EMC Effect and SRC Results from Jefferson Lab

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HiX2014

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Jefferson Lab

The EMC Effect

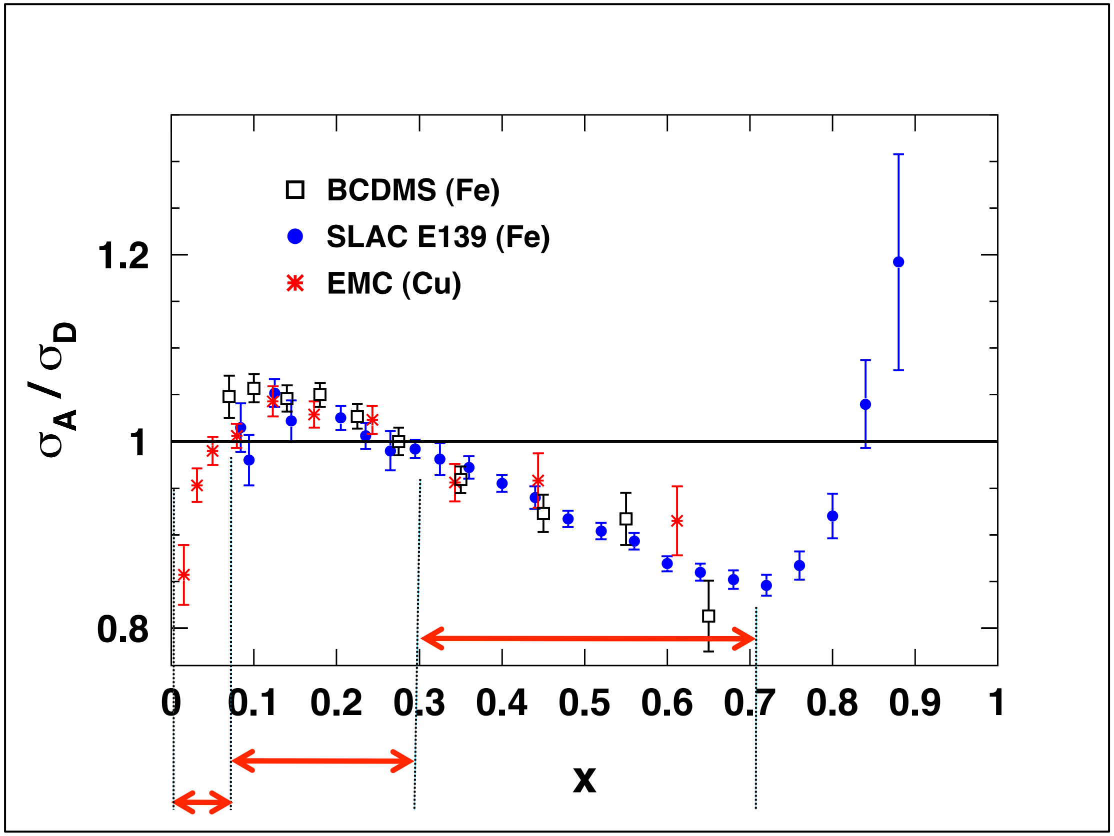
1983: First observation of the modification of inelastic structure functions in nuclei

→ Thirty years of measurements of inclusive lepton scattering from nuclei have shown definitively that quark distributions are modified in nuclei.

The atomic nucleus is not simply an incoherent sum of protons and neutrons

$\sigma_A/\sigma_D = F_2^A/F_2^D$

$$F_2(x) = \sum_i e_i^2 x q_i(x)$$

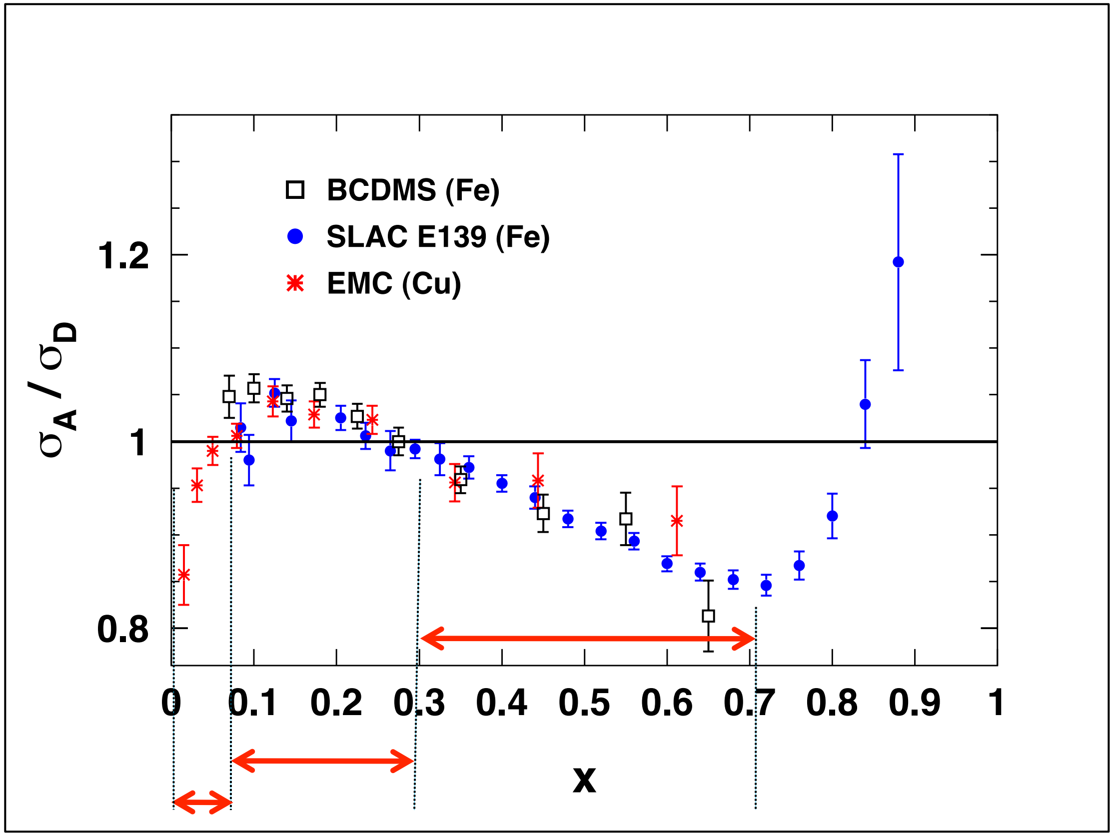


The EMC Effect

A huge theoretical and experimental effort has been expended in attempts to understand the origin of the EMC effect

Properties of the EMC effect:

1. Shape appears to be more or less universal
2. Small or no Q^2 dependence
3. *Size of the effect at large x increases with A*



EMC Effect Models

Early attempts to model the EMC effect included the “known” nuclear structure via the Fermi gas model, or some other mean field model

→Convolution calculations, combined with nuclear binding effects

→Introduction of non-nucleonic degrees of freedom → “Nuclear pions”

Other explanations rely on direct modification of nucleon structure or other “exotic” configurations

→Dynamical rescaling

→Multiquark clusters – 6 quark, 9 quark bags
→Quark-meson coupling inspired models

Recently, efforts have been made to start from the “best” nuclear structure information available (realistic wave functions beyond mean field, pion contributions constrained by Drell-Yan) *Kulagin and Petti NPA 765, 126 (2006*)

→ *Helps separate the “interesting” part of the EMC effect from regular “nuclear physics”*

Nuclear Dependence of the EMC Effect

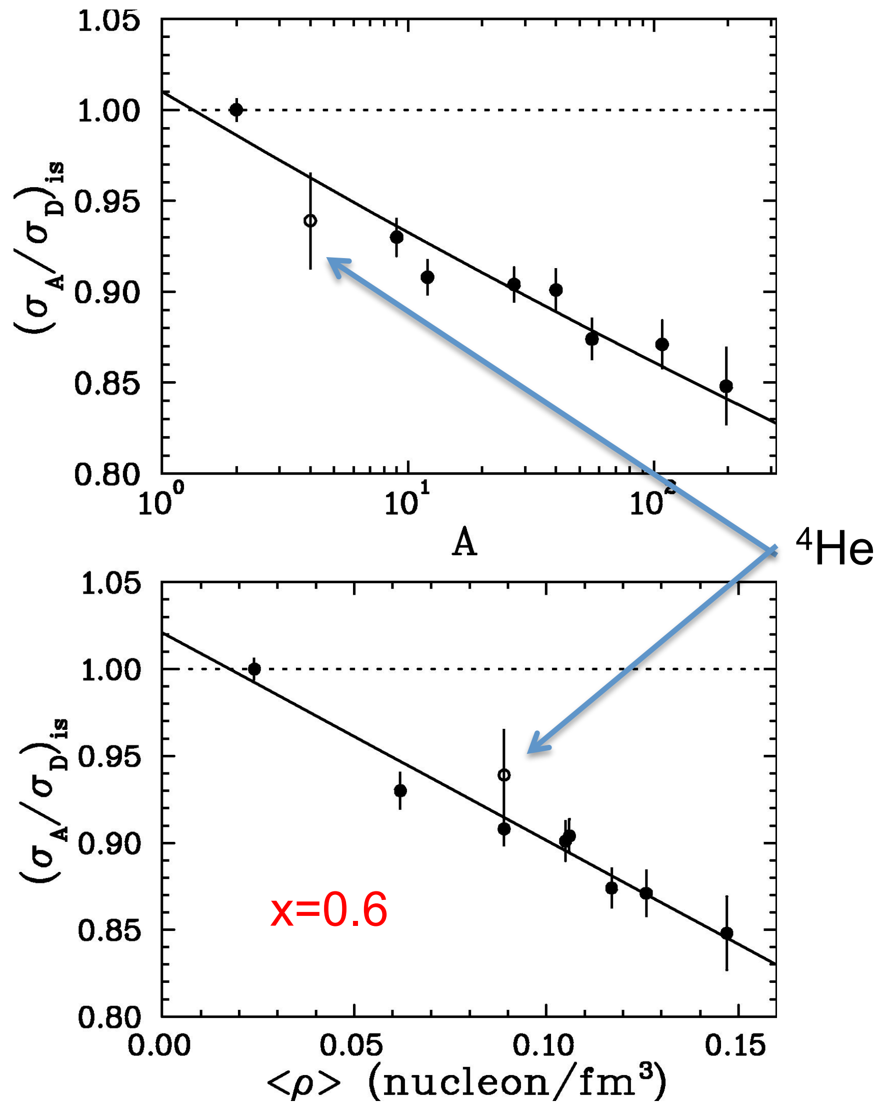
SLAC E139 studied the nuclear dependence of the EMC Effect at fixed *x*

Results consistent with
→Simple logarithmic A dependence
→Average nuclear density*

**uniform sphere with radius R_e,*
$R_e^2 = 5/3 <r^2>$ → charge radius of nucleus

Many models of the EMC effect either implicitly or explicitly assume the size of the EMC effect scales with average nuclear density

→ Constraining form of nuclear dependence can confirm or rule out this assumption



Gomez et al, PRD 49, 4348 (1994)

JLab Experiment E03-103

Measurement of the EMC Effect in light nuclei (^{3}He and ^{4}He) and at large *x*

→ ^{3}He, ^{4}He amenable to calculations using "exact" nuclear wave functions

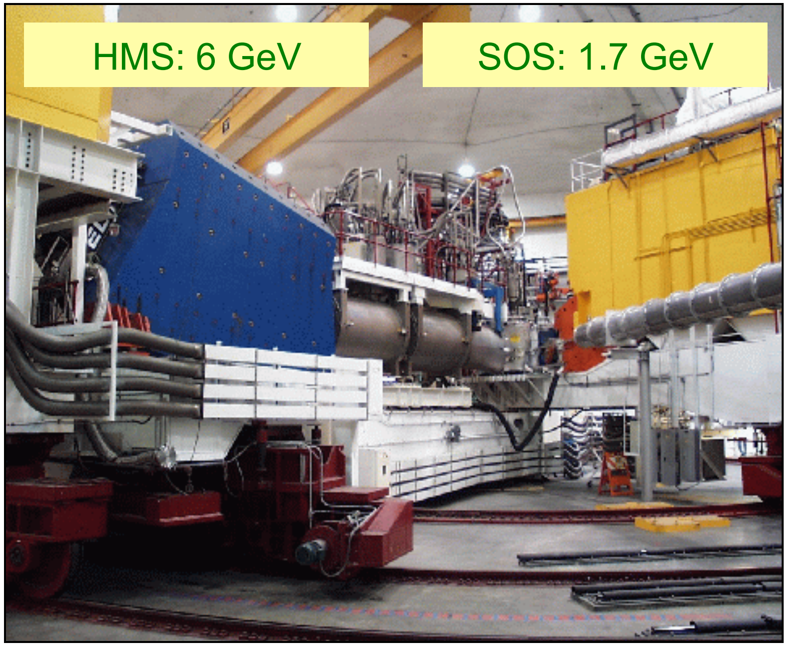
→ Large *x* dominated by binding, conventional nuclear effects

A(e,e') at *5.77* GeV in Hall C at JLAB (with E02-019, *x>1*)

Targets: H, ^{2}H, ^{3}He, ^{4}He, Be, C, Cu, Au

Six angles to measure Q^2 dependence

Spokespersons: DG and J. Arrington
Graduate students: J. Seely and A. Daniel

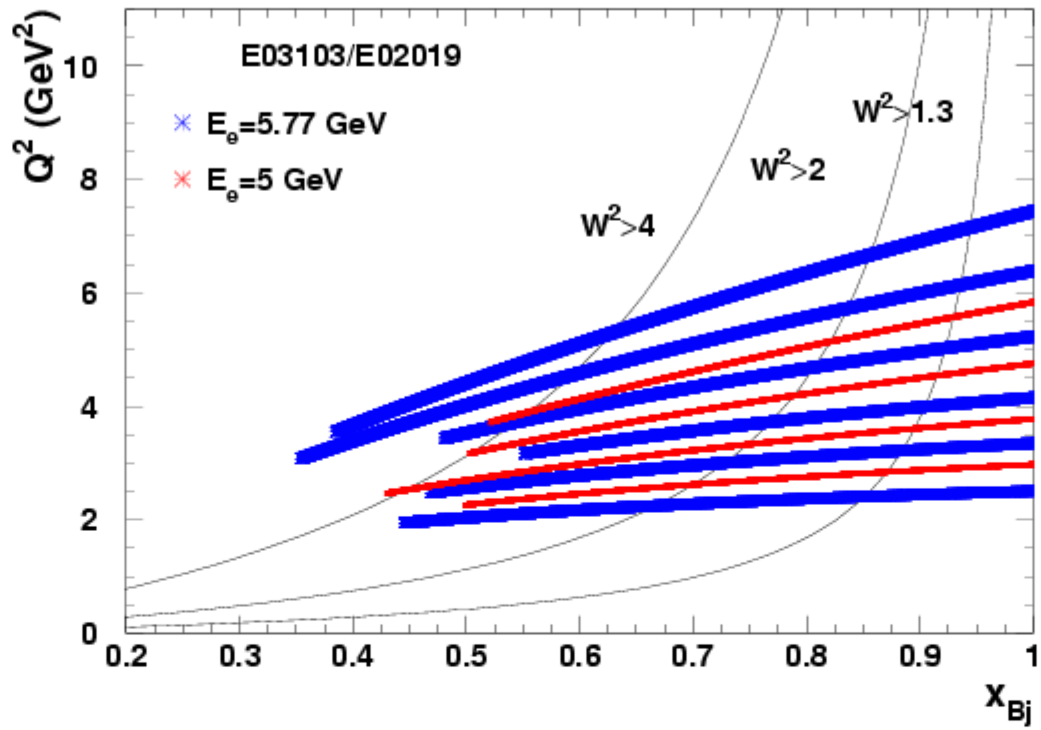


Deep Inelastic Scattering at low W

Canonical DIS regime:

