The EMC Effect and Connections to a Possible Nuclear Dependence of R

Dave Gaskell
Jefferson Lab

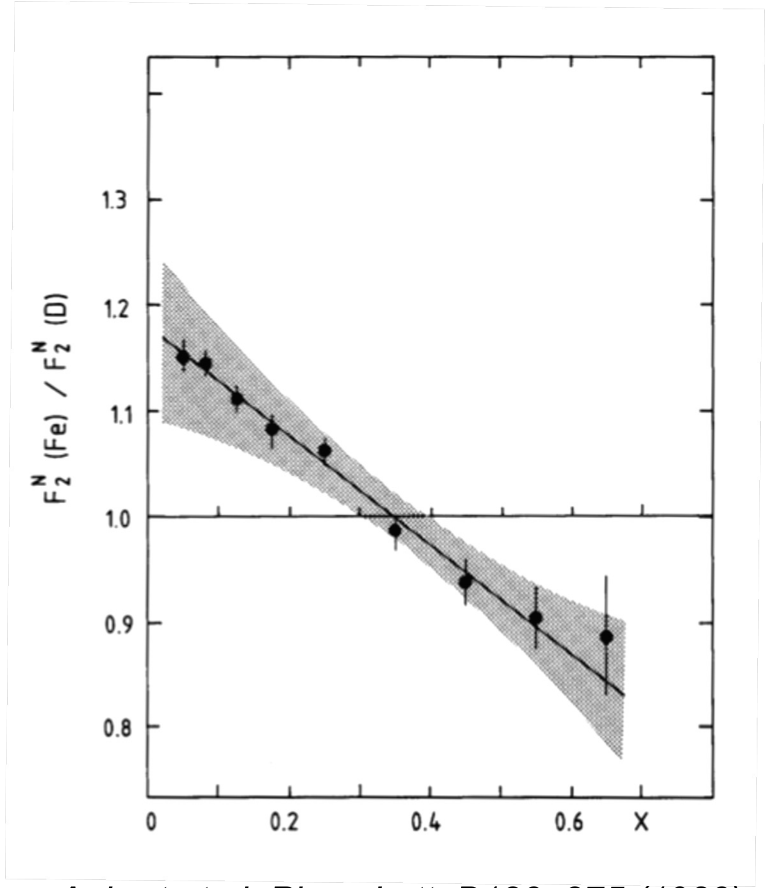
Symposium on Nucleon and Nuclear Structure from Inclusive Measurements

June 20-21, 2023

Outline

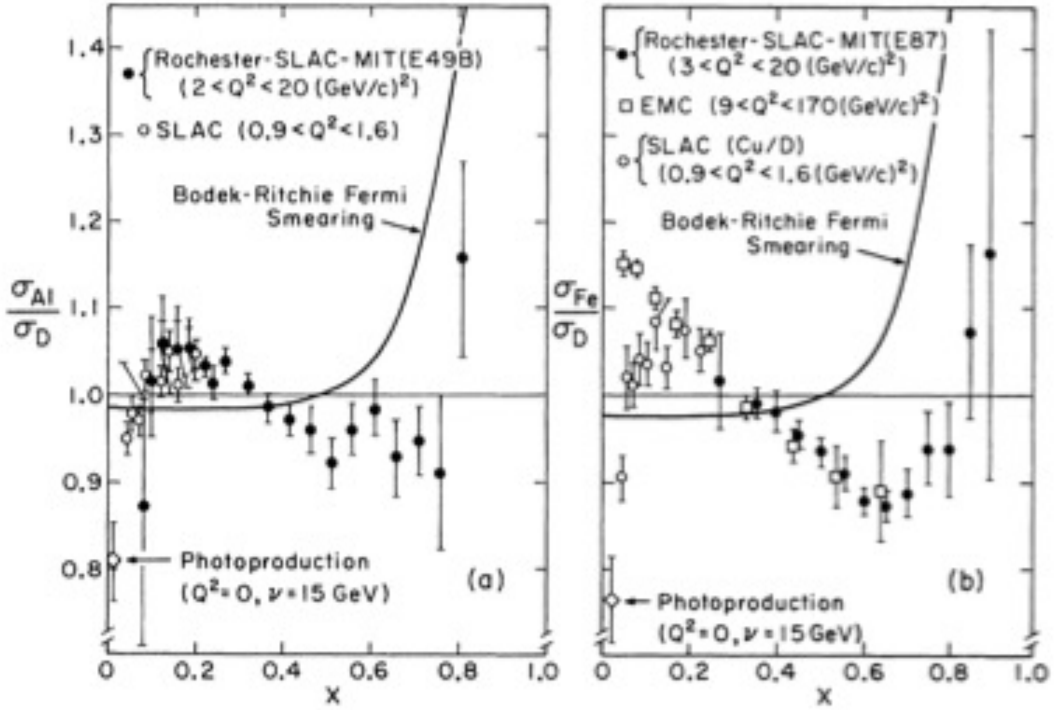
- Overview of the EMC Effect
  - Models
  - Pre-JLab data/observations
- Recent experimental results
  - Local density dependence, connection to Short Range Correlations
  - Additional information from more inclusive measurements?
- Connection to R_A-R_D

The EMC Effect – F_2 in the Nucleus



Aubert et al, Phys. Lett. B123, 275 (1983)

Discovery of the modification of ***F₂(x)*** in 1983 demonstrated that quark distributions are modified in the nucleus
→ This suggests some new, unexplained dynamics at play in nuclear environment



Bodek et al, PRL 50, 1431 (1983) and PRL 51, 534 (1983)

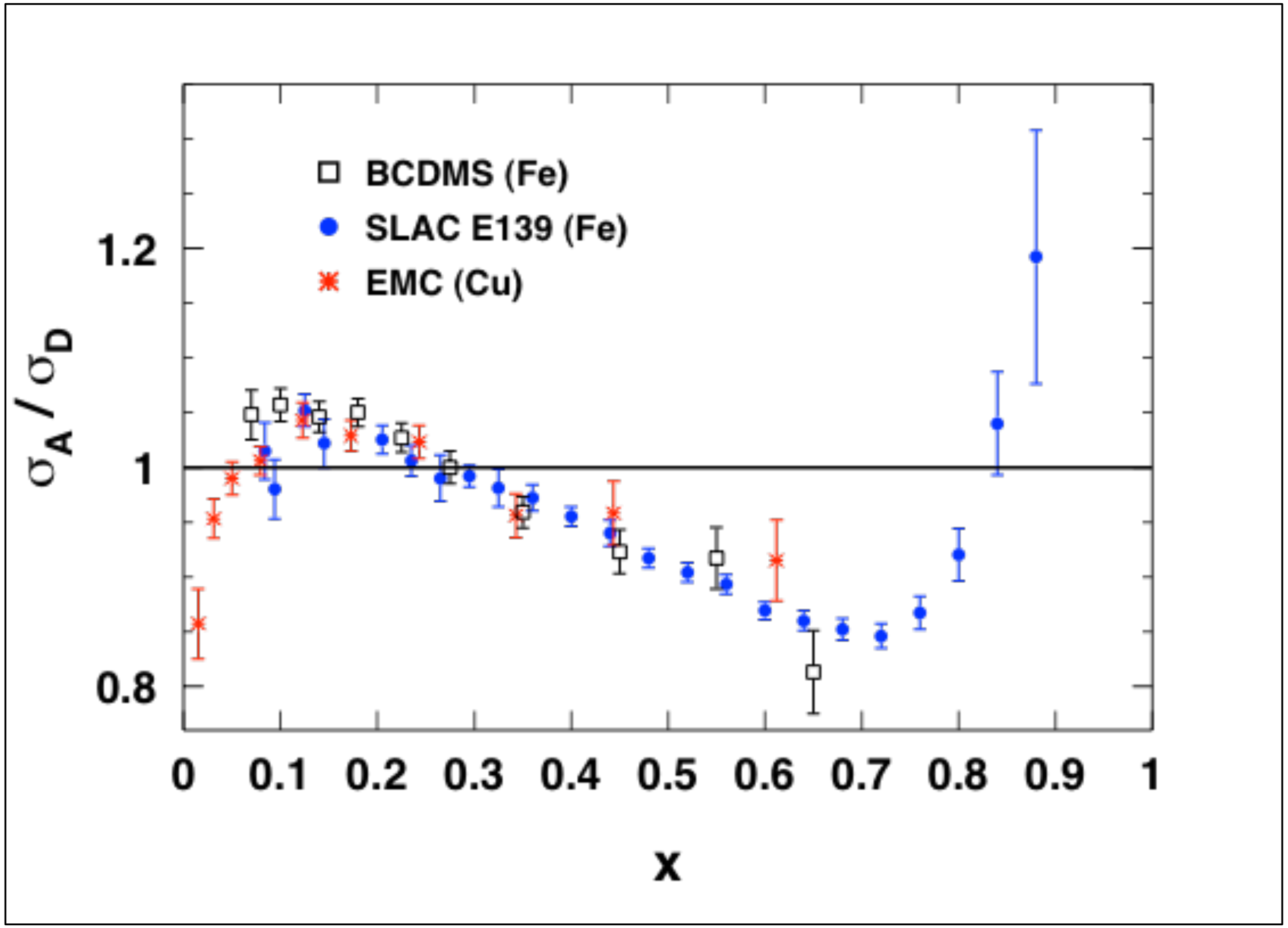
Origins of the EMC Effect

- Not just "nuclear physics" – explanations that include Fermi motion/convolution formalism, binding inadequate on their own
  - Would require the introduction of some off-shell effect (unknown origin)
  - Large effects from "nuclear pions" ruled out by Drell-Yan measurements
- Other explanations
  - Dynamical rescaling $F_2^A(x,Q^2) = F_2^N(x,\xi_A(Q^2)\cdot Q^2)$
  - Multiquark clusters → 6, 9, 12 .. quark configurations
  - Quark-meson coupling coupling
  - Connection to SRCs? → Nucleon virtuality (see off-shell effects above), or signature of local-density effects?

Measurements of the EMC Effect

Laboratory/collaboration	Beam	Energy (GeV)	Target	Year
SLAC E139	e	8-24.5	***D***,^{4}He, Be, C, Ca, Fe, Ag, Au	1994,1984
SLAC E140	e	3.75-19.5	***D***, Fe, Au	1992,1990
CERN NMC	μ	90	***^{6}Li***, ^{12}C, ^{40}Ca	1992
	μ	200	***D***, ^{4}He, C, Ca	1991, 1995
	μ	200	Be, ***C***, Al, Ca, Fe, Sn, Pb	1996
CERN BCDMS	μ	200	***D***, Fe	1987
	μ	280	***D***, N, Fe	1985
CERN EMC	μ	100-280	***D***, Cu	1993
	μ	280	***D***, C, Ca	1988
	μ	100-280	***D***, C, Cu, Sn	1988
	μ	280	H, ***D***, Fe	1987
	μ	100-280	***D***, Fe	1983
FNAL E665	μ	490	***D***, Xe	1992
	μ	490	***D***, Xe	1992
DESY HERMES	e	27	***D***, ^{3}He, N, Kr	2000, 2003
Jefferson Lab	e	6	***D***, ^{3}He, ^{4}He, Be, C, Cu, Au	2009, 2021
	e	6	***D***, C, Cu, Au	2004 (thesis)
	e	5	***D***, C, Al, Fe, Pb	2019
	e	11	***D***, Be, 10B, ^{11}B, C	2022

Properties of the EMC Effect



Properties of the EMC effect

1. Universal x-dependence
2. Little Q^2 dependence
3. EMC effect increases with *A*

→ *Anti-shadowing region shows little nuclear dependence*

Nuclear dependence one (best?) way to explore origins, test models

Nuclear Dependence of EMC Effect

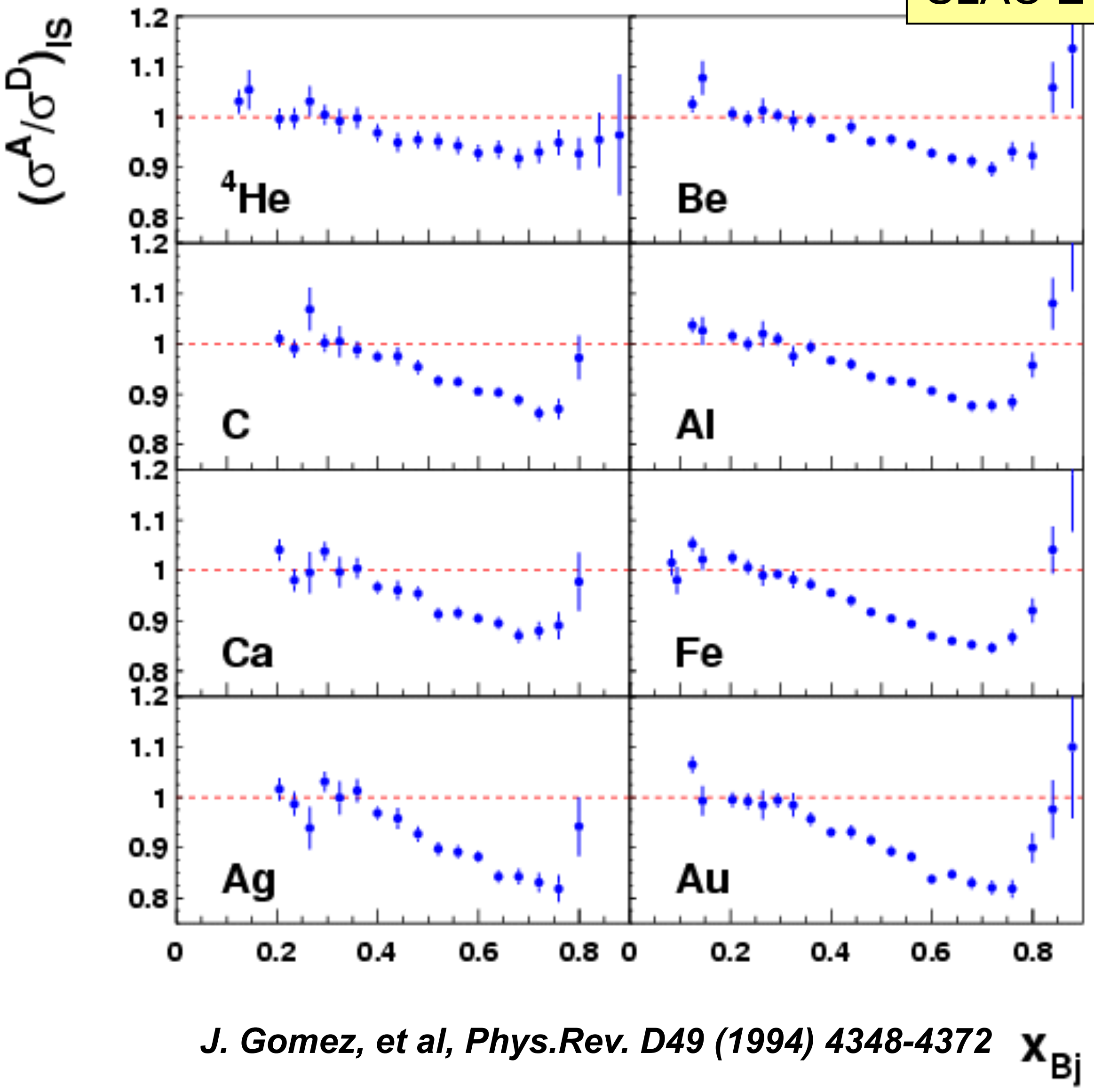
SLAC E139 explored detailed ***nuclear dependence*** to gain new insight to EMC Effect

Provided the 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, and ^{197}Au
→ Verified that the *x* dependence was roughly constant

