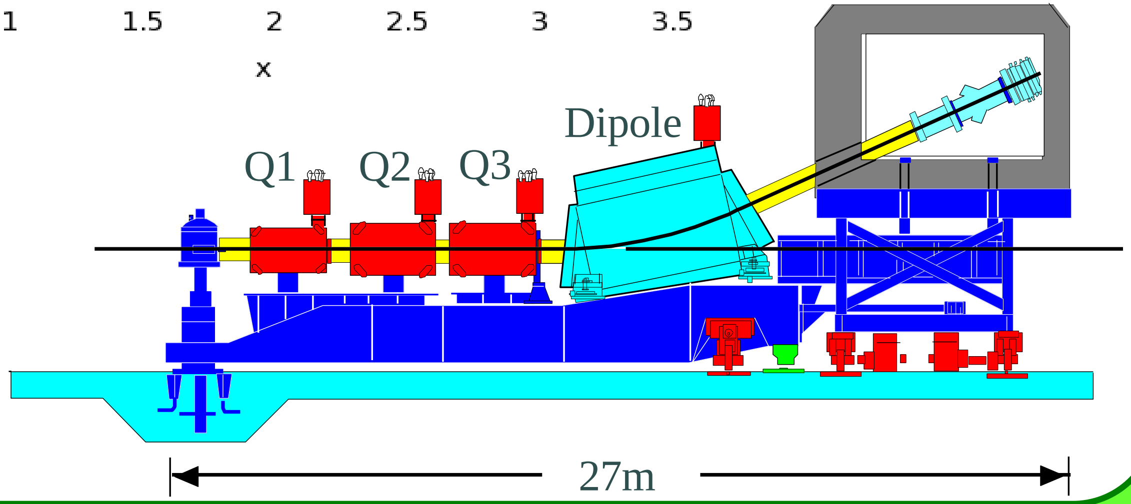
     Size of contributions from nuclear pions typically used in DIS calculations inconsistent with nuclear dependence of Drell-Yan
2. **“Exotic”** effects
   - Medium effects on quark distributions themselves → dynamical rescaling, multiquark clusters, etc.

→ Uncertainties in *1* make it difficult to determine what role mechanisms in *2* play in observed EMC effect

Jlab E03-103: A long time ago in Hall C

^{2}H
^{3}He
^{4}He
^{9}Be
^{12}C
^{27}Al*
^{63}Cu
^{197}Au





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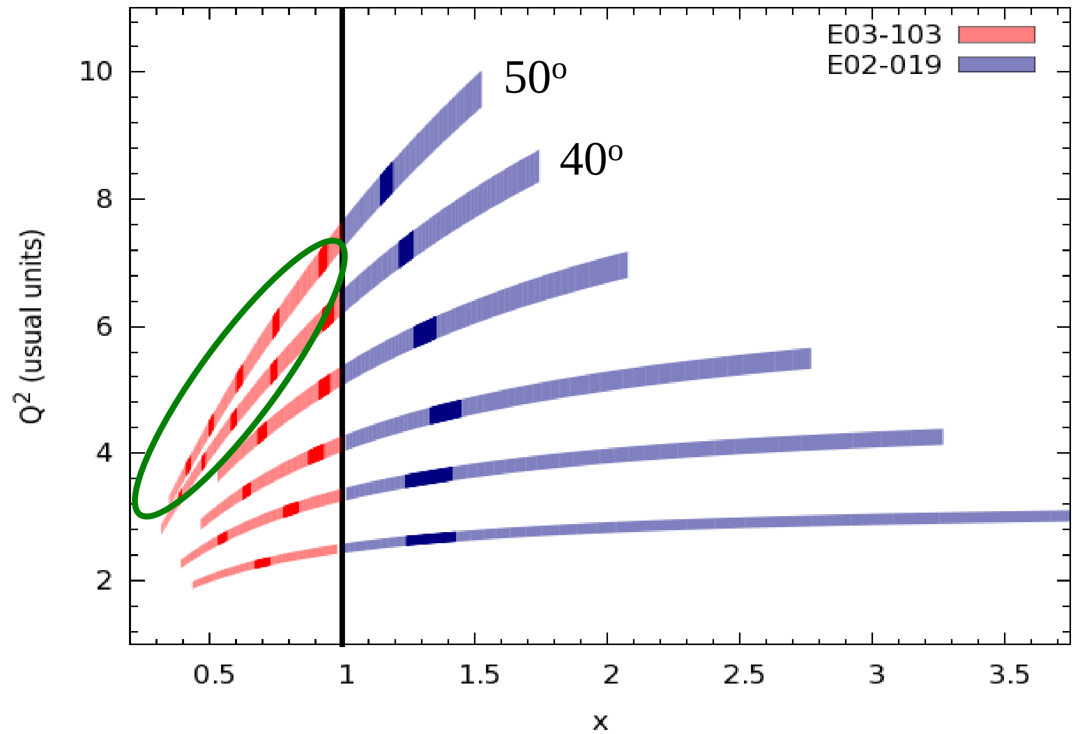
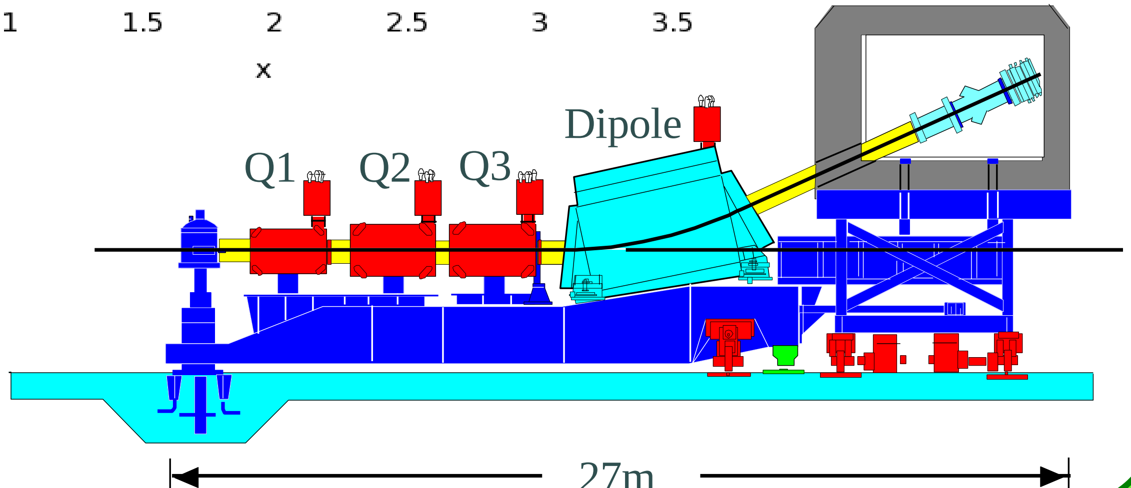
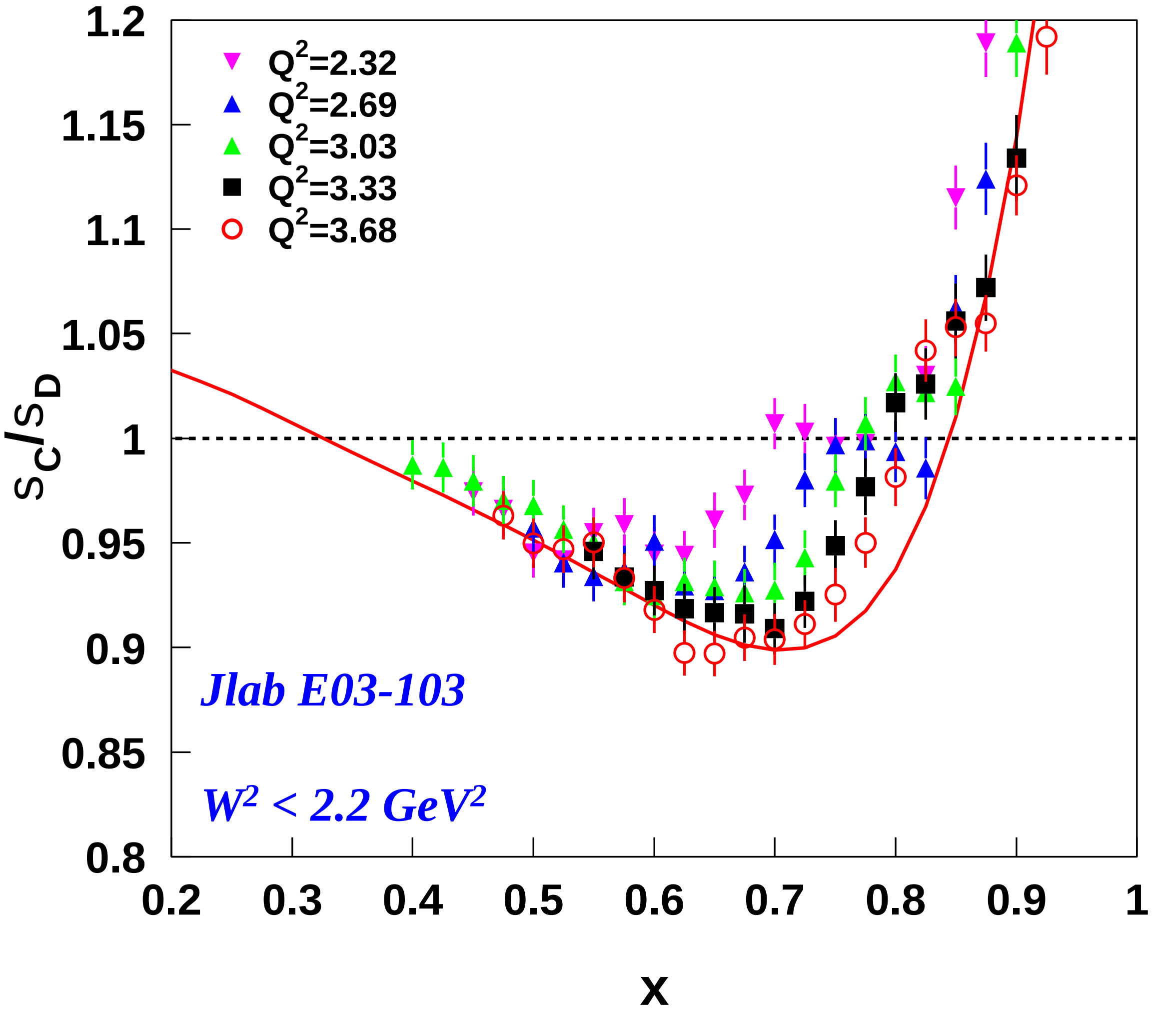
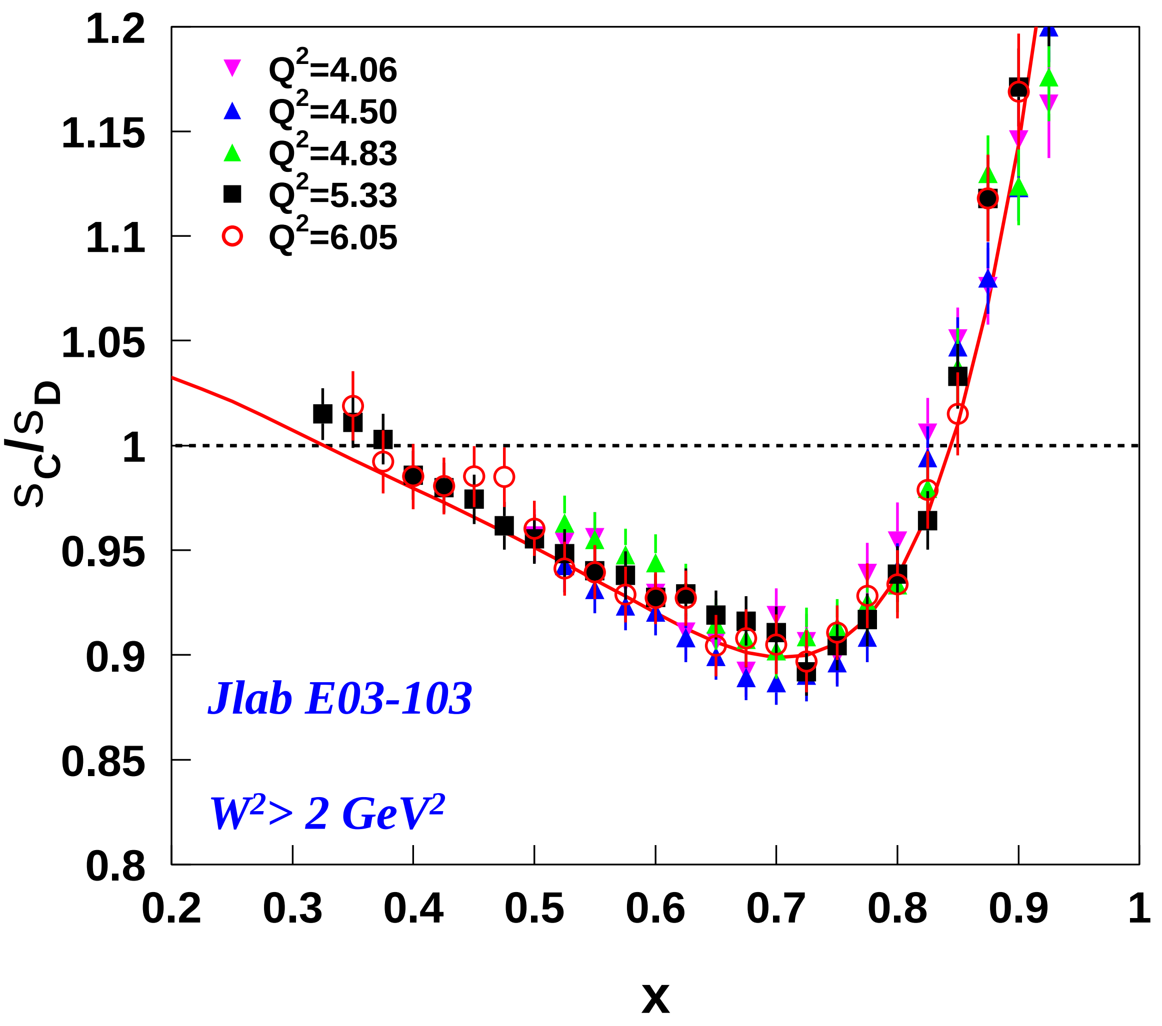