$Q^2 > 1\ GeV^2$ ***AND***
$W^2 > 4\ GeV^2$

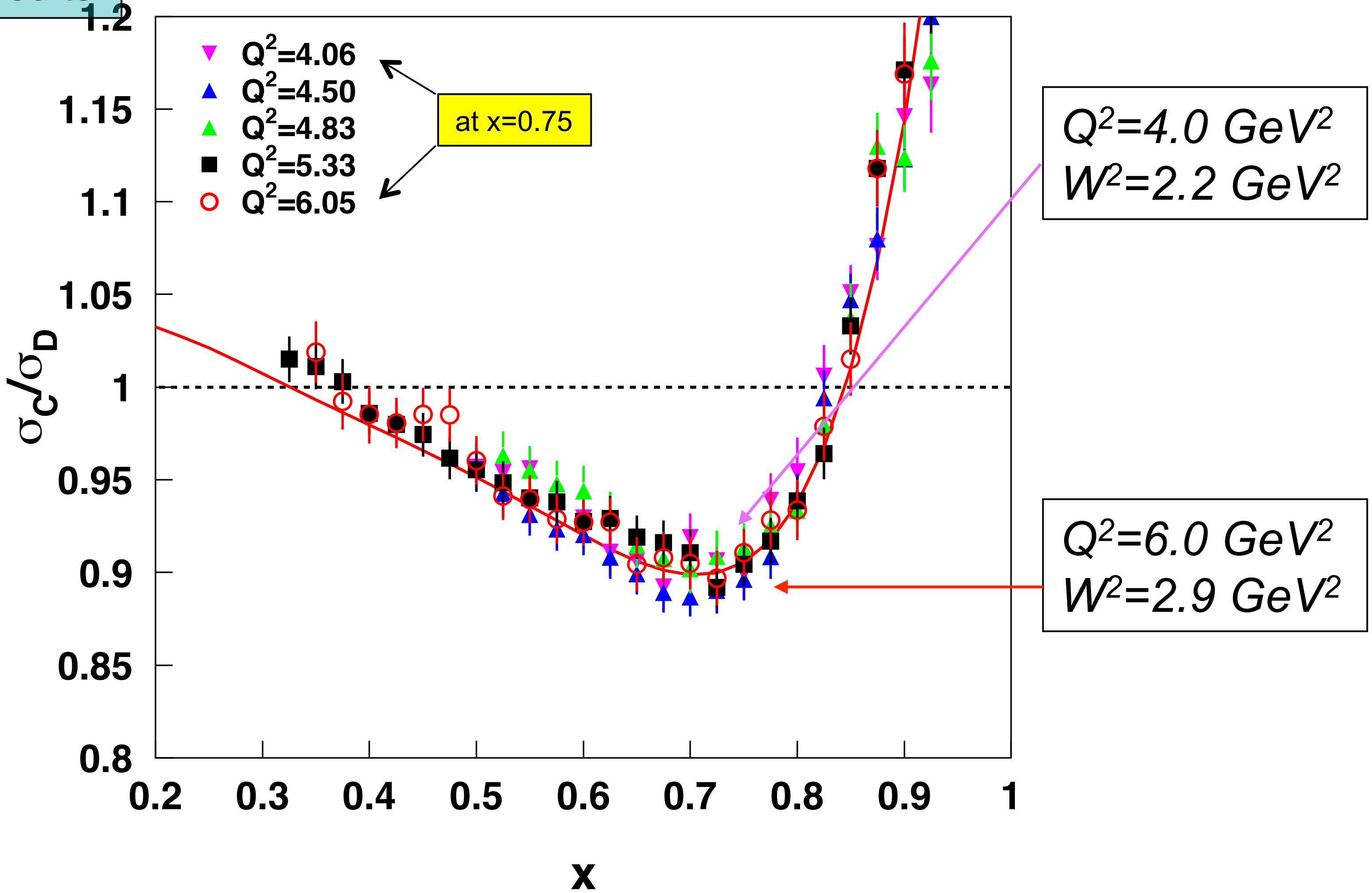
→ Scattering from "quarks" in the nucleon or nucleus



- At JLab (6 GeV), we have access to large Q^2, and $W^2>4$ GeV^2 up to $x=0.6$
- At $x>0.6$, we are in the "resonance region" → excited, bound states of the nucleon, but Q^2 is still large
- Are we really sensitive to quarks in this regime?

Carbon/^{2}H Ratio and Q^2 Dependence

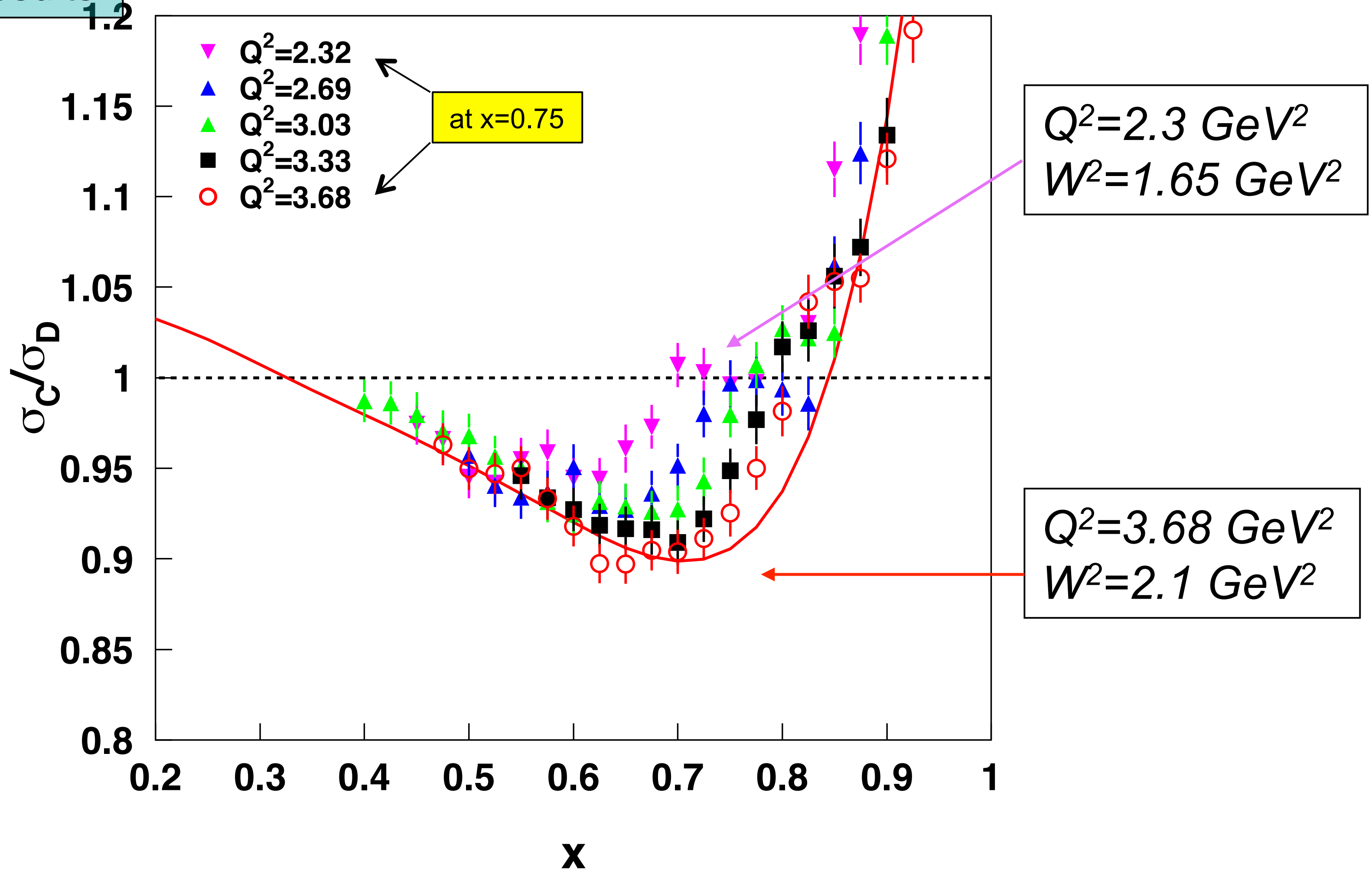
E03-103 Results



At larger angles (Q^2) the ratio appears to scale to very large x
→ W^2>2 GeV^2 and Q^2>3 GeV^2

Carbon/^{2}H Ratio and Q^2 Dependence

E03-103 Results



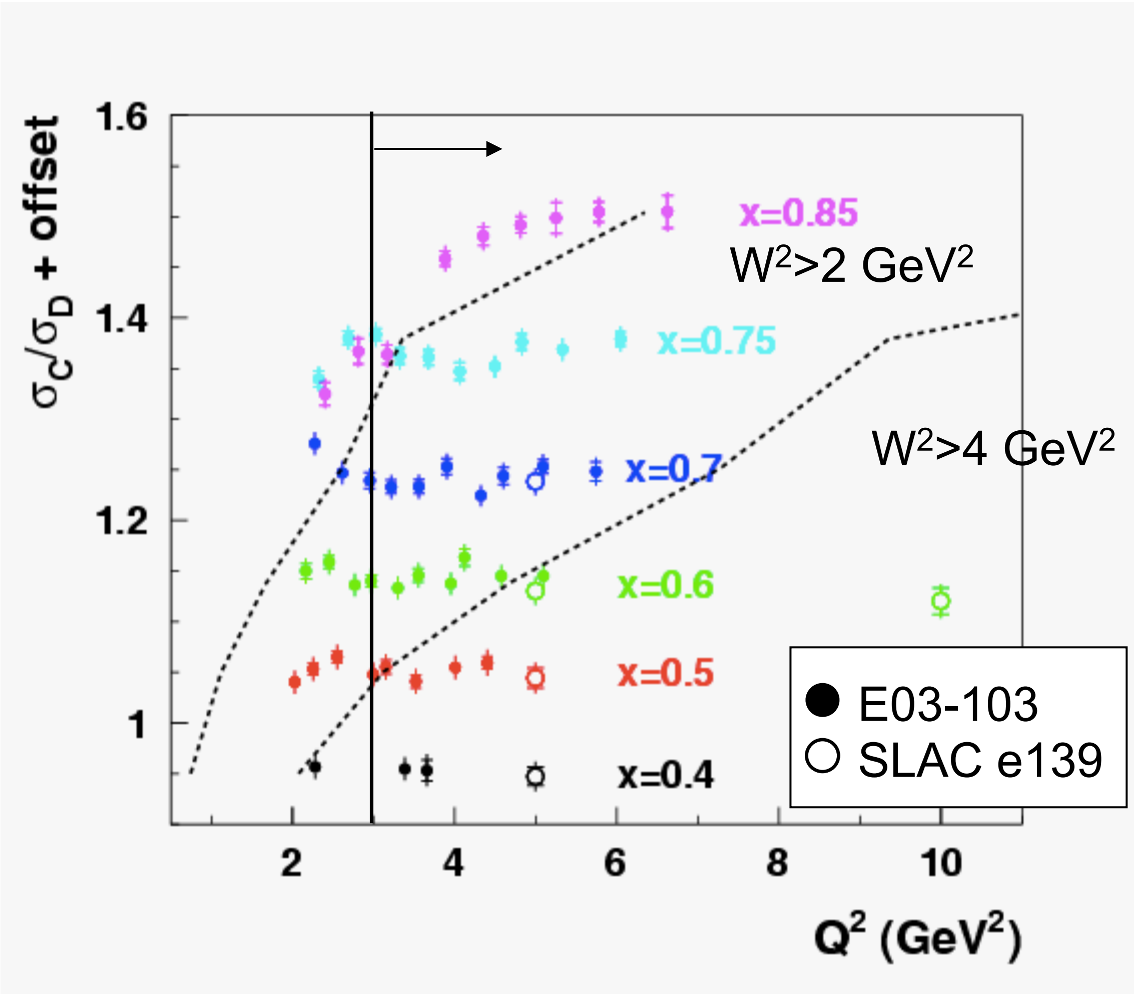
Clear deviation from scaling at W^2<2.2 GeV^2