SLAC E139



J. Gomez, et al, Phys.Rev. D49 (1994) 4348-4372

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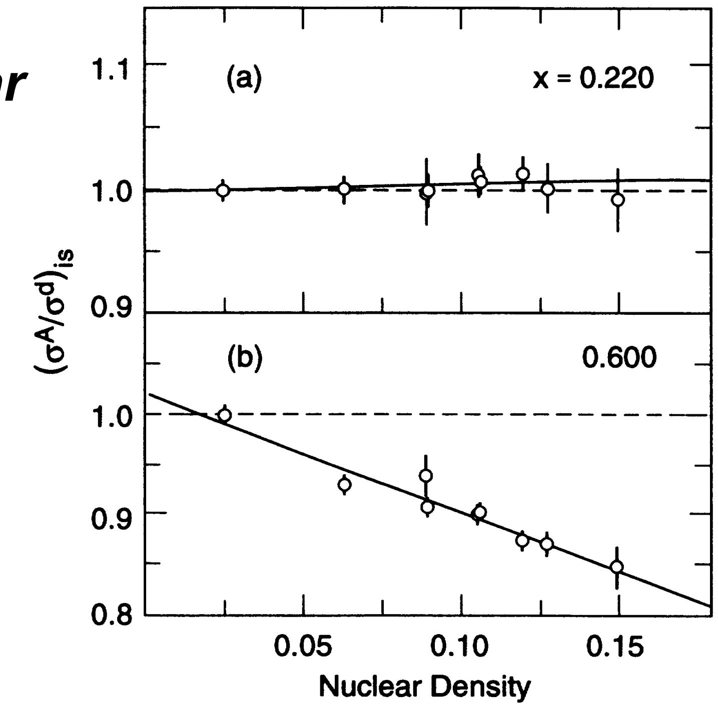
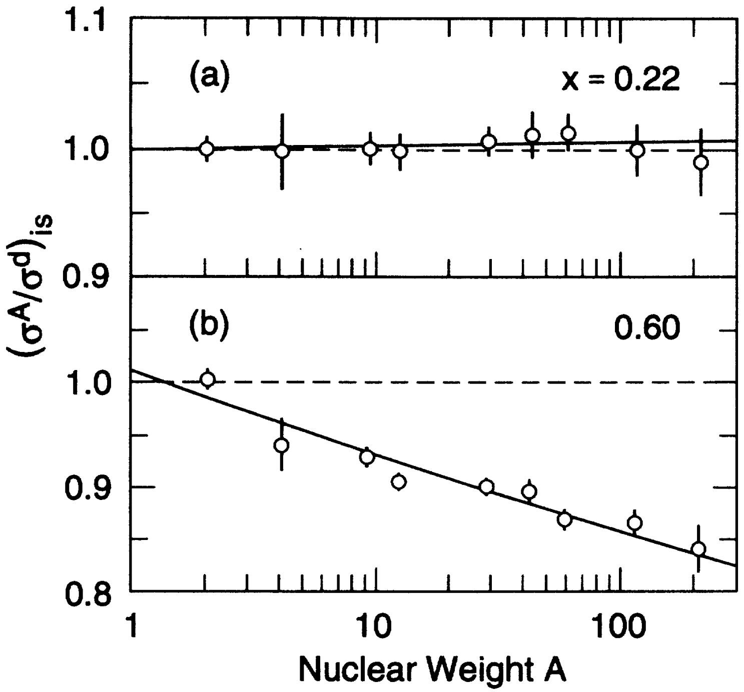


Density-dependence



A-dependence

E139 results consistent with both A and density dependent pictures

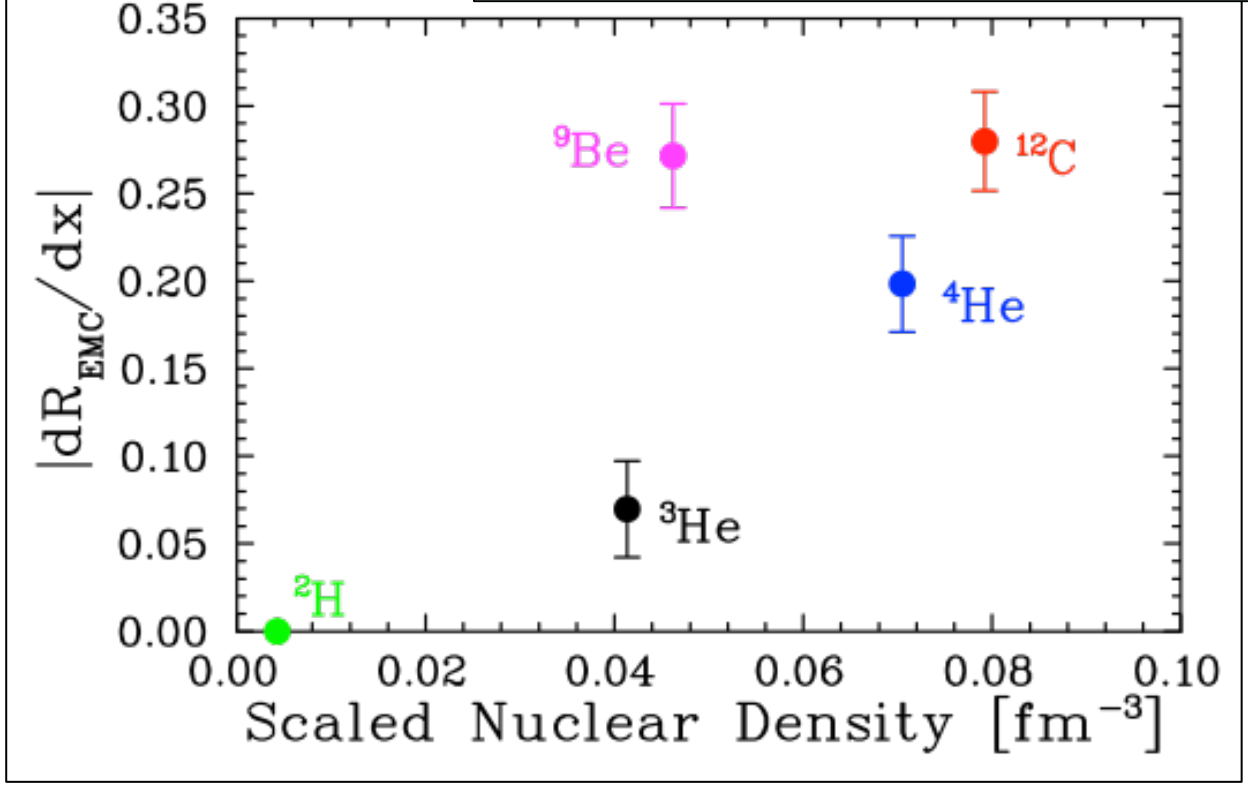
EMC Effect and Local Nuclear Density

JLab E03103 goal:
More information on nuclear dependence → emphasis on light nuclei:
^{3}He, *^{4}He, Be, C*

→ New definition of size of EMC effect:
|dR/dx| for *0.35<x<0.7*

→ ^{3}He, ^{4}He, C, EMC effect scales well with density – Be does not!

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



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

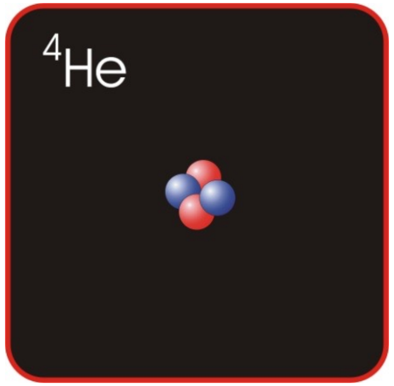
<ρ> from ab initio few-body calculations

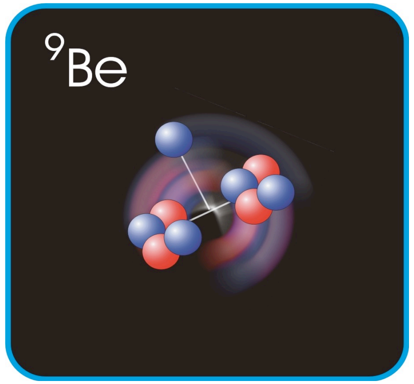
→ *[**S.C. Pieper and R.B. Wiringa**, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)]*

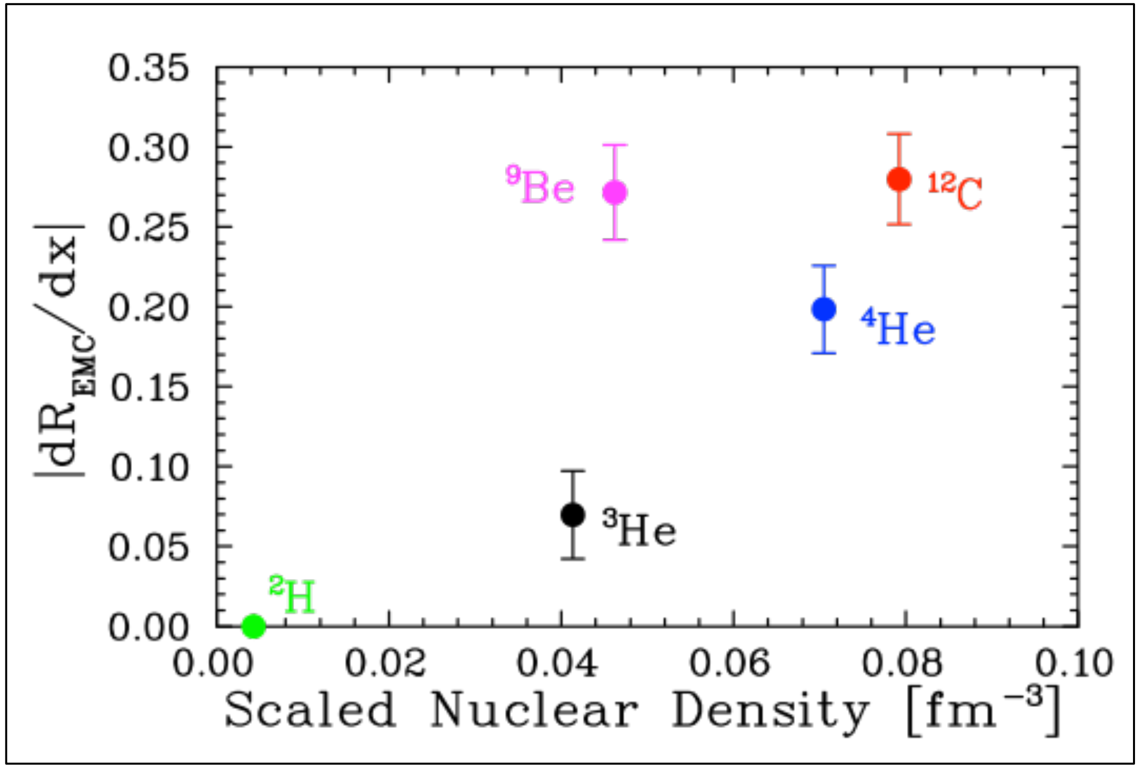
EMC Effect and Local Nuclear Density

^{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







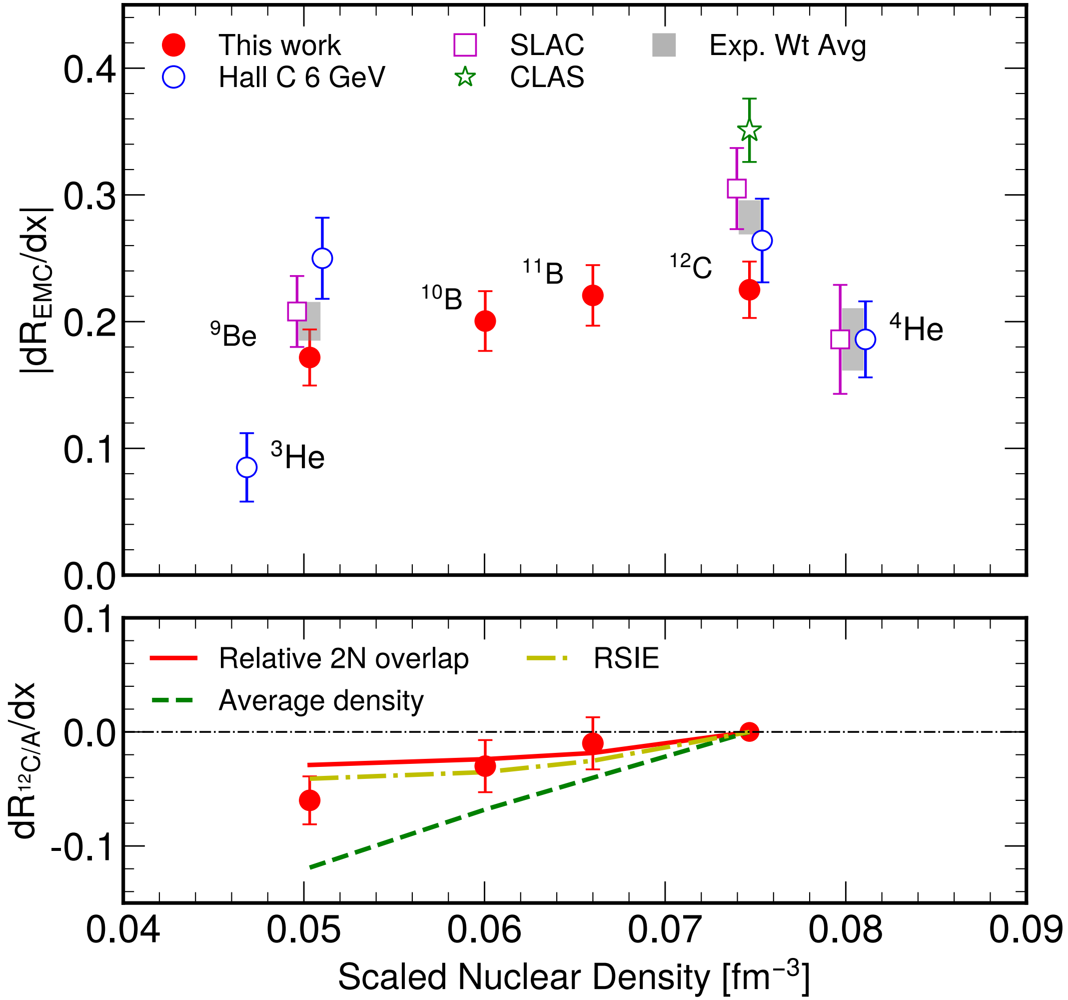
Can this "local density" picture be confirmed with other/additional nuclei?