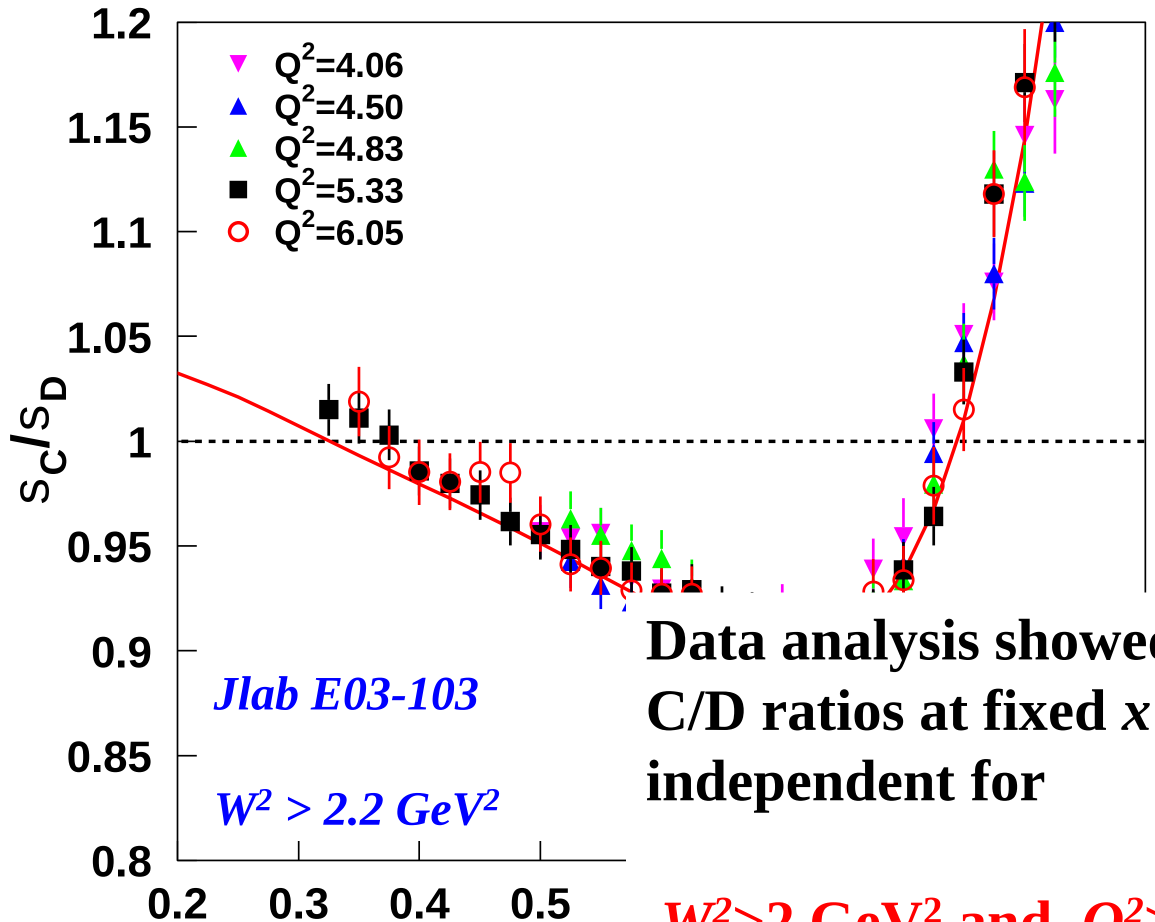
No scaling for low Q^2 data



Establish Q^2 independence



Establish Q^2 independence



Data analysis showed that: C/D ratios at fixed *x* are Q^2 independent for

W^2>2 GeV^2 and Q^2>3 GeV^2

For E03-103, this extends to *x*=0.85

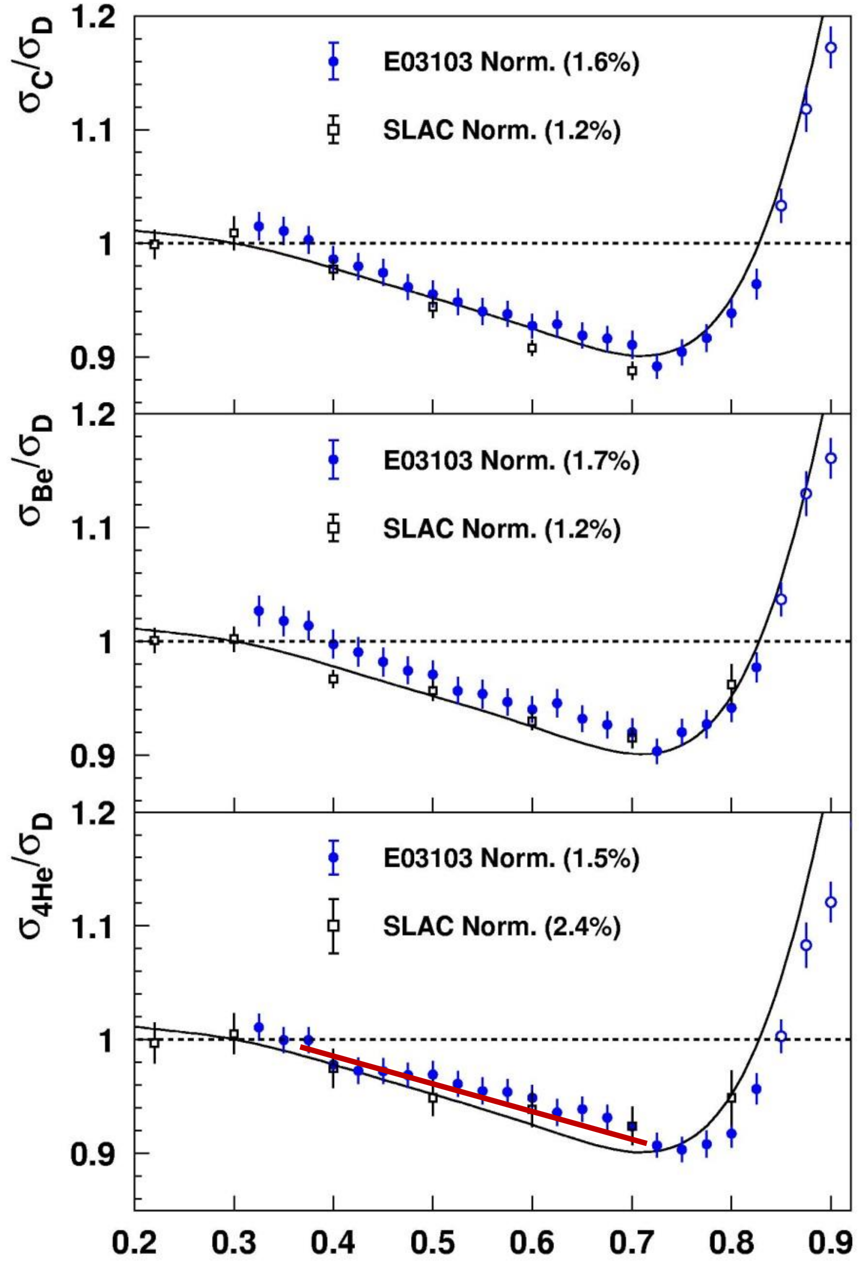
Precision results on light nuclei from JLab E03-103

- ***C/D*** and ***^{4}He/D*** ratios – no isoscalar correction necessary
- Consistent with SLAC results, but much higher precision at high x

- Fit the slope of the ratios for 0.35<x<0.7:

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

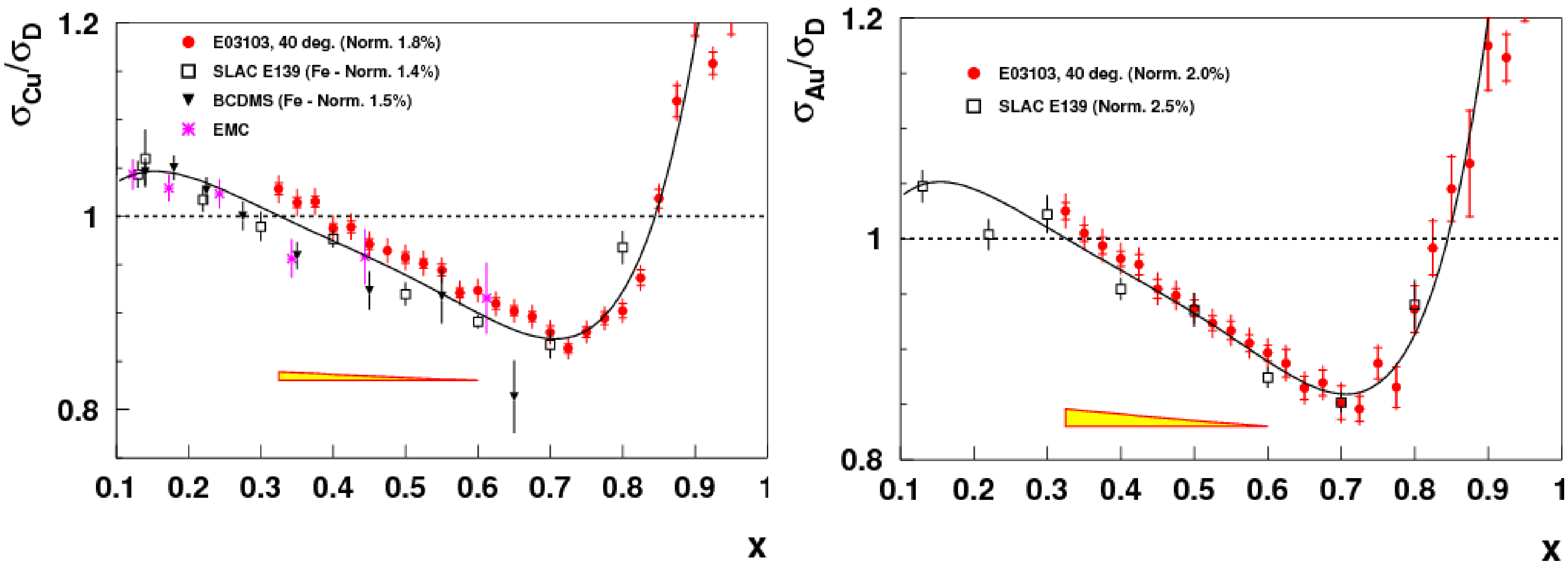
- Compare across nuclei



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

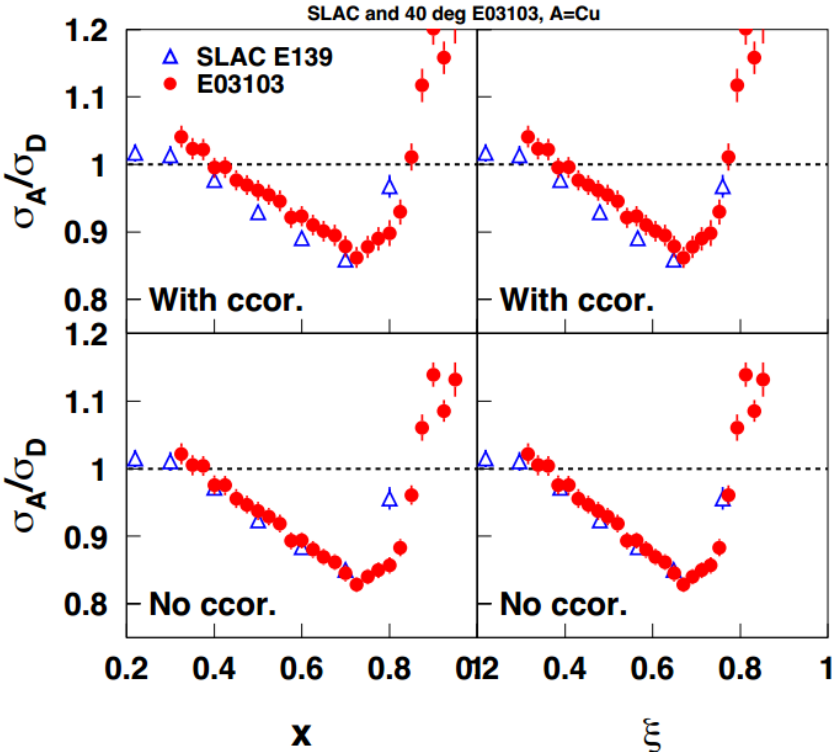
PhD theses: J. Seely, A. Daniel

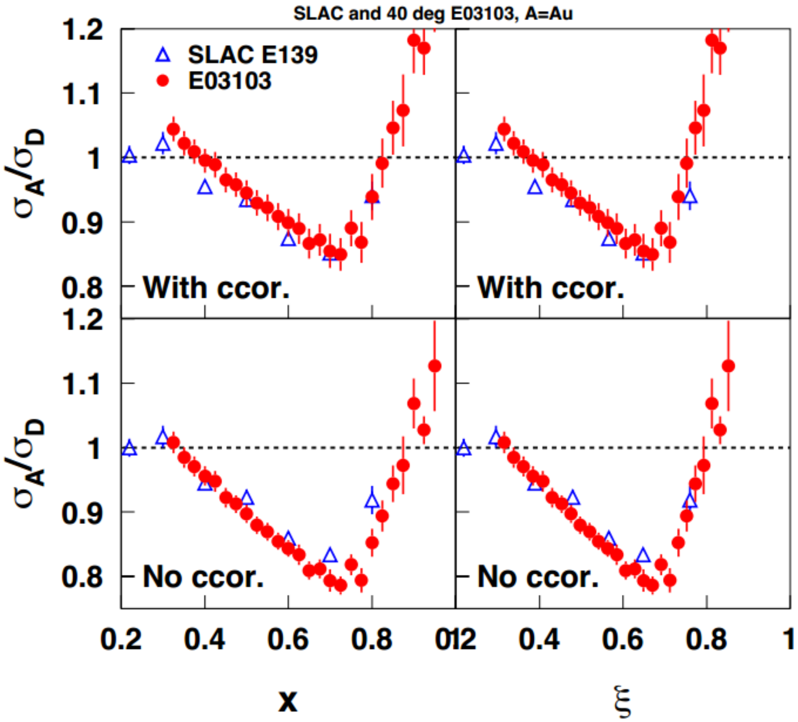
New Results on high A targets from Jlab E03-103



- Updated n/p correction
- Coulomb corrections applied to all data sets
- Corrections and uncertainties are larger than for light targets

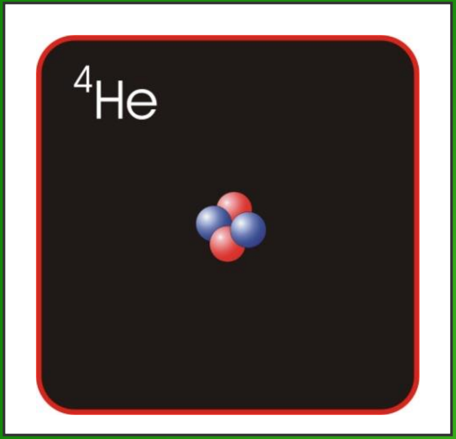
New Results on high A targets from Jlab E03-103

