EMC effect in few-body nuclei

Aji Daniel

Ohio University

(For the E03-103 collaboration)

**Jlab Users Group Workshop and Annual Meeting,
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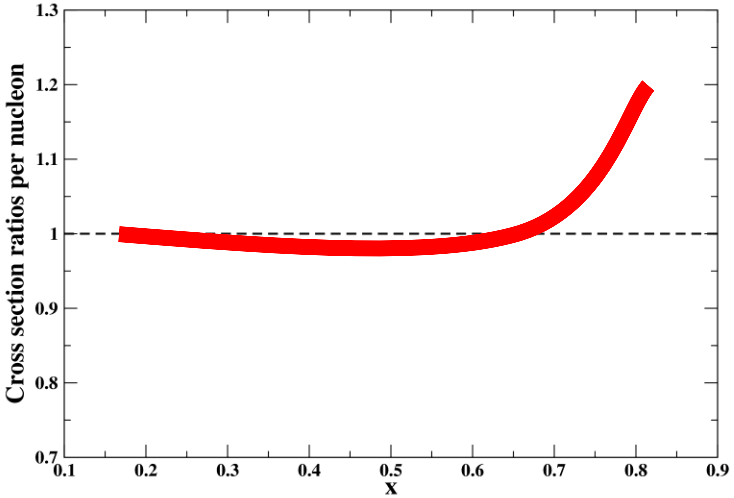
Outline

- **The EMC effect**
- **Experiment E03-103 at Jefferson Lab**
- **Results on nuclear EMC effect**
- **Approved 12 GeV experiment**
- **Summary**

The EMC effect

- **Typical energy scale of nuclear process ~ MeV**
- **Typical energy scale of DIS ~ GeV**
- **So naïve assumption (at least in the intermediate xbj region) ;**
  Nuclear quark distributions = sum of proton + neutron quark distributions

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



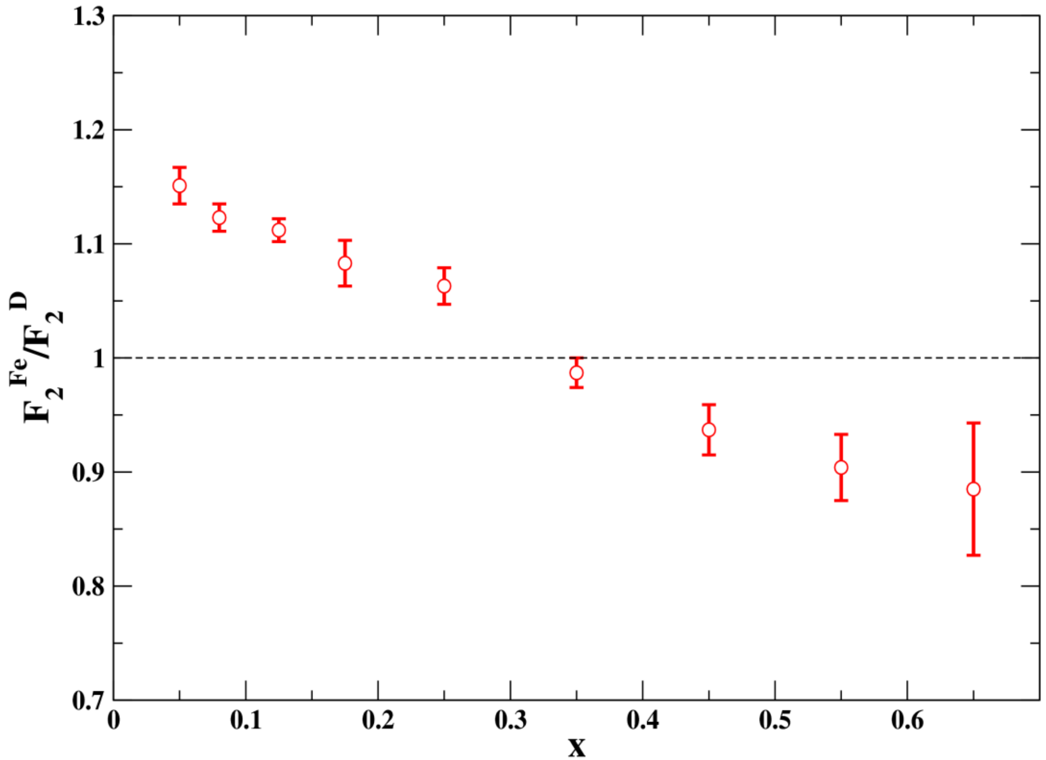
The EMC effect

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

- **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"**

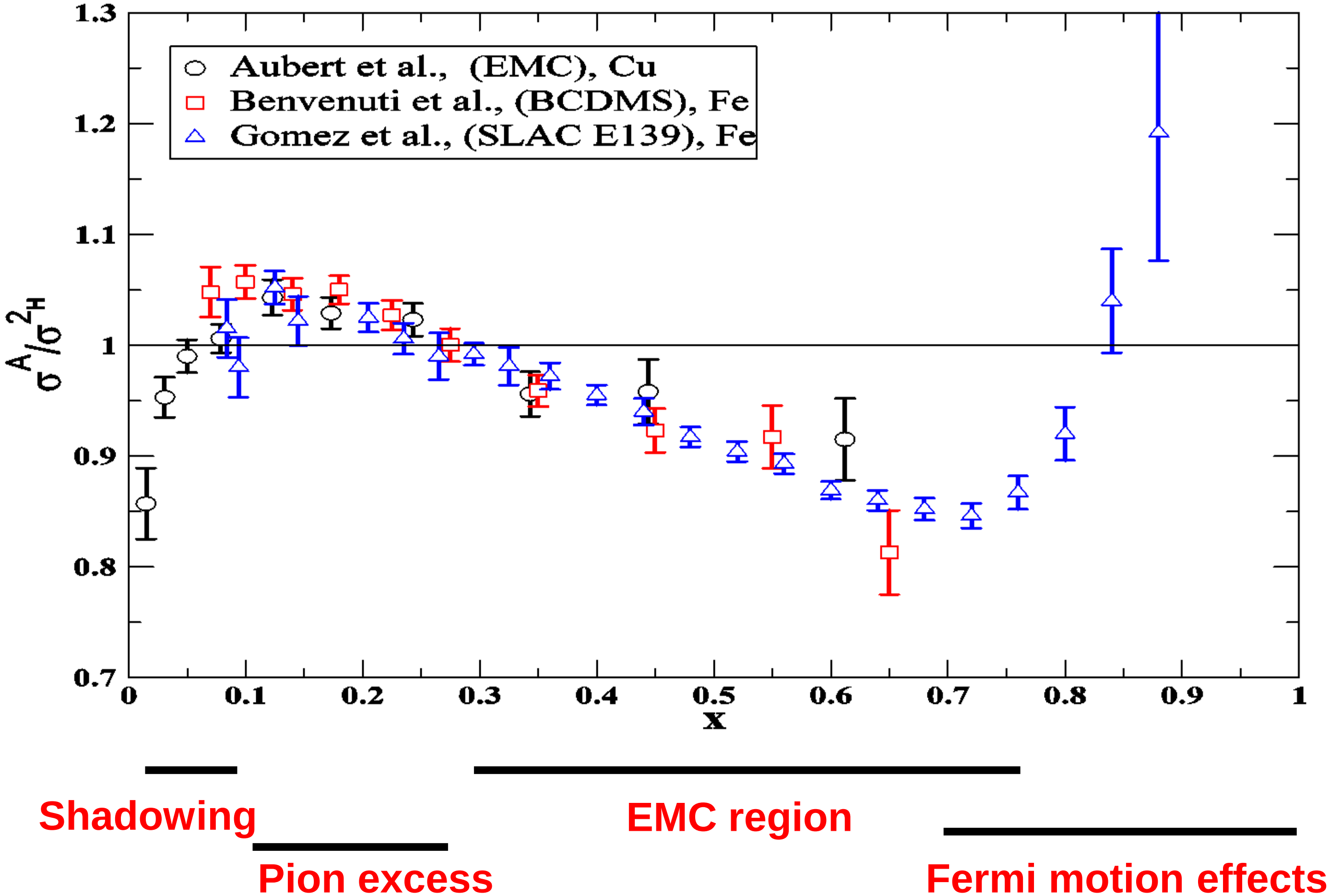
- **Quarks in nuclei behave differently than the quarks in free nucleon**



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

EMC effect: Representative data

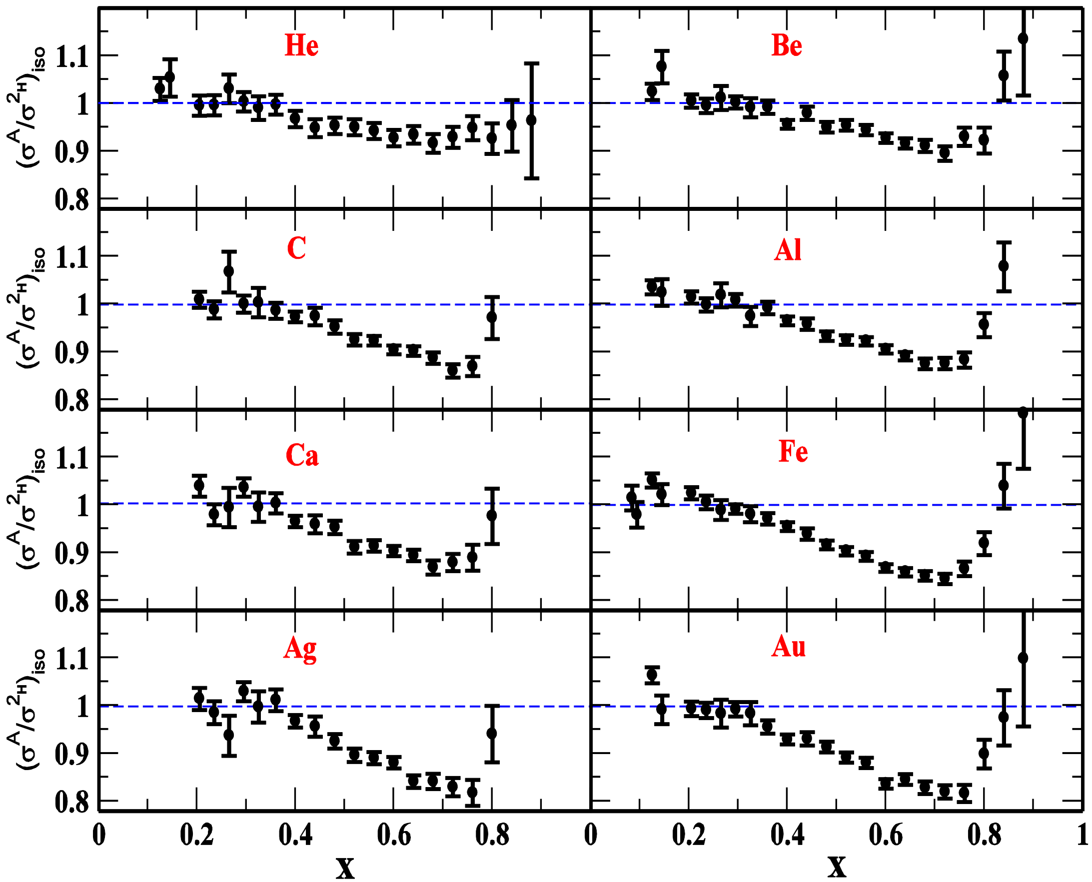
- ❑ EMC effect indicates that quark distributions are modified inside nuclei.
- ❑ Extensive measurements on heavy targets (SLAC, NMC, BCDMS, …)
- ❑ Different kinematical regions understood in terms of different processes