EMC Effect and Local Nuclear Density

New data on ^{10}B and ^{11}B → Hall C, 2018 taken as part of SHMS "commissioning experiments" group

EMC Effect for ^{10}B and ^{11}B similar to ^{9}Be and ^{12}C
→ **^{10}B and ^{11}B structure also has significant α cluster contribution**

Ratio of ^{9}Be, ^{10}B, ^{11}B relative to ^{12}C provides more precise A-dependence for A=9-12
→ Small difference between ^{9}Be and ^{12}C now more apparent



Karki et al, arXiv:2207.03850 [nucl-ex]

EMC Effect and Local Nuclear Density

Can we try to quantify “local nuclear density” more precisely?

$$O_{NN} = \int_0^\infty W(r)\rho_2^{NN}(r)d^3r$$

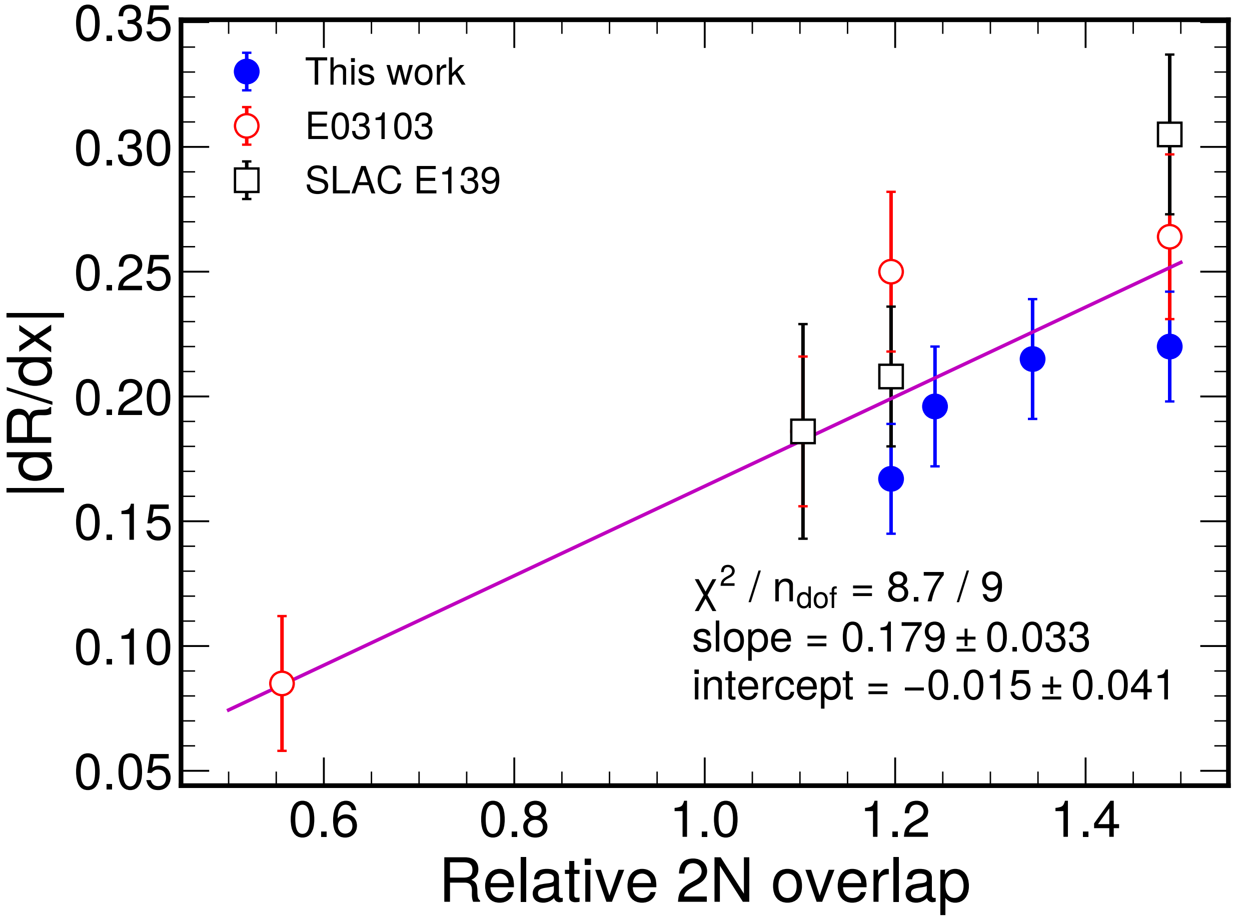
Cutoff function

2N distribution

Effective 2N -overlap

$$\langle O_N \rangle = \frac{Z\sigma_p O_p + N\sigma_n O_n}{Z\sigma_p + N\sigma_n}$$

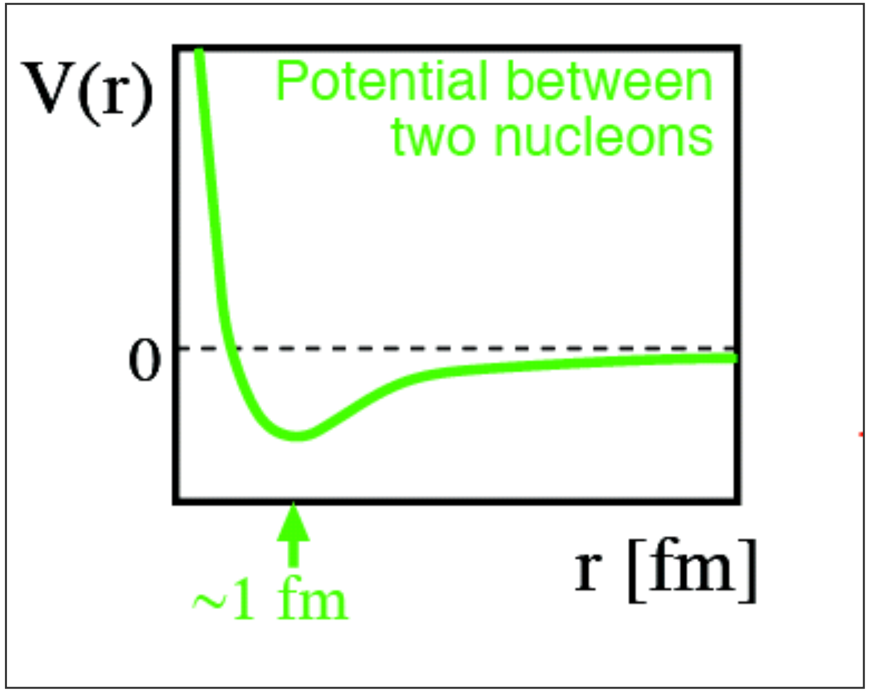
Relative to deuterium: $\langle O_N \rangle_A - \langle O_N \rangle_D$

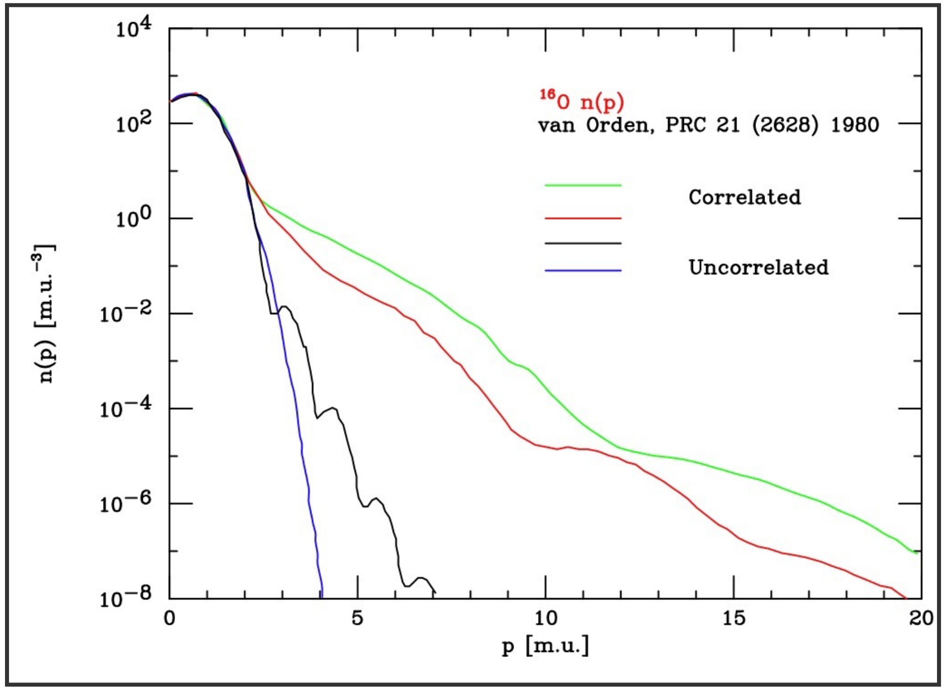


Karki et al, arXiv:2207.03850 [nucl-ex]

Local Density → Short Range Correlations

What drives high "local" density in the nucleus?

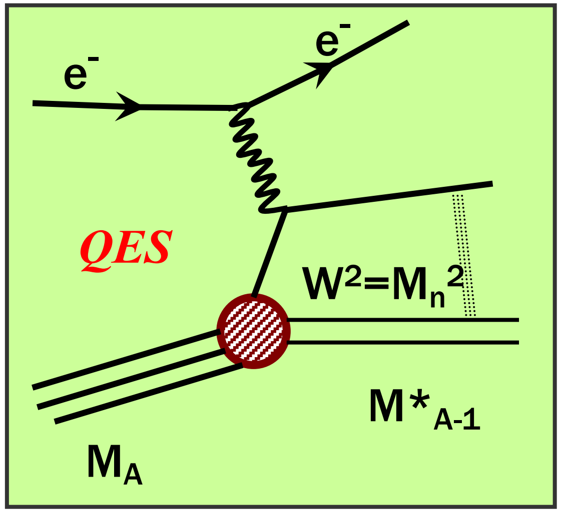




Tensor interaction and short-range repulsive core lead to high momentum tail in nuclear wave function → correlated nucleons

Accessing 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



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

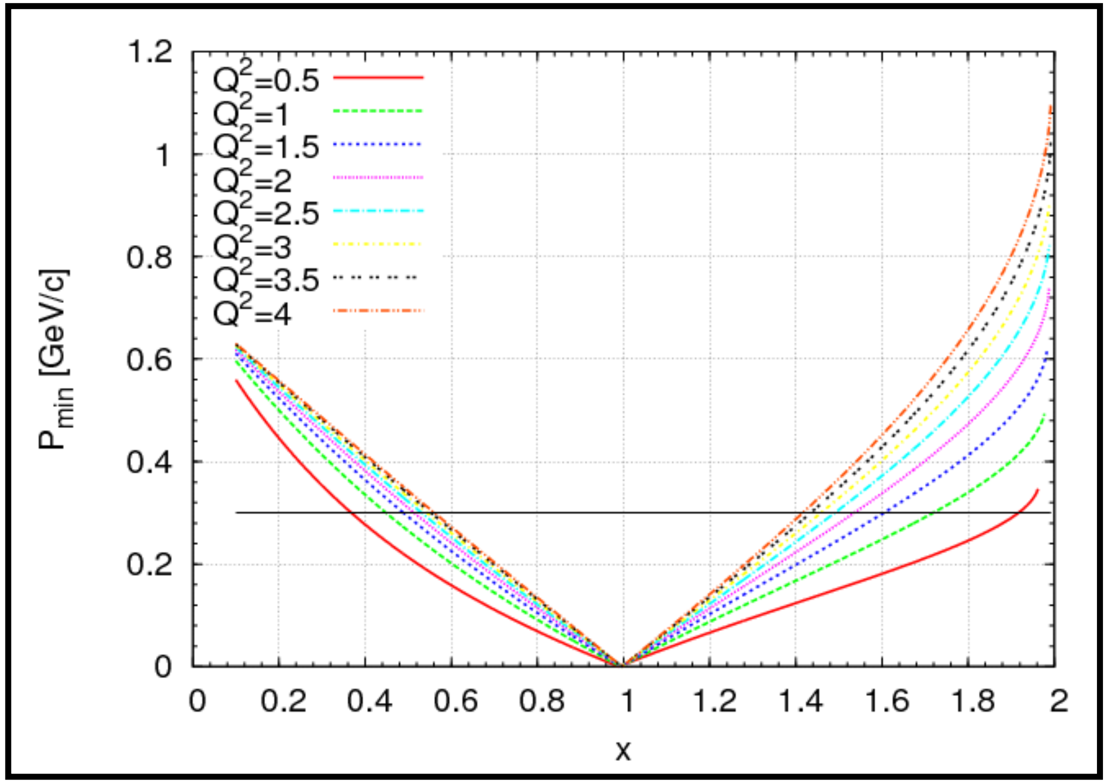
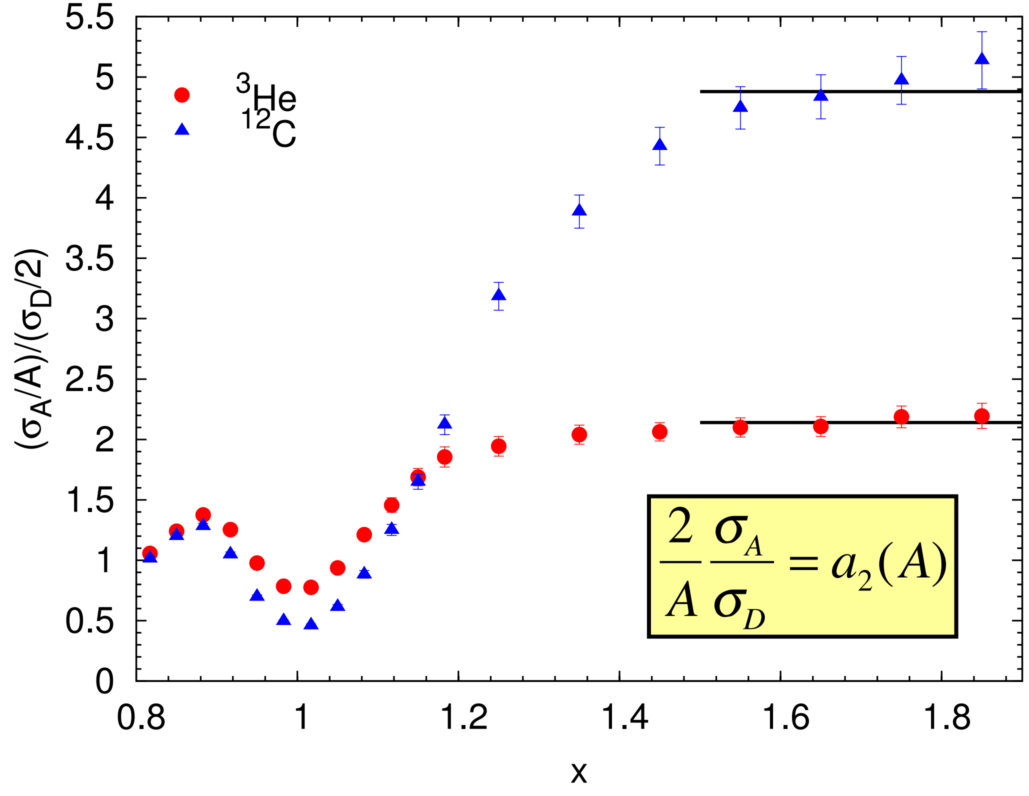


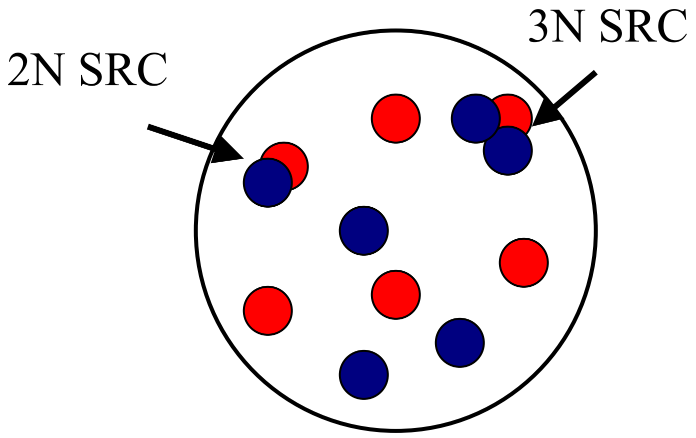
*Figure courtesy N. Fomin, after Frankfurt, Sargsian, and Strikman, **Int.J.Mod.Phys. A23 (2008) 2991-3055***

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.)



