The EMC Effect

Exploring the Structure of Nucleons in Nuclei

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Outline

- Nucleons in the nucleus
- The EMC Effect – quarks in the nucleus
  - Early measurements
  - x, Q^2, nuclear dependence, universality
- Recent results and implications
  - EMC effect and local density
  - EMC-SRC (Short Range Correlations) connection
  - Flavor dependence
- Summary

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

- *Related Areas of Study:*
  - **Do individual nucleons change their size, shape, and quark structure in the nuclear medium?**
  - **How do nucleons cluster in the nuclear medium?**
  - What are the properties of the force which binds quarks into nucleons and nuclei at distances where this force is strong and the quark confinement mechanism is important?

Models of the Nucleus

<u>Mean field picture</u>

Nucleons move independently within an average potential (ex: Fermi gas)

→ No need to build up nucleus from all possible pairwise interactions

→ Very successful for describing nuclear shell structure, other nuclear properties

→ No mechanism for high momentum components in nuclear wave function, or clustering effects

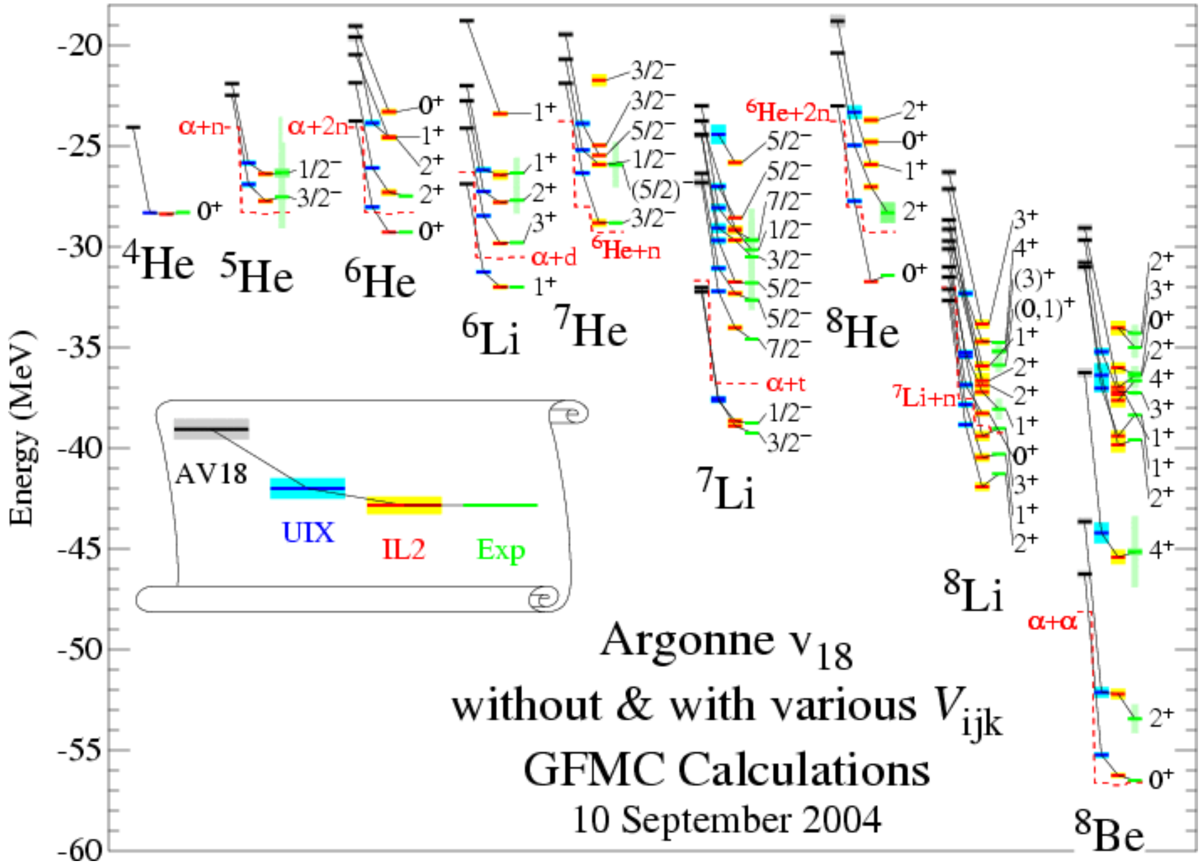
<u>Nuclei from NN interactions</u>

Start with realistic model of NN interaction, build nucleus from pairwise interactions (Argonne v18 + Green's Function Monte Carlo calculations)

→ Requires significant computing power

→ Excellent description of nucleon momentum distribution over full range (short and long distances)

Nuclei from NN Interactions



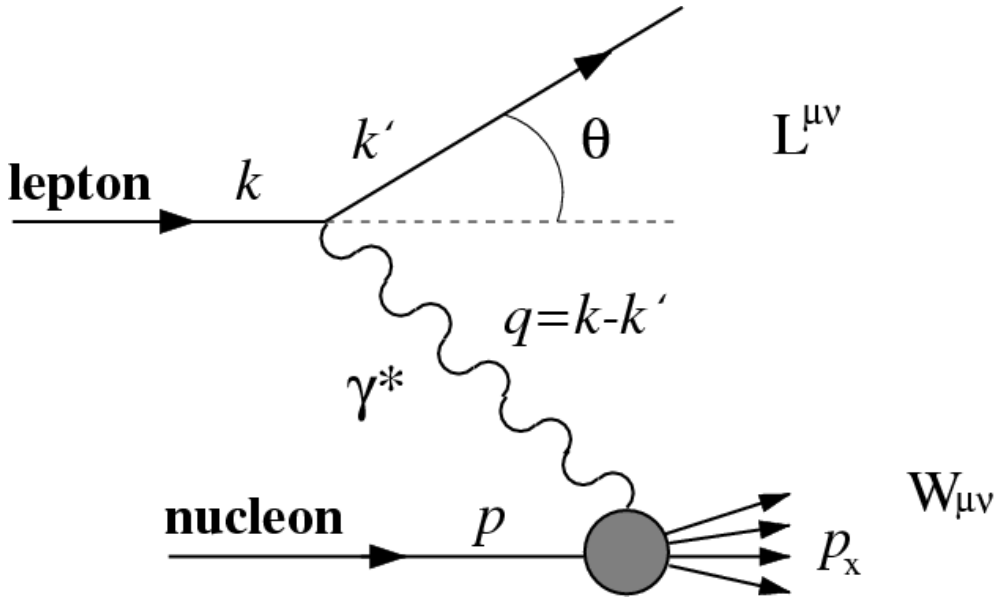
- Starting from “effective” models of interactions between protons and neutrons – we can build up any nucleus we want
  → (only limited by computing power)

Nucleons in the Nucleus

- In either picture (mean field or NN interaction), nucleons are the fundamental constituents of the nucleus*
- Nucleon sub-structure not relevant in these models
  - Energy scales very different: Fermi momenta ~ hundreds of MeV, quark substructure relevant at GeV scales
- We now know that quark distributions are modified in the nucleus → Is this important for our understanding of the nucleus?
  - Conversely, what are the origins of this modification?
- Deep Inelastic Scattering provides an excellent probe for exploring modifications to nucleon structure in the nucleus

Deep Inelastic Scattering

Cross section for inclusive lepton (electron) scattering:



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

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

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, x

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

Quarks in the Nucleus

Typical nuclear binding energies → MeV while DIS scales → GeV

(super) Naïve expectation:

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

More sophisticated approach includes effects from Fermi motion

$$F_2^A(x) = \sum_i \int_x^{M_A/m_N} dy f_i(y) F_2^N(x/y)$$

Quark distributions in nuclei were not expected to be significantly different (below x=0.6)

$$F_2^{Fe} / \left(ZF_2^p + (A-Z)F_2^n \right)$$

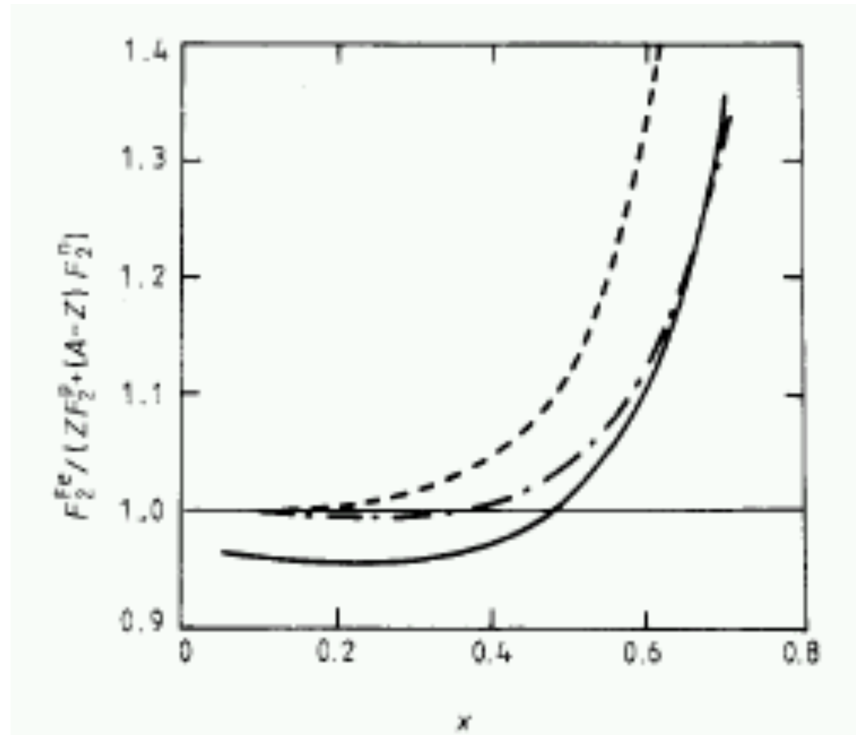
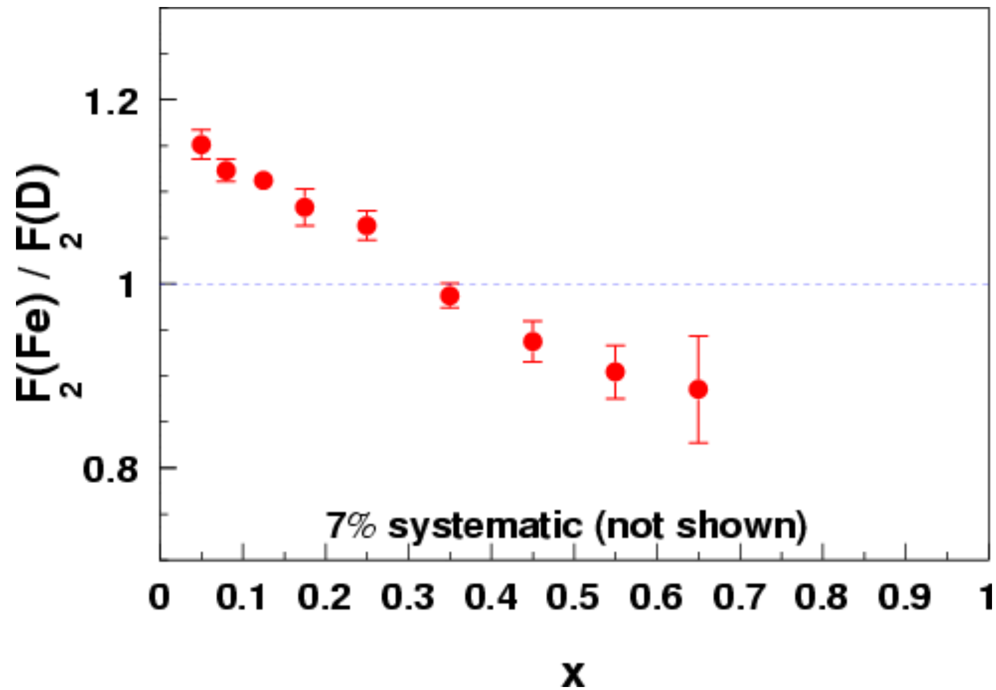


Figure from Bickerstaff and Thomas, J. Phys. G 15, 1523 (1989)
Calculation: Bodek and Ritchie PRD 23, 1070 (1981)

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! (see 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)

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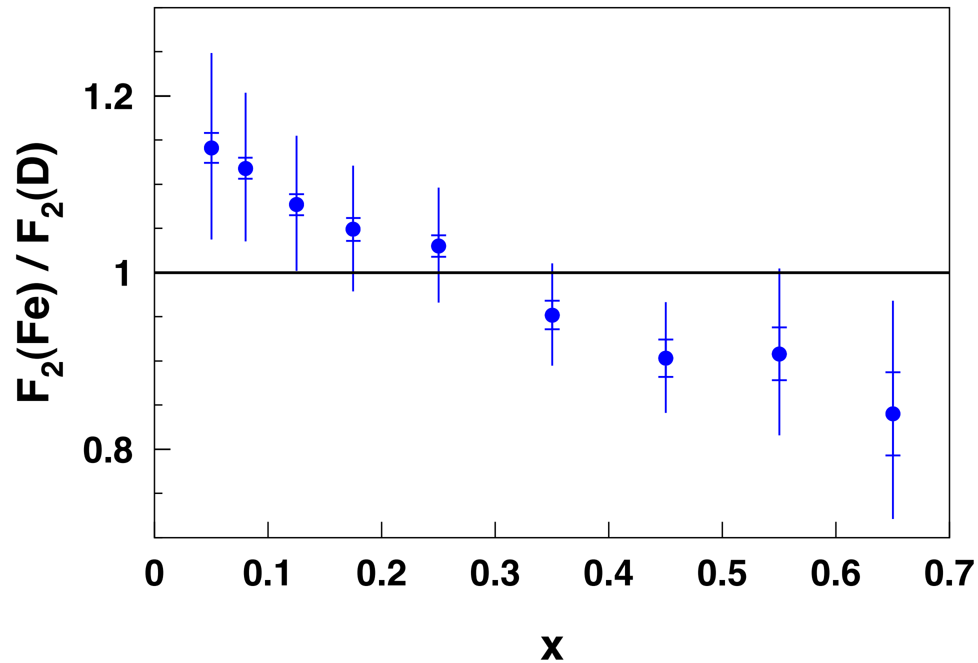
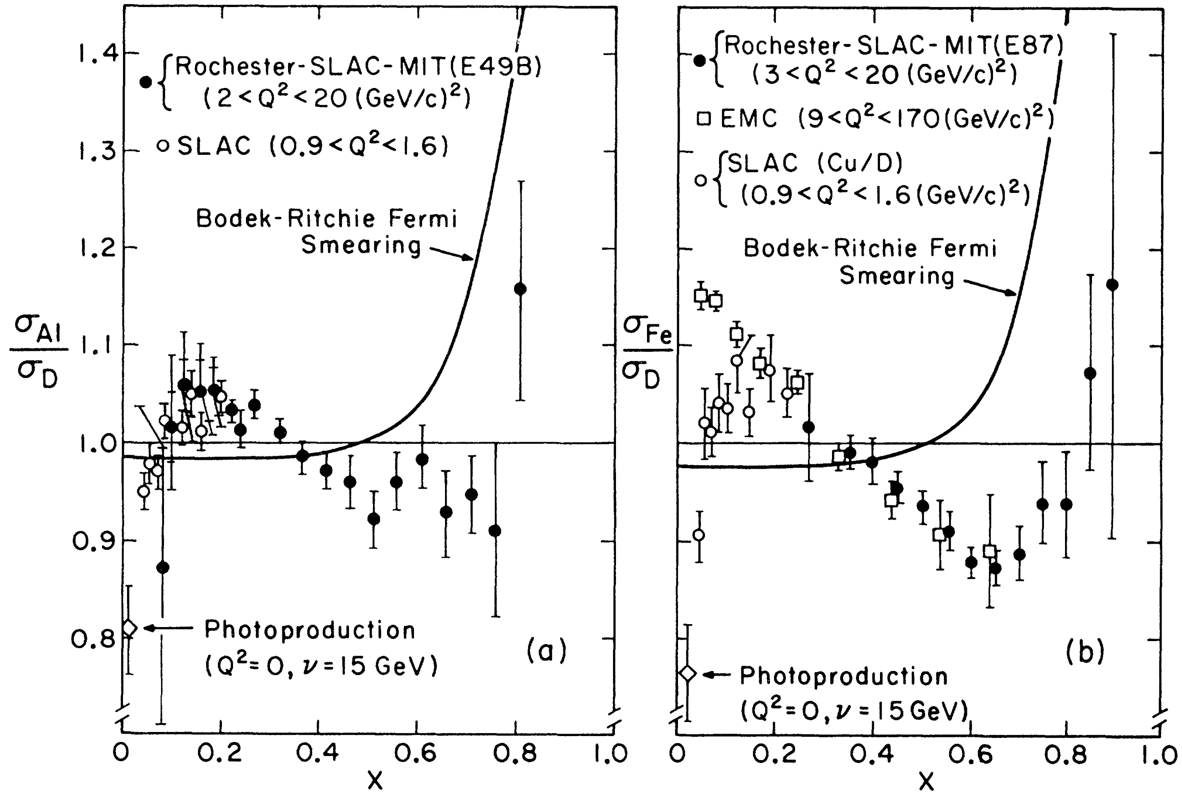


Aubert et al, Nucl. Phys. B293, 740 (1987)

Confirmation of the Effect

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

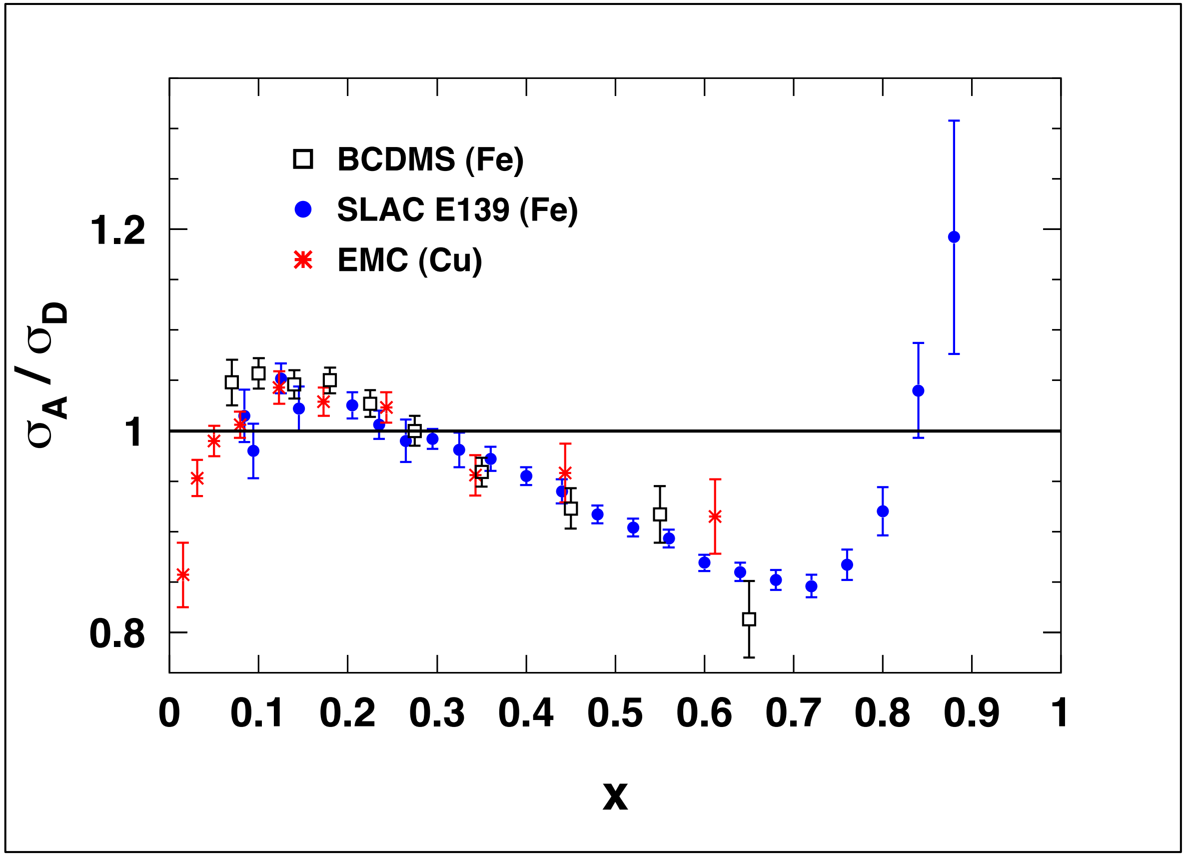


→Effect for $x>0.3$ confirmed

→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

Laboratory/ collaboration	Beam	Energy (GeV)	Target	Year
SLAC E87/E49B	e	8.7-20	***D***, Al, Fe	1983
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
	e	6	***D***, C, Cu, Au	2004 (thesis)

Jefferson Lab

Geesaman, Saito, and Thomas, Ann. Rev. Nucl. Sci. 45, 337 (1995) – updated by Gaskell

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)

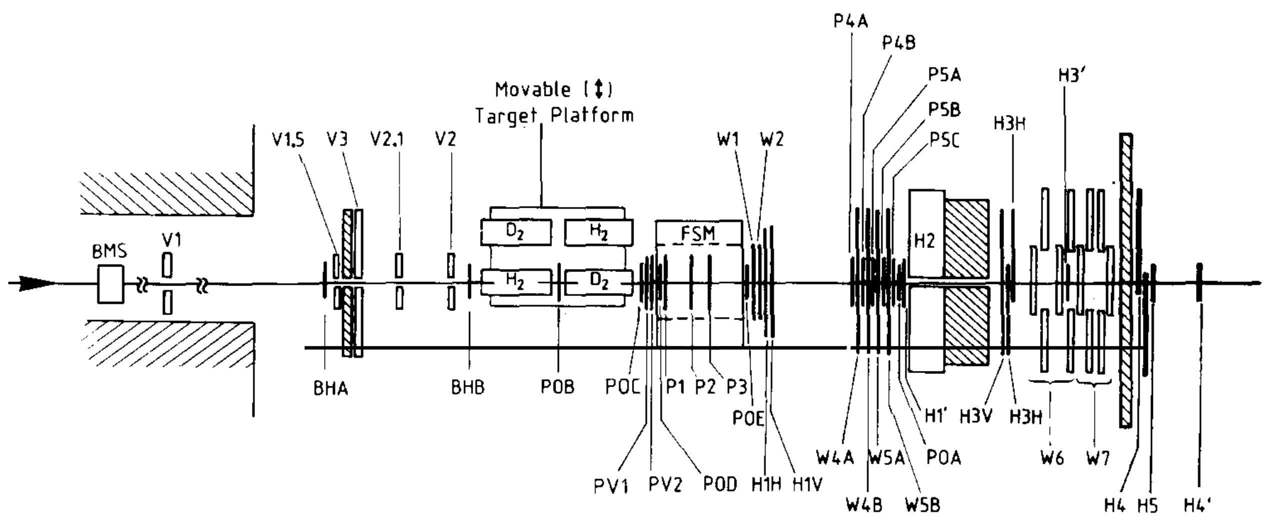
→ Energy scale 6-25 GeV
→ Well defined beam energy, narrow dE
→ Intense beams → higher statistics
→ Small acceptance devices often (but not always) used

New Muon Collaboration

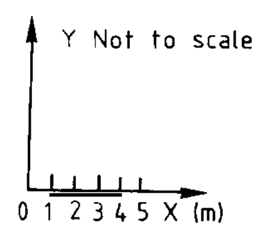
NMC: next generation experiment at CERN, building on EMC

Large acceptance spectrometer with large array of tracking chambers

NMC SPECTROMETER (TOP VIEW)



BMS	Beam momentum station
V1, V1.5, V3, V2.1, V2	Veto counters
BHA, BHB	Beam hodoscopes
POA-E, PV1-2, P1-3, P4A-5C	Proportional chambers
FSM	Forward spectrometer magnet
W1-2, W4A-5B, W6-7	Drift chambers
H1H, H1V, H3V, H3H, H4, H5	Large angle trigger hodoscopes
H1', H3', H4'	Small angle trigger hodoscopes
H2	Hadron calorimeter
	Iron absorbers