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* density

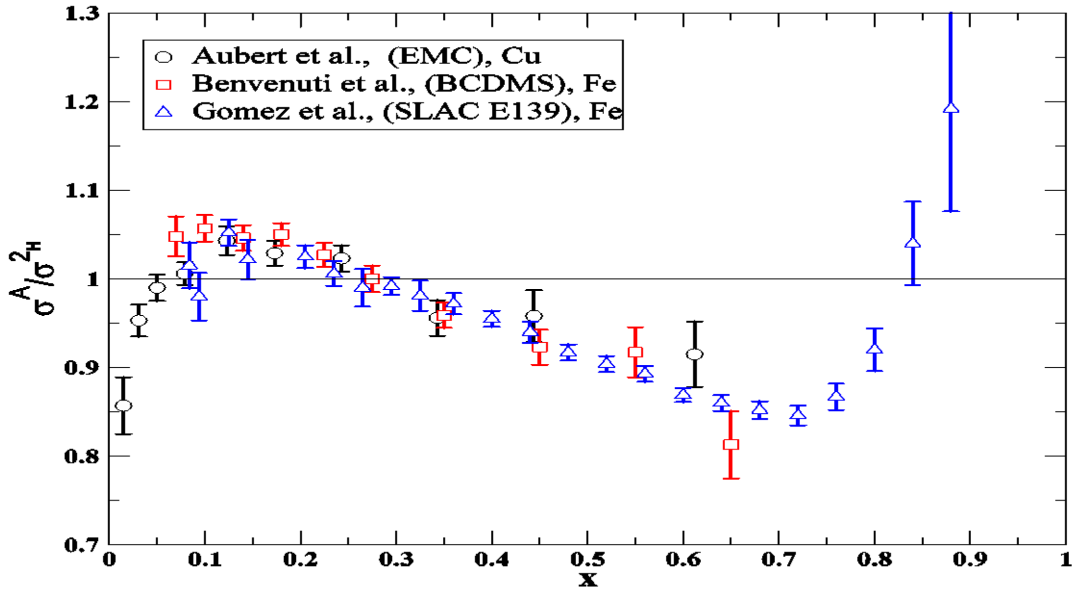


EMC effect: Models

Different kinematical regions understood in terms of different processes

Conventional nuclear physics models

- Fermi smearing
- Binding models
- Nuclear pions



Shadowing

Pion excess

EMC region

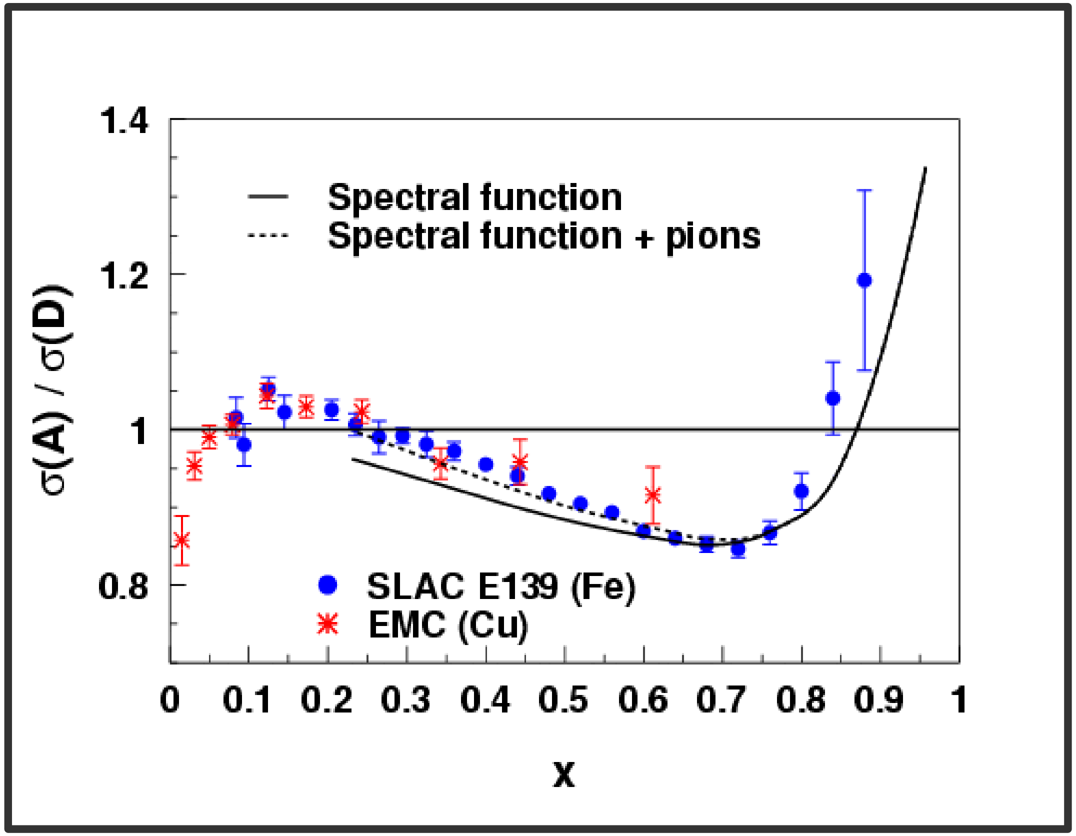
Fermi motion effects

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 : heavy nuclei



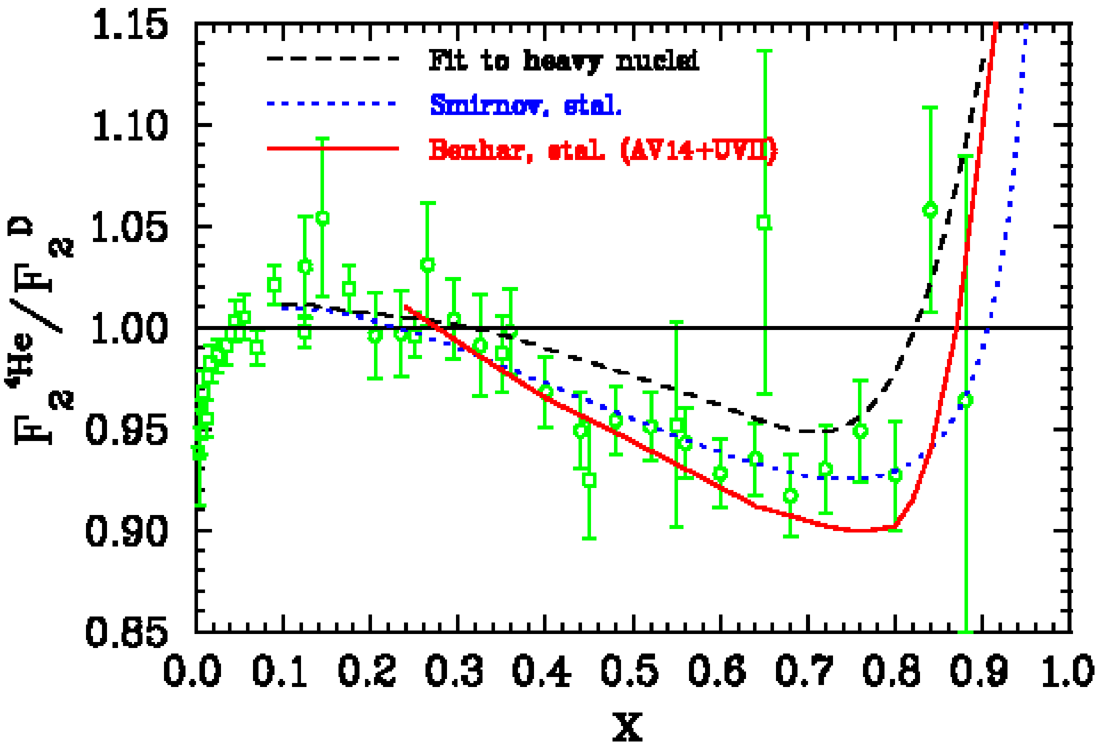
- Binding and Fermi motion important at high x.
- Binding also affects quark distribution at all x.
- Binding calculations must be evaluated against high precision high x data.
- Once we have a baseline, we can add additional exotic effects (if necessary).

Benhar, Pandharipande, and Sick PLB 410, 79 (1997)

$$F_2^A(x) = \int_x^A dz\, f_N^A(z) F_2^N\left(\frac{x}{z}\right) + \int_x^A dy\, f_\pi^A(y) F_2^\pi\left(\frac{x}{y}\right)$$

nucleons pions

The EMC effect: light nuclei



- ^{3}He and ^{4}He are crucial to understanding of the A-dependence.
- Data on light nuclei can be compared to detailed structure calculations.

The EMC effect: model summary

- Interpretation of the EMC effect requires better understanding of traditional nuclear effects.
- 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.