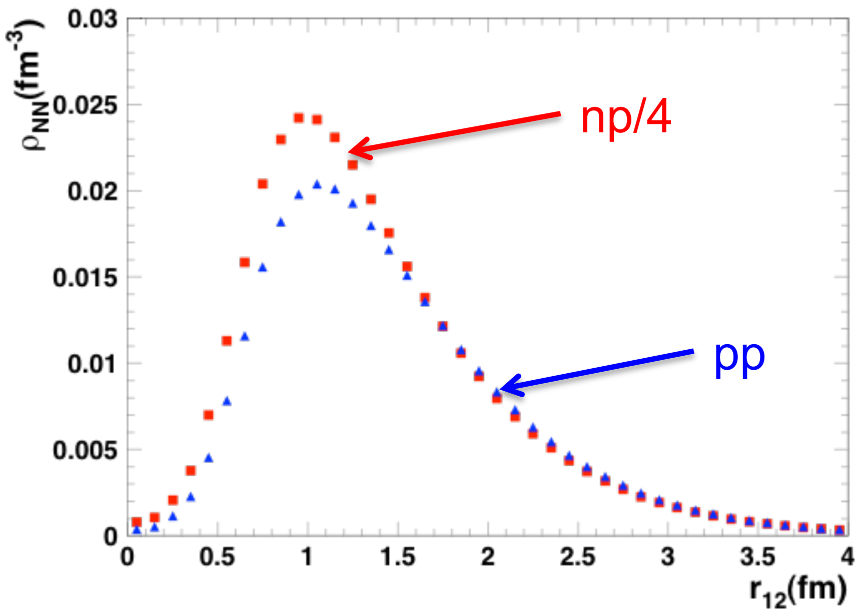


1.4<x<2 => 2 nucleon correlation

2.4<x<3 => 3 nucleon correlation

EMC Effect and Correlated Nucleons

^{4}He 2-body density



S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)

High momentum nucleons from SRCs emerge from tensor part of *NN* interaction – *np* pairs dominate

→ Probability to find 2 nucleons "close" together nearly the same for *np, nn, pp*

For $r_{12} < 1.7$ fm:

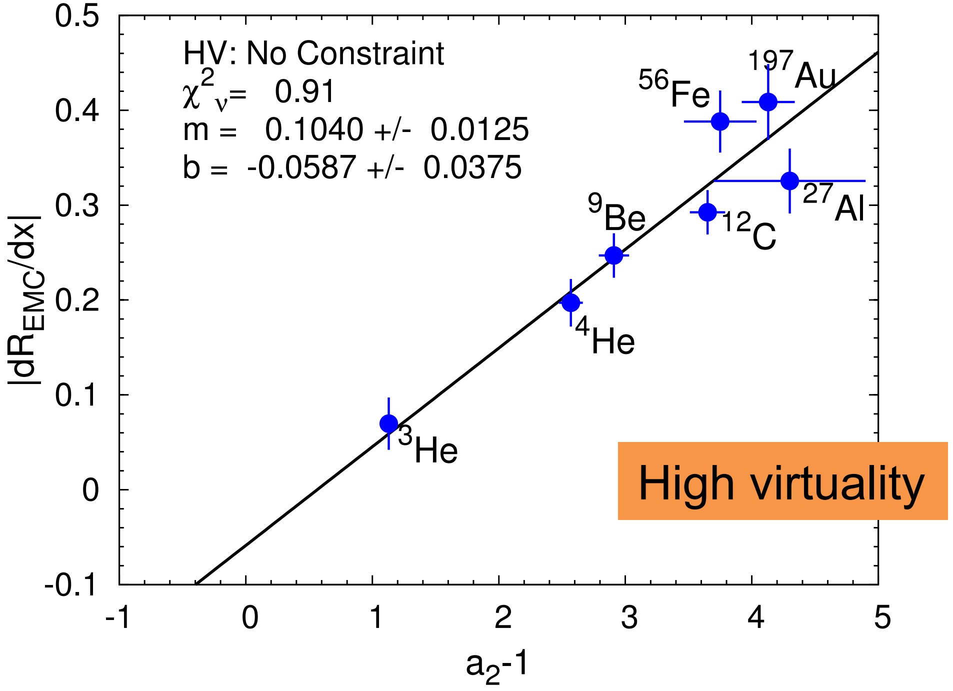
$$P_{pp} = P_{nn} \approx 0.8 P_{np}$$

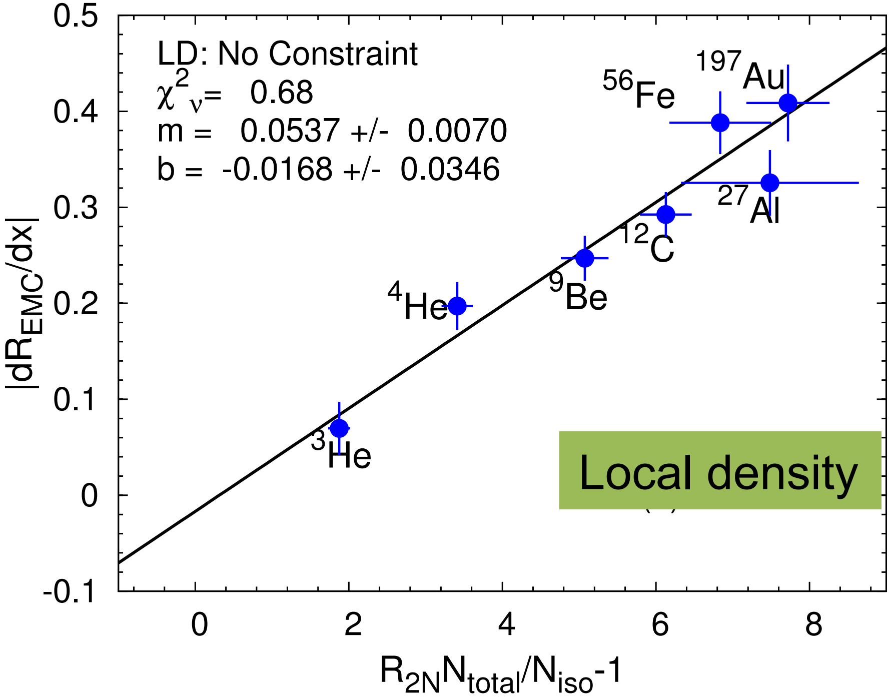
If EMC effect due to ***high virtuality***, EMC effect driven by contributions from np-pairs

→ If EMC effect from ***local density***, *np/pp/nn* pairs all contribute (roughly) equally

Nuclear Dependence of EMC and SRCs

Arrington et al, PRC 86, 065204 (2012)





a_2 ~ number of high momentum nucleons

R_{2N} ~ number of nucleons "close" together

Detailed study of nuclear dependence of EMC effect and SRCs does not favor either picture

Can we distinguish between these two pictures?

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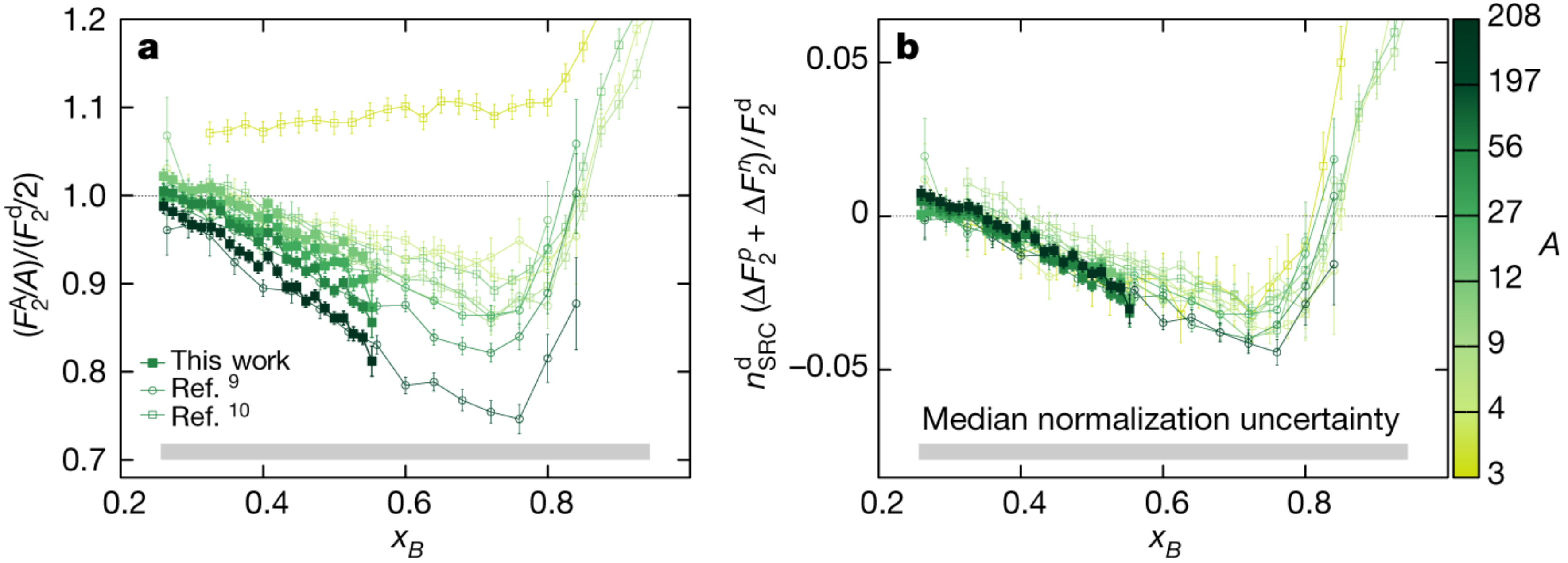
Describing the EMC Effect with SRCs

One can model the EMC effect using contributions from unmodified (mean field nucleons) and modified nucleons in SRCs

$$F_2^A = \left(Z - n_{SRC}^A\right) F_2^p + \left(N - n_{SRC}^A\right) F_2^n + n_{SRC}^A \left(F_2^{p*} + F_2^{n*}\right)$$
$$= ZF_2^p + NF_2^n + n_{SRC}^A \left(\Delta F_2^p + \Delta F_2^n\right)$$

In this picture np pairs dominate

→ Existing EMC data can be described by universal function



Schmookler et. al., Nature 566 (2019) no.7744, 354-358

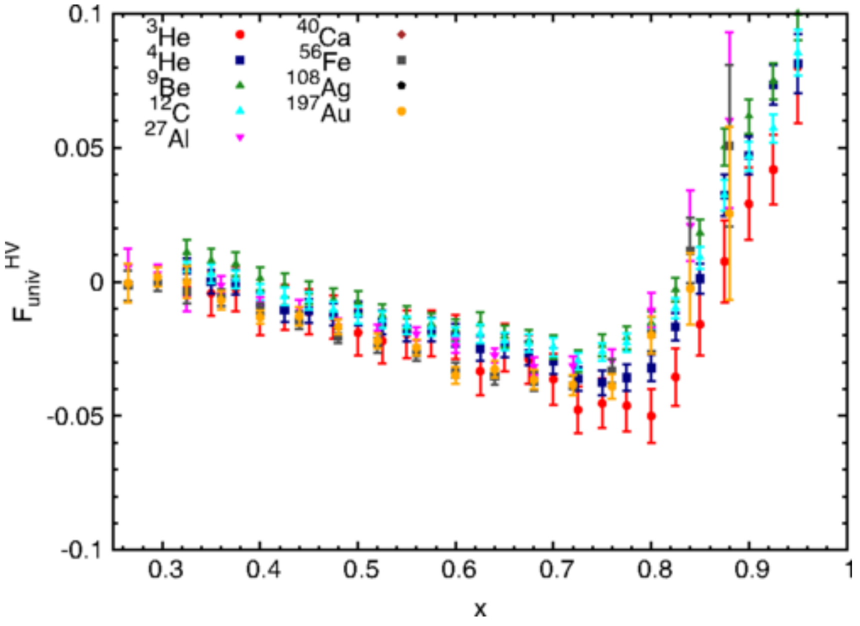
Describing the EMC Effect with SRCs

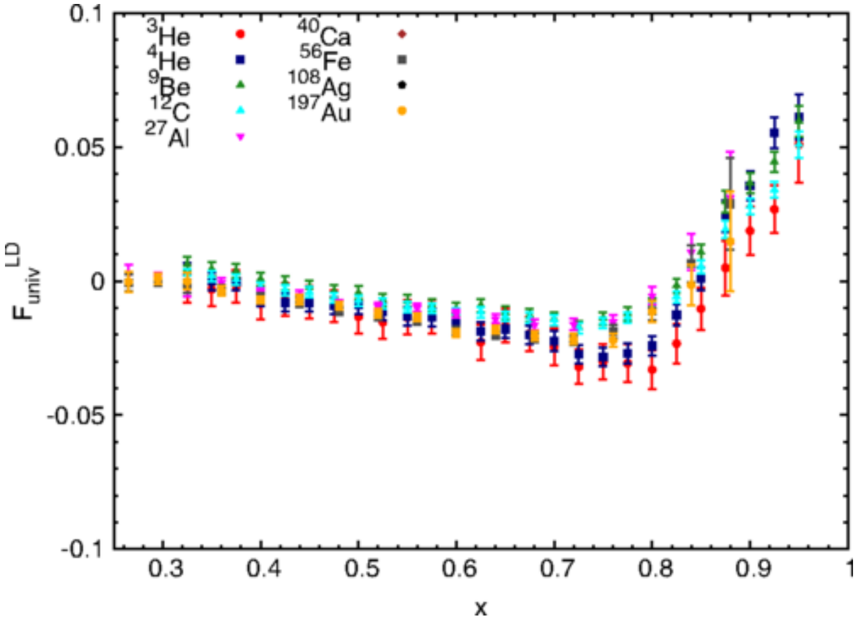
→ Universal function (from a_2) not unique
→ Alternate universal function based on R_{2N} also works well

$$F^{\text{HV}}_{\text{univ}} = \frac{(\sigma_A/\sigma_D) - (Z-N)\frac{F_2^p}{F_2^n} - N}{(A/2)a_2 - N}$$

$$F^{\text{LD}}_{\text{univ}} = \frac{R_{\text{EMC}} - 1}{R_{2N}\frac{A(A-1)}{2ZN} - 1}$$

Local density





Arrington and Fomin Phys. Rev. Lett. 123 (2019) no.4, 042501

Further Inclusive Studies of the EMC Effect

EMC effect has been studied extensively – what more can we learn via ***inclusive*** electron scattering?

