Measurements of the nuclear EMC effect at large X

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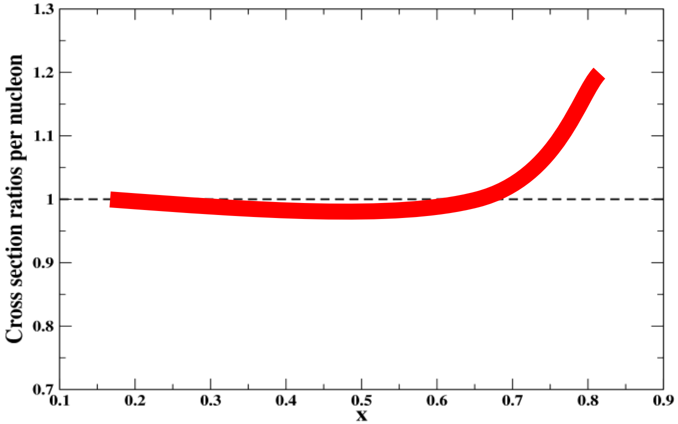
The EMC effect

- **Typical energy scale of nuclear process ~ MeV**
- **Typical energy scale of DIS ~ GeV**
- **Compared to energy scale of the probe, binding energies are less for nuclear targets.**
- **So naïve assumption (at least in the intermediate xbj region) ;**
  Nuclear quark distributions = sum of proton + neutron quark distributions

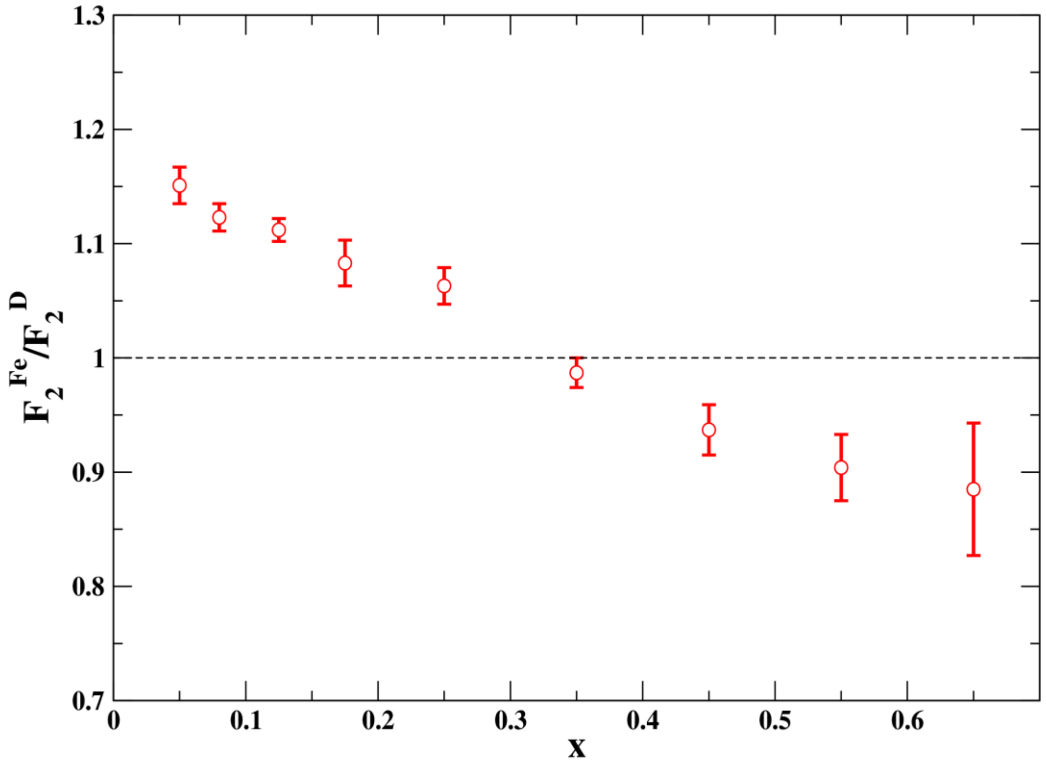
$$F_2^A(x) = ZF_2^p(x) + NF_2^n(x)$$



The EMC effect

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

- **It turns out that the above assumption is not true.**
- **Nuclear dependence of structure functions, (F_2^A/F_2^D), discovered over 25 years ago; "EMC Effect"**
- **Quarks in nuclei behave differently than the quarks in free nucleon**

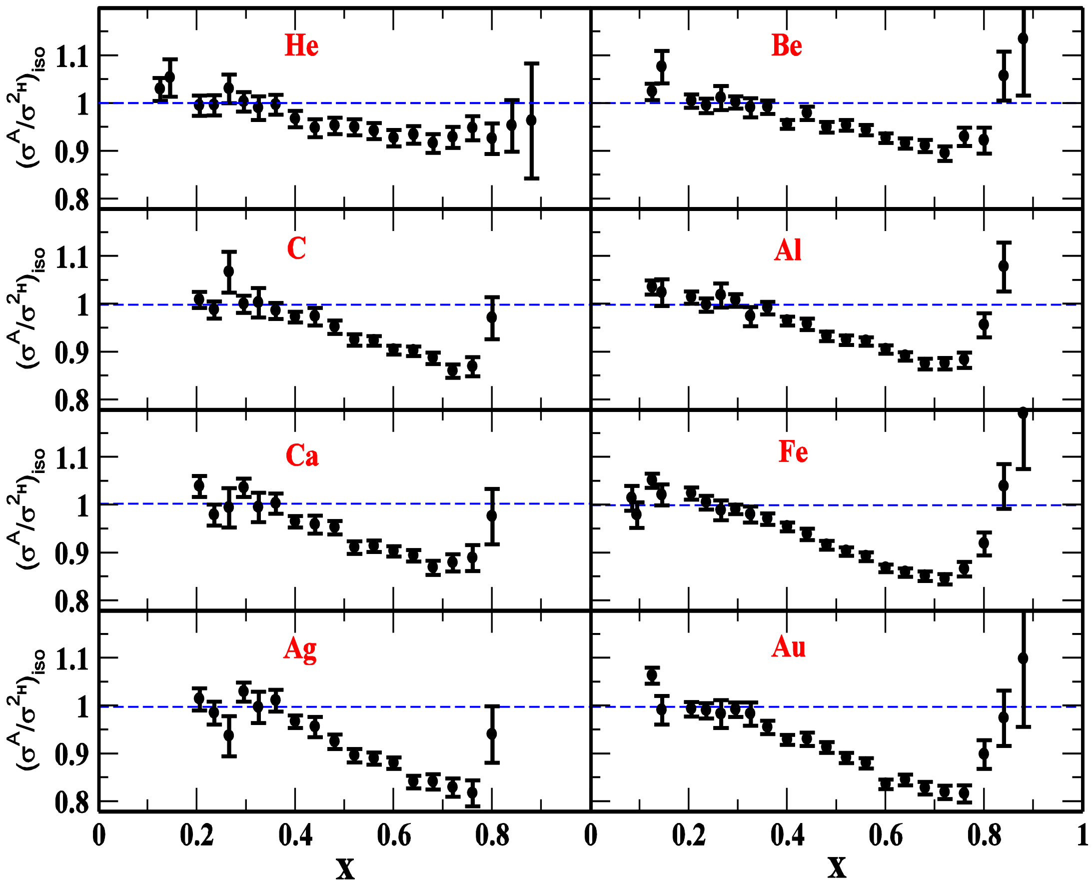


Aubert et al., Phys. Lett. B123, 275 (1983)

The EMC effect: Representative data

- EMC effect indicates that quark distributions are modified inside nuclei.
- Extensive measurements on heavy targets (SLAC, NMC, BCDMS,..)

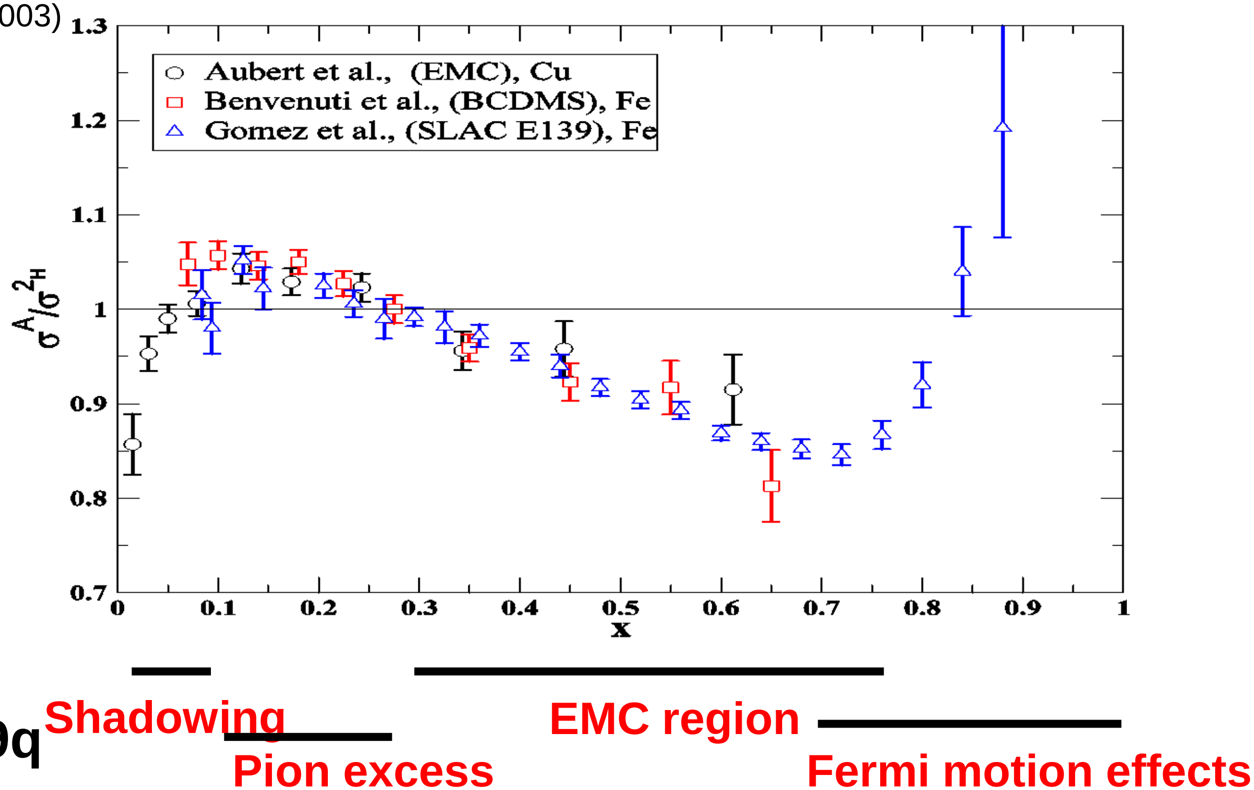
- **SLAC E139**
  - Most precise large-x data
  - Nuclei from A=4 to 197
- **Conclusions from SLAC E139**
  - Q^2-independent
  - Universal x-dependence (same shape) for all A
  - Magnitude varies with A
    - Scales with A ($\sim A^{-1/3}$)
    - Scales with *average* nuclear density



The EMC effect: Models

Different kinematical regions understood in terms of different processes

for example see D. F .Geesaman, K. Saito, A. W. Thomas, Ann. Rev. Nucl. Part. Sci 45, 337 (1995) and
P. R. Norton Rept. Prog. Phys. 66, 1253 (2003)



Conventional nuclear physics models

- Fermi smearing
- Binding models
- Nuclear pions

Exotic models

- Multi-quark clusters (6q, 9q bags)
- Dynamical rescaling
- Modification of nucleon structure.