More detailed look at scaling

C/D ratios at fixed *x* are Q^2 independent for

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

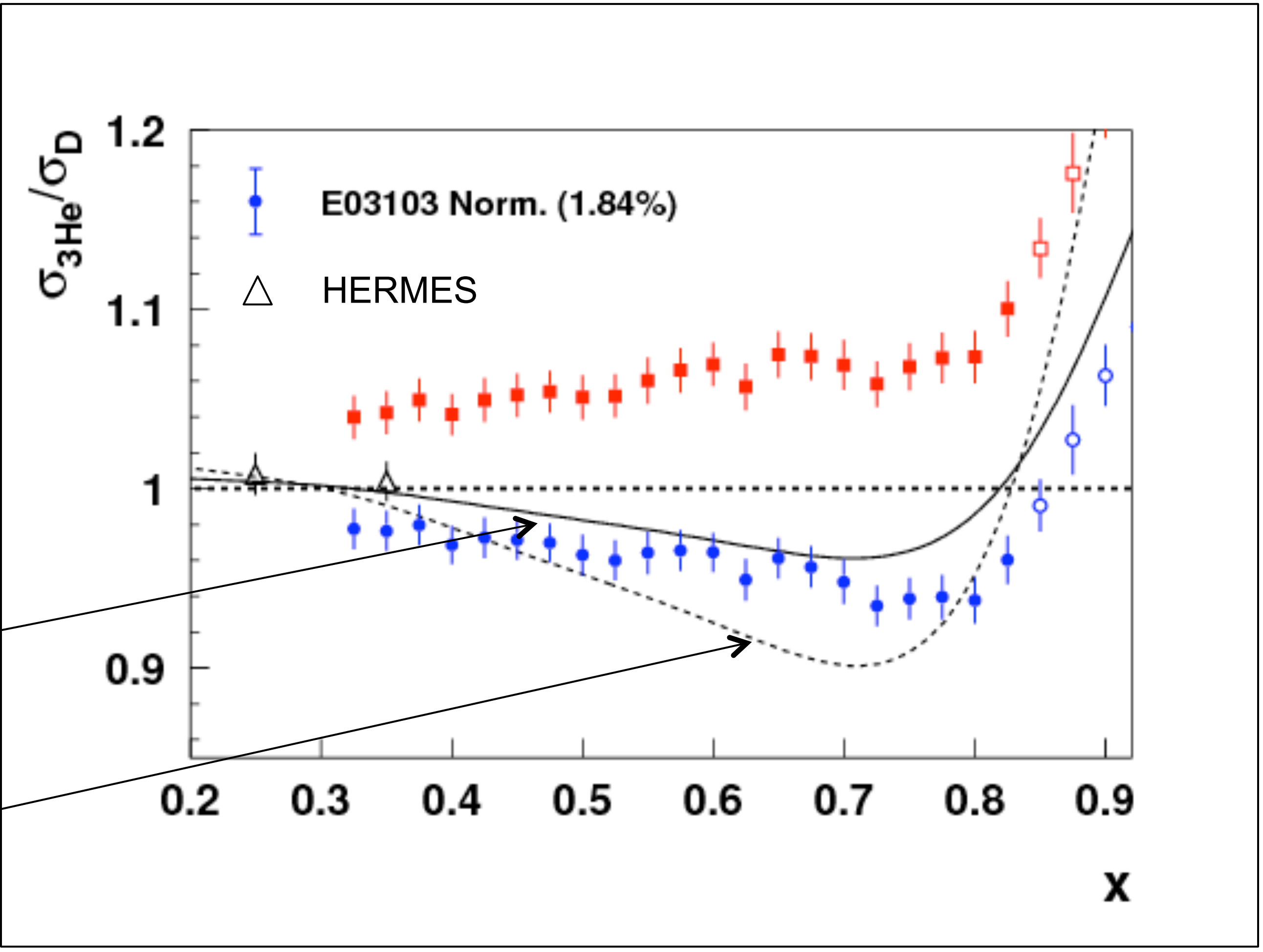
For E03-103, this extends to x=0.85



EMC Effect in ^{3}He

Large correction due to "proton excess"

Note: HERMES data has been renormalized by 1.009 → NMC



SLAC fit; A=3

SLAC fit; A=12

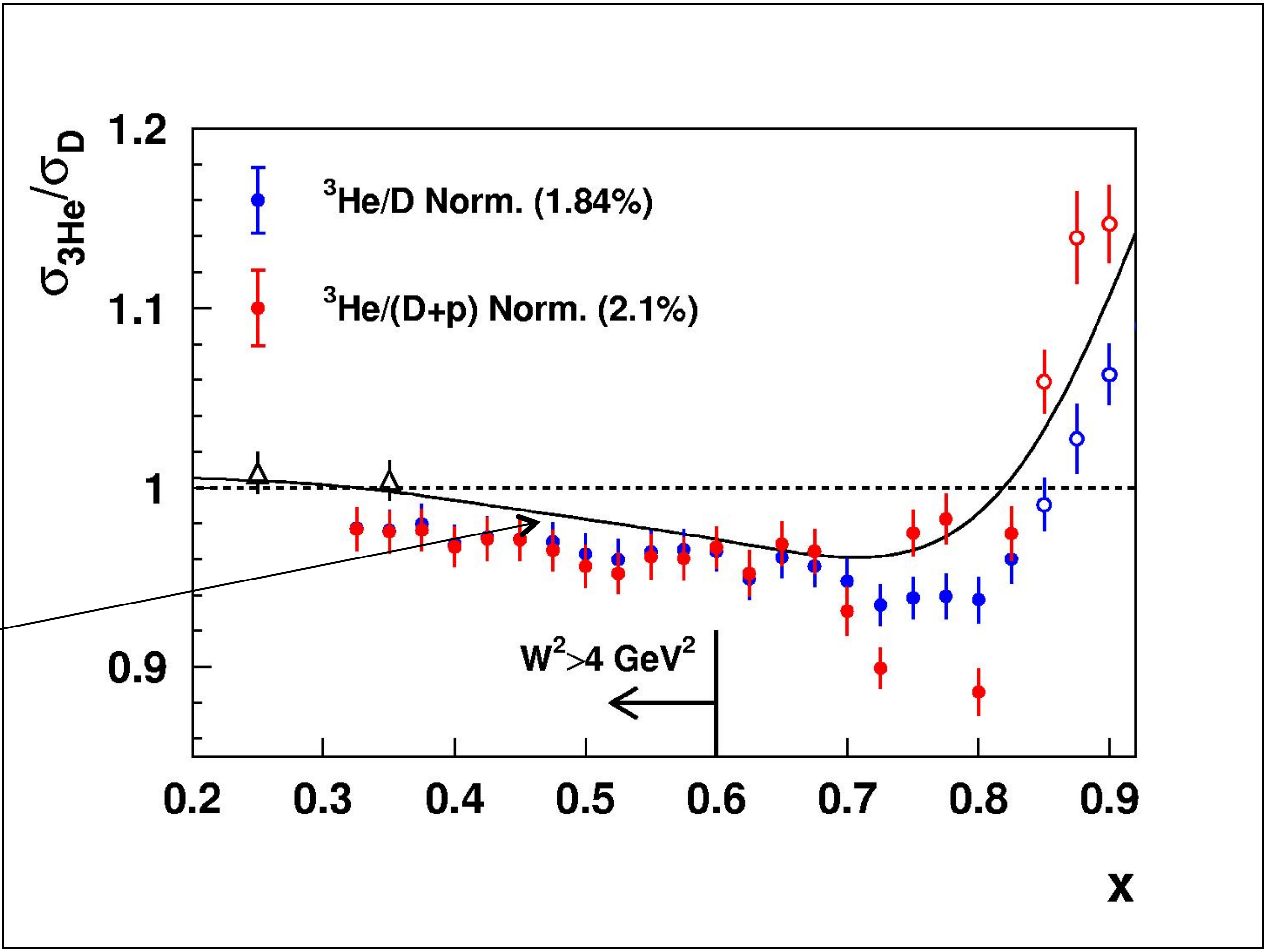
J. Seely et al, *PRL 103, 202301 (2009)*

EMC Effect in ^{3}He

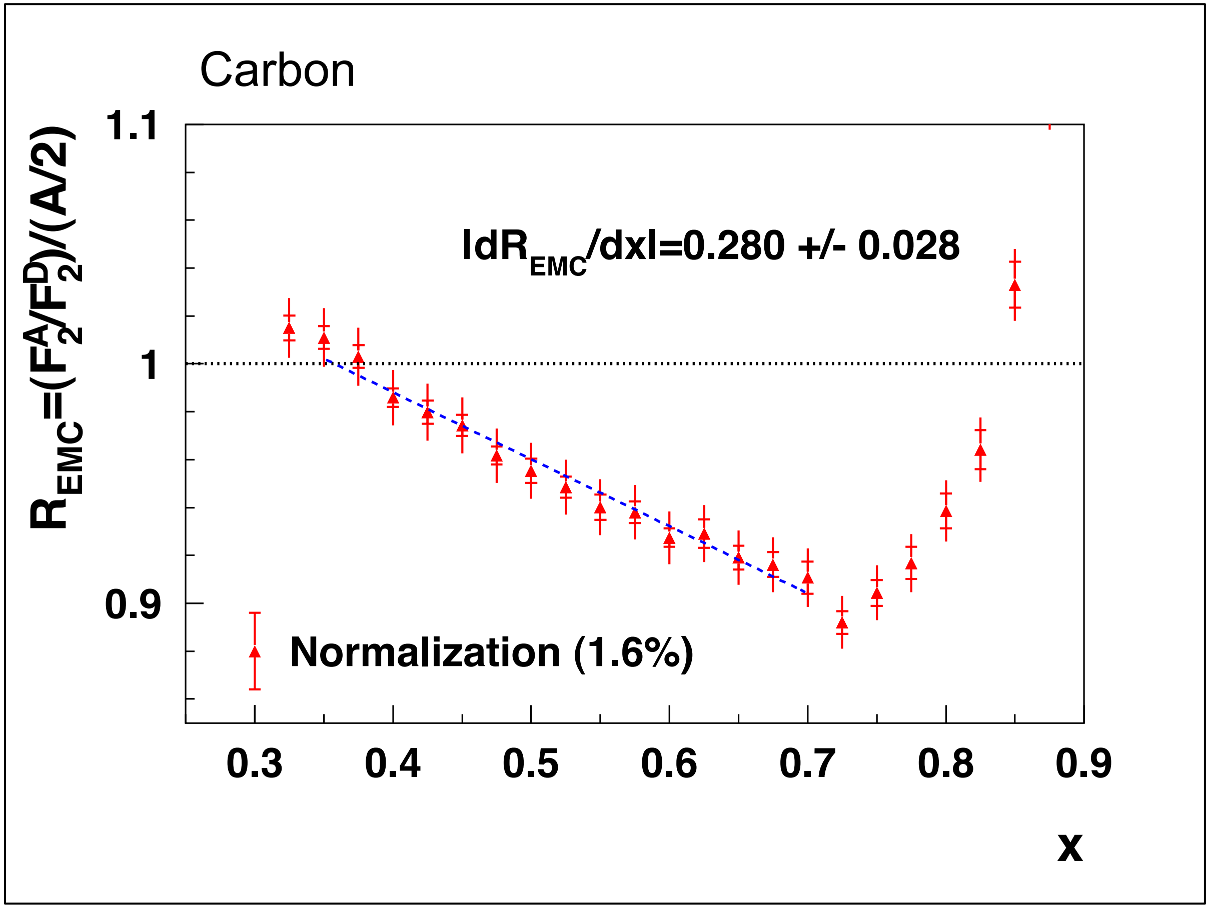
Large correction due to “proton excess”

→ Test validity of isoscalar correction using ^{3}He/(D+p) for x<0.6

SLAC fit; A=3



JLab E03103 and the Nuclear Dependence of the EMC Effect



New definition of "size" of the EMC effect

→Slope of line fit from x=0.35 to 0.7

Assumes shape is universal for all nuclei

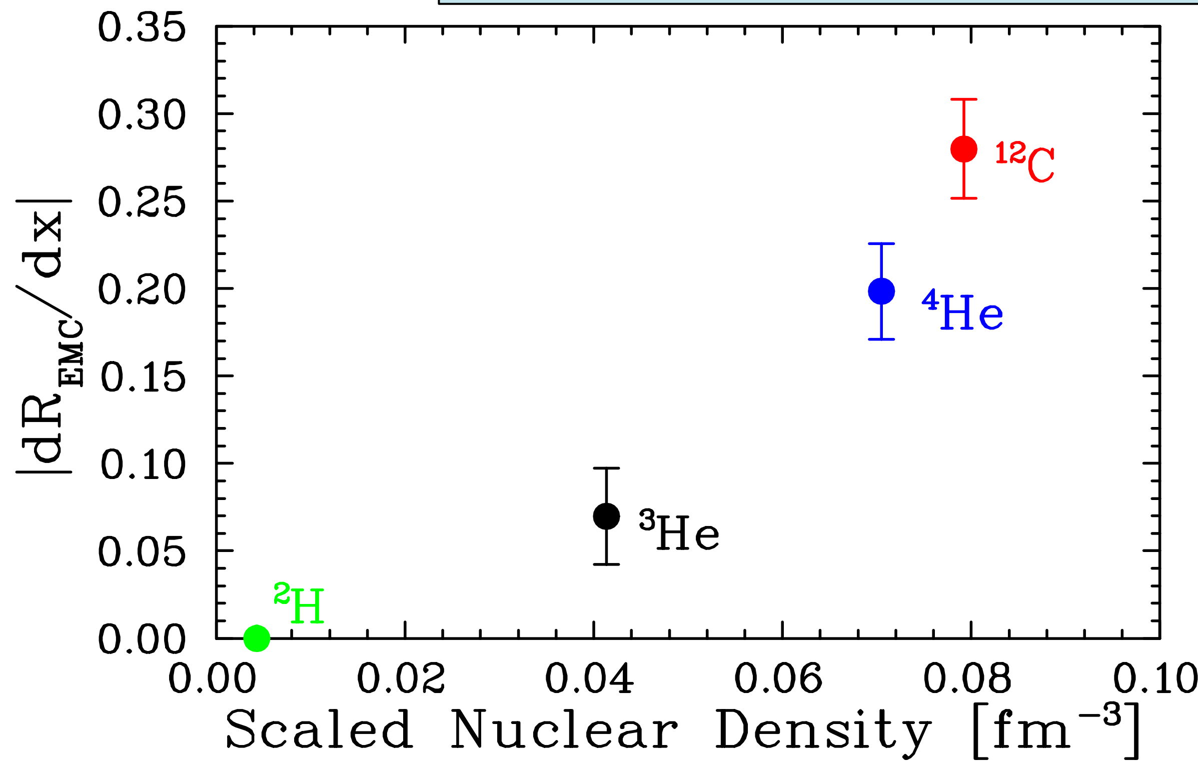
→Normalization uncertainties a much smaller relative contribution

→Measured EMC ratios for light nuclei (^{3}He, ^{4}He, Be, and C)
→Results consistent with previous world data
→Examined nuclear dependence a la E139