→Additional light and heavy nuclei
- →Light nuclei allow use of "exact" nuclear wave functions
- →Explore EMC-SRC connection via A dependence at ~ fixed N/Z, N/Z dependence at ~ fixed A

→Flavor dependence: Is EMC effect different for up and down quarks?
- → See Rakitha Beminiwattha's talk from Tuesday

→Polarized EMC Effect

→Nuclear dependence of R

JLab E12-10-008: More detailed study of Nuclear Dependence

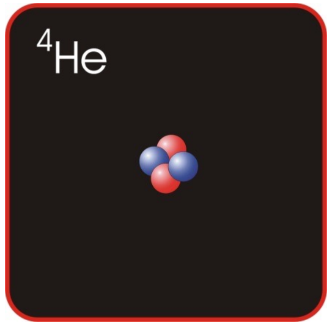
Spokespersons: J. Arrington, A. Daniel, N. Fomin, D. Gaskell

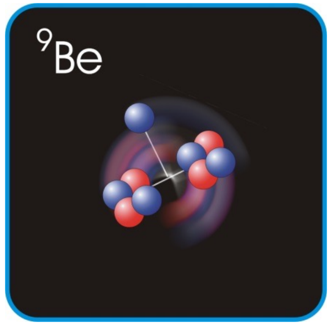
E03-103: EMC at 6 GeV

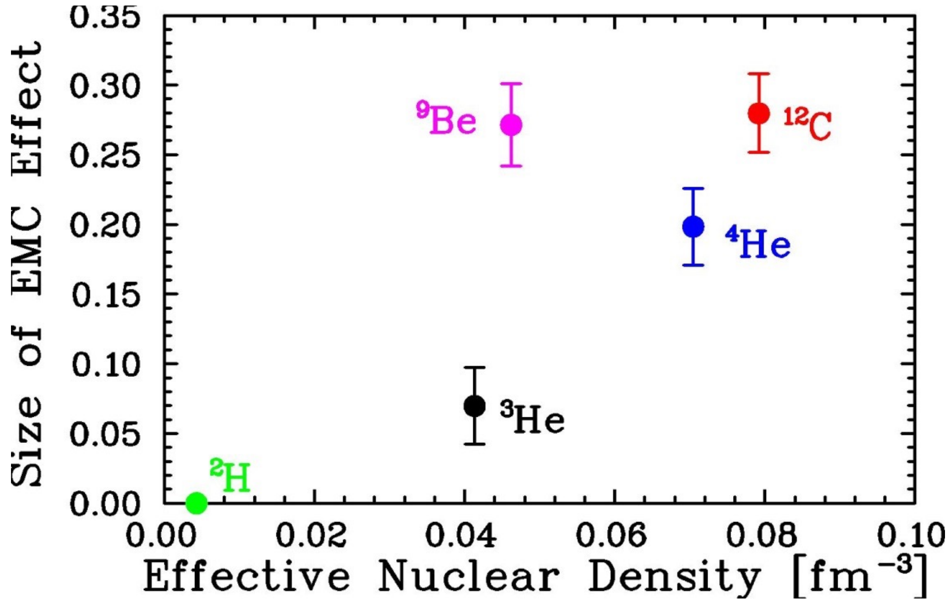
→ Focused on light nuclei

→ Large EMC effect for ^{9}Be

→ Local density/cluster effects?







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

E12-10-008: EMC effect at 12 GeV

→ Higher Q^2, expanded range in x (both low and high x)

→ Light nuclei include ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{12}C

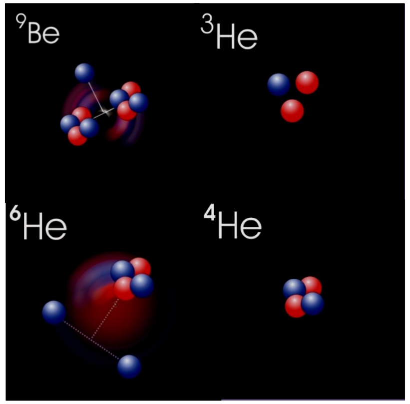
→ Heavy nuclei include ^{40}Ca, ^{48}Ca and Cu and additional heavy nuclei of particular interest for EMC-SRC correlation studies

JLab: E12-10-008 (EMC) and E12-06-105 (x>1) – Exploring the EMC-SRC Connection

- Both experiments use wide range of nuclear targets to study impact of cluster structure, separate mass and isospin dependence on SRCs, nuclear PDFs
- Experiments will use a common set of targets to provide more information in the EMC-SRC connection

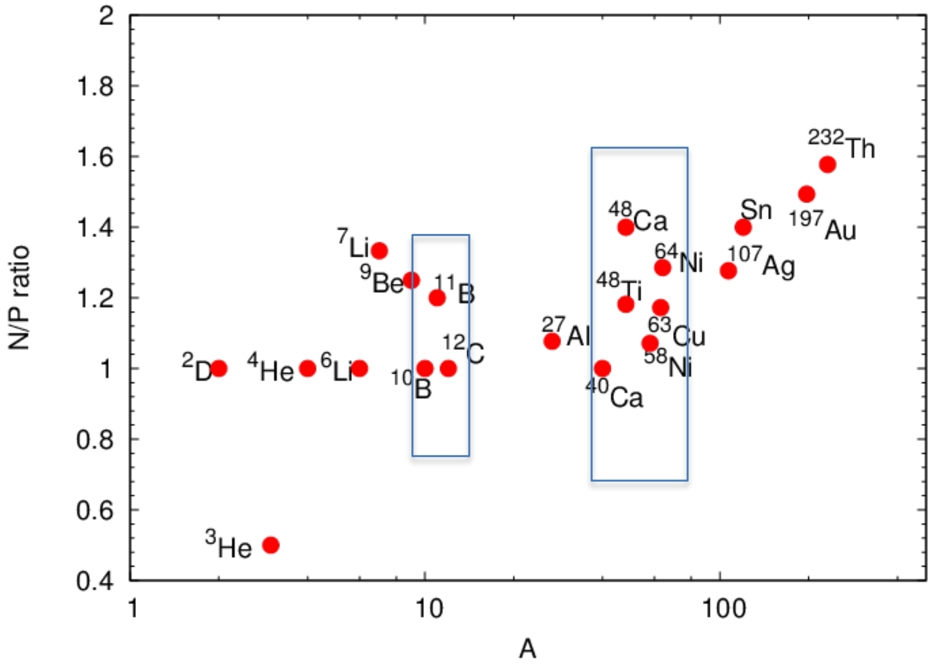
Light nuclei: Reliable calculations of nuclear structure (e.g. clustering)

^{1}H	^{6,7}Li
^{2}H	^{9}Be
^{3}He	^{10,11}B
^{4}He	^{12}C



Heavier nuclei: Cover range of N/Z at ~fixed values of A

^{27}Al	^{64*}Cu
^{40*,48}Ca	^{108*}Ag
^{48}Ti	^{119*}Sn
^{54}Fe	^{197*}Au
^{58,64}Ni	^{232}Th

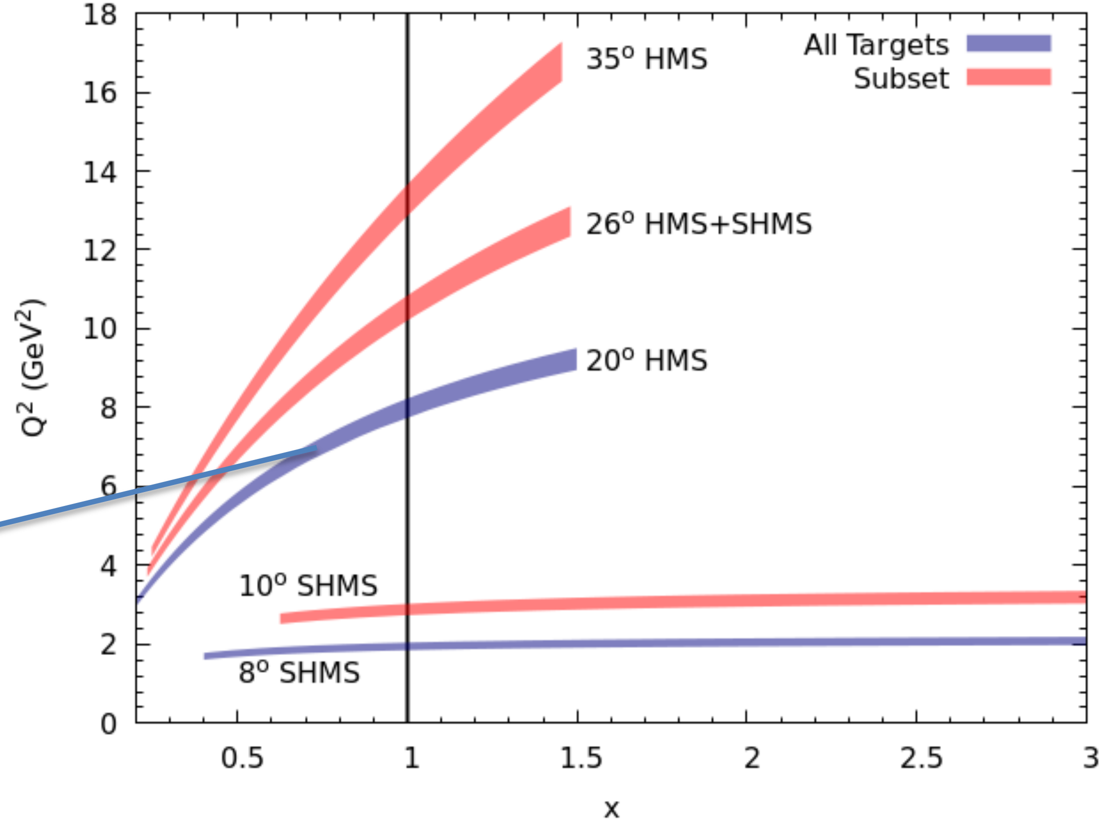


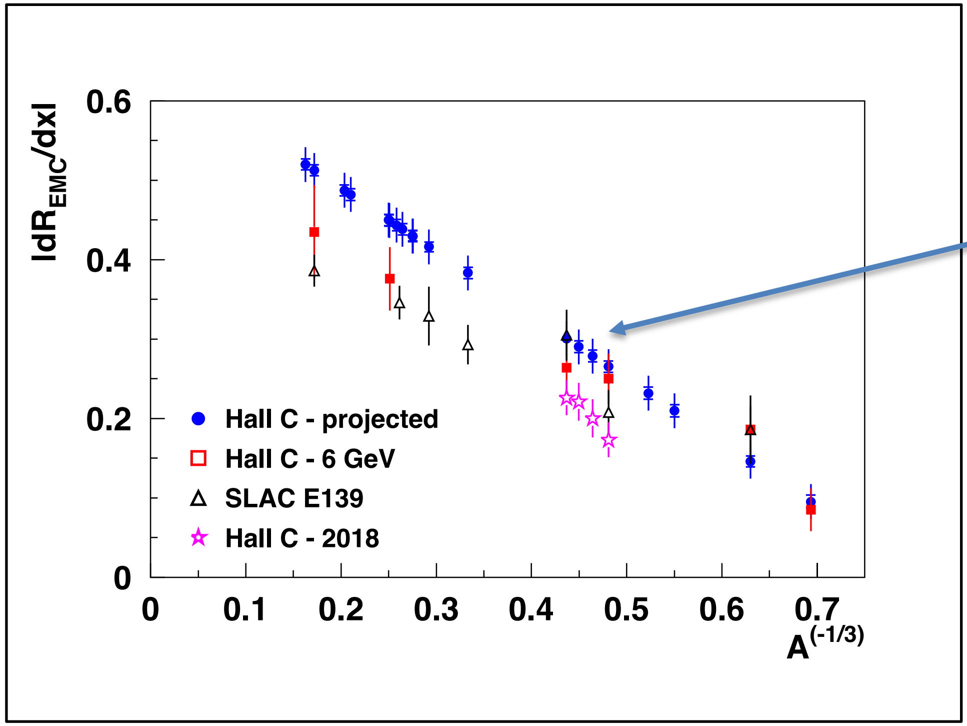
E12-10-008 (EMC) and E12-06-105 (x>1) Status

Completed running this year

→ Large number of targets required 2 different solid target ladders, and 15K→4K cryogen switch for H/D→^{3}He/^{4}He running

→ Calibrations, etc. underway – hope to have preliminary results by DNP





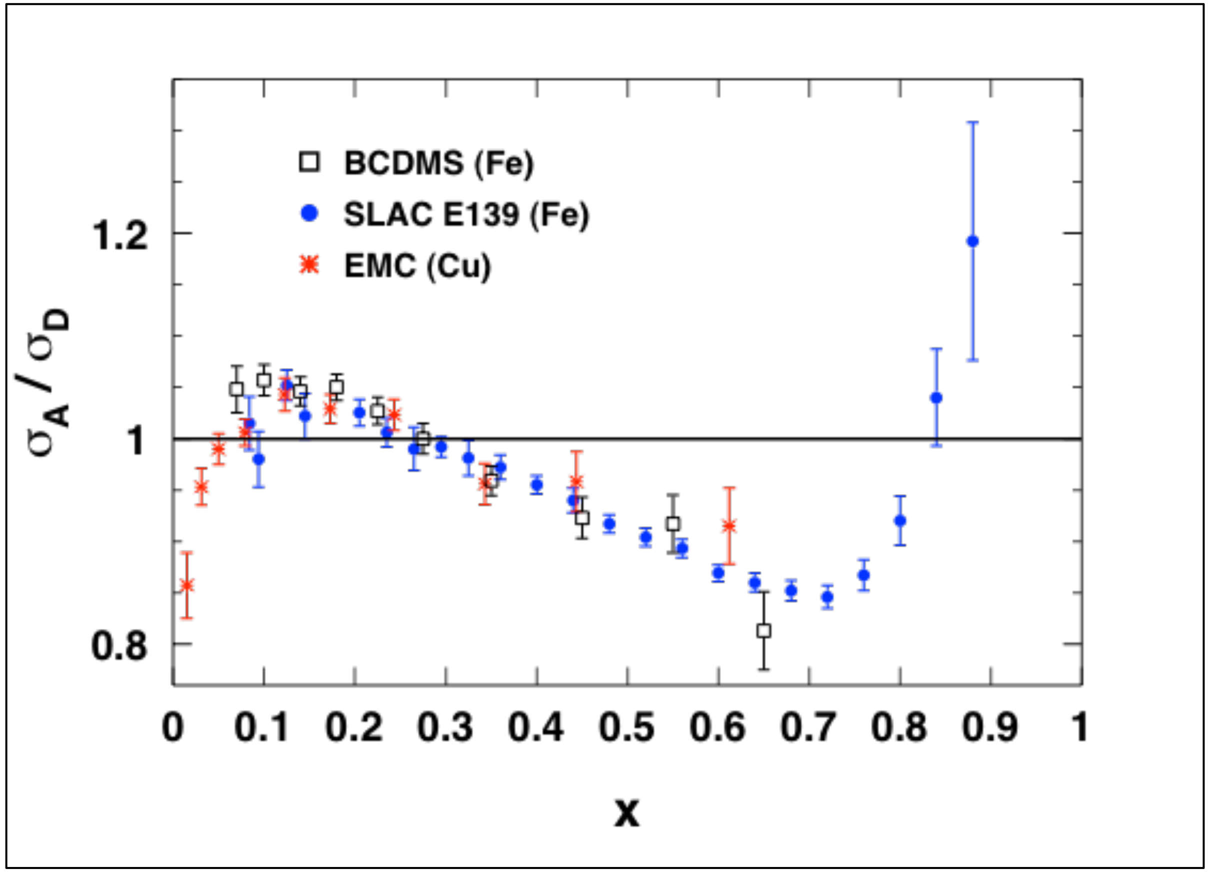
EMC Effect and Nuclear Dependence of R

The EMC Effect provides information about nuclear PDFs

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

The cross section ratio, σ_A/σ_D is typically taken to be interchangeable with the structure function ratio, F_2^A/F_2^D

→ Only true if ε=1 or R_A=R_D



$$\frac{\sigma_A}{\sigma_D} = \frac{F_2^A}{F_2^D}\left(\frac{1+R_D}{1+R_A}\right)\left(\frac{1+\epsilon R_A}{1+\epsilon R_D}\right)$$

$$R = \frac{\sigma_L}{\sigma_T} \qquad F_1 = \frac{KM}{4\pi^2\alpha}\sigma_T \qquad F_2 = \frac{K}{4\pi^2\alpha}\frac{\nu}{(1+\nu^2/Q^2)}(\sigma_T+\sigma_L)$$