Several models. Some only valid in certain regions. Some inconsistent with other reactions (e.g., Drell Yan)

The EMC effect: models

- **Interpretation of the EMC effect requires better understanding of traditional nuclear effects (*better handle at high x*).**
- **Fermi motion and binding often considered uninteresting part of EMC effect, but must be properly included in any examination of "exotic" effects.**
- ***Data are limited at large x*, where one can evaluate binding models, *limited at low-A*, where nuclear structure uncertainties are small.**

Main goals of E03-103

- **First measurement of EMC effect on ^{3}He for $x > 0.4$**
- **Increase in the precision of ^{4}He ratios.**
- **Precision data at large x for heavy nuclei.**

Overview of the experiment

- JLab E03-103 collaboration
- Spokespersons:

  J. Arrington and D. Gaskell
- Graduate students:

  J. Seely and A. Daniel
- Nuclear matter analysis:

  P. Solvignon
- Concurrent with E02-019 (inclusive cross sections at x>1, F(y) scaling, short range correlations, ...) N. Fomin

- Ran during summer and fall of 2004 in HALL C of JLAB with 5.77 GeV.
- Cryo targets: H, ^{2}H, ^{3}He, ^{4}He
- Solid targets: Be, C, Al, Cu, Au (Al for cell wall subtraction).
- Additional data at 5 GeV on carbon and deuterium to investigate detailed Q^2 dependence of the EMC ratios.

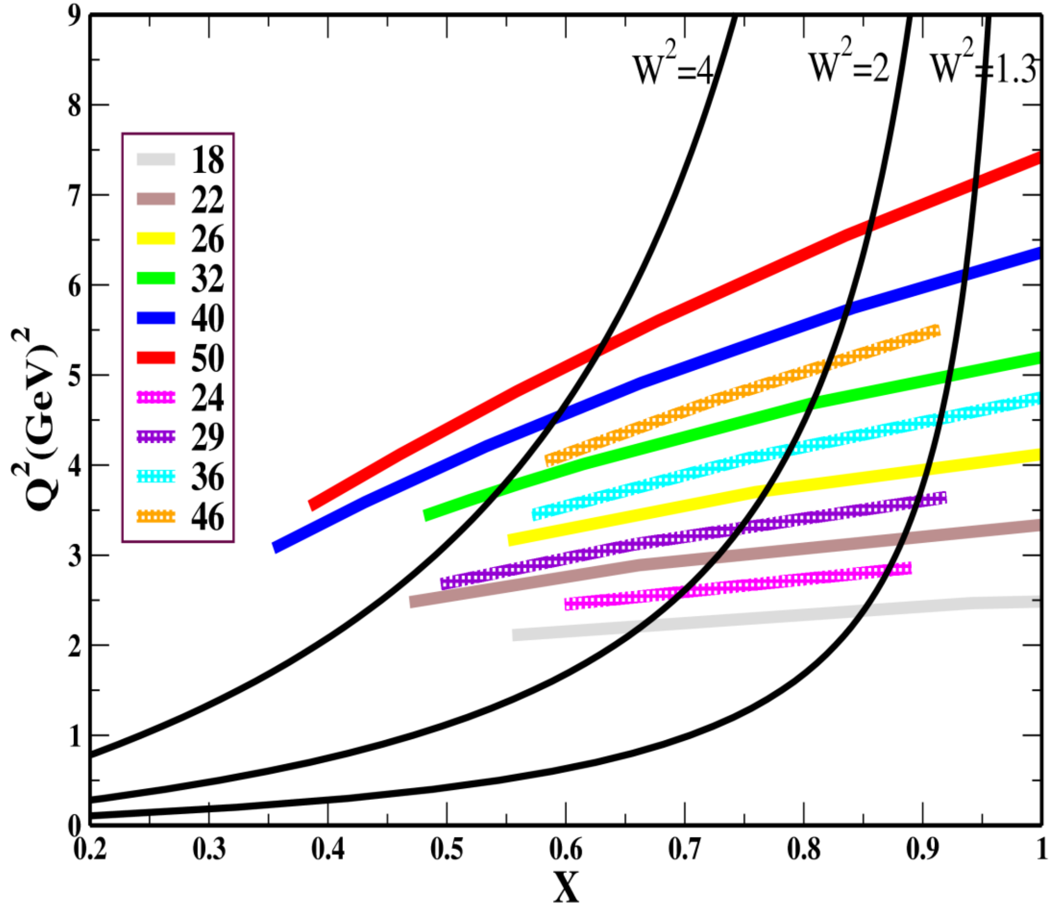
Kinematics

- **High x (x>0.6) data not in the typical DIS region (W < 2 GeV; resonance region)**
- **Data at smaller angles will allow us to put quantitative limits on deviation from scaling in the cross sections and cross section ratios**

Solid lines -> angles for 5.77 GeV

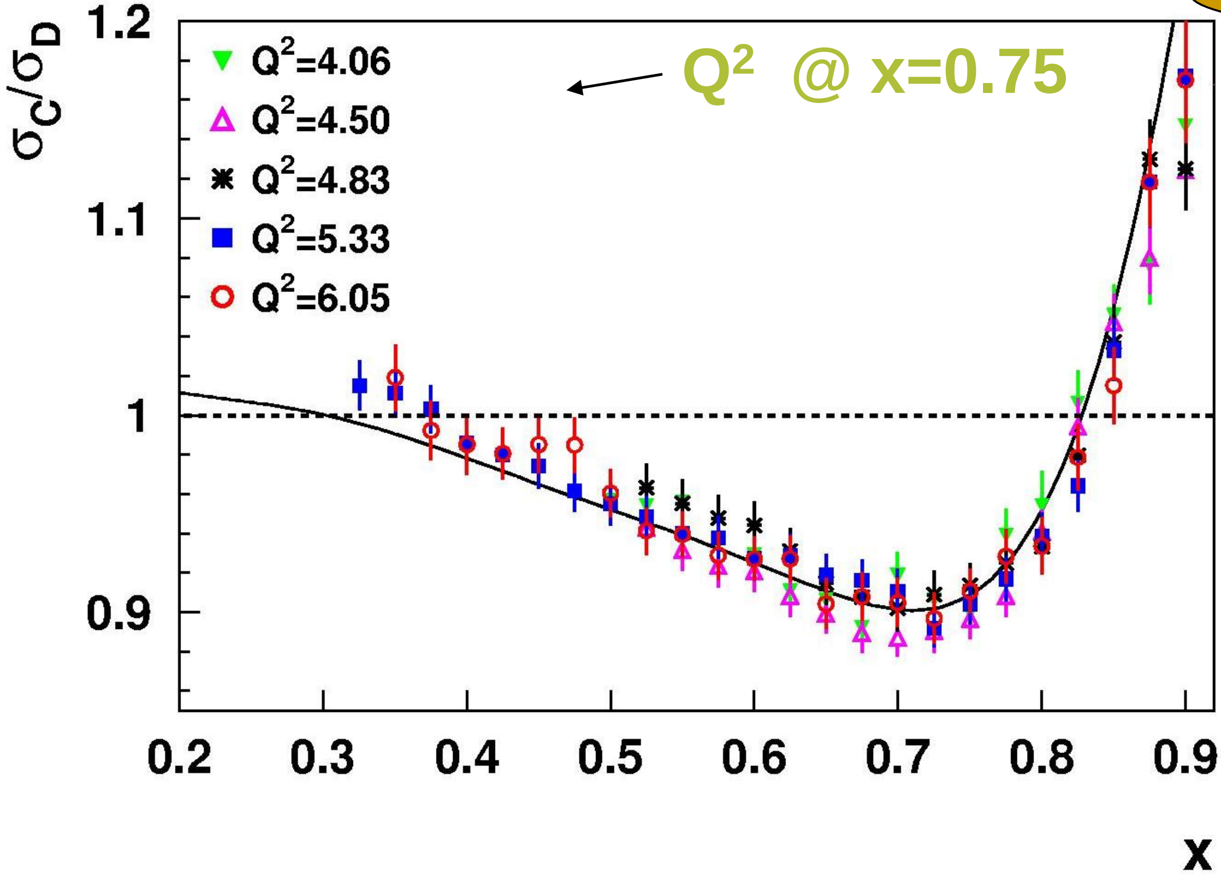
Hatched lines → angles for 5.01 GeV

Black lines are contours of fixed invariant mass



E03-103 results: scaling of cross section ratios

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

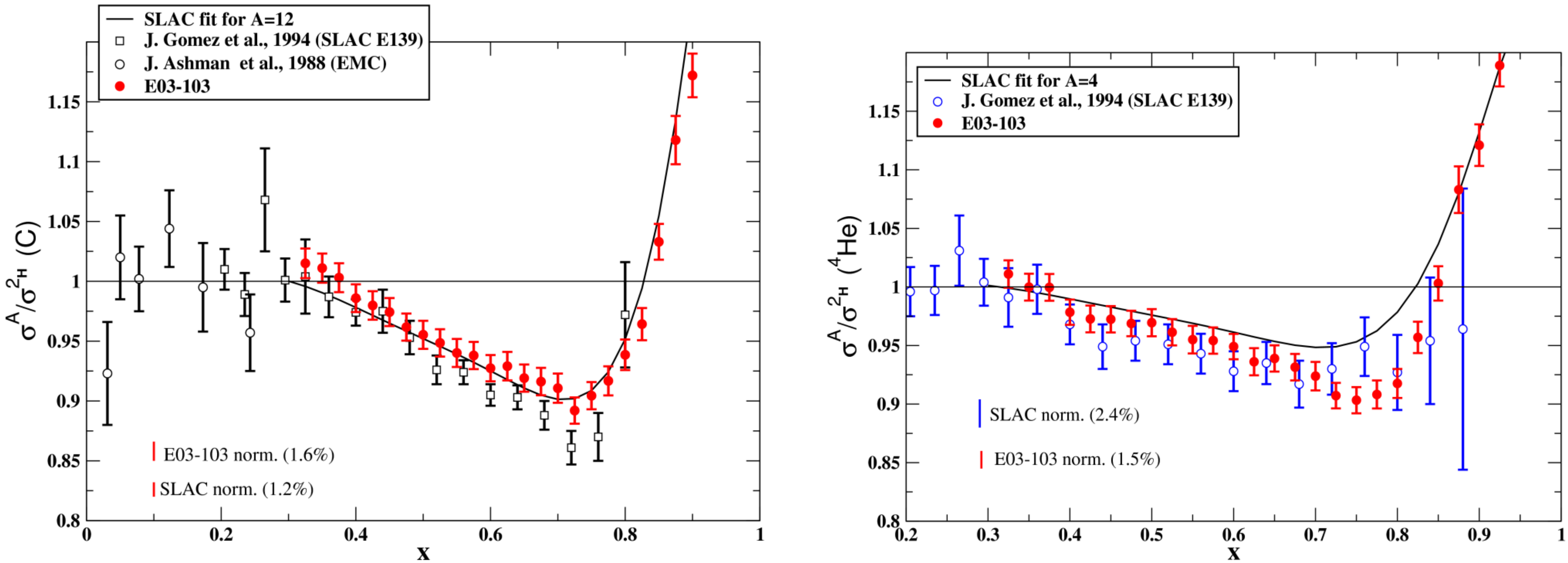


Since E03-103 is at lower Q2 and W2 than previous world data (e.g., SLAC E139) need to do detailed scaling tests.

❖ Q^2=4.06 GeV and Q^2=4.83 results are for 5 GeV; remaining results are for for 5.77 GeV

❖ Cross section ratios appears to scale (independent of Q^2) to very large x. This implies that the higher twist corrections and additional scaling violation corrections are very small in the target ratios.