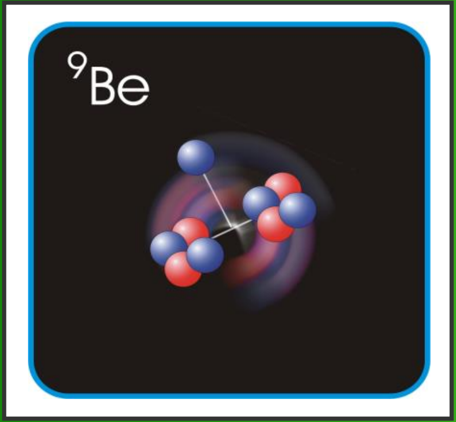




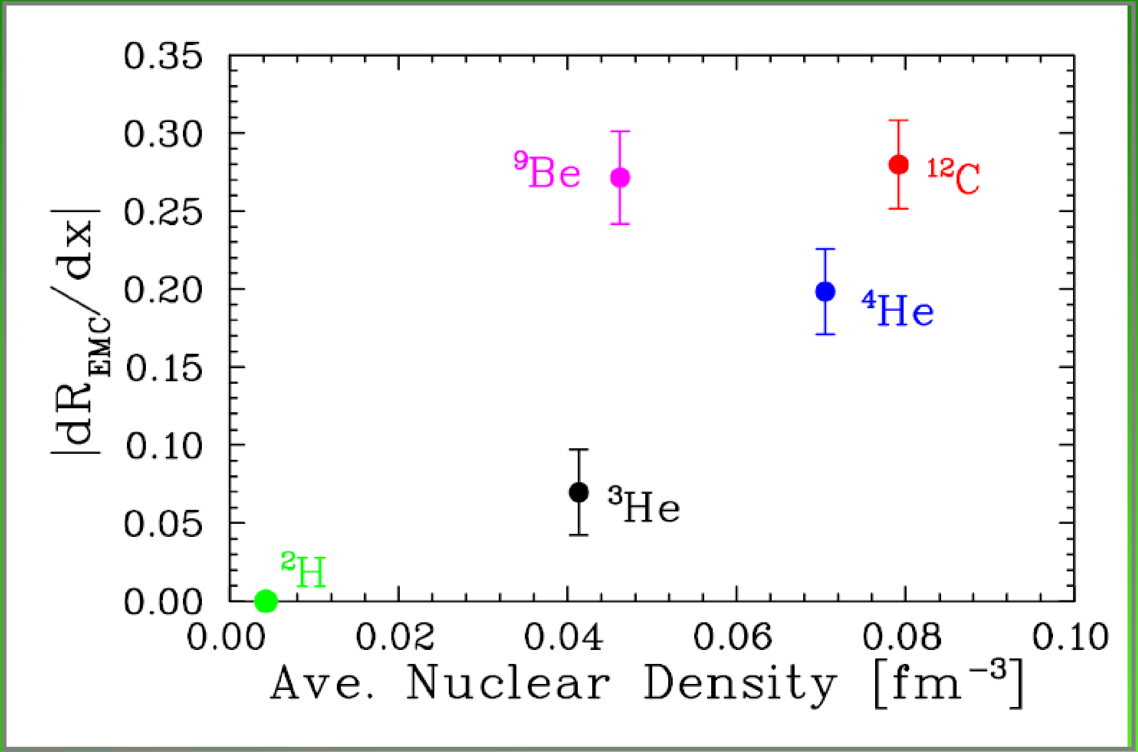
- Disagreement at high x due to TMCs and a slight mismatch in Q^2
- Small x (<0.4) systematically higher
- Large isoscalar corrections
  - But uncertainties low
- Possible A-dependence of $R=\sigma_L/\sigma_T$
  - $\sigma_A/\sigma_D != F_2^A/F_2^D$

Data don't support existing mass- or A-dependent pictures



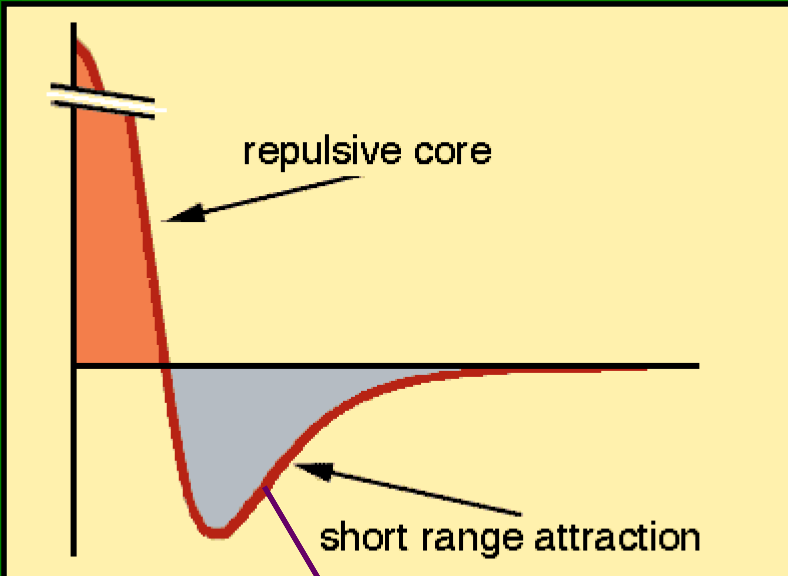


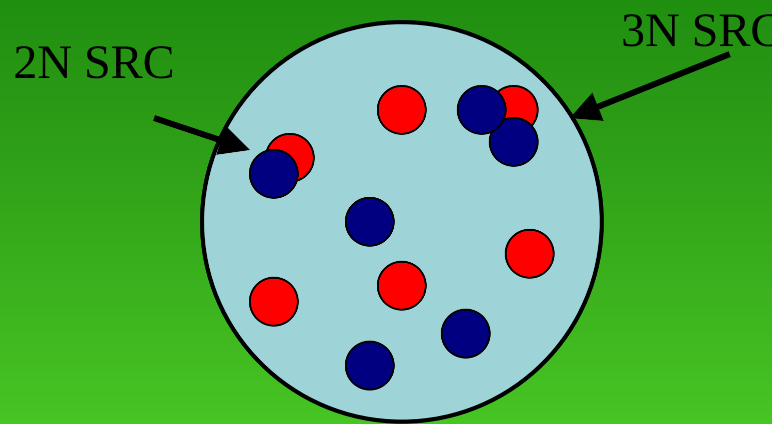
Density determined from *ab initio* few-body calculation
S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)

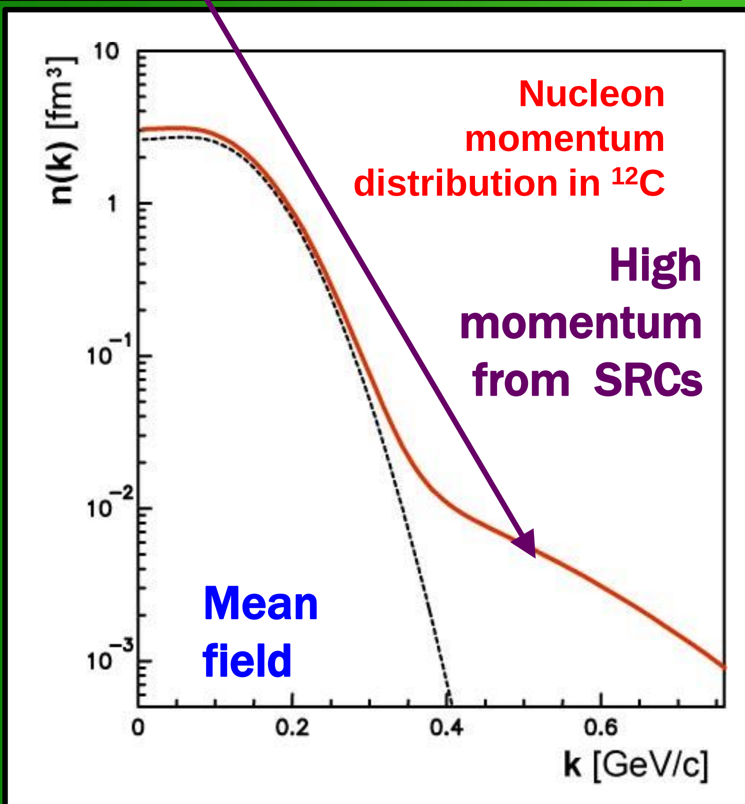


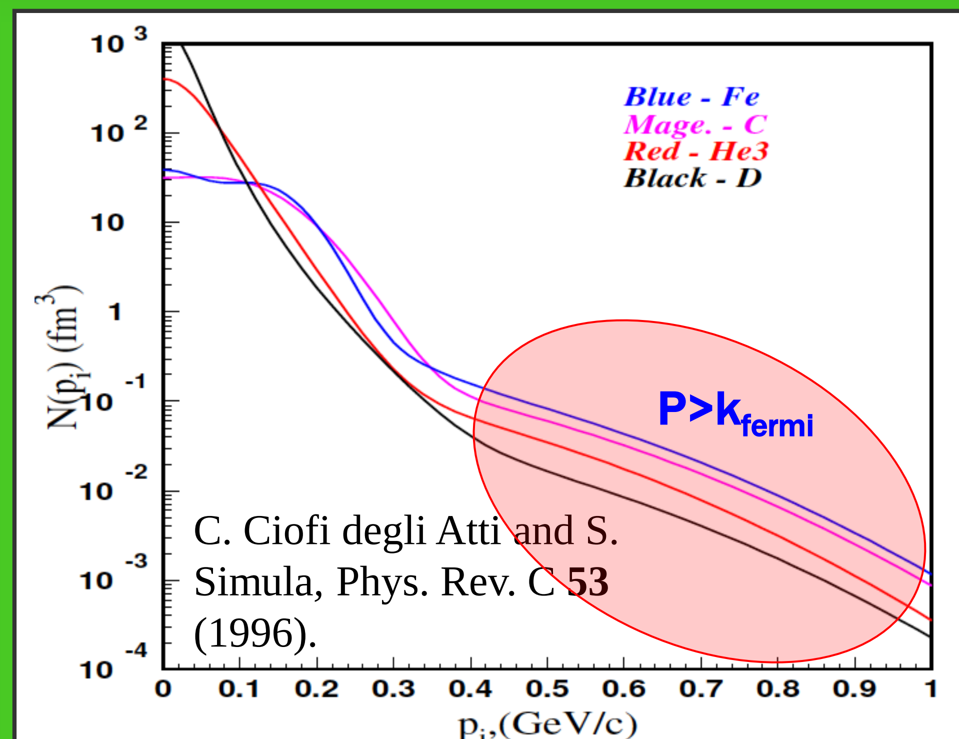
- EMC effect appears to follow "local" density
  - Sounds like the short range structure that we would normally study at x>1 (result of nucleon interaction at short range)

