Nuclear Partons at Large x: The EMC Effect

Light Ion Physics in the EIC Era

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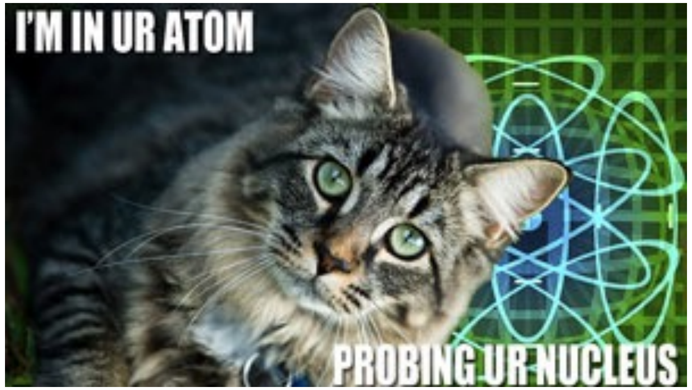
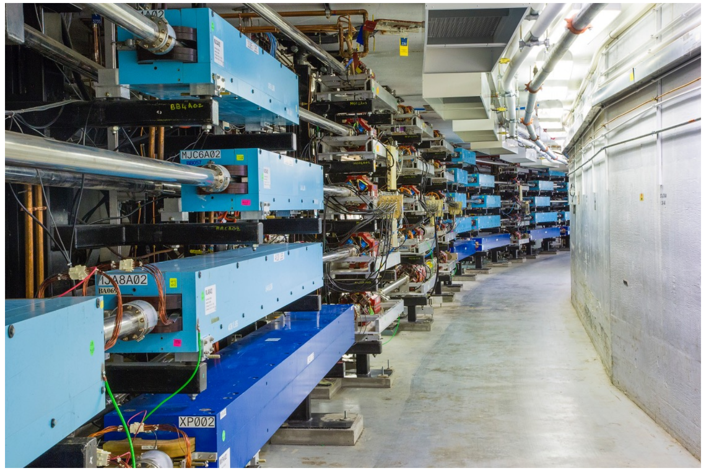
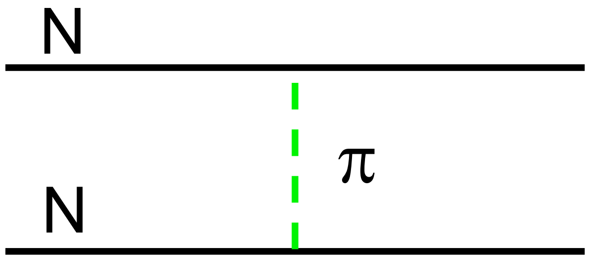




Describing the Strong Force

1935 – Hideki Yukawa proposed a theory of the strong force between nucleons involving exchange of (as yet) unknown particles → pions

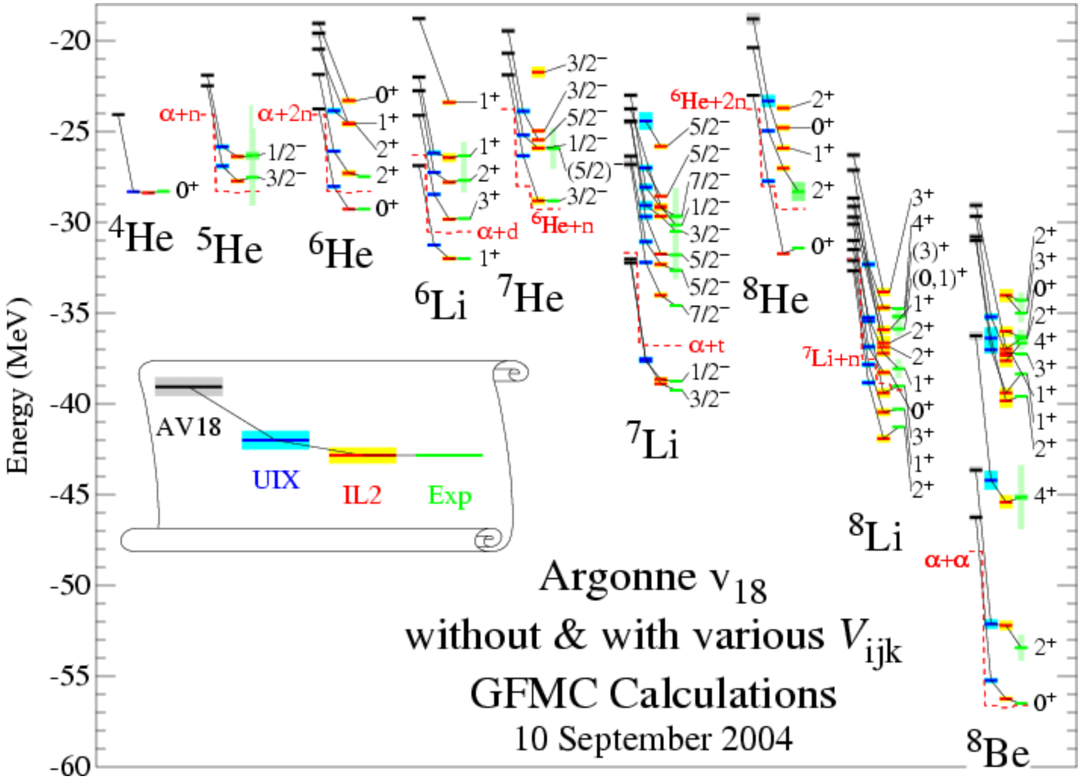


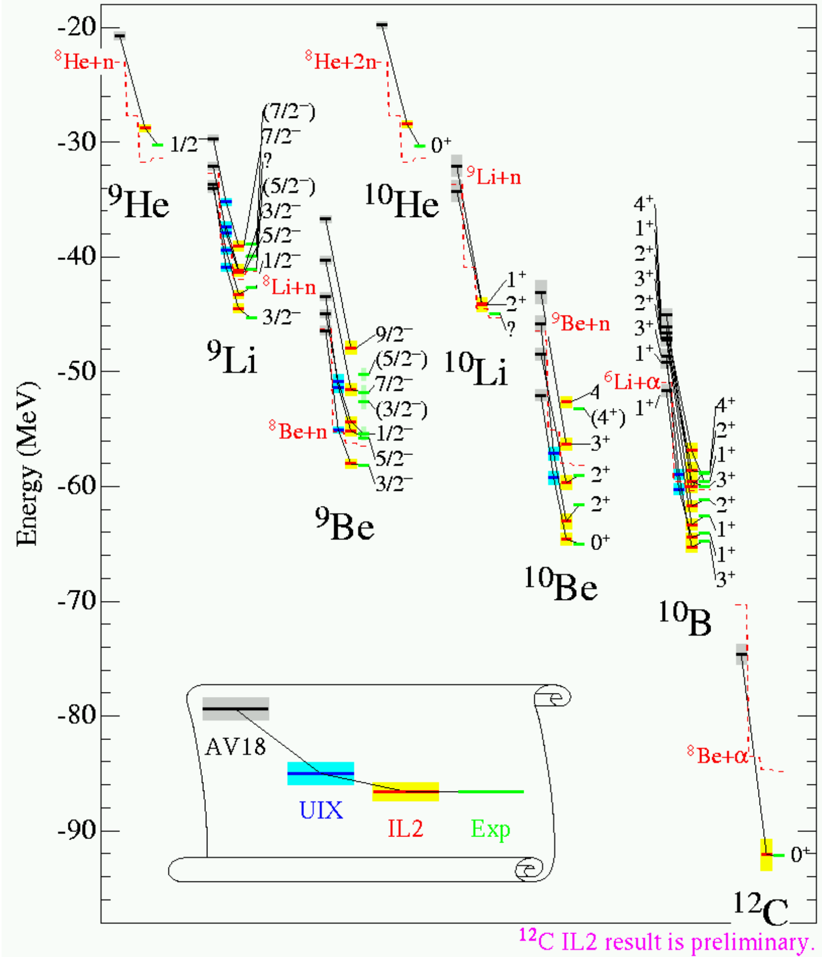
$$V(r) = \frac{-g^2}{4\pi}\frac{1}{r}e^{-\mu r}$$

Modern descriptions of interactions between nucleons are still based on this fundamental idea, but with many refinements

- Multiple pion exchange
- Include other exchange particles
- 3-body forces

Example: Argonne v18 Potential





- Starting from this “effective” model of interactions between protons and neutrons – one can build up any nucleus we want → (only limited by computing power)

Strong Interactions – QCD

- These days, we know the fundamental degrees of freedom are quarks and gluons
- Interactions between quarks and gluons, are governed by Quantum Chromodynamics
- Nucleon-nucleon interactions governed by the part of the quark-gluon interactions that "spill over outside the nucleon
- Unlike gravity and electromagnetism, interactions get stronger as particles get further apart → confinement
- 3 important points about QCD
  - It *cannot* be solved "exactly"
  - It *can* be solved approximately but only at very large energies (small distances)
  - It *can* also be solved numerically with a lot of computing power (Lattice QCD)

Meson exchange vs. QCD

Why is the effective theory of the interactions between nucleons (meson exchange) so successful?
→ Likely related to fundamental quantum mechanics → physics phenomena can be described by multiple, ***complete*** basis states

$$\sum_{\text{hadrons}} = \sum_{\text{quarks+gluons}}$$

In many situations one basis is more convenient than the other
→ Is there such a situation for quarks in nuclei?

CEBAF's Original Mission Statement

- *Key Mission and Principal Focus (1987):*
  - **The study of the largely unexplored transition between the nucleon-meson and the quark-gluon descriptions of nuclear matter.**

    The Role of Quarks in Nuclear Physics

- We can describe nuclei, for the most part, just using protons, neutrons, and other exchange particles: does there come a point at which we must describe in terms of quarks and gluons?
  - If not, why not?

Related Topics

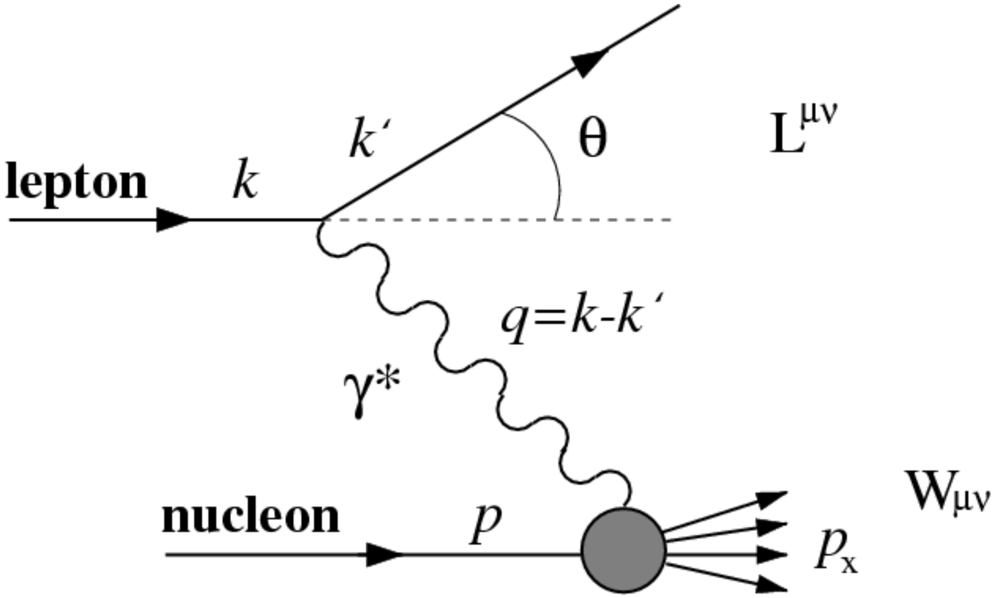
- ***Do individual nucleons change their size, shape, and quark structure in the nuclear medium?***

- ***How do quarks and gluons come together to determine the structure of the proton?***
  - What is the distribution of charge and magnetism in the nucleon?
  - How is the spin of the proton built up from quarks and gluons?

- ***What are the properties of the strong force ("QCD") in the regime where quarks are confined?***

Deep Inelastic Scattering

Cross section for inclusive lepton (electron) scattering:



$Q^2 = -q^2$
$\nu = E - E'$

$$\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{Q^4}\frac{E}{E'}L_{\mu\nu}W^{\mu\nu}$$

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 (E')^2}{Q^4}\left[W_2(\nu,Q^2)\cos^2\frac{\theta}{2} + 2W_1(\nu,Q^2)\sin^2\frac{\theta}{2}\right]$$

In the limit of large Q^2, structure functions scale

$$MW_1(\nu,Q^2) \rightarrow F_1(x)$$
$$\nu W_1(\nu,Q^2) \rightarrow F_2(x)$$

$$x = \frac{Q^2}{2M\nu}$$

F_2 and Parton Distributions

- F_2 interpreted in the quark-parton model as the charge-weighted sum over quark distributions

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

- At finite Q^2, F_2 not Q^2 independent → scaling violations can be predicted in pQCD
- At fixed x, scaling can be tested via logarithmic derivative of F_2 w.r.t. to Q^2

$$\frac{d\ln(F_2)}{d\ln(Q^2)} = \text{constant}$$

- In addition, corrections due to the finite mass of the nucleon lead to further scaling violations → these can be partially accounted for by examining data in terms of Nachtmann variable, ξ

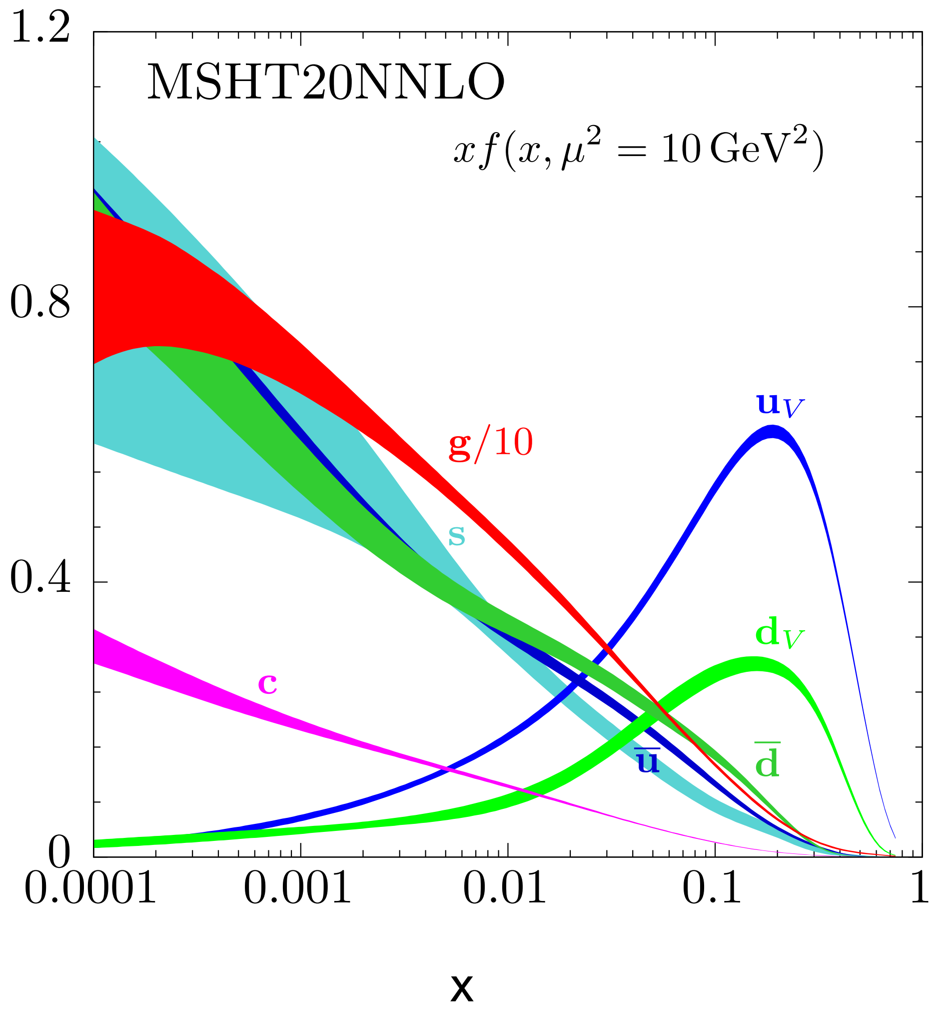
$$\xi = \frac{2x}{1+\sqrt{1+\frac{4M^2x^2}{Q^2}}}$$

F_2 and Parton Distributions

- F_2 interpreted in the quark-parton model as the charge-weighted sum over quark distributions

$$F_2(x) = \sum_i e_i^2 x q_i(x) \qquad q_i(x) = u(x), d(x), s(x) \ldots$$

- Quark structure of nucleon inferred from DIS on proton and neutron (deuteron) + complementary reactions



From Particle Data Group – 2023 Review of Particle Physics

Nuclear Structure Functions

Since nuclear binding energies are small (~MeV) compared to typical DIS energies (~GeV), the naïve expectation was that nuclear effects in DIS would be small

No nuclear effects

$$R = \frac{F_2^A}{ZF_2^p + (A-Z)F_2^n}$$

From the beginning the above expression was known to be ***too simple*** → difference in the "Fermi momentum" for heavy nuclei leads to rise at large x

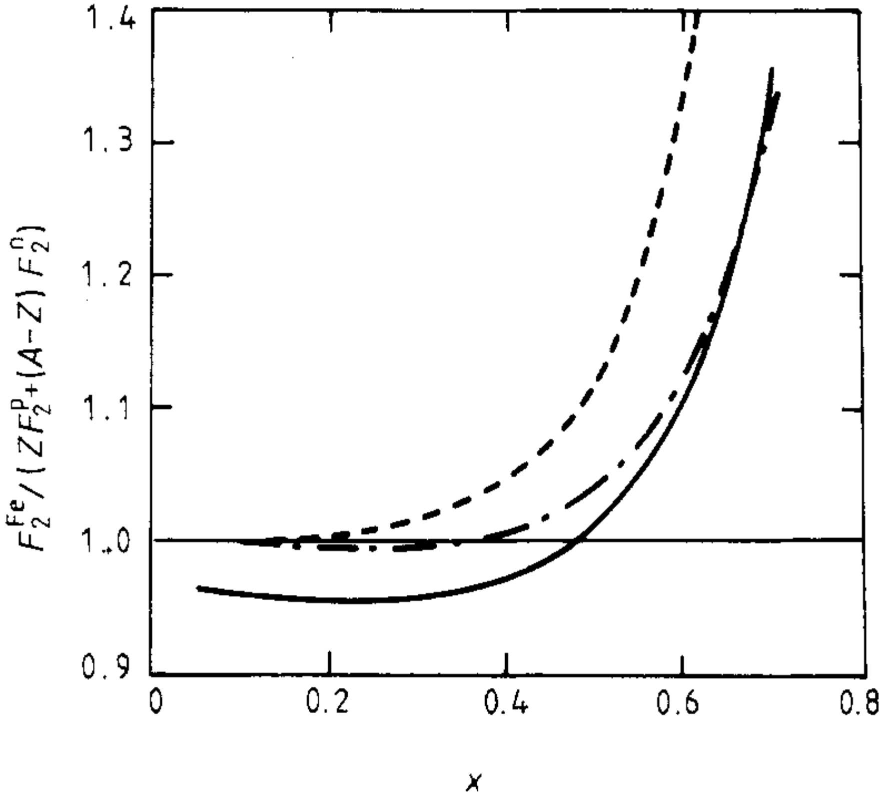
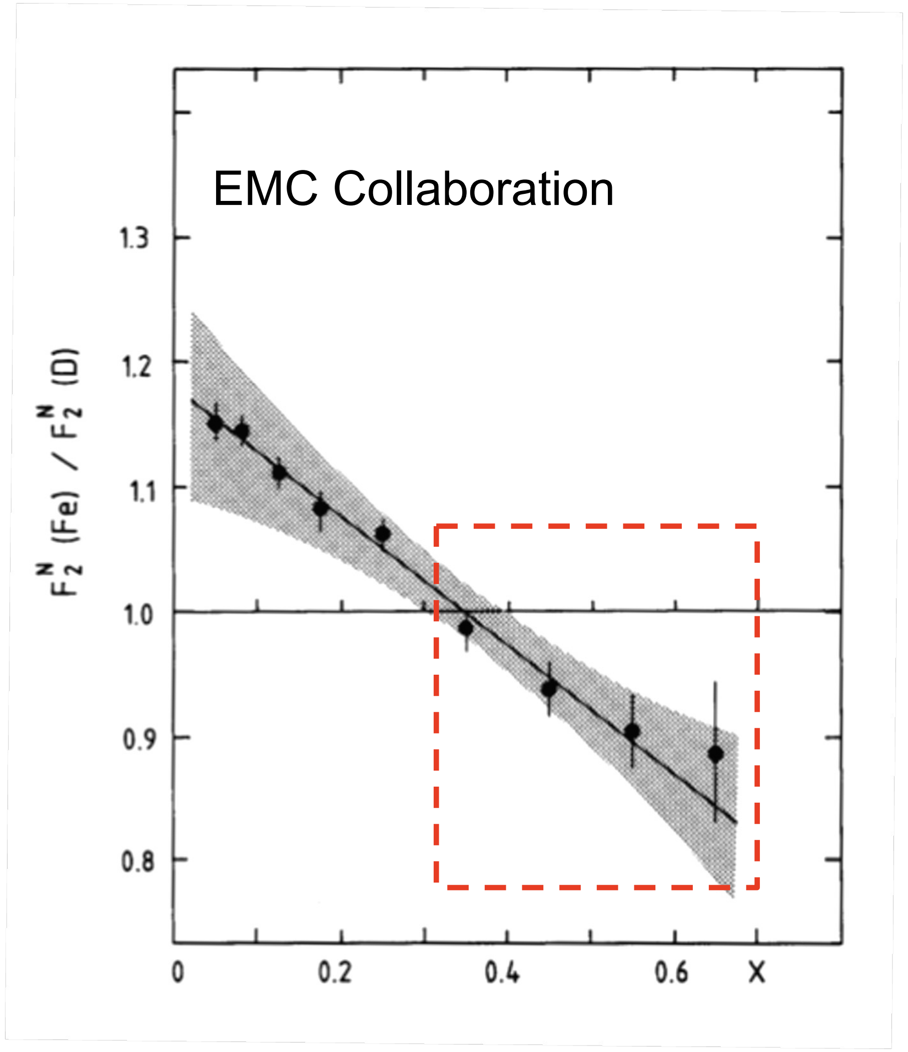