E03-103 results: cross section ratios, carbon and ^{4}He



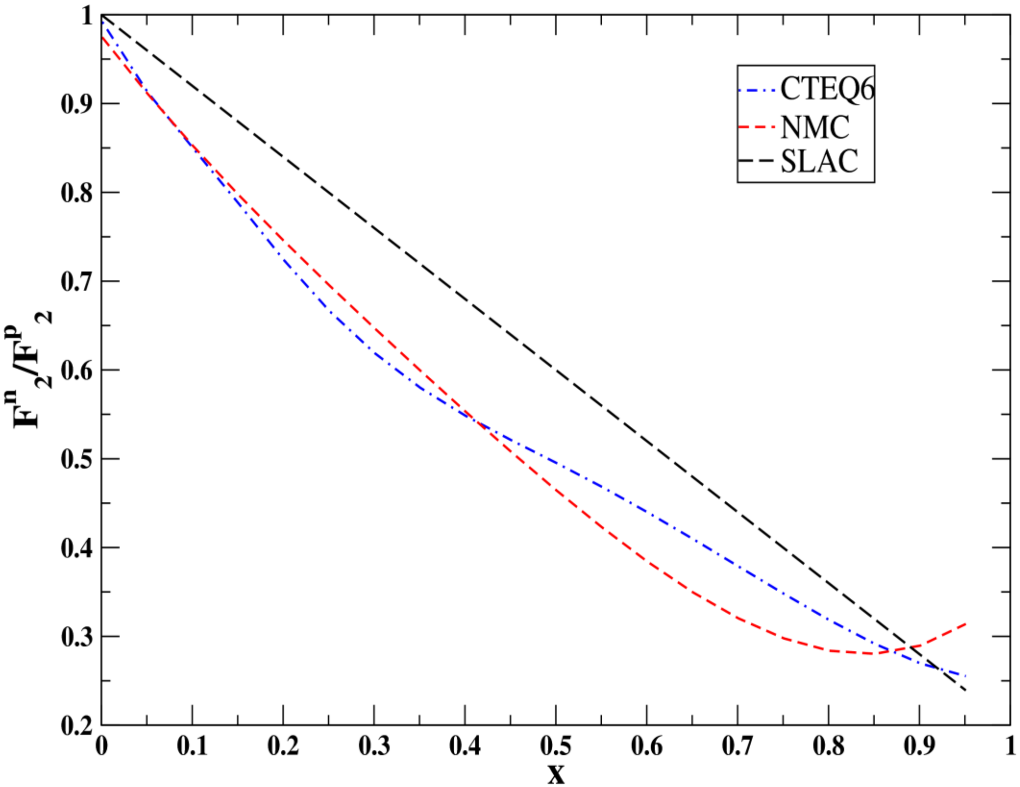
- C and ^{4}He; no complications from isoscalar corrections.

- E03-103 results are consistent with SLAC data, but have much higher precision at large x (although at lower W^2 value than SLAC).

Isoscalar corrections

- **For non-isoscalar nuclei, we need to correct for excess of neutrons or protons. The multiplicative correction factor is**

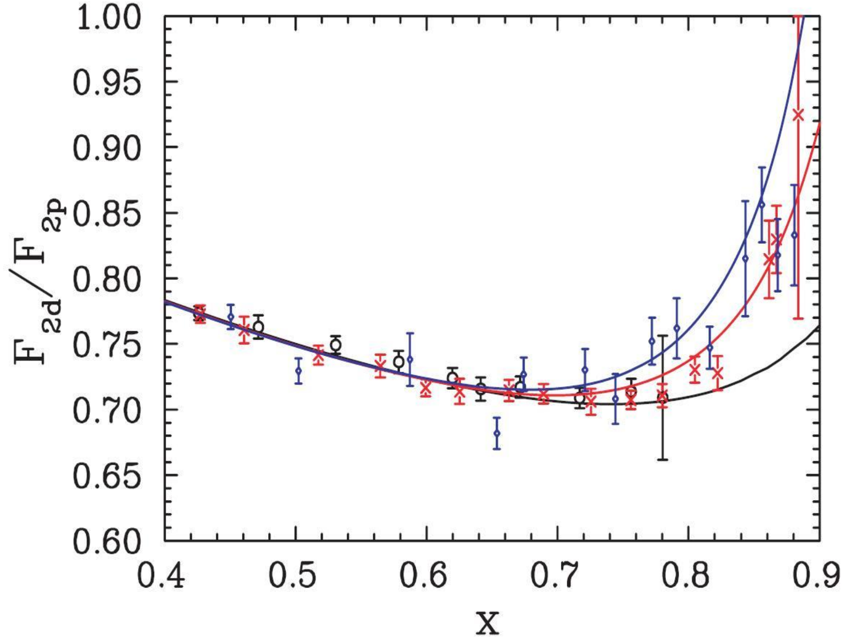
$$f^A_{iso} = \frac{\frac{1}{2}\left(1 + F_2^n/F_2^p\right)}{\frac{1}{A}\left(Z + (A-Z)F_2^n/F_2^p\right)}$$



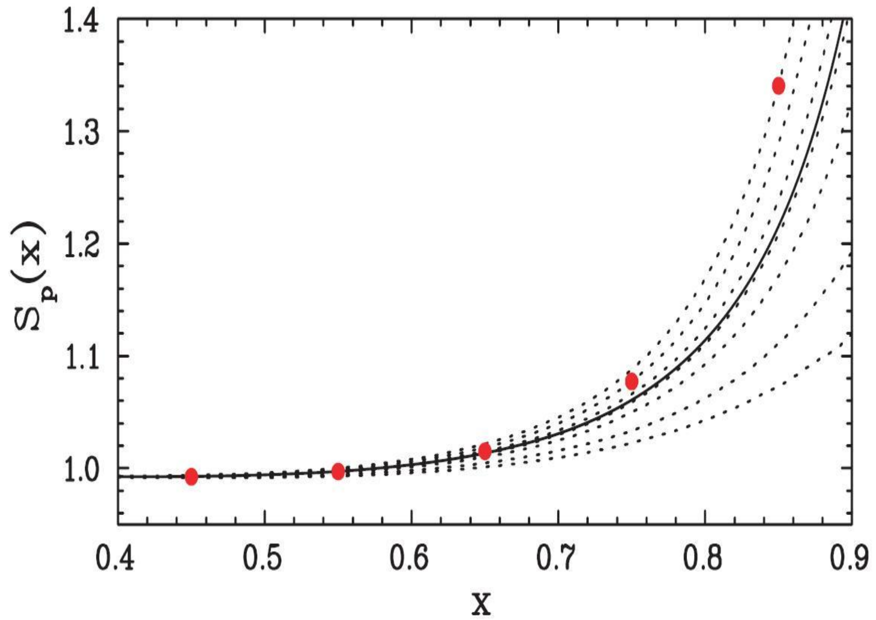
- **Since there is no free neutron target, extraction of n/p is always model-dependent.**

All the above curves are for free nucleons, want n/p in the nucleus under consideration.

Isoscalar corrections



D/p ratios ; Data are at Q^2 ranges (4 -8, 8-16 16 -32) and the calculations are done at 6,12, 20 GeV^2

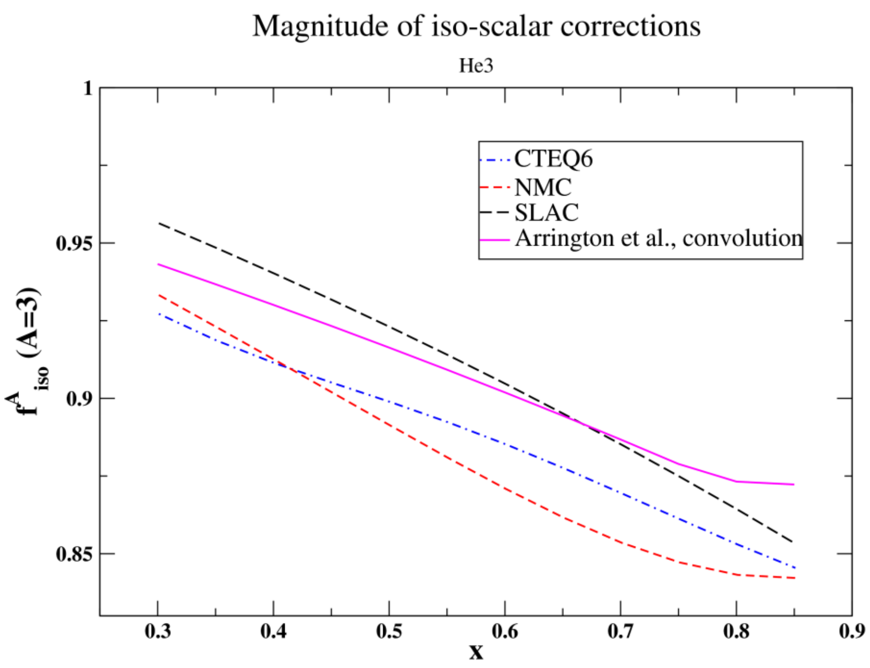


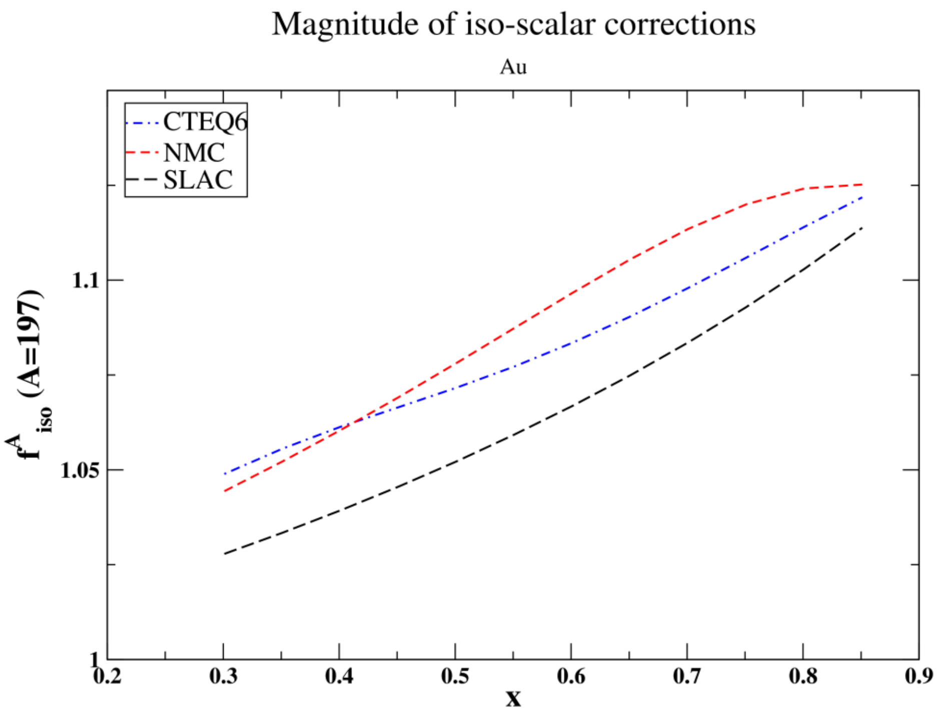
Smearing ratios calculated at different values of Q^2 Lower curve corresponds to Q^2=4.7 GeV^2 while upper curve corresponds to Q^2=23.6GeV^2

- **Calculations show strong dependence of smearing ratios on Q^2, thus the extracted n/p is a function of x and Q^2 (*this Q^2 dependence significant at large x*).**
- **n/p ratios should be evaluated at the kinematics of the experiment; simple x dependent parameterizations may not be sufficient.**
- **Thus n/p corrections depends on x, Q^2 and A**

From J. Arrington et al., Phys.G36:025005,2009

Magnitude of isoscalar corrections





- **SLAC fit: from high Q^2 global analysis, done to free n/p.**
- **E03-103 results extracted using bound n/p ratios and calculations done for E03-103 kinematics.**

(Smearing methodology in J. Arrington et al., Phys.G36:025005,2009)