Local Density → Short Range Correlations

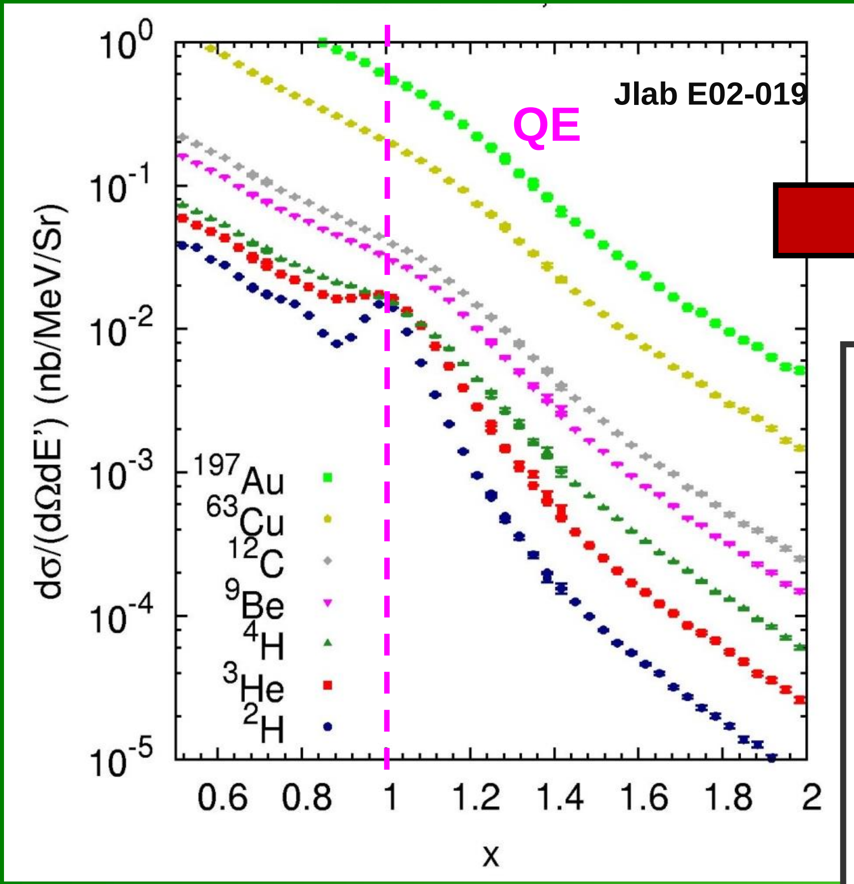


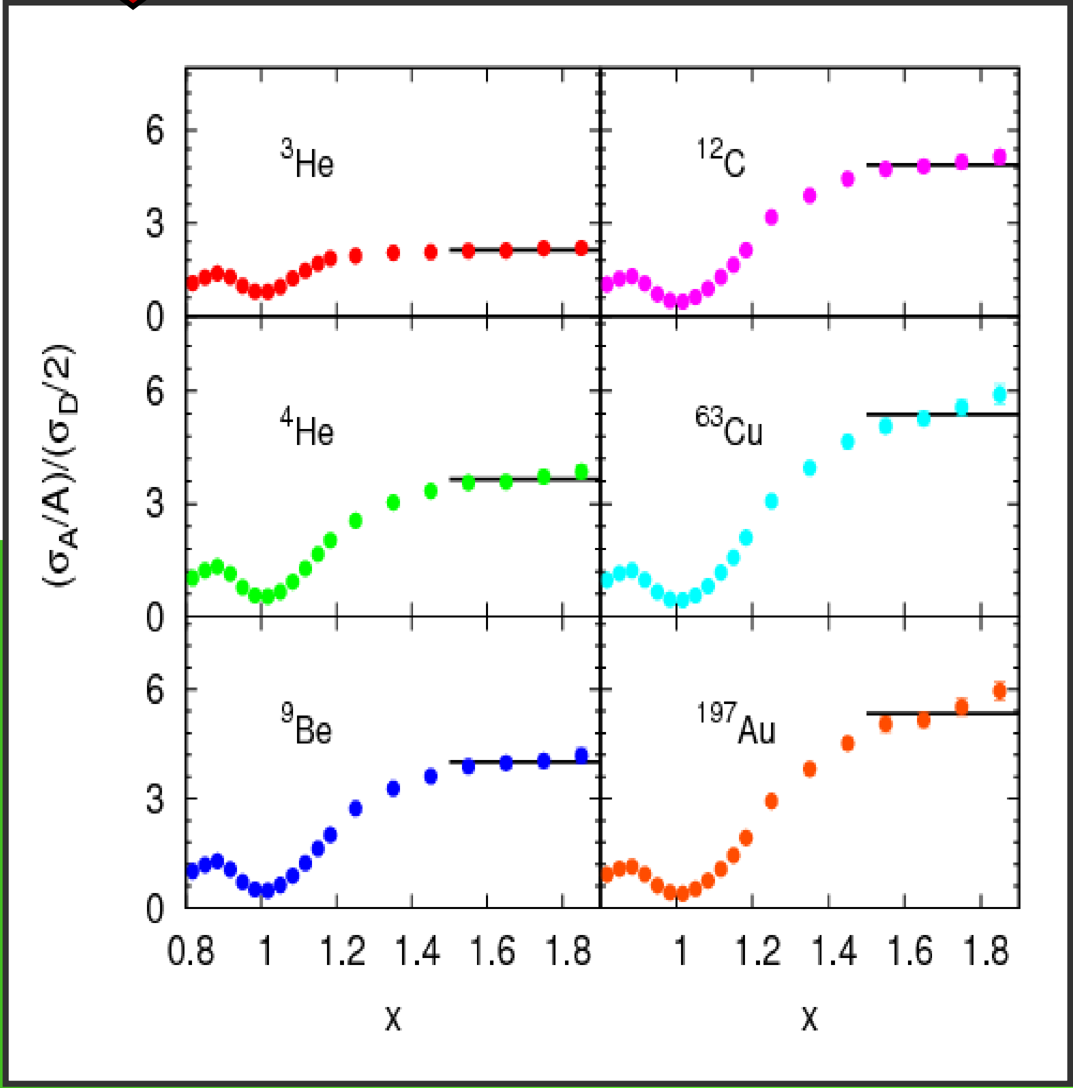






Measuring Short Range Correlations (SRCs)

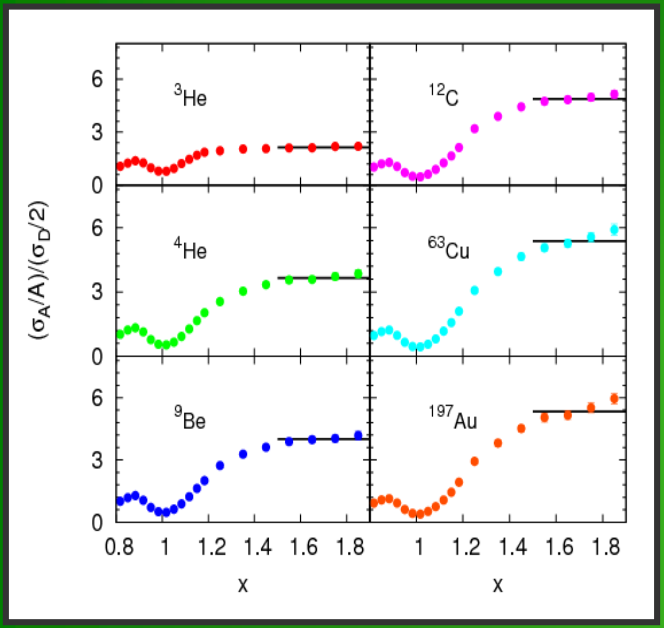




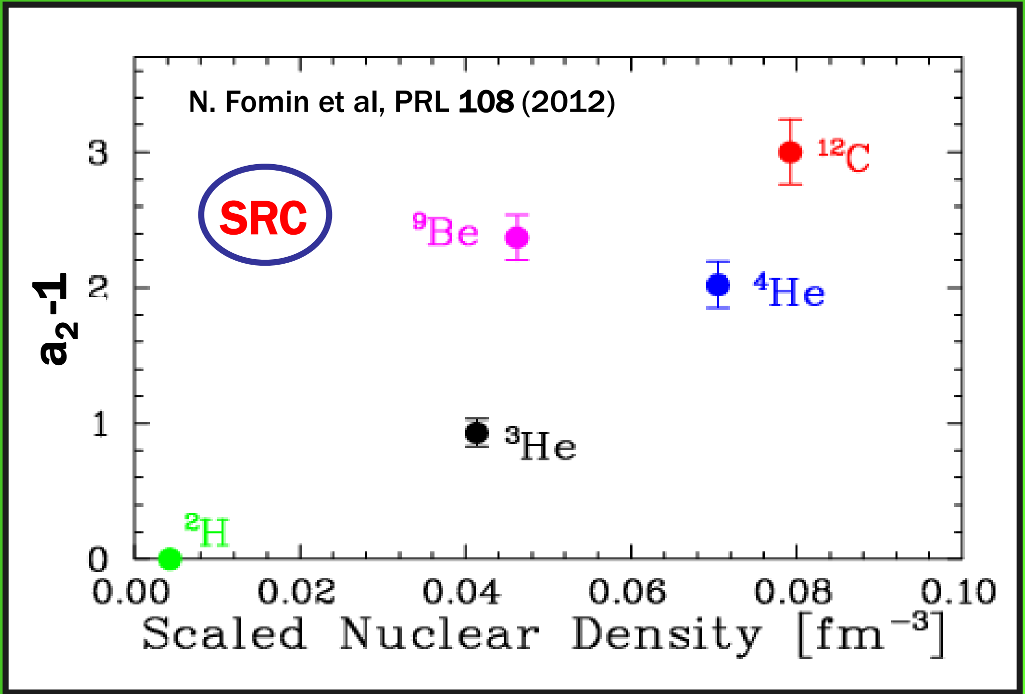
*Fomin et al, PRL **108** (2012)*

Jlab E02-019

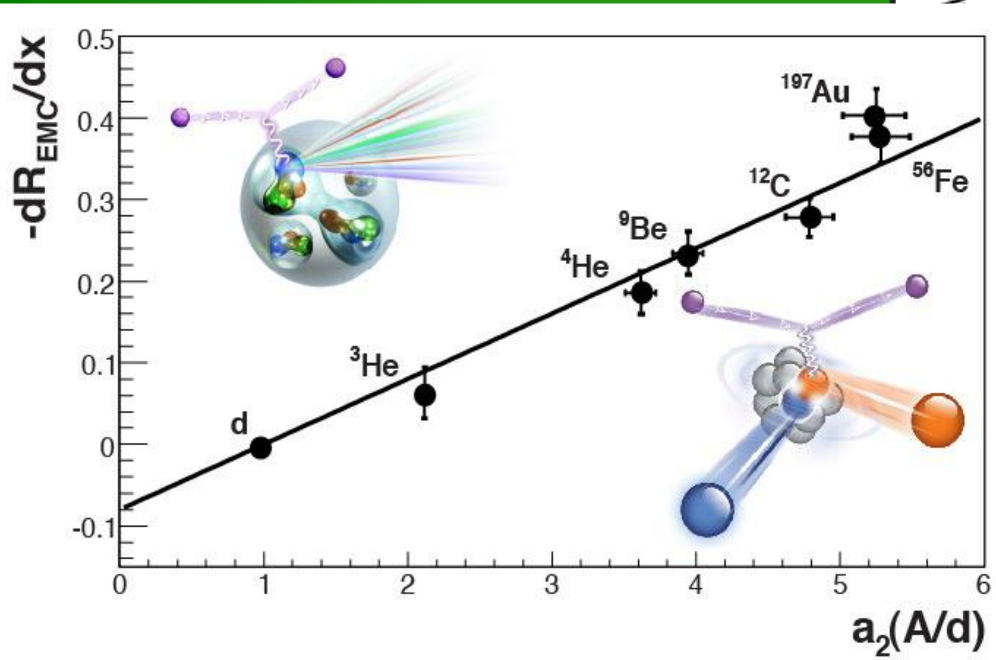
Look at nuclear dependence of NN SRCs

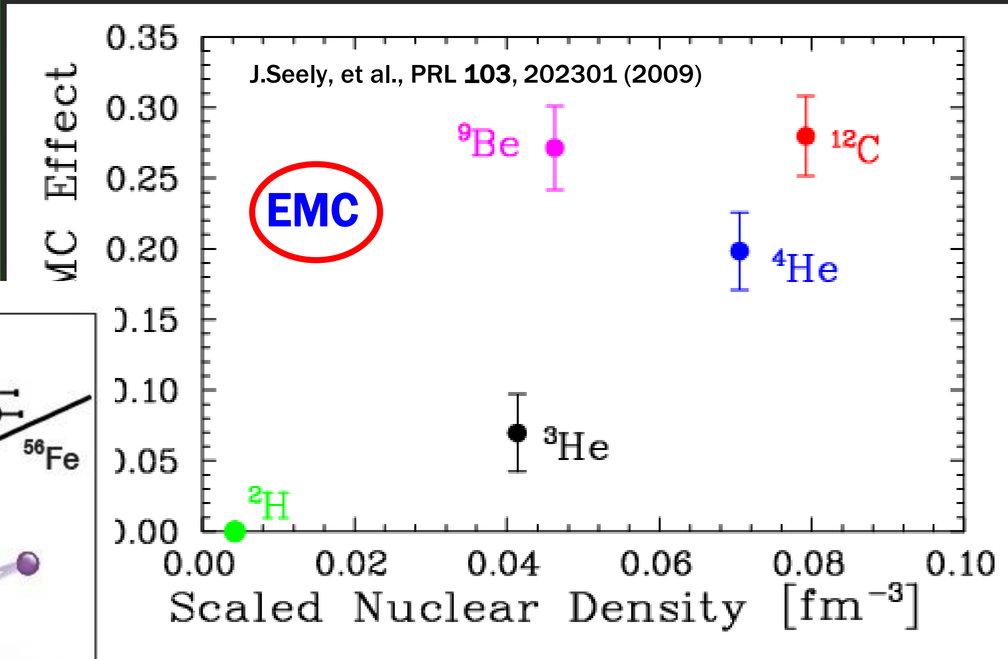


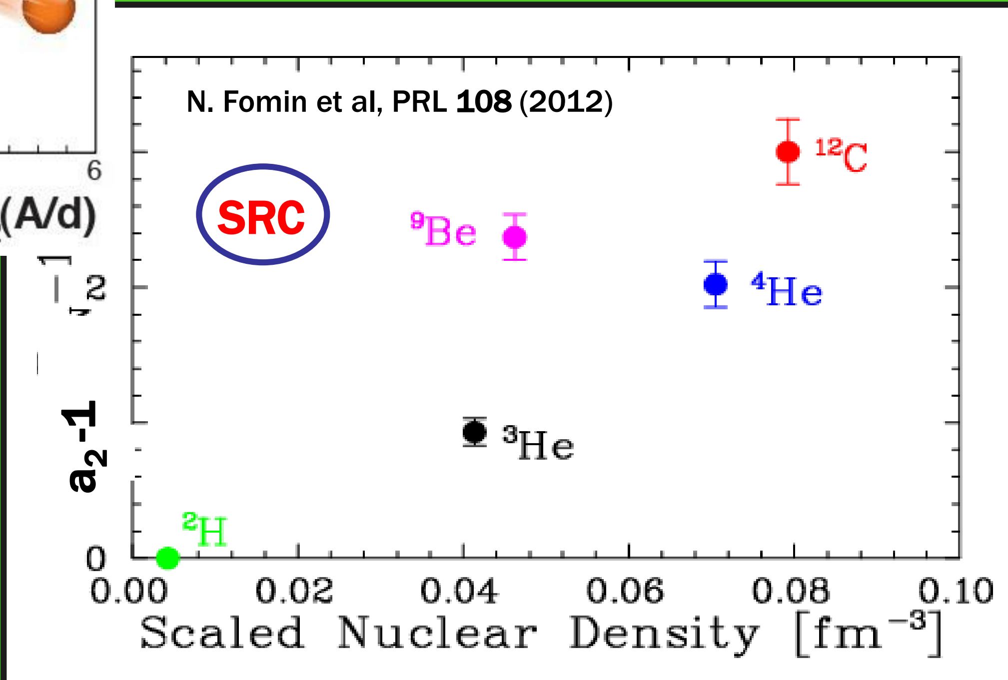
A	θ_e=18°
^{3}He	2.14±0.04
^{4}He	3.66±0.07
Be	4.00±0.08
C	4.88±0.10
Cu	5.37±0.11
Au	5.34±0.11
$\langle Q^2 \rangle$	2.7 GeV^2
x_{min}	1.5