Figure from Bickerstaff and Thomas, J. Phys. G 15, 1523 (1989)
*Calculation: Bodek and Ritchie PRD 23, 1070 (**1981**)*

Discovery of the EMC Effect

- First published measurement of nuclear dependence of F_2 by the European Muon Collaboration in 1983
- Observed 2 mysterious effects
  - Significant enhancement at small *x* → Nuclear Pions! (my thesis)
  - Depletion at large *x* → the "EMC Effect"
- Enhancement at *x<0.1* later went away

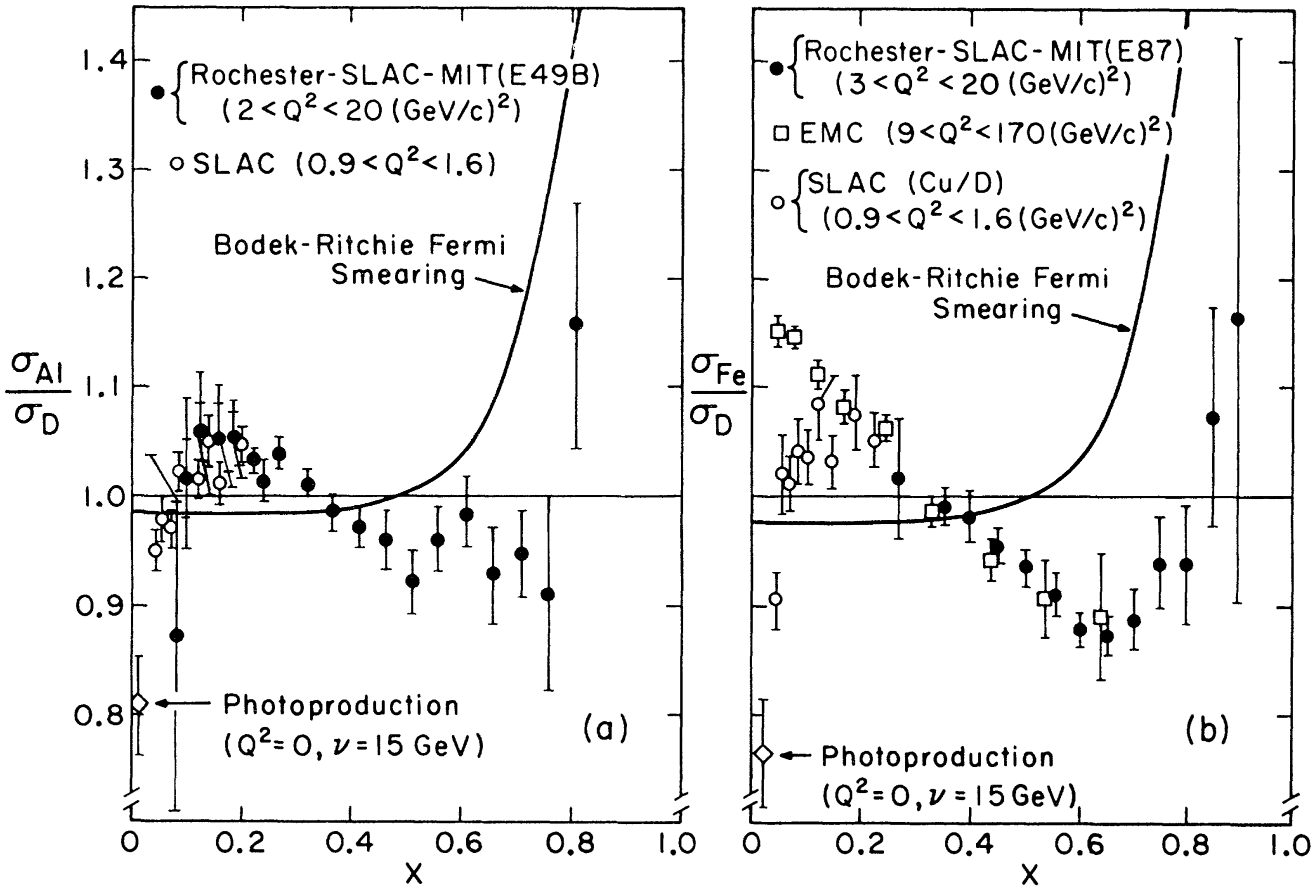


Aubert et al, Phys. Lett. B123, 275 (1983)

Confirmation of the EMC Effect

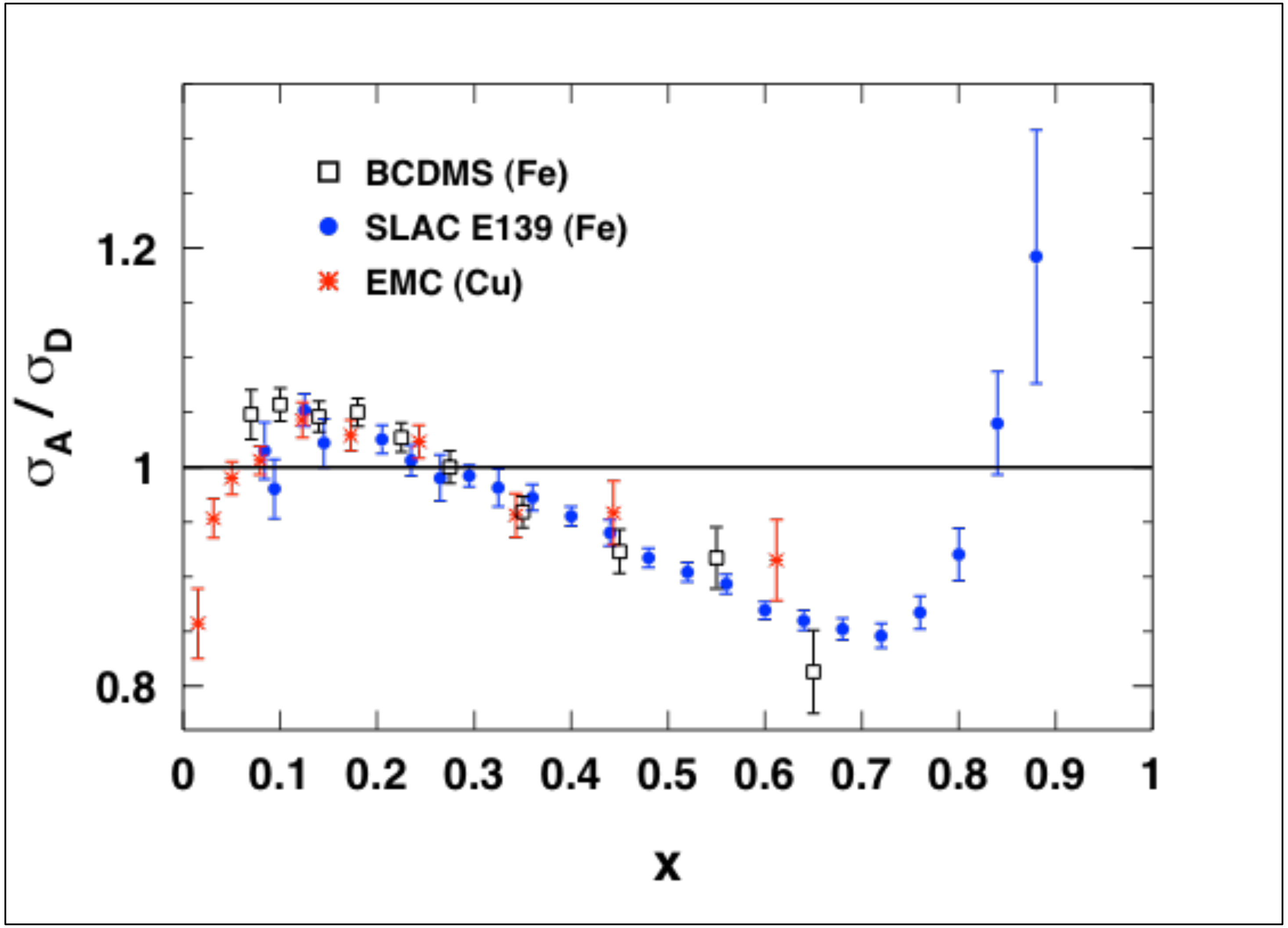
SLAC re-analysis of old solid target data used for measurements of cryotarget wall backgrounds

→Effect for *x>0.3* confirmed
→No large excess at very low *x*



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

Subsequent Measurements



A program of dedicated measurements quickly followed

The resulting data is remarkably consistent over a large range of beam energies and measurement techniques

EMC Effect Measurements

Since the original discovery in 1983, numerous measurements to explore properties of EMC Effect

→ Wide range of beam energies: 5 GeV electrons to 490 GeV muons

Laboratory/collaboration	Beam	Energy (GeV)	Targets	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, ^{10}B, ^{11}B, C	2022

Measuring the EMC Effect: Muons vs. Electrons

Muon beam experiments (EMC, NMC, BCDMS, FNAL E665)

→Energy scale ~ 100-500 GeV
→Secondary beams, relatively low intensity
→Beam energy determined event by event
→Large acceptance devices required

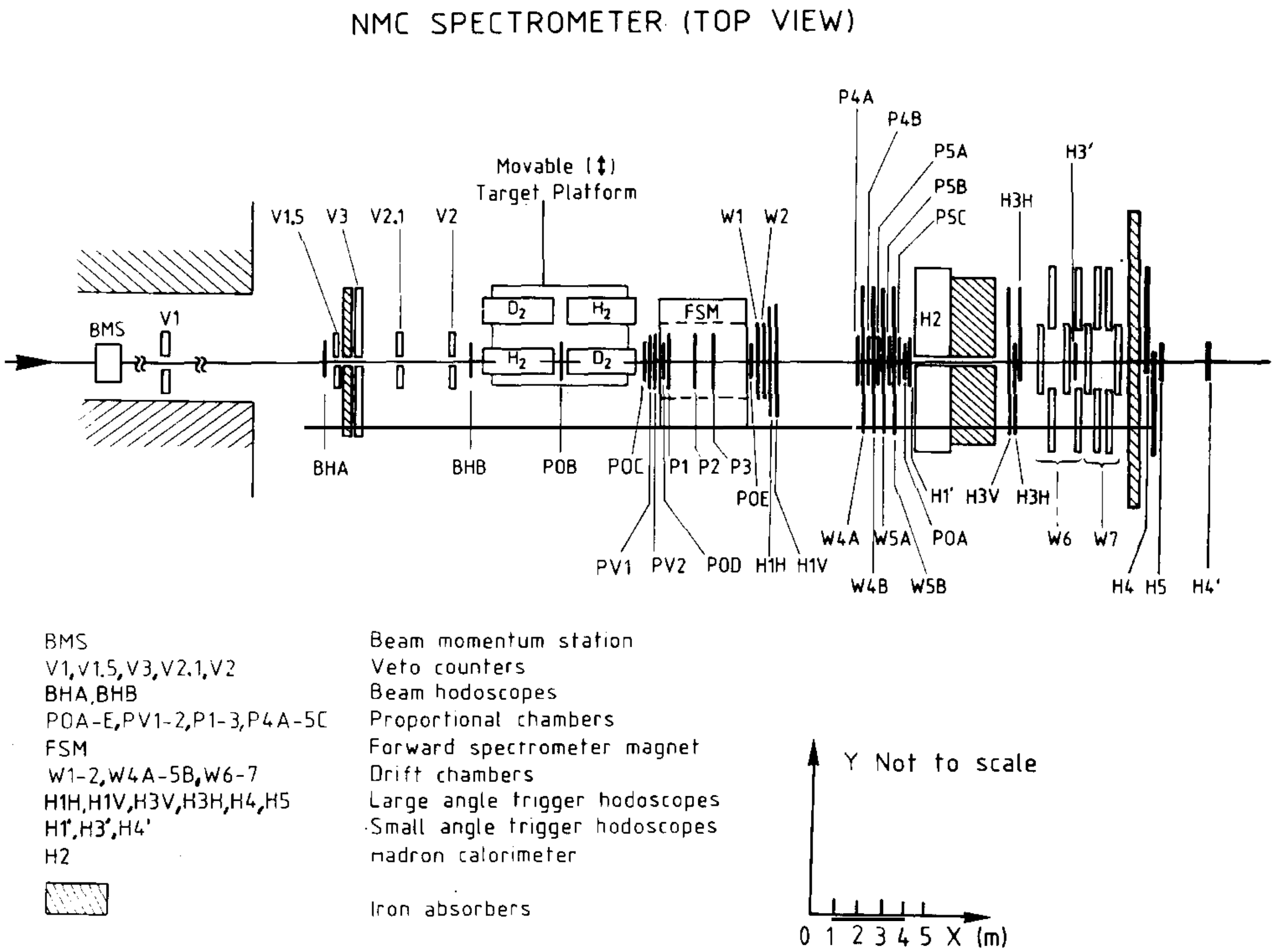
Electron beam experiments (SLAC, HERMES, JLAB)

→Energy scale 6-25 GeV
→Well defined beam energy, narrow dE
→Intense beams → higher statistics
→Small acceptance devices often (but not always) used

New Muon Collaboration

NMC: next generation experiment at CERN, building on EMC

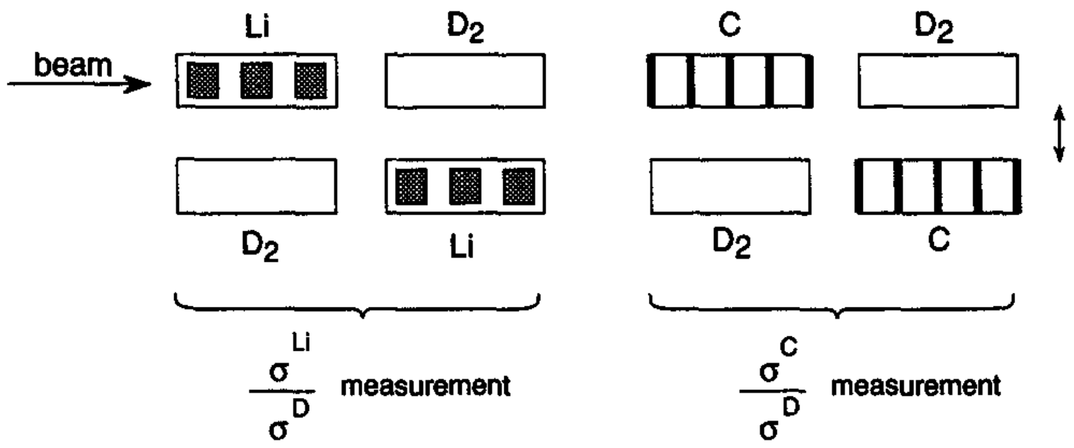
Large acceptance spectrometer with large array of tracking chambers



P. Amaudruz et al: Nucl Phys. B 371 (1992) 3-31

New Muon Collaboration

Target designed to minimize systematic uncertainties → excellent vertex resolution so several targets could be in beam simultaneously



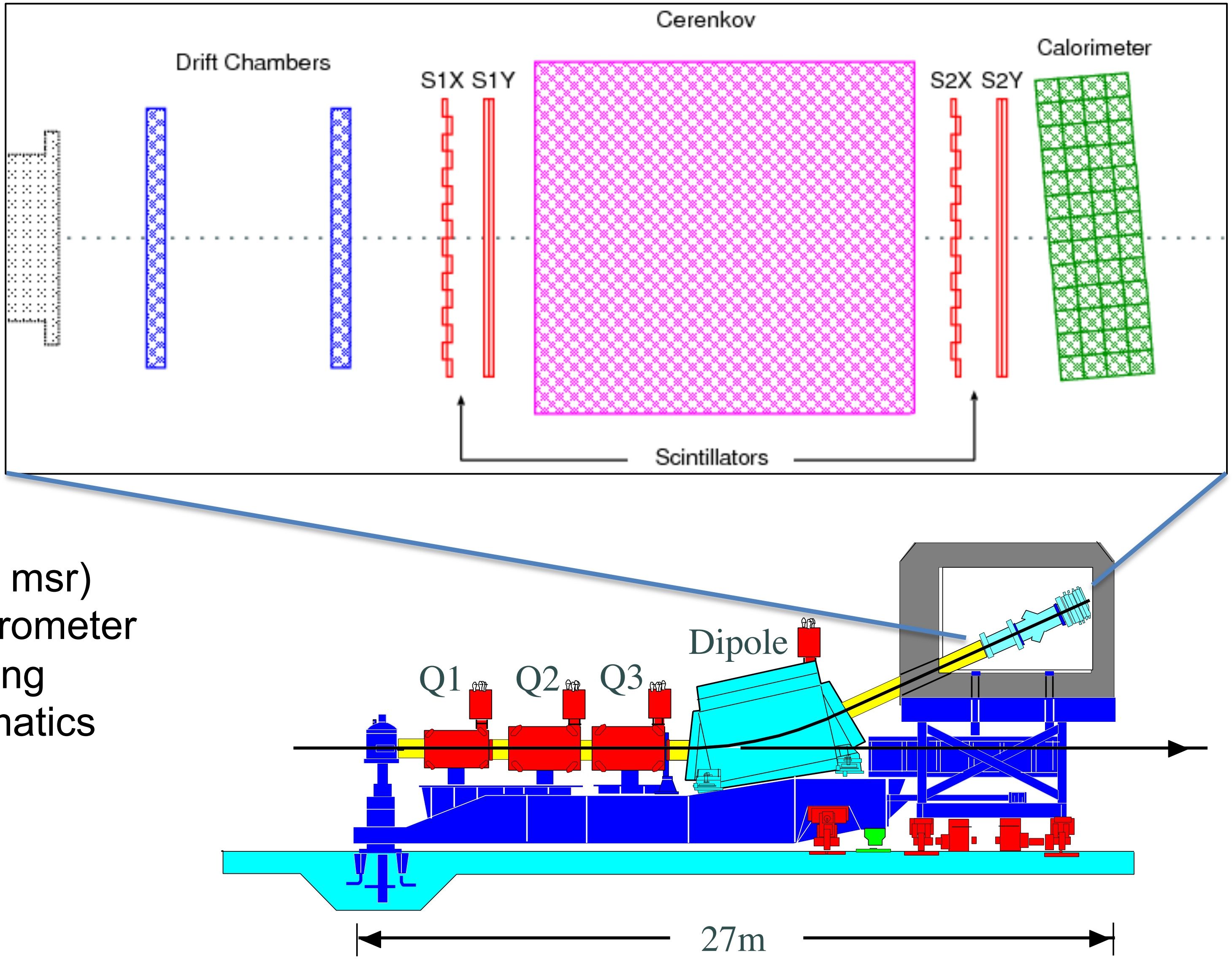
M. Arneodo et al: Nucl. Phys. B 441 (1995) 12-30

Order 10^7 muons/s: 3 m long cryotargets → Luminosity~ 10^{32} cm^{-2} s^{-1}

Normalization uncertainties for σ(A)/σ(D) → 0.4%

σ(A)/σ(C) → 0.2%

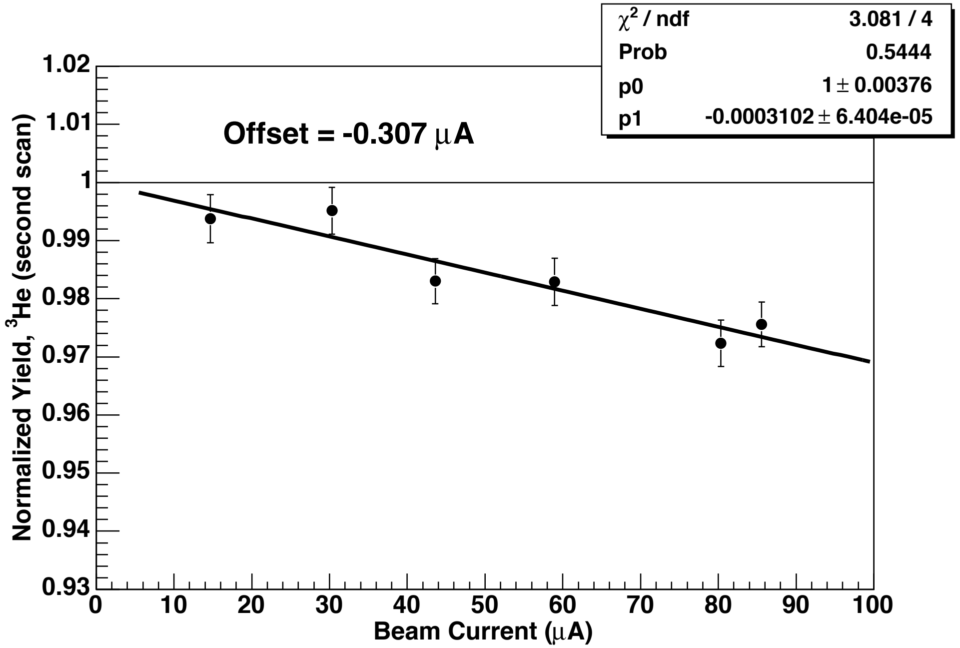
Jefferson Lab – Hall C



Moderate acceptance (6 msr) magnetic focusing spectrometer
→ Excellent understanding of acceptance and kinematics

Jefferson Lab – Hall C

High current electron beam requires high power cryogenic targets
→ Knowledge of the absolute target density sometimes challenging due to target boiling effects



Yield from ^{3}He target vs. beam current

Order 5 10^{14} electrons/s: 4-10 cm long cryotargets → Luminosity~ 10^{38} cm^{-2} s^{-1}

Normalization uncertainties for σ(A)/σ(D) → 1-2%

Nuclear dependence of structure functions

Experimentally, we measure cross sections (and the ratios of cross sections)

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

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2}{2xF_1}\left(1+4\frac{M^2x^2}{Q^2}\right) - 1 \qquad \epsilon = \left[1 + 2\left(1+\frac{Q^2}{4M^2x^2}\right)\tan^2\frac{\theta}{2}\right]^{-1}$$

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

In the limit $R_A = R_D$ or ε=1 → $\boxed{\sigma_A/\sigma_D = F_2^A/F_2^D}$

Experiments almost always display cross section ratios, σ_A/σ_D
→Often these ratios are labeled or called F_2^A/F_2^D
→ Sometimes there is an additional uncertainty estimated to account for the $\sigma \rightarrow F_2$ translation. Sometimes there is not.