JLab Results – Light Nuclei

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

→ ^{3}He, ^{4}He, C, EMC effect scales well with density



Scaled nuclear density = *(A-1)/A <ρ>*
→ remove contribution from struck nucleon

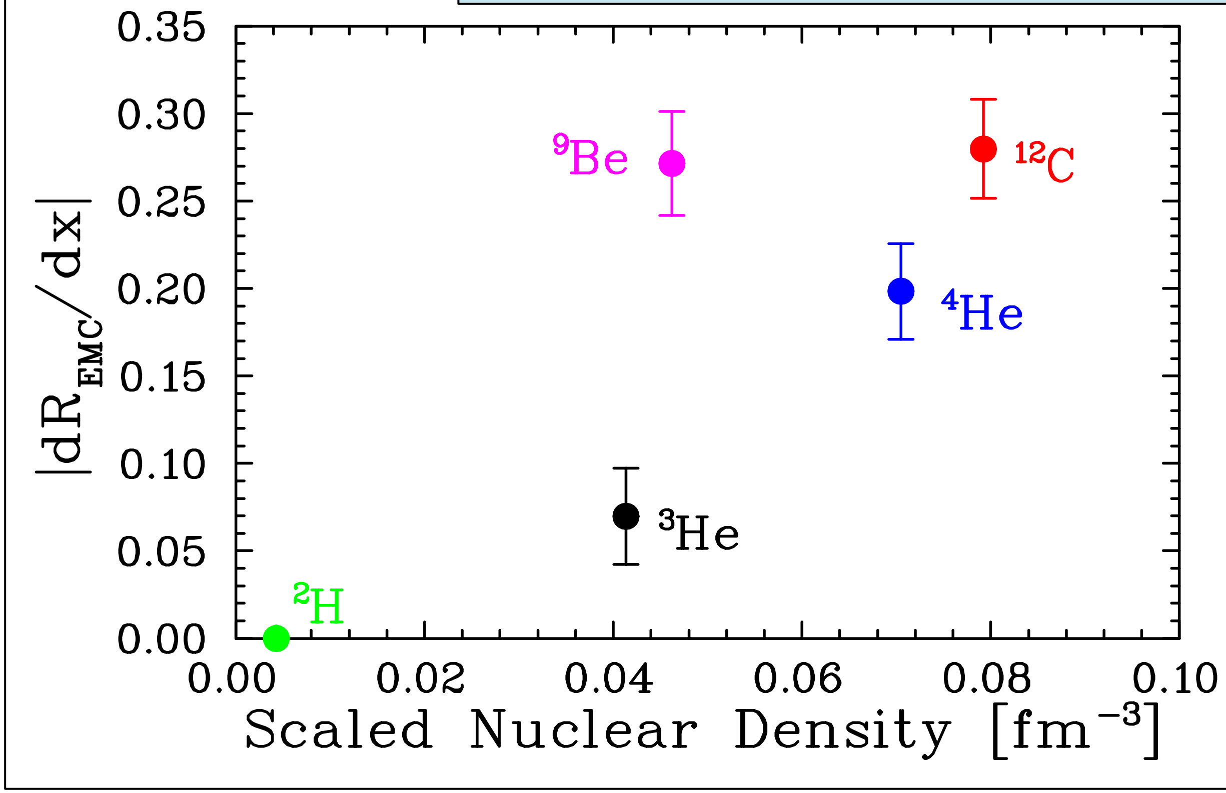
<ρ> from ab initio few-body calculations
→ ***[S.C. Pieper and R.B. Wiringa,*** *Ann. Rev. Nucl. Part. Sci 51, 53 (2001)]*

JLab Results – Light Nuclei

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

→^{3}He, ^{4}He, C, EMC effect scales well with density

→***Beryllium does not fit the trend***



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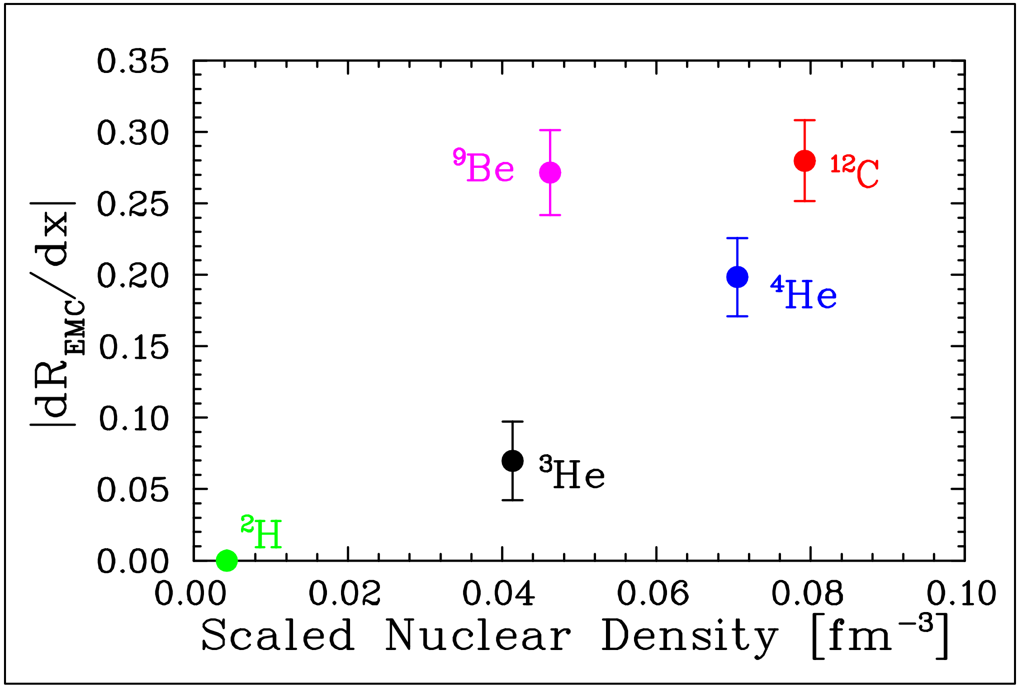
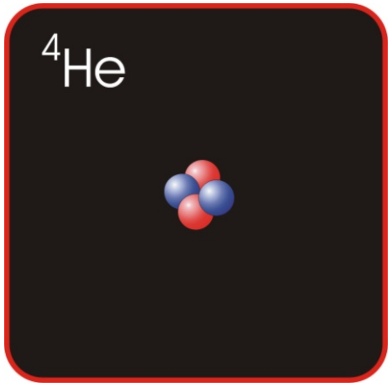
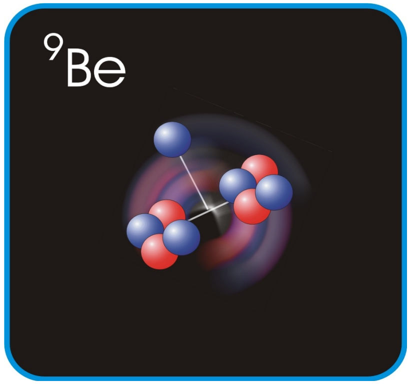
EMC Effect and Local Nuclear Density

^{9}Be has low *average* density
→ Large component of structure is ***2α+n***
→ Most nucleons in tight, *α*-like configurations

EMC effect driven by ***local*** rather than *average* nuclear density







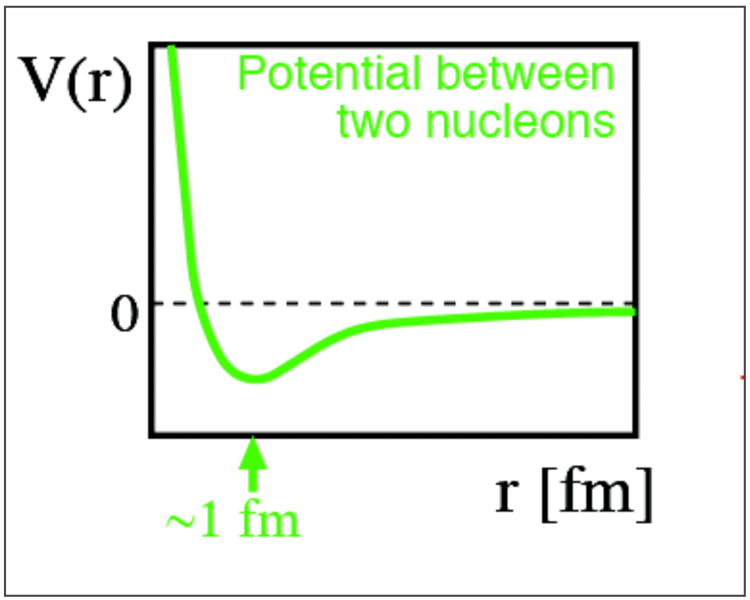
Are there other quantities sensitive or related to local density?

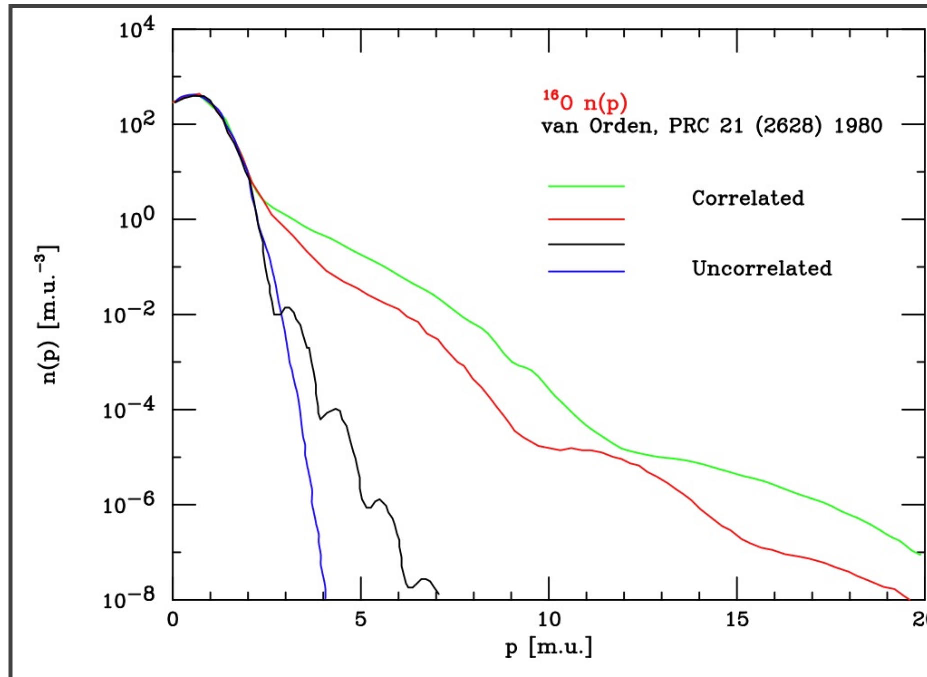
Credit: P. Mueller

Local Density → Short Range Correlations

What drives high "local" density in the nucleus?

Tensor interaction and short range repulsive core in NN potential lead to high momentum tail in nuclear wave function → correlated nucleons



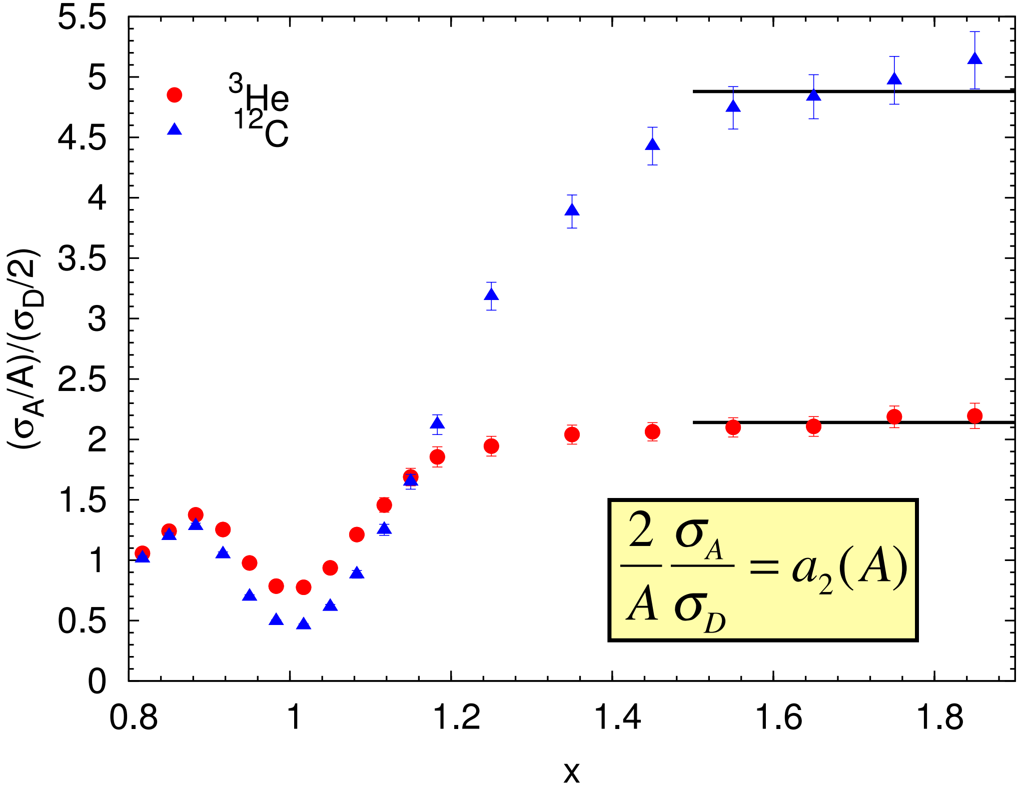


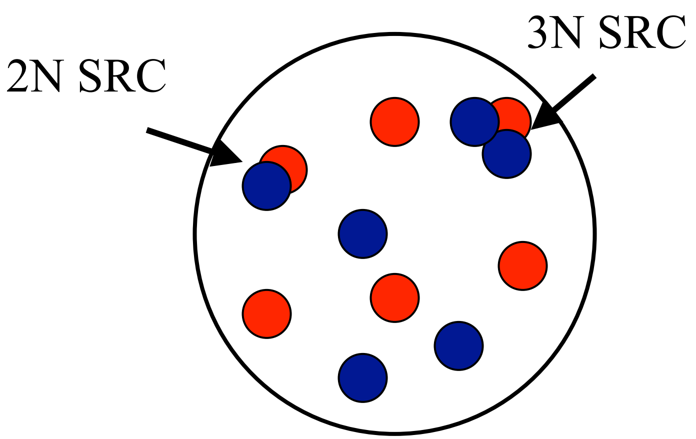
High momentum → short distance scales
SRCs an indication of two nucleons at relatively small separation

Measuring Short Range Correlations

To measure the (relative) probability of finding a correlated pair, ratios of heavy to light nuclei are taken at ***x>1*** → QE scattering

If high momentum nucleons in nuclei come from correlated pairs, ratio of A/D should show a plateau (assumes FSIs cancel, etc.)