World Data on Nuclear Dependence of R

Model-independent extraction of *R* requires L-T separation

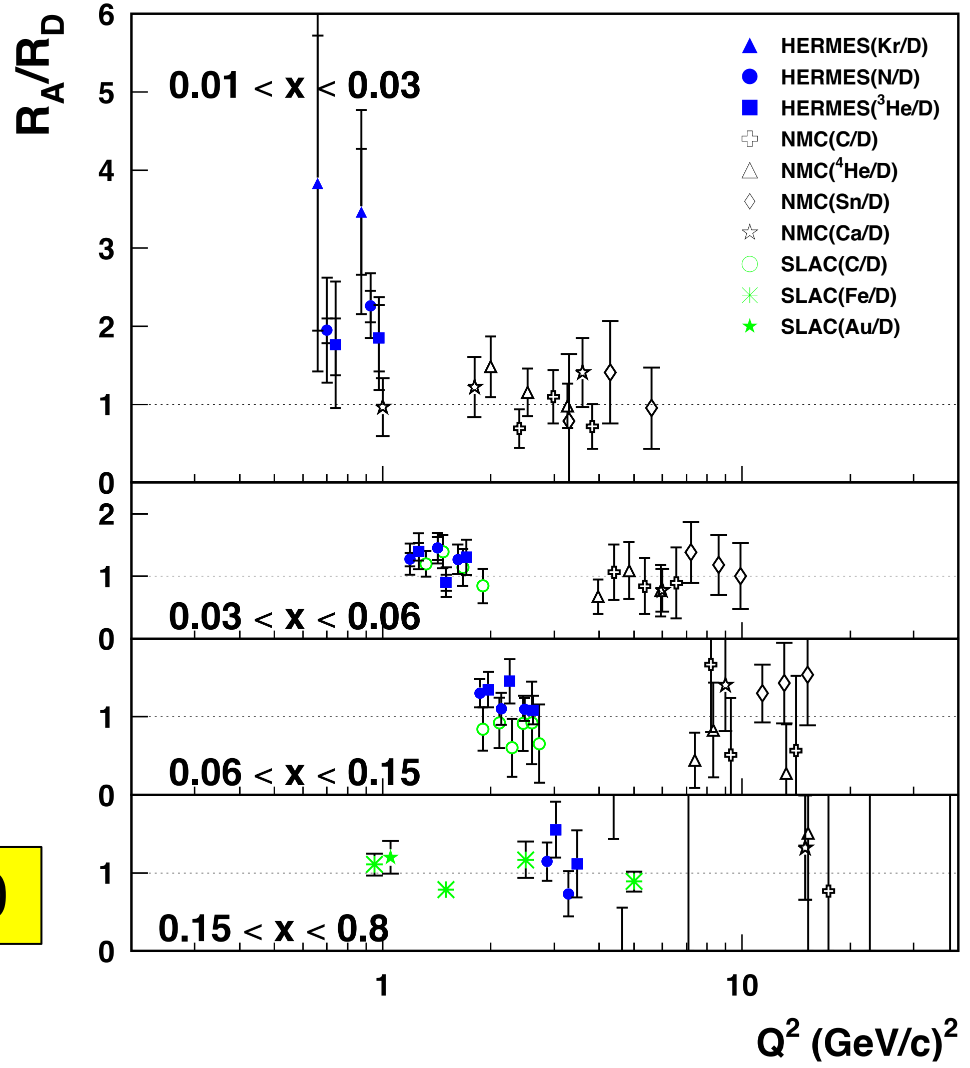
→ Bulk of world data on nuclear dependence of *R* comes from global fit to unseparated cross sections

→ Example: NMC fit data to 4 parameters

$$F_2^{Sn}/F_2^{C} = (a_1 + a_2 \ln Q^2)(1 + a_3/Q^2)$$

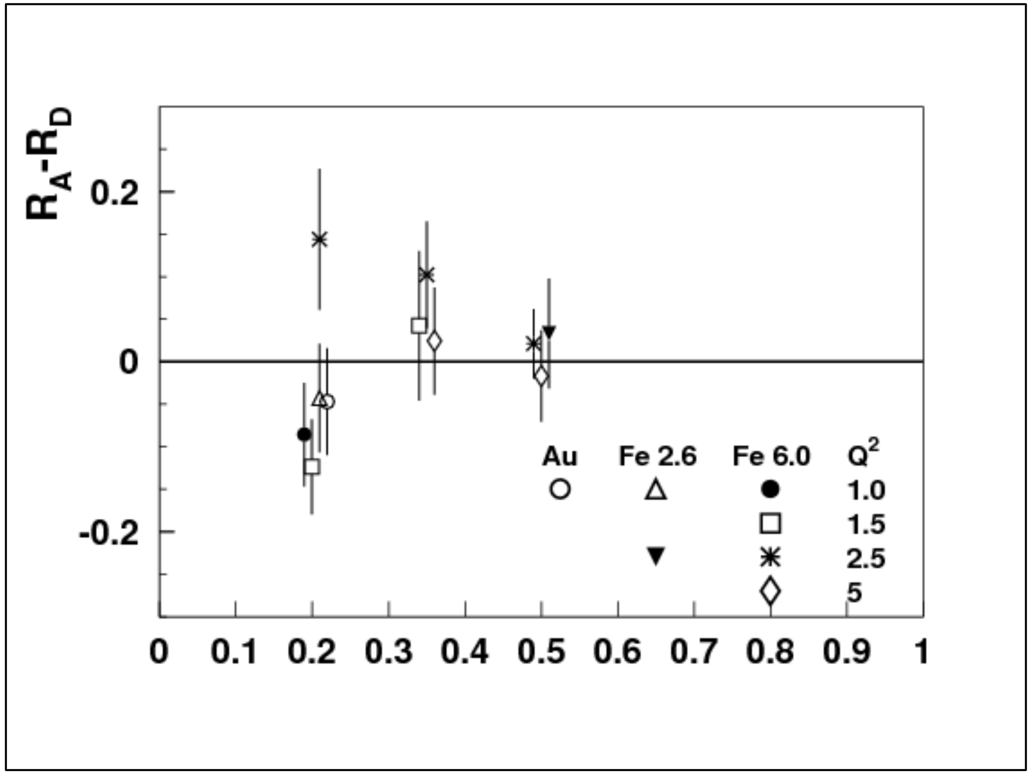
4th parameter: $\Delta R = R^{Sn} - R^{C}$

Only true L-T separated data from SLAC E140



SLAC E140

Nuclear dependence of $R=\sigma_L/\sigma_T$ extracted via measurement of ε dependence of σ_A/σ_D



[E140 Phys. Rev. D 49 5641 (1993)]

$$\frac{\sigma_A}{\sigma_D} = \frac{\sigma_A^T}{\sigma_D^T}\left[1 + \frac{\epsilon}{1+\epsilon R_D}(R_A - R_D)\right]$$

SLAC E140 Measurements

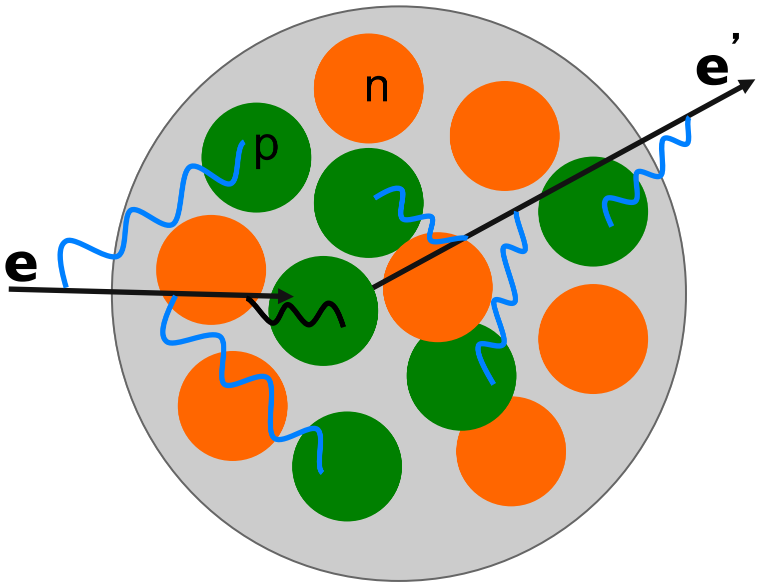
x=0.2, 0.35, 0.5
Q^2 = *1.0, 1.5, 2.5, 5.0* GeV^2
Iron and Gold targets

$R_A - R_D$ consistent with zero within errors

Possible issue:

No Coulomb corrections were applied

Coulomb Distortion in Heavy Nuclei



Electrons scattering from nuclei can be accelerated/decelerated in the Coulomb field of the nucleus

→ This effect is in general **NOT** included in most radiative corrections procedures

→ *Note: Coulomb Corrections perhaps more appropriately described in terms of multi-photon exchange, but Coulomb Corrections provide convenient shorthand*

In a simple picture – Coulomb field induces a change in kinematics in the reaction

Effective Momentum Approximation (EMA)

$E_e \rightarrow E_e + V_0$

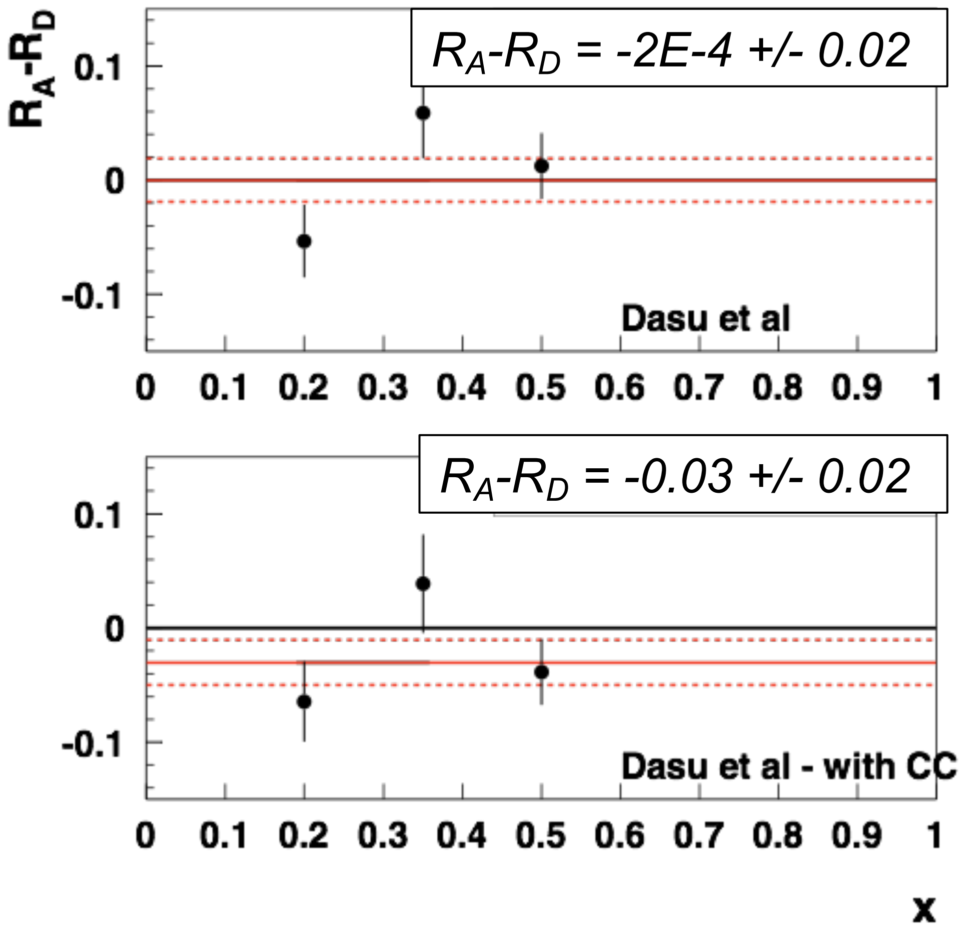
$E_e' \rightarrow E_e' + V_0$

$V_0 = 3\alpha Z/2R$ ⟵ Electrostatic potential energy at center of nucleus

R_A-R_D: E140 Re-analysis

Re-analyzed E140 data using Effective Momentum Approximation for published "Born"-level cross sections

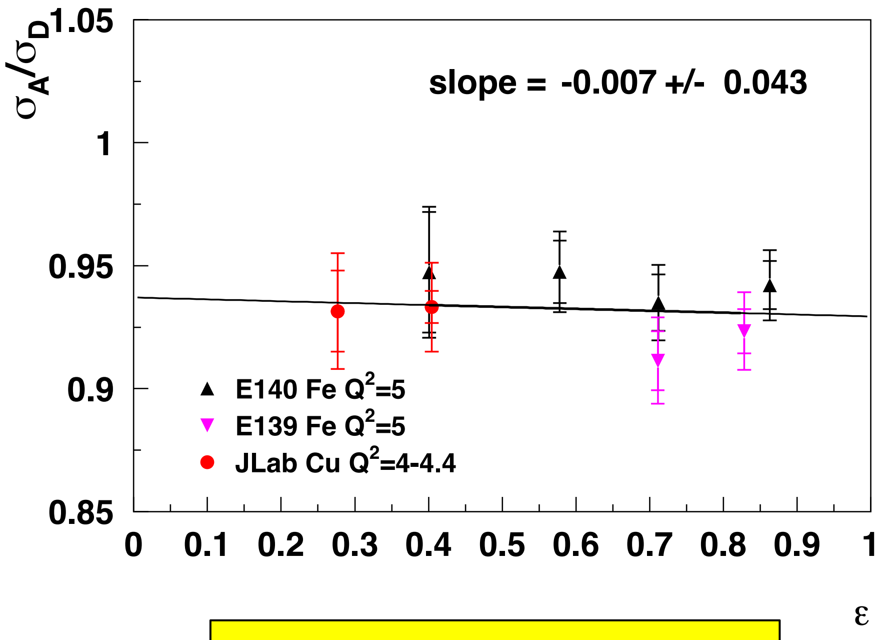
→ Total consistency requires application to radiative corrections model as well



Including Coulomb Corrections yields result 1.5 σ from zero when averaged over ***x***