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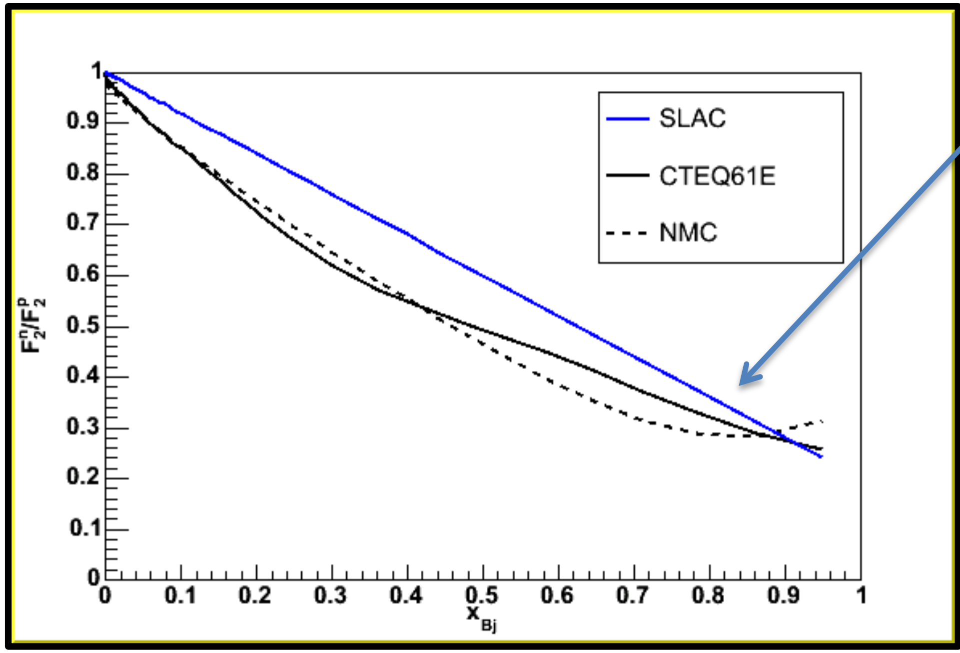
Isoscalar Corrections

In the case of nuclei where N≠Z, need to remove the “trivial” change in nuclear cross section due to $\sigma_n \neq \sigma_p$

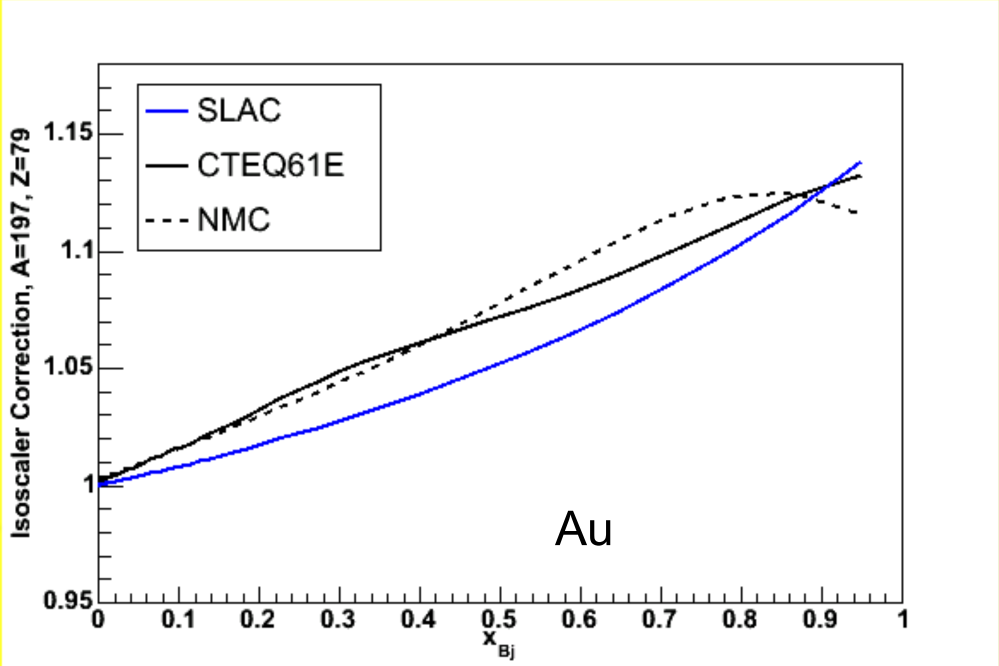
→ Different experiments often use slightly different parameterizations/estimates for this correction