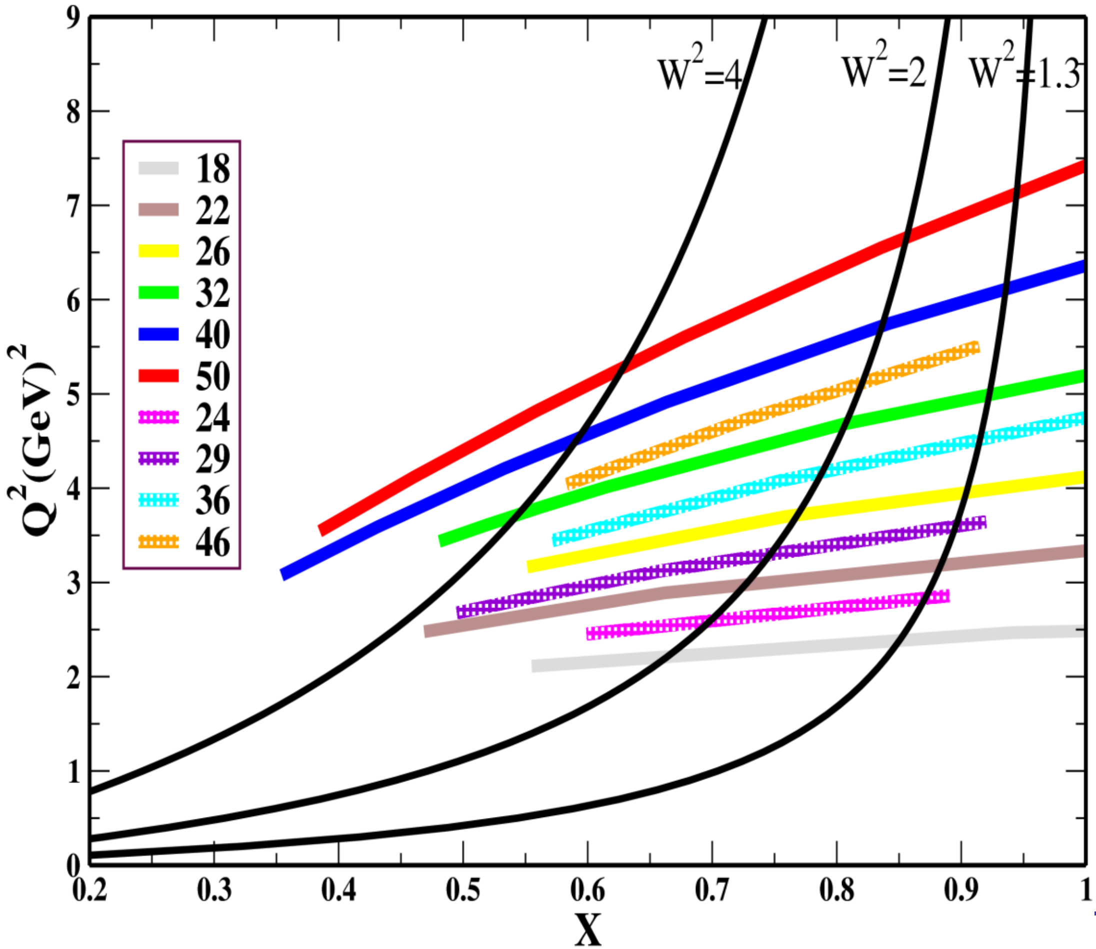
Kinematics

- 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



x>1

see Fomin's talk

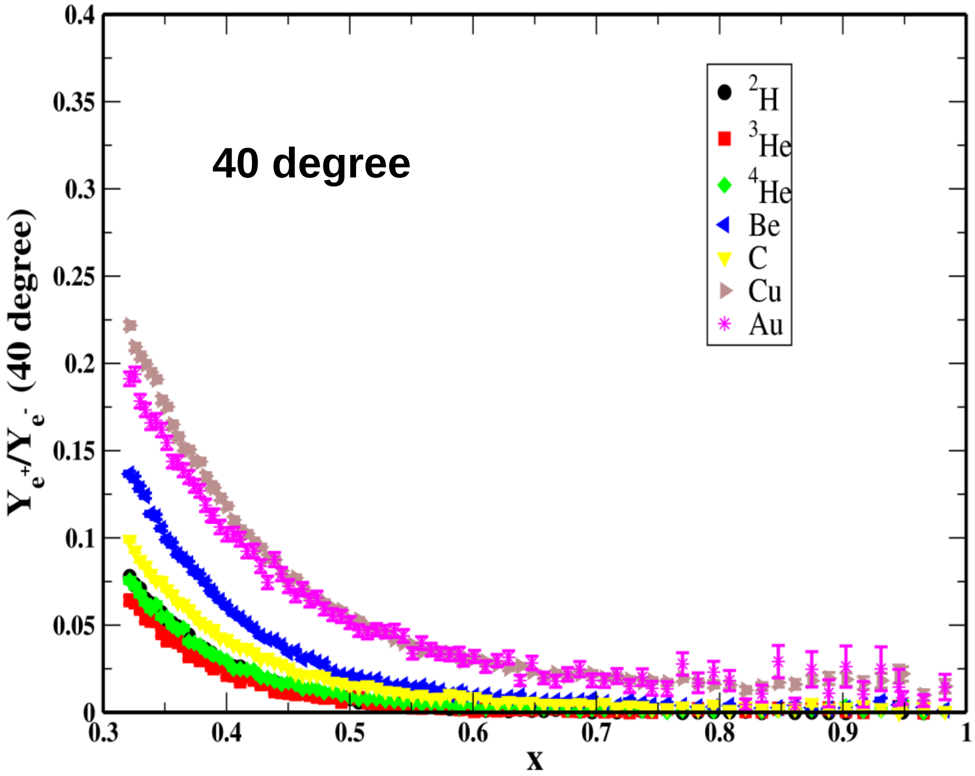
Background : charge symmetric processes (CSB)

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

One problem -> significant CSB

Electro production of neutral pions in target

$$\pi^0 \rightarrow \gamma + \gamma$$
$$\gamma + Nucleus \rightarrow e^+ + e^-$$
$$\pi^0 \rightarrow \gamma + e^+ + e^-$$



e^+ and e^- data acquisition on HMS, hence yields are directly subtracted.

Targets with large radiation length have a significant background.

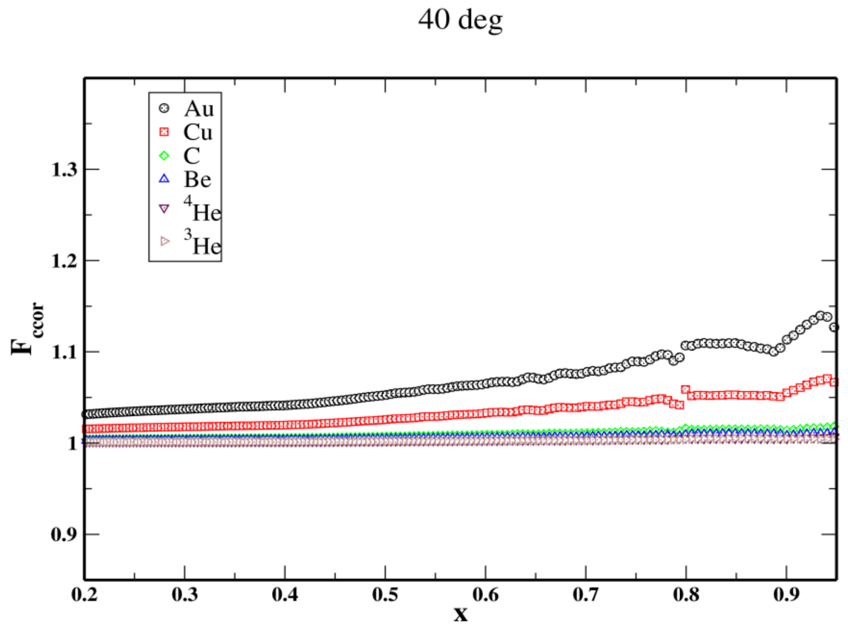
Coulomb corrections

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

Another problem -> significant Coulomb distortion effects

- **Plane wave Born approximation not valid for heavy nuclei (high Z) .**
- **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.**
- **Analysis done using an improved version of Effective Momentum Approximation.**

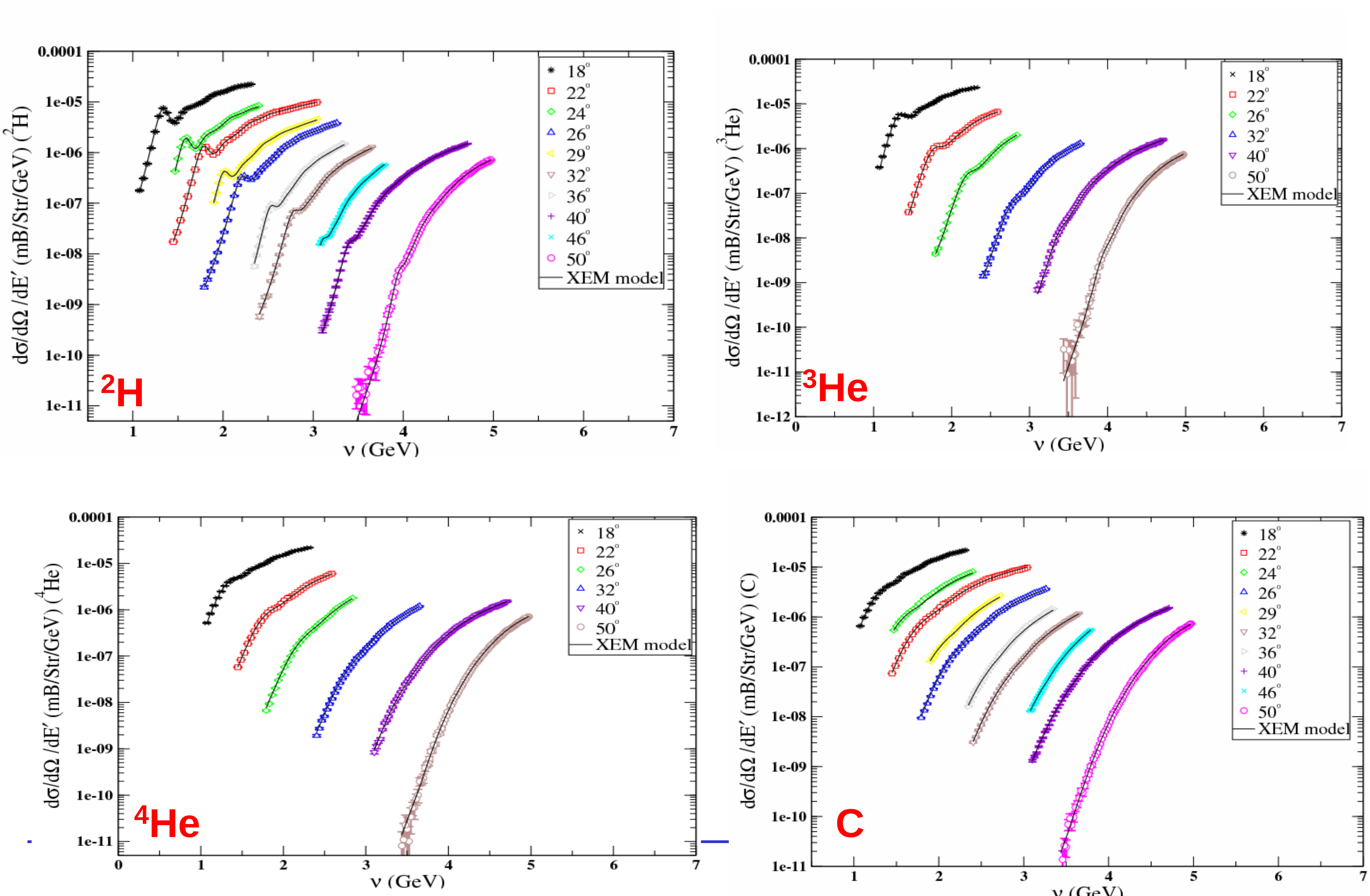
(Aste and Trautmann, Eur. Phys. J. A26, 167 (2005))



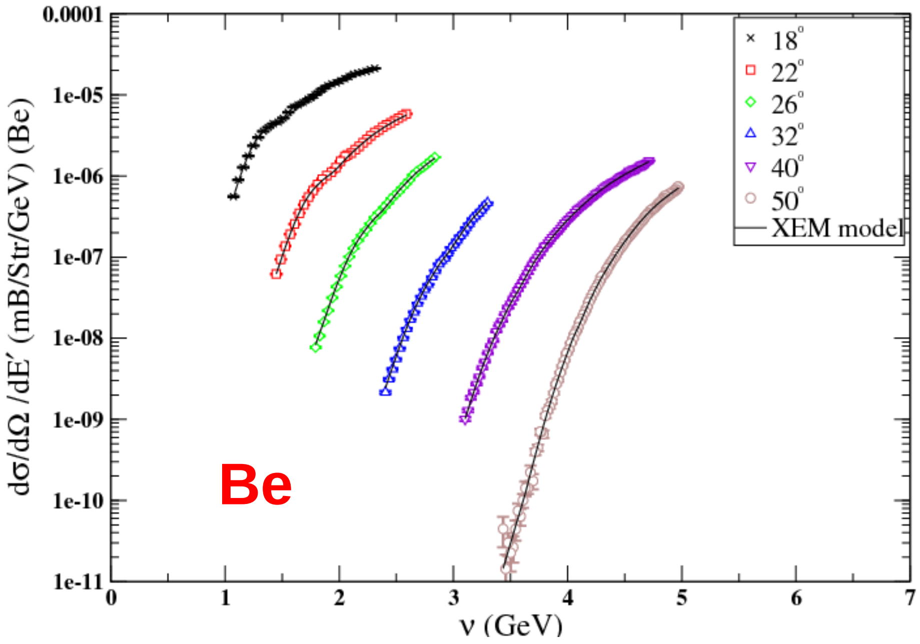
$$F_{ccor} = \frac{\sigma_{(E,E')}}{\sigma_{(E+\Delta E,\, E'+\Delta E)}} \left[\frac{E}{E+\Delta E} \right]^2$$