Enter ^{9}Be







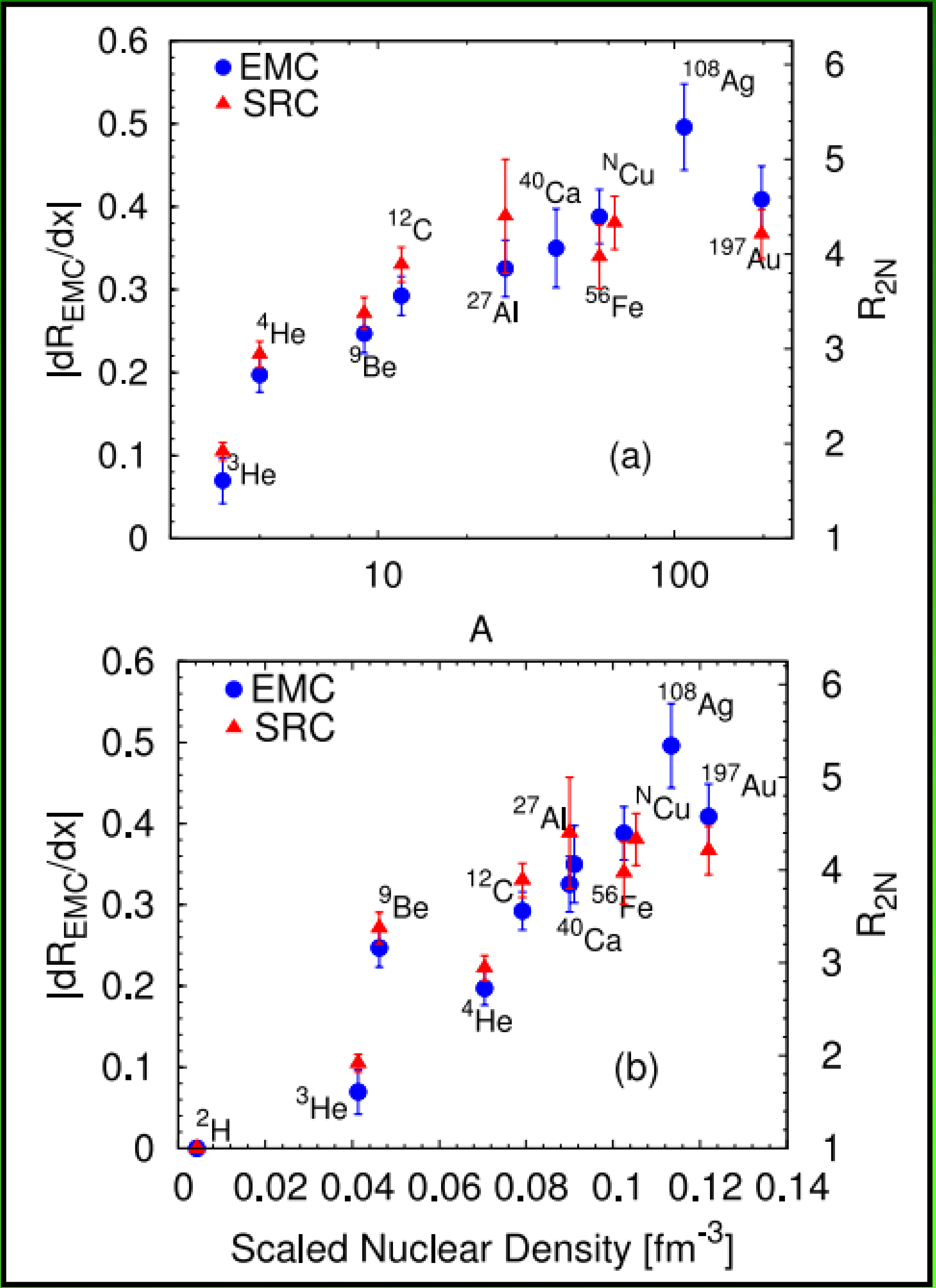
J. Seely, et al., PRL103, 202301 (2009)

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

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

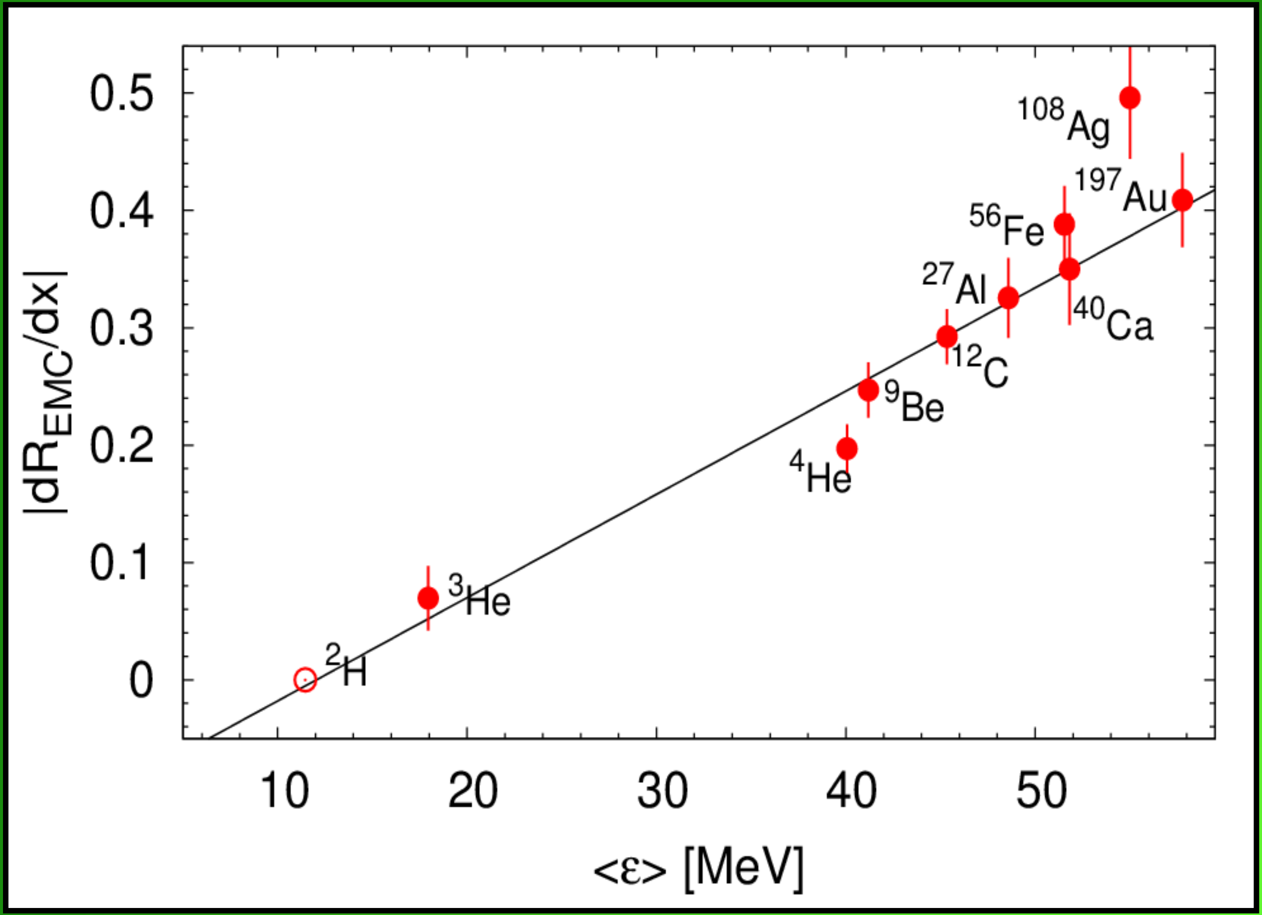
O. Hen, et al, PRC 85, 047301 (2012)
L. Weinstein, et al., PRL 106, 052301 (2011)

- Correlation between EMC effect and SRC data can no longer be explained by common density- or A-scaling
- However, the trends for both sets of data mirror each other as a function of A, or density



Both driven by a similar underlying cause?

Separation Energy

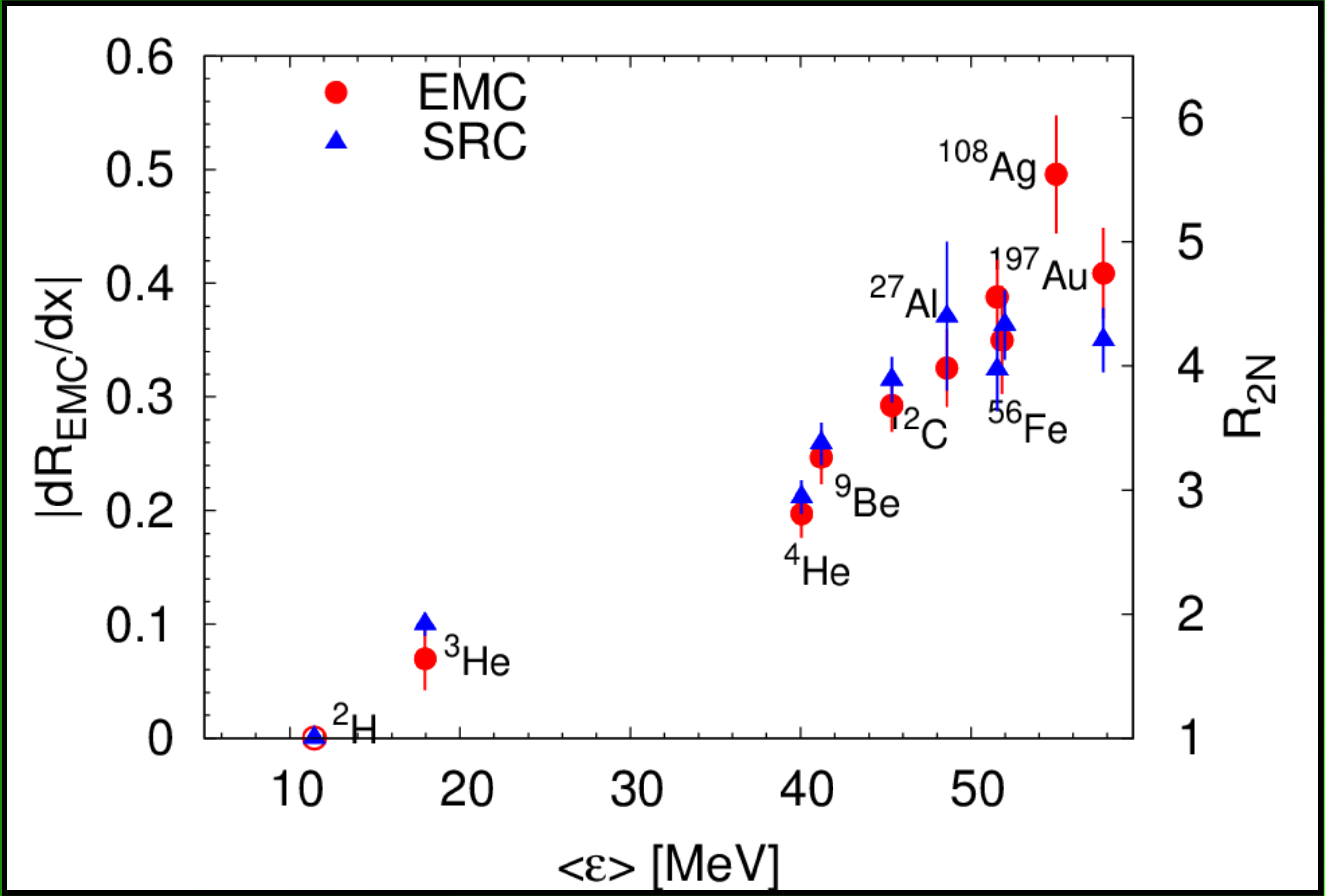


Separation energies were calculated from spectral functions, including MF and correlations

S.A. Kulagin and R. Petti, Nucl. Phys. A 176, 126 (2006)

Both driven by a similar underlying cause?

Separation Energy

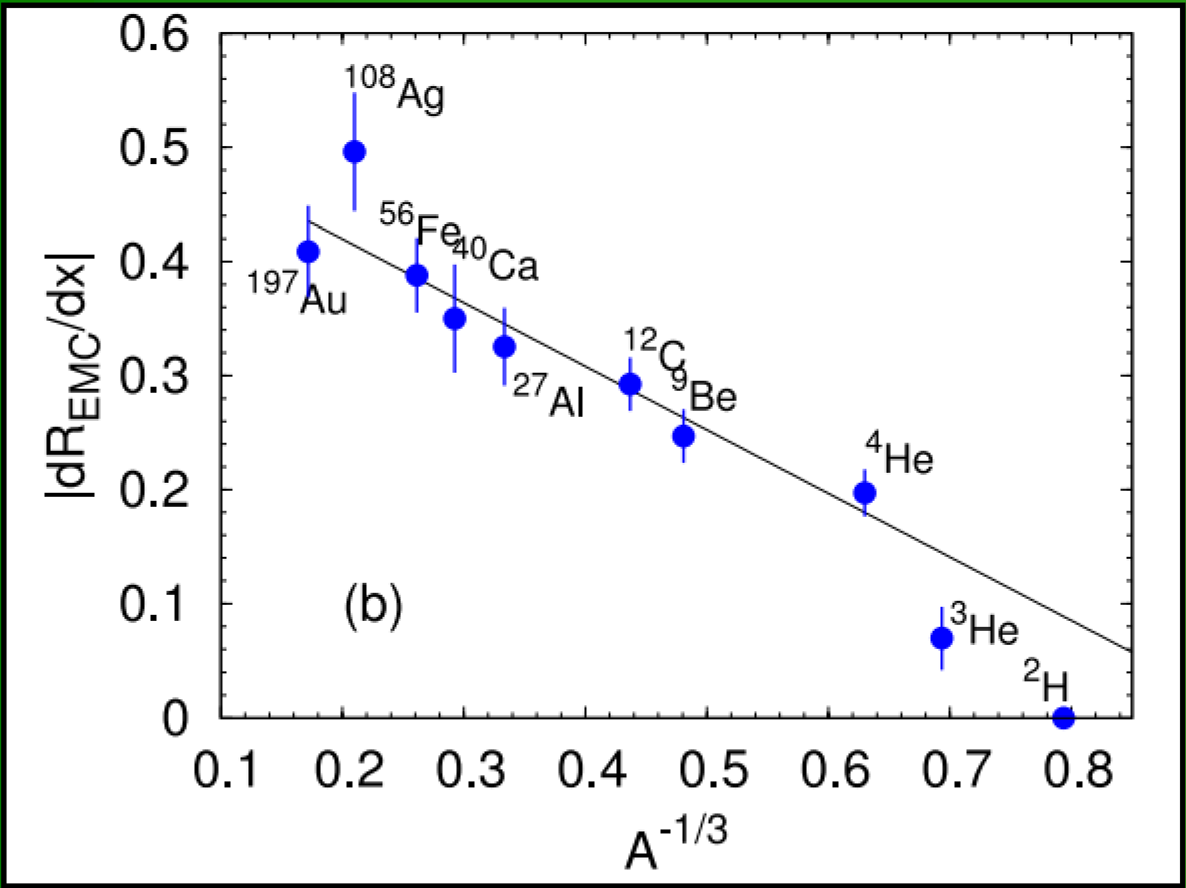


For SRCs, a linear relationship with <ε> is less suggestive

S.A. Kulagin and R. Petti, Nucl. Phys. A 176, 126 (2006)

Both driven by a similar underlying cause?