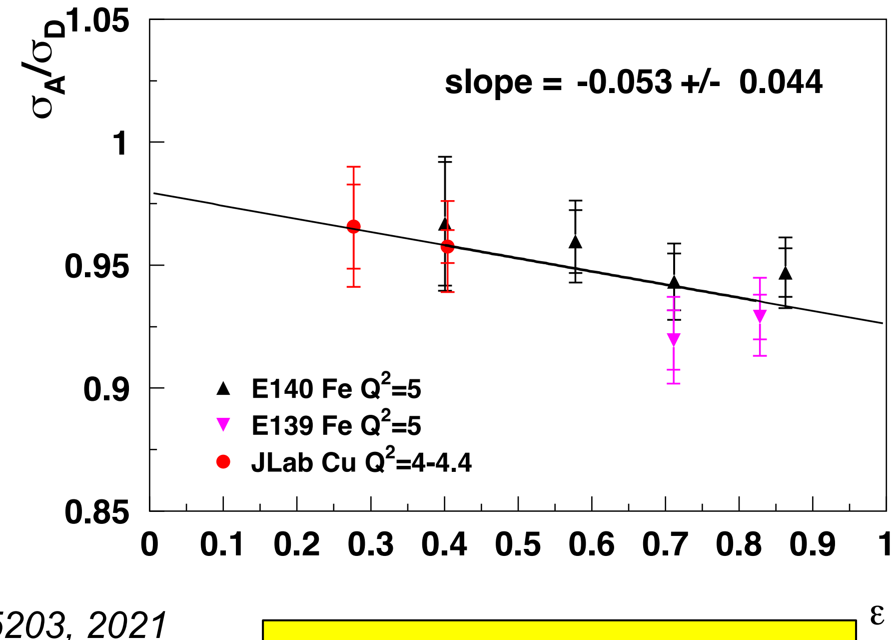
SLAC/JLab Combined Analysis

x=0.5, Q^2=4-5 GeV^2



No Coulomb Corrections

PRC 104(6):065203, 2021



with Coulomb Corrections

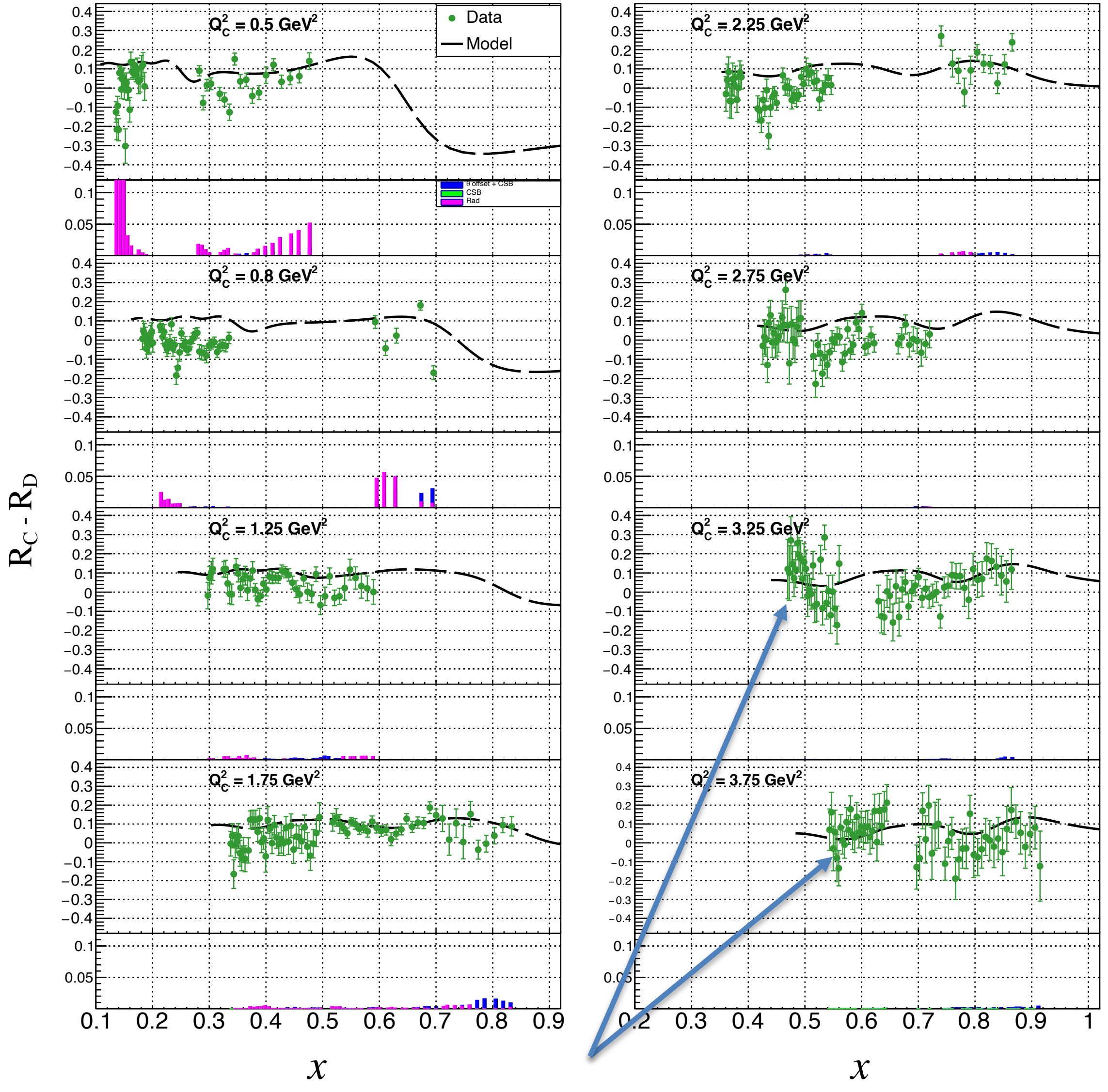
Combined analysis of SLAC E139, E140 and JLab 6 GeV data for Fe/Cu at *x=0.5*, *Q^2~5 GeV^2*

JLab Hall C Resonance Region Data

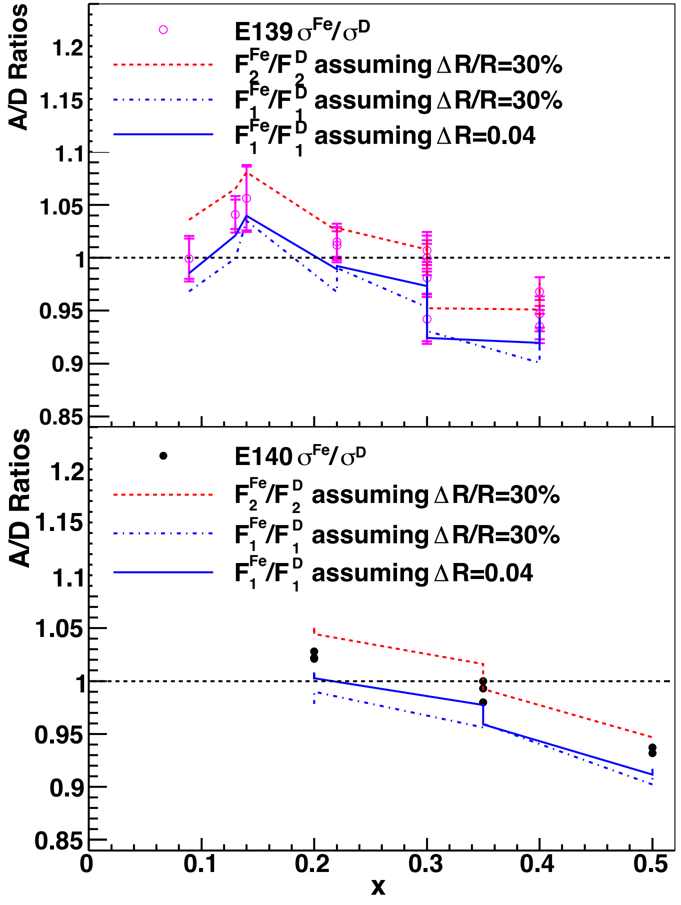
E04-001 (Hall C, 6 GeV) measured nuclear dependence of *R* in resonance region

While DIS data suggest R_A-R_D<0 at large x/Q^2, 6 GeV suggests R_A-R_D>0

The 2 results need to be reconciled
→ Large x result dominated by uncertainties in comparing data from different experiments



Consequences of non-zero R_A-R_D



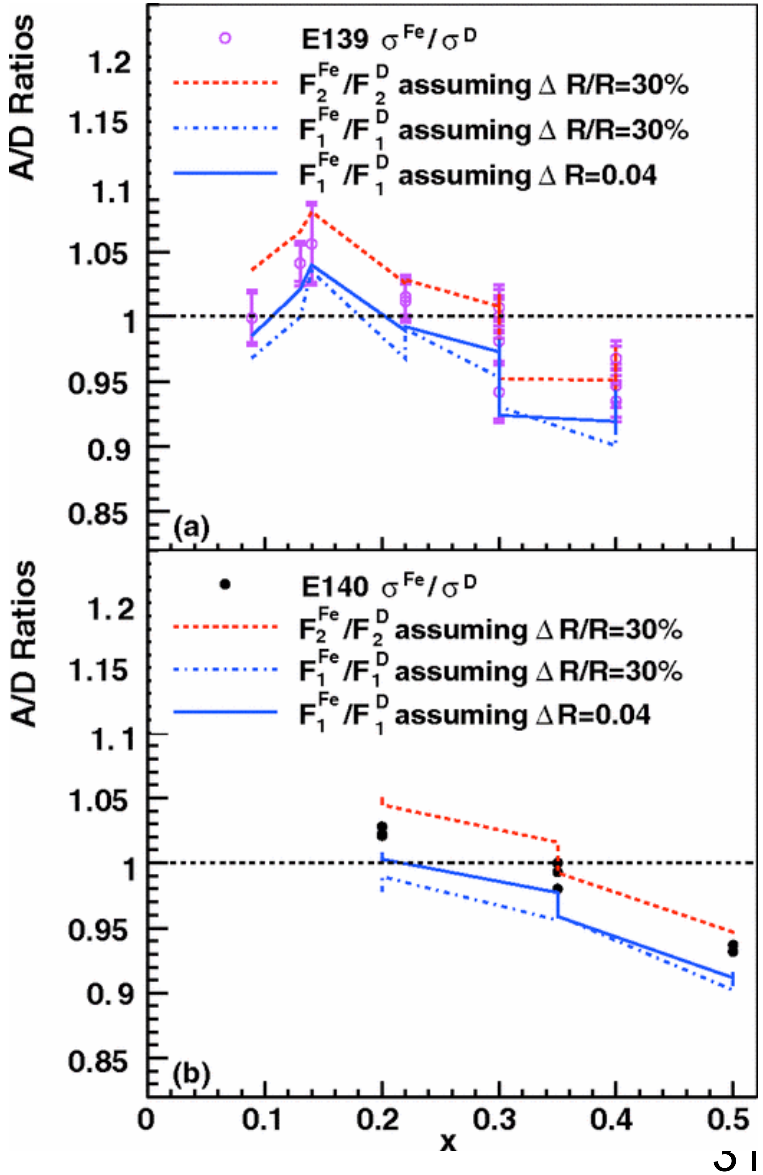
<u>Implications of non-zero RA-RD</u>

→ F1, F2 not modified in the same way in nuclei → impact on EMC effect?

→ Anti-shadowing a longitudinal photon effect → gluons?

→ Parton model: $R=4\langle k_T^2\rangle/Q^2$, $\langle k_T^2\rangle$ smaller for bound nucleons? [A. Bodek, PoS DIS2015 (2015) 026]

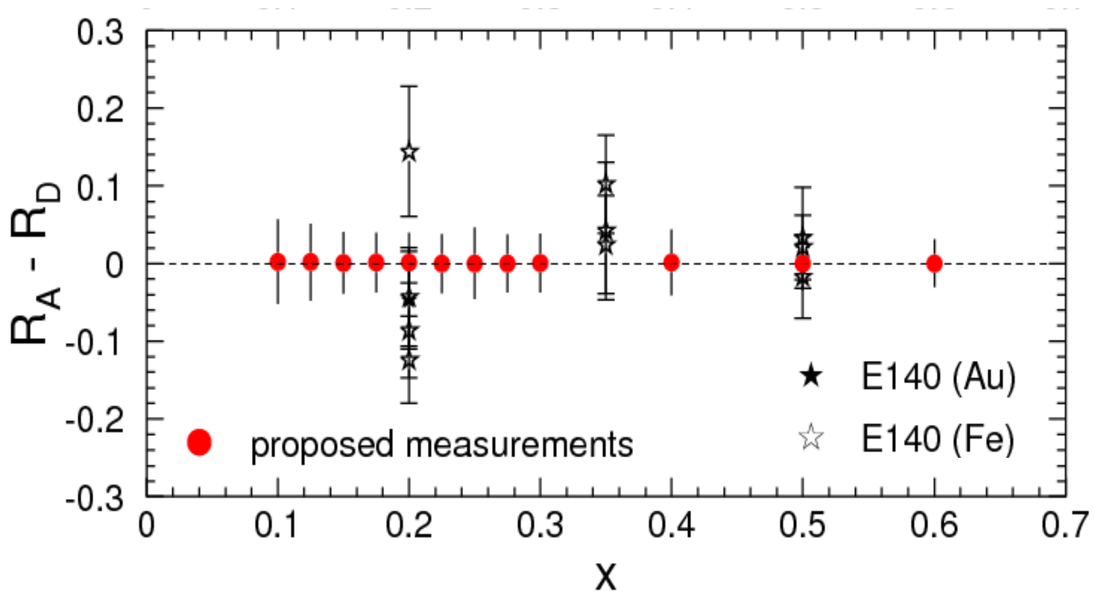
New, precision data required
→ E12-14-002

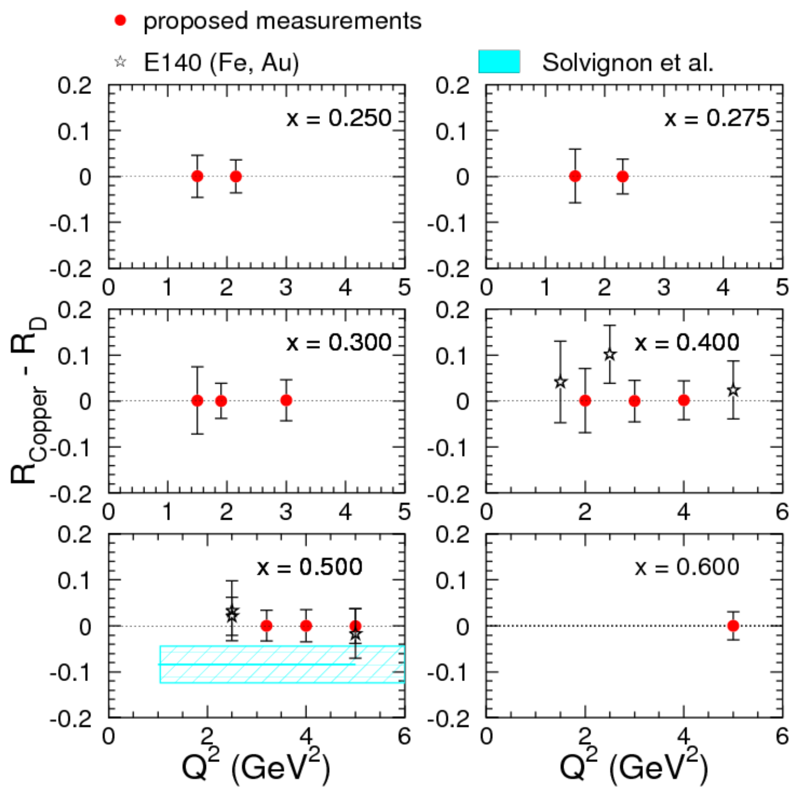


Phys. Rev. C, 86:045201, 2012

Hall C E12-14-002

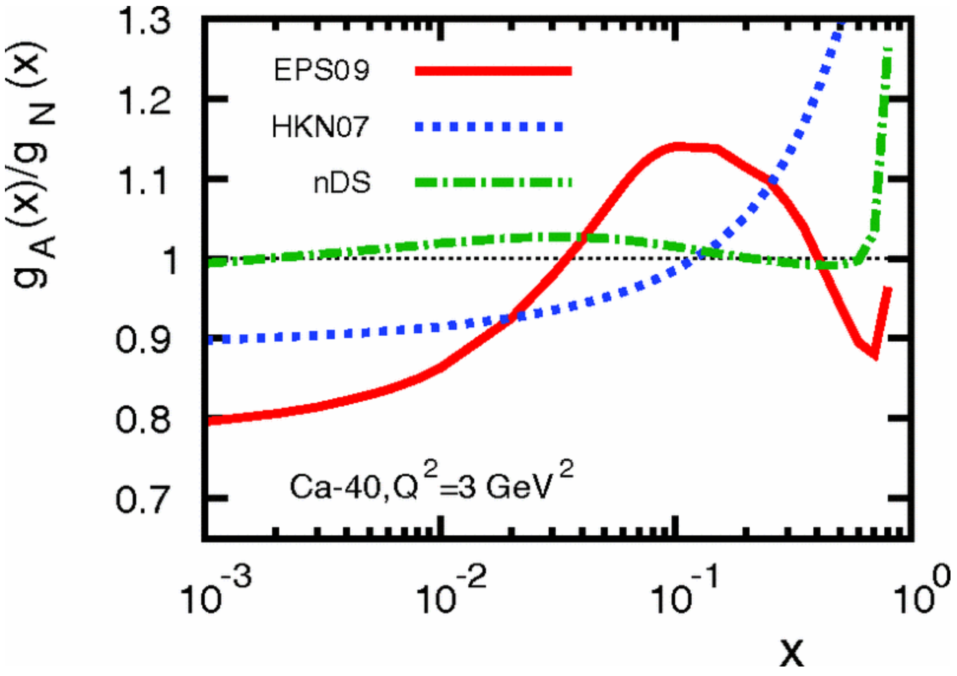
- Precision Measurements and Studies of a Possible Nuclear Dependence of $R=\sigma_L/\sigma_T$
  [S. Alsalmi, M.E. Christy, D. Gaskell, W. Henry, S. Malace, D. Nguyen, T.J. Hague, P. Solvignon]
- Measurements of nuclear dependence of structure functions, R_A-R_D via direct L-T separations
- Measurements with H, D, C, Cu, Au targets → will provide absolute cross sections, unseparated ratios (*A/D*, *D/H*), separated structure functions (F_1, F_2), absolute values of *R*