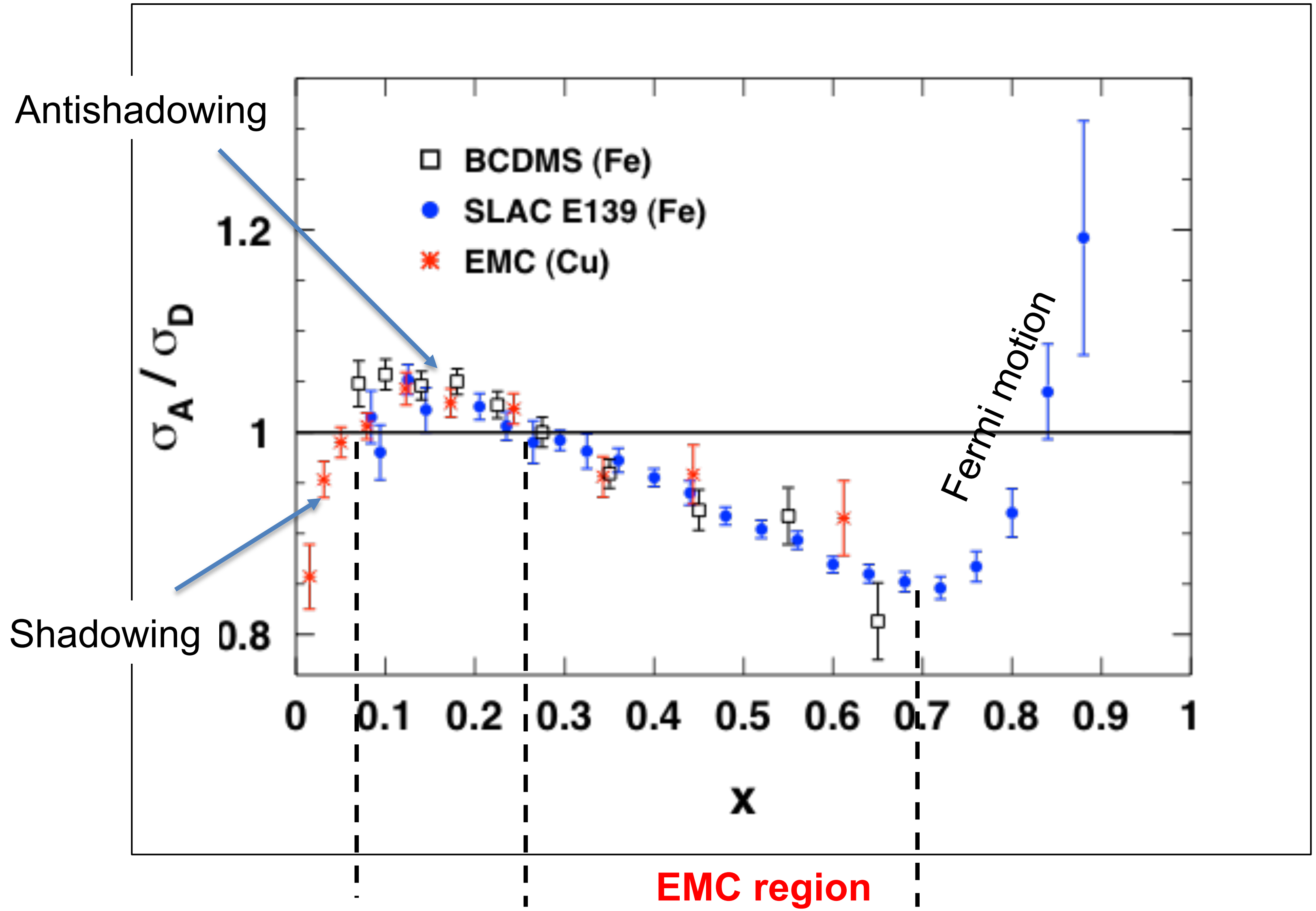
$$\frac{F_2^n}{F_2^p}$$

- SLAC param. *(1-0.8x)*
- CTEQ
- NMC fit

Isoscalar correction applied to data

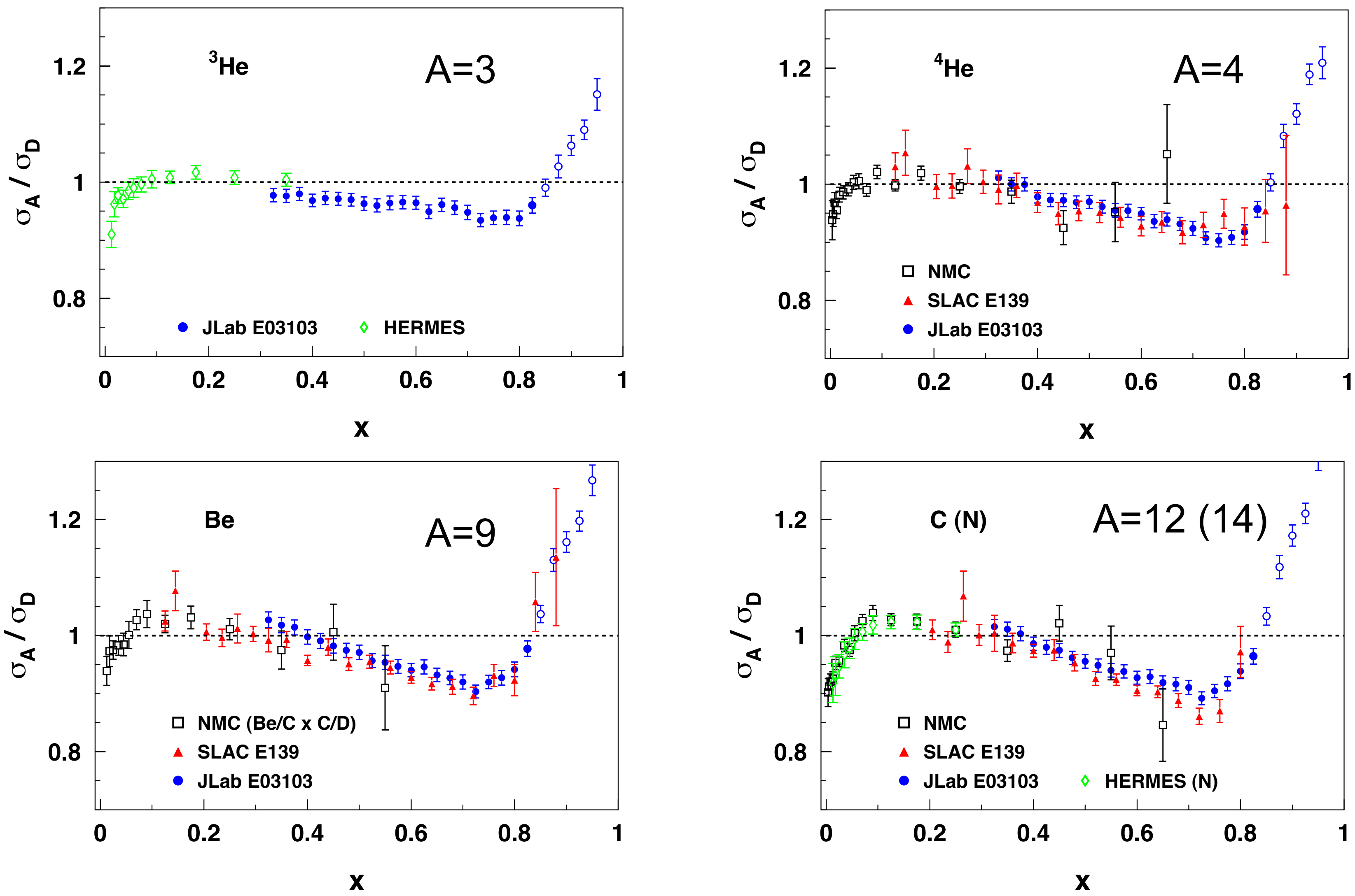


Properties of the EMC Effect

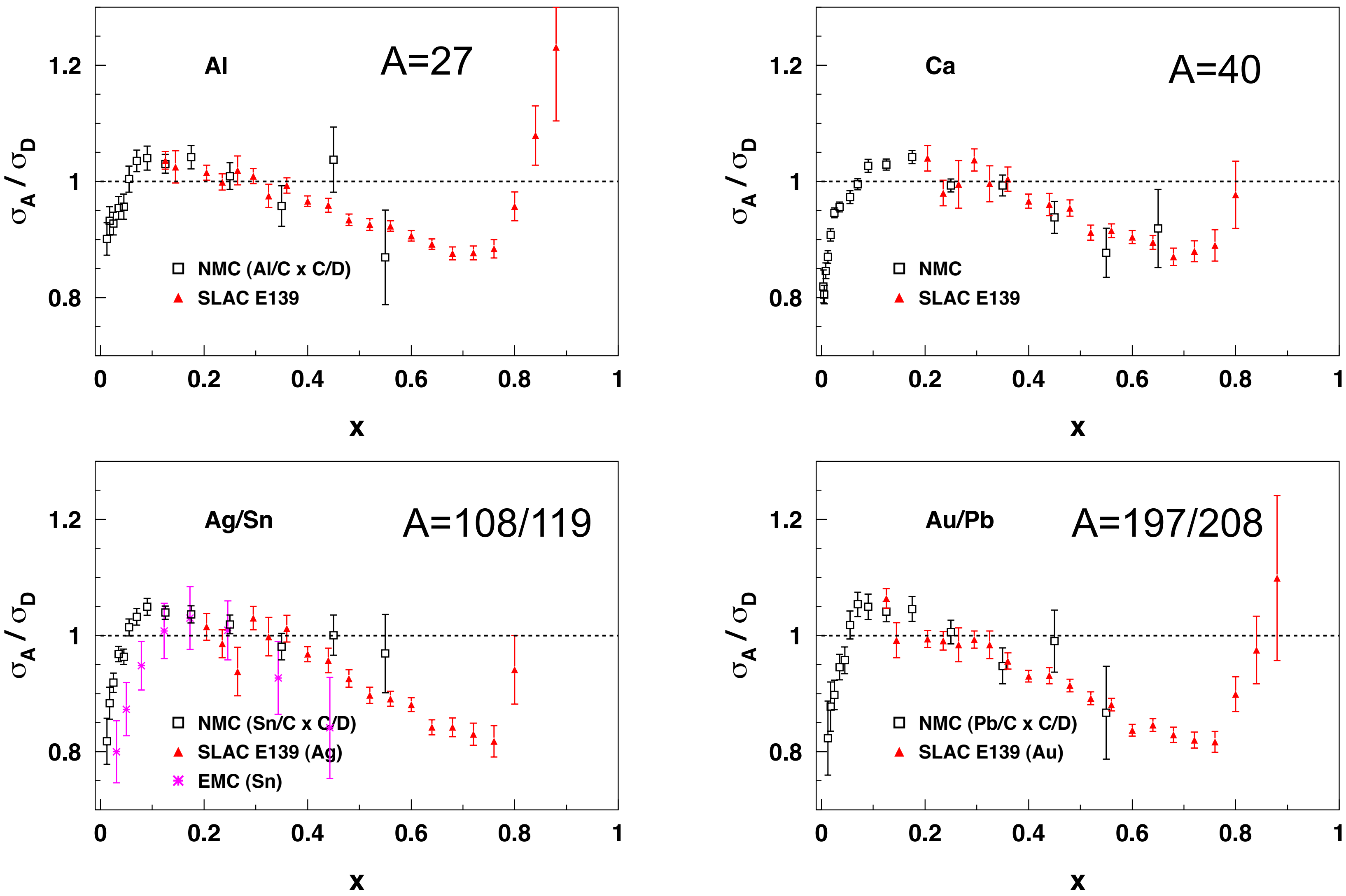


1. Universal x-dependence

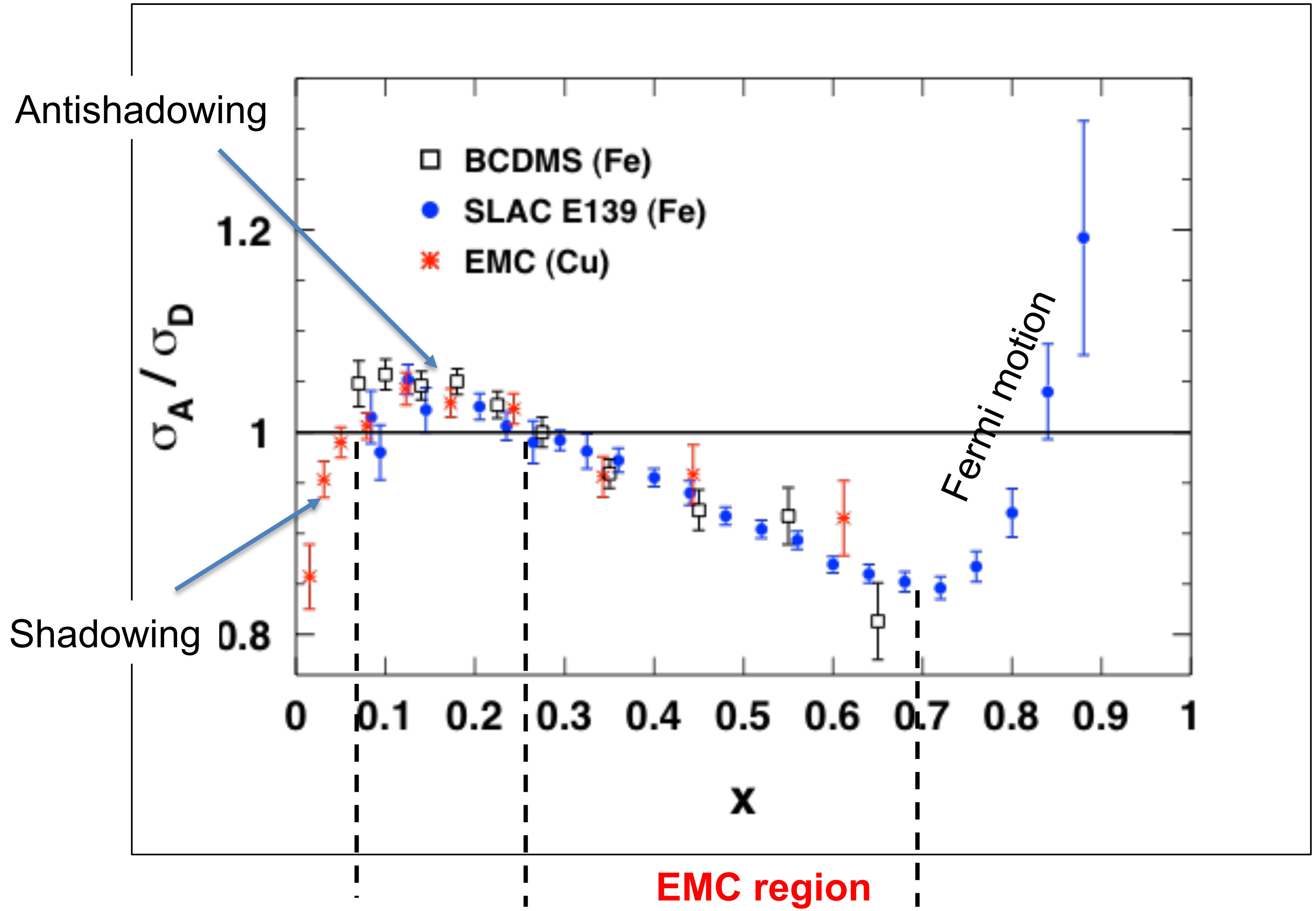
x Dependence



x Dependence



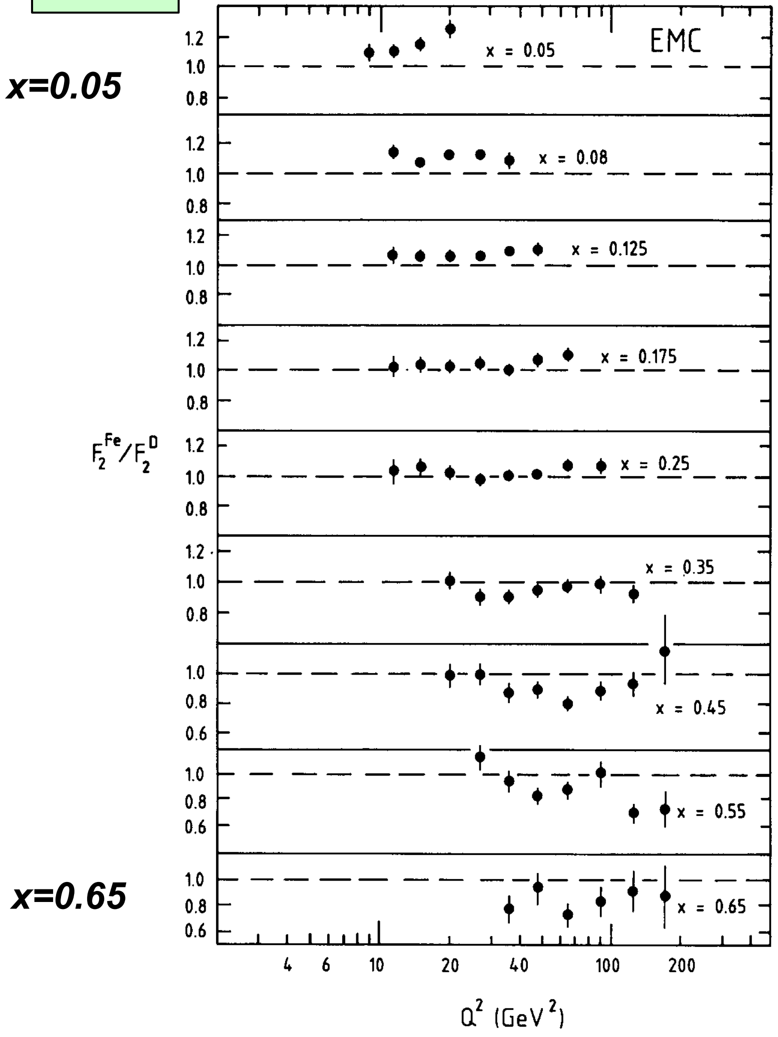
Properties of the EMC Effect



1. Universal x-dependence
2. Little Q^2 dependence*

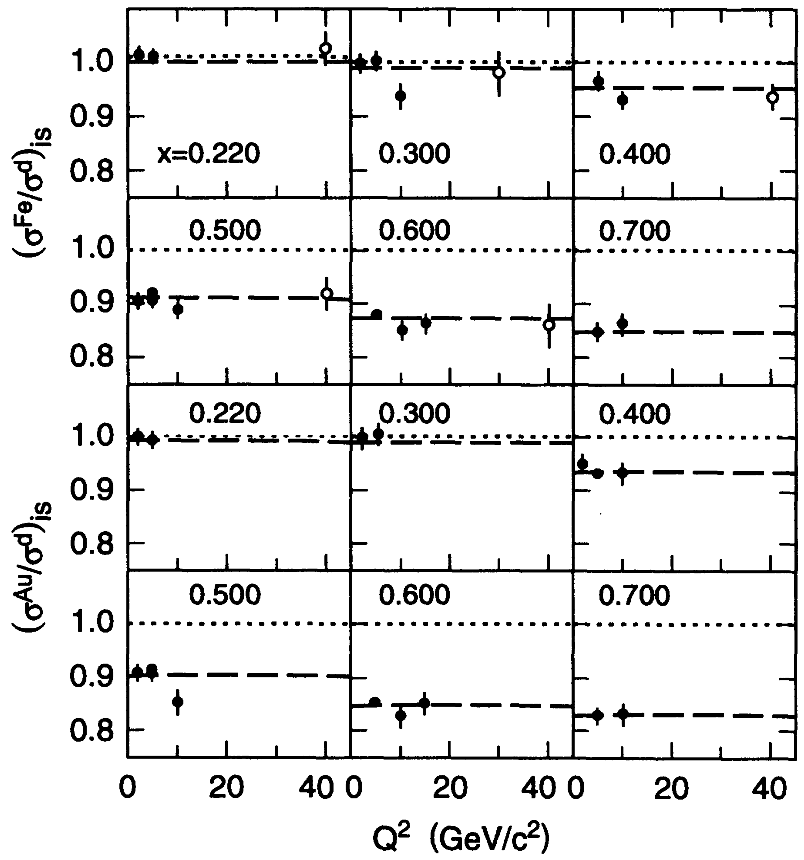
Q^2 Dependence of the EMC Effect

EMC Q^2=10-200 GeV^2



Aubert et al, Nucl. Phys. B293, 740 (1987)

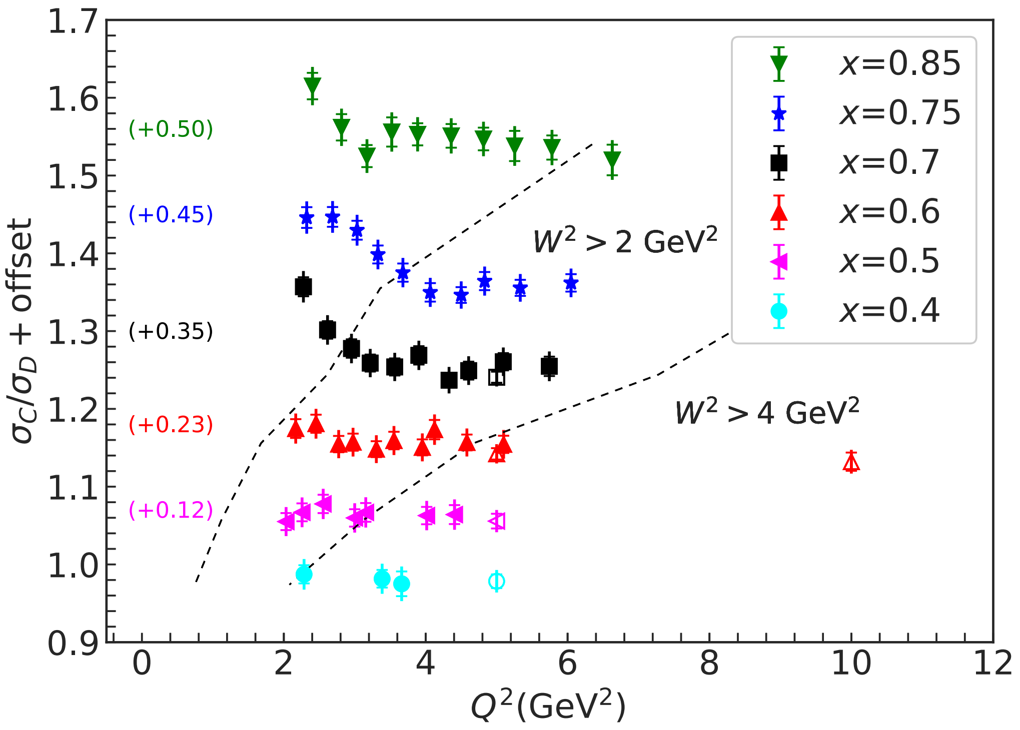
SLAC E139 Q^2=1-10 GeV^2



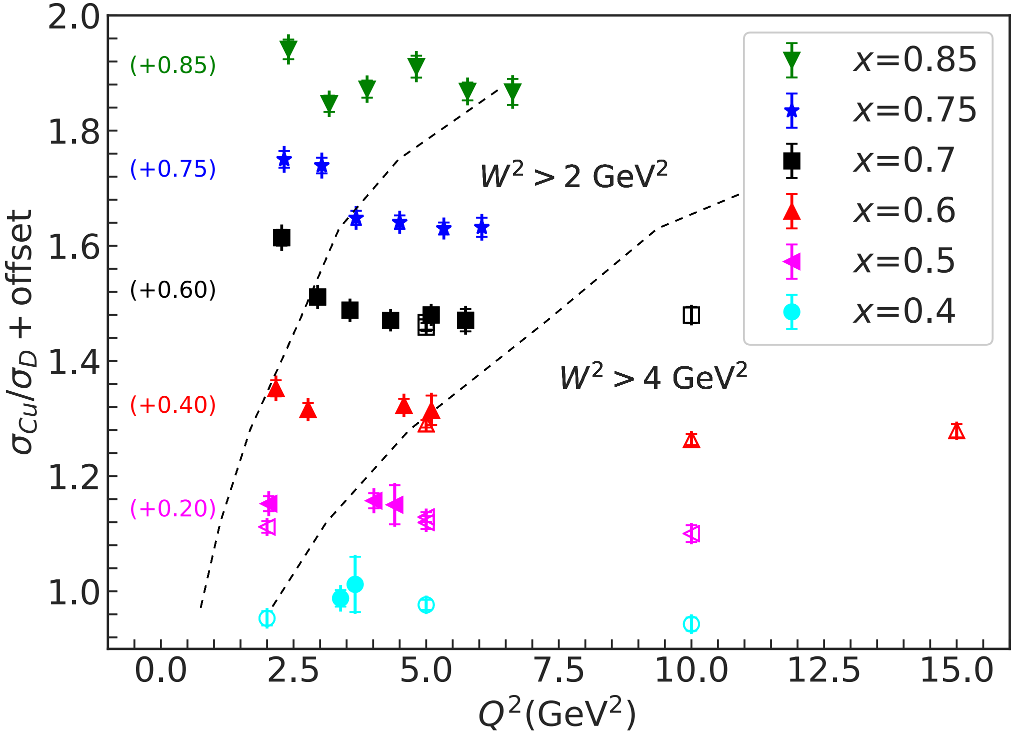
Gomez et al, Phys. Rev. D 49, 4348 (1994)

Q^2 Dependence of the EMC Effect

Carbon



Copper/Iron

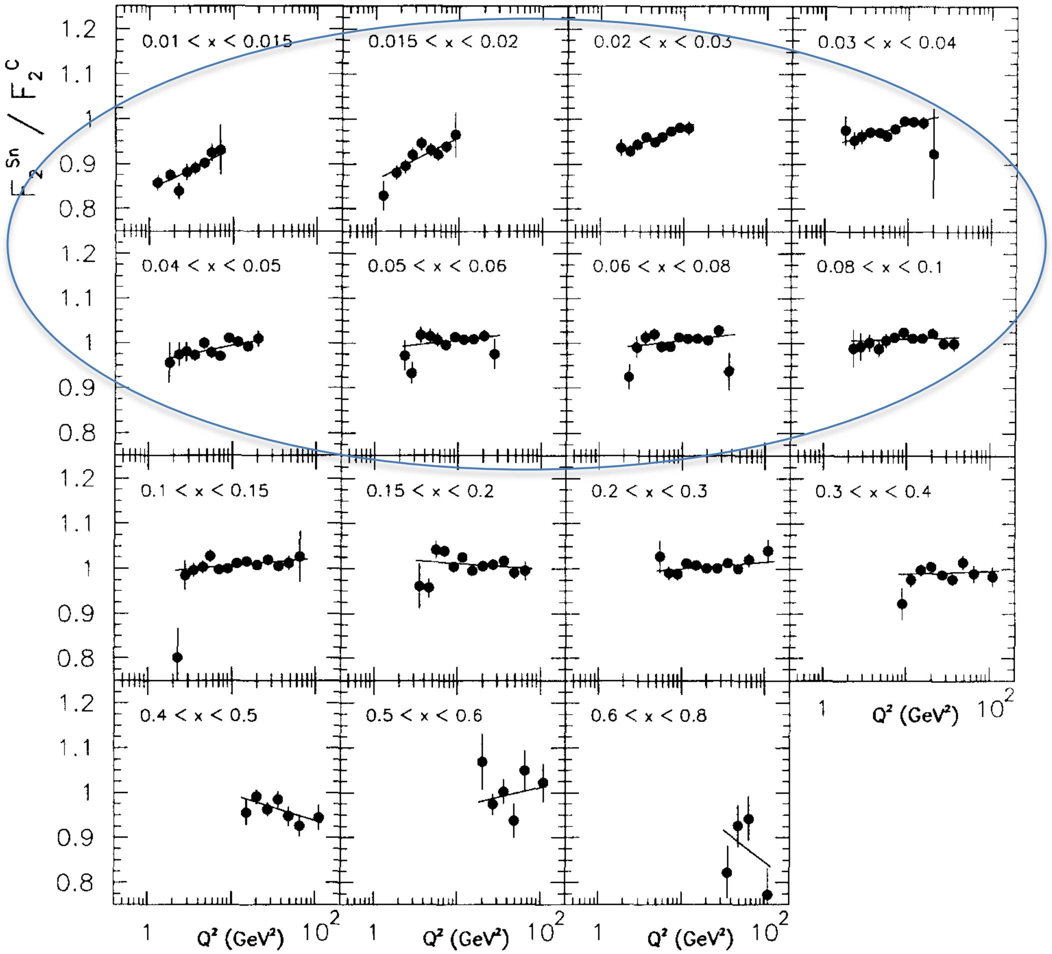


Very little Q^2 dependence – even in the resonance region! (W^2>2 GeV^2, Q^2>3 GeV^2)

Arrington et al, Phys.Rev.C 104 (2021) 6, 065203

Jefferson Lab

(*) Q^2 Dependence of Sn/C

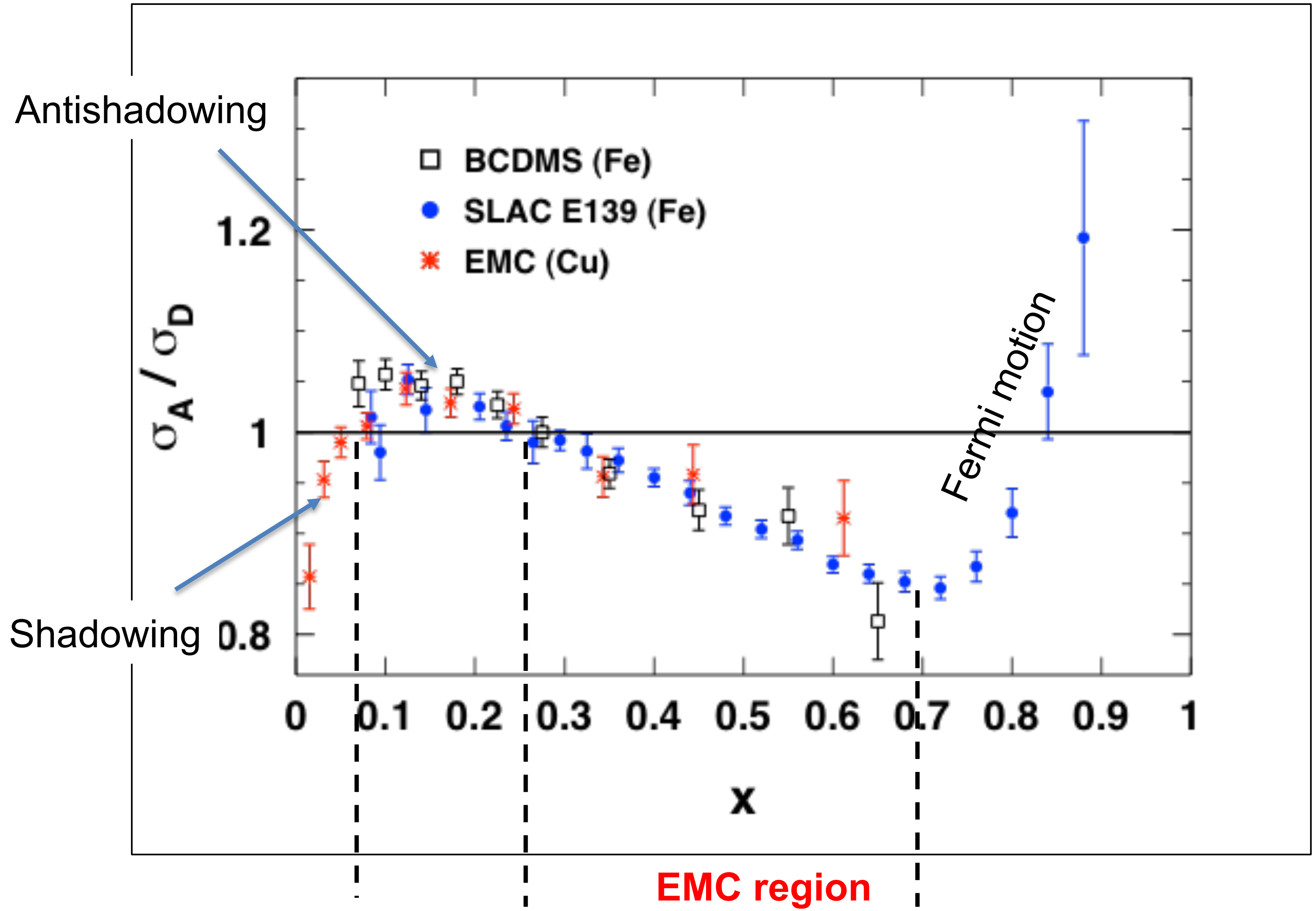


Arneodo et al, Nucl. Phys. B 481, 23 (1996)