A $^{-1/3}$



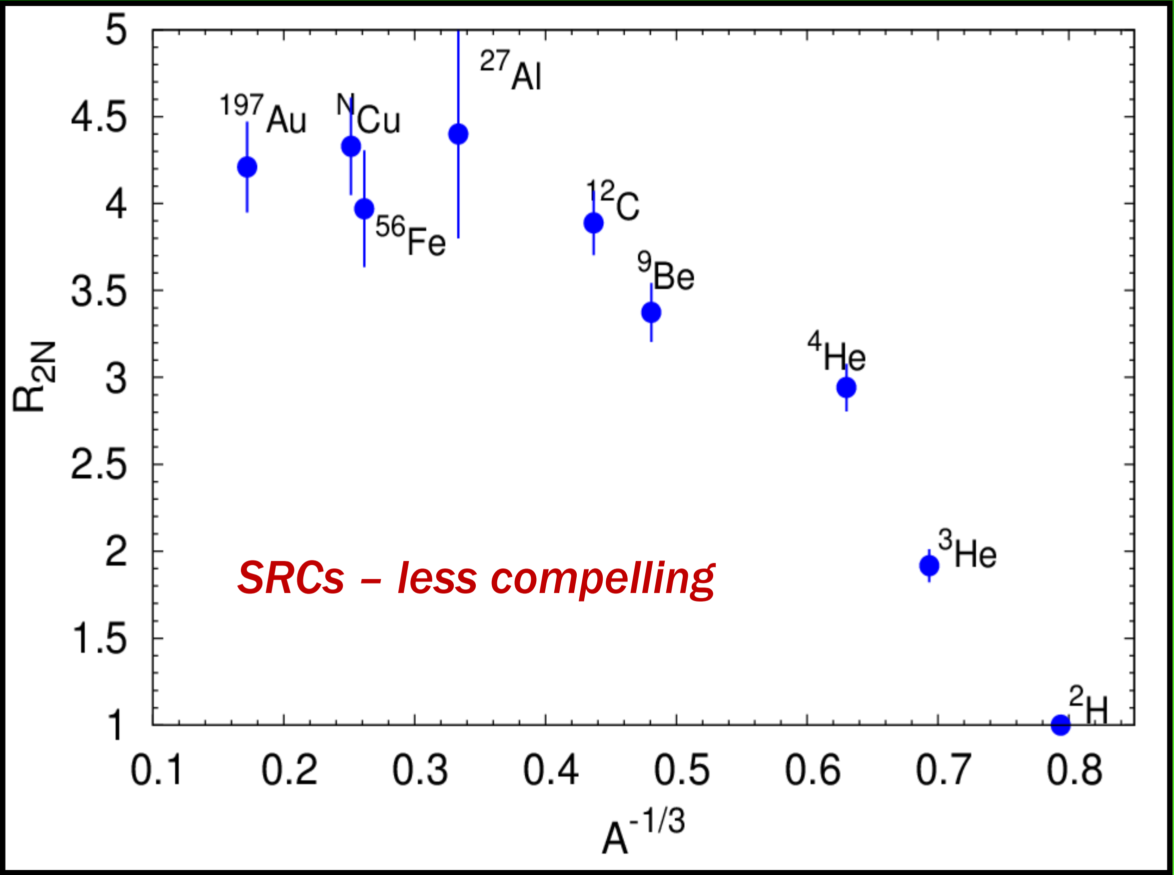
Apply exact NM calculations to finite nuclei via LDA

- *(A. Antonov and I. Petkov, Nuovo Cimento A 94, 68 (1986)*
- *(I. Sick and D. Day, Phys. Lett B 274, 16 (1992))*

- For A>12, the nuclear density distribution has a common shape; constant in the nuclear interior (bulk)
  → ***Scale with A***
- Nuclear surface contributions grow ***as*** $A^{2/3}$ (R^2)
- σ per nucleon would be constant with small deviations that go with $A^{-1/3}$

Both driven by a similar underlying cause?

$A^{-1/3}$



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- Nuclear surface contributions grow ***as*** $A^{2/3}$ (R^2)
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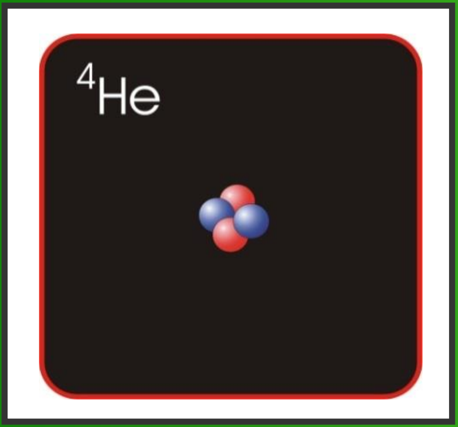
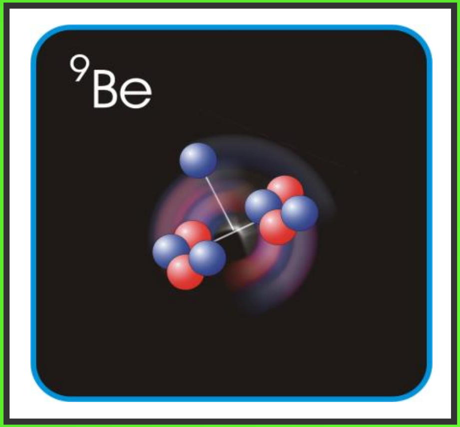
Two Hypotheses

1. Both quantities reflect ***virtuality*** of the nucleons (*L. Weinstein et al, PRL 106:052301,2011*)
   - 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 R_{2N}
     – measure of correlated pairs relative to the deuteron
   - EMC effect samples ***all*** the nucleons, whereas R_{2N} is only sensitive to *np* pairs, a subset of all possible NN configurations



The data show a weak preference for "local density" hypothesis



SRCs and EMC effect

- SRC ratios (via measurements of high momentum nucleon) probe NP pairs
- In N>Z nuclei, protons are more likely to be paired up than neutrons
- If related to EMC effect, ***u*** quark modification might be greater than that of ***d*** quarks

$$n_p^A(p) \approx \frac{1}{2x_p} a_2(A,y) n_d(p)$$

$$n_n^A(p) \approx \frac{1}{2x_n} a_2(A,y) n_d(p)$$

$$x_p = \frac{Z}{A}$$

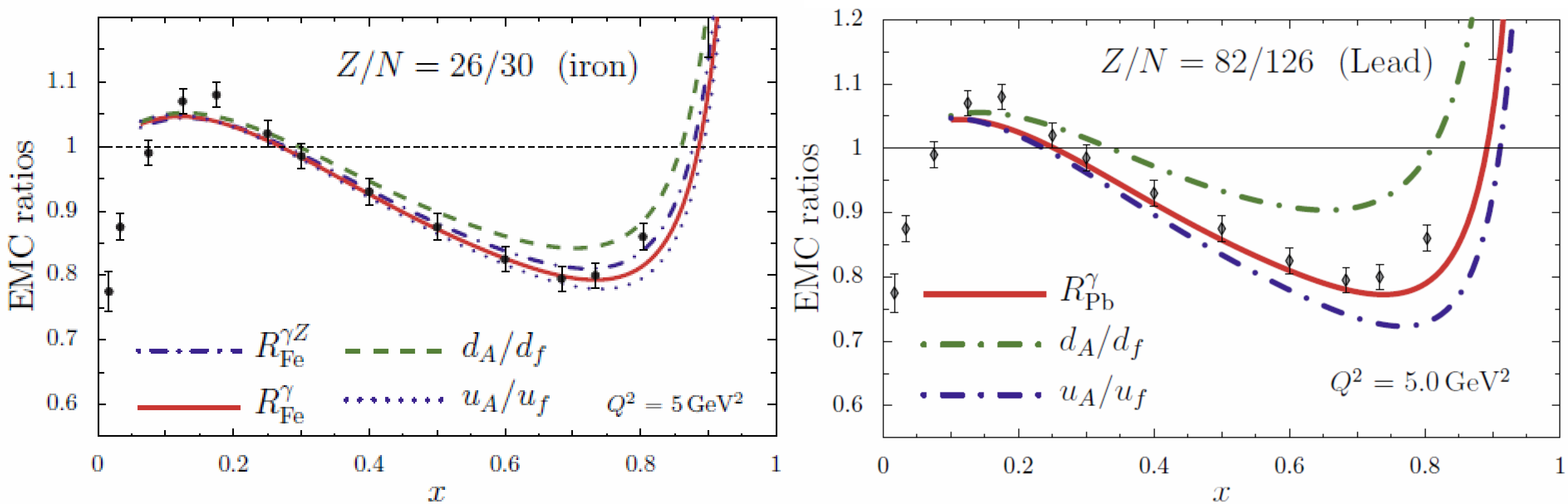
$$x_n = \frac{A-Z}{A}$$

M. Sargsian, arXiv:1209.2477 [nucl-th] and arXiv:1210.3280 [nucl-th]
O. Hen et al, Science 346 (2014)

Is EMC effect different for *p* and *n*?

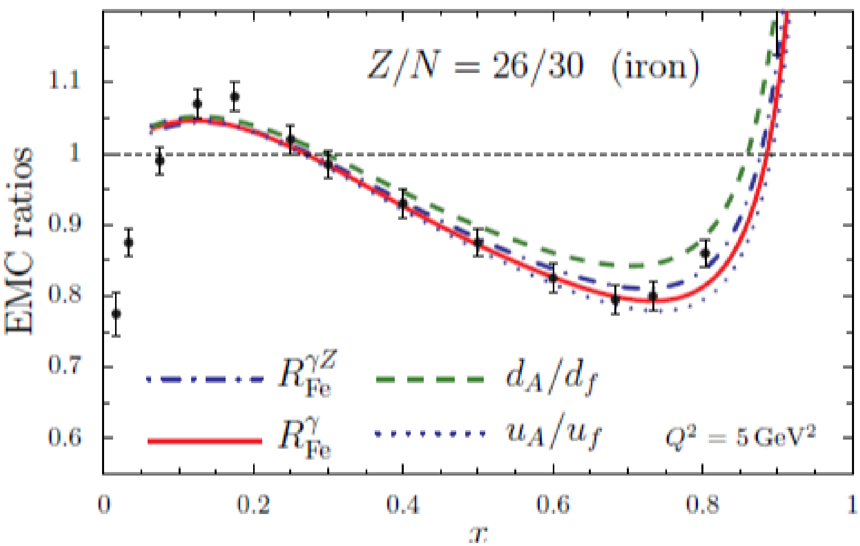
Isovector-vector mean field causes ***u (d)*** quark to feel additional vector attraction (repulsion) in $N \neq Z$ nuclei

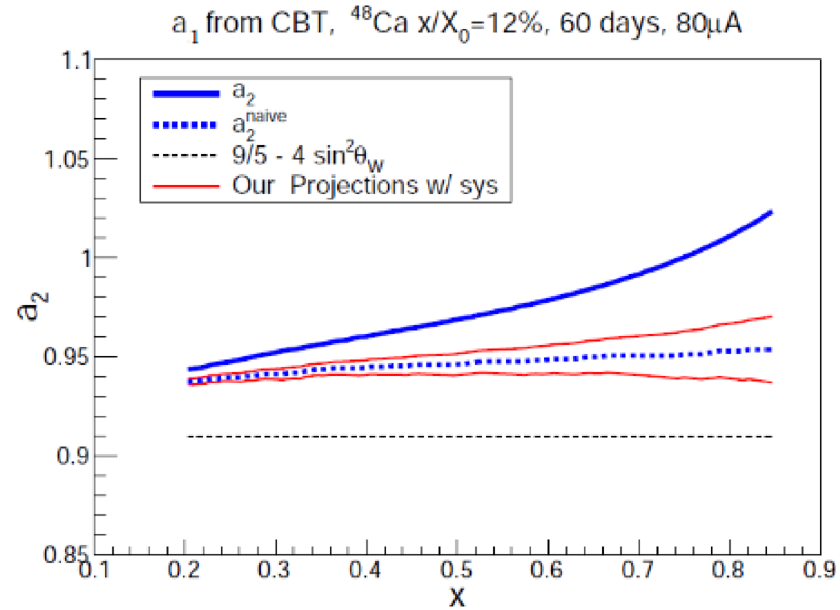
Has not been experimentally verified – can be probed in PV EMC effect



[I. Cloet, et al, PRL 109, 182301 (2012); PRL 102, 252301 (2009)]

Flavor Dependent Model EMC Predictions



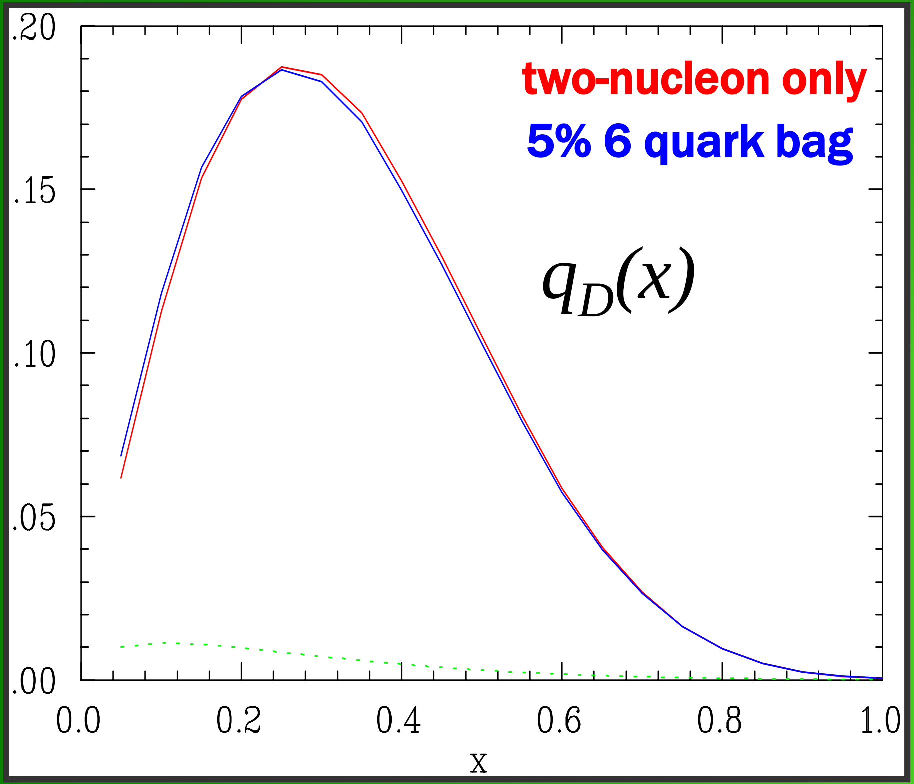


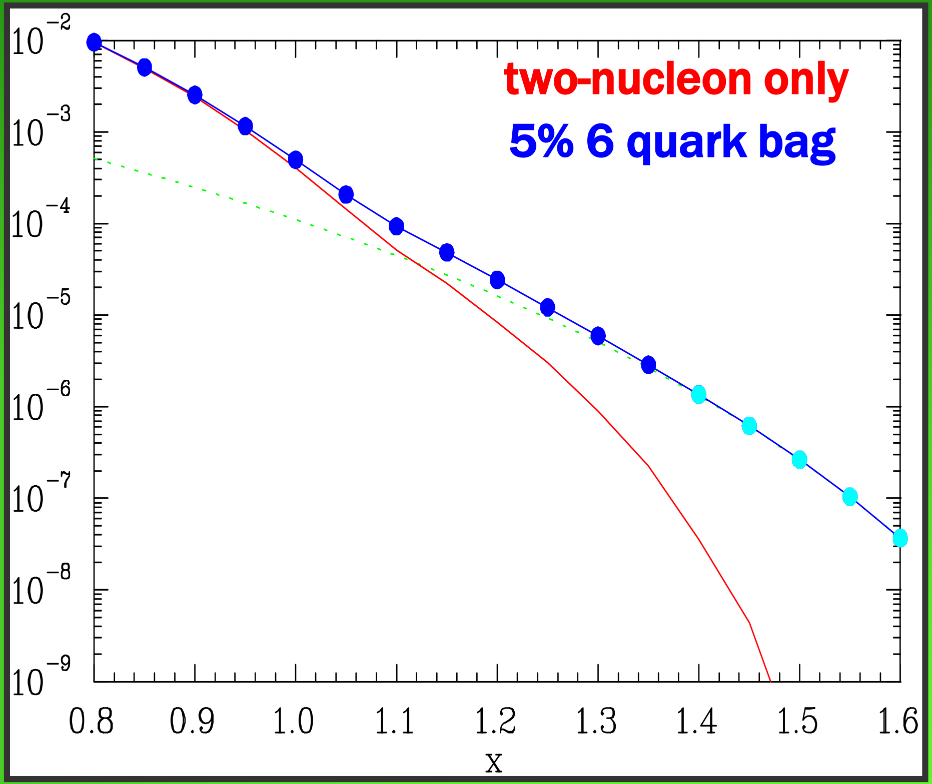
- PVDIS with neutron rich nuclei (^{48}Ca) can constrain possible flavor-dependent nuclear medium modification effects on quarks
  - PVDIS asymmetry is a direct measurement of differences in the quark flavors