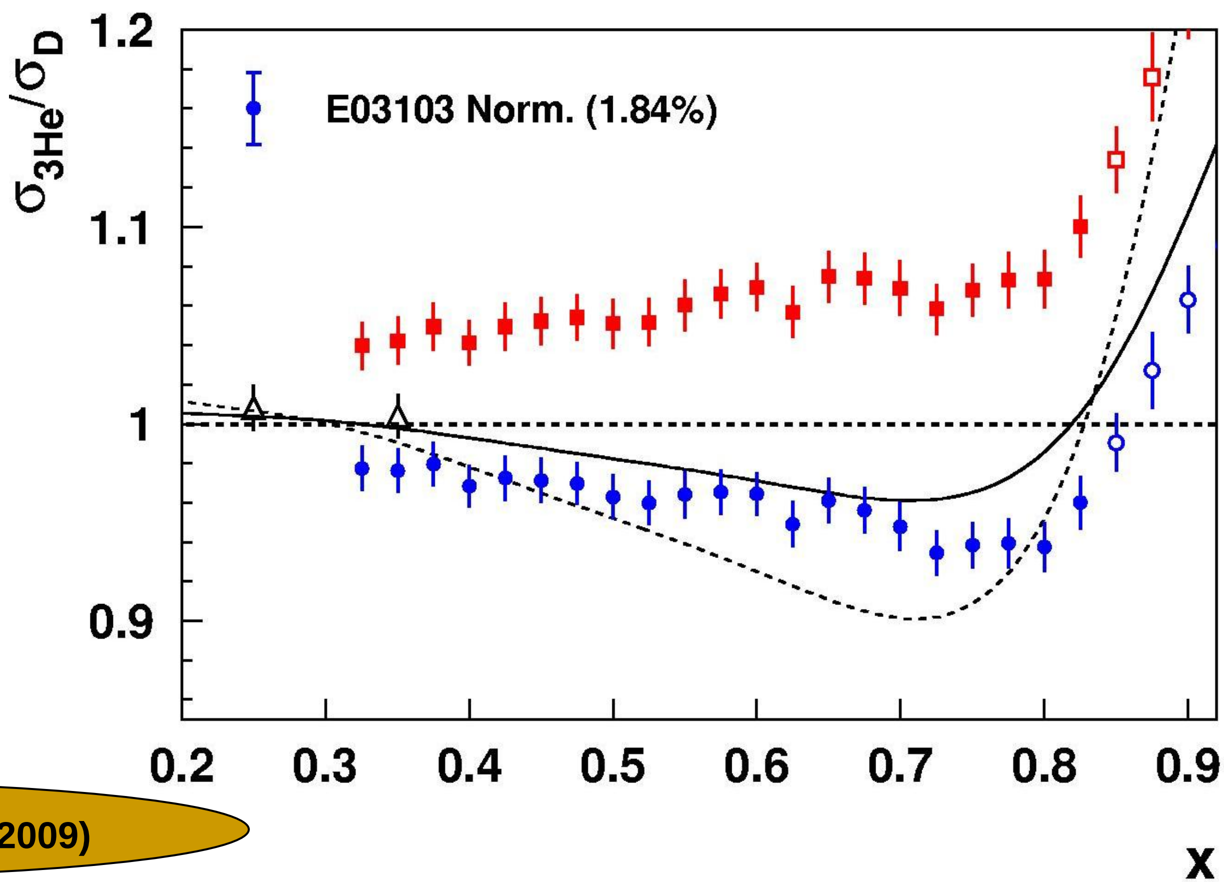
E03-103 results: cross section ratios for ^{3}He

Squares: raw ratios

Circles: isoscalar corrected ratios

Solid curve SLAC fit for A=3

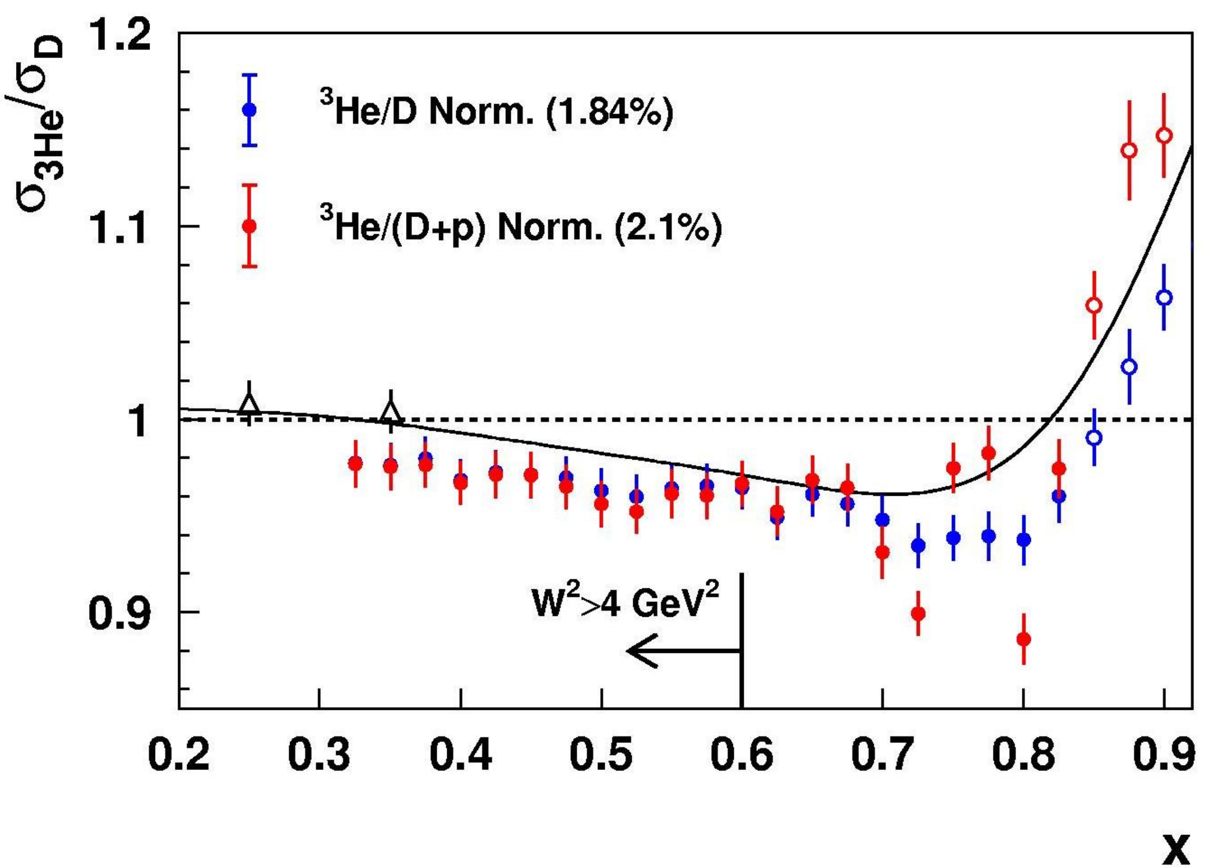
Dashed line SLAC fit for A=12



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

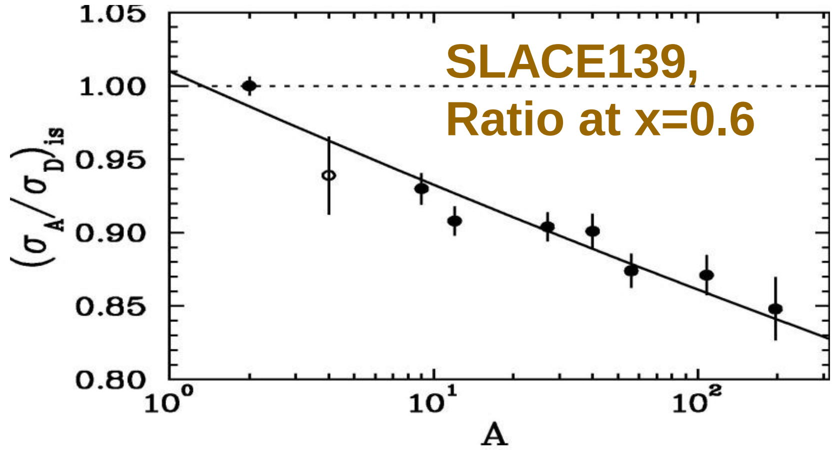
- ❑E03-103 isoscalar corrections done with ratio of bound neutron to bound proton in ^{3}He .
- ❑EMC effect small, but shape consistent with other nuclei.

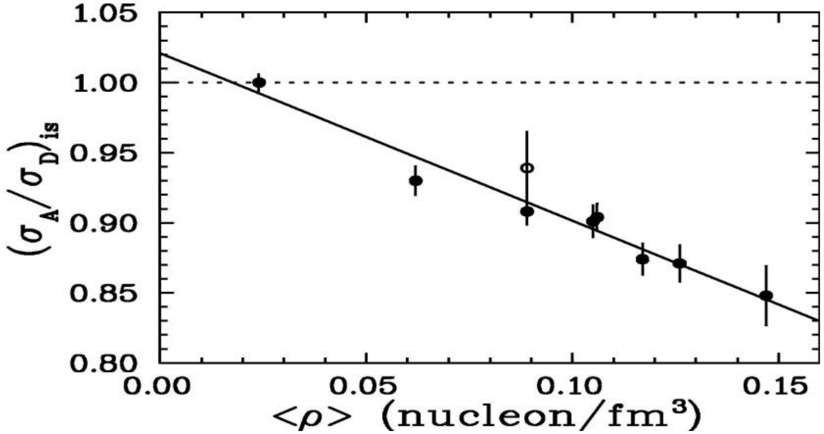
E03-103 results: cross section ratios for ^{3}He

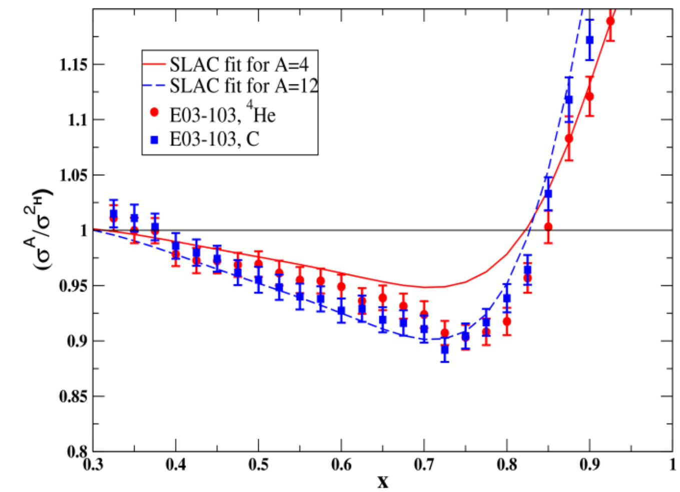


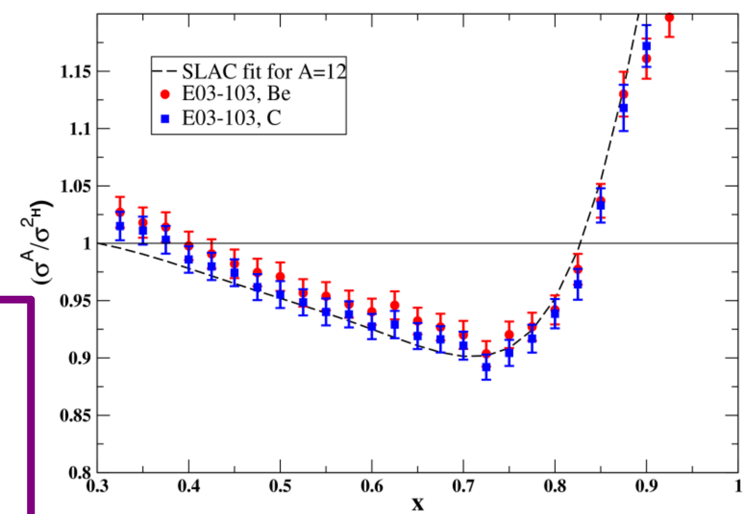
- **E03-103 isoscalar corrections done with ratio of bound neutron to bound proton in ^{3}He .**
- **Ratio of ^{3}He/(D+p); check for applied isoscalar correction; limited to x<0.65 due to proton resonance contributions.**

E03-103 results:
Mass number dependence vs density dependence









❖^{4}He matches better with C data and with SLAC parameterization (ln(A) fit with A=12).