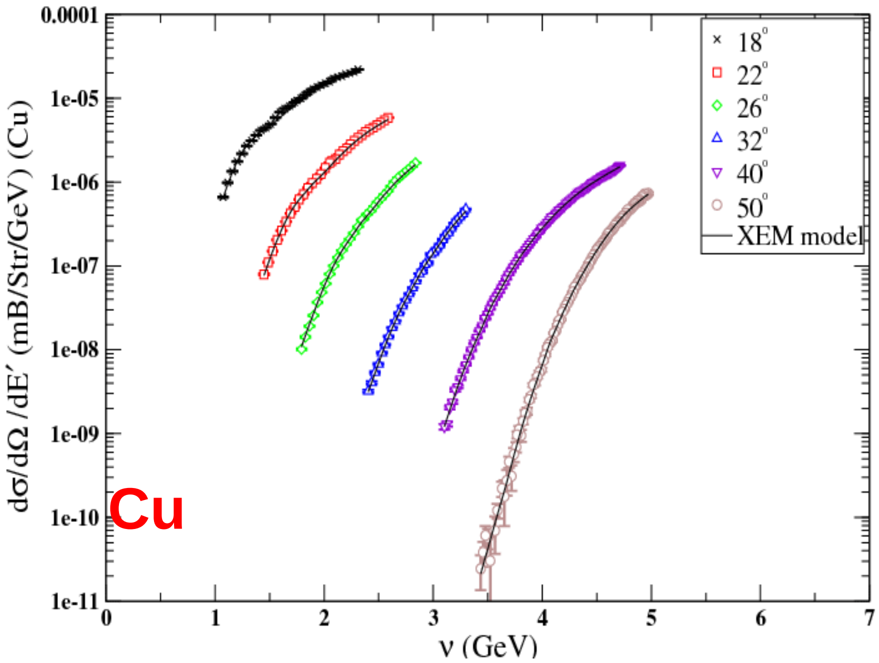
Although EMA is tested against DWBA calculations, it is not clear whether EMA can be applied to DIS.

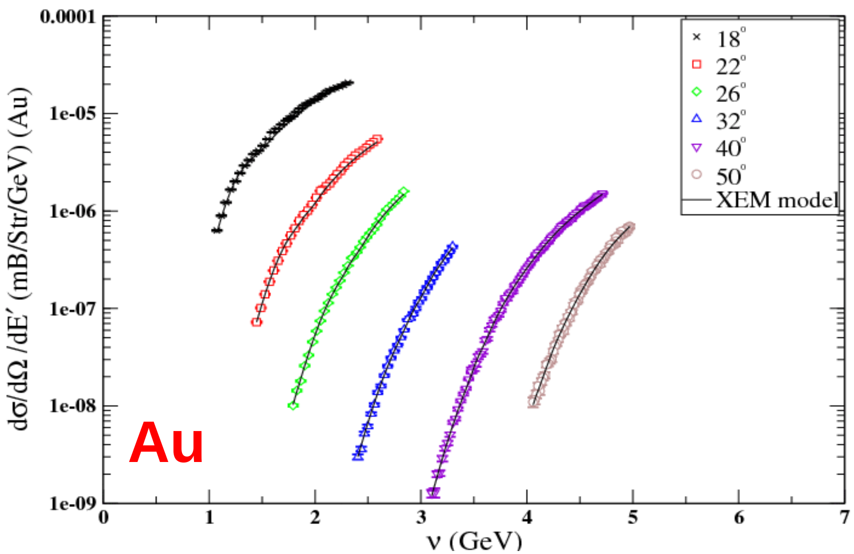
Differential cross sections



Differential cross sections

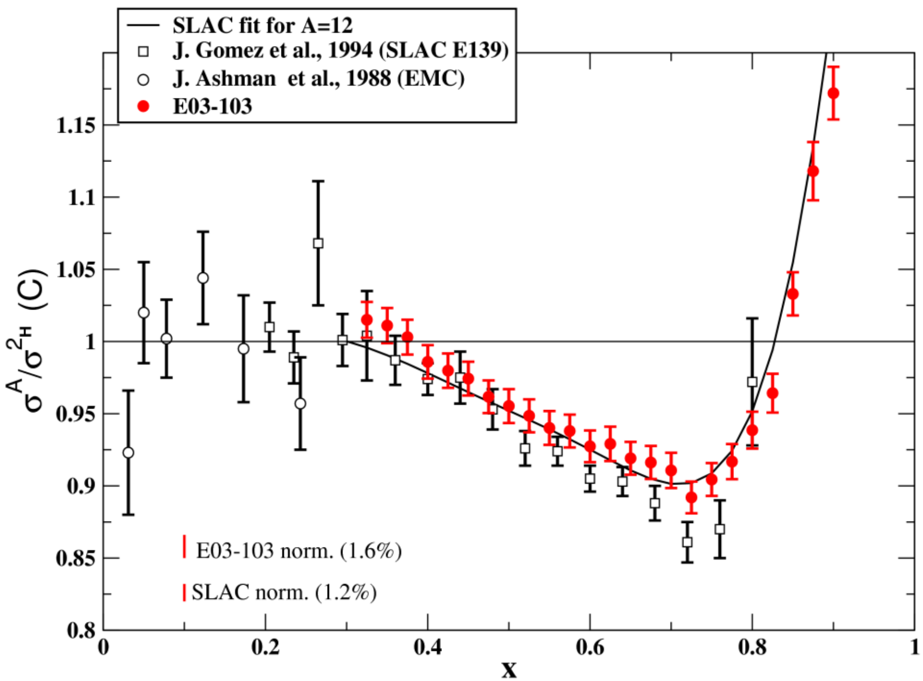


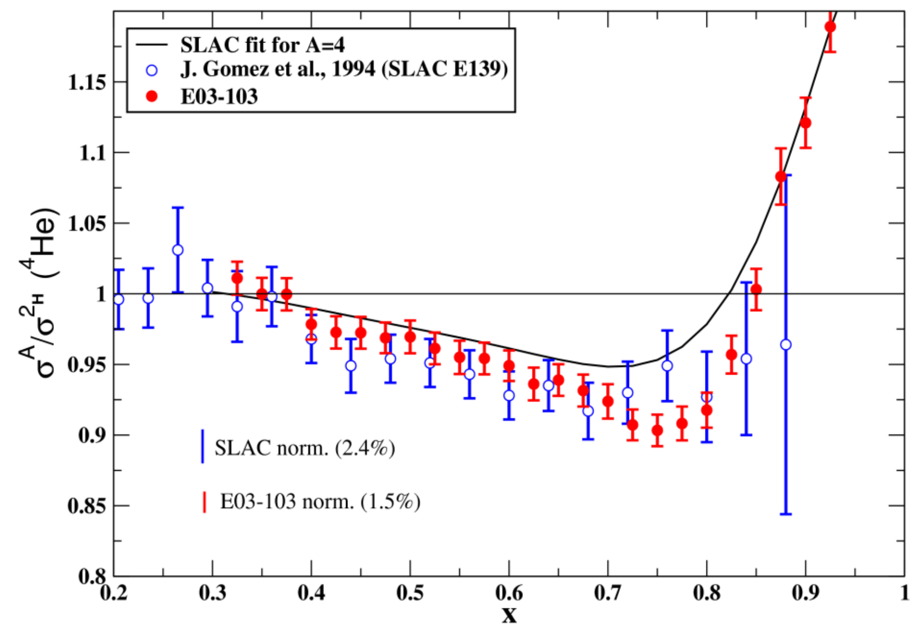




See Fomin’s talk

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

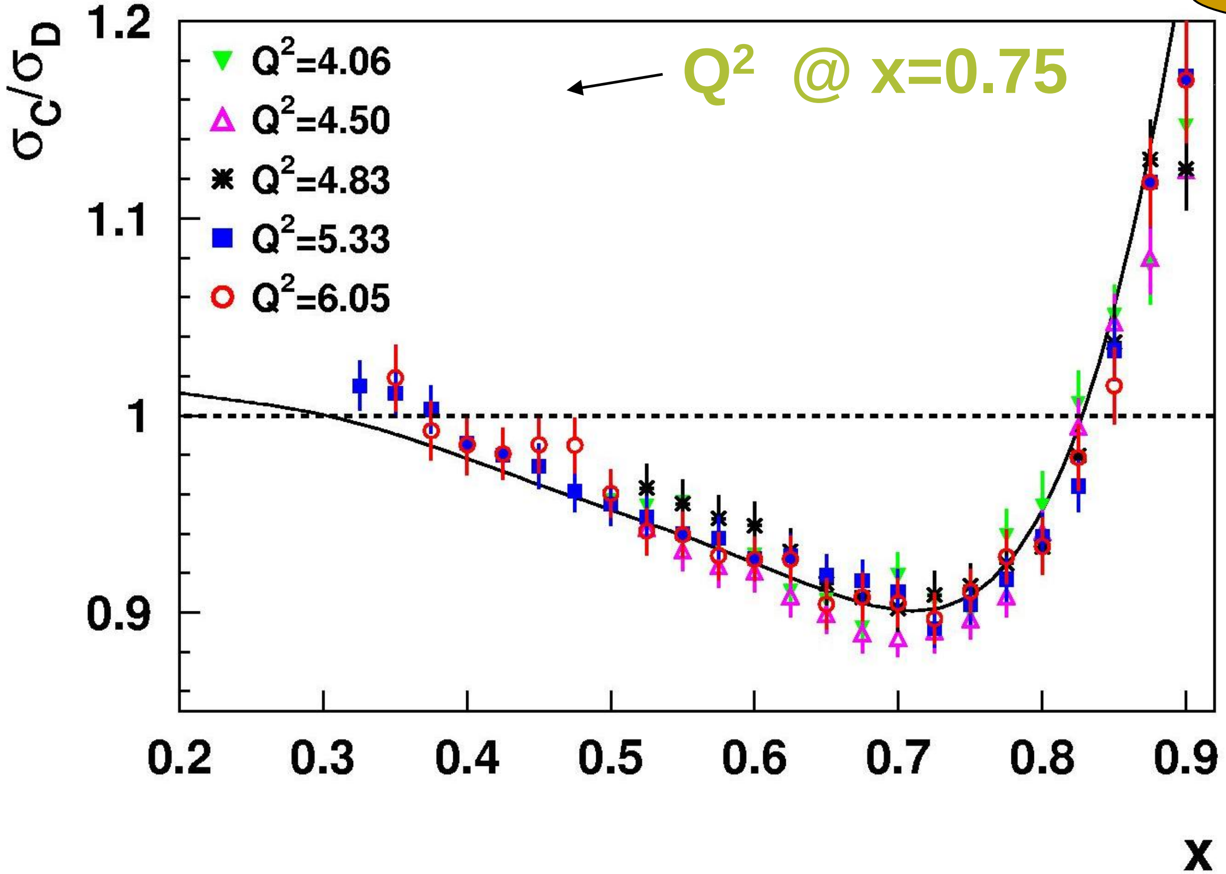




- ❑No complications from isoscalar corrections.
- ❑E03-103 results are consistent with SLAC data, but have much higher precision at large x (although at lower W^2 value than SLAC).