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

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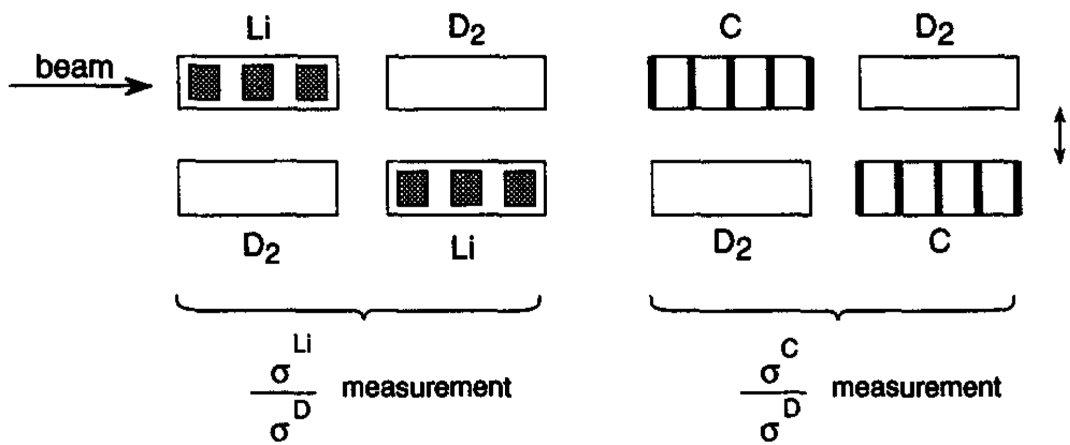
New Muon Collaboration

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%

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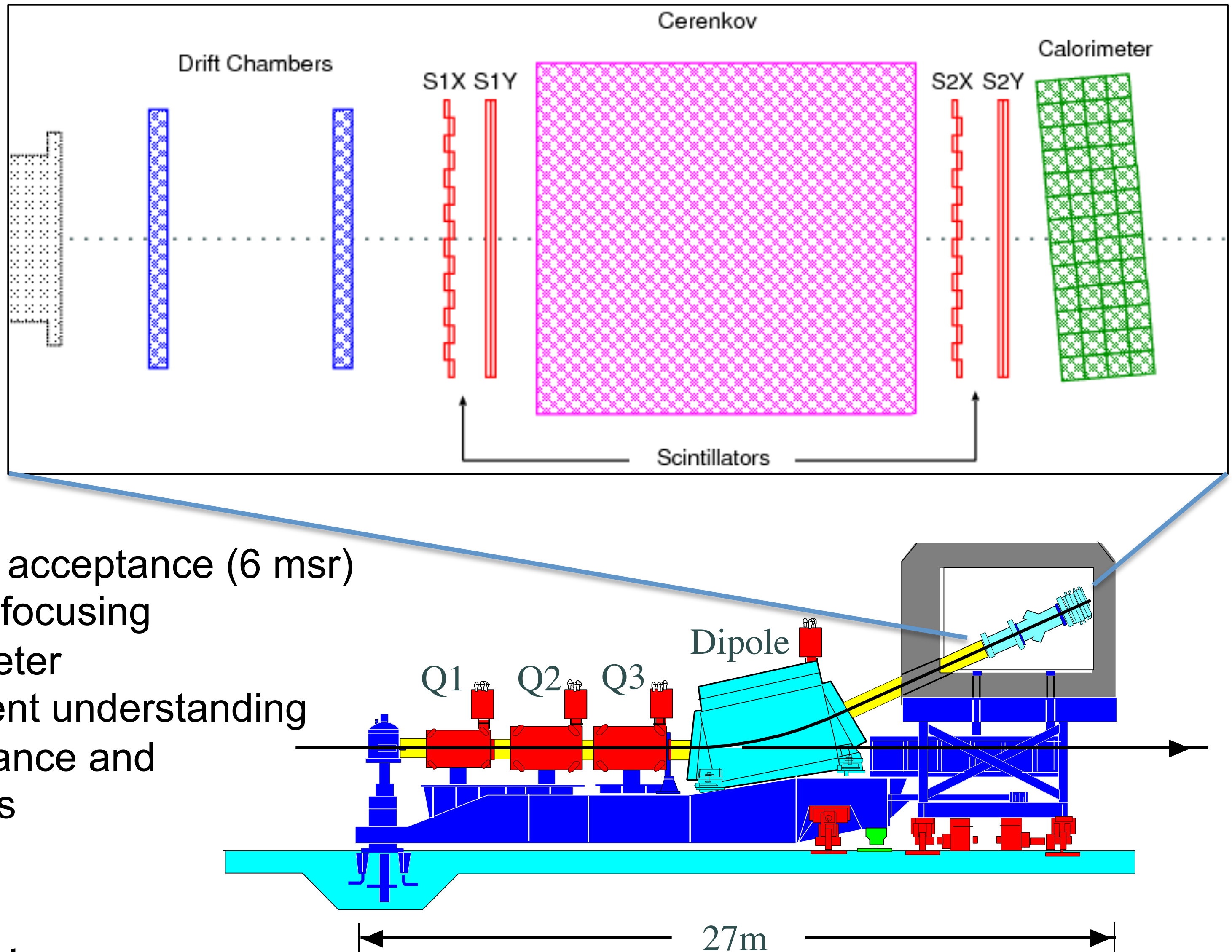

Moderate acceptance (6 msr) magnetic focusing spectrometer
→ Excellent understanding of acceptance and kinematics

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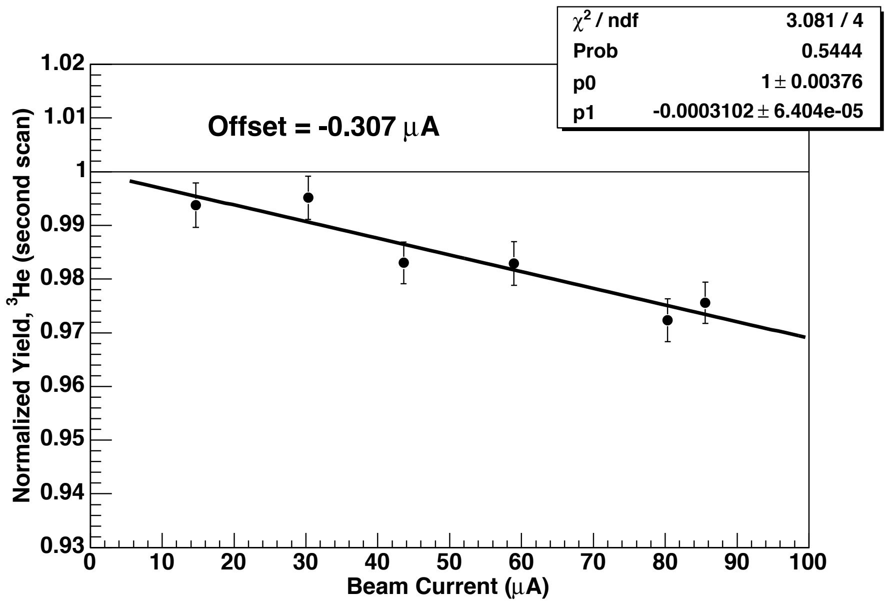
High current electron beam requires high power cryogenic targets
→ Knowledge of the absolute target density sometimes challenging due to target boiling effects



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

Order 5 10^{14} electrons/s: 4 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)

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

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

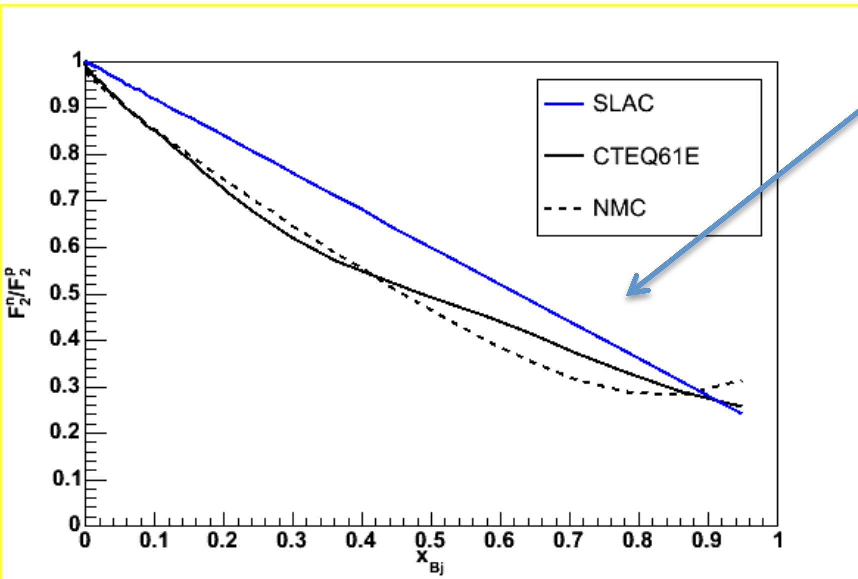
$$\frac{\sigma_A}{\sigma_D} = \frac{F_2^A (1+\epsilon R_A)(1+R_D)}{F_2^D (1+R_A)(1+\epsilon R_D)}$$

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

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.

Isoscalar Corrections

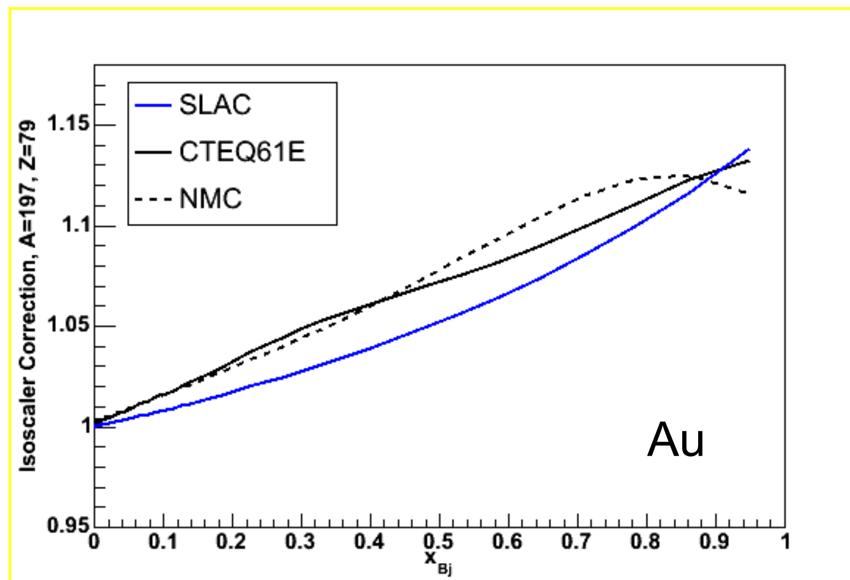
In the case of nuclei where N≠Z, need to remove the "trivial" change in nuclear cross section due to $\sigma_n \neq \sigma_p$
→ Different experiments often use slightly different parameterizations/estimates for this correction