NMC measured non-zero Q^2 dependence in Sn/C ratio at small x

→ This result is in some tension with other NMC C/D and HERMES Kr/D results

Properties of the EMC Effect

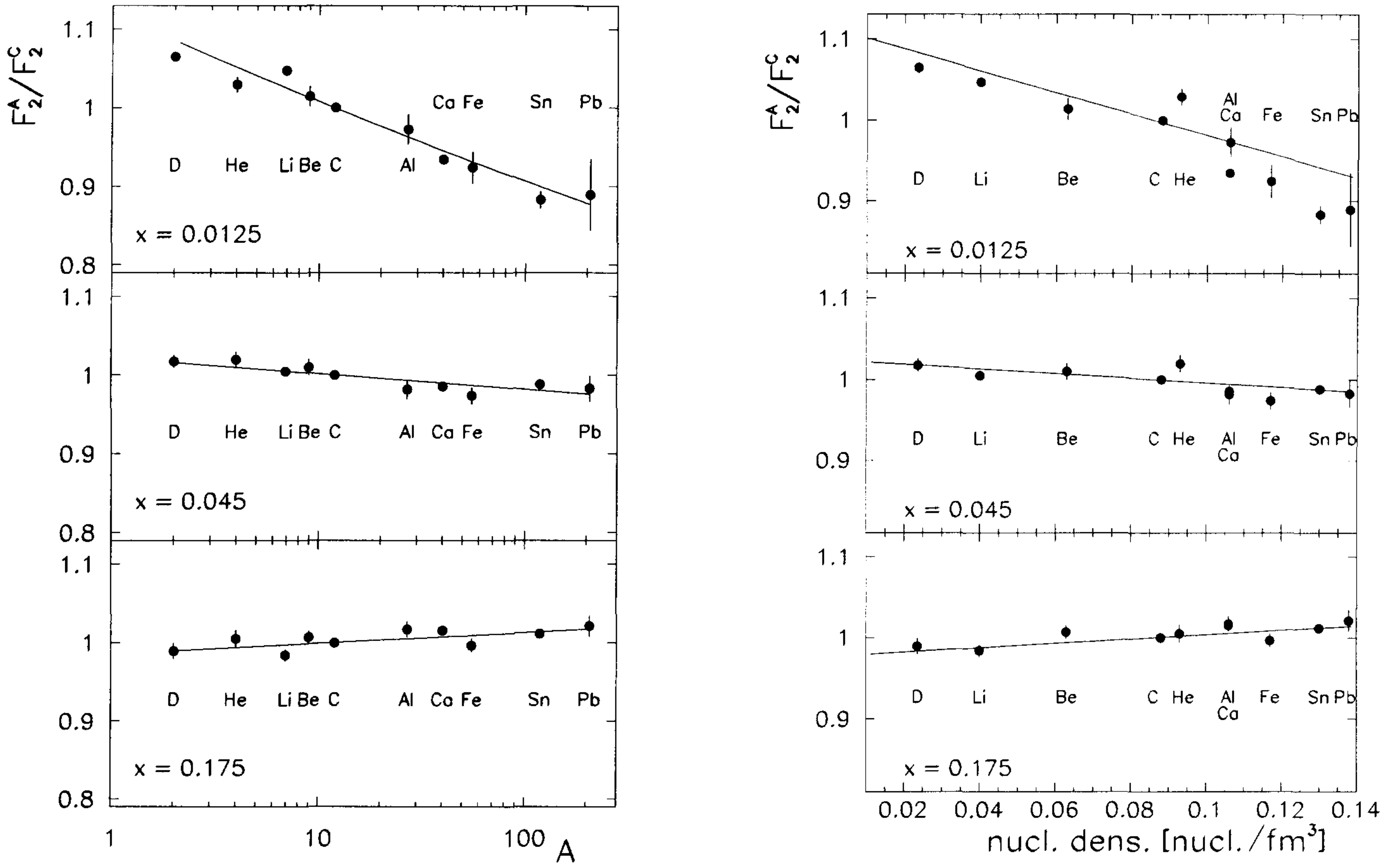


1. Universal x-dependence

2. Little Q^2 dependence*

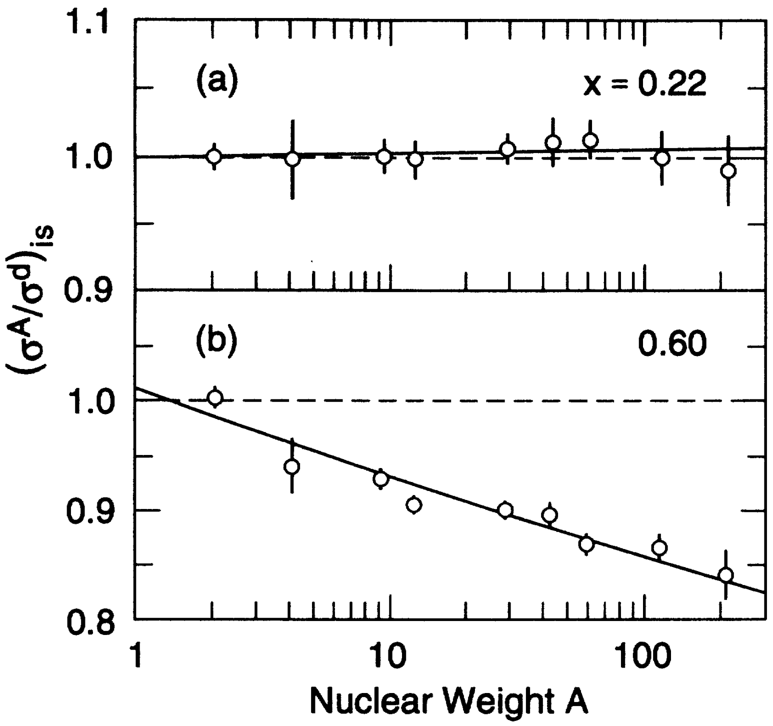
3. EMC effect increases with *A*
→ *Anti-shadowing region shows little nuclear dependence*

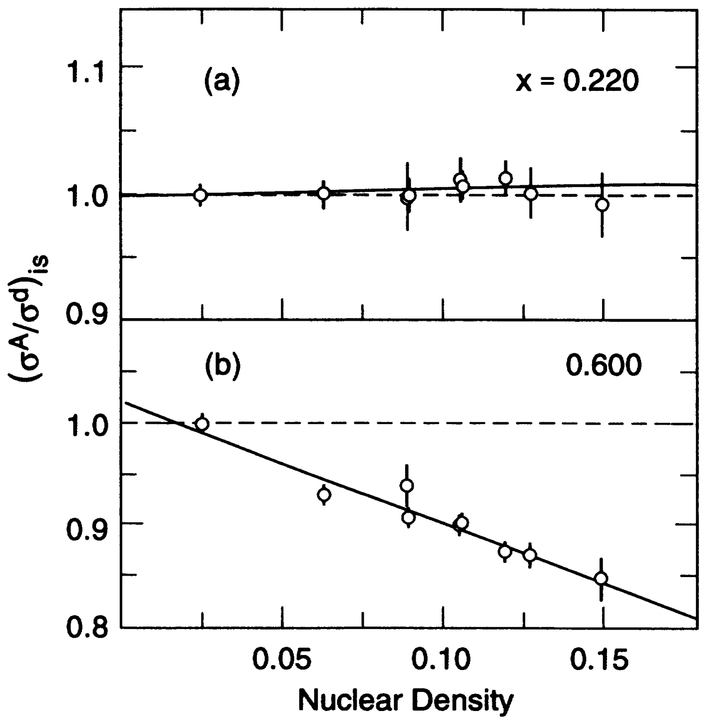
A-Dependence of EMC Effect



NMC: *Arneodo et al, Nucl. Phys. B 481, 3 (1996)*

A-Dependence of EMC Effect





$\rho=3A/4\pi R_e^3$ $\quad R_e^2=5\langle r^2\rangle/3$

$<r^2>$=RMS electron scattering radius

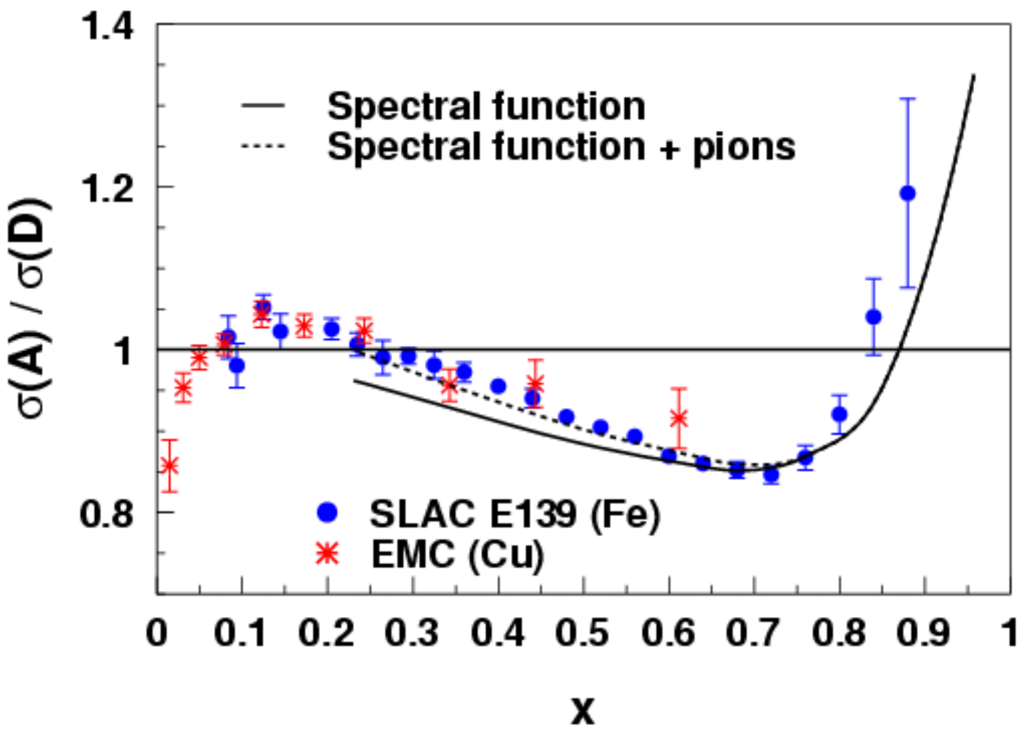
SLAC E139: *Gomez et al, PRD 49, 4348 (1992)*

Explaining the EMC Effect

- Plethora of models attempting to explain the EMC Effect
- “Conventional” nuclear physics not sufficient
  - Fermi motion dominates at large x, but minimal impact elsewhere
  - Binding effects small, nuclear pions ruled out by other measurements (Drell-Yan)
- Other models require more “exotic” effects
  - Dynamical rescaling
  - Multiquark clusters → 6, 9, 12 .. quark configurations
- Newer models involve direct coupling of meson fields to quarks
- More recently, models connecting the EMC Effect to “Short Range Correlations” under investigation

Binding and Nuclear Pions

- Start with a "realistic" description of nucleons in the nucleus
  → Use a spectral function rather than simple Fermi gas
- Start with convolution picture
  → Allow virtual photon to scatter from quarks in pions in the nucleus
- Requires ***ad-hoc prescription for off-shell behavior*** of structure functions



Benhar, Pandharipande, and Sick Phys. Lett. B410, 79 (1997)

- Fair agreement is achieved at large x – including nuclear pions improves agreement at lower x

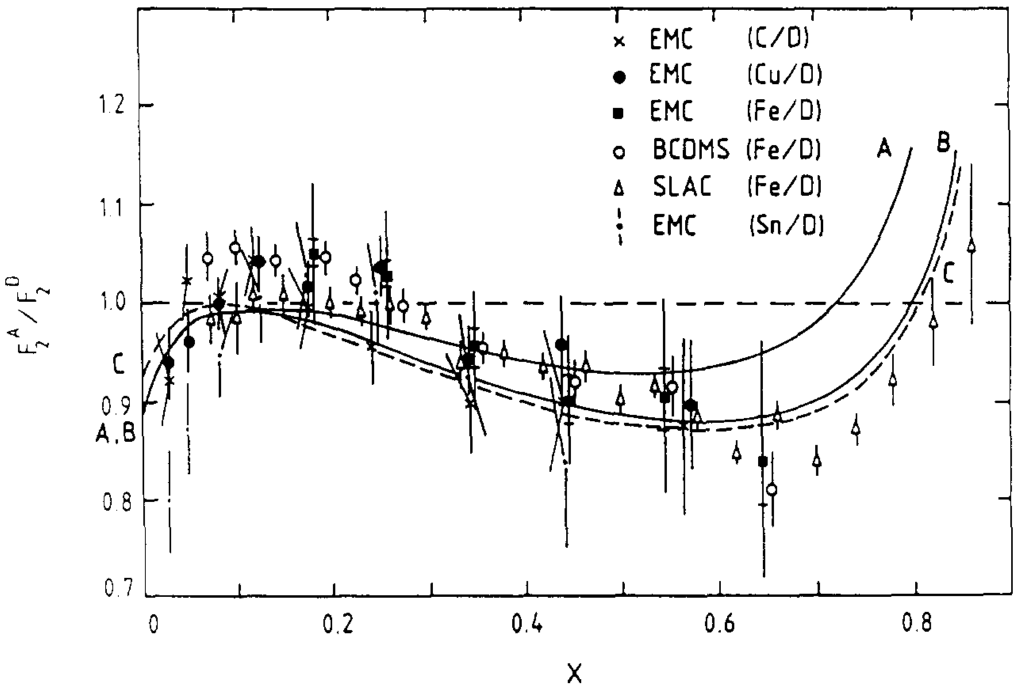
$$F_2^A(x) = \int_x^1 dy f_N(y) F_2^N(x/y) + \int_x^1 dy f_\pi(y) F_2^\pi(x/y)$$

Multiquark Clusters

Multiquark cluster model assumes that, ***in nuclei***, quarks may combine into clusters that include more than 3 quarks

Nuclear structure function is a convolution over contribution from nucleons (F_2^N) and contribution from 6 quark clusters (F_2^6)

Requires $F_2^N \neq F_2^6$ to get EMC effect



K.E. Lassila and U.P. Sakhatme
Phys. Lett. B209, 343 (1988)

$$F_2^A(x) = \int_x^1 dy f_N(y) F_2^N(x/y) + \int_x^1 dy f_6(y) F_2^6(x/y)$$

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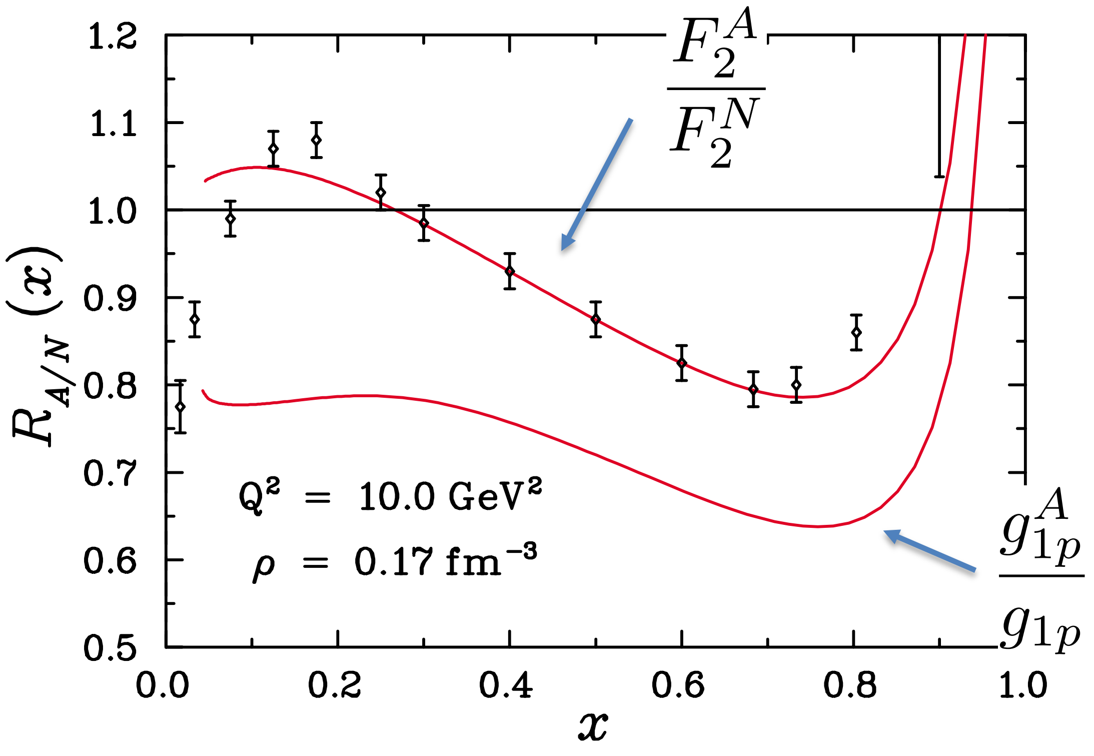
Quark-Meson Coupling Model

Quark-meson coupling model describes nuclei in terms of quark interactions with (scalar and vector) meson fields
→ *Guichon, Stone, Thomas, PPNP 100, 262-297, 2018*

Calculations using NJL model (similar properties as QMC) give good description of unpolarized EMC Effect
→ Also predict EMC effect for polarized nucleons



Cloët, Bentz, and Thomas, PRL 95, 052302 (2005)

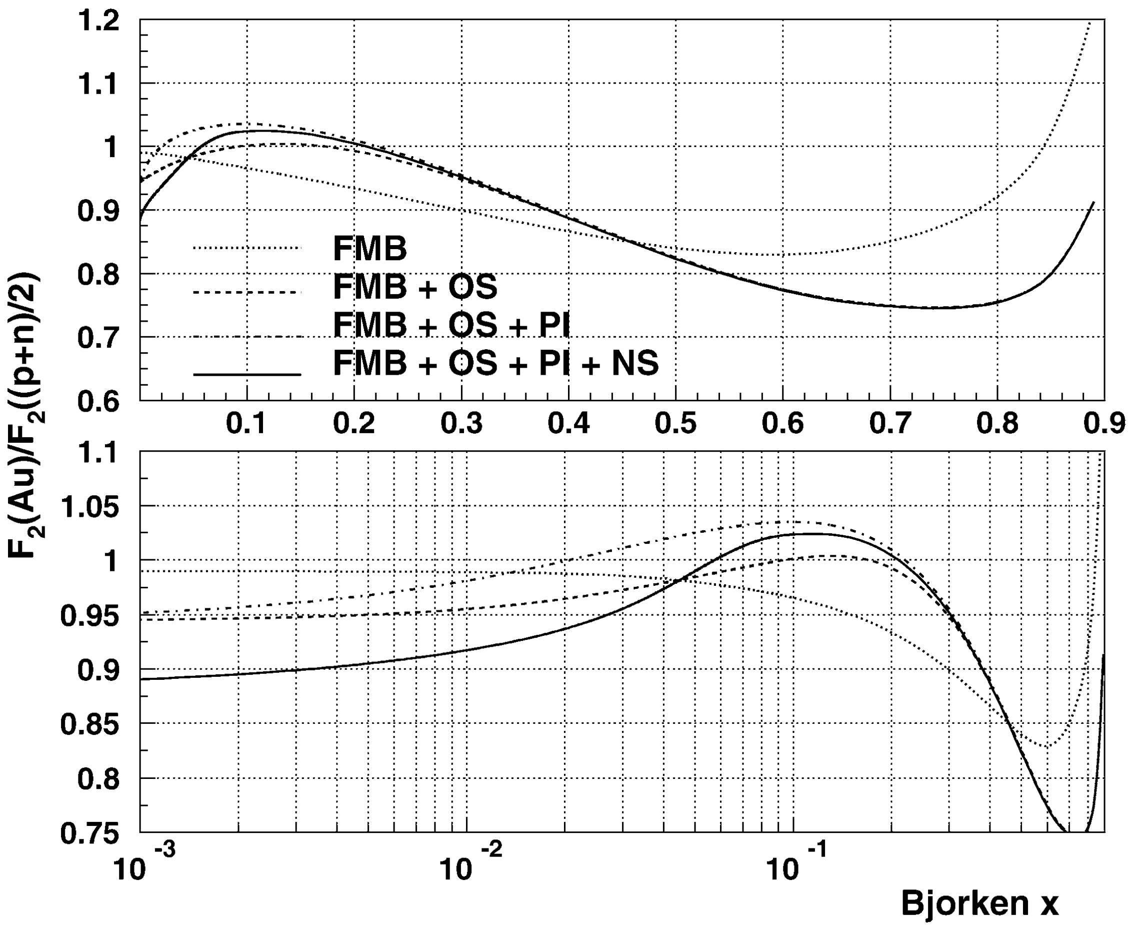
Isolating the Physics of Interest

"Conventional" nuclear effects play non-trivial role in DIS target ratios

Kulagin and Petti performed calculations including these effects to attempt to isolate the interesting effects

Calculations included:

1. Fermi motion and binding w/realistic nucleon distributions (FMB) → large x
2. Nuclear pion excess (PI) → antishadowing
3. Coherent nuclear processes (NS) → low x
4. Off-shell correction to structure function (OS)



Nucl.Phys.A 765 (2006) 126-187

Isolating the Physics of Interest

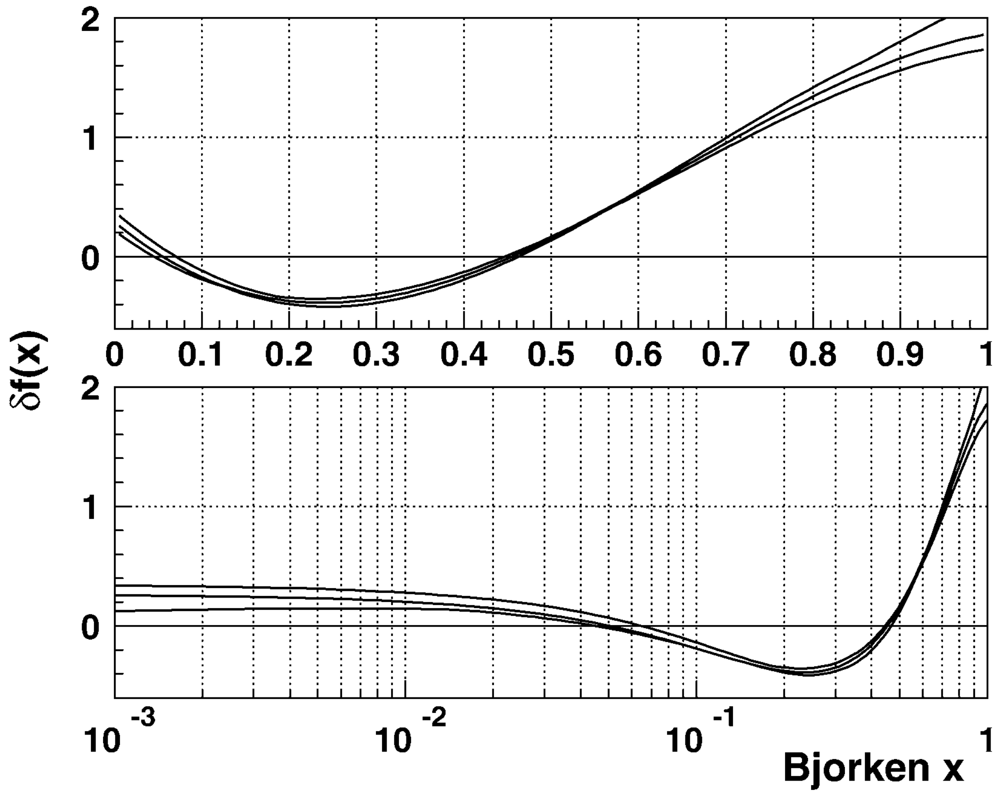
The interesting physics is encoded in the off-shell correction to the F_2 structure function

$$\delta f_2(x) = C_N(x - x_1)(x - x_0)(h - x)$$

C_N = normalization parameter
$0<x_1<x_0<1$
$h>1$

Surprisingly, a single set of parameters works pretty well for most nuclei

Successful parametrization and interesting approach, but this does ***not*** provide fundamental information about the origins of the EMC effect



$$F_2(x, Q^2, p) = F_2(x, Q^2)\left(1 + \delta f_2(x, Q^2)\frac{p^2 - M^2}{M^2}\right)$$

40+ Years of the EMC Effect

- No clear consensus on origin of EMC Effect
  - Conventional nuclear physics contributions can be handled with more precision, but still cannot explain whole effect
  - Testing models challenging – only a few observables (Inclusive DIS and Drell-Yan)
- Settling the question of the origin of the EMC effect requires new information
  - New ways of looking at existing data
  - Explore effect for wider range of nuclei (different A, n/p ratios..)
  - New experimental avenues beyond inclusive DIS cross sections are likely required
- Information from JLab has helped provide some direction, but more information needed!