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.

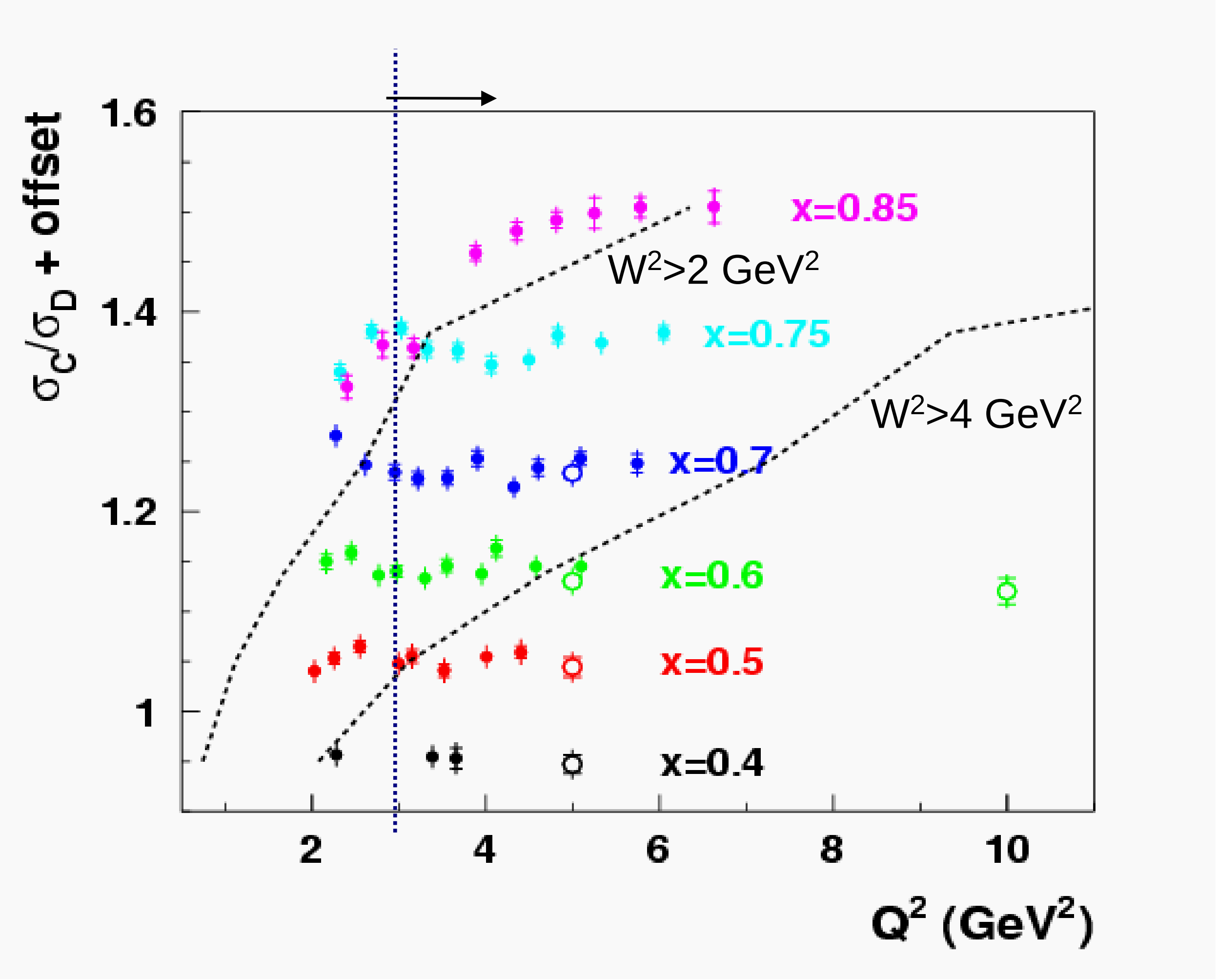
❖**Q^2=4.06 GeV and Q^2=4.83 results are for 5 GeV; remaining results are for for 5.77 GeV**

❖**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: scaling of cross section ratios

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

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

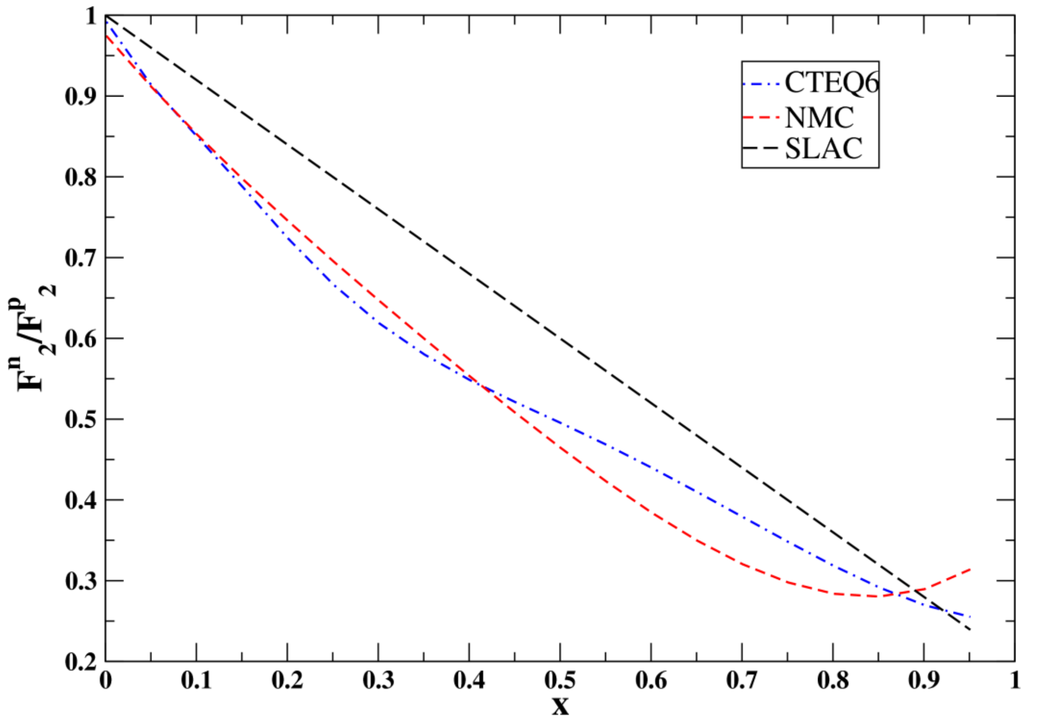


Hollow symbols SLAC and solid symbols E03-103

Isoscalar corrections

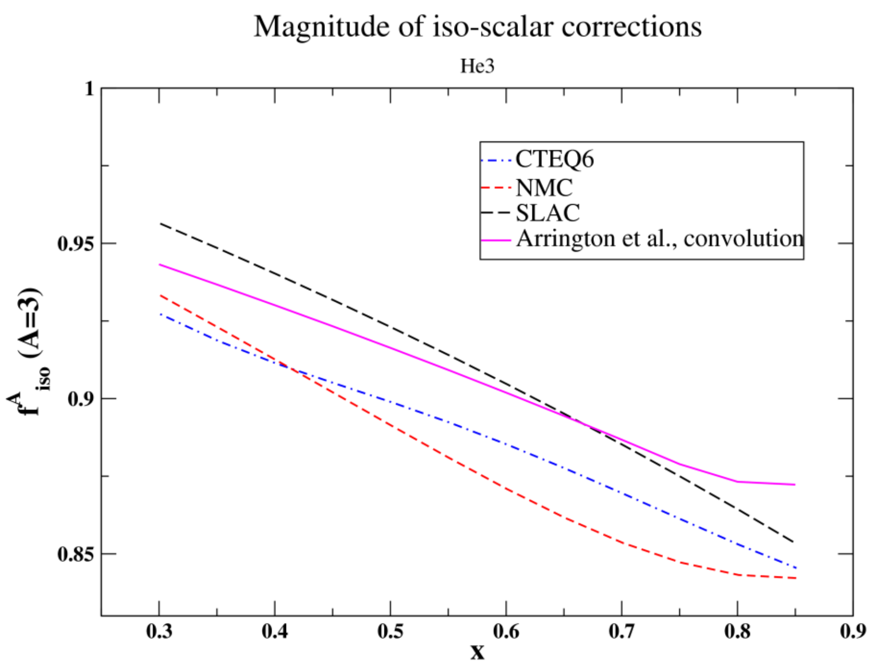
- For non-isoscalar nuclei, we need to correct for excess of neutrons or protons. The multiplicative correction factor is

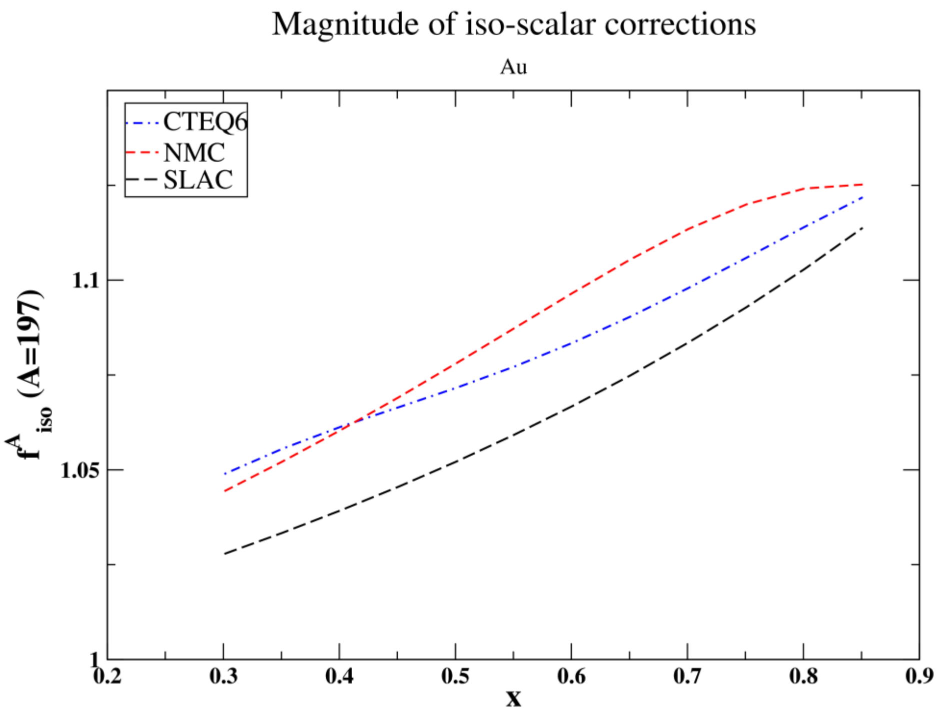
$$f_{iso}^{A} = \frac{\frac{1}{2}\left(1 + F_2^n / F_2^p\right)}{\frac{1}{A}\left(Z + (A-Z) F_2^n / F_2^p\right)}$$