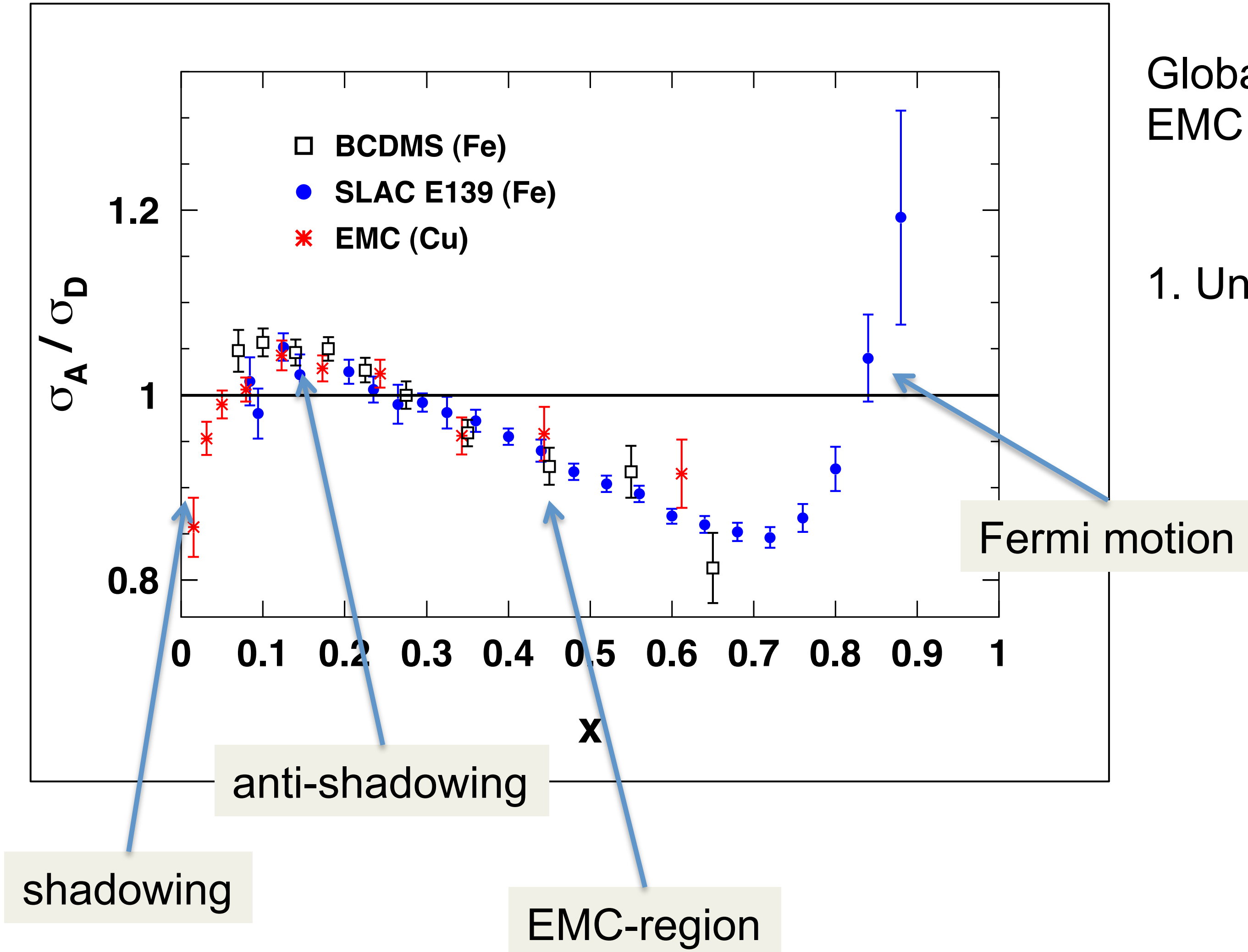
$$\frac{F_2^n}{F_2^p}$$

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

Isoscalar correction applied to data



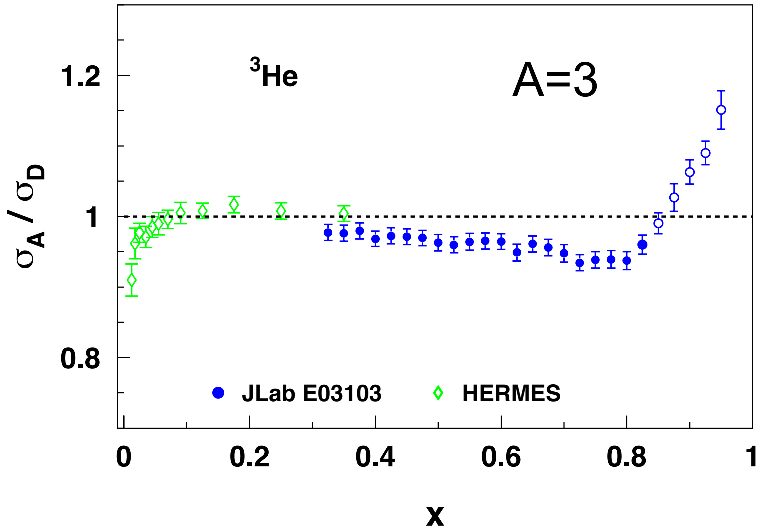
Properties of the EMC Effect

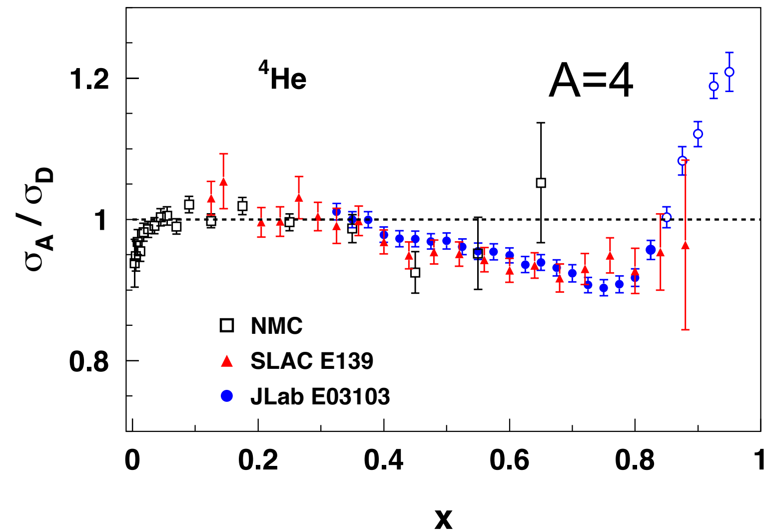


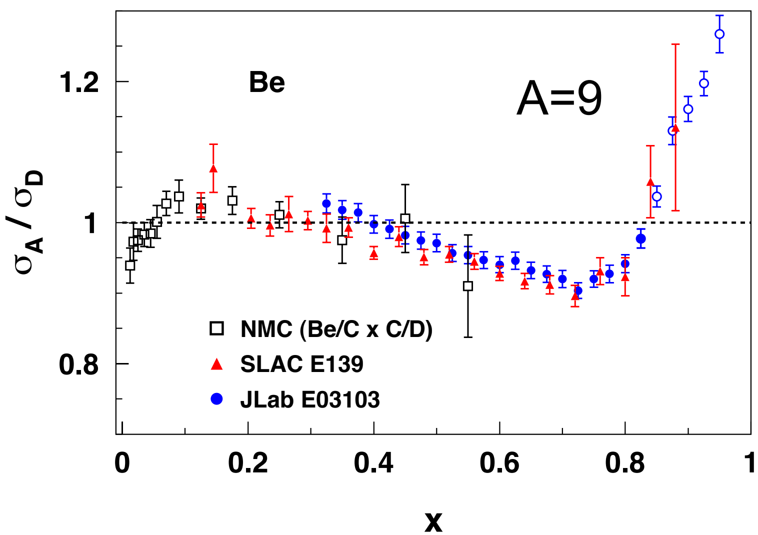
Global properties of the EMC effect

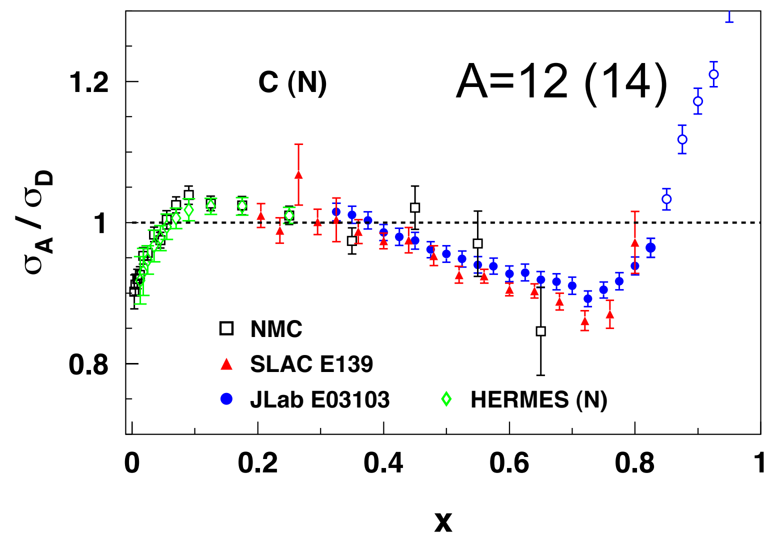
1. Universal x-dependence

x Dependence

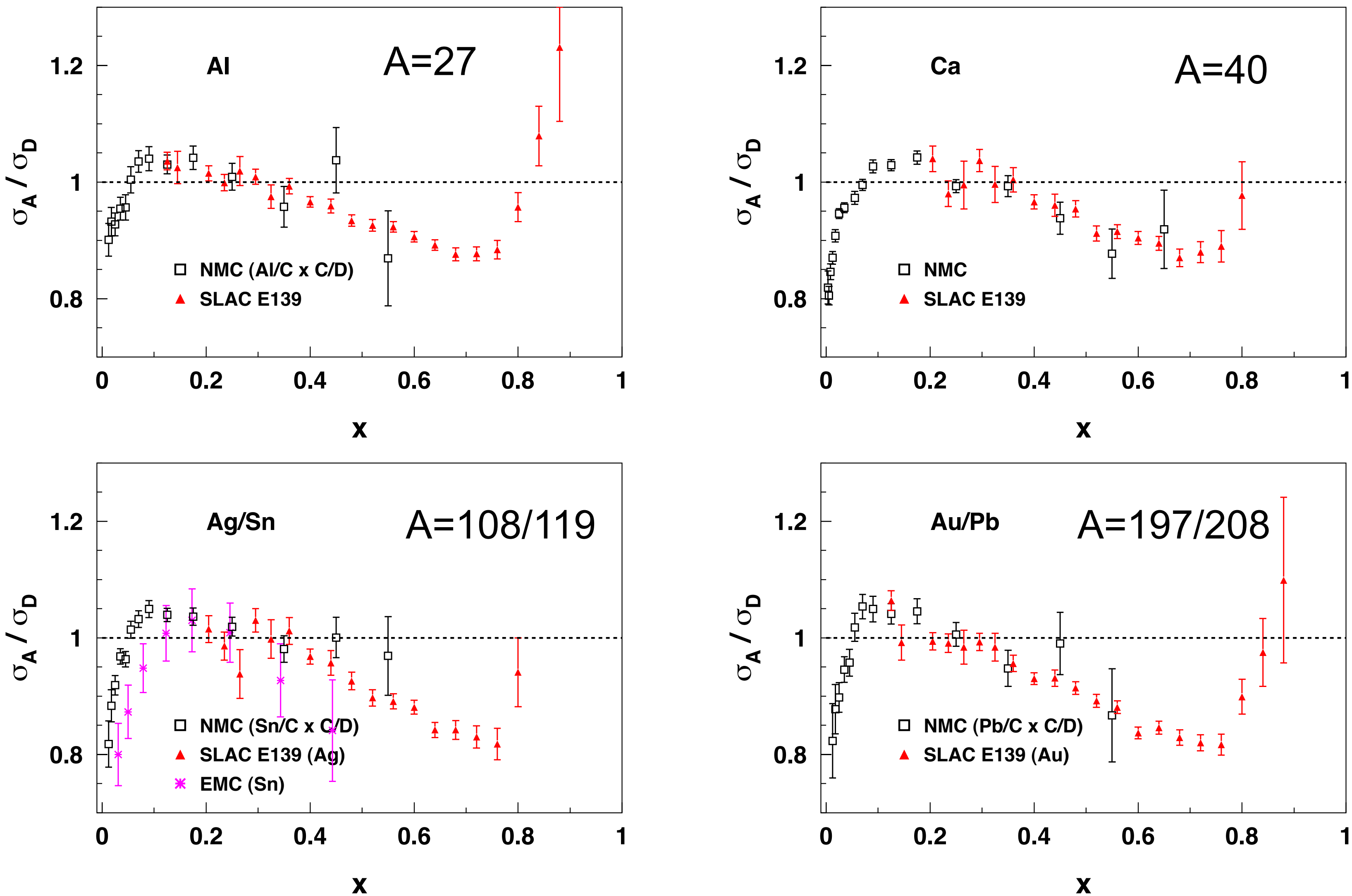




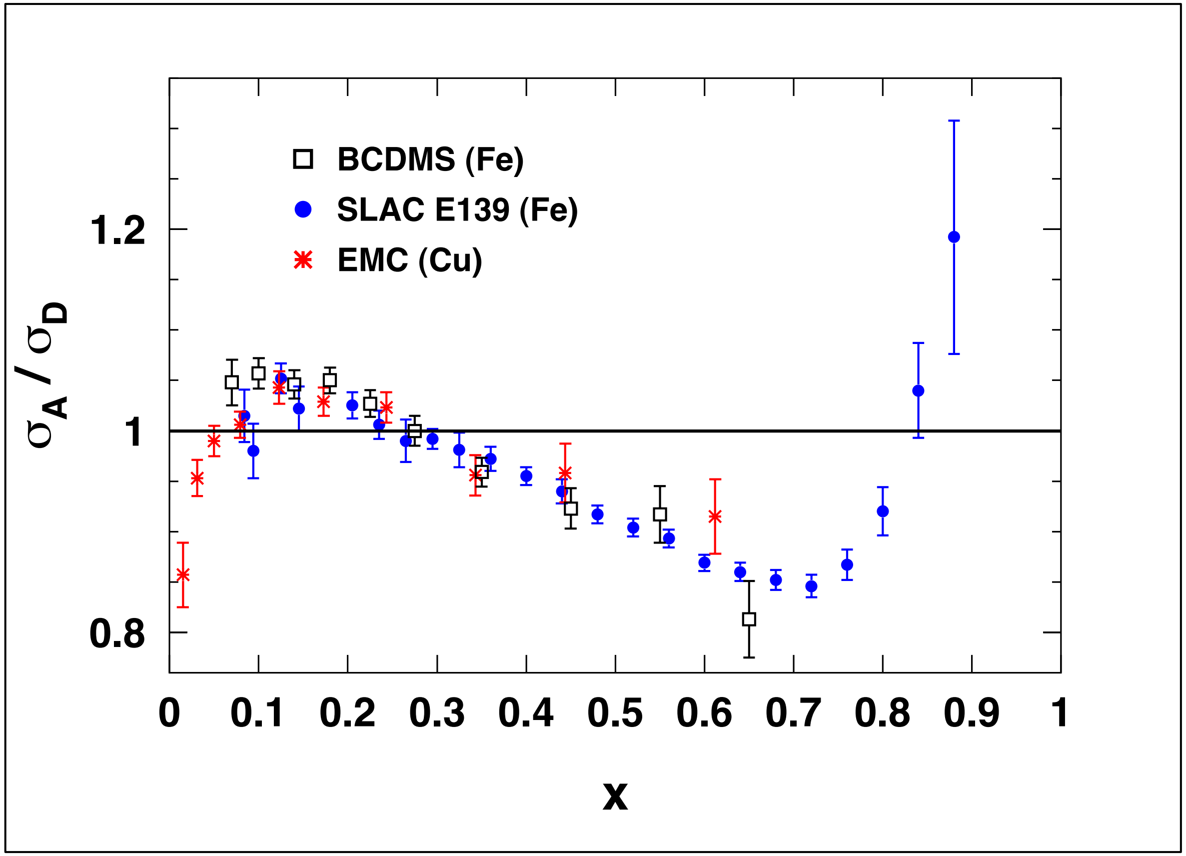




x Dependence



Properties of the EMC Effect



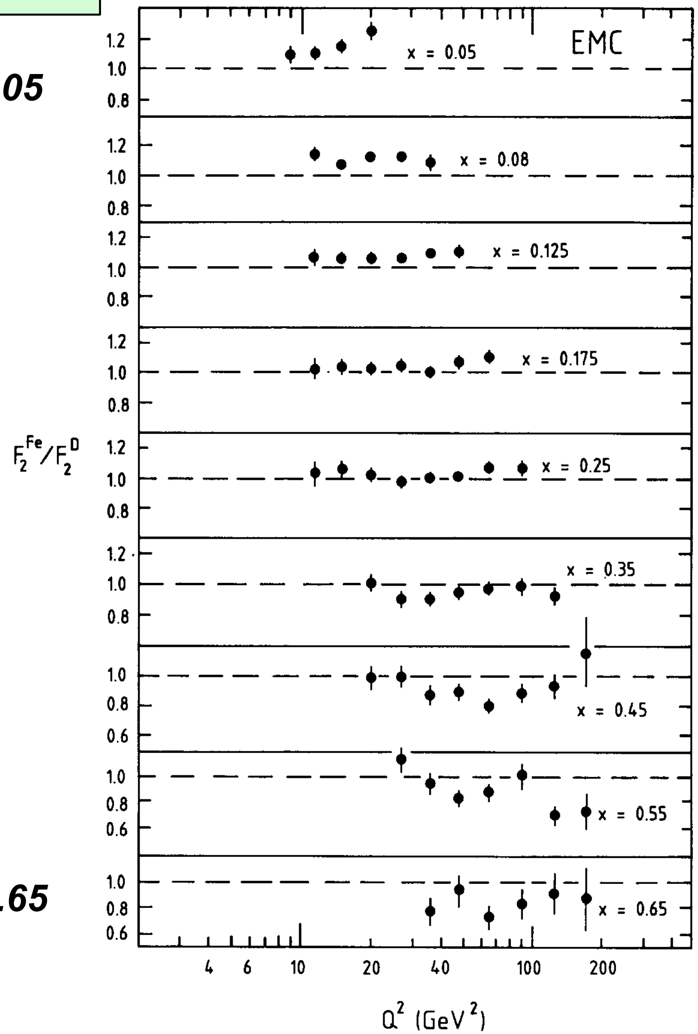
Global properties of the EMC effect

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

Q^2 Dependence of the EMC Effect

EMC Q^2=10-200 GeV^2

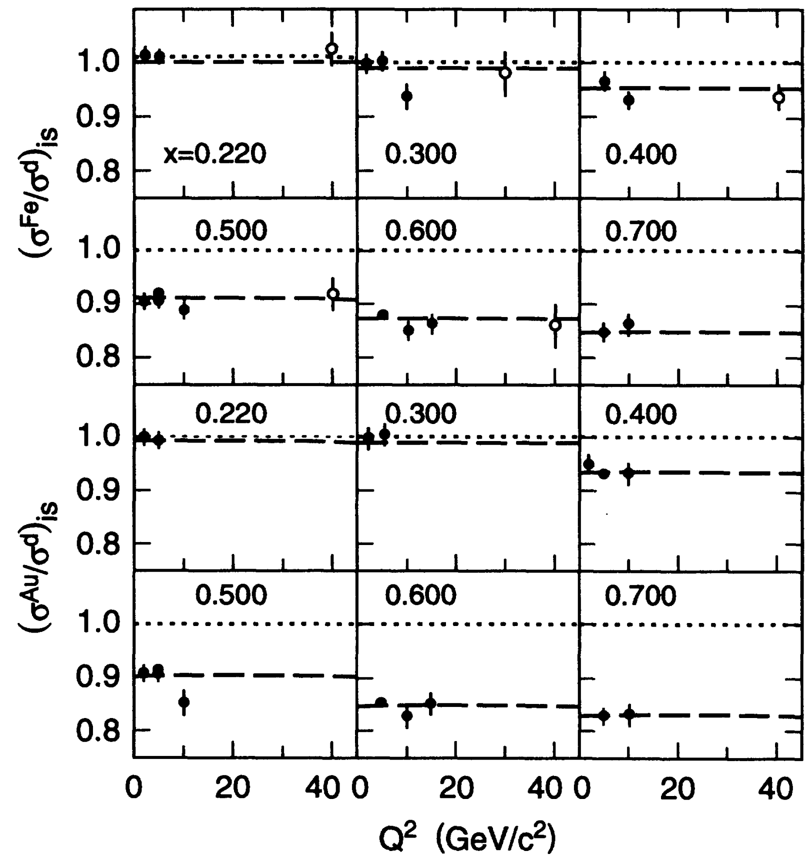
x=0.05



x=0.65

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)

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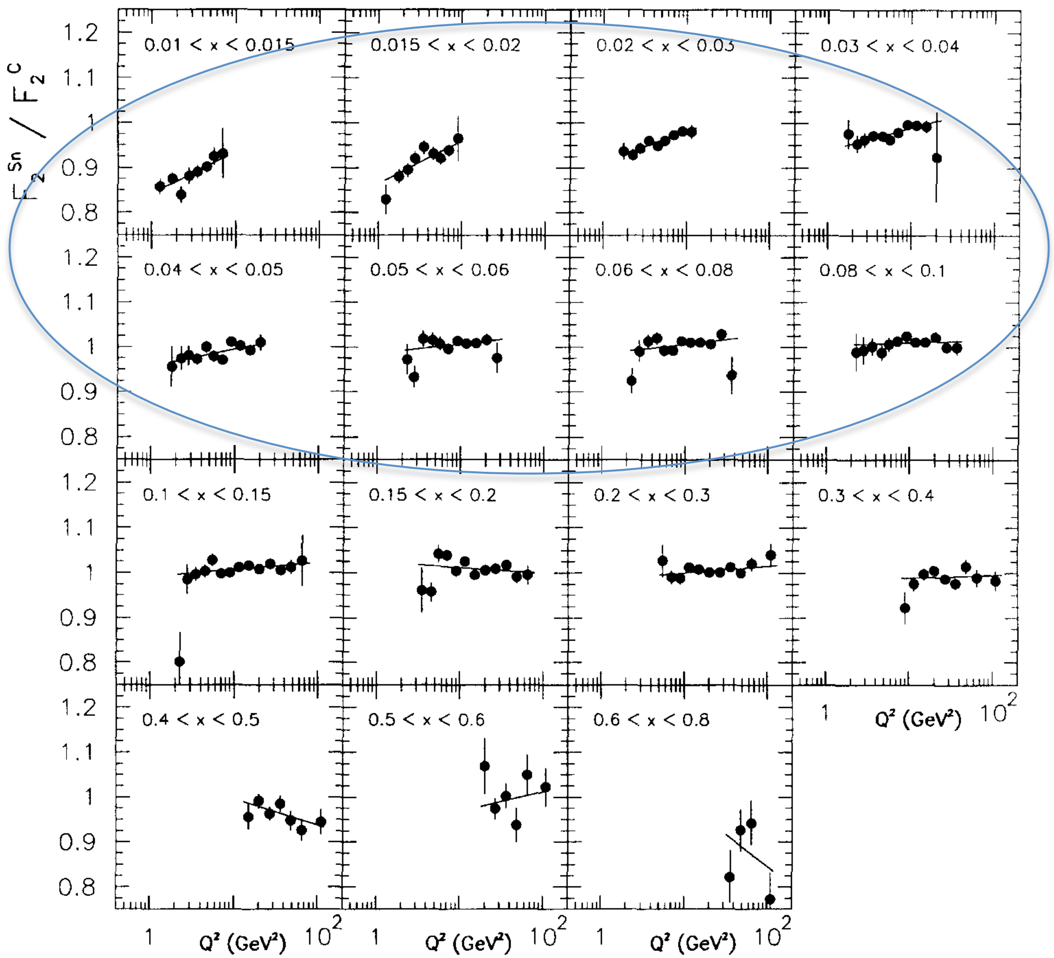
(*) Q^2 Dependence of Sn/C

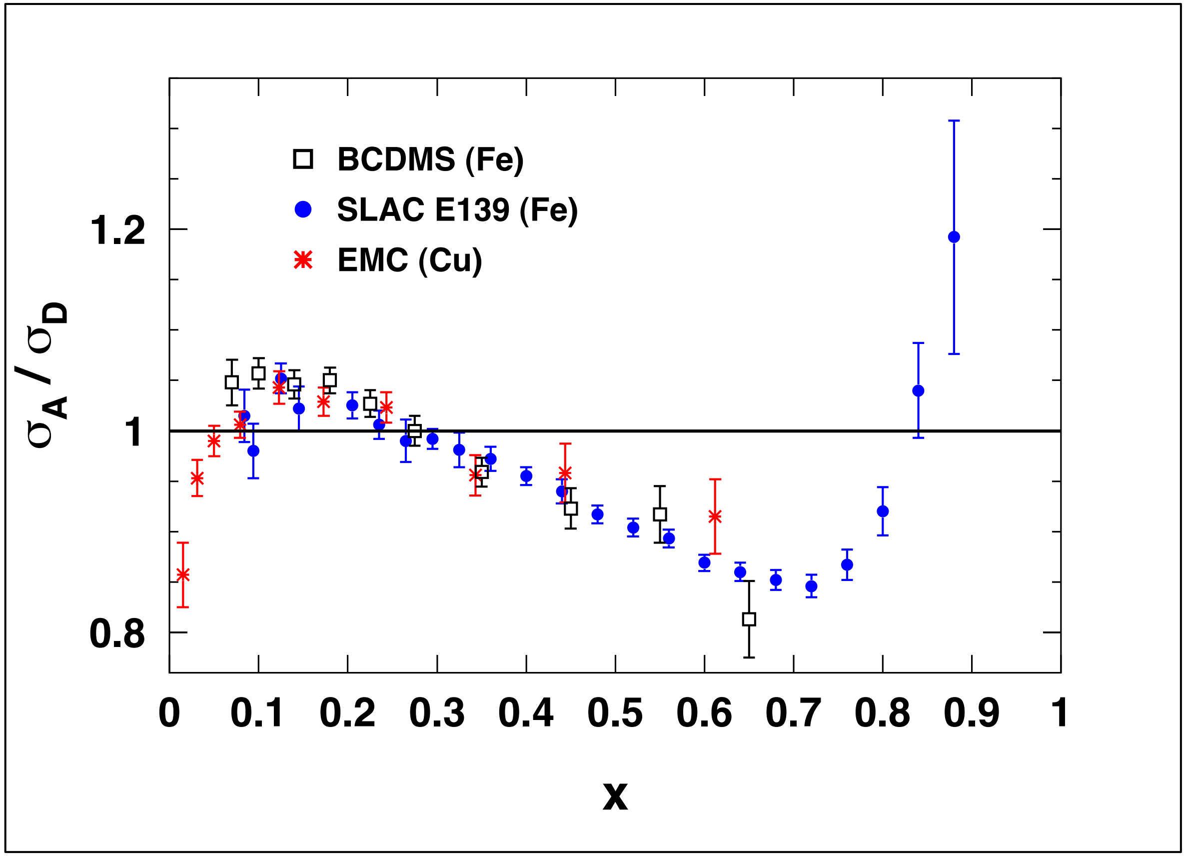


Arneodo et al, Nucl. Phys. B 481, 23 (1996)

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

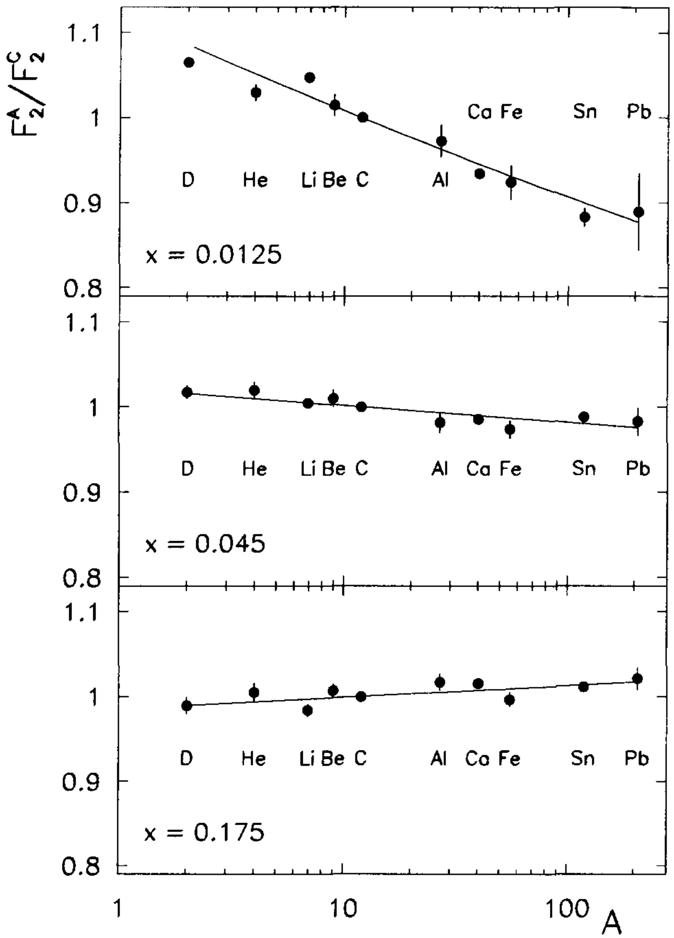


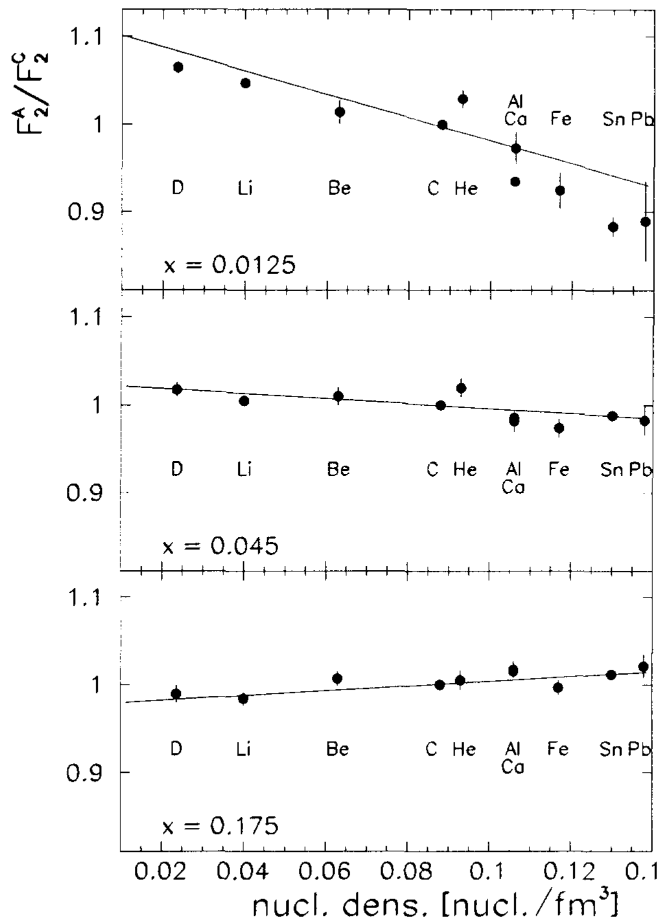
Global properties of the EMC effect

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

→ *Anti-shadowing region shows little nuclear dependence*

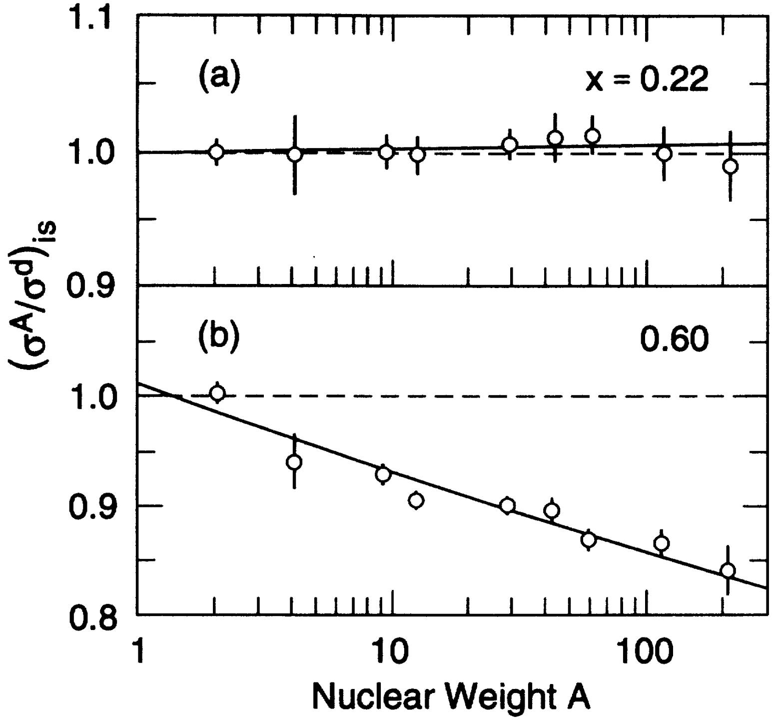
A-Dependence of EMC Effect

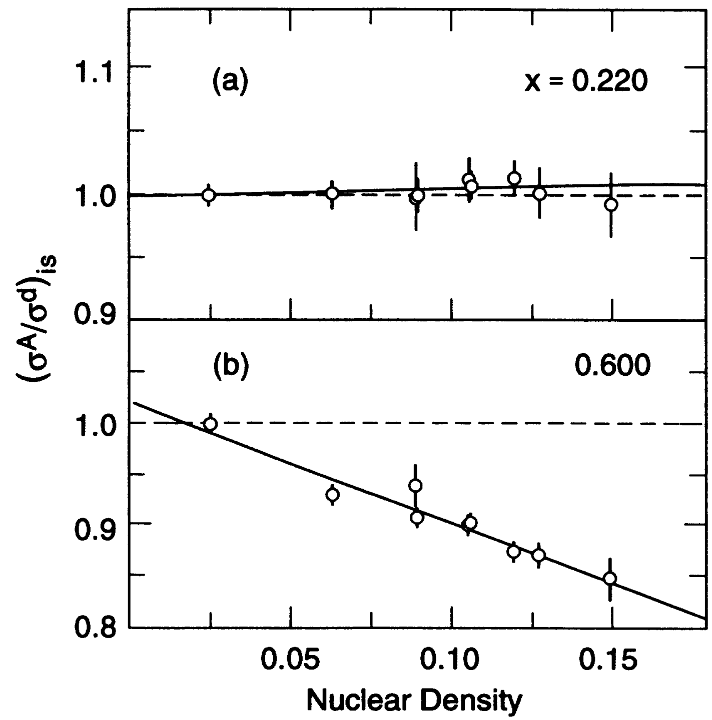




NMC: *Arneodo et al, Nucl. Phys. B 481, 3 (1996)*

A-Dependence of EMC Effect





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

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

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

Explaining the EMC Effect

- "Conventional" nuclear physics models
  - Fermi motion → reproduces rise at large x
  - Binding
  - Fermi motion + binding + nuclear pions
- Exotic models ←?
  - Multiquark clusters
  - Dynamical rescaling $F_2^A(x,Q^2) = F_2^N(x,\xi_A(Q^2)\cdot Q^2)$
- All of these models have a fair degree of success describing the EMC effect

Binding and Nuclear Pions

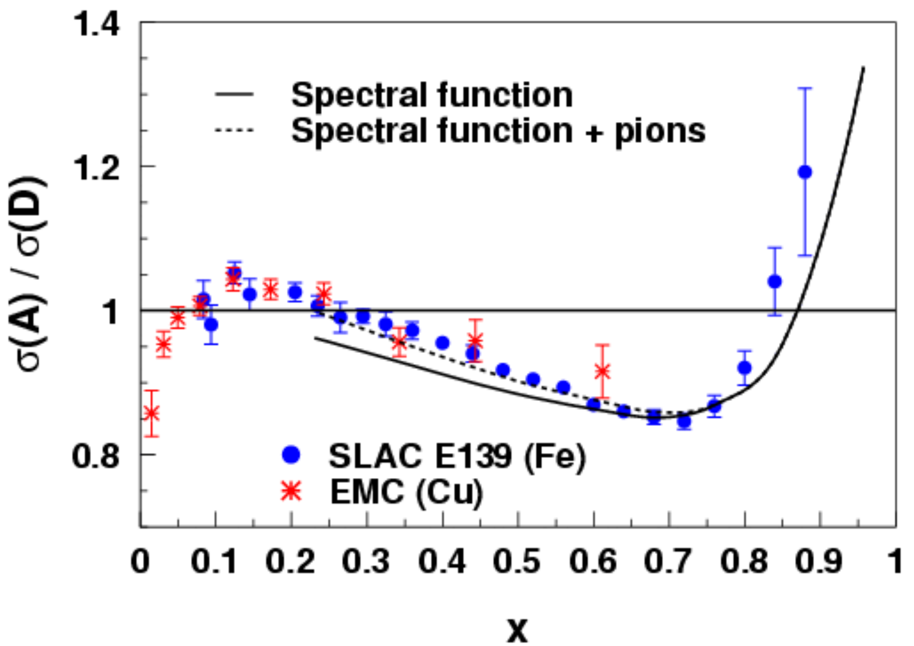
Start with a "realistic" description of nucleons in the nucleus