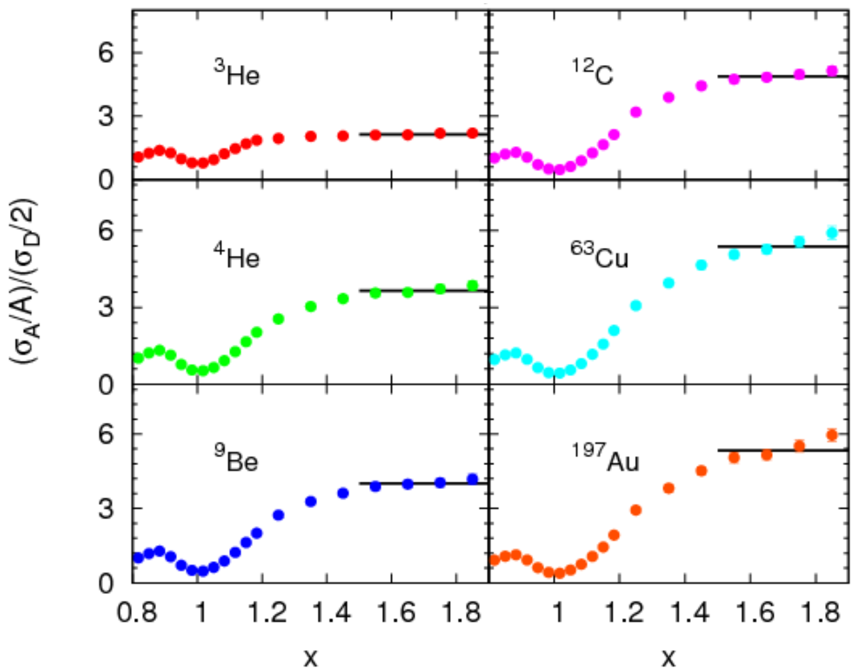




1.4<x<2 => 2 nucleon correlation

2.4<x<3 => 3 nucleon correlation

SRCs and Nuclear Density



N. Fomin et al, Phys.Rev.Lett. 108 (2012) 092502

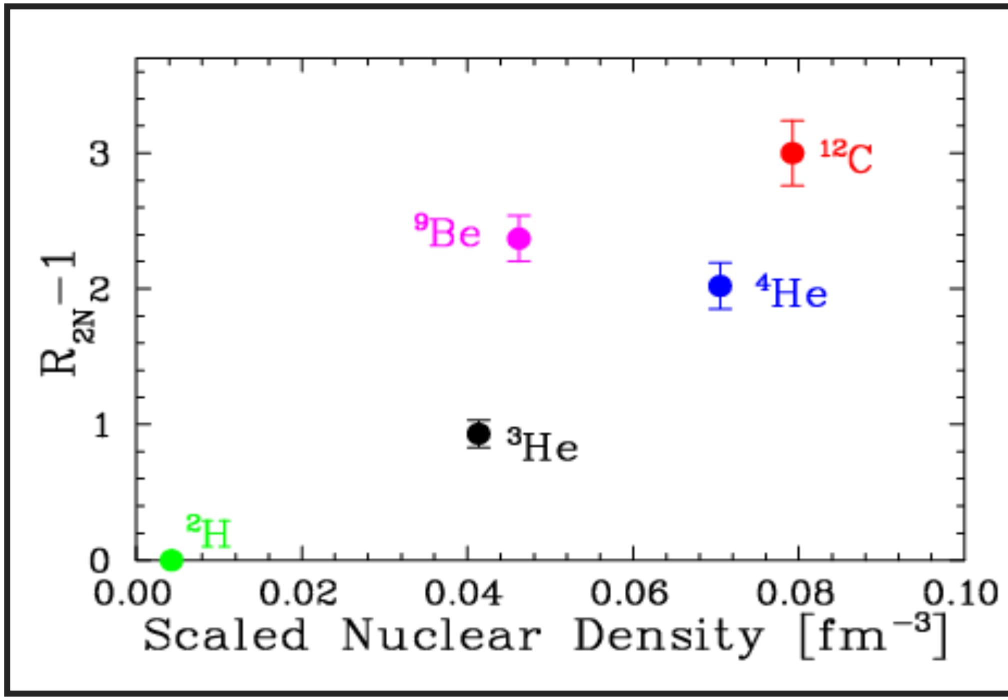
<u>New JLab data on ratios at *x>1*</u>

a_2 ratios for:

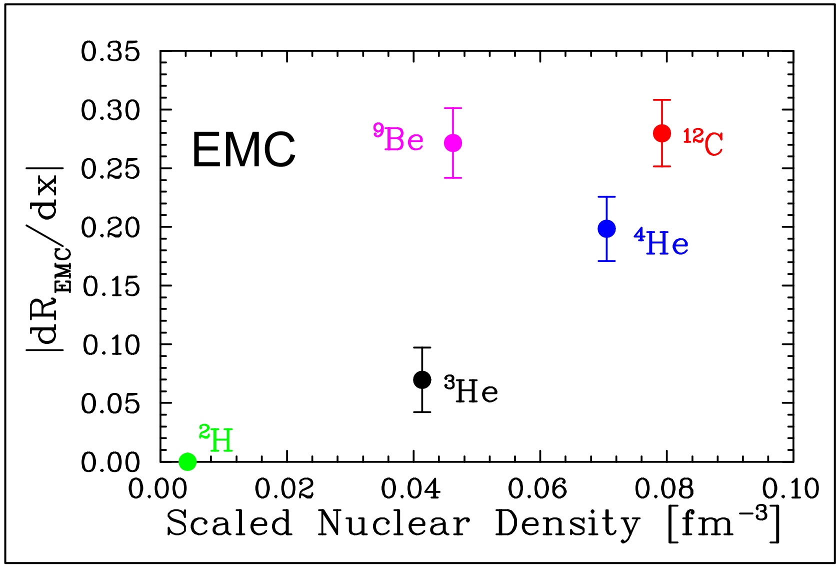
→Additional nuclei (Be, Cu, Au)

→Higher precision for targets with already existing ratios

→ Relative probability to find SRC shows similar dependence on nuclear density as EMC effect



SRCs and Nuclear Density



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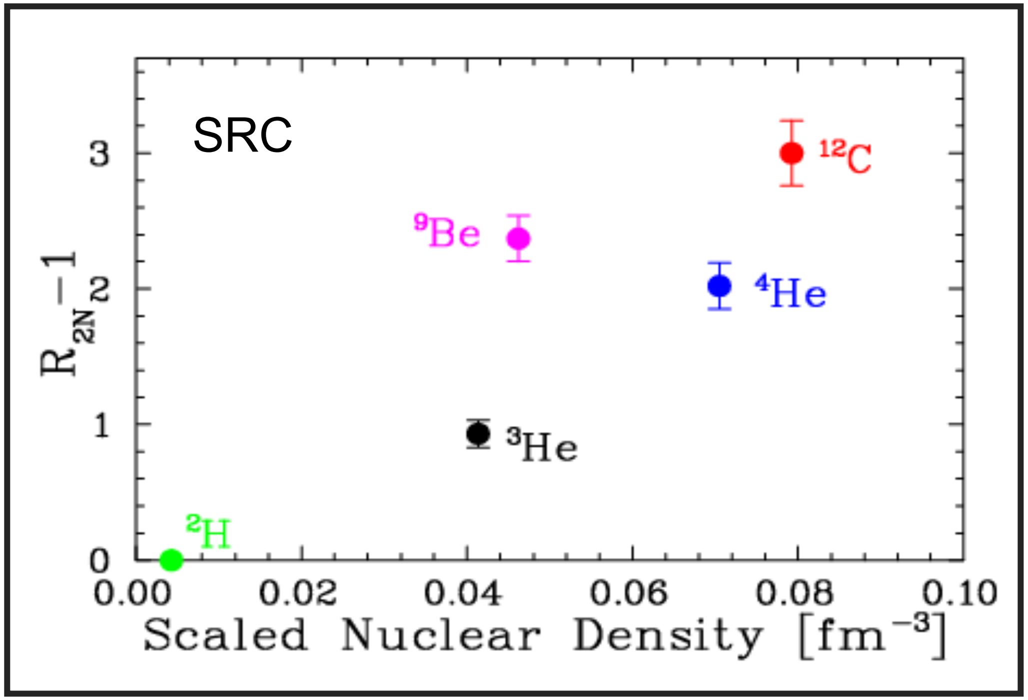
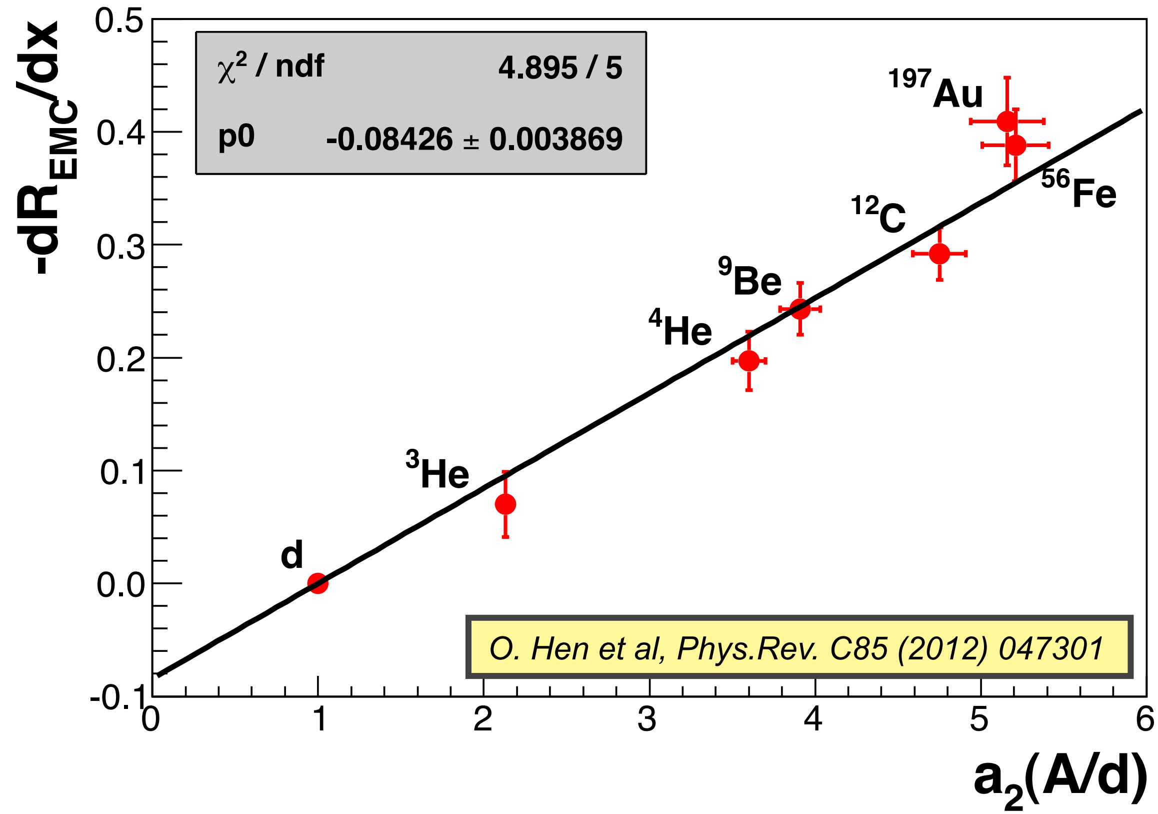


→ Relative probability to find SRC shows similar dependence on nuclear density as EMC effect

EMC Effect and SRC

Weinstein *et al* first observed linear correlation between size of EMC effect and Short Range Correlation “plateau”

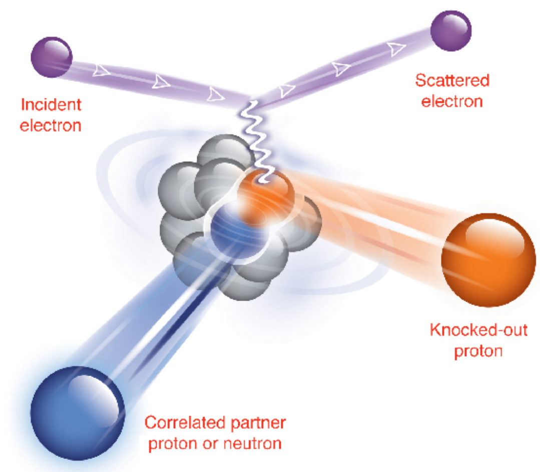
Connection strengthened with addition of Beryllium data



This result provides a ***quantitative*** test of level of correlation between the two effects

→ Is the EMC effect a result of SRCs? High momentum nucleons very far off shell?

Short Range Correlations – np Dominance



SRCs can be studied in more detail via triple-coincidence reactions

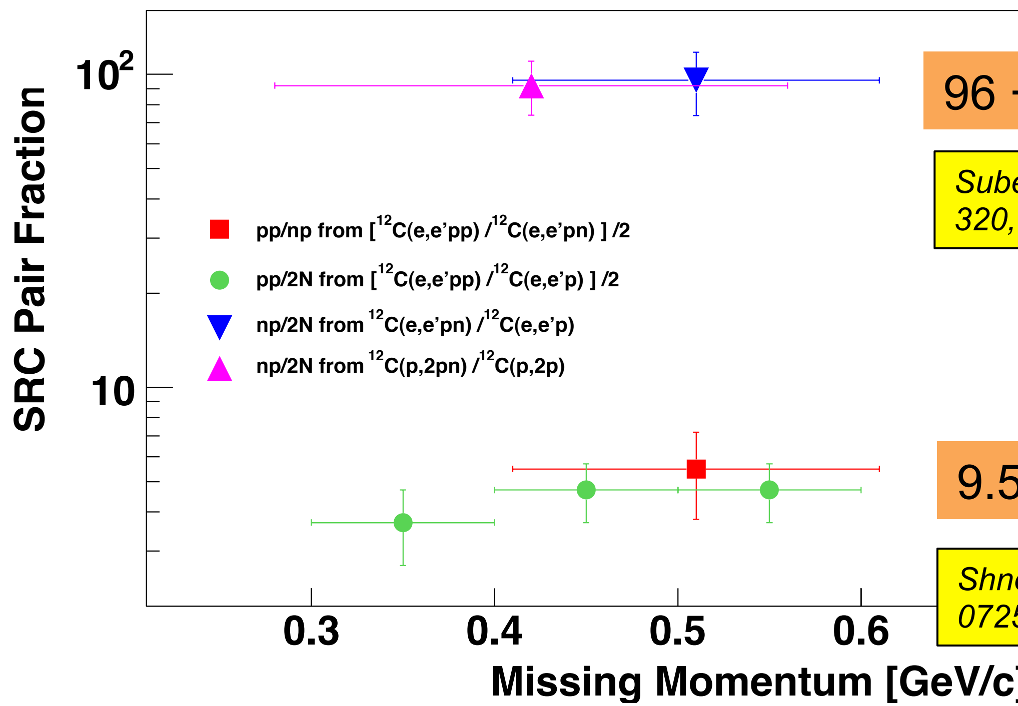
→ Electron knocks out high momentum proton from carbon nucleus

→ "Partner" backward-going proton or neutron also detected

Conclusion: High momentum nucleons are dominated by ***np*** pairs

Similar measurements for ^{4}He recently published → Larger P_m, approaching repulsive core