- Since there is no free neutron target, extraction of F2n/F2p is always model-dependent.
- Want n/p in the nucleus, not for free nucleon

Magnitude of isoscalar corrections

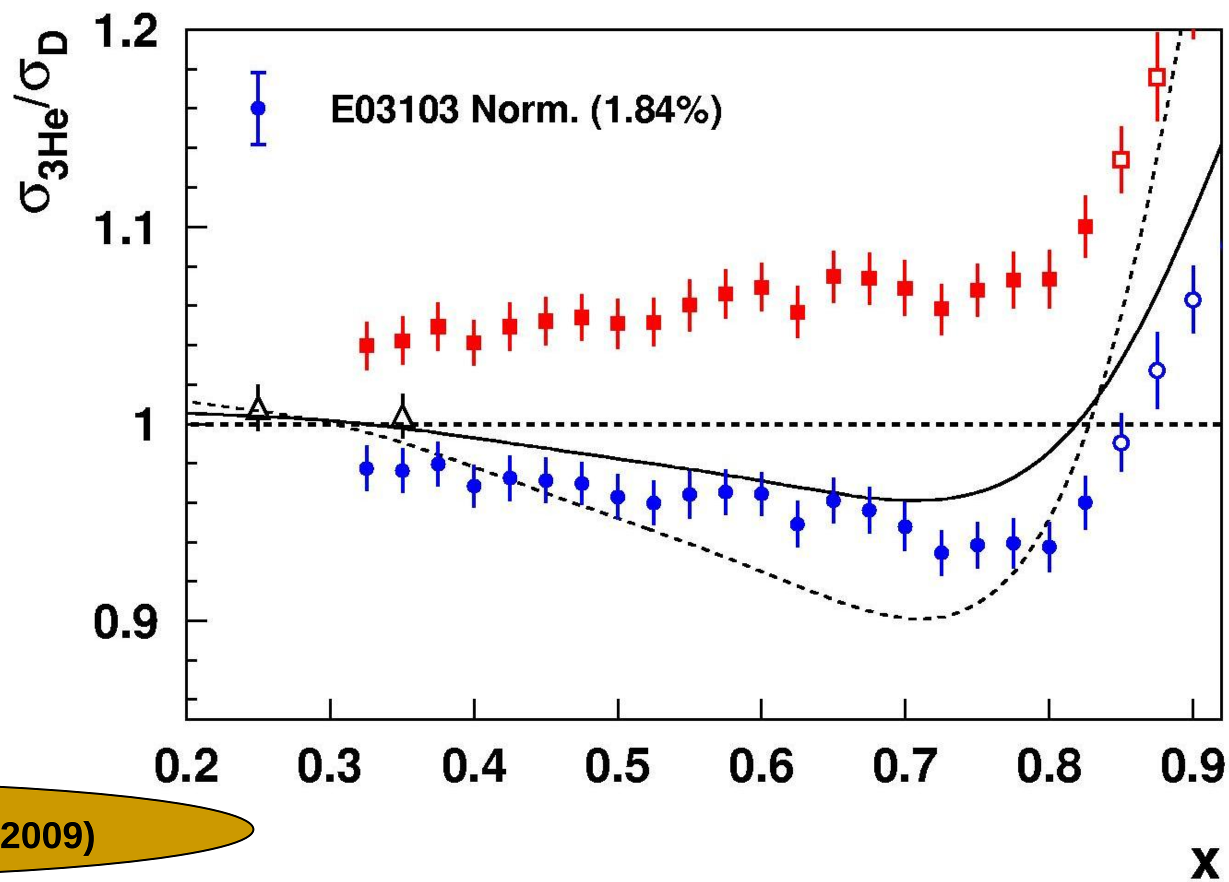




- **SLAC fit: from high Q^2 global analysis, done to free n/p.**
- **E03-103 results extracted using bound n/p ratios and calculations done for E03-103 kinematics.**

(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

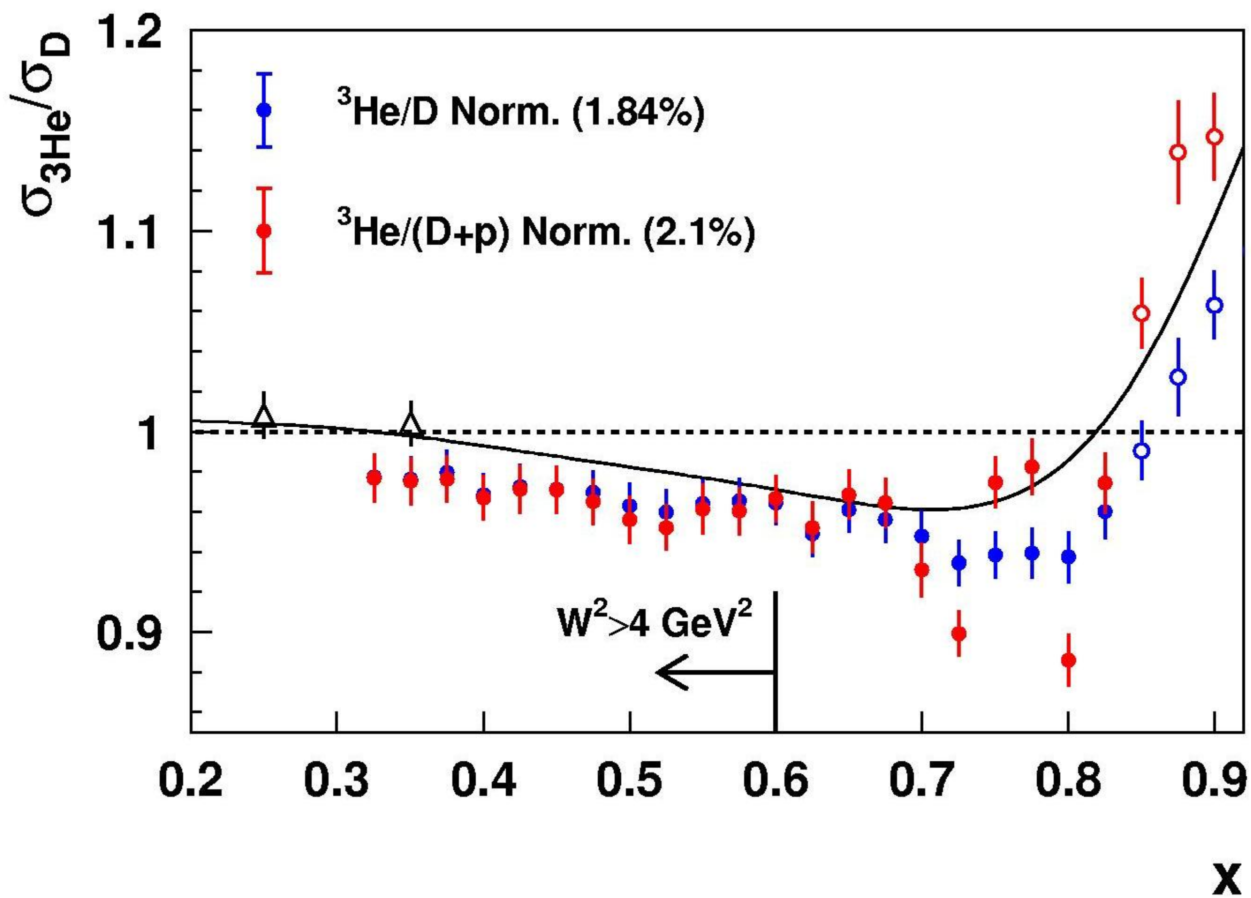
Solid curve SLAC fit for A=3

Dashed line SLAC fit for A=12

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

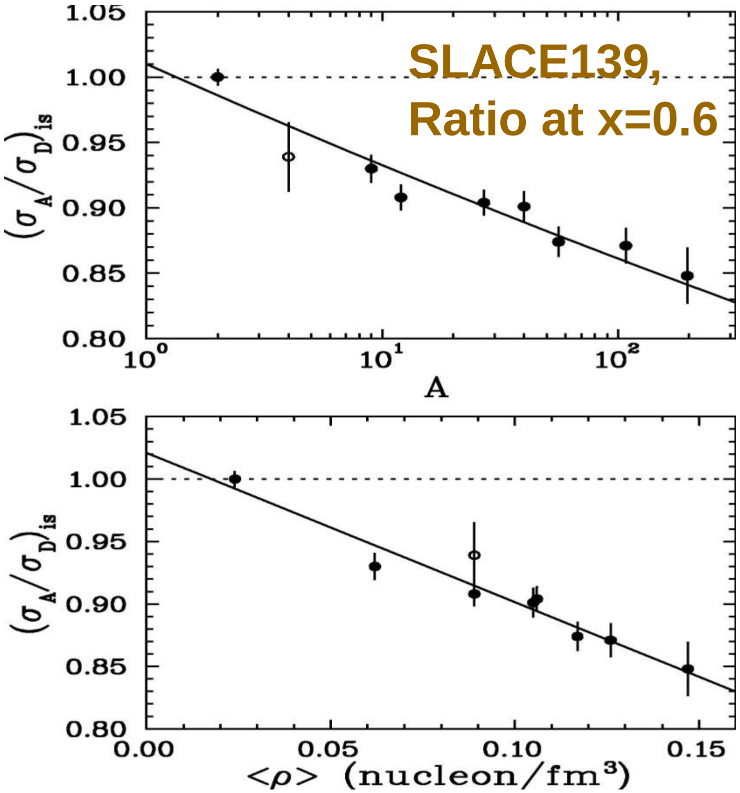
- E03-103 isoscalar corrections done with ratio of bound neutron to bound proton in ^{3}He .
- EMC effect small, but shape consistent with other nuclei.