$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+}$$

slide courtesy of Rakitha Beminiwattha

Another place to look: Overlapping nucleons → enhancement of F_2 structure function





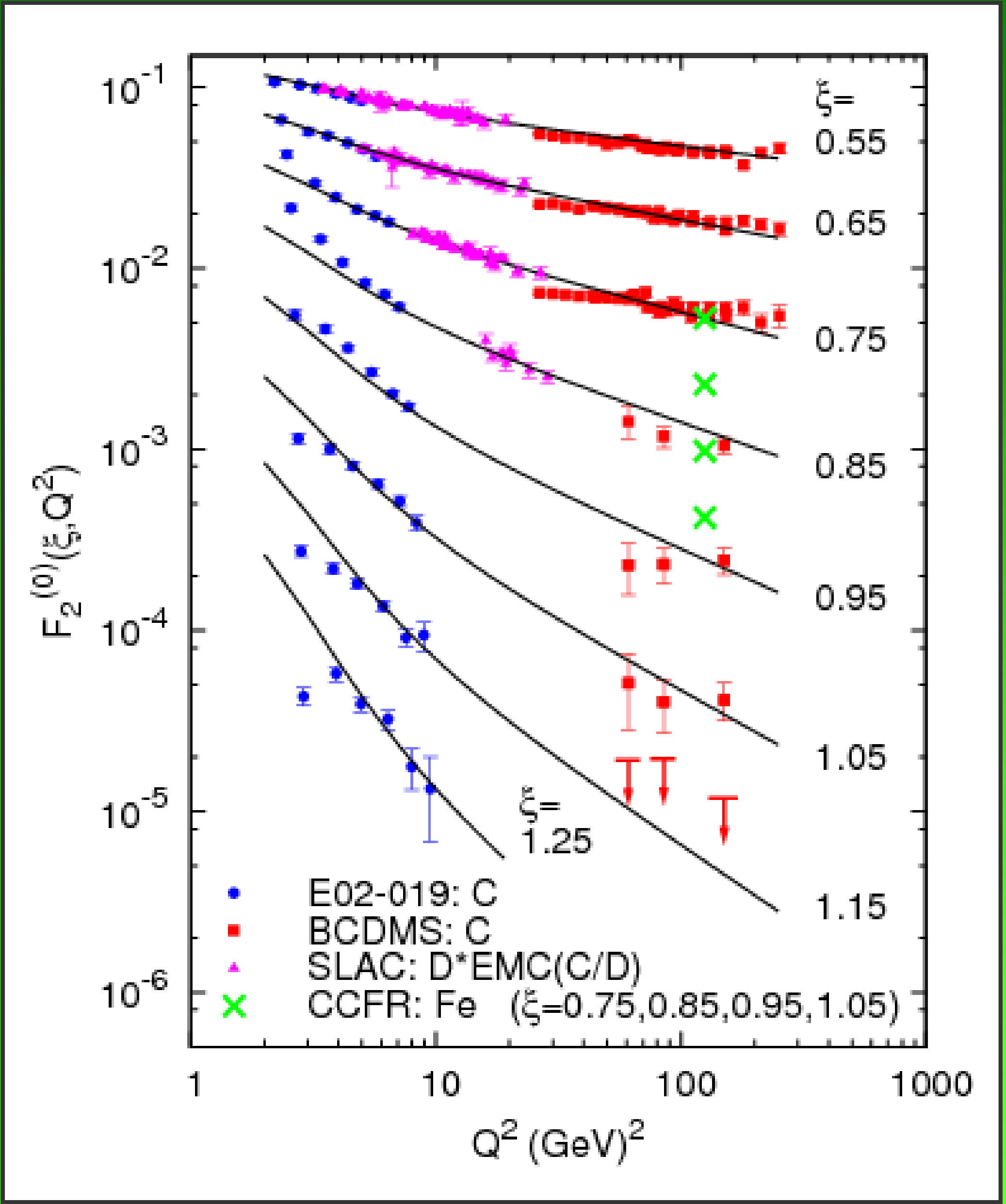
Small effect, possible contribution to EMC effect?

Noticeable effect at x>1

"Superfast" quarks

Current data at highest Q^2 (JLab E02-019) already sensitive to partonic behavior at x>1

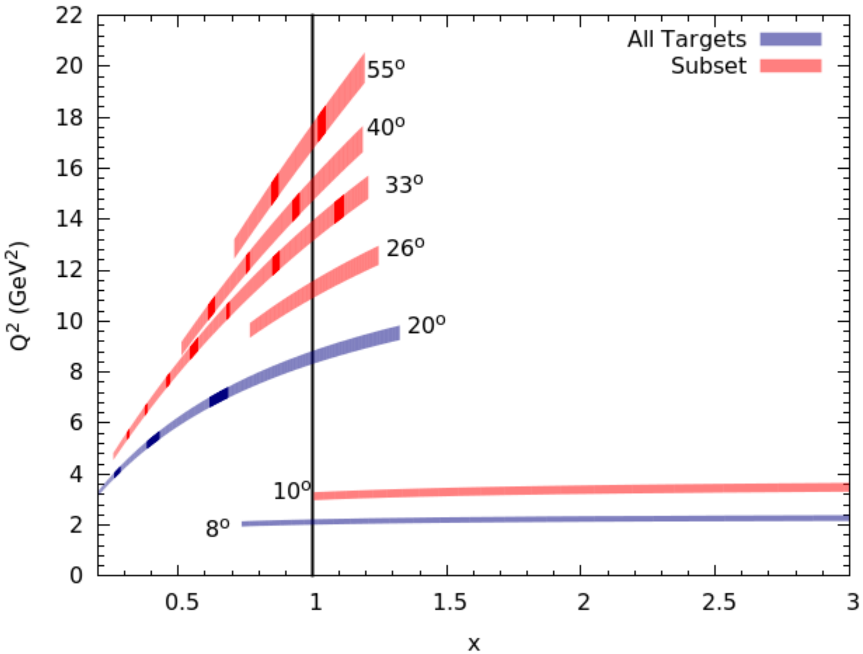
N. Fomin et al, PRL 105, 212502 (2010)



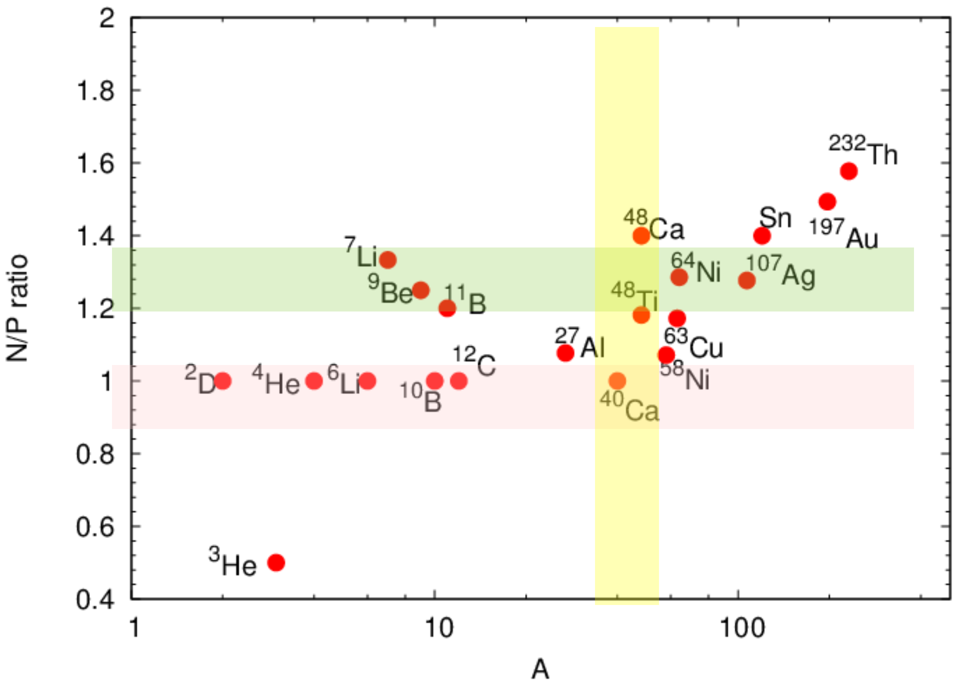
Upcoming Measurements

Detailed studies of the nuclear dependence of F_2 in light nuclei

[E12-10-008: J. Arrington, A. Daniel, NF, D. Gaskell]



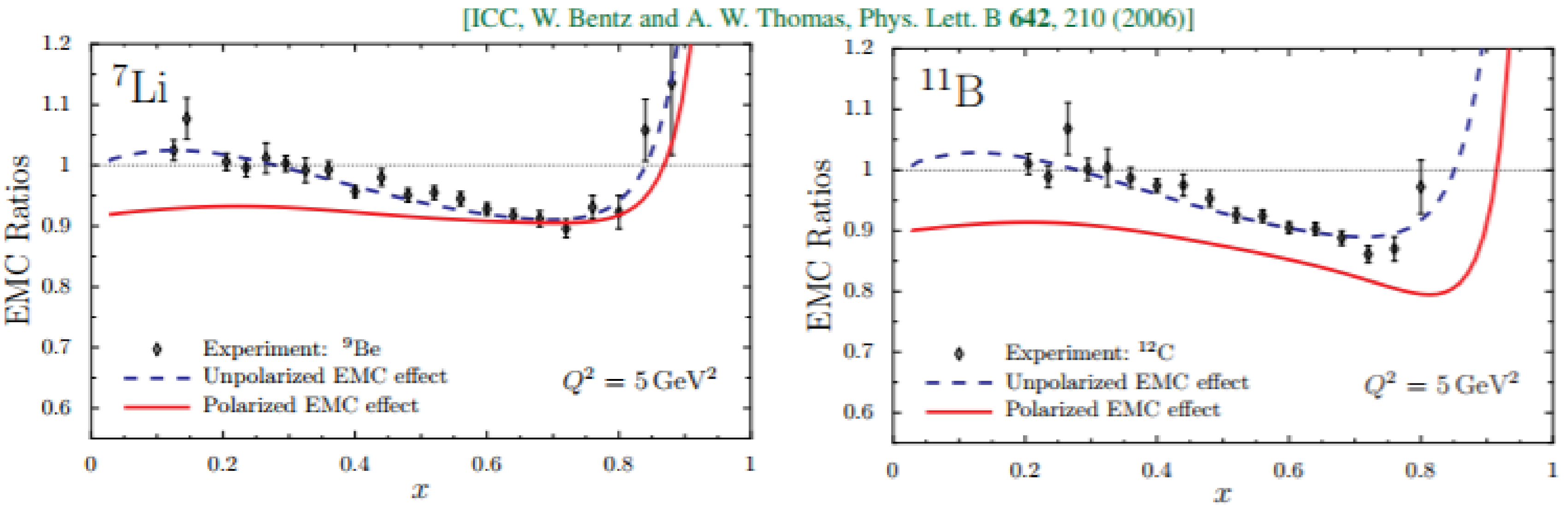
To run concurrently with inclusive x>1 (E12-06-105)



Coming soon to Hall C

The EMC effect in spin structure functions

[E12-14-001: Will Brooks and Sebastian Kuhn]