PRL 113 (2014) 022501



96 +/- 22%

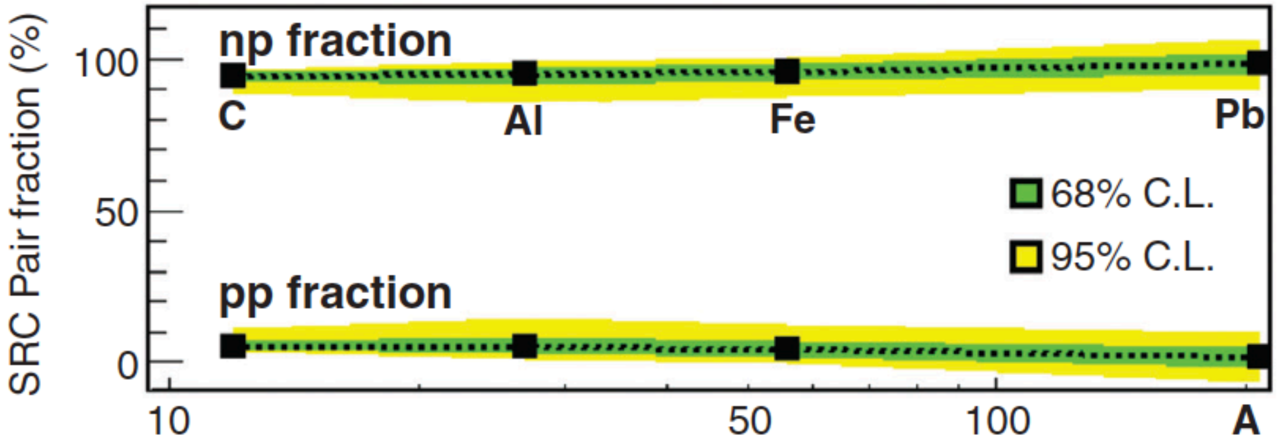
Subedi, et al, Science 320, 1476 (2008)

9.5 +/- 2%

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

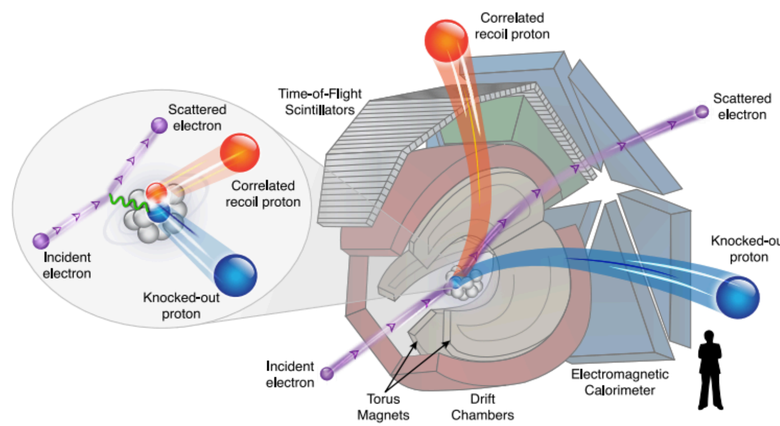
NP Dominance in Heavy Nuclei

O. Hen *et al.*, Science **346** (2014) 614, *doi:10.1126/science.1256785*
The Jefferson Lab CLAS Collaboration
Selected for Science Express (16 October 2014)



CLAS data mining initiative examined high-momentum protons at *x>1* to examine np dominance for large range of nuclei

Examined double ratio:
[A(e,e′pp)/ A(e,e′p)]/[12C(e,e′pp)/12C(e,e′p)]



Flavor Dependence and Short Range Correlations

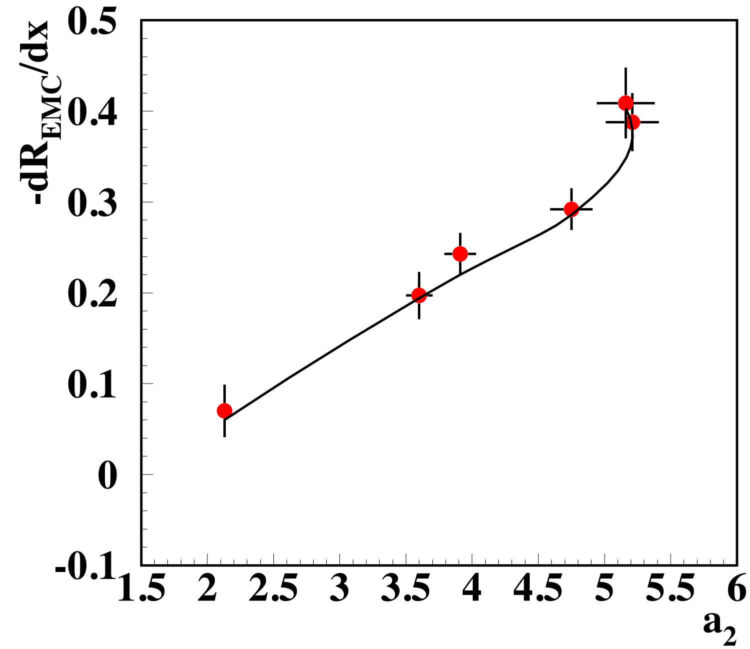
High momentum nucleons in the nucleus come primarily from *np* pairs

→The relative probability to find a high momentum proton is larger than for neutron for *N>Z* nuclei

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

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

Probability to find SRC



If the EMC effect comes from high momentum nucleons then effect driven by protons (u-quark dominates) →

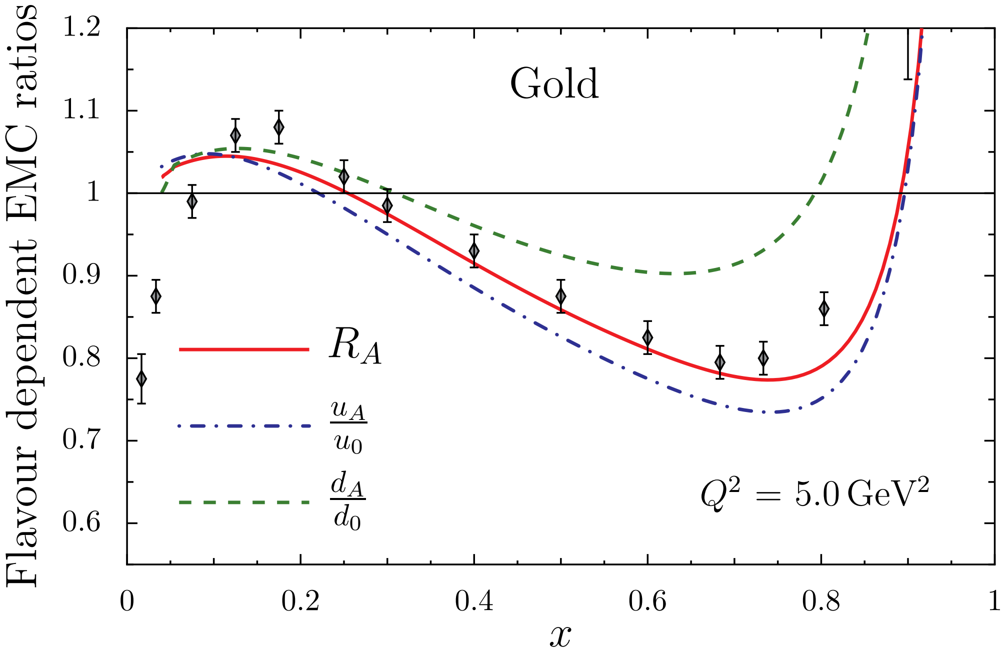
u-quarks modified more than d-quarks

Similar flavor dependence predicted earlier in mean-field approach

M. Sargsian, arXiv:1209.2477 [nucl-th] and arXiv:1210.3280 [nucl-th]

Flavor Dependence of the EMC Effect

Mean-field calculations predict a flavor dependent EMC effect for *N≠Z* nuclei



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

Cloët, Bentz, and Thomas, PRL 102, 252301 (2009)

Experimentally, this flavor dependence has not been observed directly

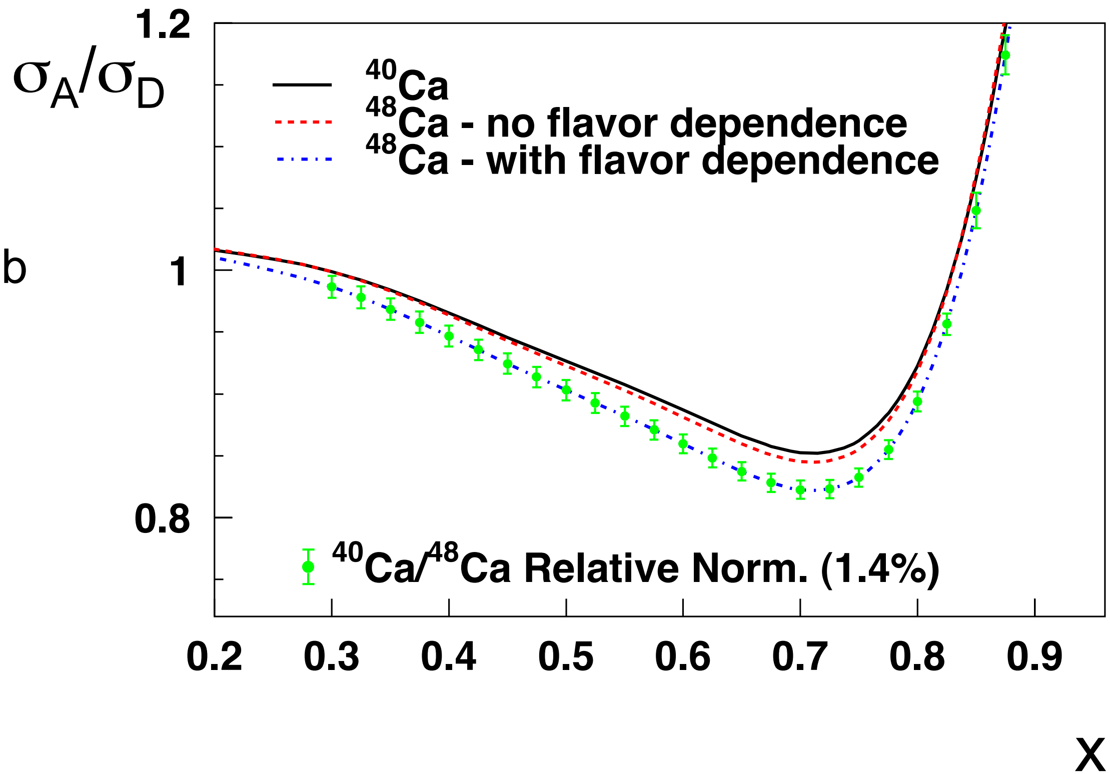
Flavor dependence could be measured using PVDIS, pion Drell-Yan, SIDIS, unpolarized EMC Effect…

Flavor dependence from ^{40}Ca and ^{48}Ca

CBT model predicts a ~3% effect for ^{48}Ca at *x=0.6*
→*N/Z = 1.4*

Will be measured at JLab @ 12 GeV

E12-10-008
Spokespersons: Daniel, Arrington, Gaskell



Assuming no flavor dependence, difference between ^{40}Ca and ^{48}Ca should be less than < 1% assuming SLAC E139 A-dependant parametrization

Summary: EMC-SRC Connection

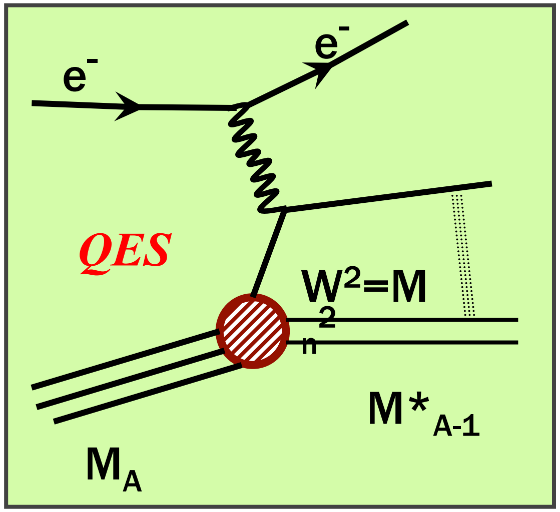
- New, high precision data has provided insight into the nuclear dependence of the EMC effect → local density
- A wealth of new data in the arena of Short Range Correlations has allowed quantitative, detailed comparisons of the "number" of SRCs in nuclei to the size of the EMC effect
- The striking EMC-SRC correlation implies that both share the same origin, or one drives the other
- If EMC effect caused by highly virtual nucleons, expect to see enhanced effect for up quarks (for N>Z nuclei)
- Calculation by Cloët *et al* also predicts enhancement for *u* quarks even for pure shell model structure

Quarks in the Nucleus

- The observed EMC-SRC connection provides exciting new information about the “mechanics” of the origin of the EMC effect
- Fundamental questions remain:
  - Description of the nucleus using only hadronic degrees of freedom remarkably successful- why?
  - Related: at what point do we need quarks and gluons?
  - SRCs may tell us where to find the EMC effect – (high momentum nucleons) – but what are the dynamics that lead to this modification of quark distributions?

EXTRA

Measuring Short Range Correlations



High momentum nucleons in the nucleus can be accessed using quasi-elastic scattering

→ At quasi-elastic peak ($x=1$), all parts of the nucleon momentum distribution contribute

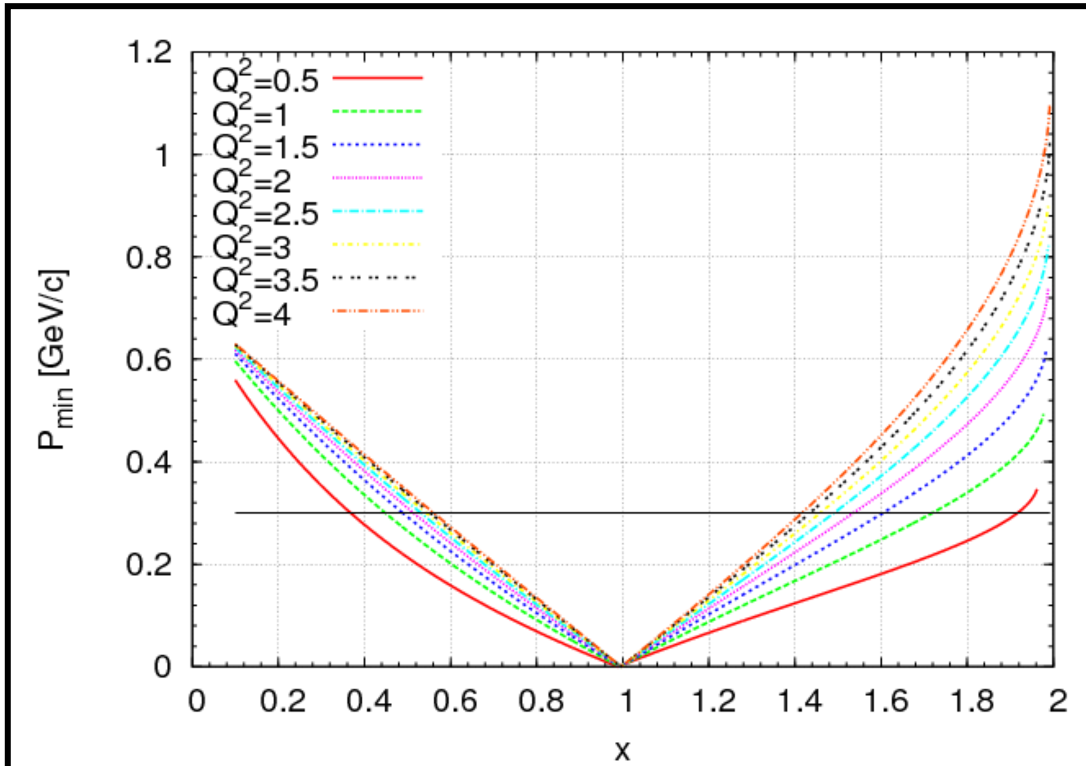


Figure courtesy N. Fomin, after Frankfurt, Sargsian, and Strikman, ***Int.J.Mod.Phys. A23 (2008) 2991-3055***