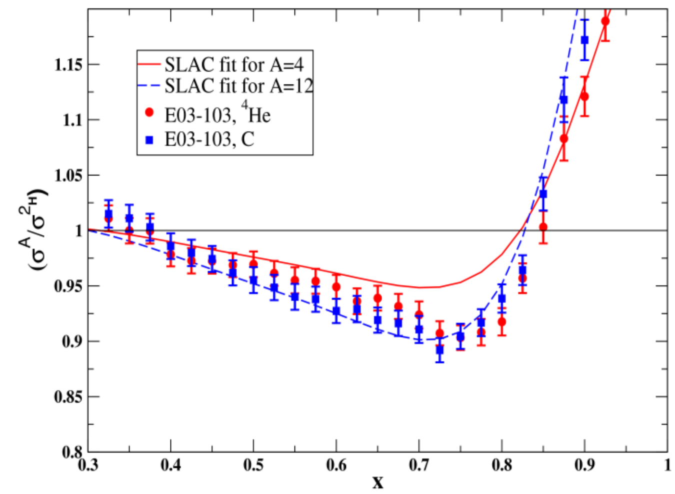
E03-103 results: cross section ratios for ^{3}He

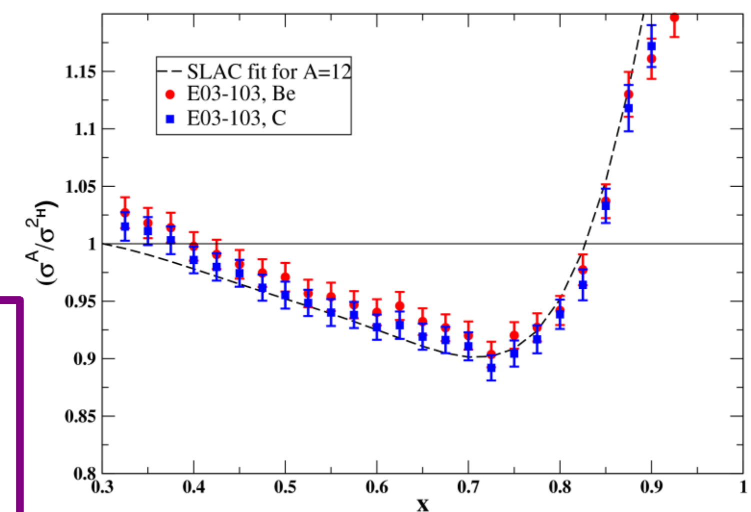


- E03-103 isoscalar corrections done with ratio of bound neutron to bound proton in ^{3}He .
- Ratio of ^{3}He/(D+p); check for applied isoscalar correction; limited to x<0.65 due to proton resonance contributions

E03-103 results:
Mass number dependence vs density dependence







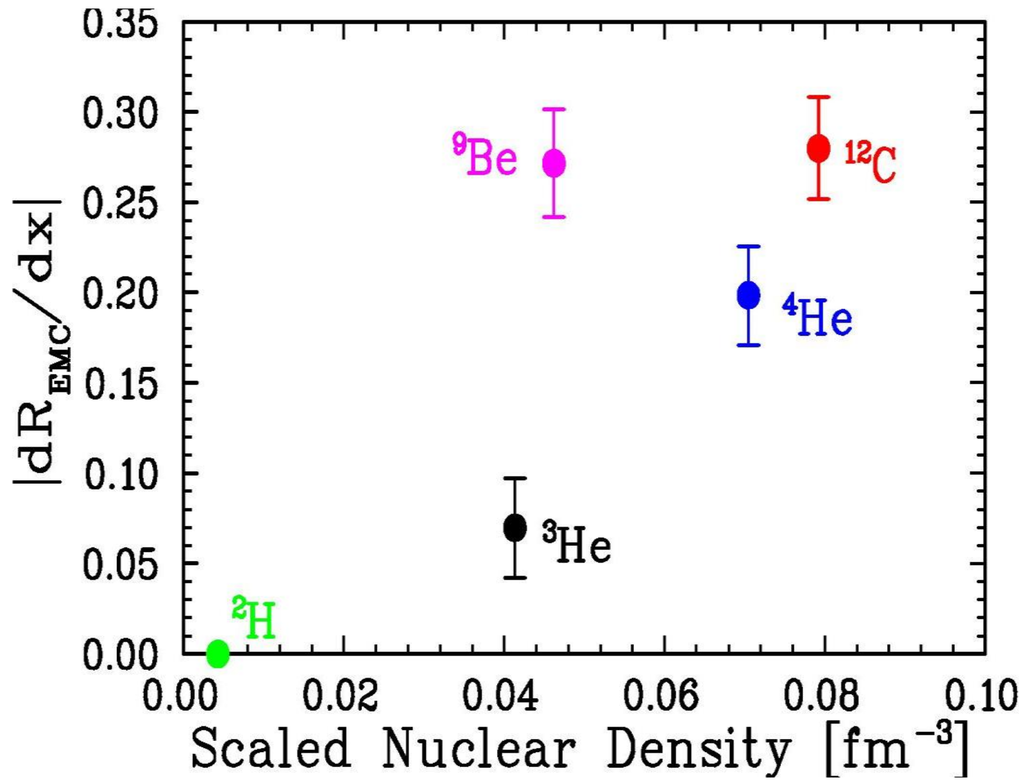
- ❖ ^{4}He matches better with C data and with SLAC parameterization (ln(A) fit with A=12).
- ❖ Average nuclear density of ^{4}He and C are similar.
- ❖ Also, Be data matches better with C data. However, average nuclear density of Be << C.

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.



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

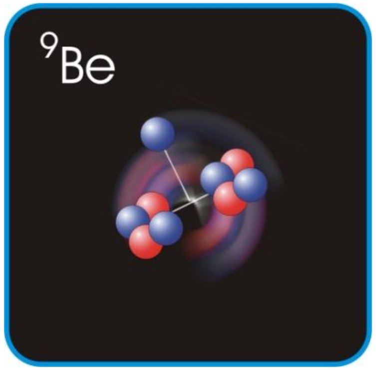
❖Density calculated using ab-initio GFMC calculation

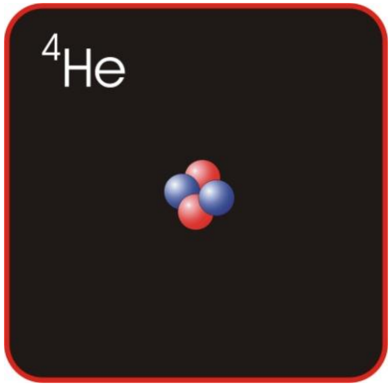
(S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001))

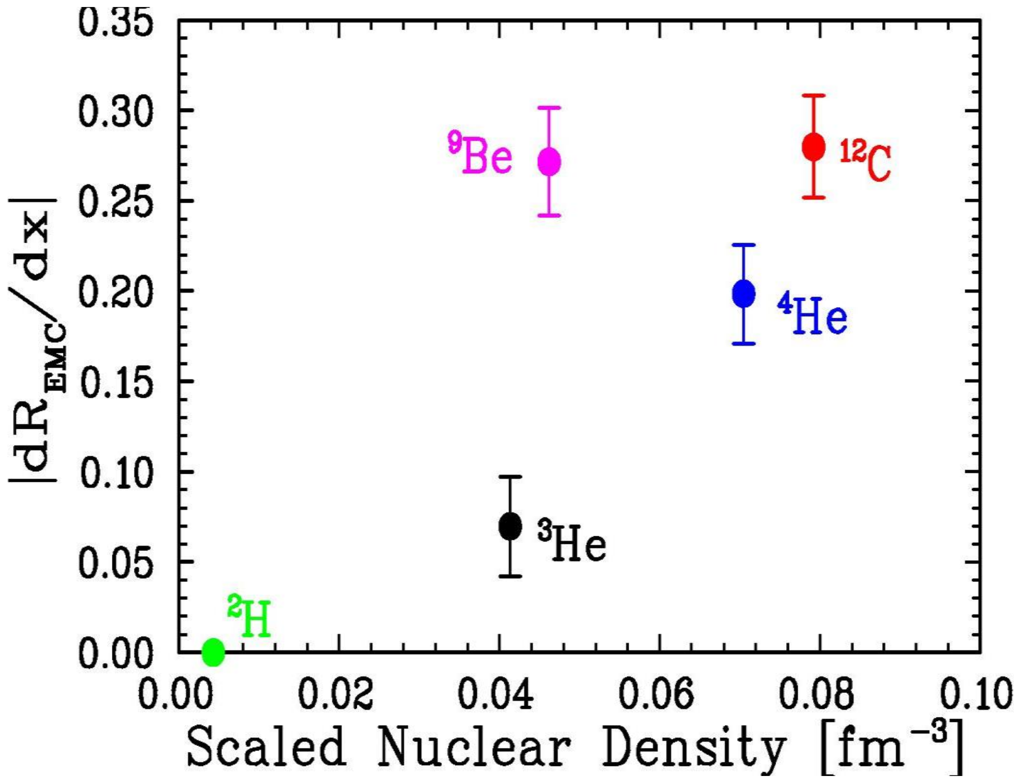
E03-103 results

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

- **Data show smooth behavior as density increases except for ^{9}Be**
- **One possible explanation is that the effect depends on nucleon's local environment.**







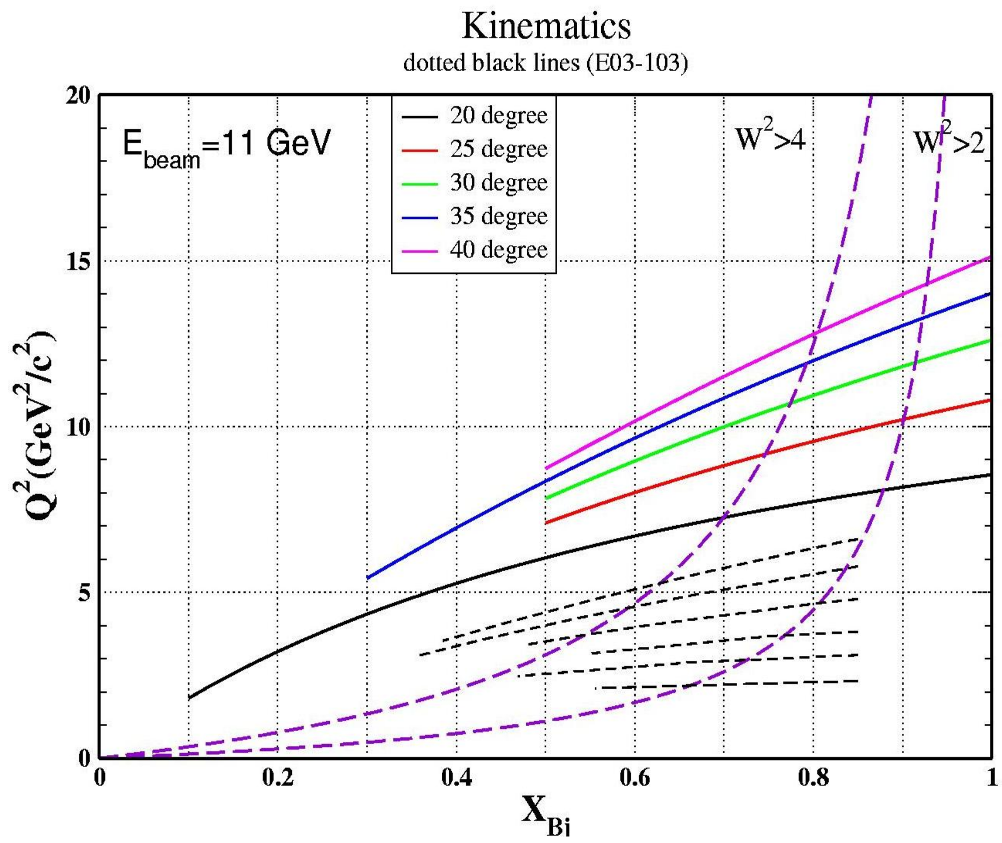
- **Average density of ^{9}Be is relatively low, but most nucleons are in high local densities of alpha cluster.**