→ Use a spectral function rather than simple Fermi gas

Convolution picture

→ Allow virtual photon to scatter from quarks in pions in the nucleus

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



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

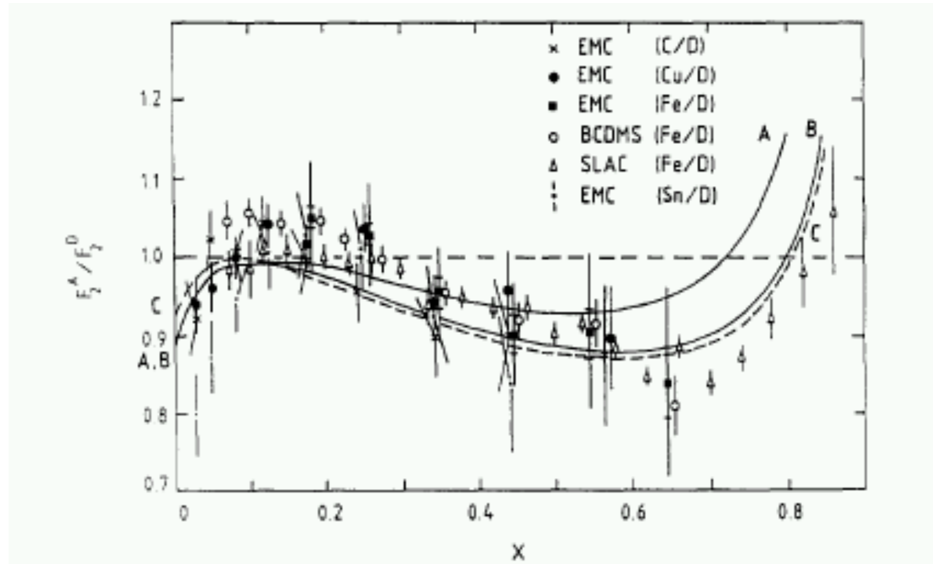
$$F_2^A(x) = \int_x^1 dy f_N(y) F_2^N(x/y) + \int_x^1 dy f_\pi(y) F_2^\pi(x/y)$$

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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EMC Effect Model Issues

- Conventional nuclear physics based explanations
  - 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 "nuclear pions"
    - Size of contributions from nuclear pions typically used in DIS calculations inconsistent with nuclear dependence of Drell-Yan
- Exotic effects
  - Multiquark clusters, dynamical rescaling calculations often ignore contributions from binding, use simple models of nucleus
- Almost universally, EMC effect was calculated at some fixed A and assumed to scale with nuclear density

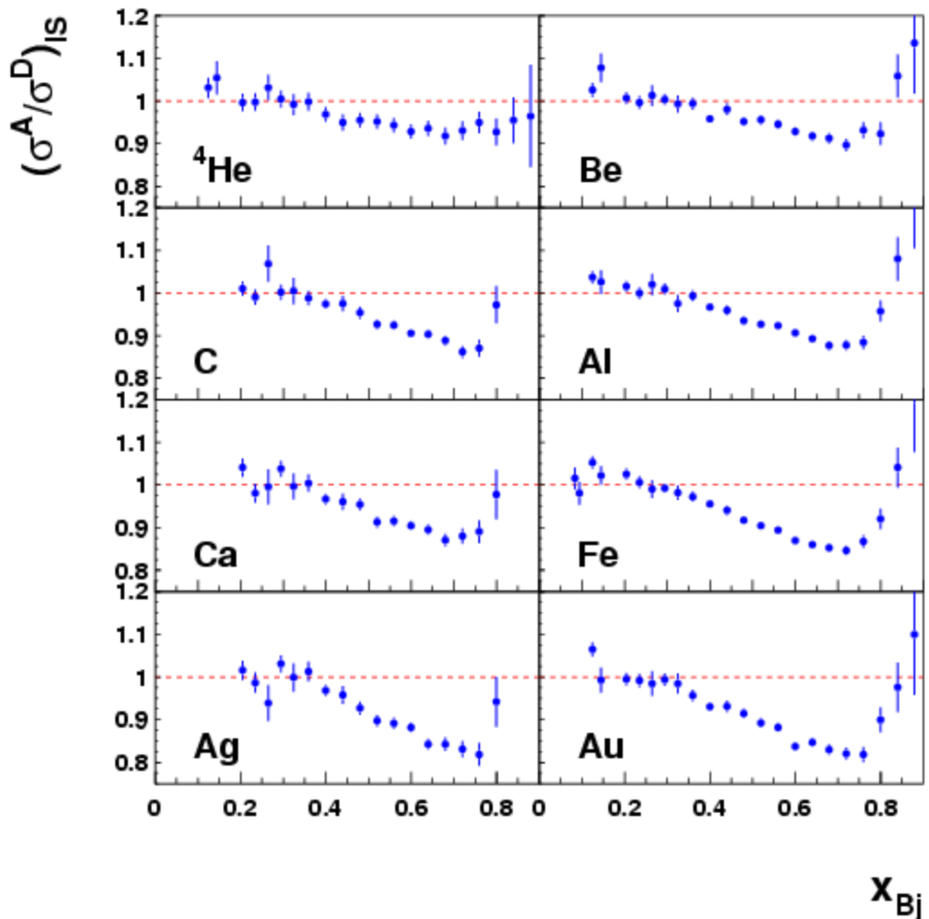
EMC Effect Measurements at Large x

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*

SLAC E139



Nuclear Dependence of the EMC Effect

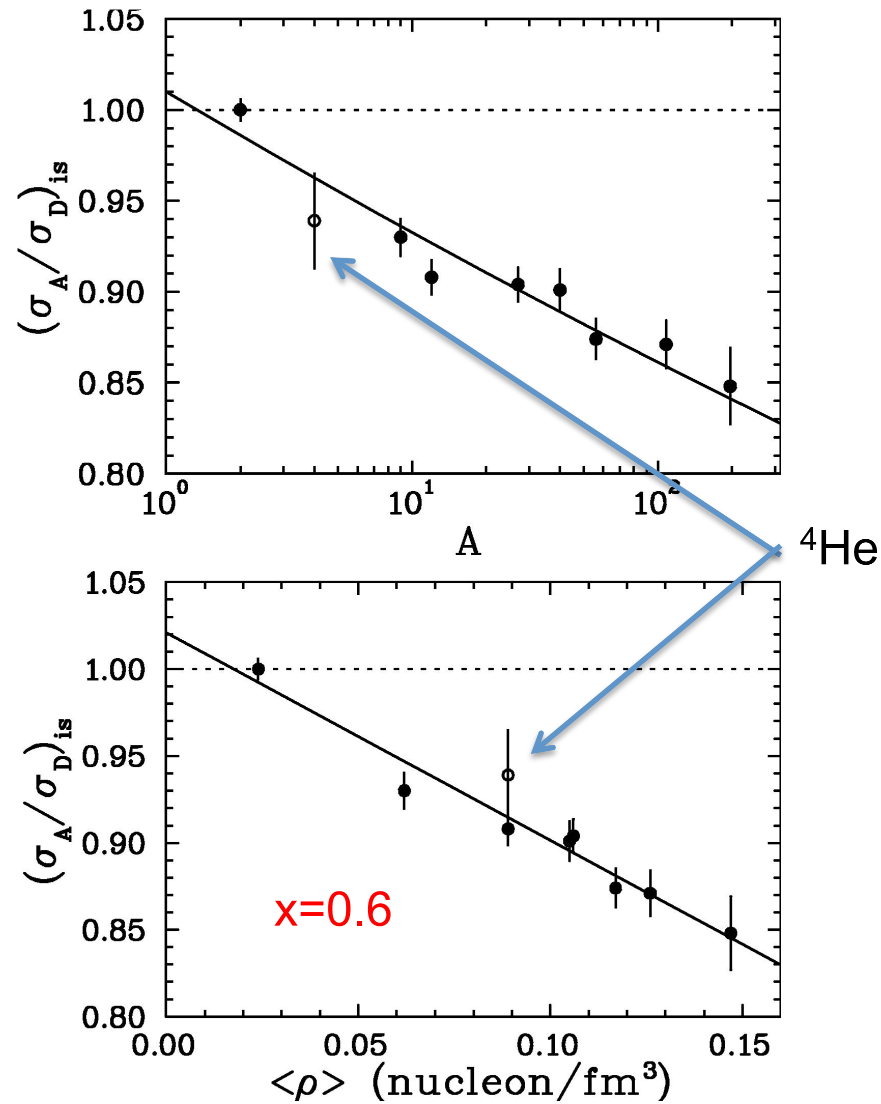
SLAC E139 studied the nuclear dependence of the EMC Effect at fixed *x*

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

**uniform sphere with radius R_e,*
$R_e^2 = 5/3 \langle r^2 \rangle$ → charge radius of nucleus

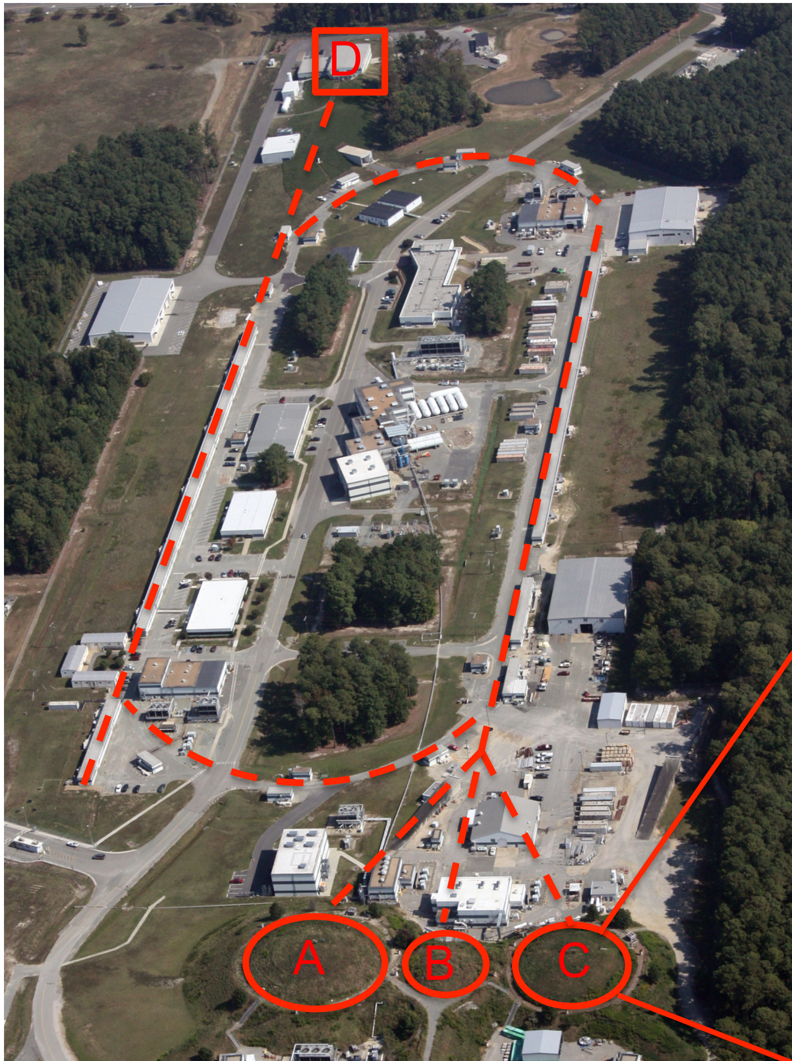
Many models of the EMC effect either implicitly or explicitly assume the size of the EMC effect scales with average nuclear density

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

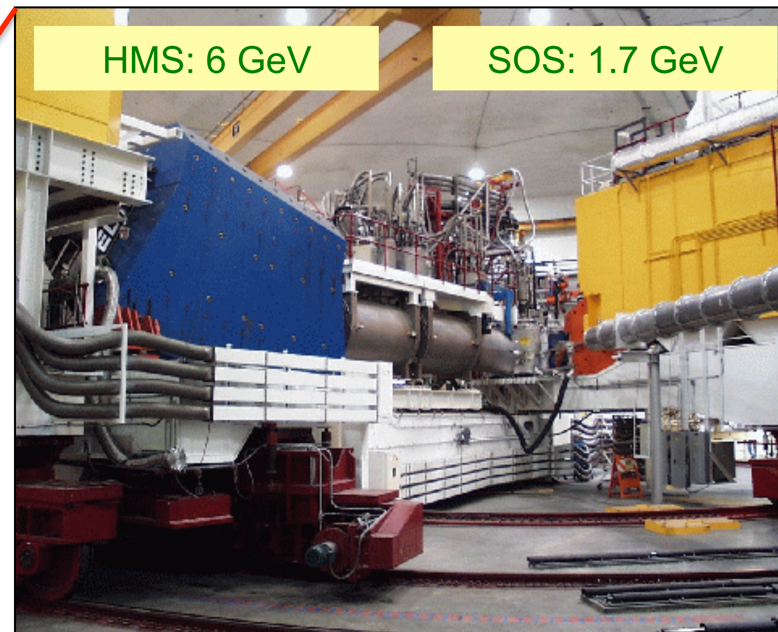


Gomez et al, PRD 49, 4348 (1994)

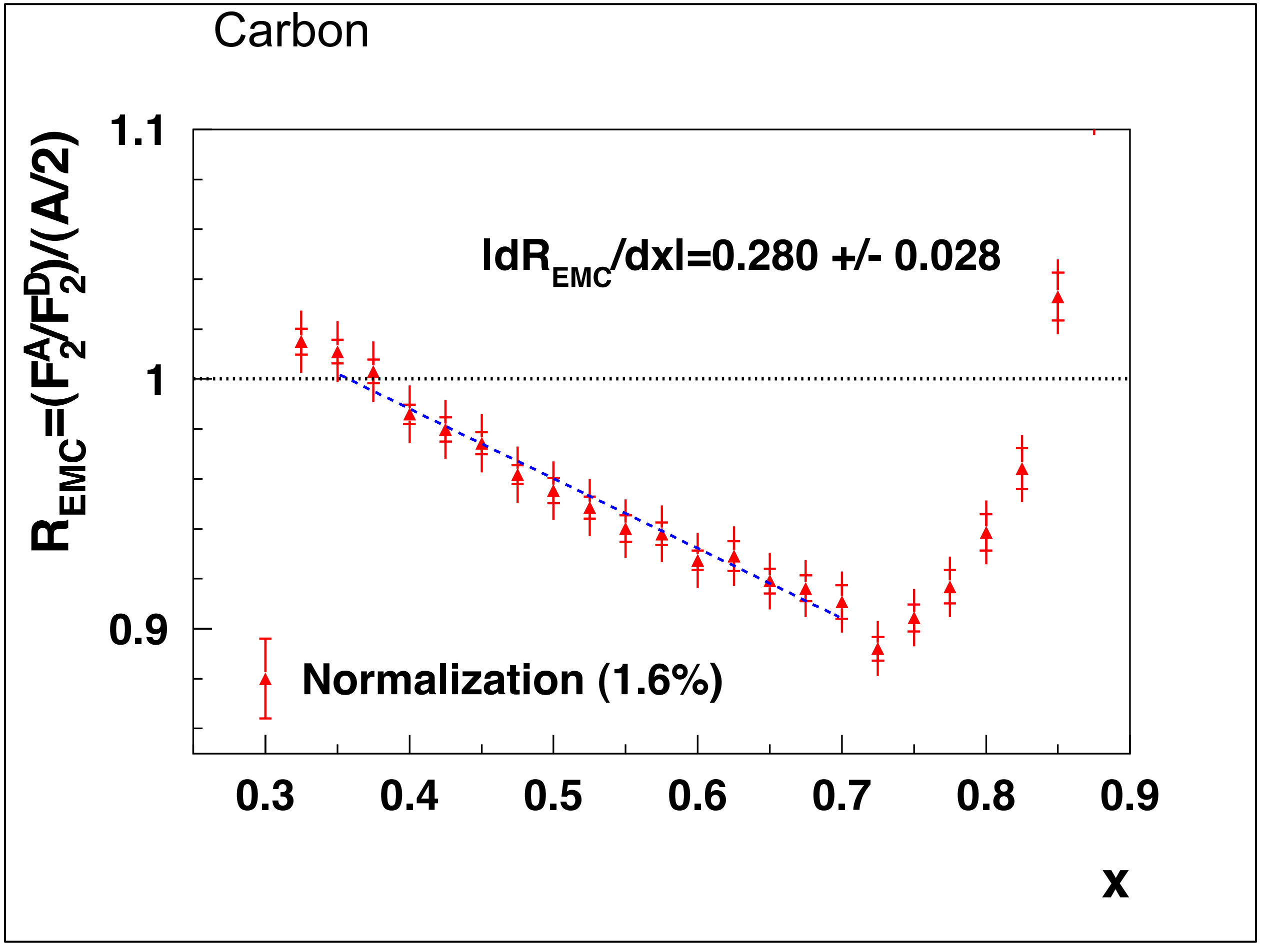
Jefferson Lab Experiment E03103



E03103 in **Hall C** at **Jefferson Lab** ran Fall 2004
→ Measured EMC ratios for light nuclei (^{3}He, ^{4}He, Be, and C)
→ Examined nuclear dependence a la SLAC E139



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

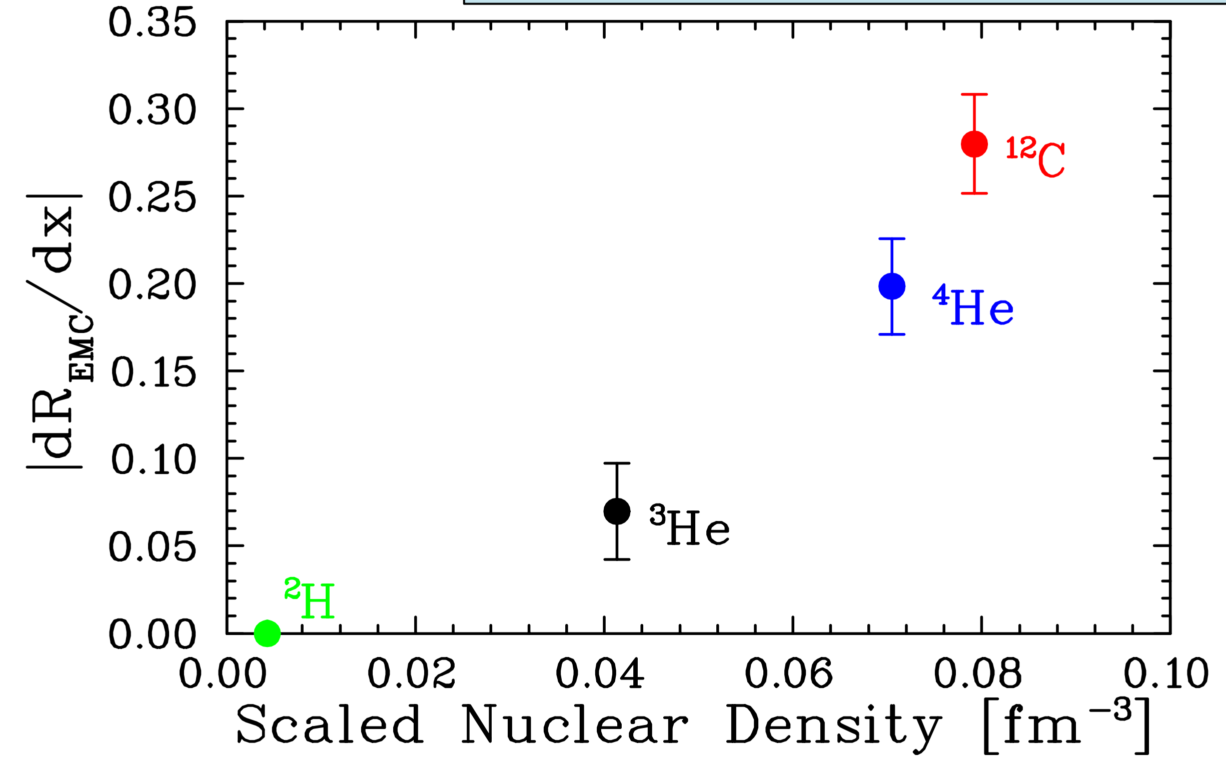
→Normalization uncertainties a much smaller relative contribution

JLab E03103 Results

E03103 measured σ_A/σ_D for ^{3}He, ^{4}He, Be, C

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

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



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

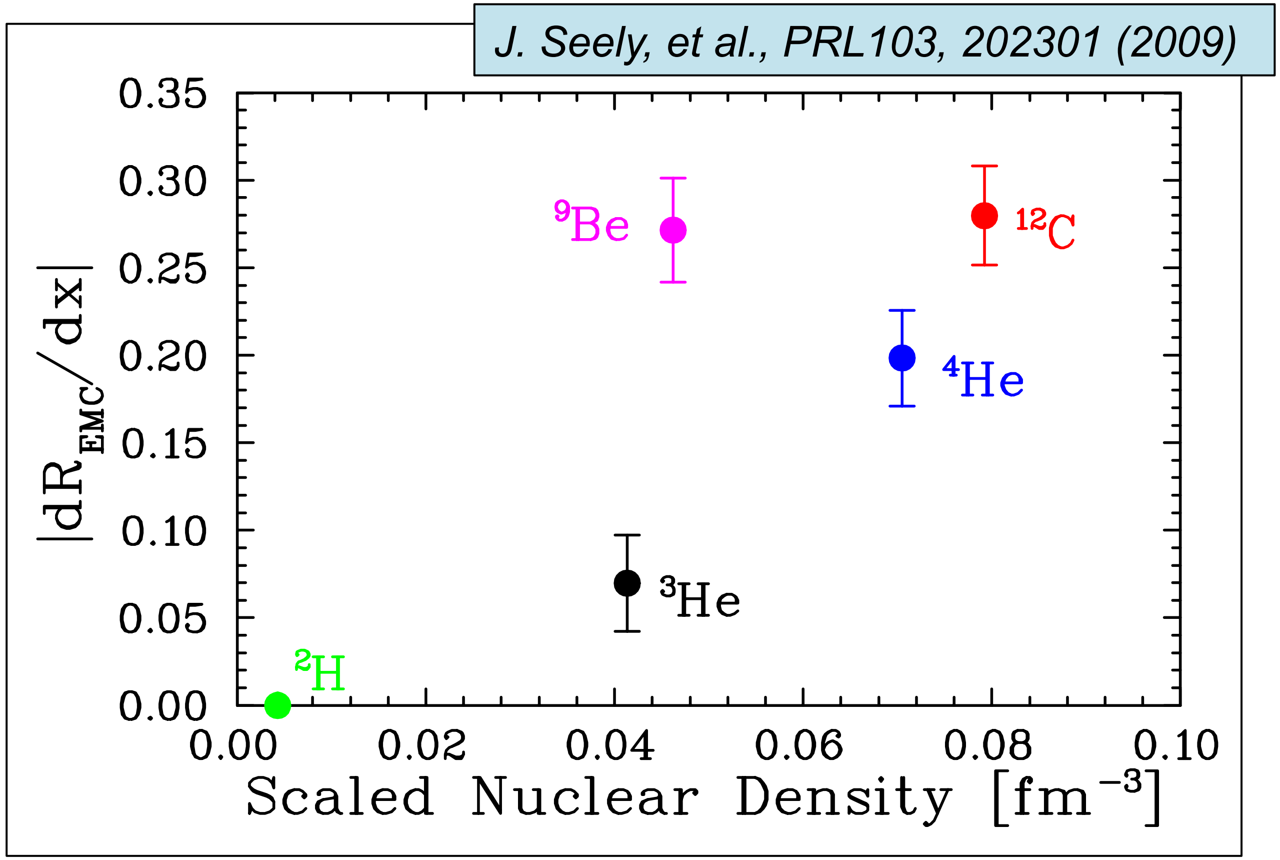
<ρ> from ab initio few-body calculations