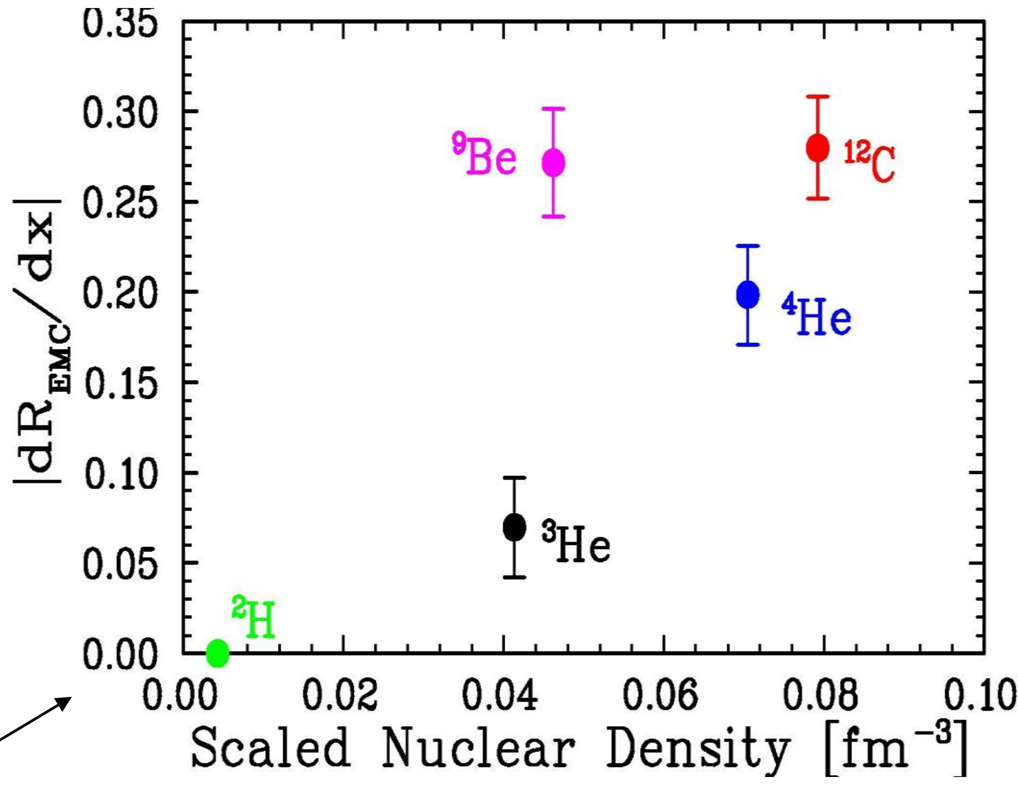
❖Average nuclear density of ^{4}He and C are similar.

❖Also, Be data matches better with C data. However, average nuclear density of Be << C.

E03-103 results

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

- **Large difference in the magnitude of the EMC effect in ^{3}He and ^{4}He doesn't support previous mass dependent fits.**
- **Both A- and ρ-dependent fits fail to describe these light nuclei.**
- **Data show smooth behavior as density increases except for ^{9}Be.**
- **One possible explanation is that the effect depends on nucleon's local environment.**



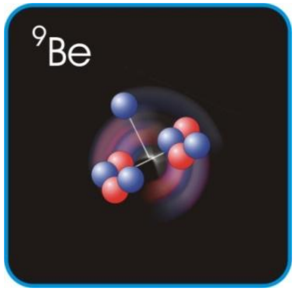
❖ **Size of the effect given by a fit to the cross section ratios between x= 0.35 and x= 0.7**

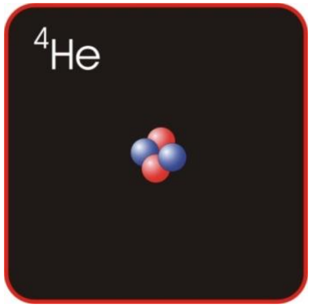
❖ **Density calculated using ab-initio GFMC calculation**

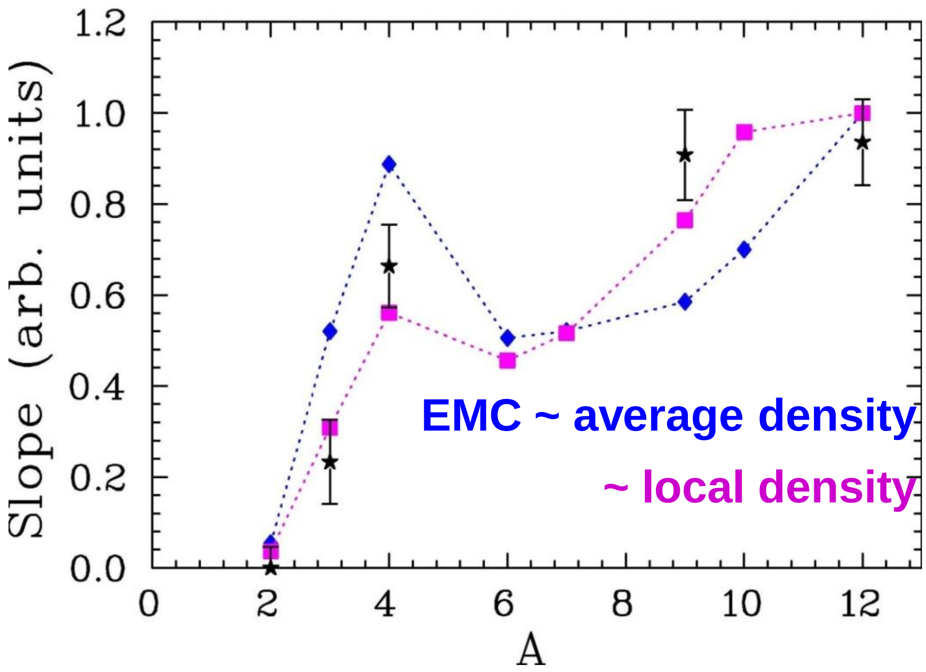
(S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001))

E03-103 results

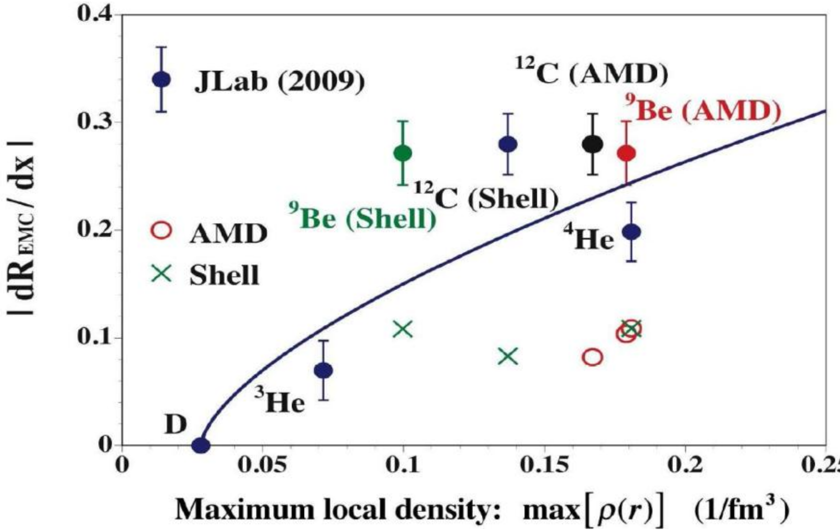
- **Ab initio GFMC calc. of 2-body correlation function to calculate average nucleon ‘overlap’ and the local density is calculated.**







- **Recent AMD calculations also suggests that nuclear modifications are mainly driven by the high-density clusters in nuclei.**
- **Higher density regions contribute to larger nuclear modifications than expected from simple shell model calculations**
- **High dense regions could alter the nucleon (and quark) momentum distributions or even internal structure of nucleon itself**



M. Hirai, S. Kumano, K. Saito, T. Watanabe, arxiv:1008.1313

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Heavy Nuclei: Coulomb corrections

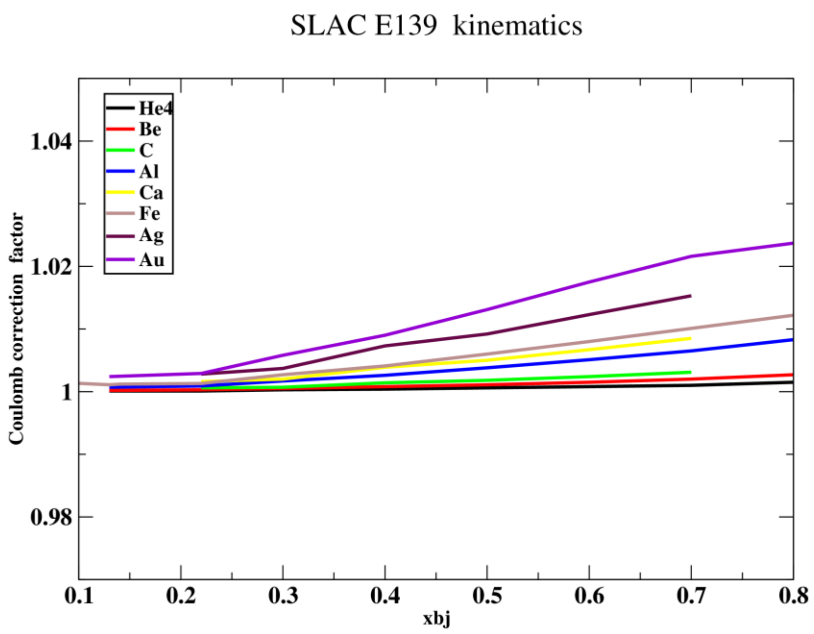
At Jlab energies: To go to large Q^2 (to be in the scaling region), the electron scattering angle should be larger. This causes significant Coulomb distortion effects.

- **Plane wave Born approximation not valid for heavy nuclei (high Z) .**
- **In addition to the hard photon exchange, additional (soft) photon exchange with the nucleon in target nucleus.**
- **Coulomb distortion changes the vertex values (focusing, acceleration, deceleration), and the measured asymptotic values should be corrected.**
- **Not accounted for in the usual radiative correction procedure.**
- **Our analysis done using an improved version of Effective Momentum Approximation.**

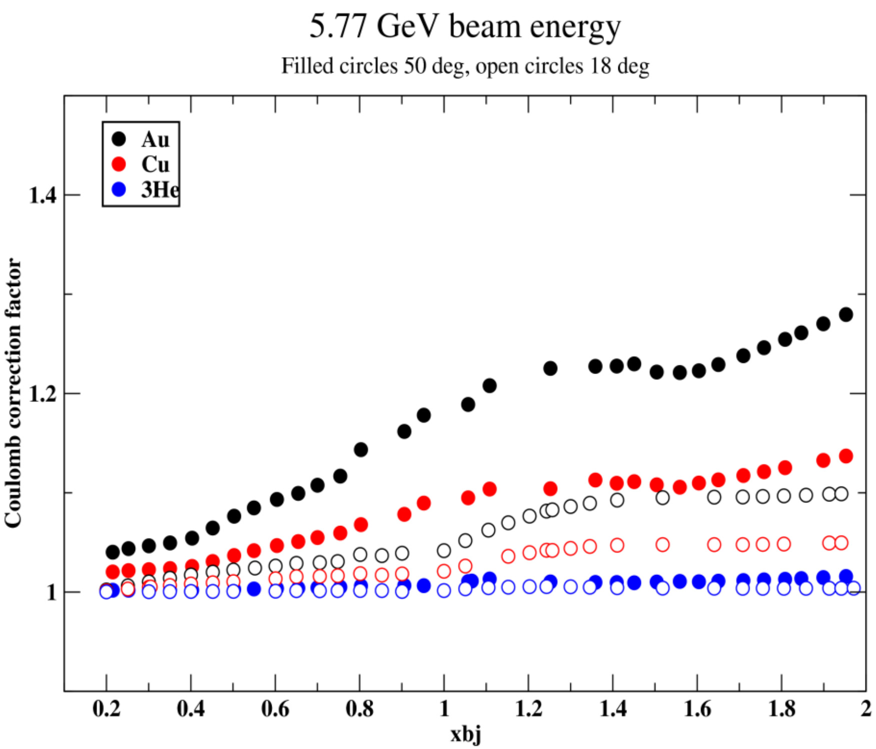
(Aste and Trautmann, Eur. Phys. J. A26, 167 (2005))

$$F_{ccor} = \frac{\sigma_{(E,E')}}{\sigma_{(E+\Delta E,\, E'+\Delta E)}} \left[\frac{E}{E+\Delta E}\right]^2$$

Magnitude of Coulomb distortion



(Coulomb correction factor for SLAC E139)