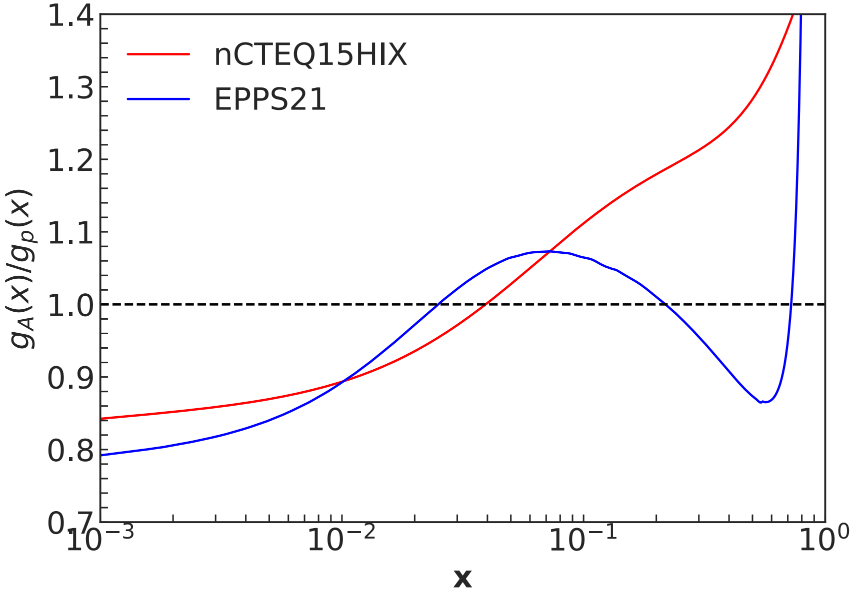




Hall C E12-14-002: Gluons in the nucleus

$$F_L(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \left[\frac{8}{3}F_2(z,Q^2) + \frac{40}{9}\left(1-\frac{x}{z}\right) zG(z,Q^2)\right]\frac{dz}{z^3}.$$





F_L sensitive to nuclear gluon distribution → measurements at large/moderate x constrain gluons at low x via momentum sum rule

Hall C E12-14-002: EMC-SRC Correlation

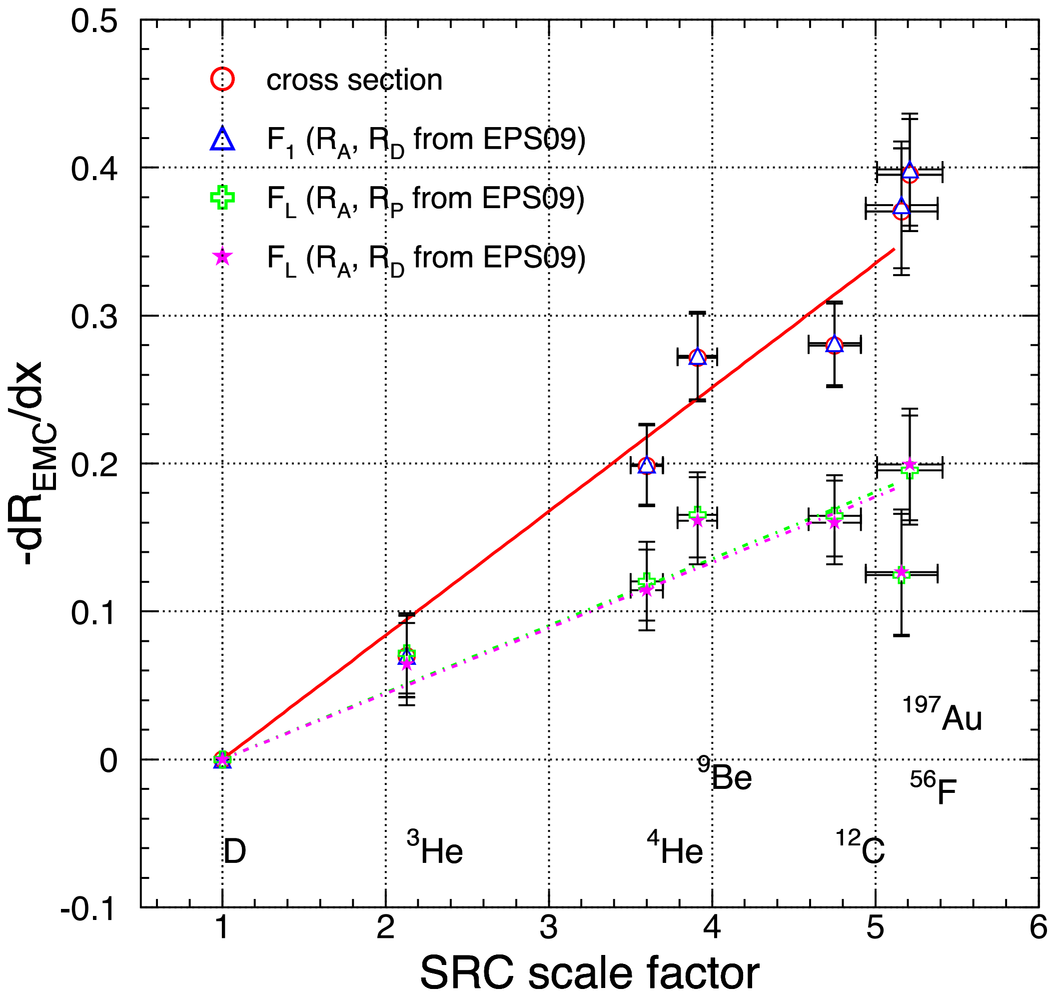
Observed correlation between EMC effect and SRCs from unseparated ratios

EMC Effect and SRCs arise from common origin? SRCs serve as “measurement” of nucleon virtuality or local density?

→ If ΔR is non-zero, this correlation will not be the same for all structure functions (F_1, F_2, F_L)

→ If longitudinal photons are significant contribution to EMC effect, what does this mean for origin of EMC effect?

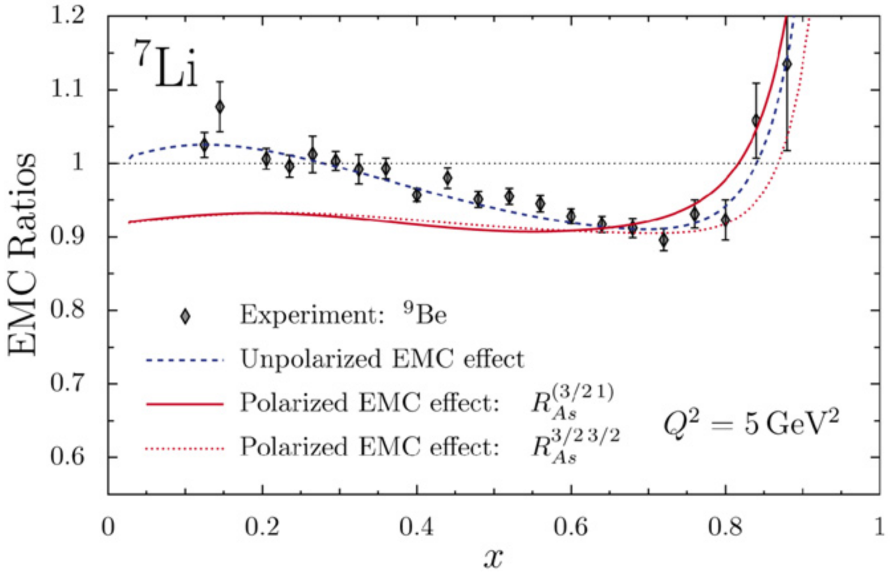
→ Will correlation be linear for all structure functions?

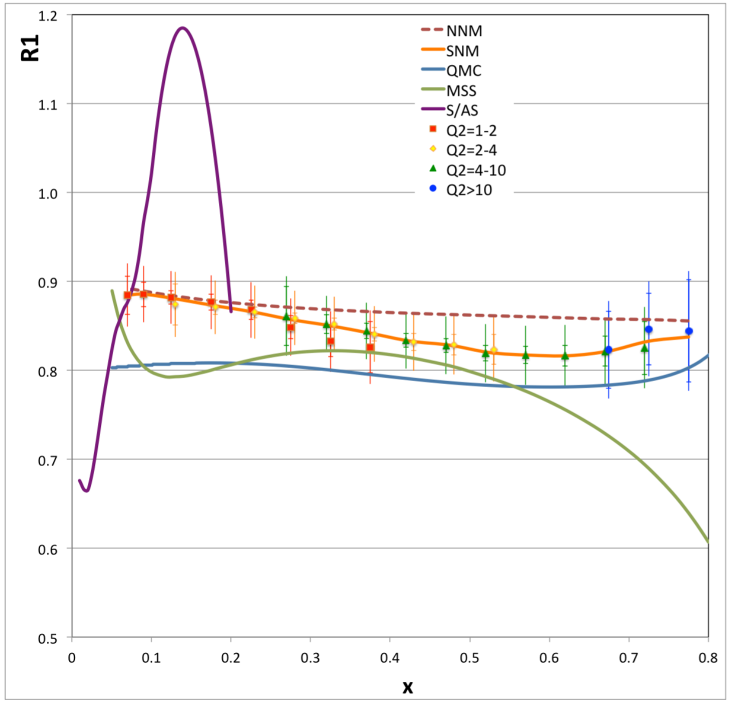


Polarized EMC Effect

Similar to unpolarized DIS, can define nuclear ratio for polarized structure functions

$$R = \frac{F_2^A}{ZF_2^p + (A-Z)F_2^n} \Rightarrow R = \frac{g_{1A}}{P_p g_{1p} + P_n g_{1n}}$$





JLab E12-14-001 in Hall B
→Uses ^{7}LiD solid polarized target

Polarized EMC effect provides another possible handle on connection to SRCs
→ Smaller fraction of polarized nucleons involved in SRCs

The EMC Effect via Inclusive Processes

- Hall C E12-10-008 and E12-06-105 have essentially exhausted the available phase space (nuclear targets) for "standard" EMC Effect/x>1 measurements
- Other inclusive measurements
  - Polarized EMC Effect
  - PV processes
  - **L-T separations**
- A possible nuclear dependence of $R=\sigma_L/\sigma_T$ would have profound impact on our understanding of the EMC effect
  - Cross section ratios not structure function ratios → impact on nuclear PDFs
  - What is the role of longitudinal photons at large *x* (EMC) and in the anti-shadowing region?

EXTRA

Application: R_A-R_D

DIS/Inelastic cross section:

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 (E')^2}{Q^4 \nu}\left[F_2(\nu,Q^2)\cos^2\frac{\theta}{2} + \frac{2}{M\nu}F_1(\nu,Q^2)\sin^2\frac{\theta}{2}\right]$$

$F_2(x) = \sum_i e_i^2 x q_i(x)$ ⟵ Quark distribution functions

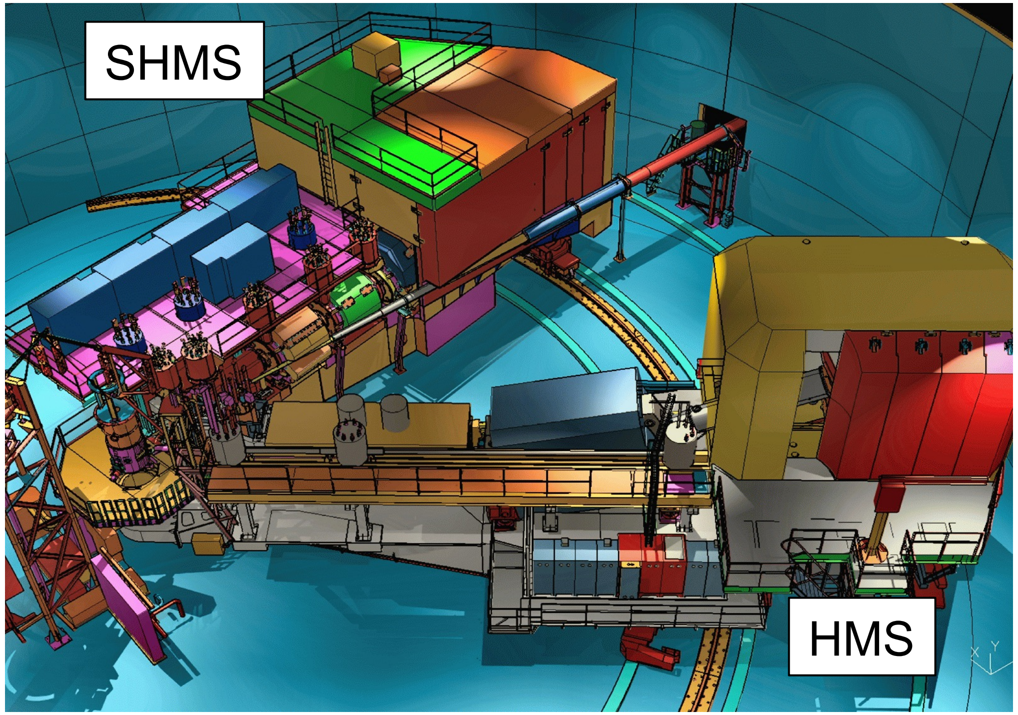
$$\frac{d\sigma}{d\Omega dE'} = \Gamma\left[\sigma_T(\nu,Q^2) + \varepsilon\sigma_L(\nu,Q^2)\right]$$

$F_1 \; \alpha \; \sigma_T$ F_2 linear combination of σ_T and σ_L

Measurements of EMC effect often assume $\boldsymbol{\sigma_A/\sigma_D = F_2^A/F_2^D}$
→ this is true if $R=\sigma_L/\sigma_T$ is the same for A and D

SLAC E140 set out to measure $R=\sigma_L/\sigma_T$ in deuterium and the nuclear dependence of R, i.e., measure R_A - R_D

E12-14-002



Spectrometers

HMS:
dΩ ~ *6* msr, P_0= *0.5 – 7 GeV/c*
θ_0=*10.5 to 80 degrees*
e ID via calorimeter and gas Cerenkov

SHMS:
dΩ ~ *4* msr, P_0= *1 – 11 GeV/c*
θ_0=*5.5 to 40 degrees*
e ID via heavy gas Cerenkov and calorimeter

Excellent control of point-to-point systematic uncertainties required for precise L-T separations
→ Ideally suited for focusing spectrometers

Perform L-T separations using same spectrometer for all ε points as much as possible