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

JLab E03103 Results

E03103 measured σ_A/σ_D for ^3He, ^4He, Be, C

→ ^3He, ^4He, C, EMC effect scales well with density
→ Be does not fit the trend



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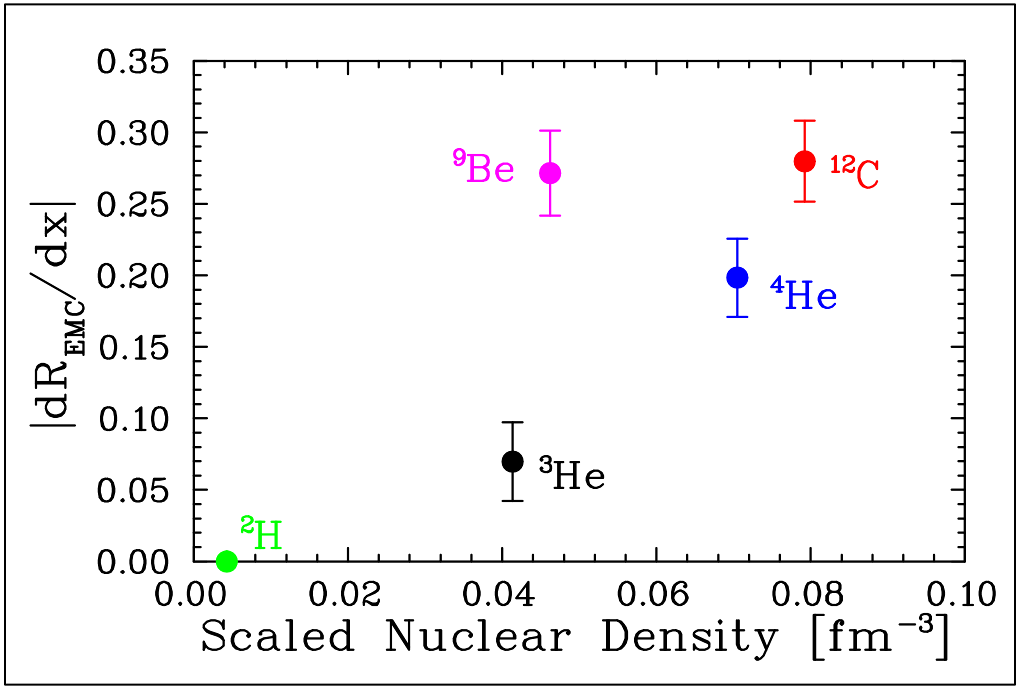
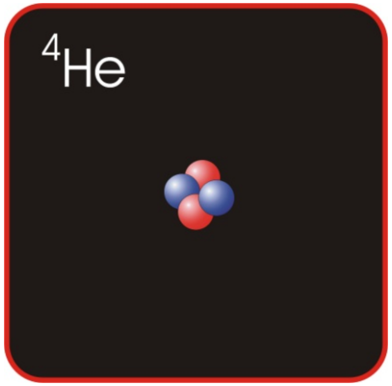
<ρ> from ab initio few-body calculations
→ ***[S.C. Pieper and R.B. Wiringa**, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)]*

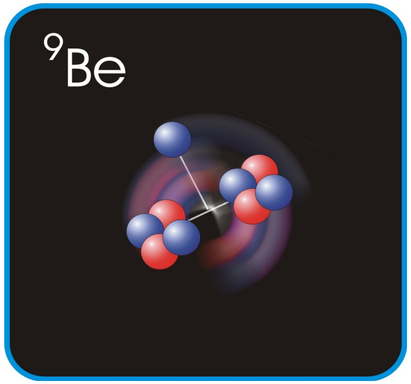
EMC Effect and Local Nuclear Density

^{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

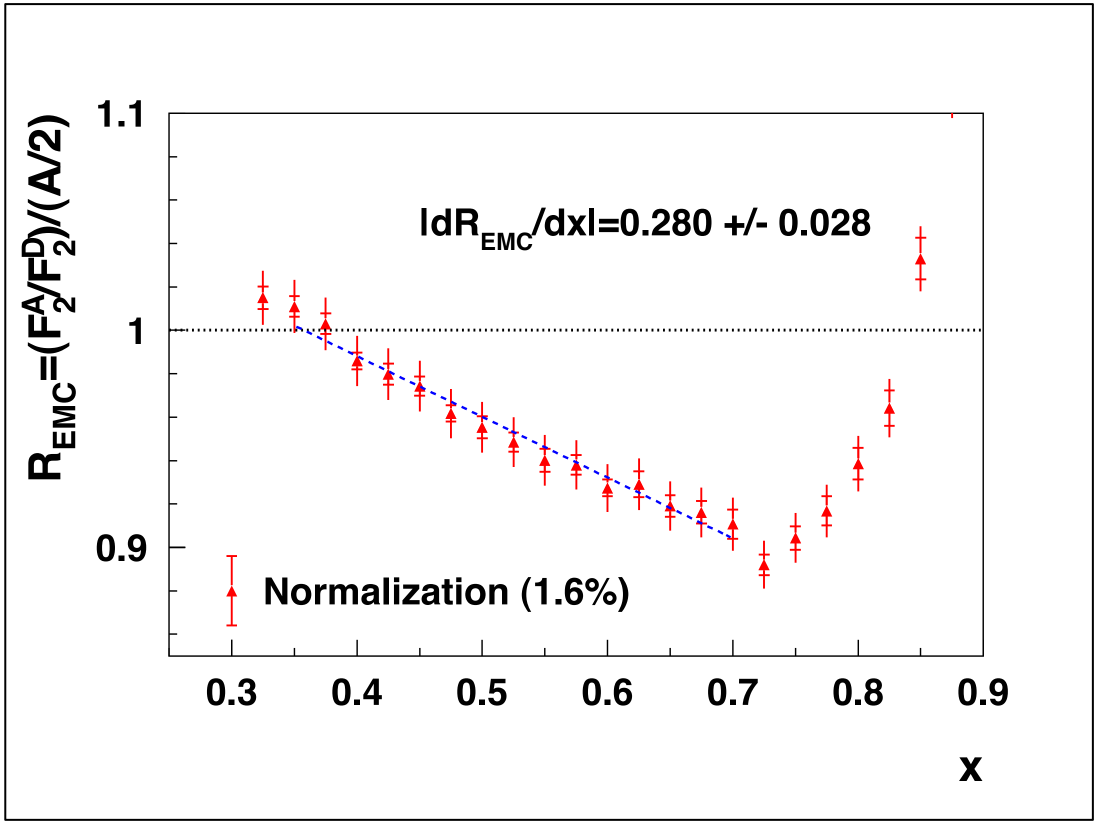






"Local density" is appealing in that it makes sense intuitively – can we make this more quantitative?

Improved Precision via New Observable



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

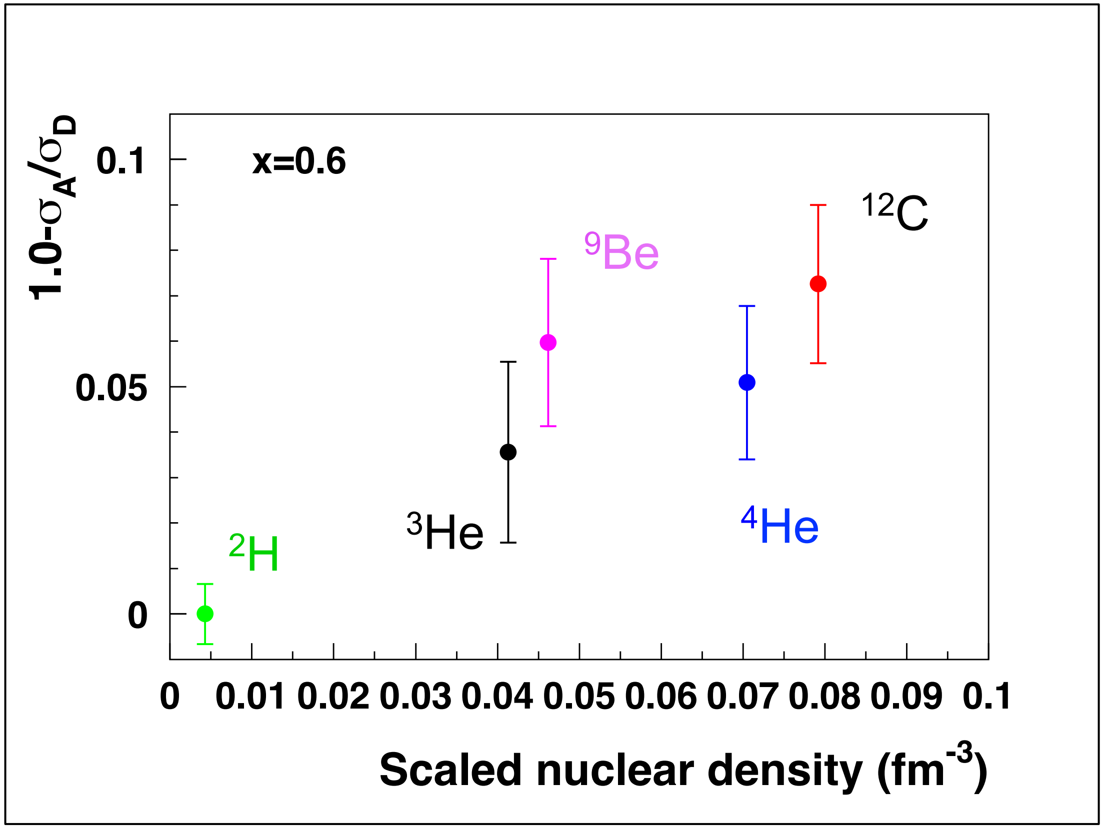
→ Nuclear dependence of EMC effect typically examined at fixed x

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

EMC effect ~ 10% deviation from 1.0

Normalization uncertainties ~ 1-2%

Improved Precision via New Observable



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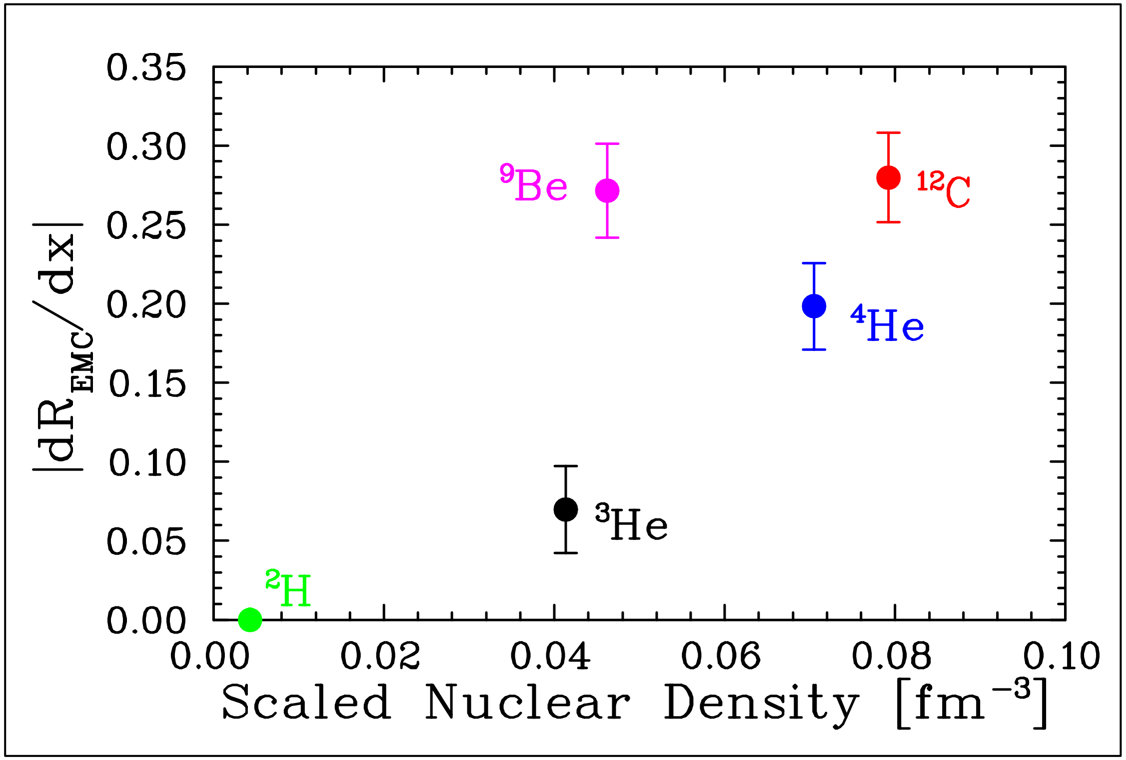

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Normalization uncertainties ~ 1-2%

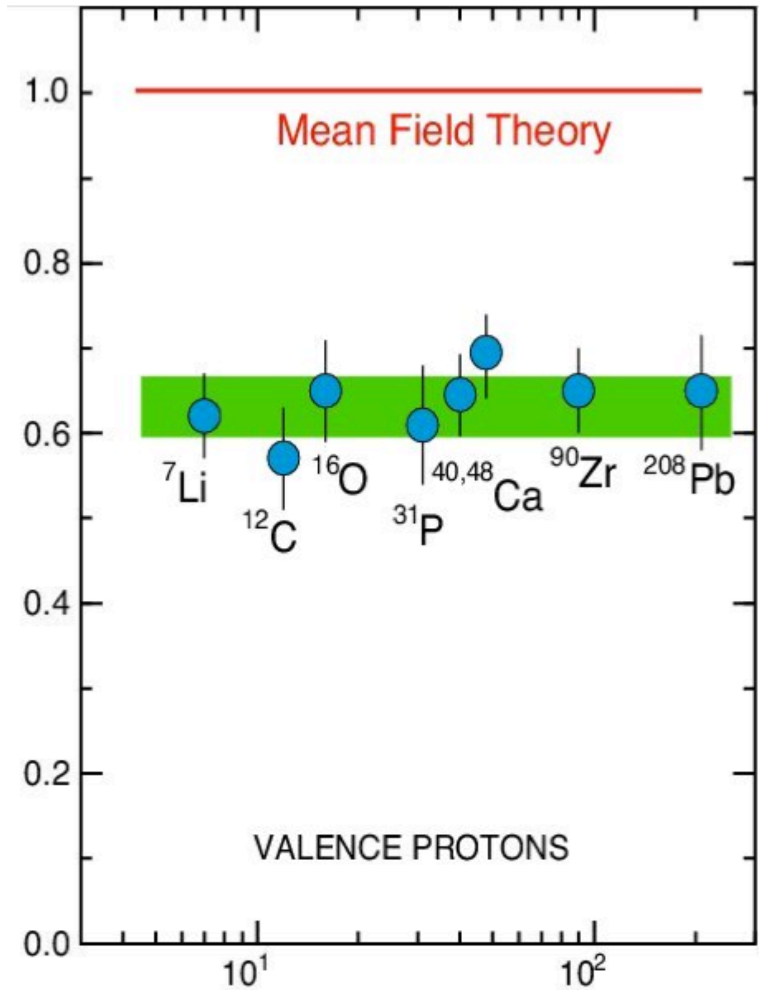
Local Density → Short Range Correlations

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

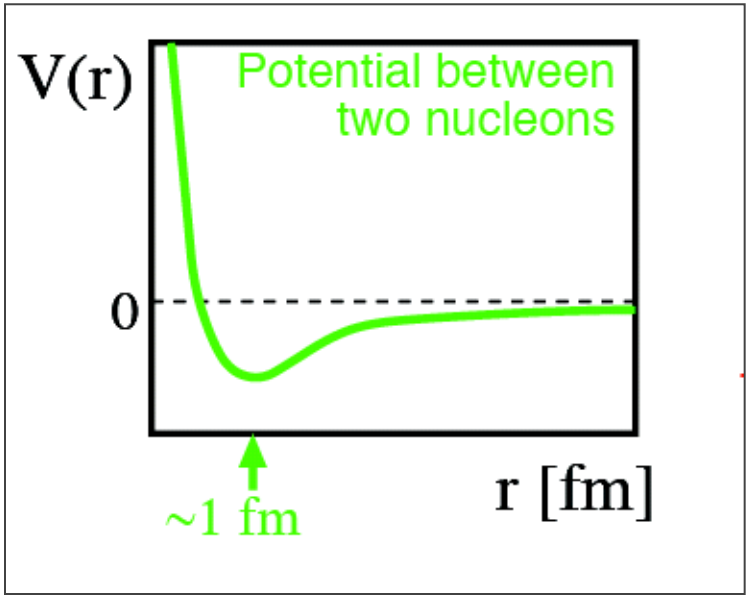


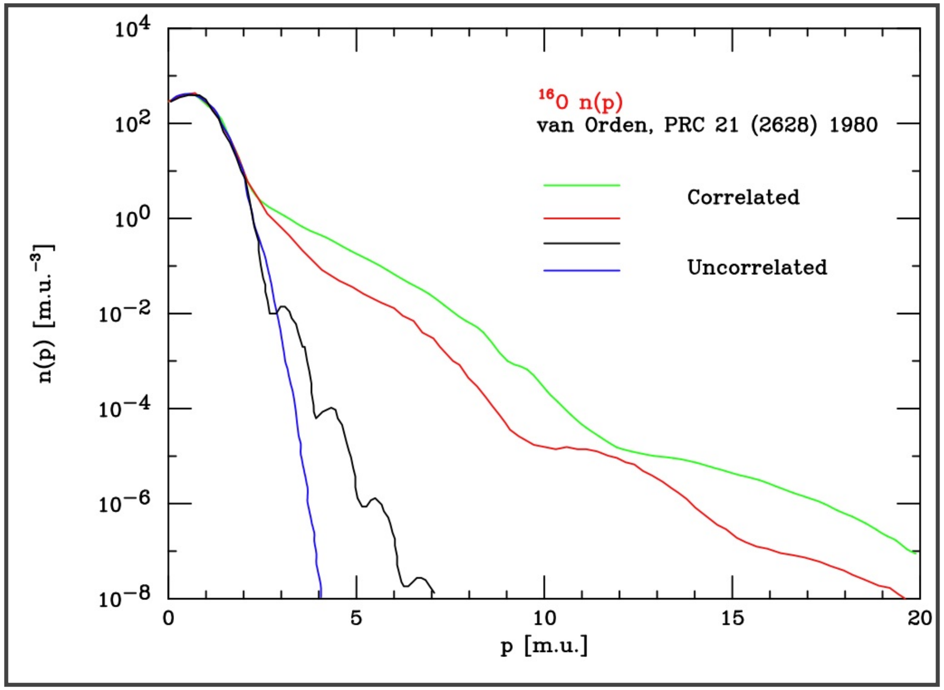
L. Lapikas, Nucl. Phys. A553 (1993) 297

Local Density → Short Range Correlations

What drives high "local" density in the nucleus?

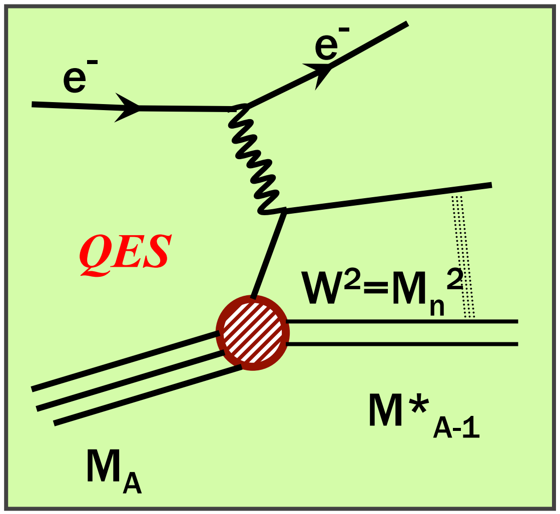
More complex calculations start from realistic NN potentials





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

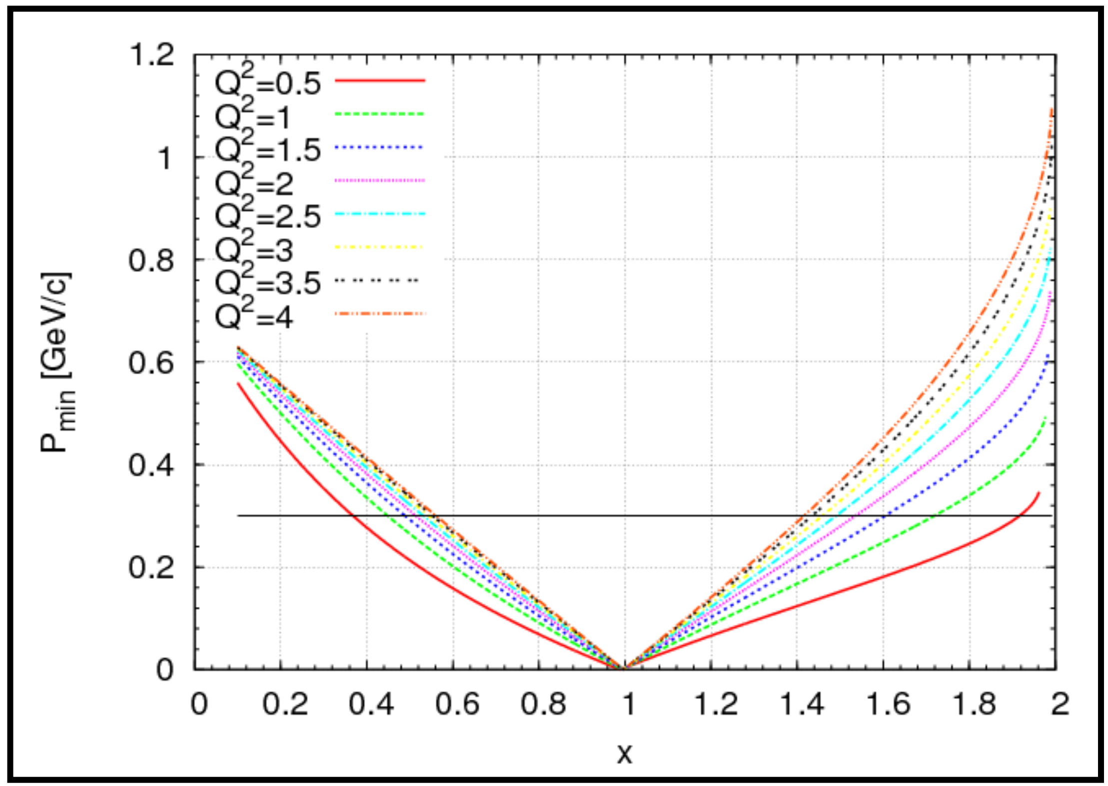
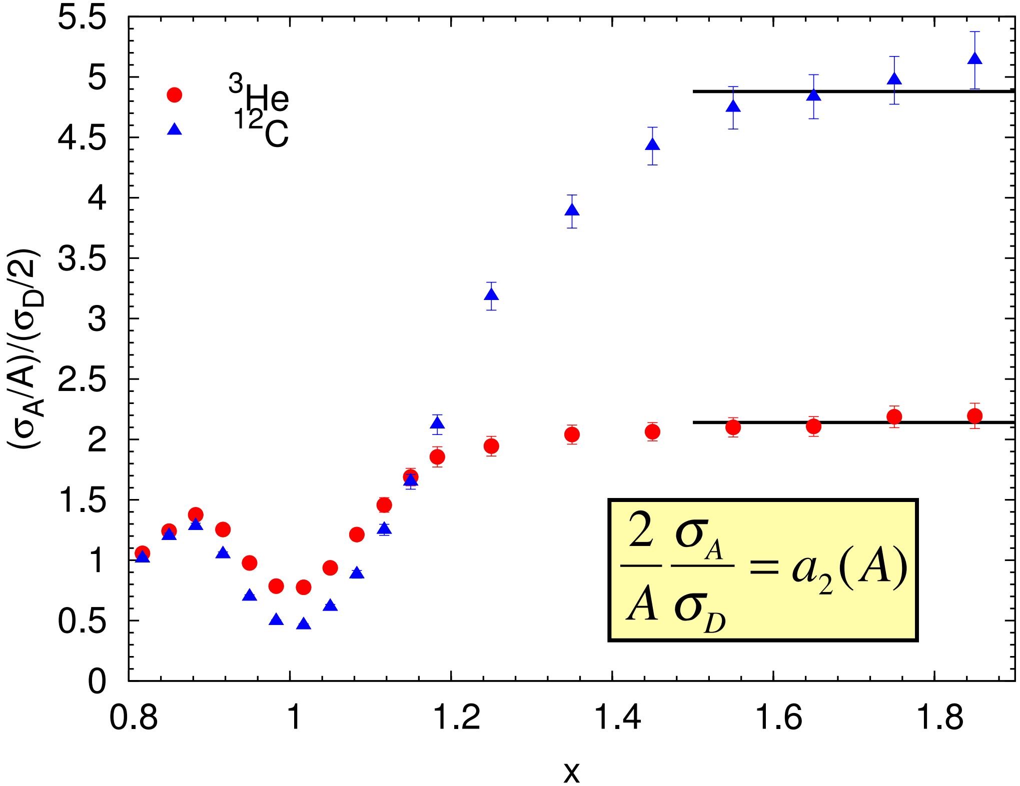


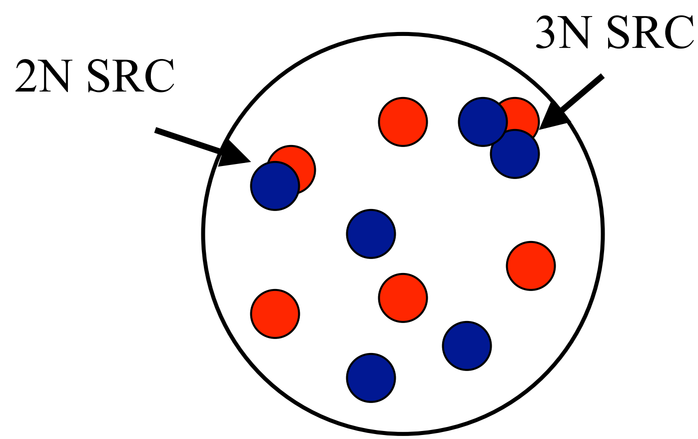
Figure courtesy N. Fomin, after Frankfurt, Sargsian, and Strikman, ***Int.J.Mod.Phys. A23 (2008) 2991-3055***

Measuring Short Range Correlations

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.)