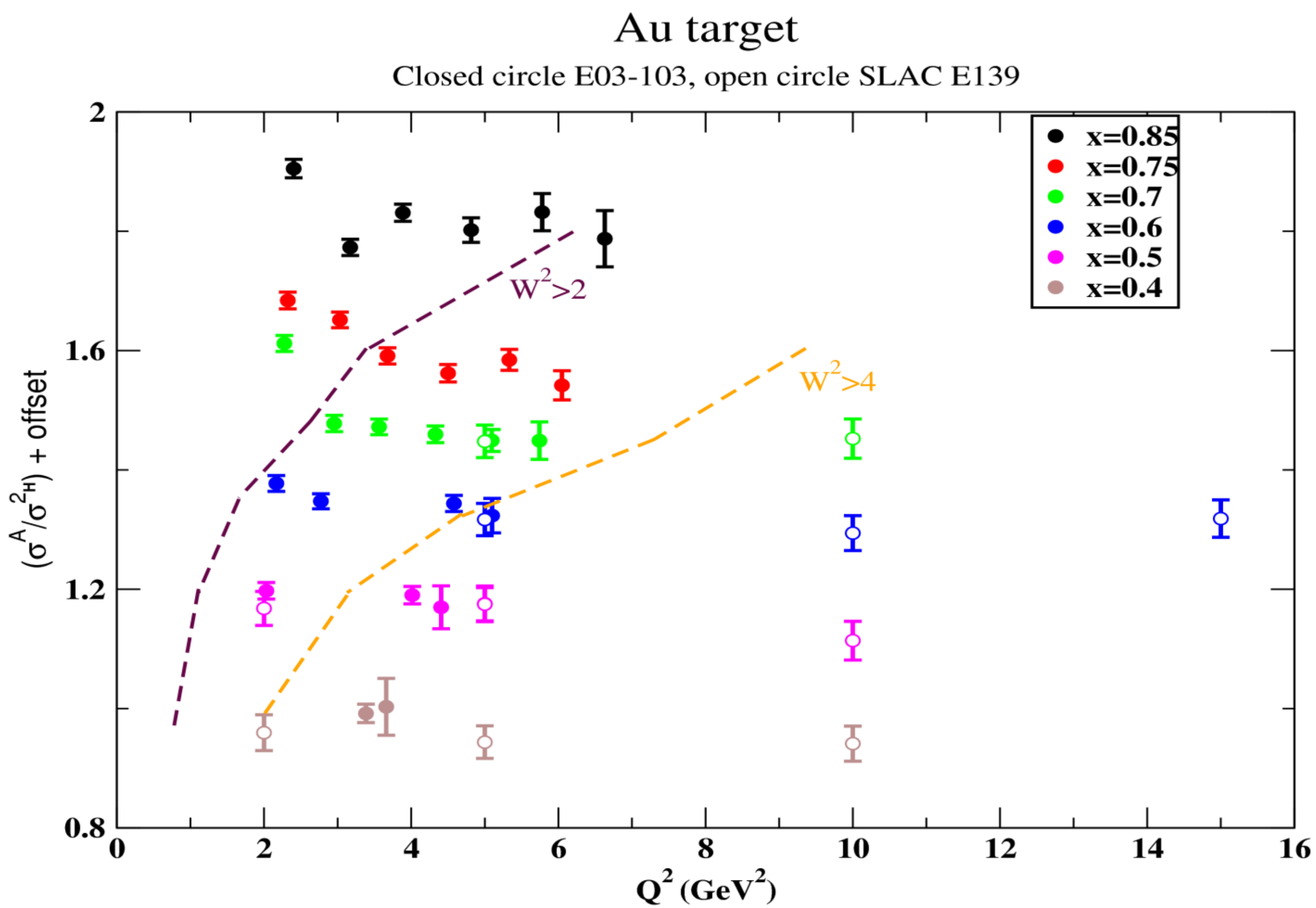


- **Multiplicative correction factors for cross section (and cross section ratios)**
- **Significant for heavy nuclei and at large x**
- **x dependence**
- **At a given x; angular dependence implies Q^2 dependence**

Also, our global analysis shows Coulomb corrections are ϵ dependent

P. Solvignon, D. Gaskell, J. Arrington, AIP Conf.Proc.1160:155 ,2009

E03-103 results: scaling of cross section ratios

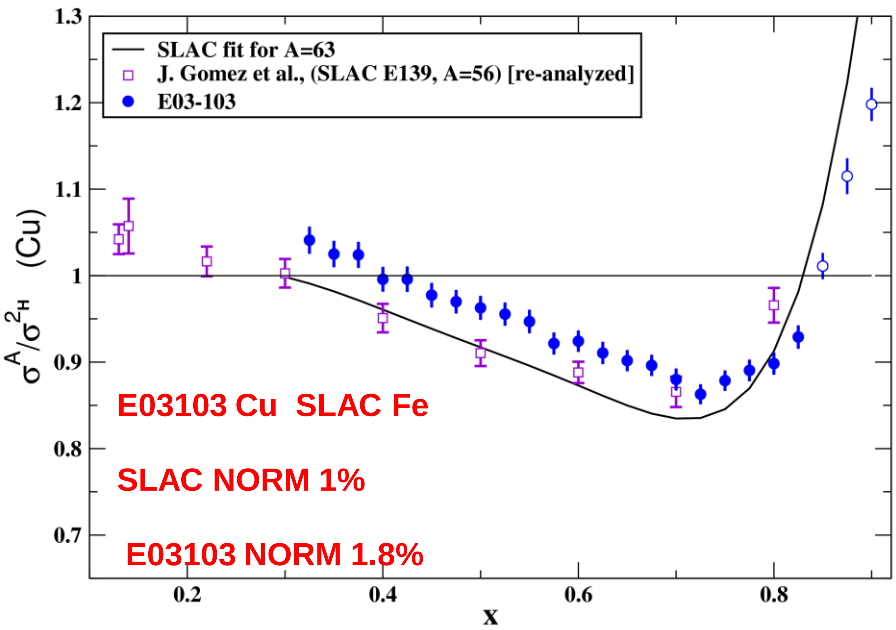


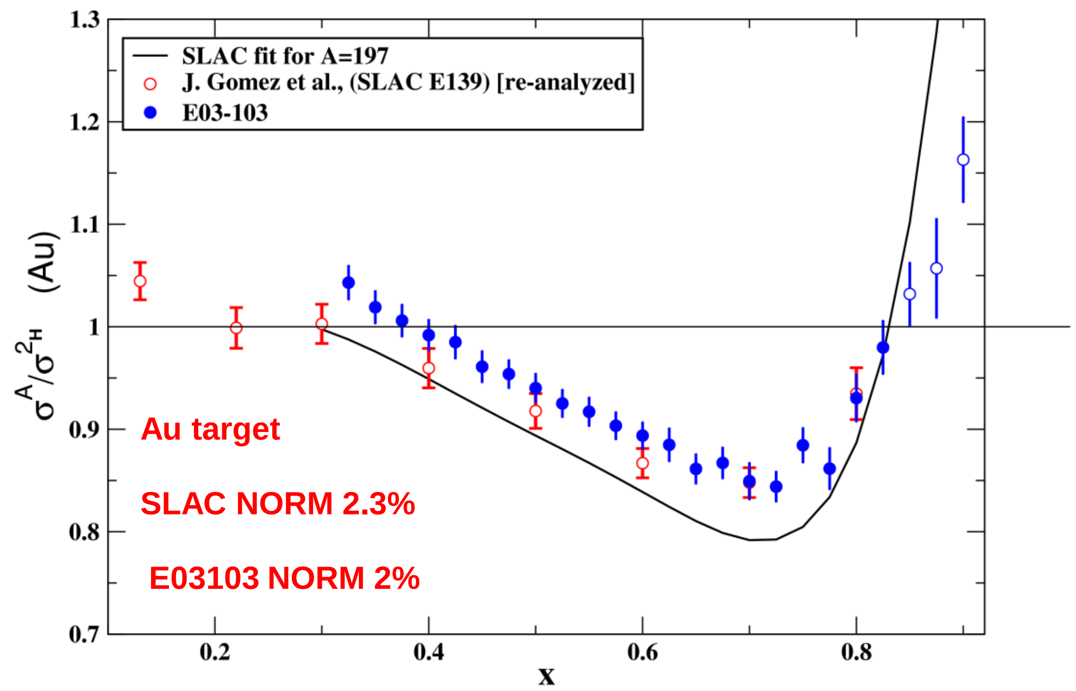
Hollow symbols SLAC and solid symbols E03-103

- Q^2 dependence of cross section ratios at fixed x for Au target
- Coulomb corrected data
- A/D at fixed x are Q^2 independent for $W^2 > 2$ GeV^2 and $Q^2 > 3$ GeV^2 and consistent with SLAC data even at high x values

E03-103 results: preliminary cross section ratios for Cu and Au

Hollow blue circles $W^2>2$

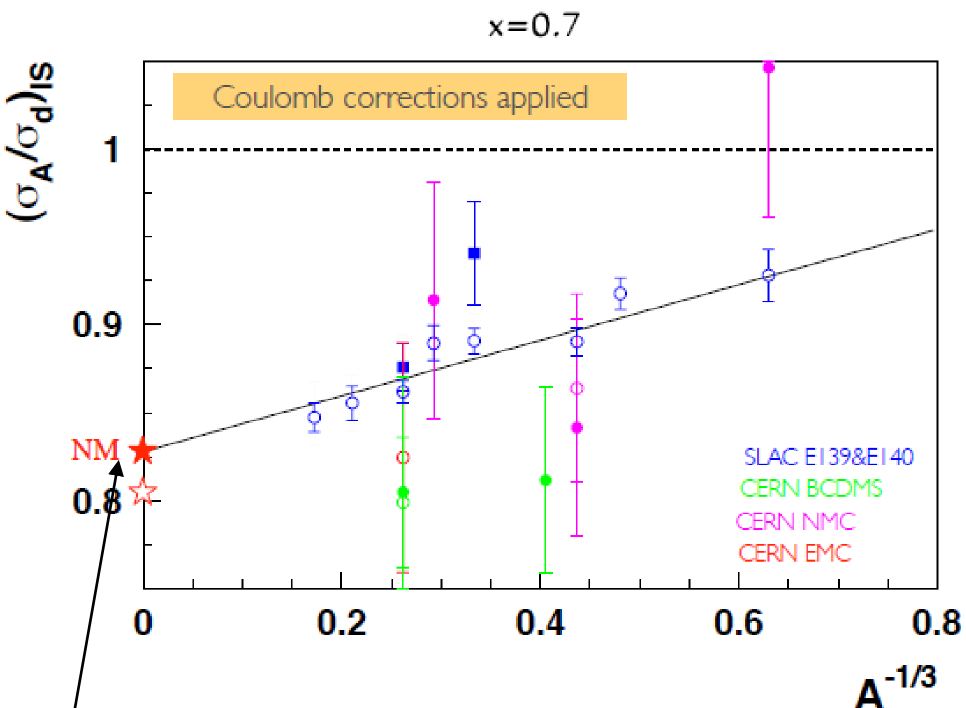


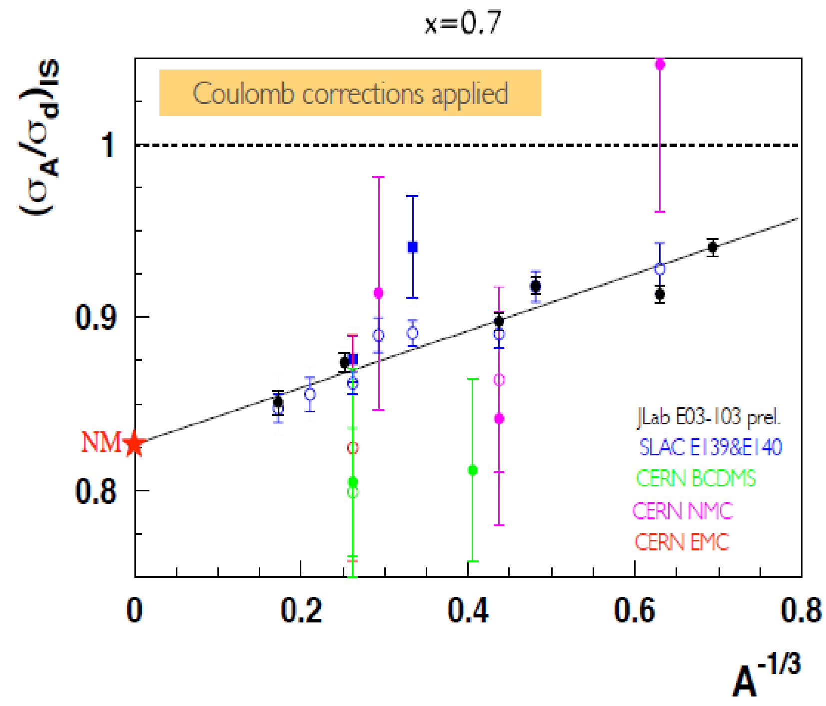


- **Data are corrected for Coulomb distortion effects**
- **At the moment, isoscalar corrections are done with SLAC parameterization.**