→ At $x>1$, we can access higher momentum components, if we go to large enough Q^2

EMC Effect: From Light to Heavy Nuclei

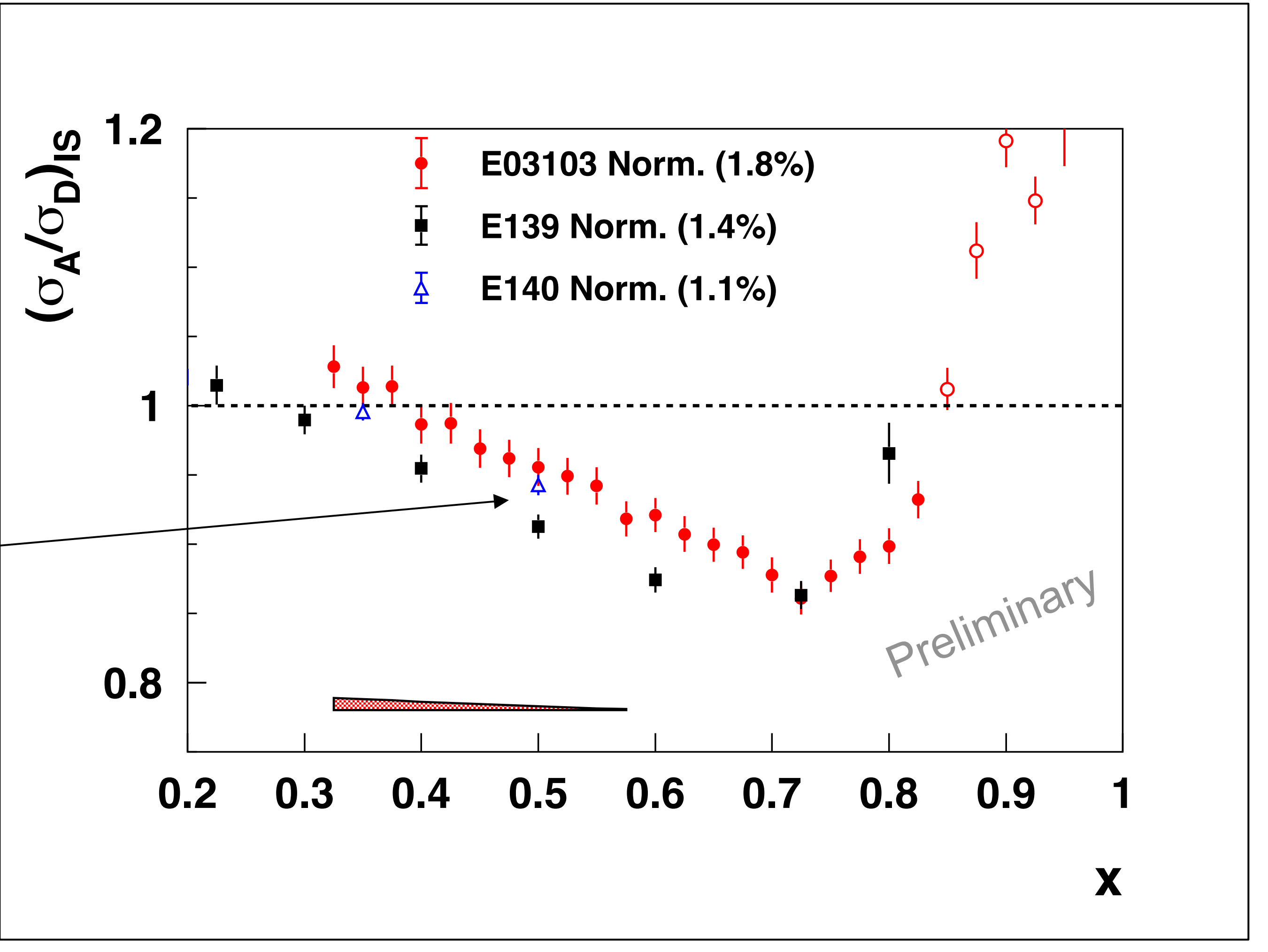
- Few-body nuclei provide an excellent opportunity to attempt calculations incorporating detailed nuclear structure
- Infinite nuclear matter also a useful limit for EMC effect calculations/modeling
  - E03-103 took additional data from Cu and Au in part to examine shape of EMC effect at very large *x*
- Analysis of large *A* data complicated by Coulomb Corrections → no clear prescription for DIS

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

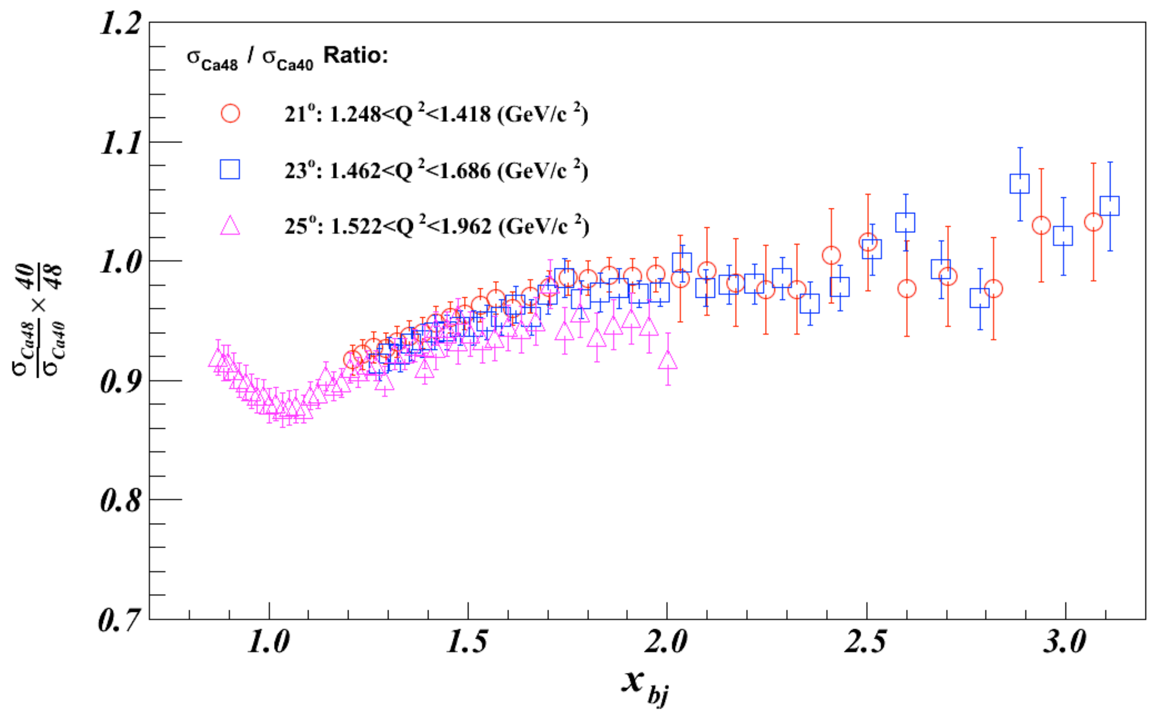


Ongoing Studies at JLab

E03-103: Heavy target data for more information on EMC ratios → higher precision QE ratios (a2) on aluminum?

E07-006: Triple coincidence measurement (e,e'pN) from ^{4}He. Study SRCs from a few body target

E08-014: Inclusive electron scattering at x>1 (x>2) from ^{40}Ca, ^{48}Ca, ^{3}He, ^{4}He



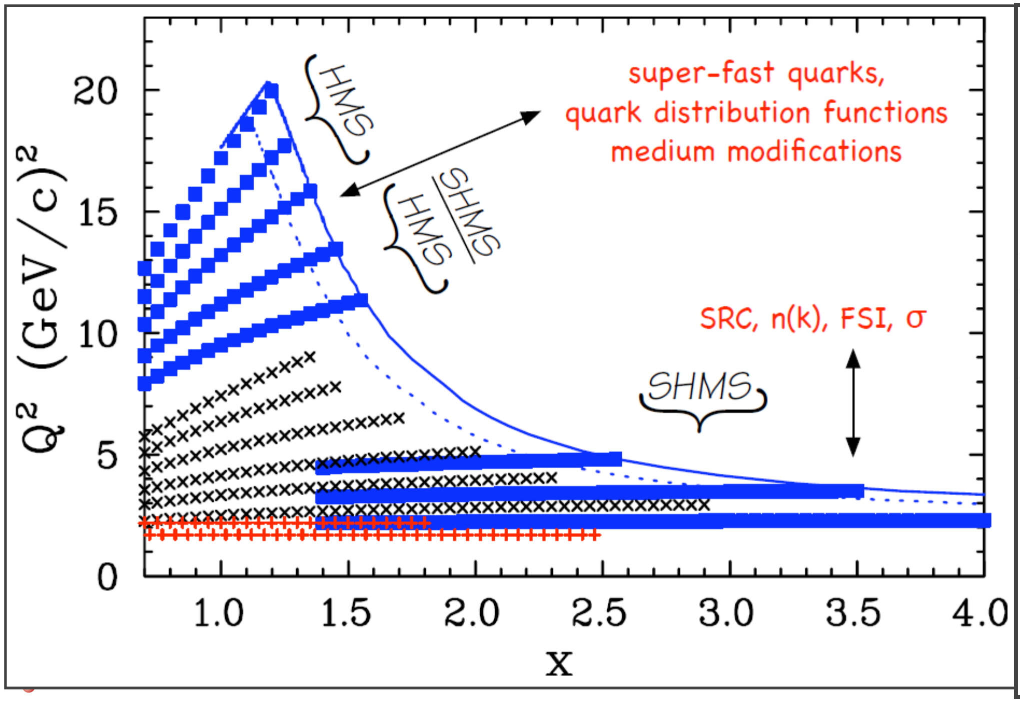
Inclusive EMC and SRC Ratios at 12 GeV

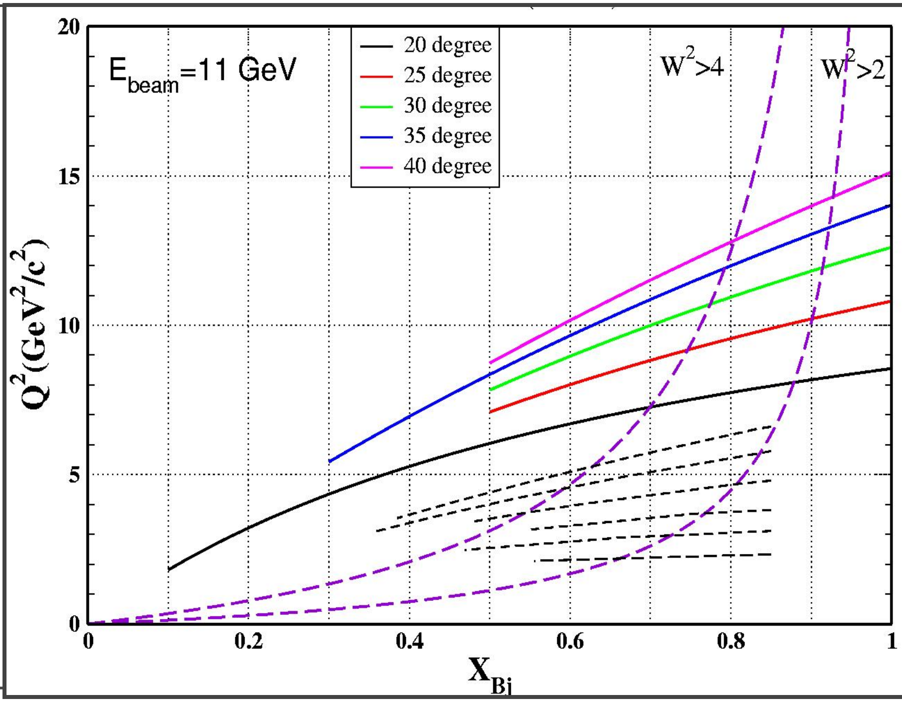
Straightforward extension of EMC-SRC correlation studies with additional nuclei

→JLab 12 GeV experiments will provide data on a variety of targets, including:

→^{2}H, ^{3}He, ^{4}He
→**^{6}Li**, ^{7}Li, Be, **^{10}B**, **^{11}B**, C
→Al, **^{40}Ca**, **^{48}Ca**, Cu

EMC: E12-10-008 (Arrington, Daniel, Gaskell)
SRC: E12-06-105 (Arrington, Day, Fomin, Solvignon)

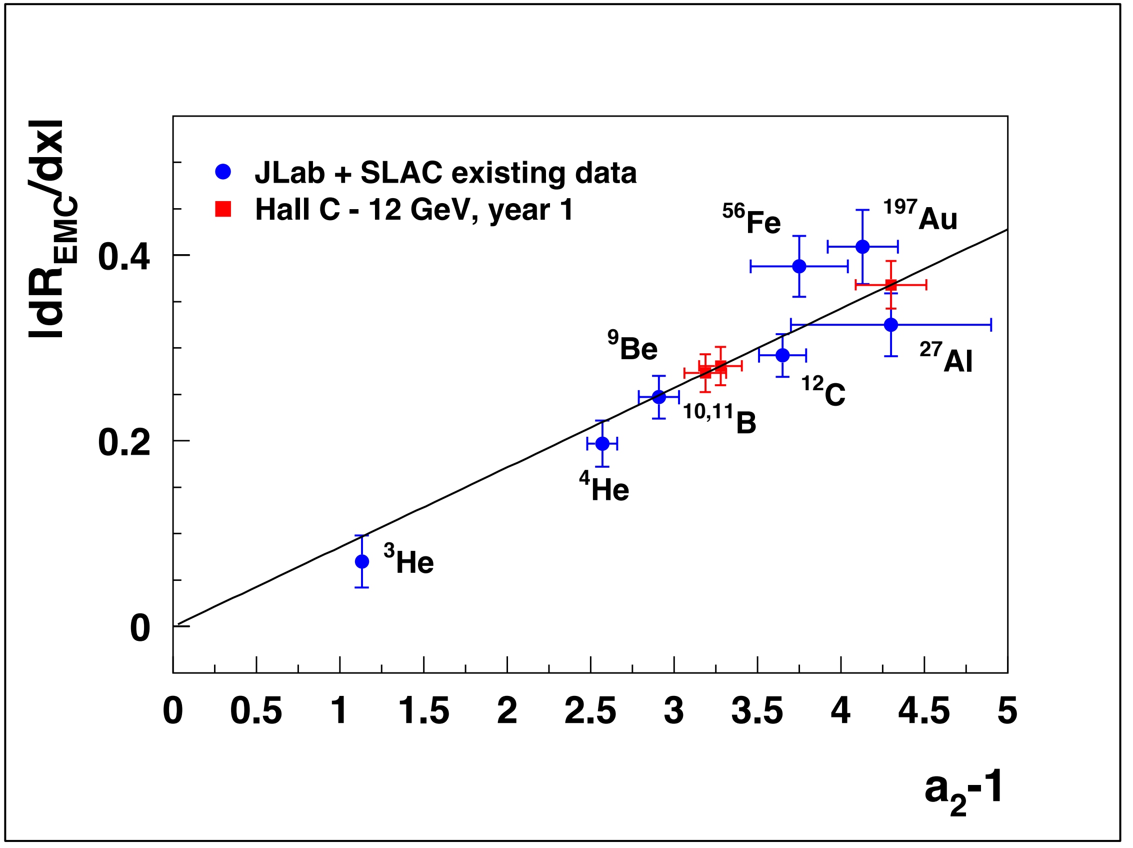




E12-10-008 and E12-06-105

Hall C experiments will provide more inclusive data
→E12-06-105 *x>1*
→E12-10-008 *EMC Effect*