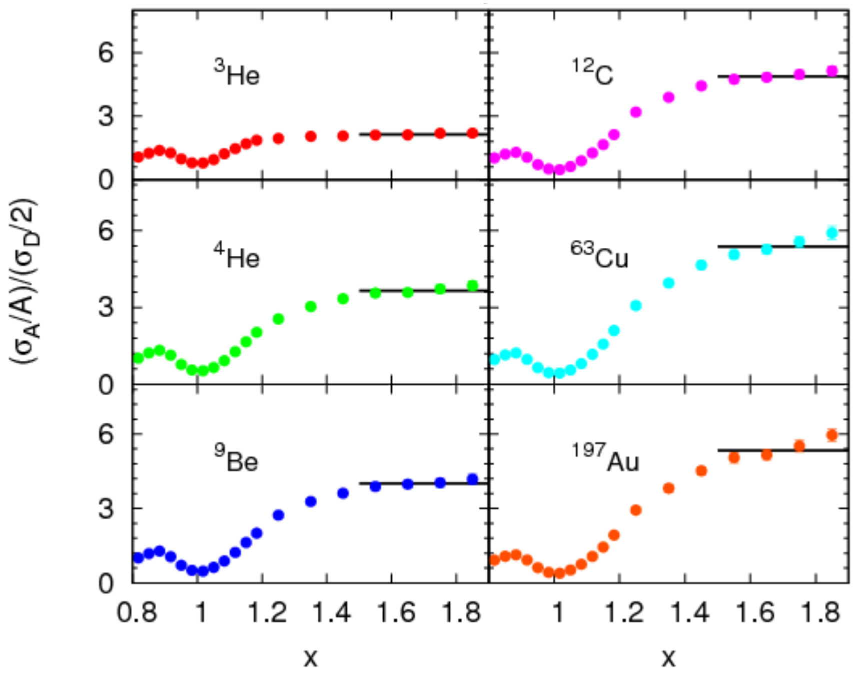




1.4<x<2 => 2 nucleon correlation

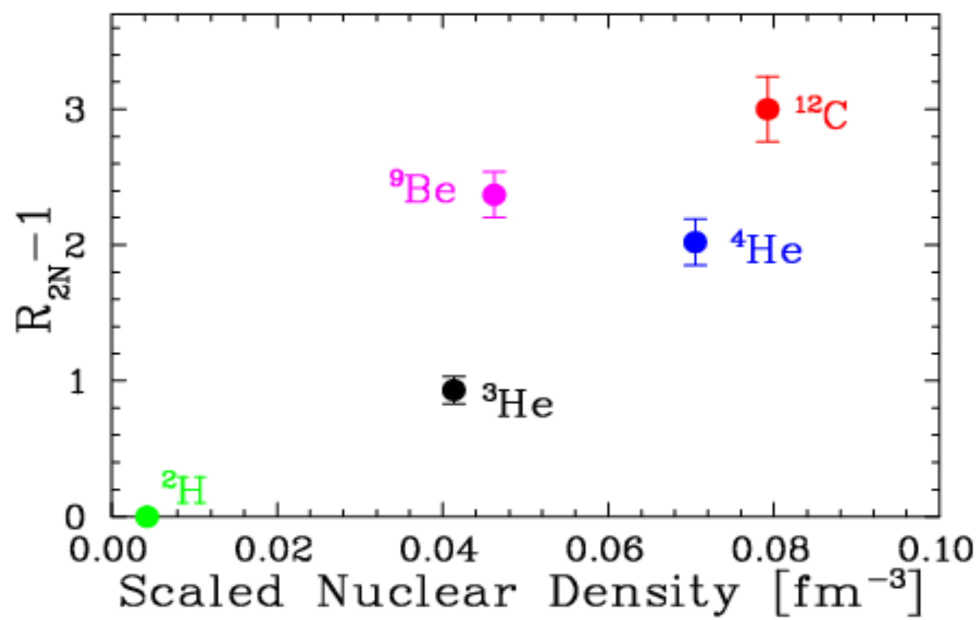
2.4<x<3 => 3 nucleon correlation

SRCs and Nuclear Density



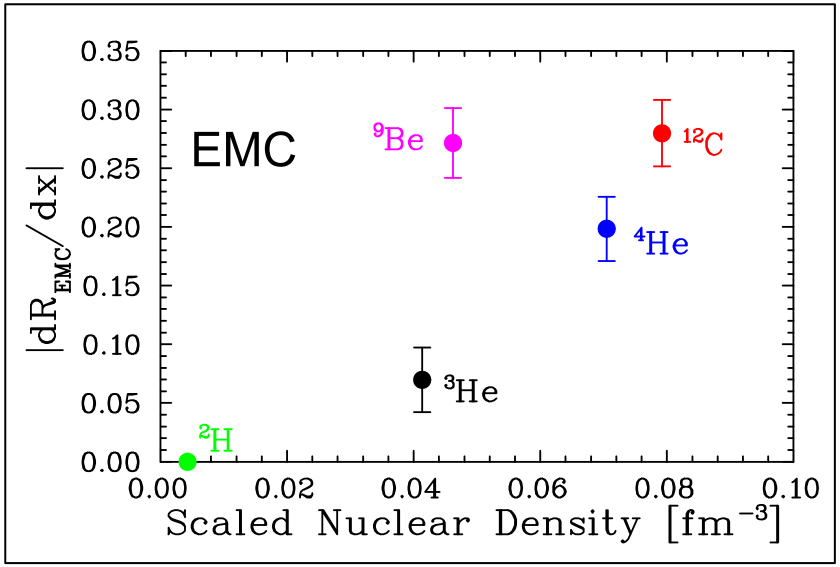
N. Fomin et al, Phys.Rev.Lett. 108 (2012) 092502

<u>New JLab data on ratios at *x>1*</u>
a_2 ratios for:
→Additional nuclei (Cu, Be, 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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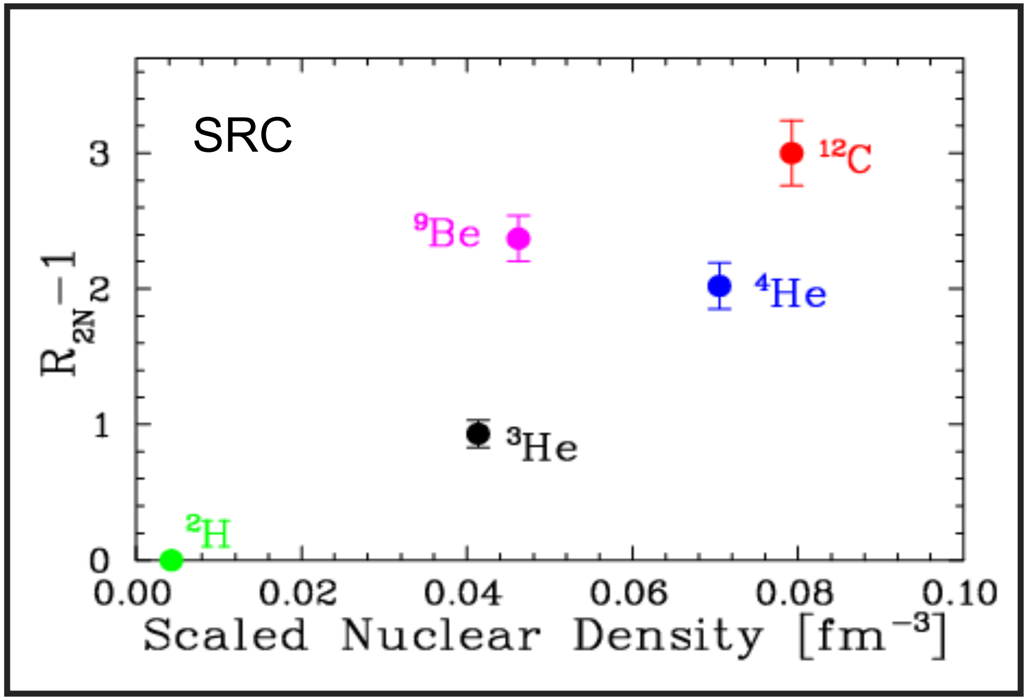


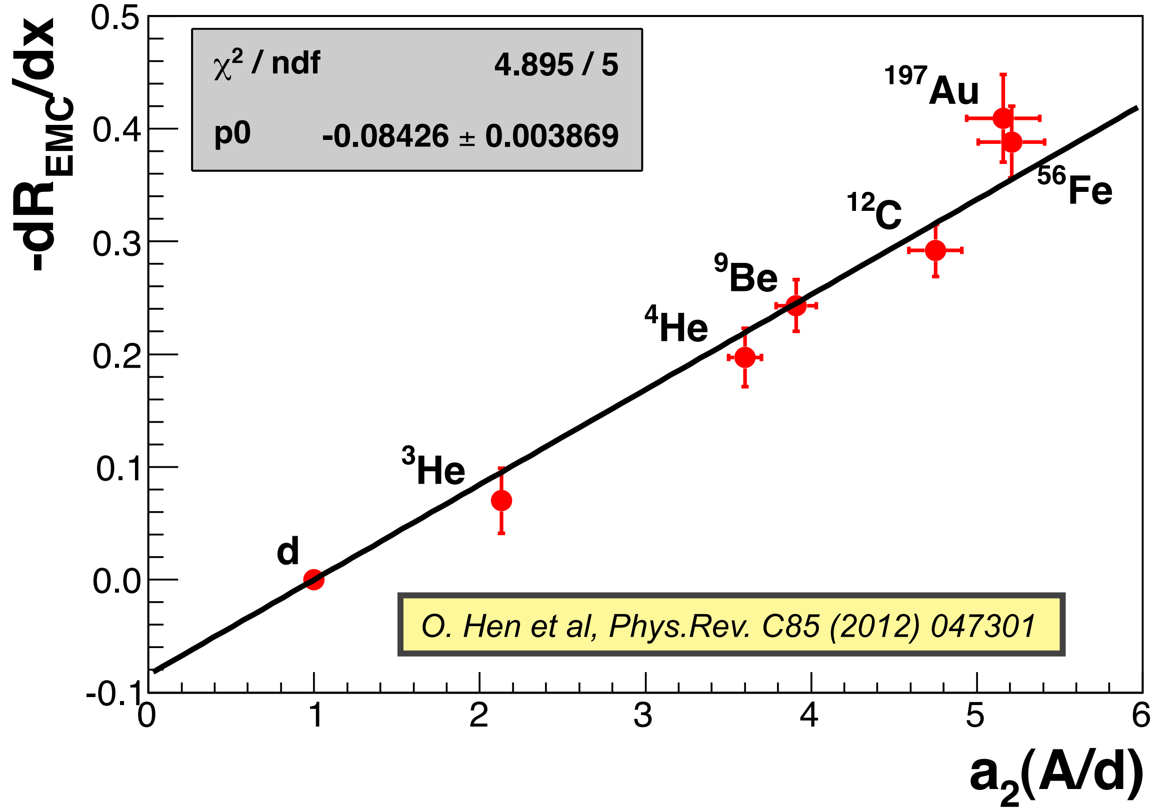
→ Relative probability to find SRC shows similar dependence on nuclear density as EMC effect

Jefferson Lab

EMC Effect and SRC

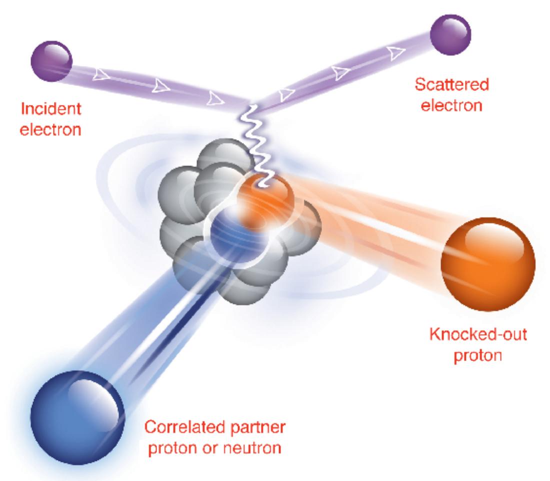
Weinstein *et al* first observed linear correlation between size of EMC effect and Short Range Correlation "plateau"

Correlation <u>strengthened</u> with addition of Beryllium data



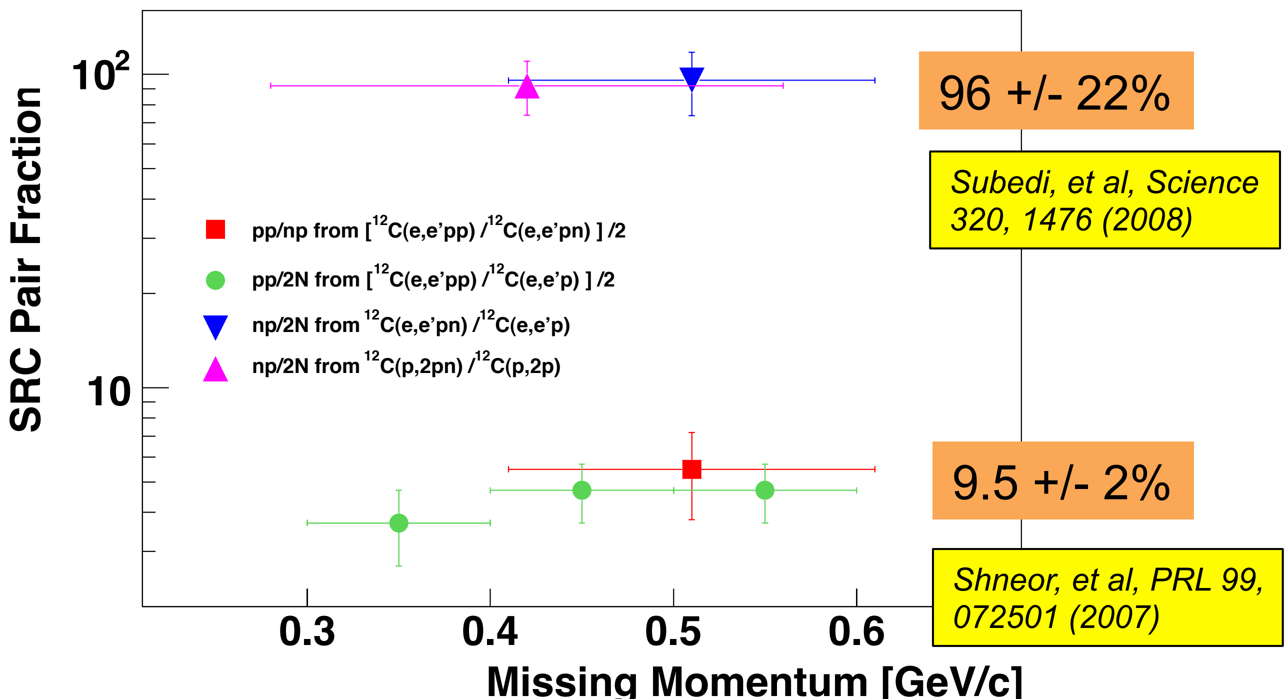
This result provides a ***quantitative*** test of level of correlation between the two effects

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



EMC-SRC Correlation

What causes the detailed nuclear dependence to be the same?
→Common cause? Does one drive the other?

Two hypotheses:

1. ***High virtuality***
→EMC effect driven by virtuality of nucleon – relative probability to have high-momentum nucleon

2. ***Local Density***
→ EMC effect driven by local density – nucleons are close together

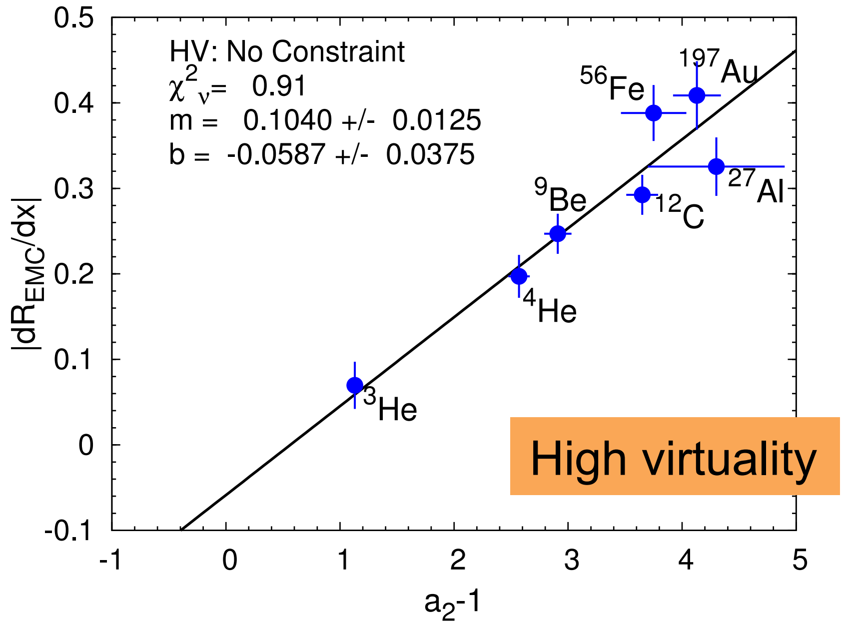
These hypotheses can be tested to looking at correlation vs. modified SRC variable

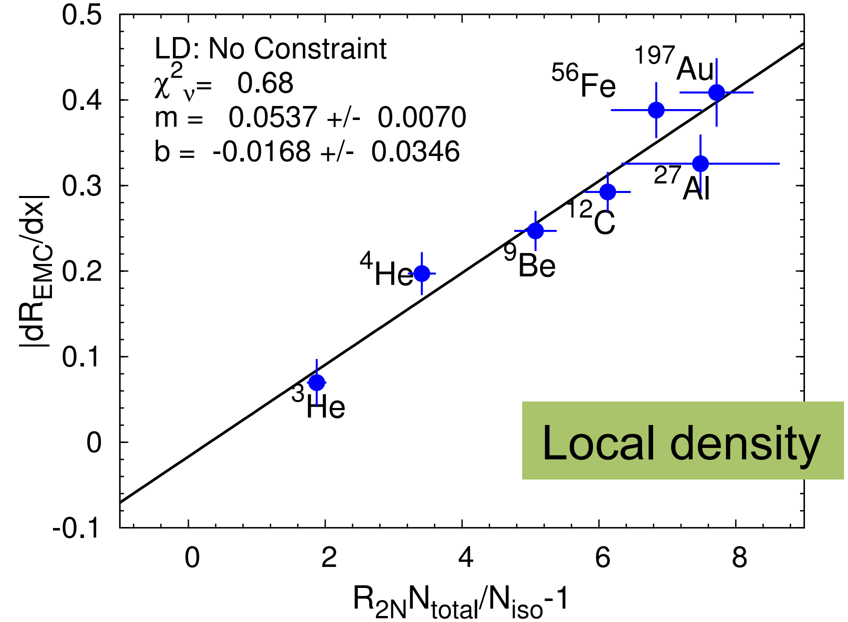
R_{2N} → a_2 corrected for CM motion of correlated pair → number of SRCs
a_2 → number of high-momentum nucleons coming from SRCs and pair motion

Neither picture ruled out by existing data

Nuclear Dependence of EMC and SRCs

Arrington et al, PRC 86, 065204 (2012)





a_2 ~ number of high momentum nucleons

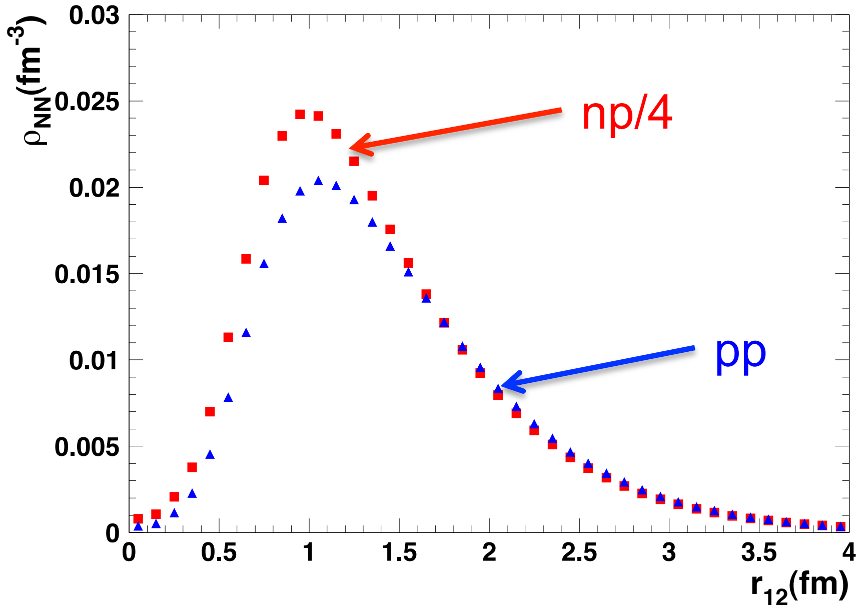
R_{2N} ~ number of nucleons "close" together

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

Can we distinguish between these two pictures via some new observable? → Flavor dependence of the EMC effect

Flavor dependence and SRCs

^{4}He 2-body density from



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 <u>– *np* pairs dominate</u>

→ 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***, flavor dependence of EMC effect emerges naturally