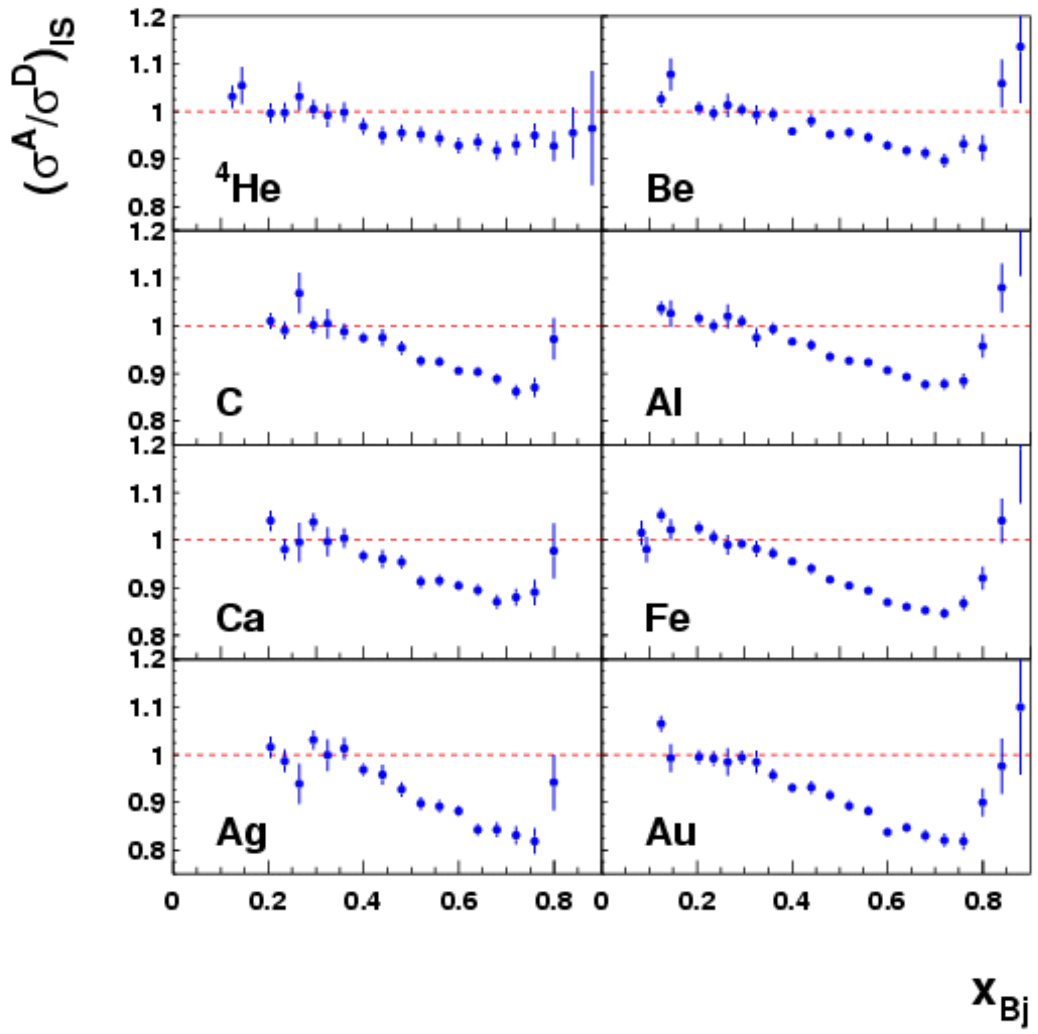
EMC Effect Measurements at Large x

SLAC E139

SLAC E139 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
→ Best determination of the *A* dependence
→ Verified that the *x* dependence was roughly constant

Building on the SLAC data
→ Higher precision data for ^{4}He
→ Addition of ^{3}He
→ Precision data at large *x*



Nuclear Dependence of the EMC Effect

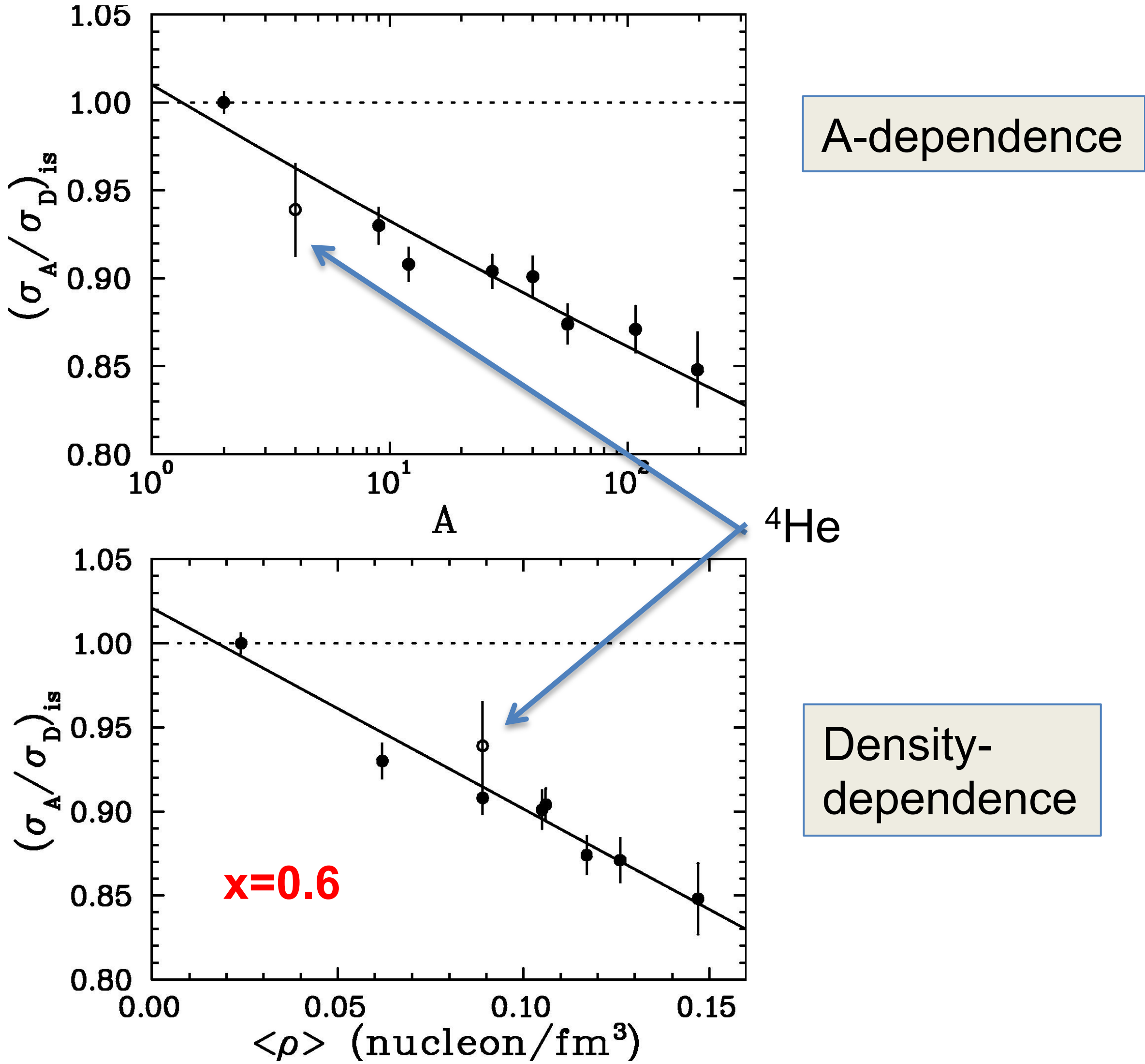
SLAC E139 studied the nuclear dependence of the EMC Effect at
fixed *x*

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



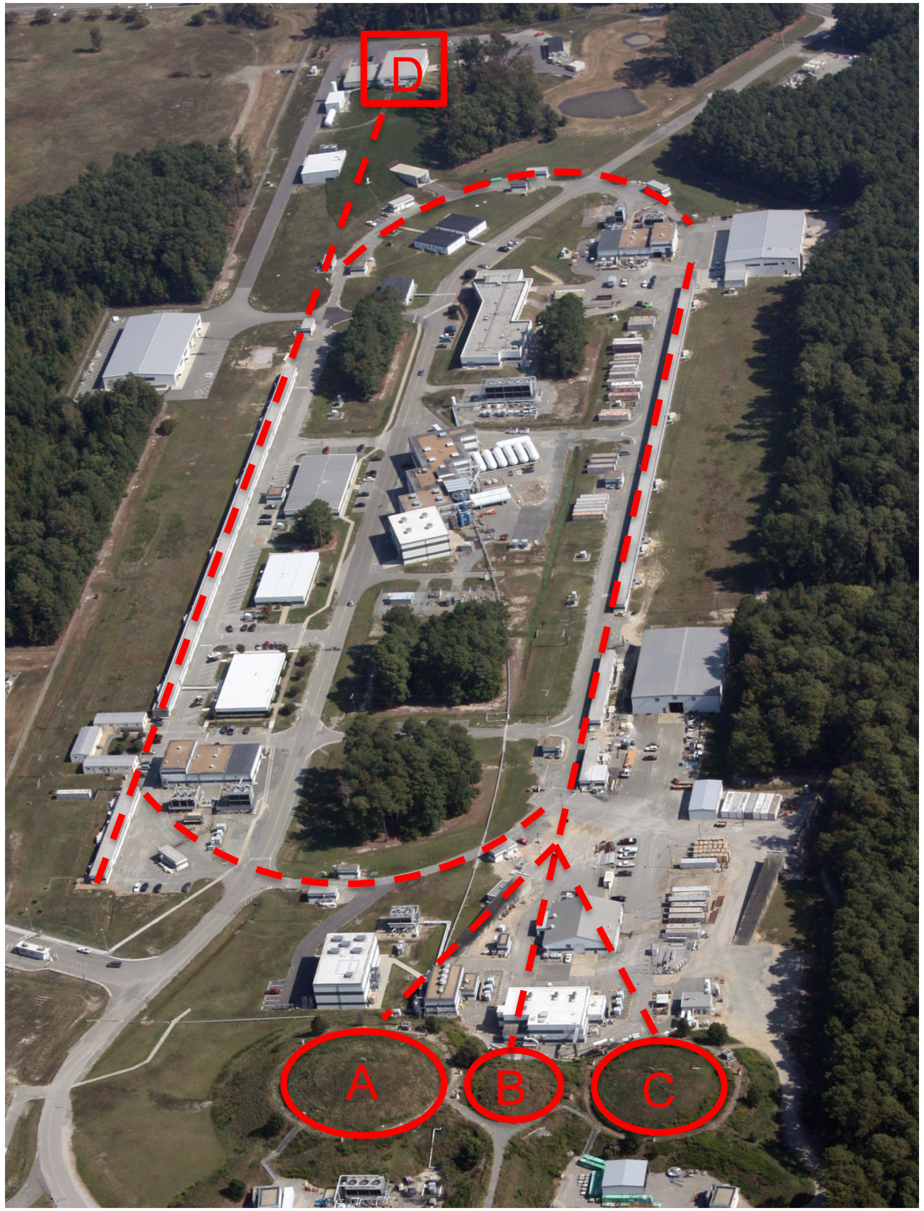
Gomez et al, PRD 49, 4348 (1994)

Exploring the EMC Effect at Jefferson Lab

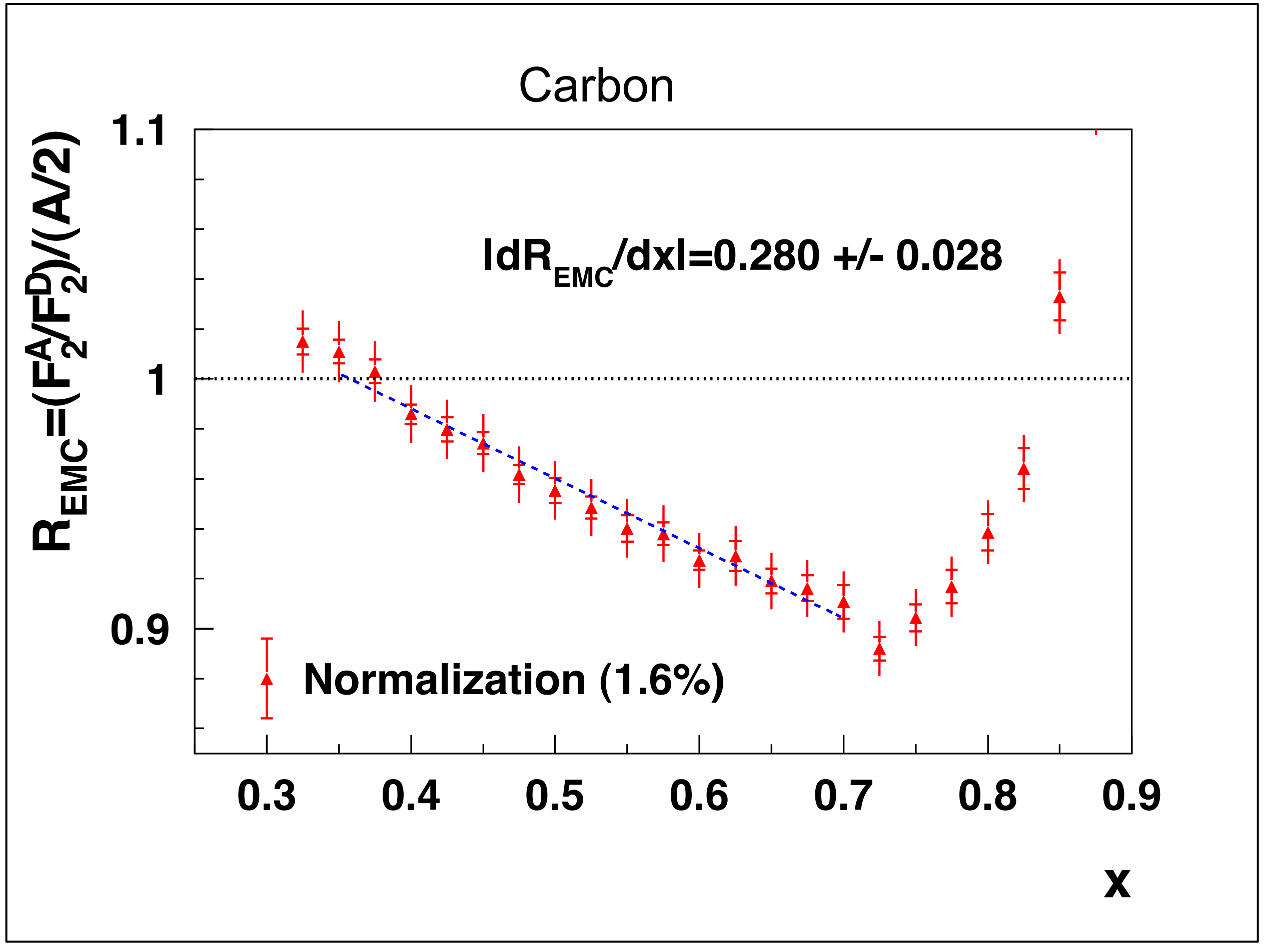
High intensity electron beam and improved target technology provides excellent opportunity for studying EMC Effect

→ Originally, max beam energy = 6 GeV, limited kinematic reach
→ Upgrade to 12 GeV provided wider access to the DIS region

Unexpected results from the 6 GeV program have motivated a significant number of experiments at 12 GeV



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

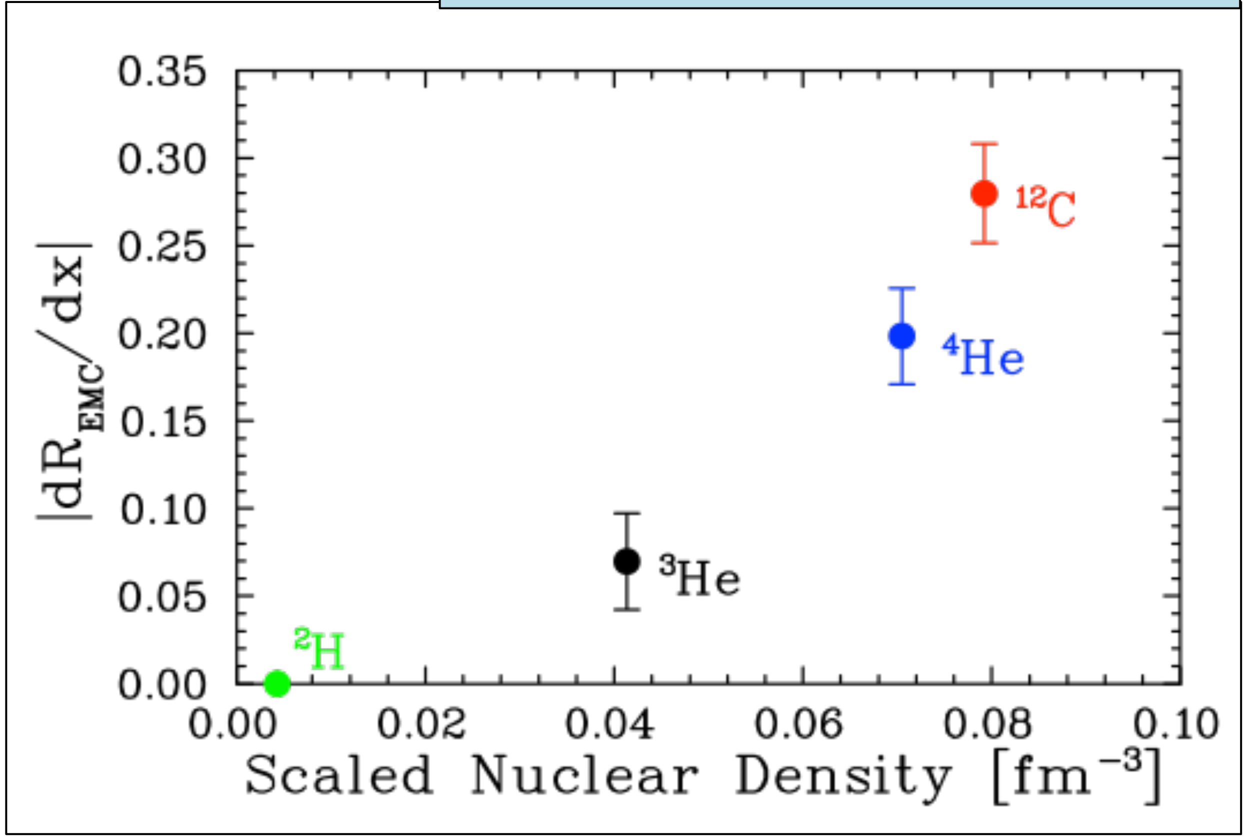
JLab (Hall C) Measurements on Light Nuclei (6 GeV)

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

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



Scaled nuclear density = *(A-1)/A* $\langle\rho\rangle$
→ remove contribution from struck nucleon

$\langle\rho\rangle$ from ab initio few-body calculations
→ ***[S.C. Pieper and R.B. Wiringa**, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)]*

JLab (Hall C) Measurements on Light Nuclei (6 GeV)