EMC effect in nuclear matter

- **Realistic nucleon potentials can be easily solved for light nuclei and nuclear matter**





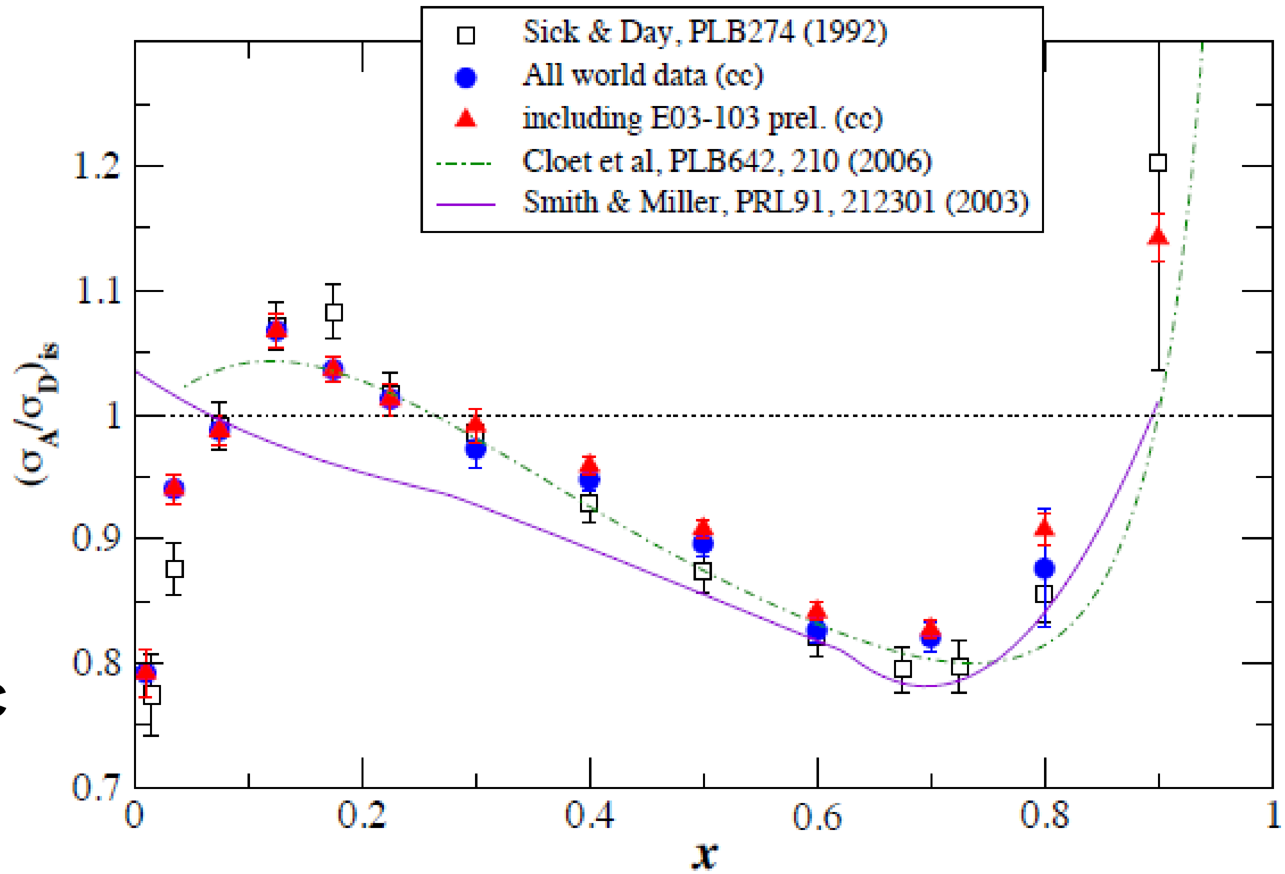
Nuclear matter value at x=0.7 with Coulomb correction to world data (open star with out ccor)

Nuclear matter value including E03-103 data

From P. Solvignon

EMC effect in nuclear matter

- **Realistic nucleon potentials can be easily solved for light nuclei and nuclear matter**



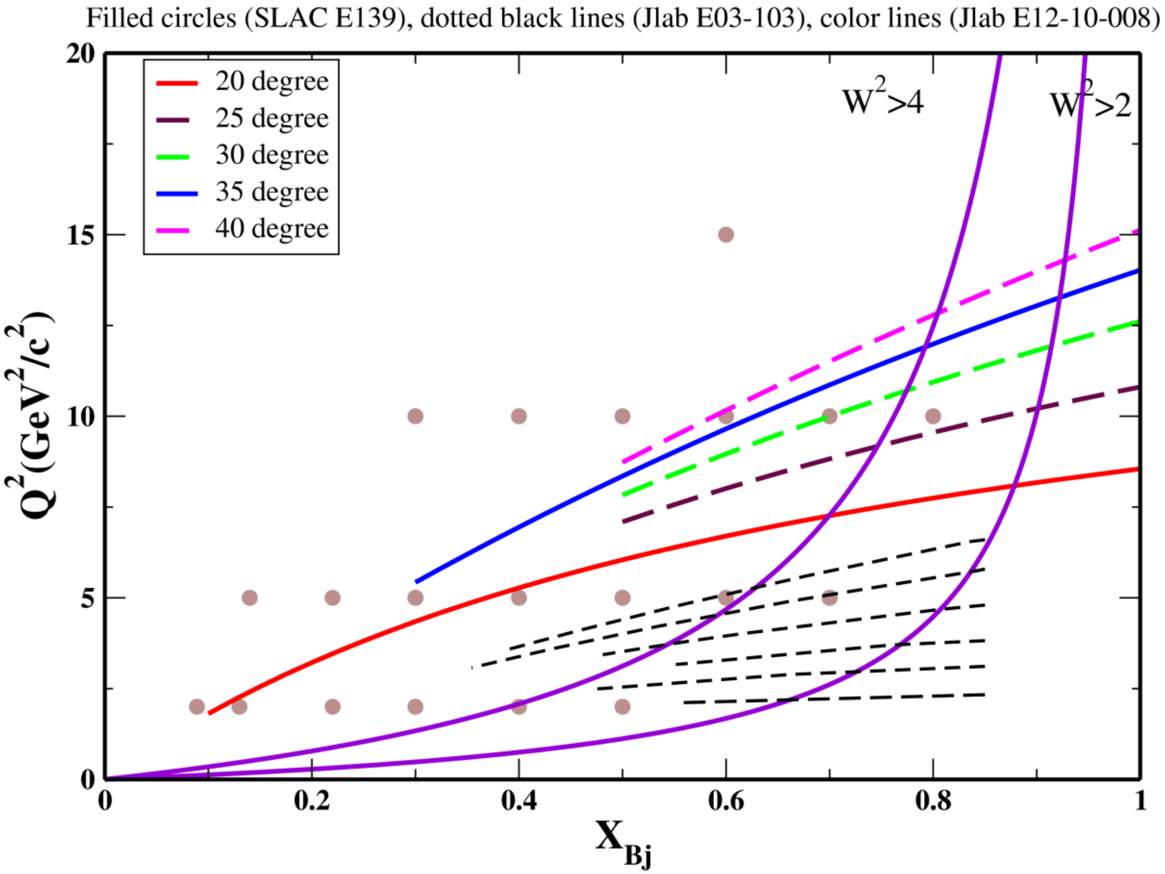
- **Xbj dependence of the EMC effect in nuclear matter including E03-103 data**
- ***Improved precision at high x***

From P. Solvignon

EMC effect: Future opportunities with 11 GeV upgrade

- Nuclei examined with E03-103 were sufficient to examine the simple A-dependence or density dependence.

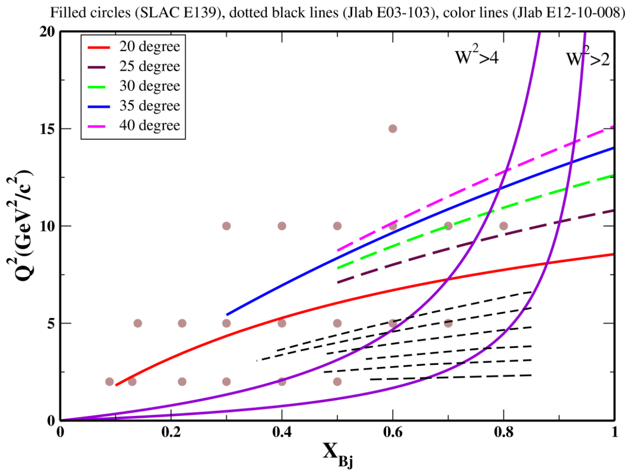
- However, a detailed systematic investigation of the effect in well understood light nuclei is needed; (e.g., nuclei with significant clustering contributions)



EMC effect: Future opportunities with 11 GeV upgrade

11 GeV experiment E10-008 (approved by PAC36)

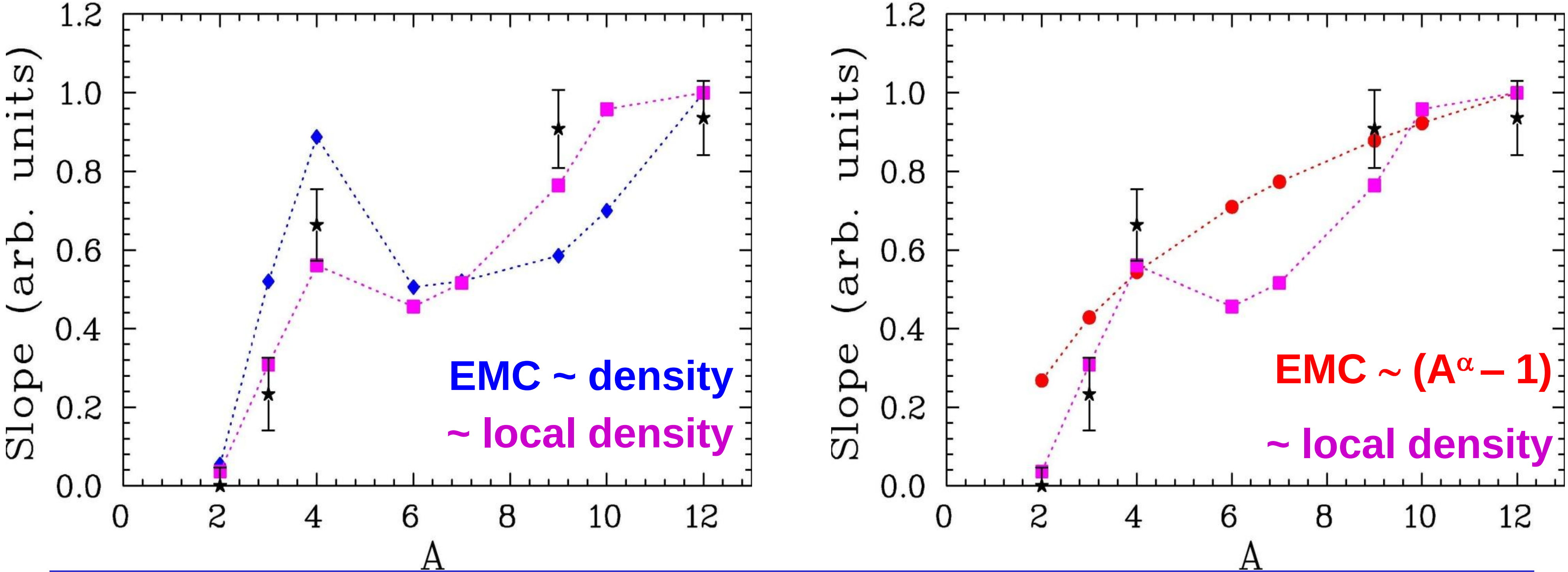
Spokespersons: J. Arrington, A. Daniel, D. Gaskell