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

Flavor dependence and SRCs

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

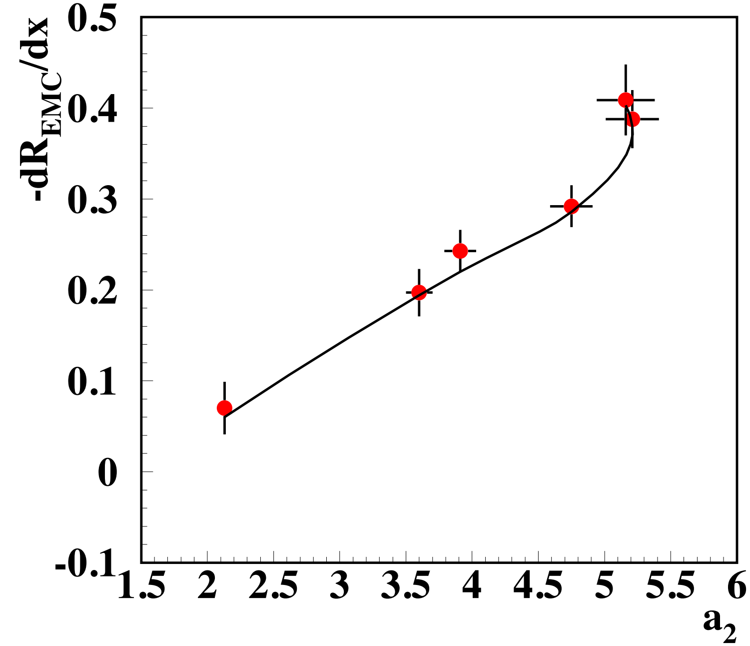
→The relative probability to find a high momentum proton is larger than for neutron for *N>Z* nuclei

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

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

Probability to find SRC

$$u_A = \frac{Z\tilde{u}_p + N\tilde{d}_p}{A} \qquad d_A = \frac{Z\tilde{d}_p + N\tilde{u}_p}{A}$$

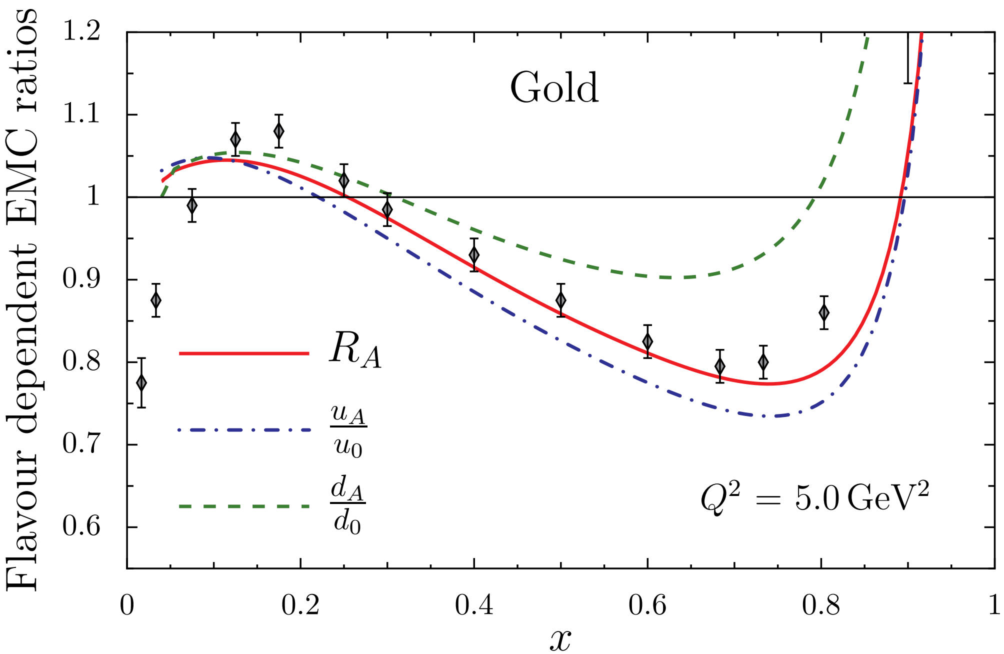


Under the assumption the EMC effect comes from "high virtuality" (high momentum nucleons), effect driven by protons (u-quark dominates) → similar flavor dependence is seen in some "mean-field" approaches

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



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

Medium modified quark distributions

$$u_A = \frac{Z\tilde{u}_p + N\tilde{d}_p}{A} \quad d_A = \frac{Z\tilde{d}_p + N\tilde{u}_p}{A}$$

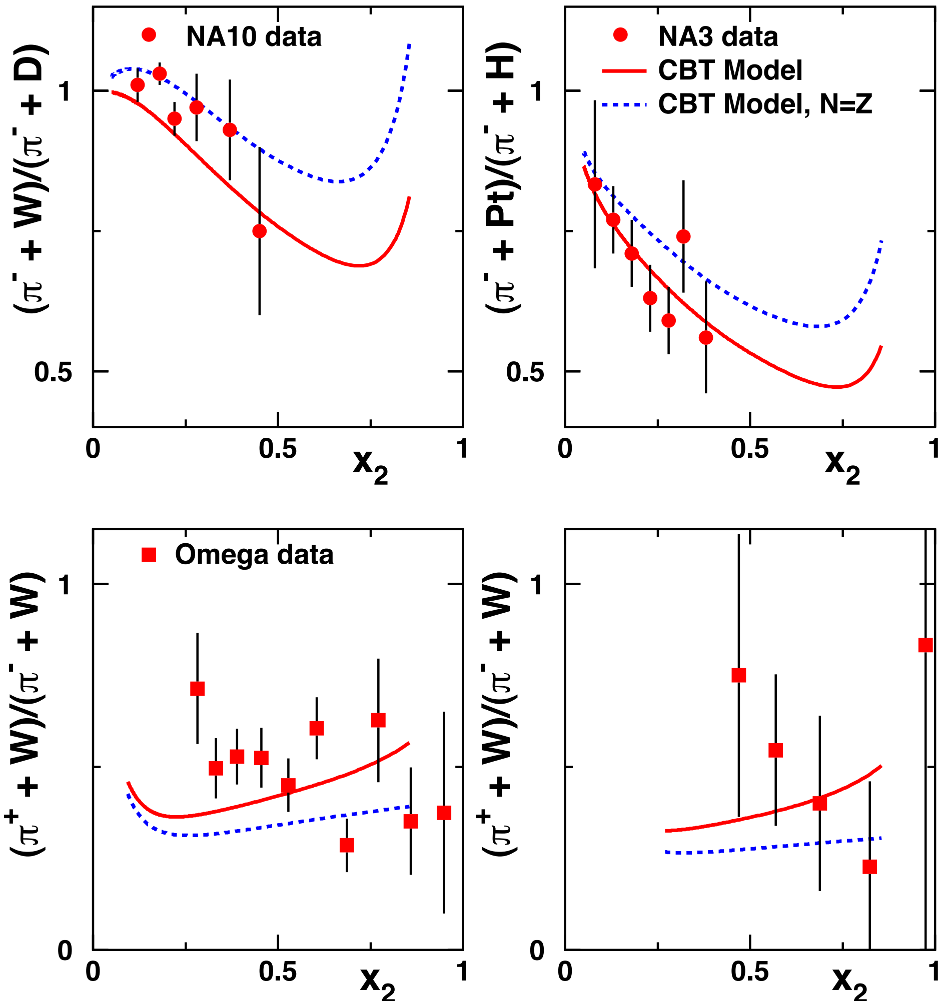
Free nucleon quark distributions

$$u_0 = \frac{Zu_p + Nd_p}{A} \quad d_0 = \frac{Zd_p + Nu_p}{A}$$

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

Experimentally, this flavor dependence has not been observed directly

EMC Flavor Dependence: Pion Drell-Yan



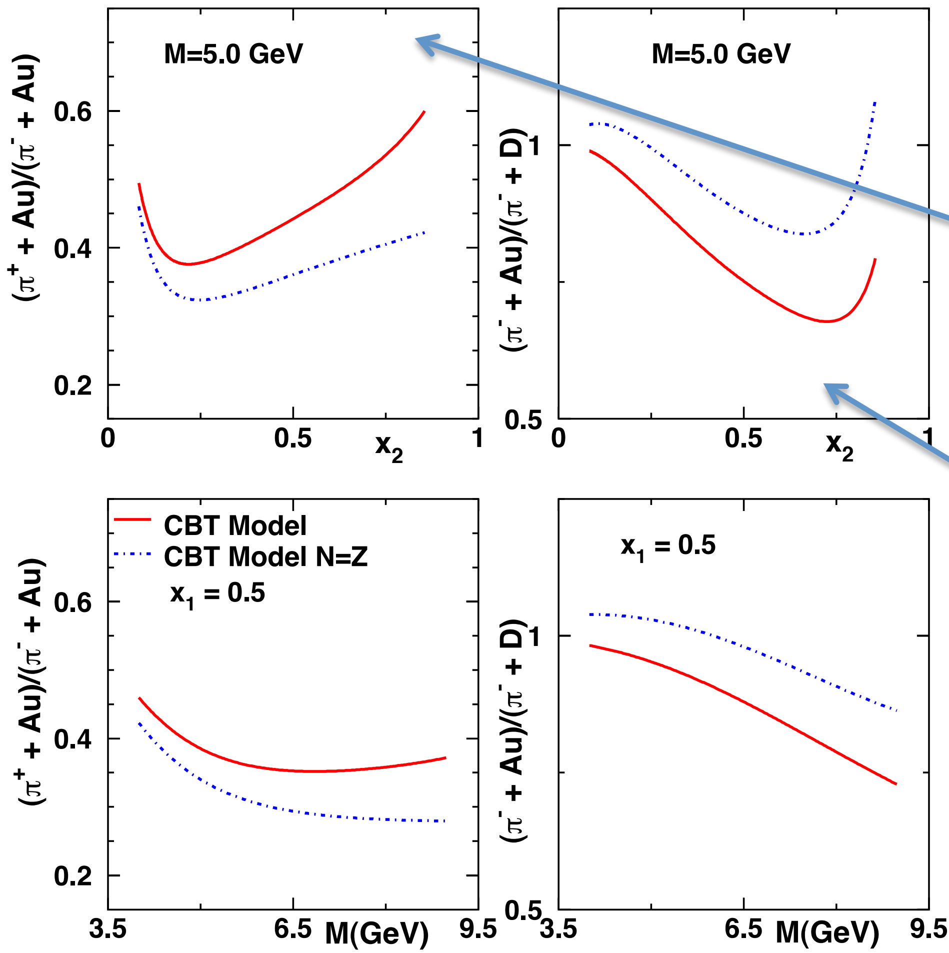
Experiment	Flavor Ind.	Flavor dep.
NA3	1.3	0.5
NA10	0.60	2.5
Omega (low Q^2)	6.2	3.2
Omega (high Q^2)	1.4	0.96

χ^2/DOF

Pion-induced Drell-Yan sensitive to potential flavor dependence, but existing data lack precision

Dutta, Peng, Cloët, DG, PRC 83, 042201 (2011)

Pion Drell-Yan at COMPASS



160 GeV pions on gold

$$\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)}$$

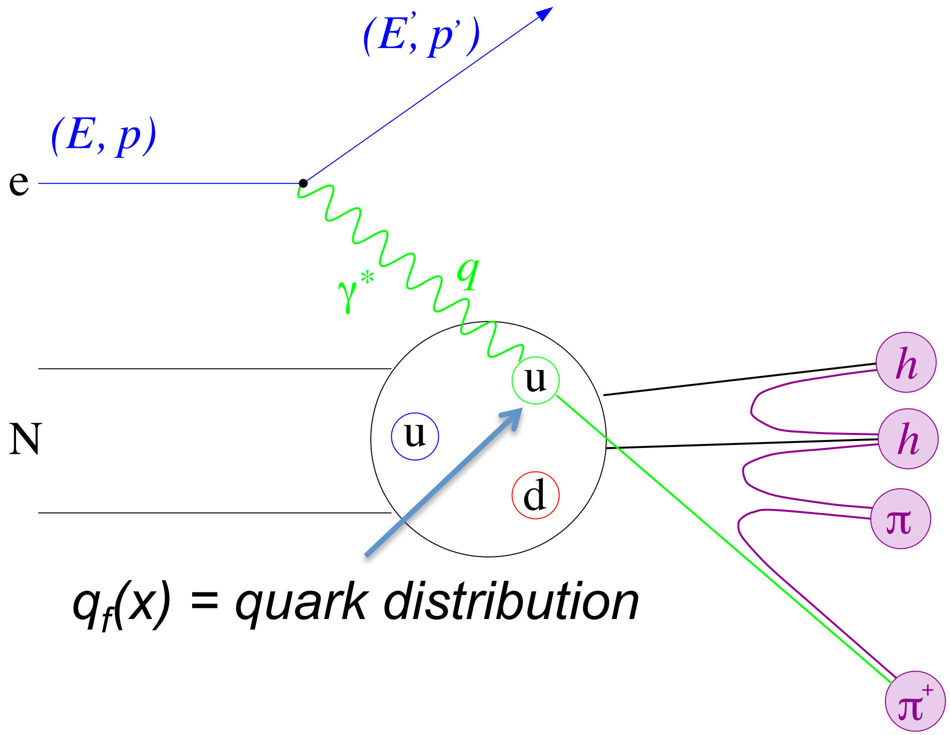
$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$

Dutta et al, PRC 83, 042201 (2011)

First measurements on NH3 (and nuclear targets) planned for 2014

$$\frac{d\sigma_{\pi^\pm A}}{dx_\pi dx_2} = \frac{4\pi\alpha^2}{9sx_\pi x_2} \sum_q e_q^2 [q_{\pi^\pm}(x_\pi)\bar{q}_A(x_2) + \bar{q}_{\pi^\pm}(x_\pi) q_A(x_2)]$$

Semi-Inclusive DIS



$q_f(x)$ = *quark distribution*

Assuming factorization holds, SIDIS acts as a "flavor tag" for struck quark
→ Similar to polarized quark distribution extractions

$D_f^h(z)$ – fragmentation function quark of flavor *f* → hadron *h*

$$\frac{d\sigma}{dx\,dQ^2\,dz} = \frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)} \left(\frac{d\sigma}{dx\,dQ^2} \right)$$

x = fraction of proton momentum carried by quark
$z = E_{hadron}/n$

Semi-Inclusive DIS

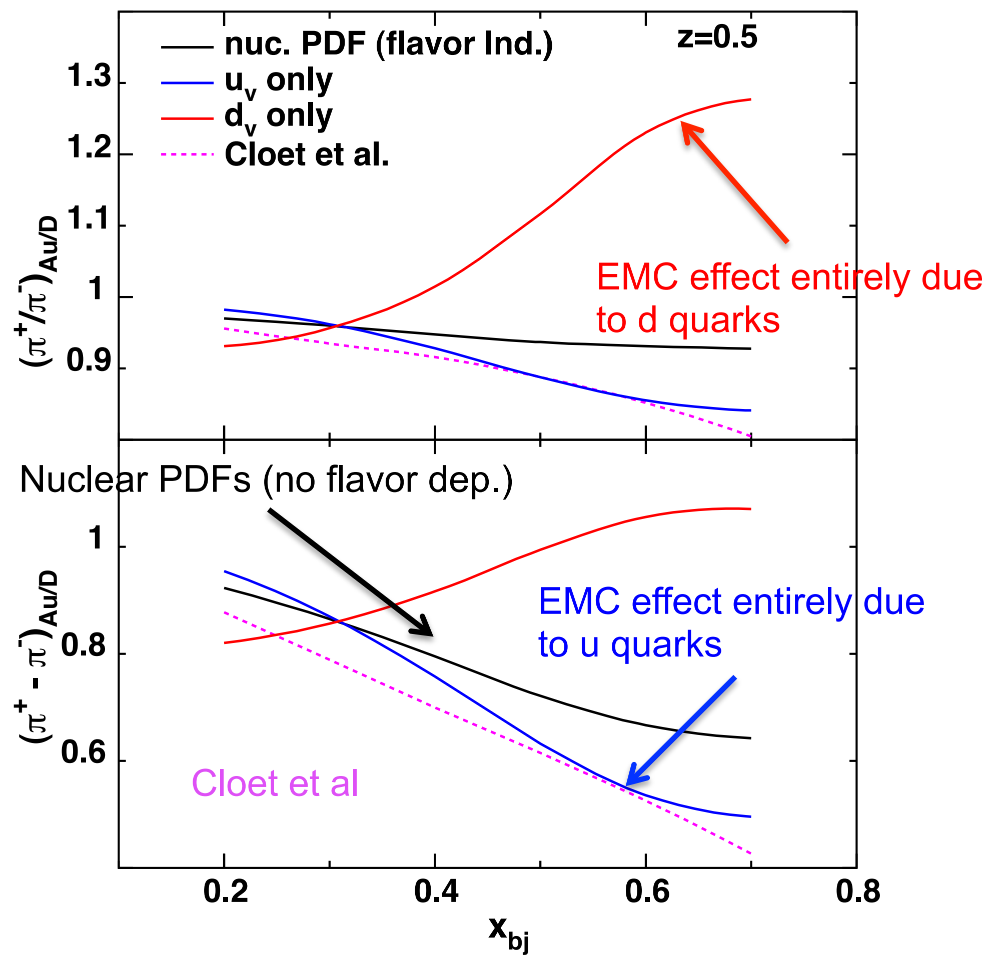
Extract flavor dependence via semi-inclusive pion yields from gold and deuterium

Super-ratio

$$\frac{Y^{\pi^+}_{Au} / Y^{\pi^-}_{Au}}{Y^{\pi^+}_{D} / Y^{\pi^-}_{D}}$$

Difference ratio

$$\frac{Y^{\pi^+}_{Au} - Y^{\pi^-}_{Au}}{Y^{\pi^+}_{D} - Y^{\pi^-}_{D}}$$



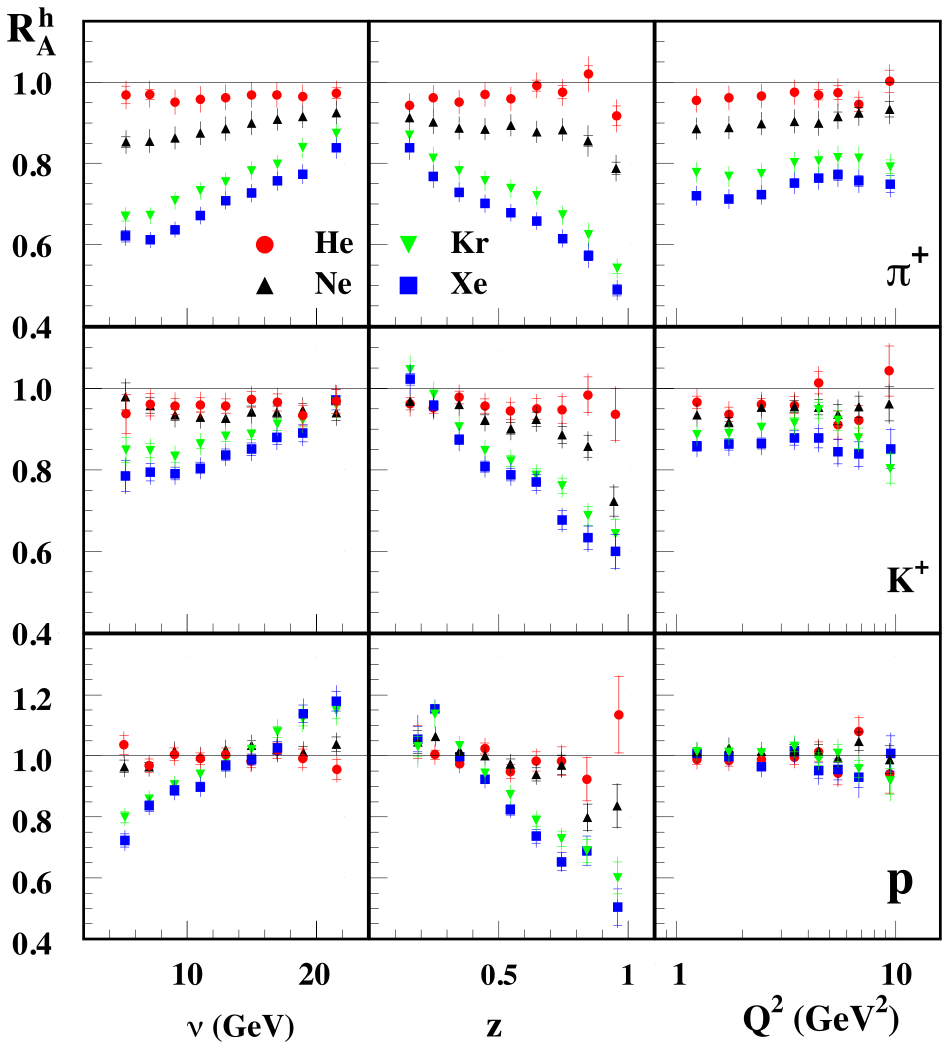
Toy model:

u_V only: EMC effect due to modification of u_A only

d_V only: EMC effect due to modification of d_A only

→ F_2^A unchanged

SIDIS - Interpretability



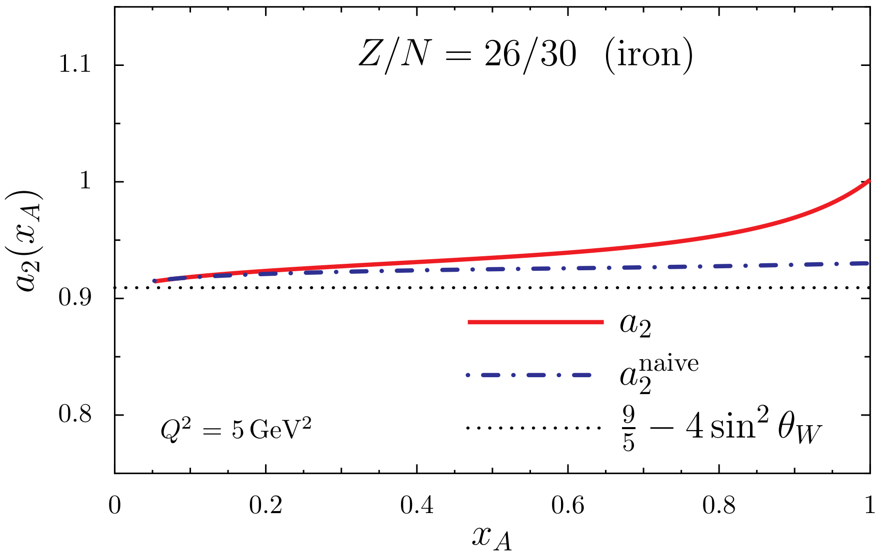
$$R_h^A(z,\nu) = \frac{\left(\frac{1}{\sigma_e}\frac{d\sigma}{dz\,d\nu}\right)_A}{\left(\frac{1}{\sigma_e}\frac{d\sigma}{dz\,d\nu}\right)_D}$$

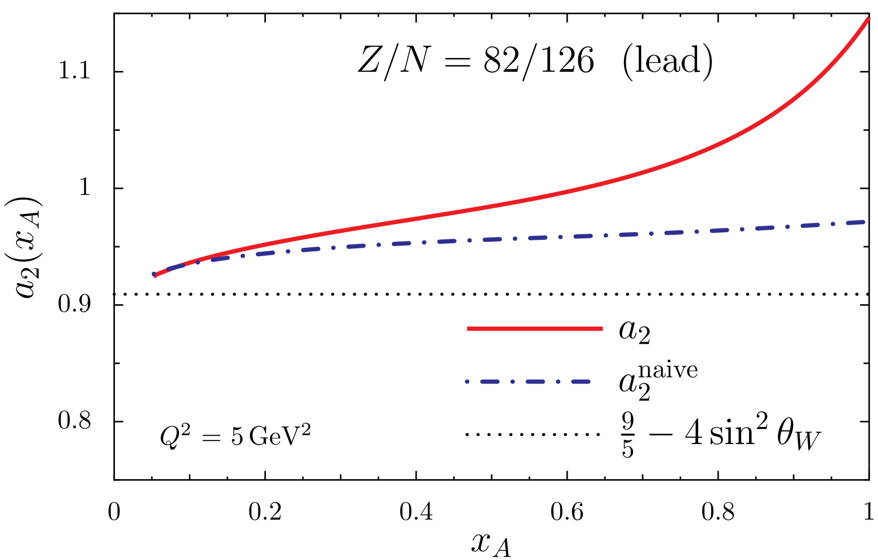
Hadronization is modified in the nuclear medium
→ Probability for quark *f* to form hadron *h* changes
→ Depends on *A*, hadron kinematics

Complicates interpretation of SIDIS measurements of flavor dependence if effect different for p^+ and p^-

→ This can be checked with measurements at *x=0.3* (no EMC effect)