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More information on nuclear dependence → emphasis on light nuclei:
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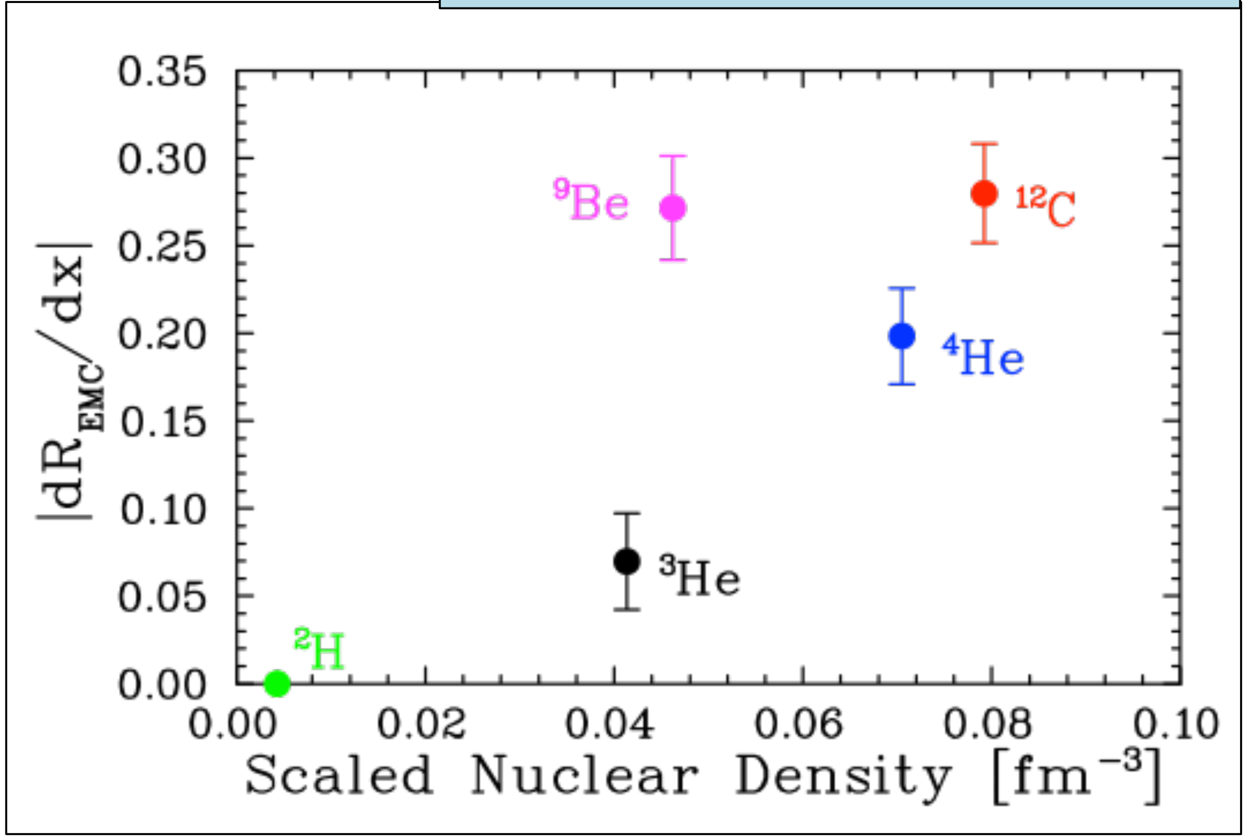
→ New definition of size of EMC effect:
|dR/dx| for *0.35<x<0.7*

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

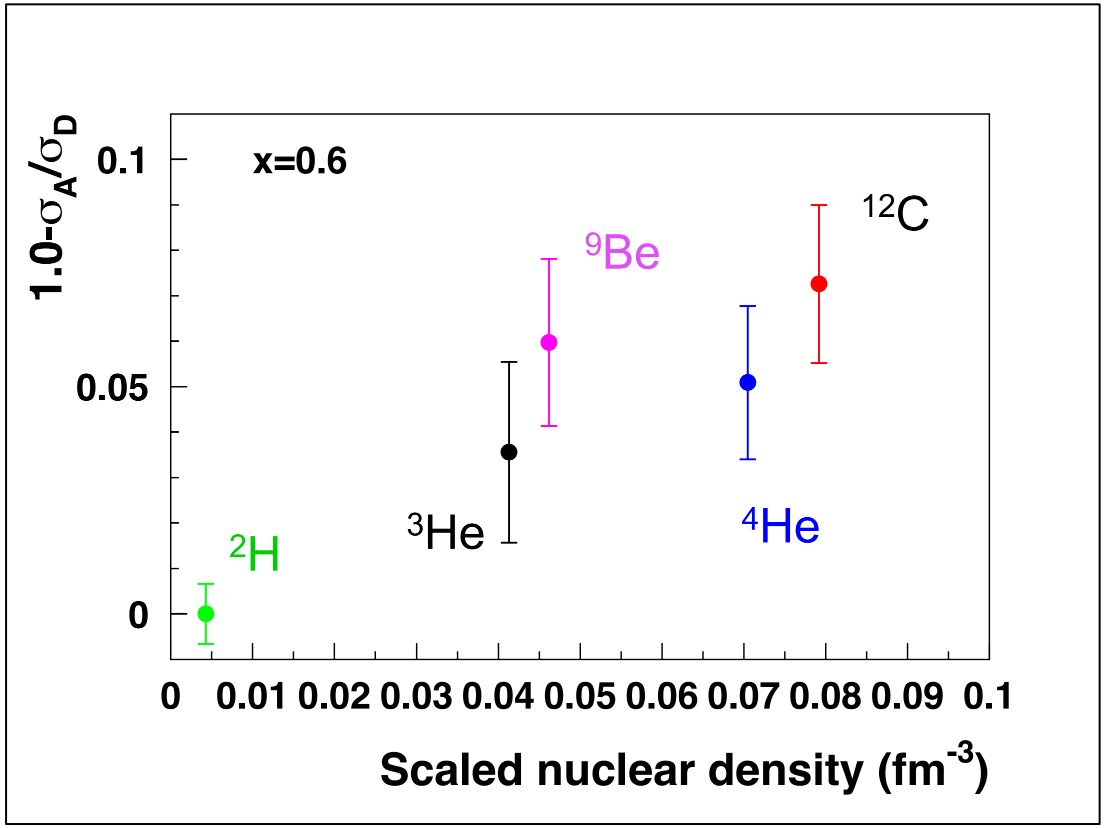
Scaled nuclear density = *(A-1)/A <ρ>*
→ remove contribution from struck nucleon

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



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

Improved Precision via New Observable



Key to observation of "local density" dependence is *modified definition of size of EMC Effect**

→ Nuclear dependence of EMC effect typically examined at fixed x

→ Use of *dR/dx* greatly reduced sensitivity to normalization uncertainties

EMC effect ~ 10% deviation from 1.0

Normalization uncertainties ~ 1-2%

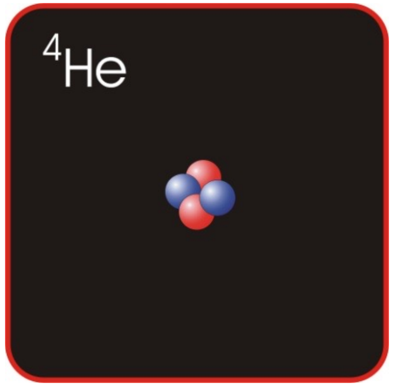
**Full disclosure: I was initially skeptical of this approach*

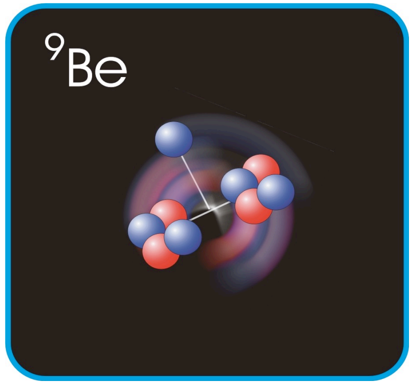
EMC Effect and Local Nuclear Density

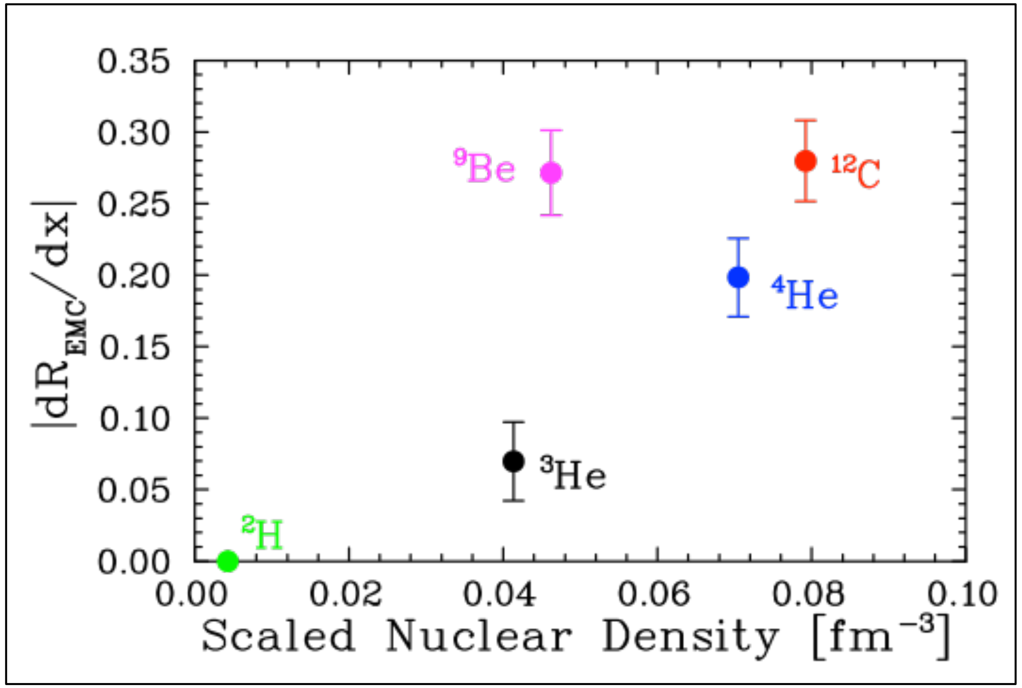
^{9}Be has low average density

→ 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 tied to other observables?

Jefferson Lab

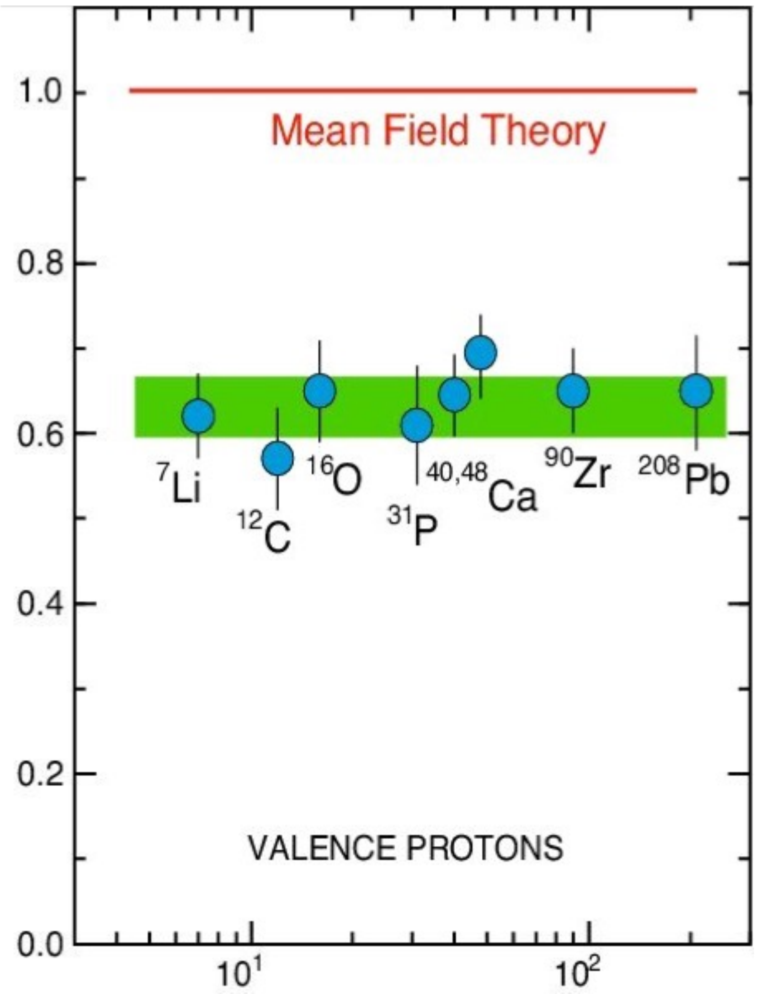
Local Density → Short Range Correlations

What drives high "local" density in the nucleus?

In simple models of the nucleus (Fermi gas), all nucleons experience basically the same local environment

Fermi gas, or other mean field models ***incomplete***

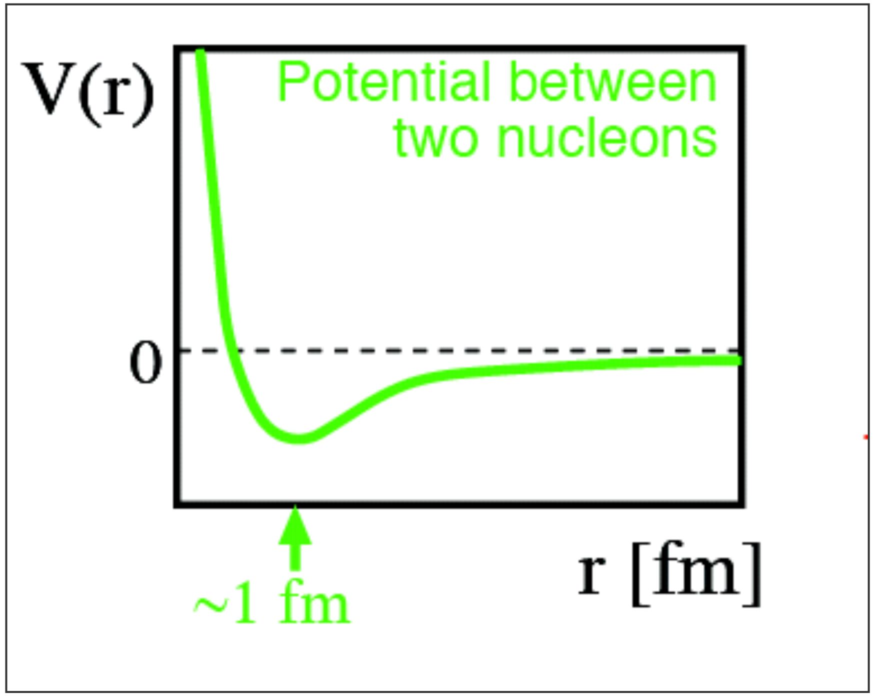
(e,e'p) data for knockout of protons with momenta lower than "Fermi" momentum indicates significant missing strength

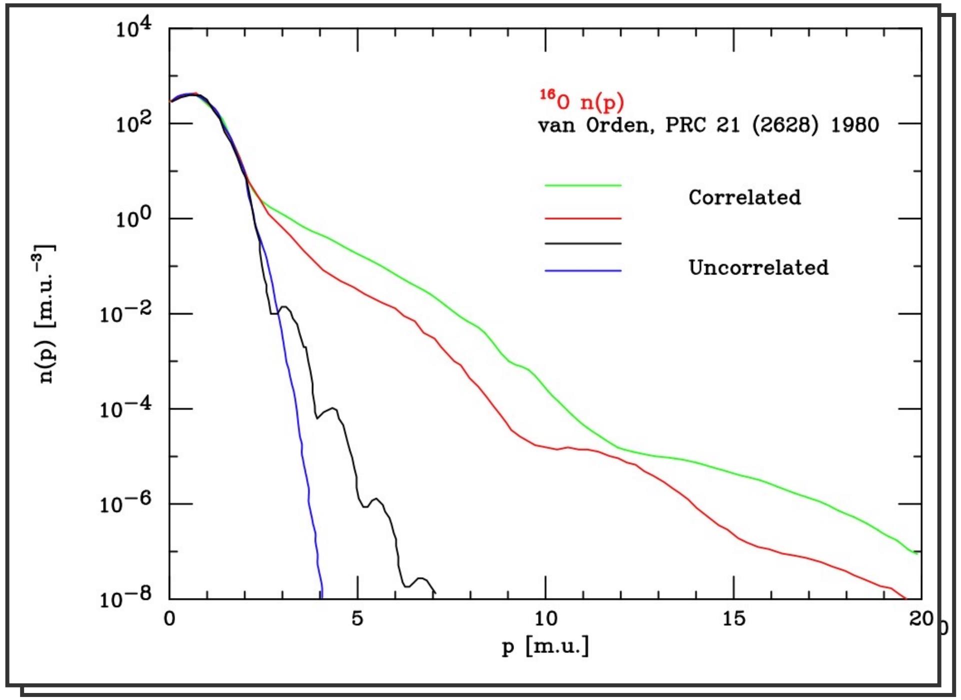


L. Lapikas, Nucl. Phys. A553 (1993) 297

Local Density → Short-Range Correlations

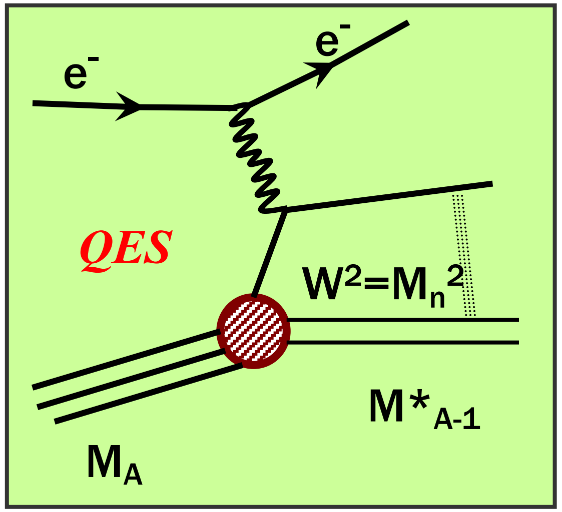
What drives high “local” density in the nucleus?



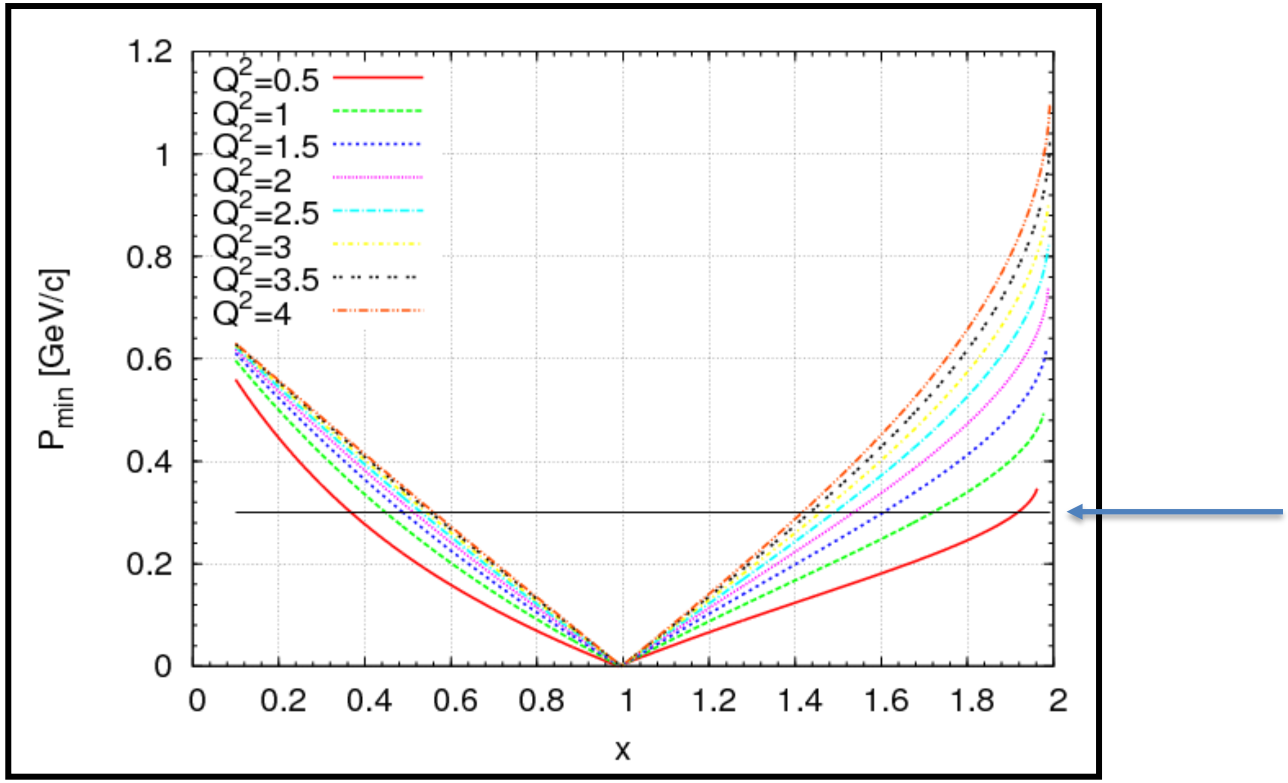


Tensor interaction and short-range repulsive core lead to high momentum tail in nuclear wave function → correlated nucleons