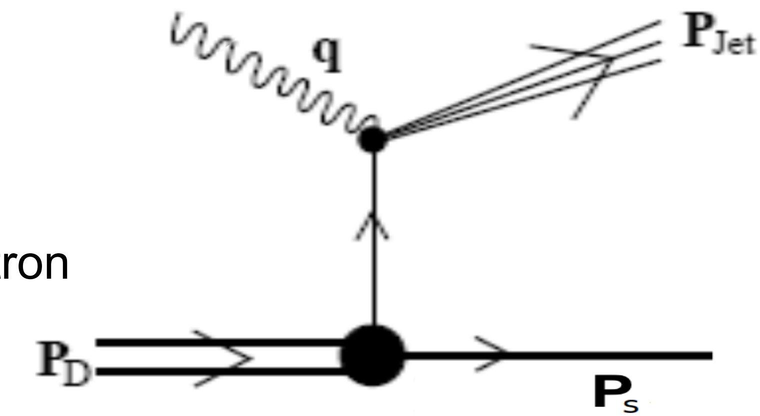
Will provide additional data on light and medium-heavy targets
→^{2}H, ^{3}He, ^{4}He
→^{6}Li, ^{7}Li, Be, ^{10}B,^{11}B, C
→Al, ^{40}Ca, ^{48}Ca, Cu

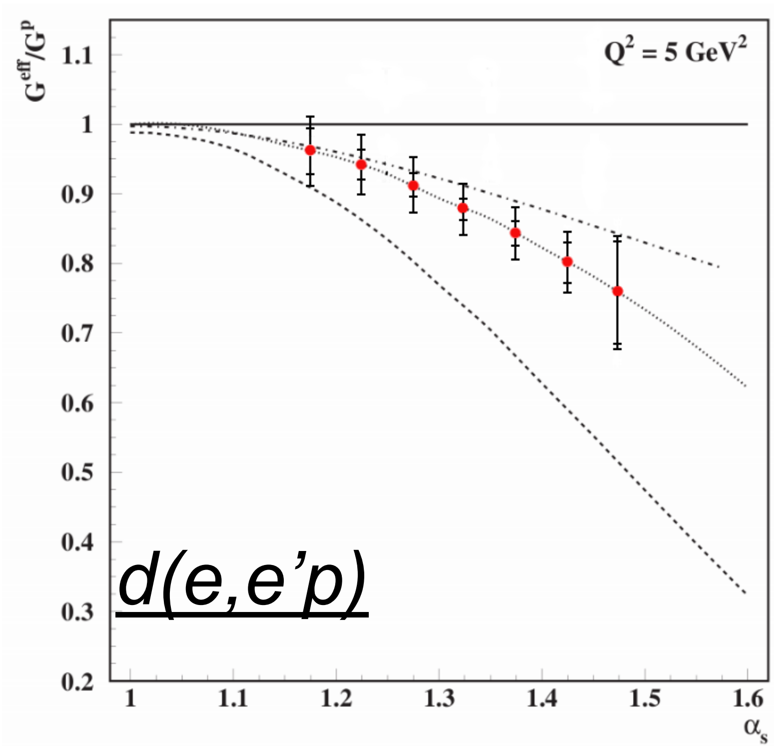


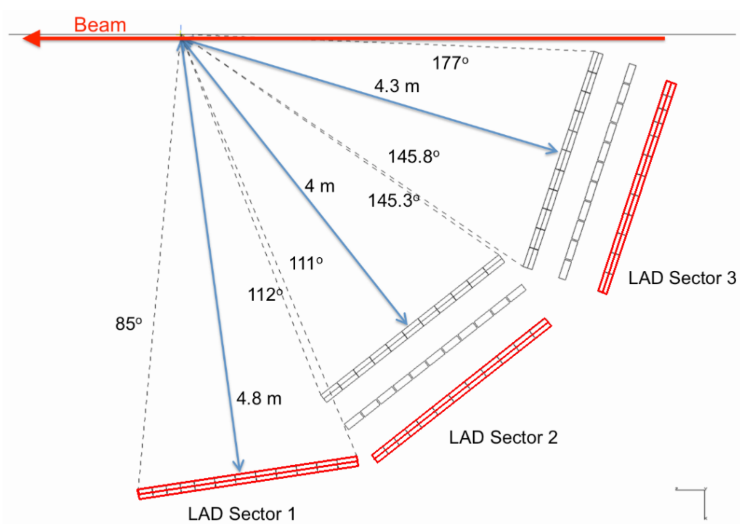
First running in Hall C after completion of 12 GeV Upgrade will include a few days for EMC/x>1 measurements on ^{10}B, ^{11}B, and Al (parasitic)

E12-11-107: In-Medium Structure Functions

Measure structure function of high momentum nucleon in deuterium by tagging the spectator
→Final state interactions cancelled by taking double ratios
→Requires new, large acceptance proton/neutron detector at back angles







Spokespersons: O. Hen, L. Weinstein, S. Gilad, S. Wood

Sensitivity to flavor dependence

Extracting the flavor dependence from the inclusive ratio relies on comparing the measured to the "expected" EMC effect in ^{48}Ca relative ^{40}Ca
→ Can measure "size" of the EMC effect either at fixed x, or via "slope"

Ratio	R @ x=0.6	dR/dx (x=0.3-0.7)
$^{48}Ca/^{40}Ca$ (no flavor dep.)	0.993	1.050
$^{48}Ca/^{40}Ca$ (w/flavor dep.)	0.970 +/- 0.013 +/- 0.014	1.115 +/- 0.057 +/- 0.016

stat + random sys → (first uncertainty); normalization → (second uncertainty)

The "no flavor dependence" ratio above uses the nuclear dependence of the EMC effect from SLAC E139 A-dependent fit

→ Other, plausible nuclear dependencies (e.g. $A^{-1/3}$) yield similar results, change the expected ratio by < 0.5% at fixed x=0.6, or by 2.5% for the slope

EMC Effect Measurements at Large x

SLAC E139 most extensive and precise data set for *x>0.2*

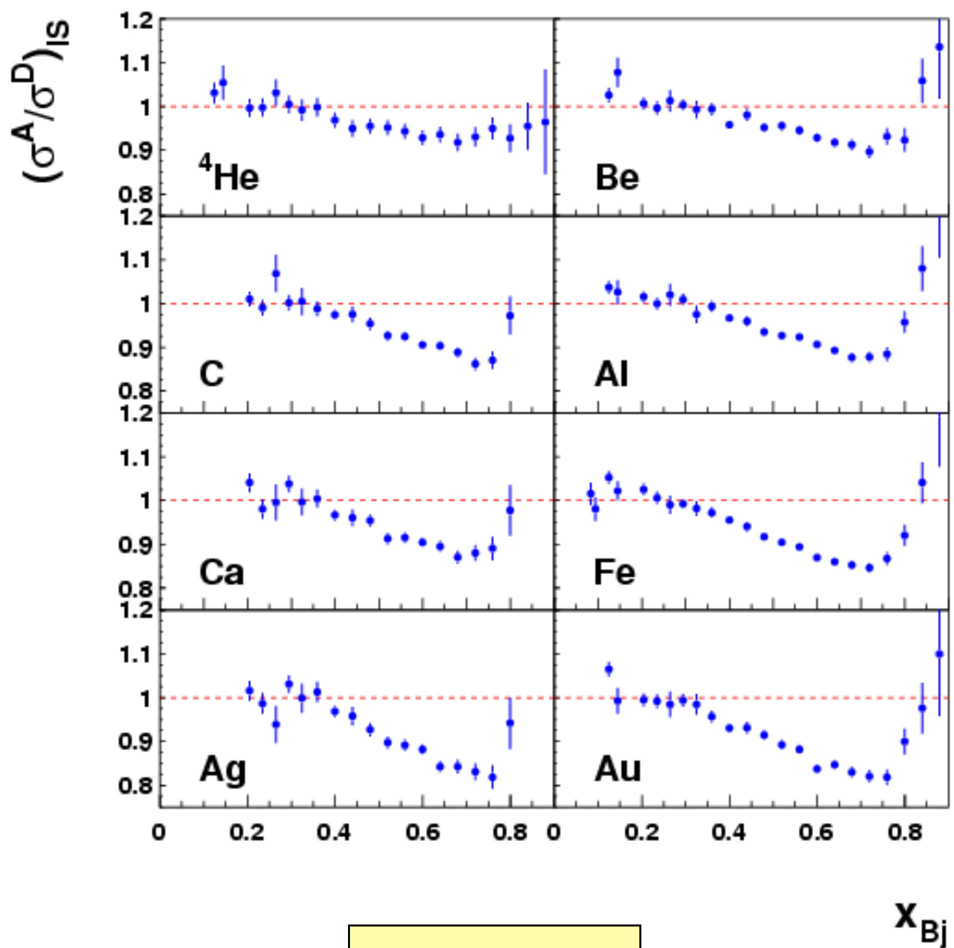
Measured σ_A/σ_D for A=4 to 197
^{4}He, ^{9}Be, C, ^{27}Al, ^{40}Ca, ^{56}Fe, ^{108}Ag, ^{197}Au

Size at fixed *x* varies with *A*, but shape (*x* dep.) nearly constant

JLab E03103 aimed to build on E139 with:

- → Higher precision data for ^{4}He
- → Addition of ^{3}He data
- → Precision data at large *x*

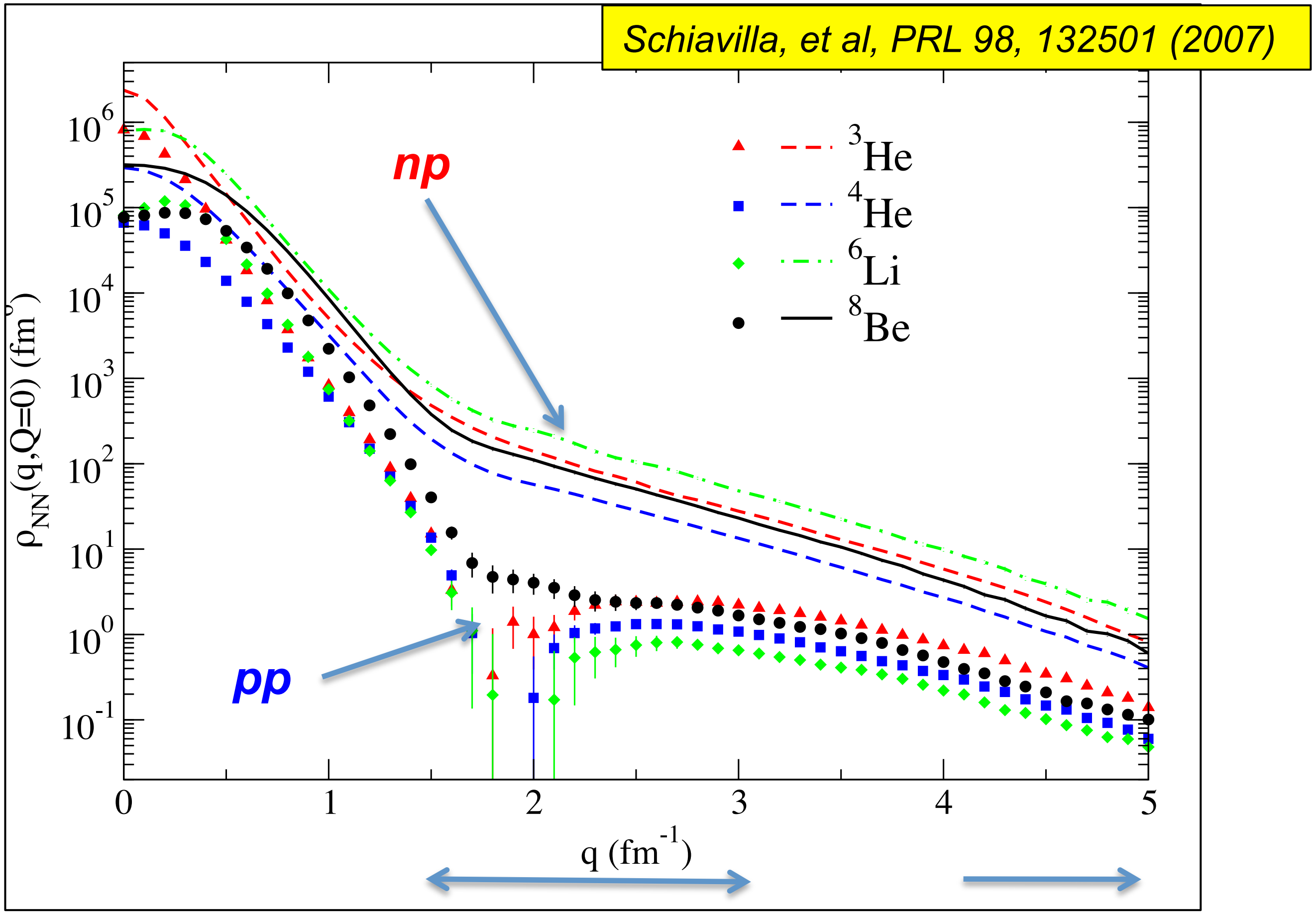
Determine if EMC Effect depends on *A* or density, *ρ*



SLAC E139

Short Range Correlations

Experimentally, has been shown that high momentum nucleons dominated by ***np*** pairs – also seen in variational Monte Carlo calculations



Tensor interaction

Repulsive core