Parity Violating DIS





Flavor dependence of EMC effect can also be explored via parity violating DIS

$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{em}}\left[a_2(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right]$$

suppressed

quark weak vector couplings

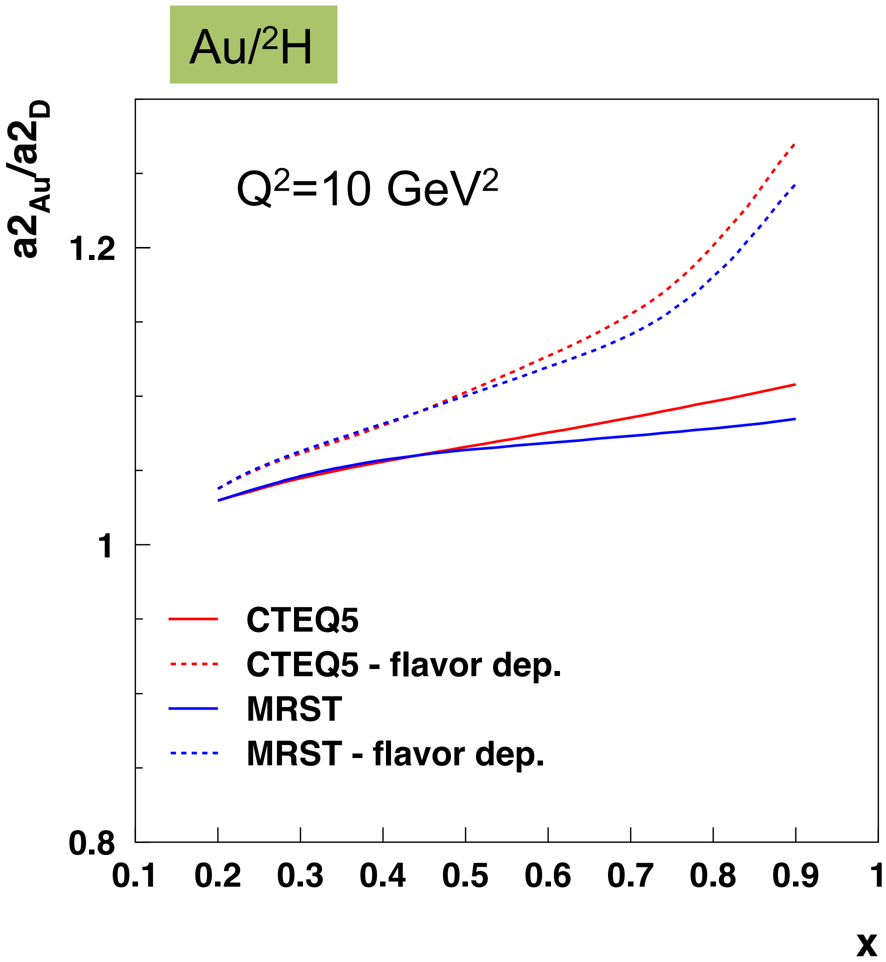
$$a_2(x) = \frac{2\sum_q e_q g_V^q [q_A(x) + \bar{q}_A(x)]}{\sum_q e_q^2 [q_A(x) + \bar{q}_A(x)]}$$

Avoids complications due to hadronization issues

CBT model predicts 5% effect at x=0.6

Cloët, Bentz, and Thomas, PRL 109, 182301 (2012)

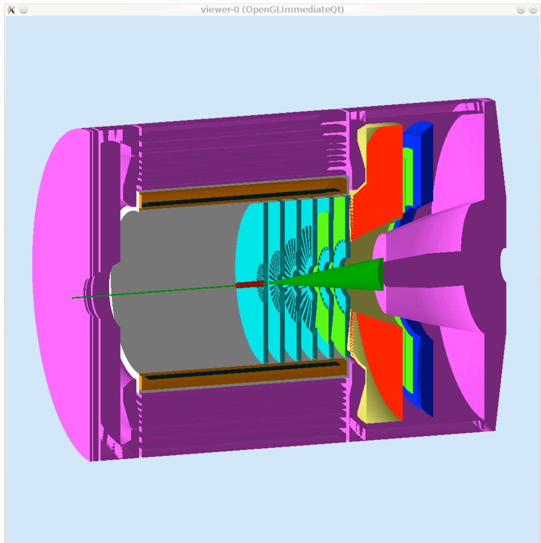
Measuring Flavor Dependence with PVDIS



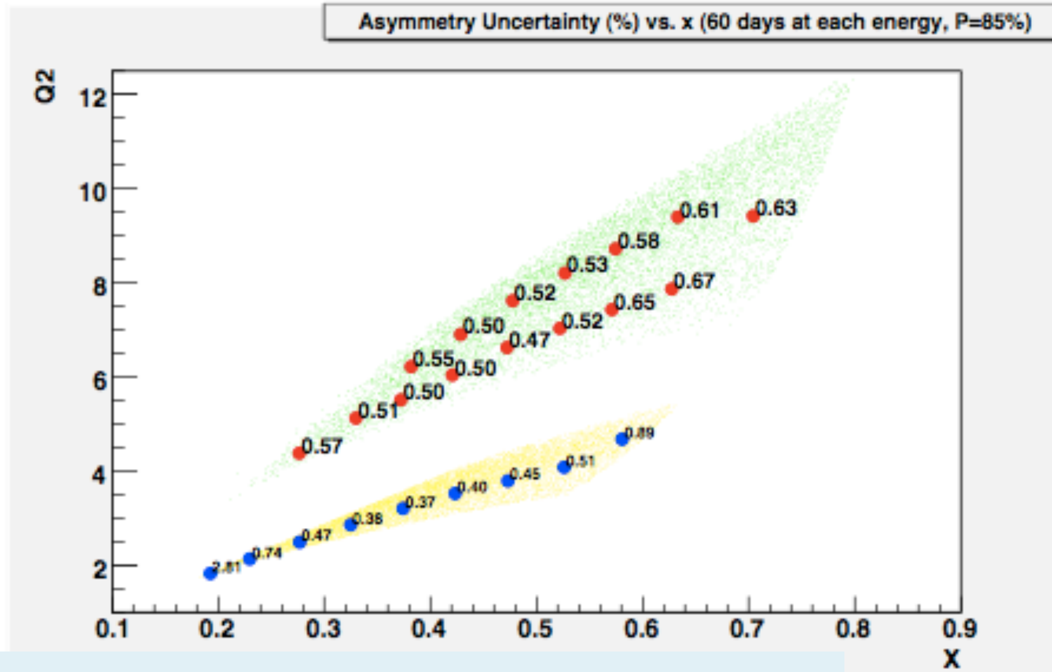
Experimentally – simpler to measure super-ratio
→Certain systematics are reduced (beam polarization)
→Less sensitivity to absolute value of weak vector couplings

Note that even the “no flavor dependence” calculation not identically 1.0
→ Must compare experimental result to the “naïve” estimate
→ Naïve estimate has some dependence on nucleon PDFs
→ May be non-negligible contribution to uncertainty

PVDIS at JLab



New solenoidal spectrometer



Proposed kinematic coverage and statistical precisions

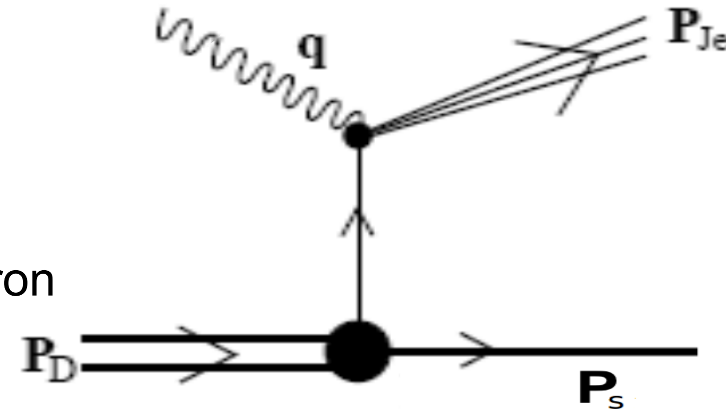
SOLID experiment at JLab (P. Souder, spokesperson) – use PVDIS to look for physics beyond Standard Model, *d/u* at large *x*

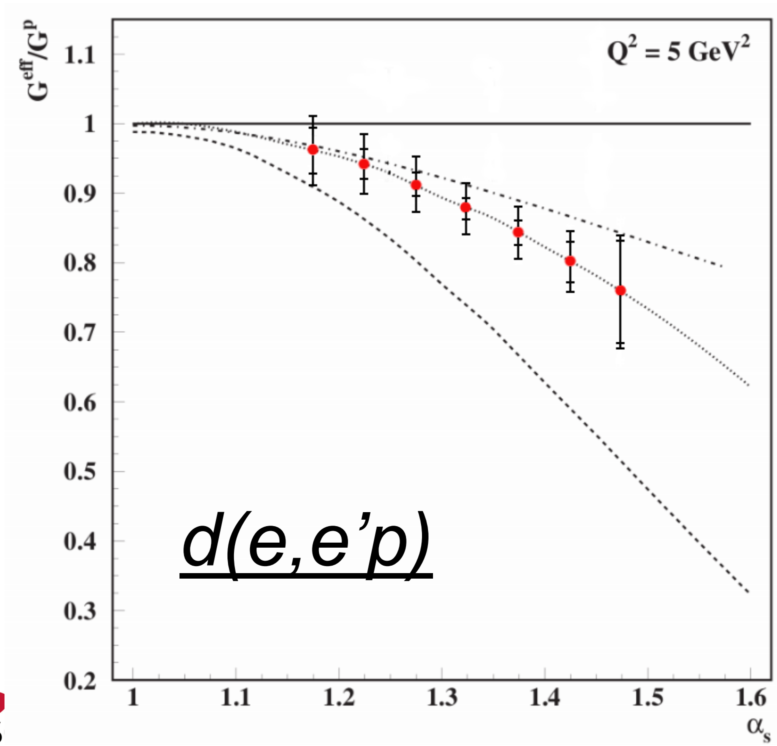
→awarded 169 days for H and D running

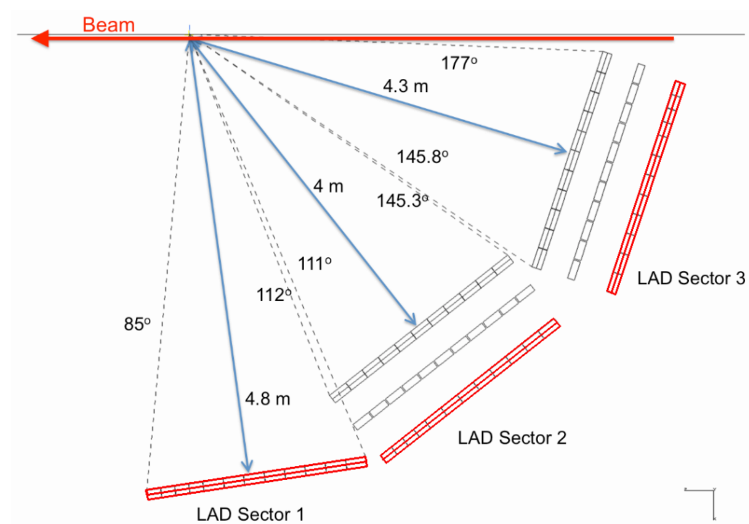
→no time for solid target running (flavor dependent EMC) requested yet

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





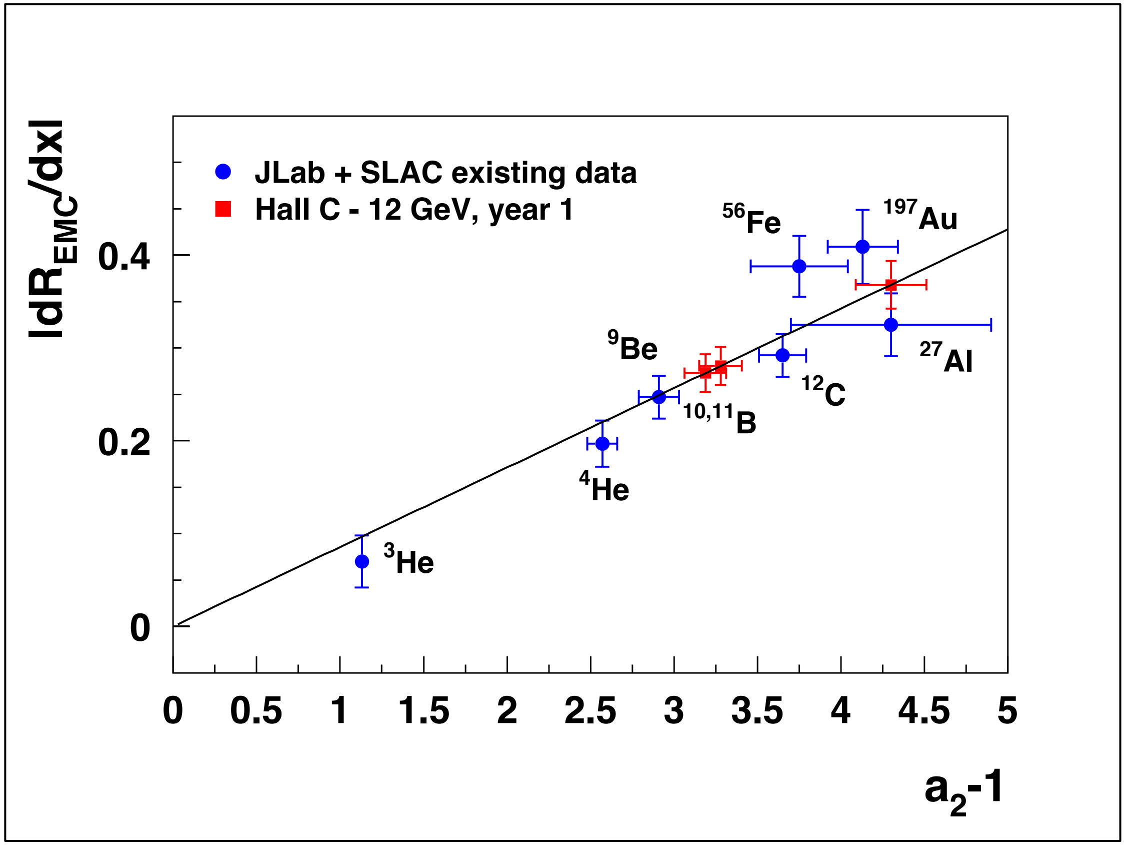


Spokespersons: O. Hen, L. Weinstein, S. Gilad, S. Wood

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

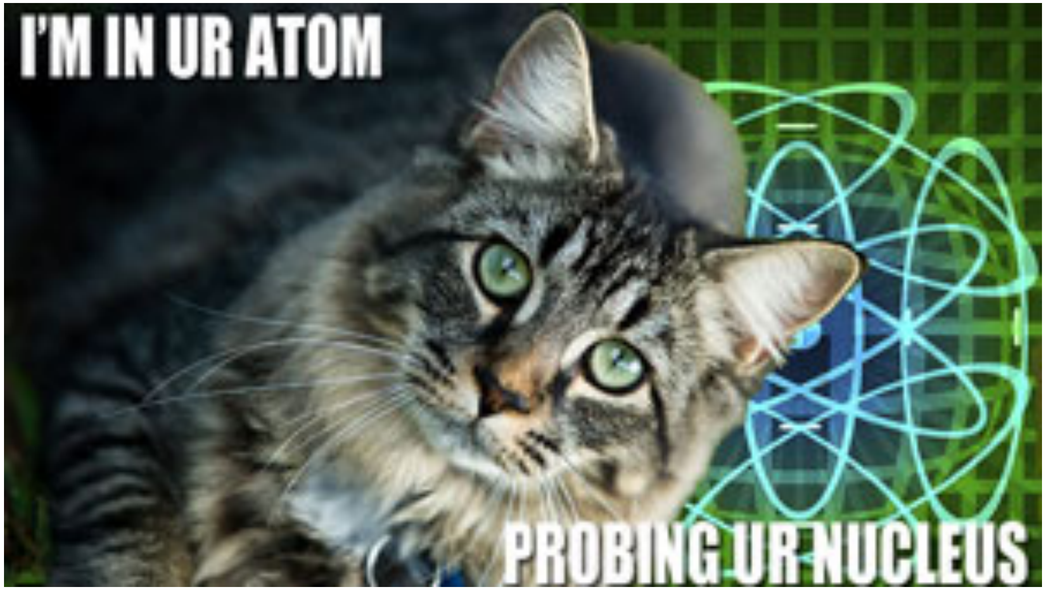


First running in Hall C after completion of 12 GeV Upgrade will include a few days for EMC/x>1 measurements on ^{10}B, ^{11}B, and Al (parasitic)

Summary

- The EMC effect has been with us for 30 years and motivated intense experimental (and theoretical) study
- Two developments have led to renewed excitement and interest
  - New approach to quantifying "size" of EMC effect at large x
  - New data at x<1 and x>1 allowed precise comparison of EMC effect with Short Range Correlations
- What is the origin of this EMC/SRC correlation?
  - Measurements of the flavor dependence of the EMC effect will play a key role
- Many new experiments at JLab after the 12 GeV upgrade will help address the EMC/SRC issue
- Issues I did not discuss
  - Polarized EMC effect
  - Low x measurements → Electron Ion Collider
  - Several other processes that aim to quantify the modification of nucleons in the nucleus (proton Drell-Yan, elastic form factors…)

Thank You

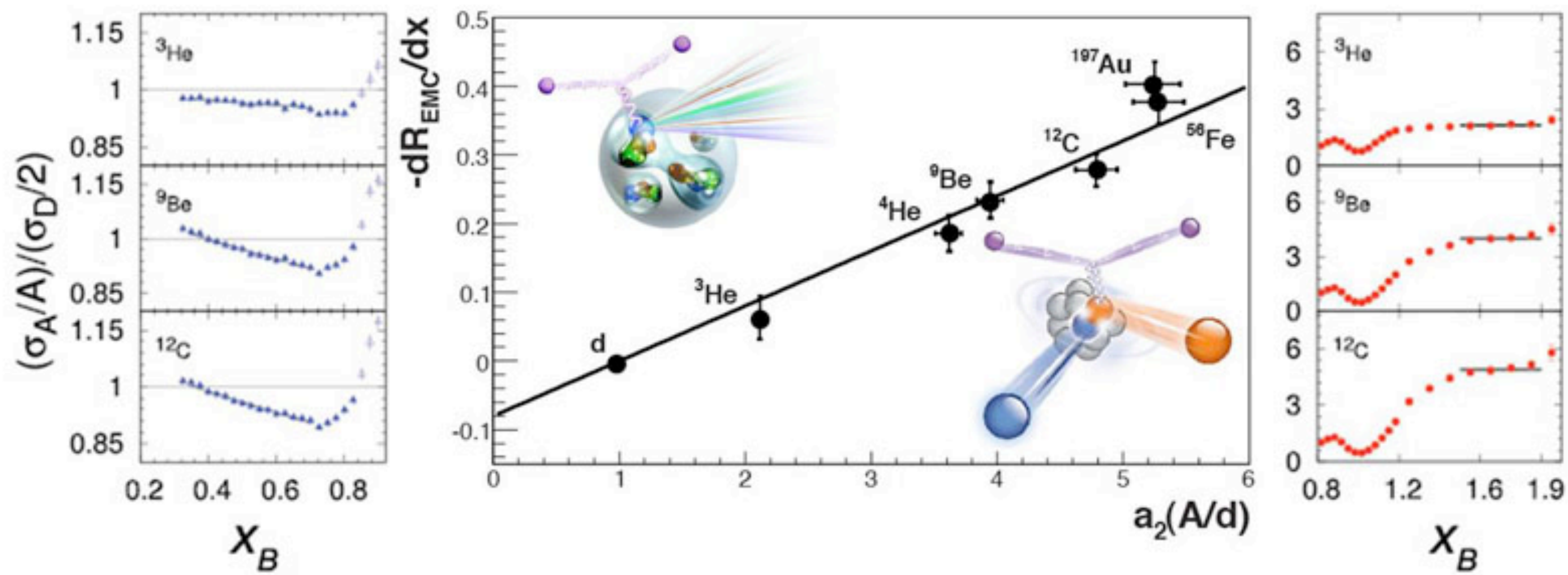


http://arstechnica.com/science/2009/11/iz-in-ur-atom-probing-ur-nucleus/

Extra

INT Workshop INT-13-52W

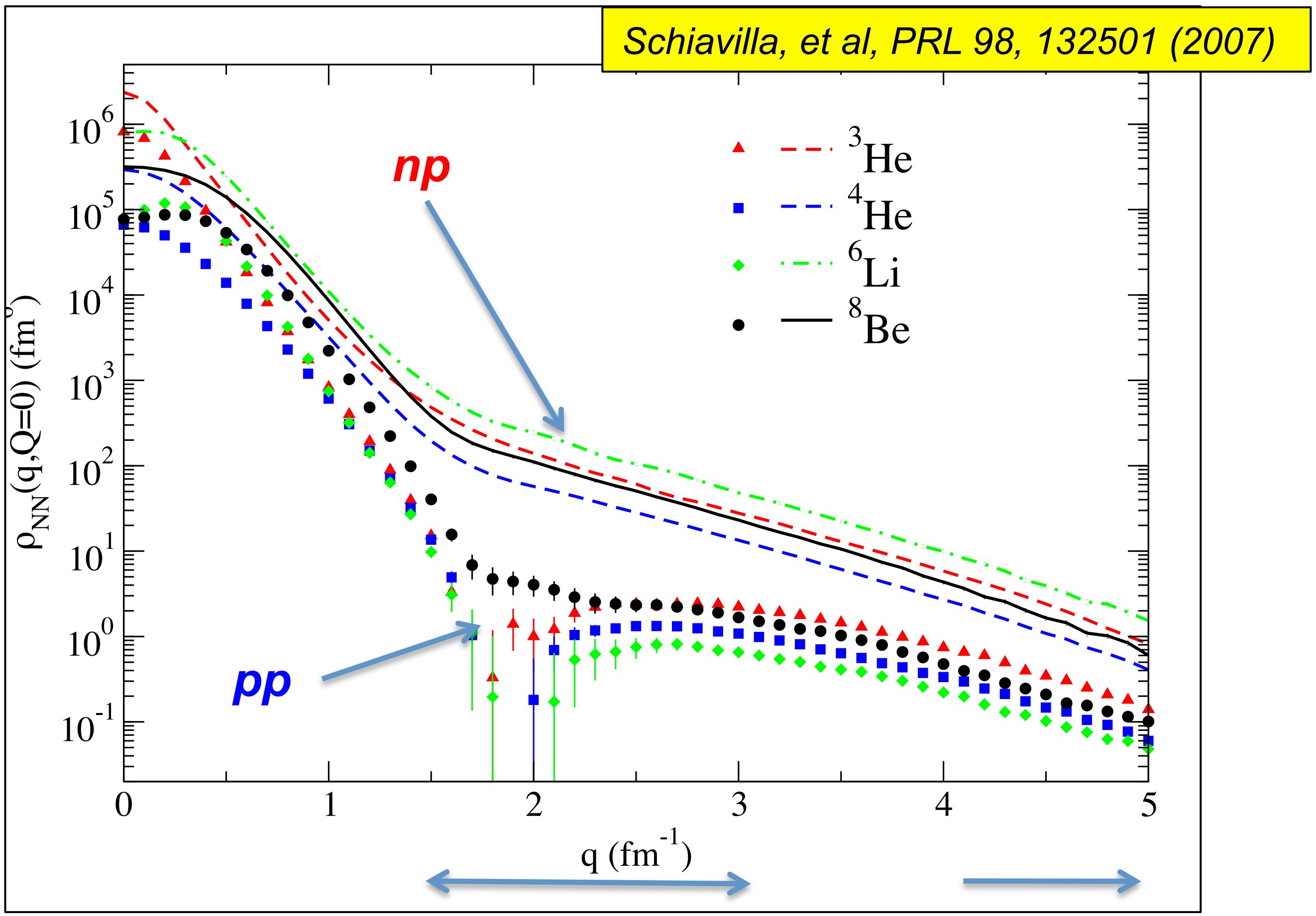
Nuclear Structure and Dynamics at Short Distances
Feb. 11-22, 2013



http://www.int.washington.edu/PROGRAMS/13-52w/

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