EMC effect: Future opportunities with 11 GeV upgrade

11 GeV experiment E10-008

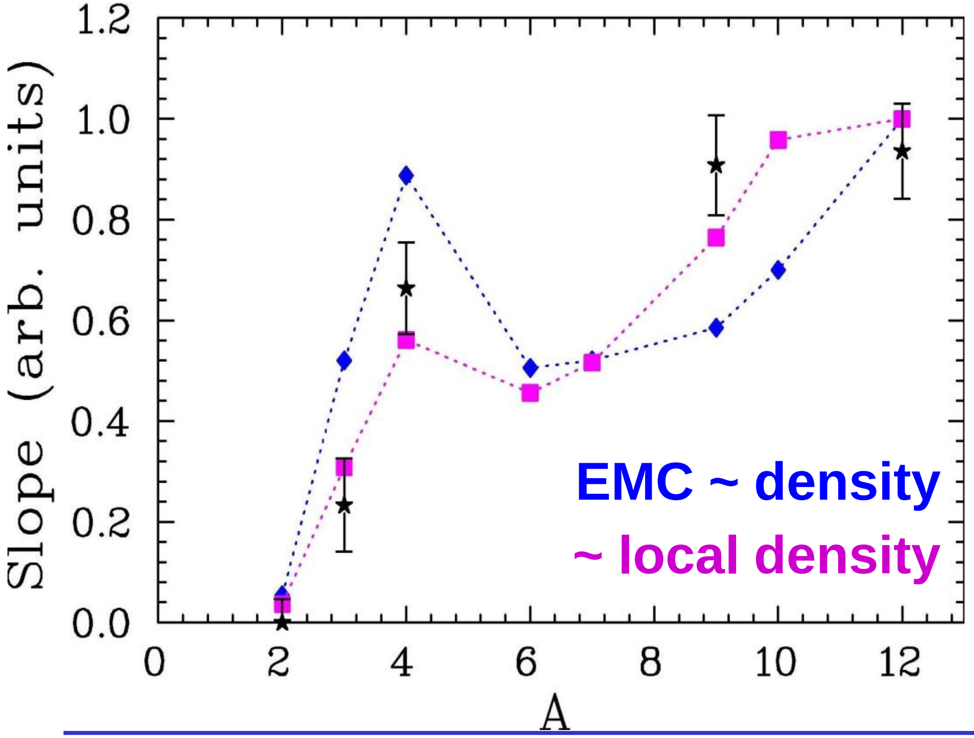
Spokespersons: J. Arrington, A. Daniel, D. Gaskell

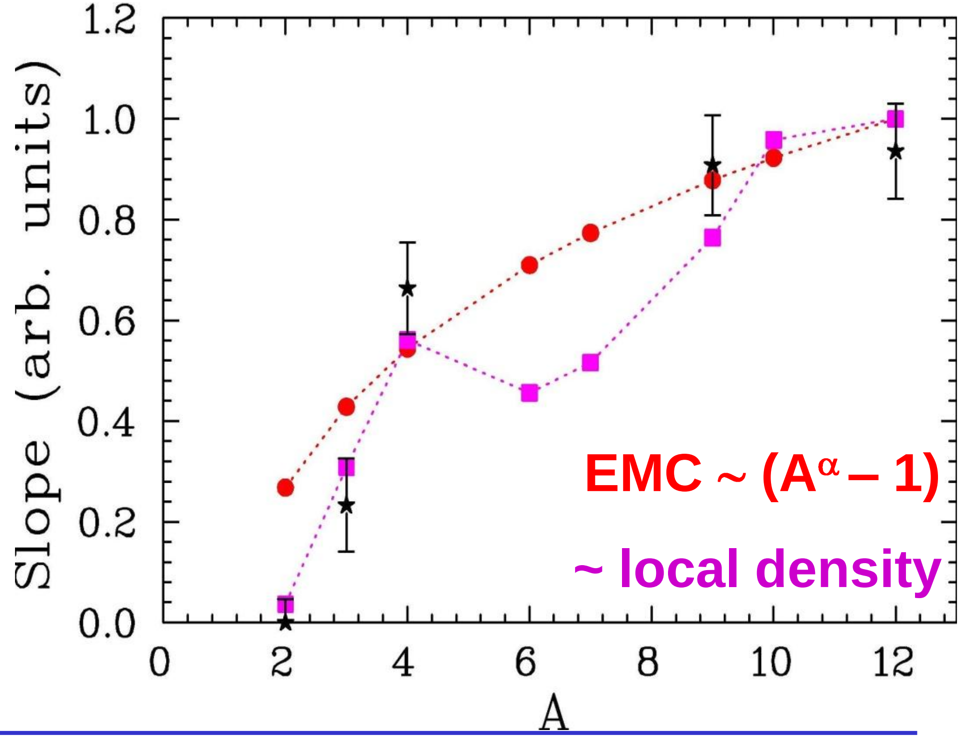
- **Higher Q^2, expanded range in x (both low and high x) ; DIS extends to x=0.8, W^2>2 extends to x=0.92**
- **Will further investigate the influence of local environment on the observed nuclear dependence with a more complete nuclei.**
- **Light nuclei includes ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{12}C**



Future measurements (E10-008)

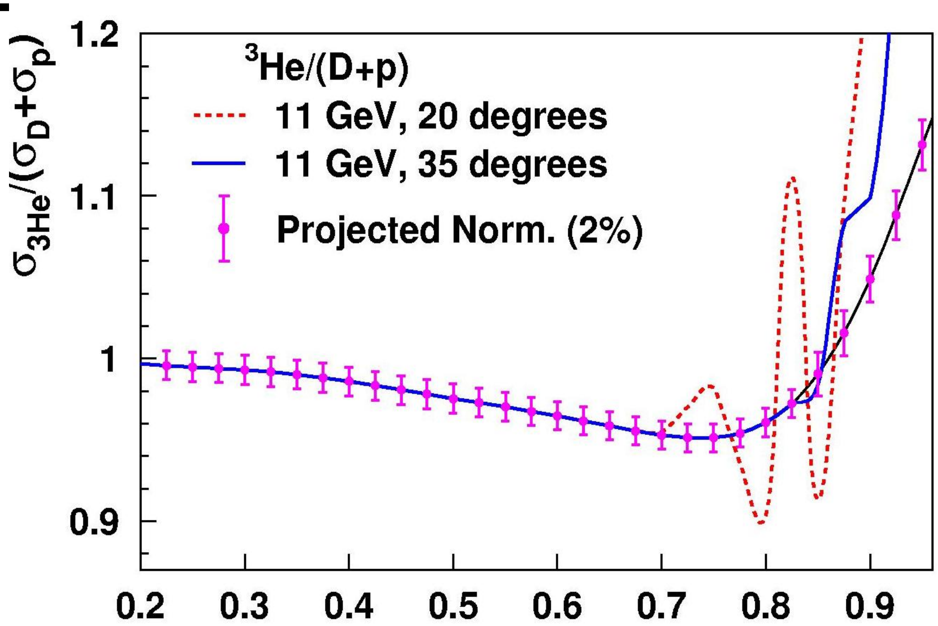
- Map out A-dependence in more detail using additional light nuclei
  - Very hard to explain large ^{3}He – ^{9}Be difference in ρ-dependent fit
  - Hard to explain large ^{3}He – ^{4}He difference in mass-dependent fit
  - "Local density" works well, provides different predictions
    - **Use ab initio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



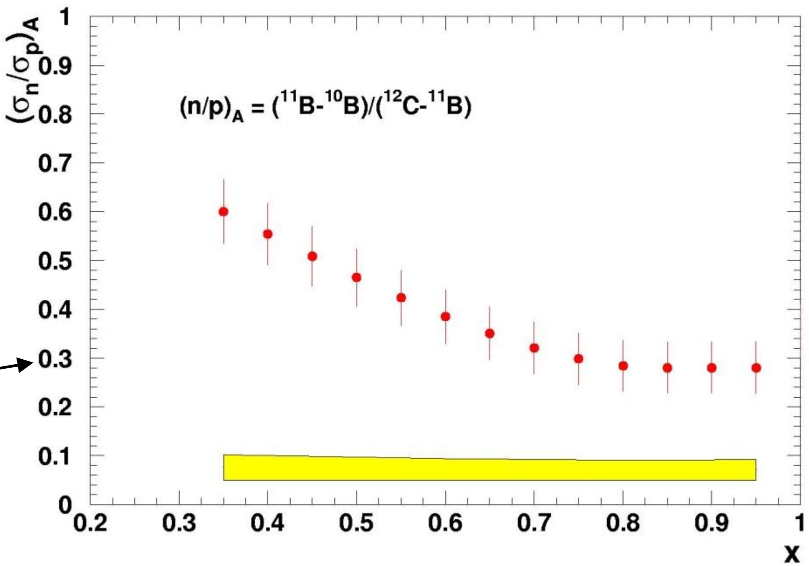


Future measurements (E10-008)

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



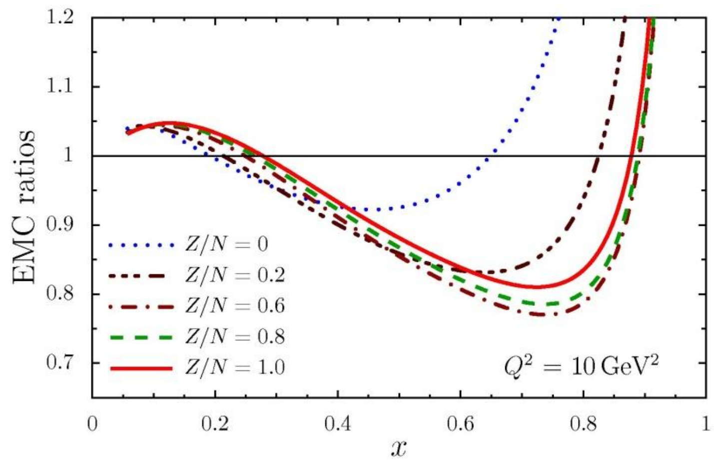
❖ Comparisons of non-isoscalar nuclei
- Information about neutron or proton in-medium from combinations of nuclei such as ^{11}B-^{10}B, ^{7}Li-^{6}Li, ^{12}C-^{11}B
- Ratio of n/p in-medium is direct check of applied isoscalar corrections



Future measurements (E10-008)

❖ **Isospin dependence of EMC effect**

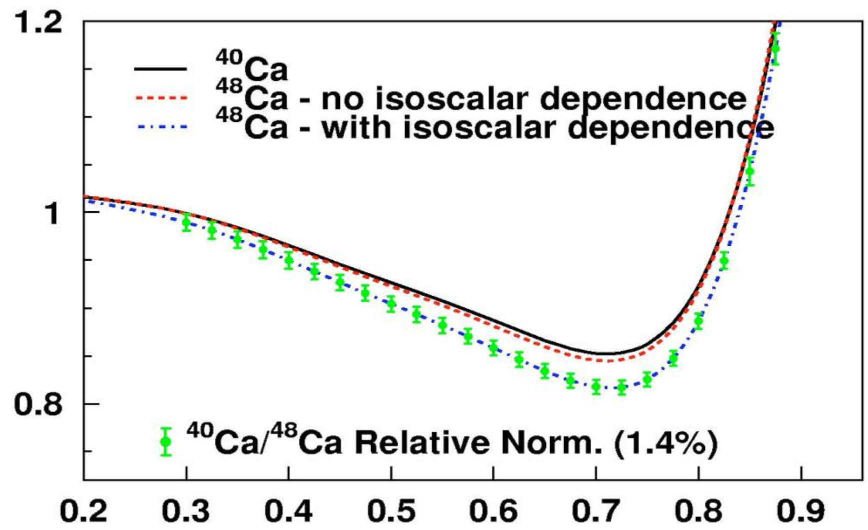
I.Cloet, W.Benz, A.Thomas, PRL102, 252301(2009)



- **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.**

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



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 Q2.

- First measurement of the EMC effect in ^{3}He above x=0.4 and precision measurement in ^{4}He.

- 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.

- Also, absolute cross sections will be available for comparison to detailed calculations for a large selection of light nuclei.