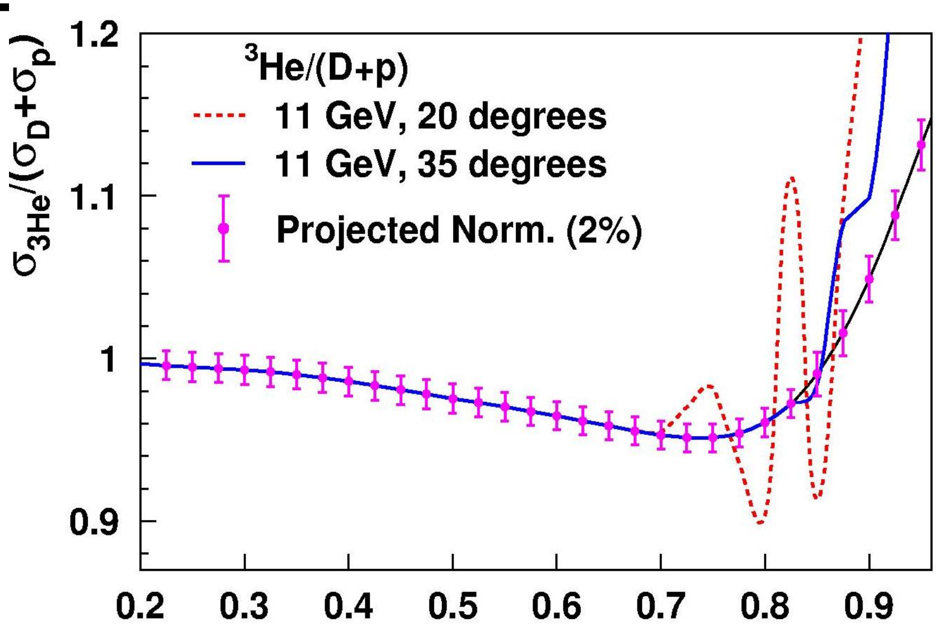
- **Higher Q^2, expanded range in x (both low and high x) ; *DIS extends to x=0.8, W^2>2 extends to x=0.92***
- **Light nuclei includes ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{12}C**
- **Heavy nuclei includes ^{40}Ca, ^{48}Ca and Cu.**
- **Approved E12-06-105 (x>1; spokespersons D. Day and J. Arrington) experiment will take data on more or less same targets, *thus providing direct cross section ratios at x>1 and x<1 regions*.**
- **Data on this collection of nuclei and broad kinematic range will shed additional light on scaling and microscopic origin of the EMC effect.**

Future measurements (E10-008)

- Map out A-dependence in more detail using additional light nuclei
  - Very hard to explain large ^3He – ^9Be difference in ρ-dependent fit
  - Hard to explain large ^3He – ^4He difference in mass-dependent fit
  - “Local density” works well, provides different predictions
    - **Use ab initio GFMC calc. of 2-body correlation function to calculate average nucleon ‘overlap’**

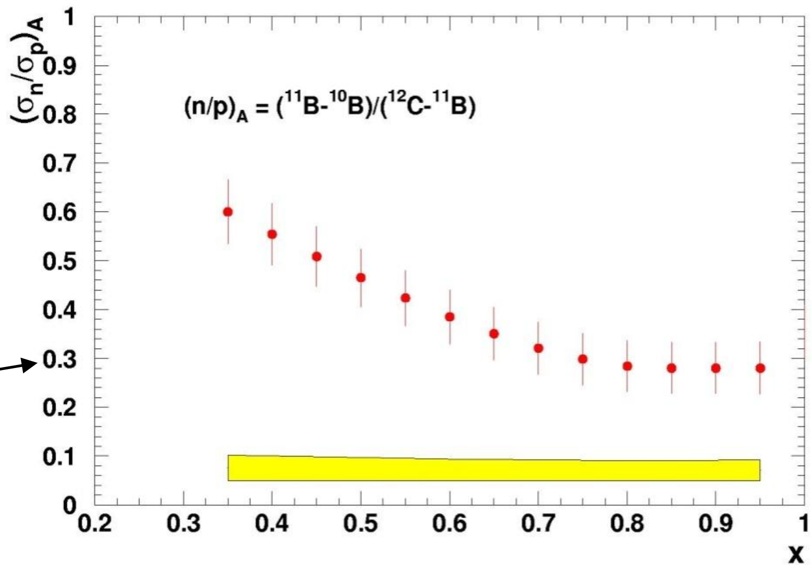


Future measurements (E10-008)



- **Avoid ^{3}He isoscalar corrections**
  - **Compare to calculations of 3He/(D+p)**
  - ***Push to largest x possible without large resonance contributions.***

- **Comparisons of non-isoscalar nuclei**
  - **Information about neutron or proton in-medium from combinations of nuclei such as ^{11}B-^{10}B, ^{7}Li-^{6}Li, ^{12}C-^{11}B**
  - **Ratio of n/p in-medium is direct check of applied isoscalar corrections**



Future measurements (E10-008)

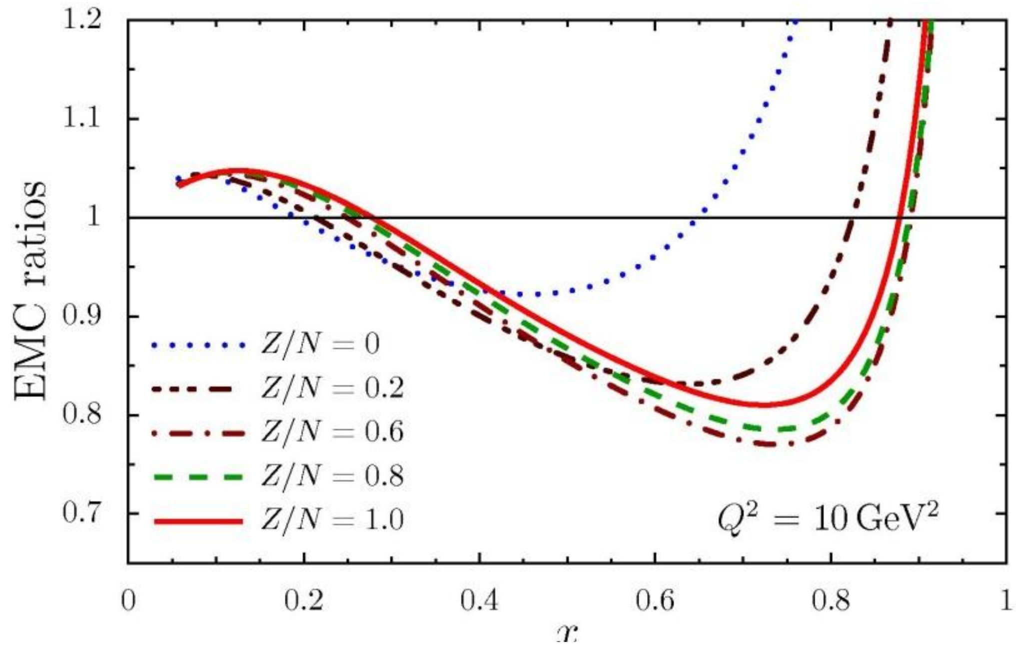
❖Isospin dependence of EMC effect

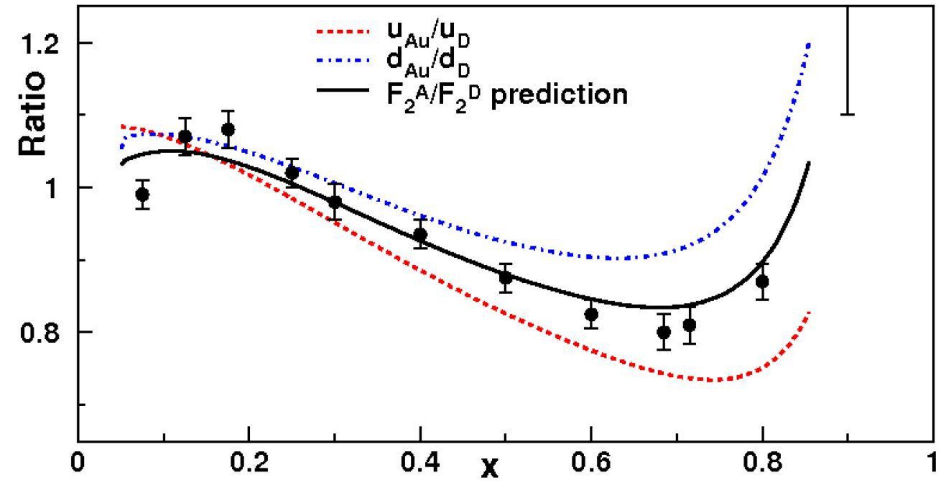
I.Cloet, W.Benz, A.Thomas, PRL102, 252301(2009)

- **Isospin dependence of the interaction generates different degree of modification for the *up* and *down* quark distributions.**

- **Neutron excess implies magnitude of the effect larger for *up*, and smaller for *down* quarks.**

Solid circles and solid curve NM, dashed lines modification of quark distributions in Gold nuclei.





D. Dutta, J.C. Peng, I.Cloet, D. Gaskell
arxiv:1007.3916

Future measurements (E10-008)

❖ Isospin dependence of EMC effect

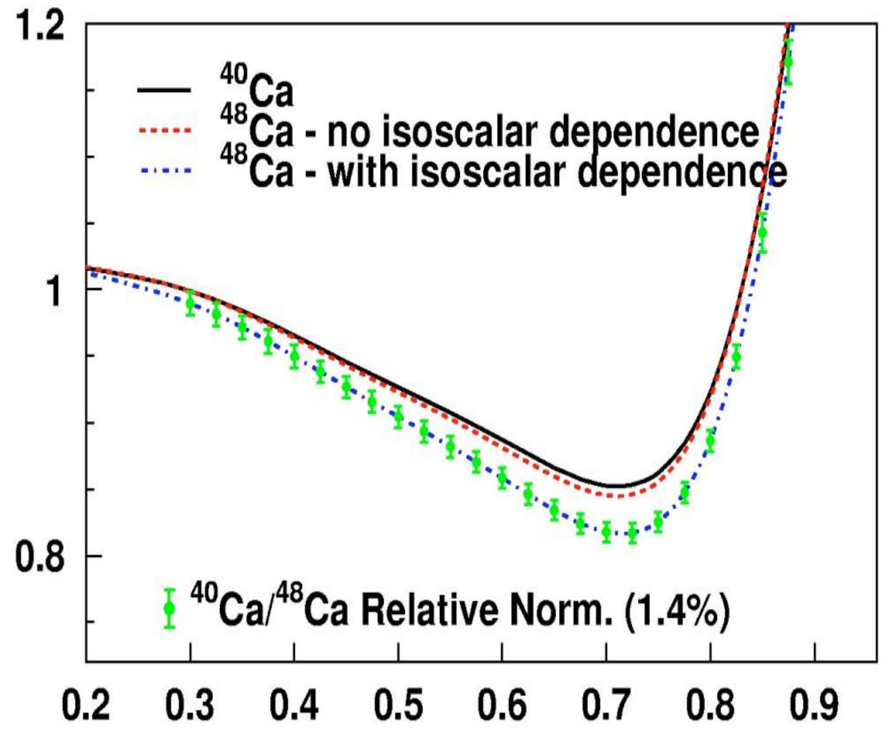
I.Cloet, W.Benz, A.Thomas, PRL102, 252301(2009)

- **Neutron excess implies magnitude of the effect larger for *up*, and smaller for *down* quarks.**

- ***For this particular model, ^{40}Ca and ^{48}Ca difference is same at small x, but the difference grows as x increases, better sensitivity at large x.***

- **More recent calculations based on non-nucleonic degrees of freedom (photon parton distributions) in nuclei predicts identical results for the measured ratios in these nuclei.**

L. Frankfurt, M. Strikman arxiv:1009.4920



Summary

- EMC effect shows that the quark distributions in nuclei are modified in a non –trivial way. Specific origin of the observed modification is not clearly identified yet.

- E03-103 provides differential cross sections and structure functions for ^{2}H, ^{3}He, ^{4}He, C, Be, Cu and Au over a broad range in x and Q^2.

- First measurement of the EMC effect in ^{3}He in the valence region and improved precision for heavy nuclei at high x.

- Cross section ratios shows excellent scaling behavior to low values of Q^2 even at the large x values.

- E03-103 results doesn't support previous A dependent and average density dependent fits, and hints that the nuclear modifications might be mainly driven by nucleon's local environment.

- Approved 12 GeV experiment will further investigate the influence of nucleon's local environment on the observed nuclear effects; DIS coverage will be extended to x=0.8