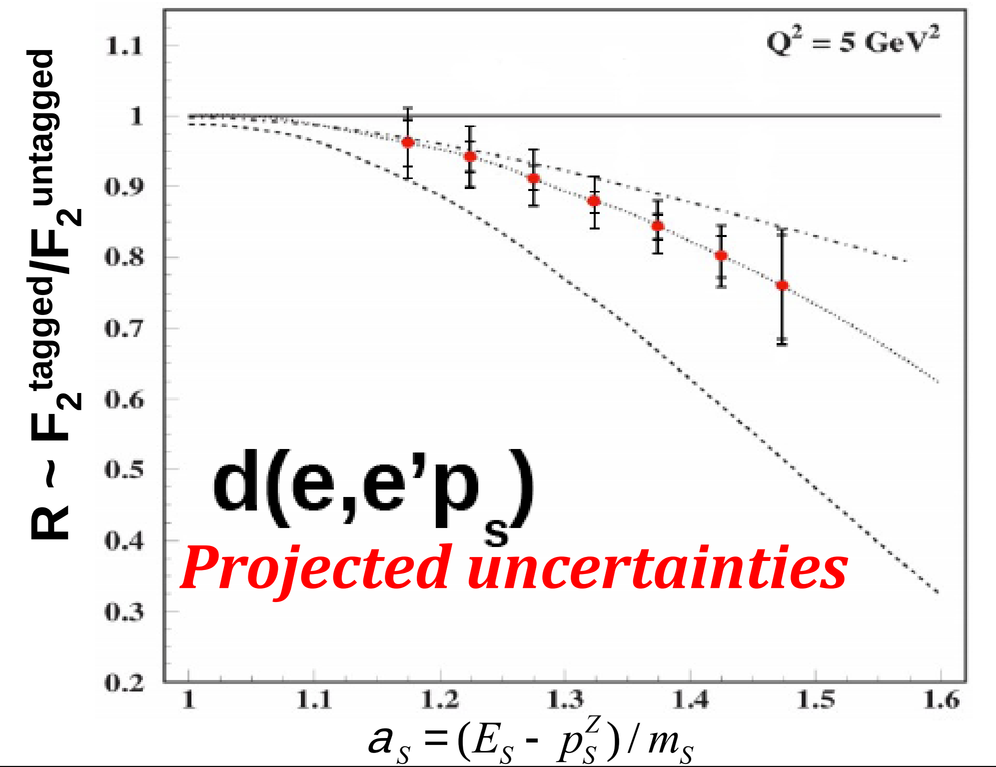
- A polarized EMC effect arises because in-medium quarks are more relativisitic
  - Lower components of quark wave functions are enhanced
  - Quark Spin is converted to orbital angular momentum
- Spin Dependent cross-section is suppressed by 1/A
- Experiment to measure spin structure functions of 7Li

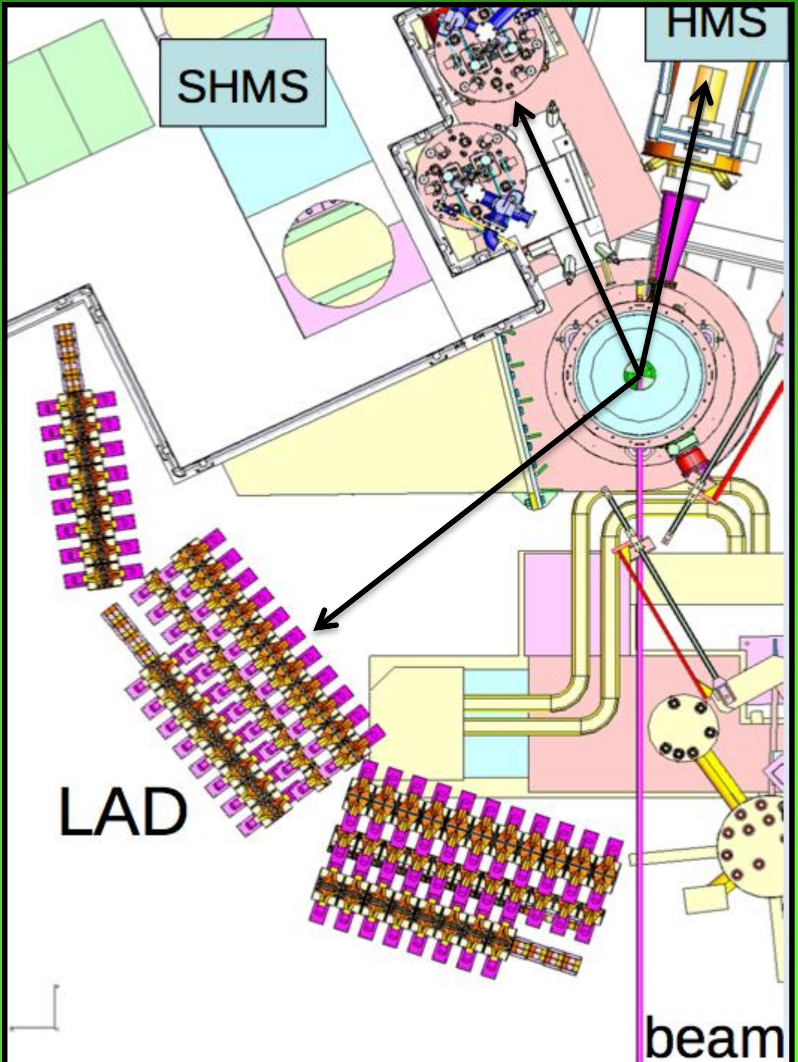
Slide after I. Cloet

In-Medium Nucleon Structure Functions

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

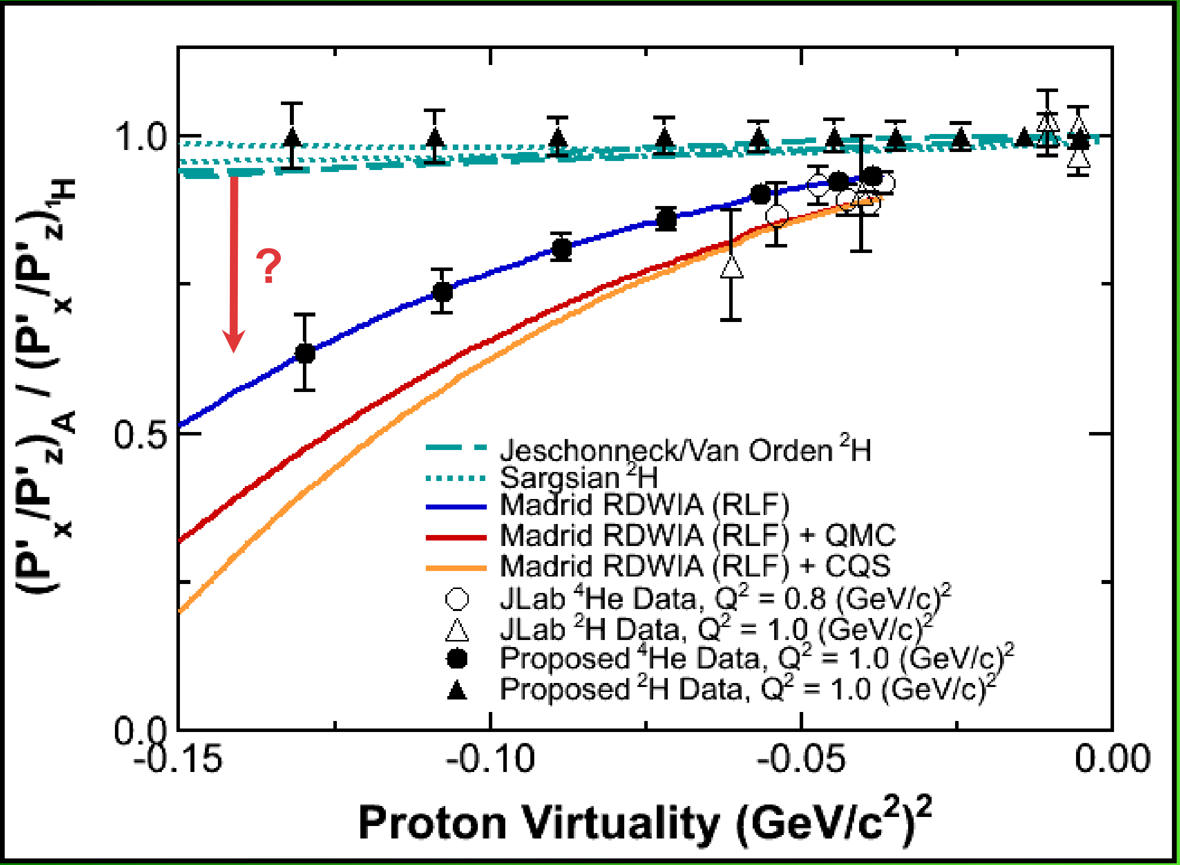
- **DIS scattering from nucleon in deuterium**
- **Tag high-momentum struck nucleons by detecting backward "spectator" nucleon in Large-Angle Detector**





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:** ***$^4He(e,e'p)^3H$*** **and** ***$^2H(e,e'p)n$***
- **Modern, rigorous $^2H(e,e'p)n$ 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

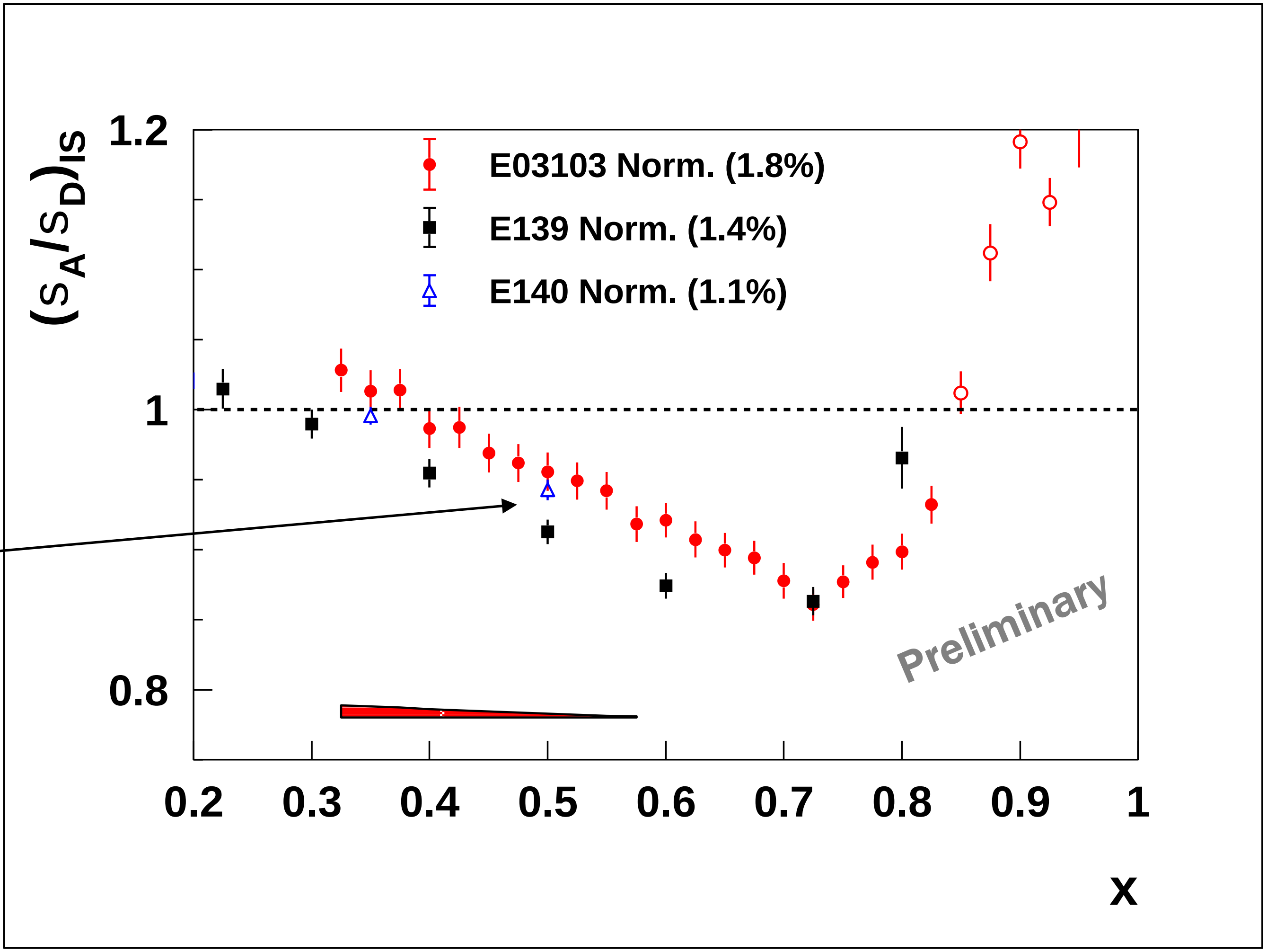
- After 30 years under the microscope, 6 GeV data offers a suggestion for more targeted studies of the EMC effect
- 12 GeV experiments continue the search
- New results in the next few years!

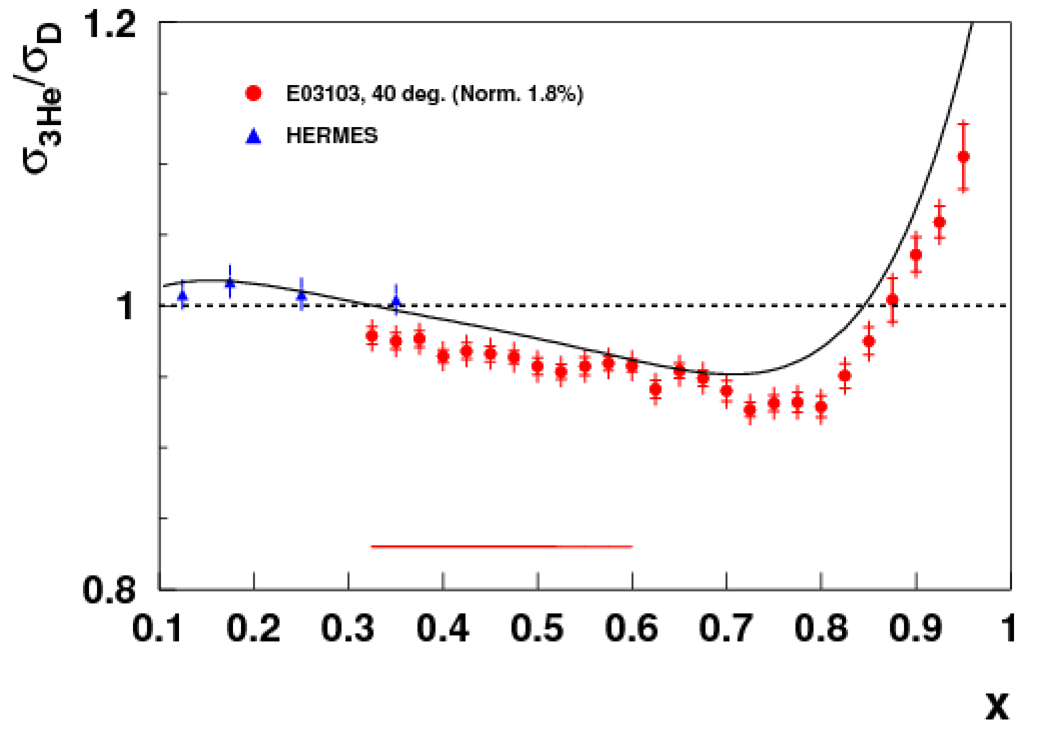
EMC Effect in Heavy Nuclei - Cu

All data sets corrected for coulomb distortion (E139/E140 did not include in published results)

Some tension between E03103/E140 and E139 results

Potential nuclear dependence of *R*? → See Simona Malace's talk





E03103, 40 deg. (Norm. 1.8%)
HERMES
1.2
1
0.8
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x