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

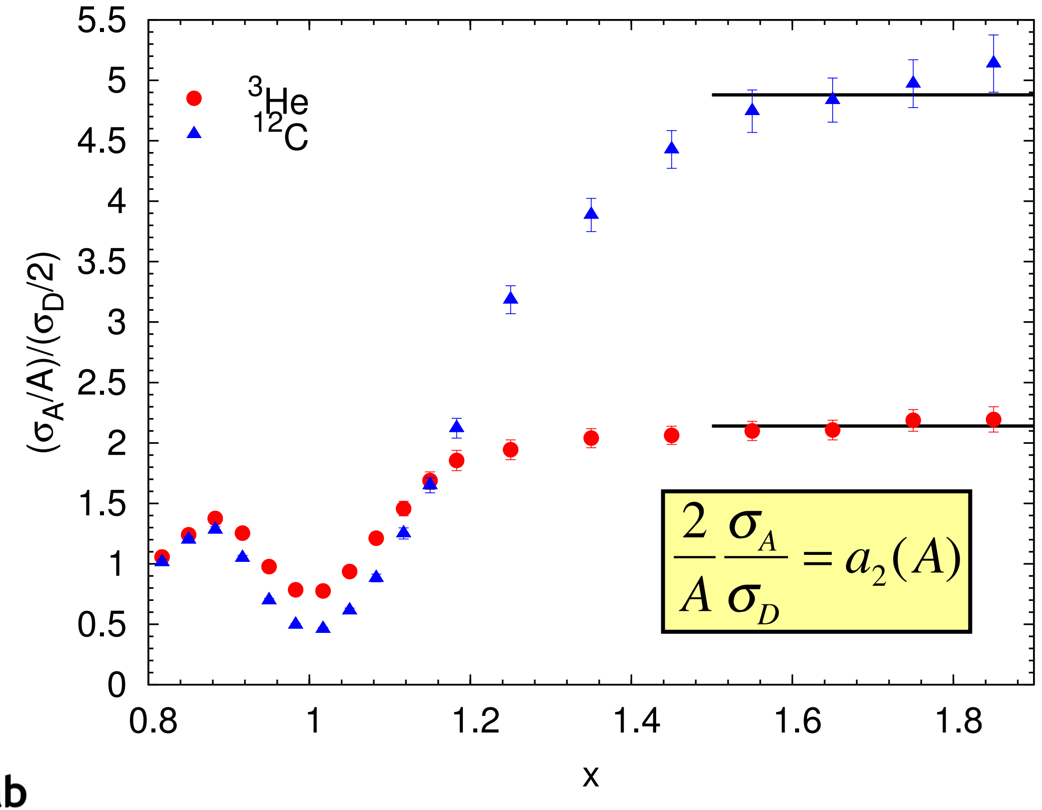


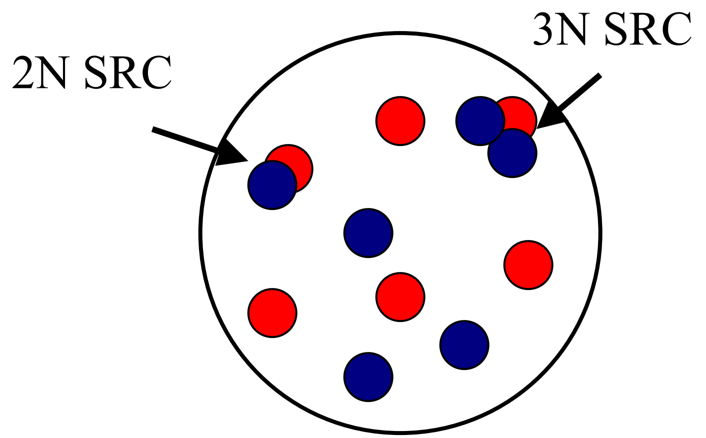
→ At *x>1*, we can access higher momentum components, if we go to large enough *Q*²

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

Measuring Short-Range Correlations

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



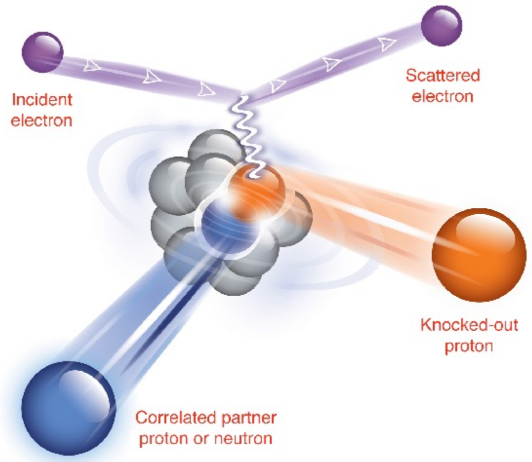


1.4<x<2 => 2 nucleon correlation

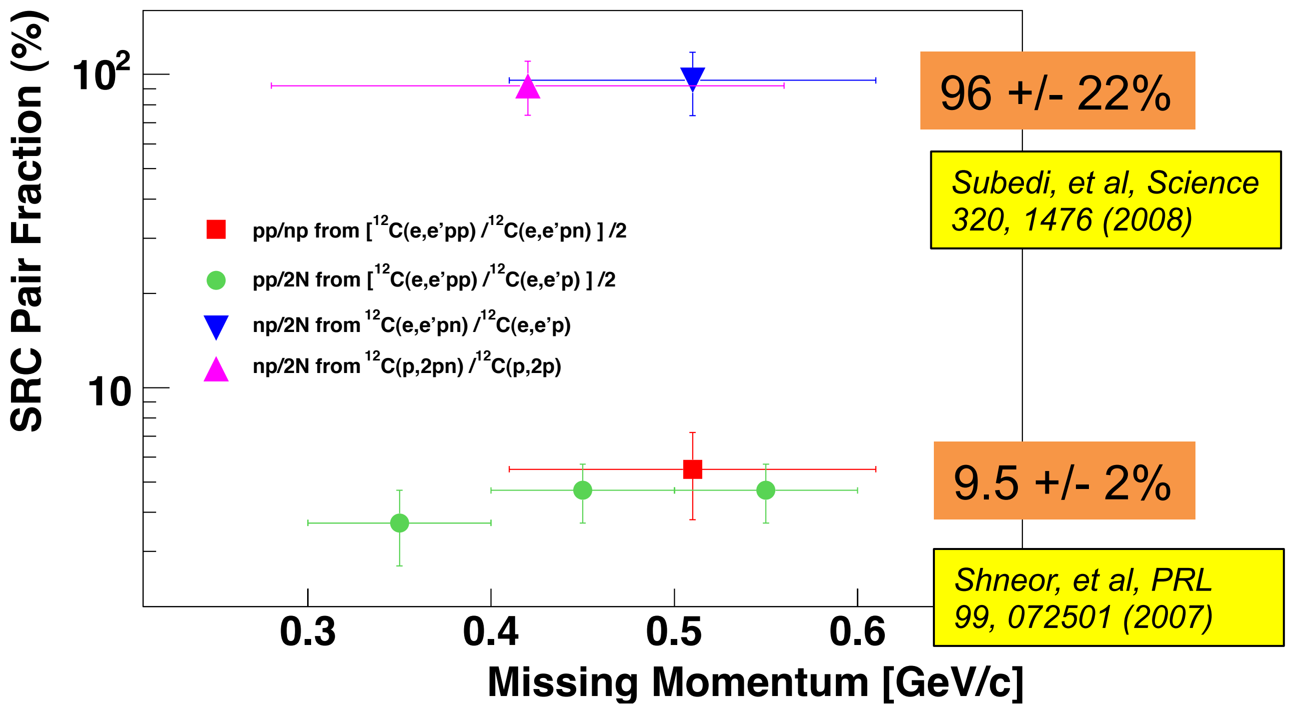
2.4<x<3 => 3 nucleon correlation

Jefferson Lab

Short Range Correlations – np Dominance

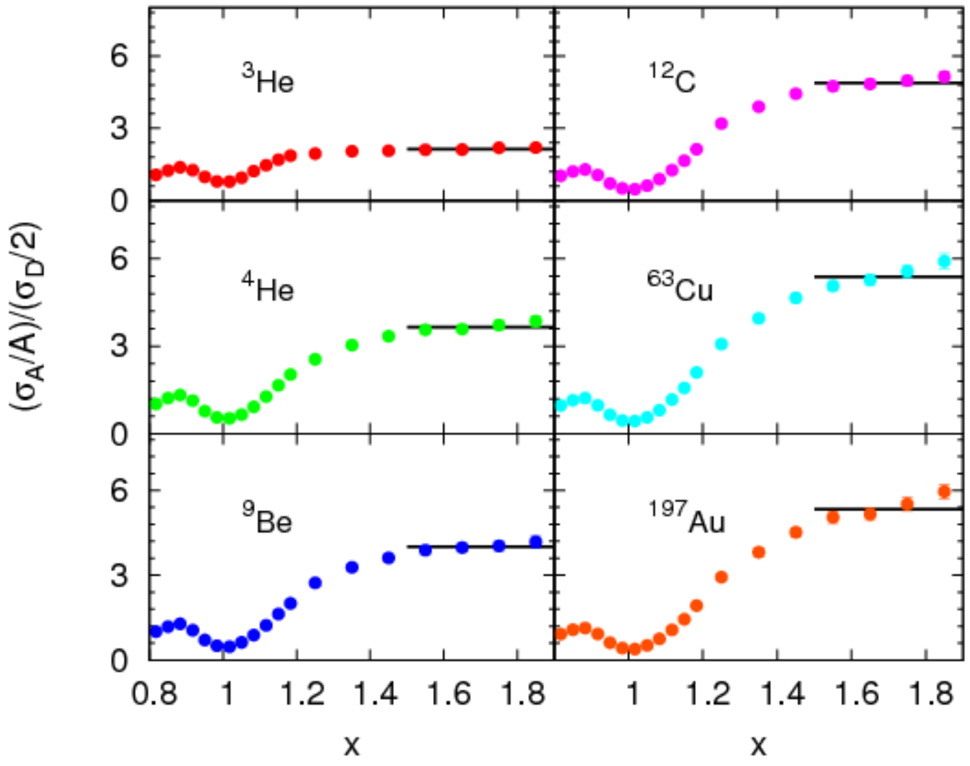


SRCs can be studied in more detail via triple-coincidence reactions
→ Electron knocks out high momentum proton from carbon nucleus
→ “Partner” backward-going proton or neutron also detected



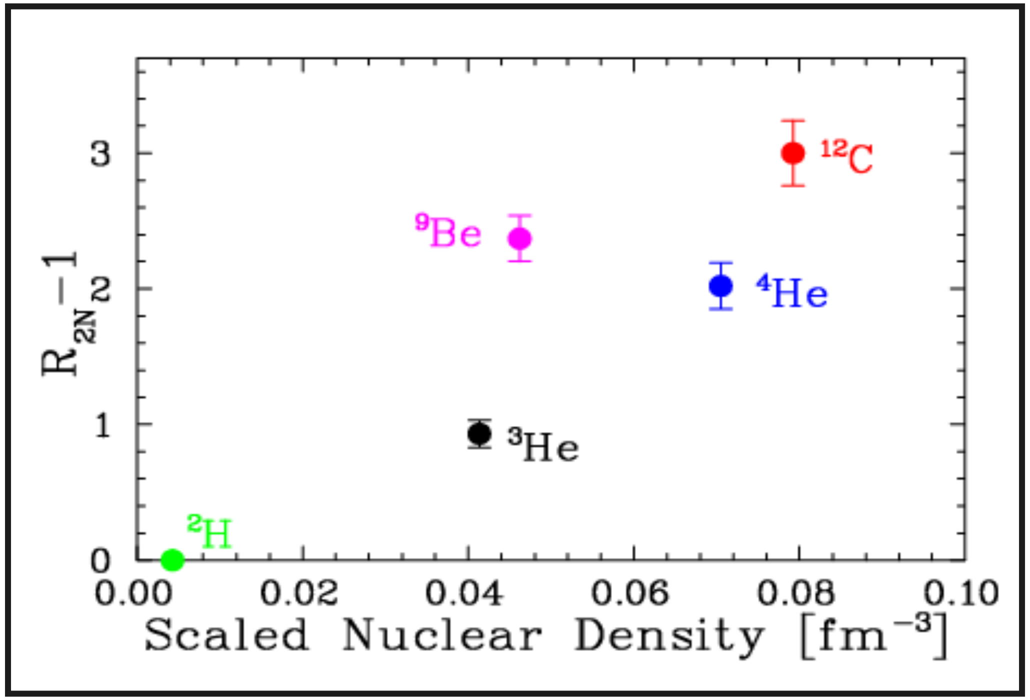
Conclusion: High momentum nucleons are dominated by ***np*** pairs

Nuclear Dependence of SRCs



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

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



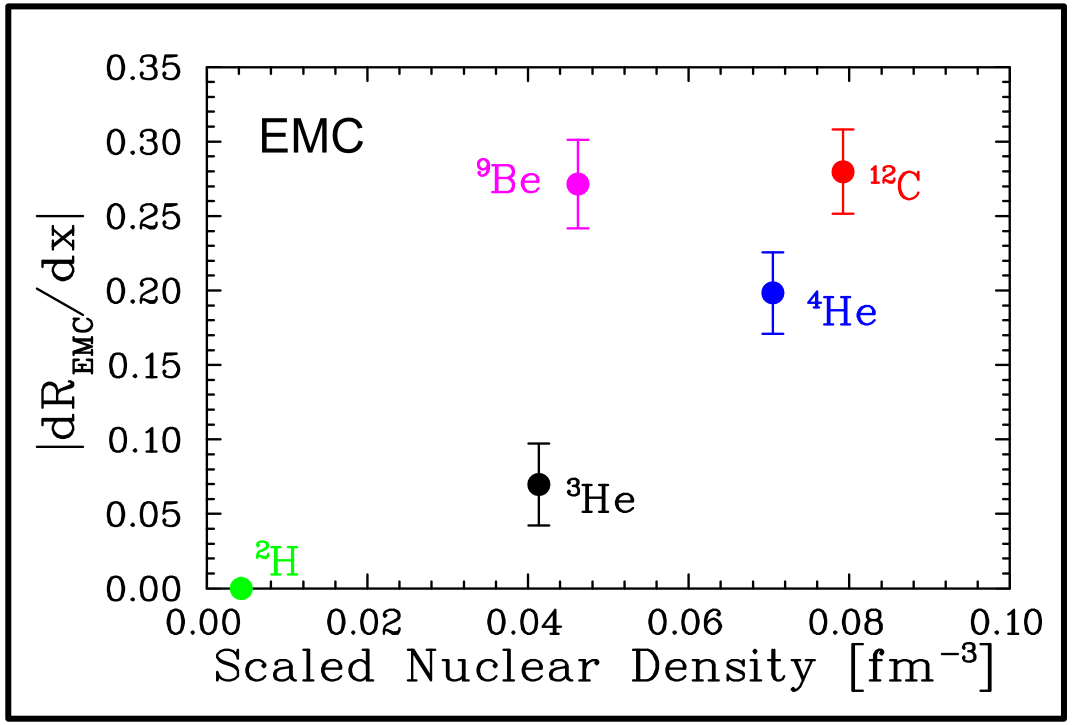
JLab also data on A/D ratios at *x>1* at 6 GeV

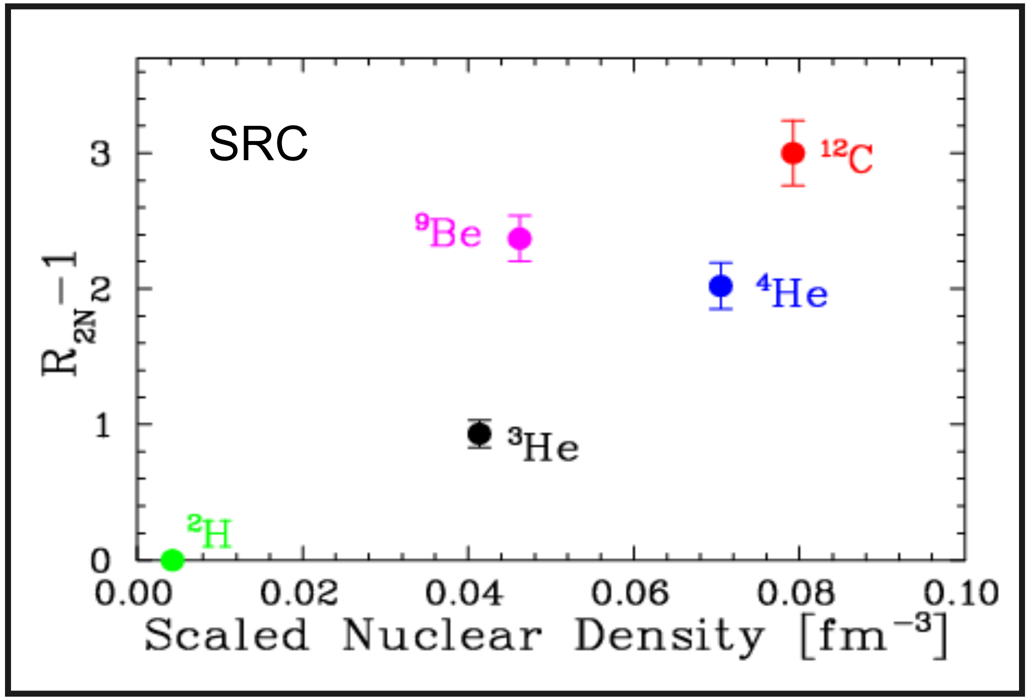
a_2 ratios for:

→Additional nuclei (Cu, Be, Au)

→Higher precision for targets with already existing ratios

Nuclear Dependence of SRCs and the EMC Effect



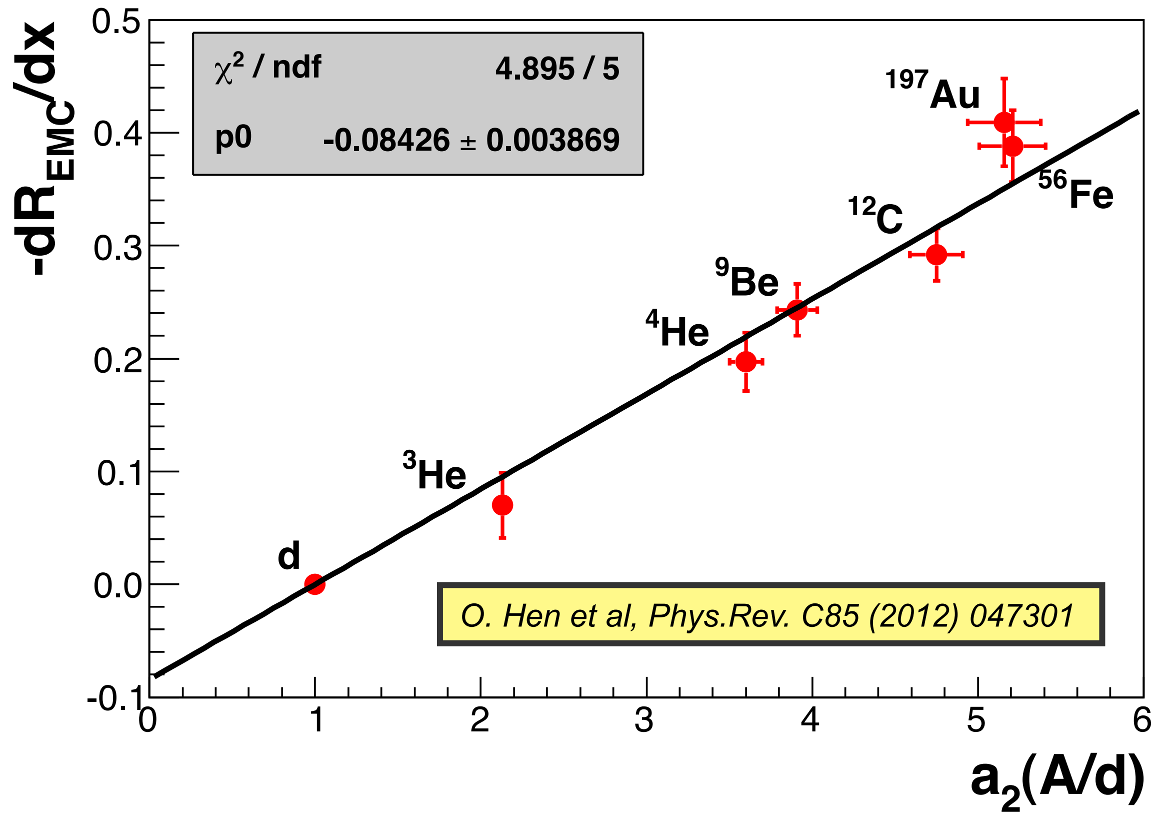


→ *Relative probability to find SRC shows similar dependence on nuclear density as EMC effect!*

EMC Effect and Short-Range Correlations

Weinstein *et al* first observed linear correlation between size of EMC effect and Short-Range Correlation "plateau" using EMC and older SRC data

Correlation strengthened with addition of JLab 6 GeV SRC (beryllium) data



This result provides a ***quantitative*** test of level of correlation between the two effects, but does not provide a microscopic explanation for EMC Effect

Summary: Part 1

- Discovery of the EMC Effect was perhaps the first indication of the relevance of quark degrees of freedom in the nucleus
- Significant experimental and theoretical effort over the last 40+ years
  - ***Still so consensus on origin!***
- “Conventional” nuclear effects (Fermi motion, binding, nuclear pions) are insufficient to explain the EMC Effect
- Observation of correlation with SRCs has generated a lot of excitement
  - Are there testable predictions/observables in this picture?