Duality in Nuclei: The EMC Effect

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Jefferson Lab

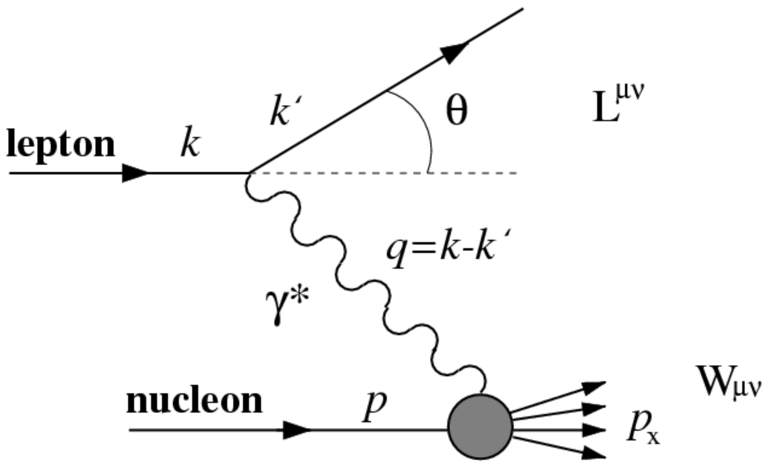
Quark Hadron Duality Workshop: Probing the Transition from Free to Confined Quarks

September 23-25, 2018

Outline

- The EMC Effect
- Structure functions in the resonance region – nucleons → nuclei
- Duality in nuclear structure functions → the EMC Effect
- JLab measurements at 6 and 11 GeV

DIS: Structure Functions and Quarks in the Nucleus



Deep Inelastic Scattering provides access to quark distributions in ***nucleon*** via structure functions:

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

Nuclear binding energies (~MeV) small compared to typical DIS energies (~GeV) → (Naïve) expectation was that nuclear effects in DIS would be small

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

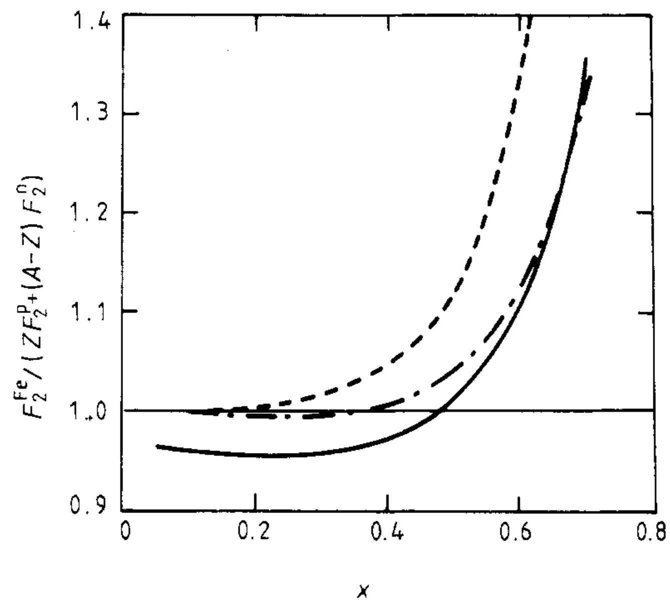
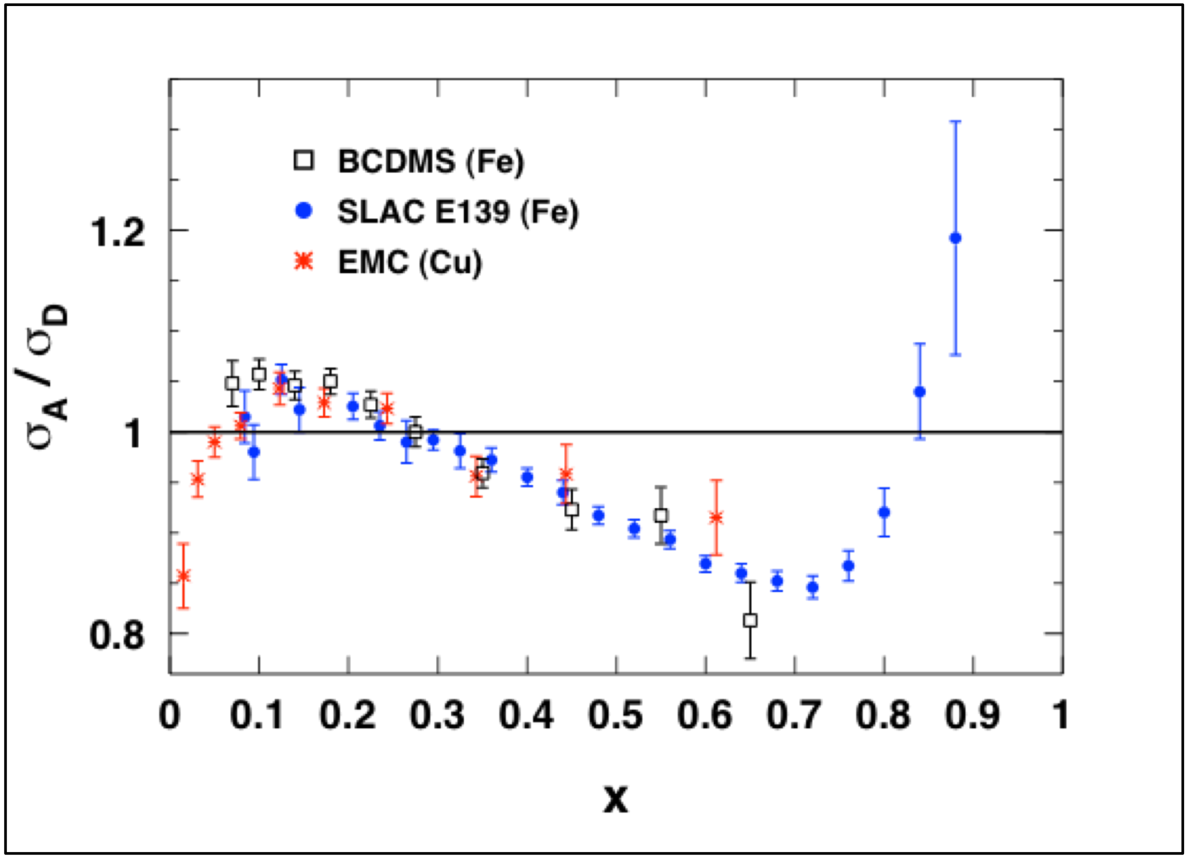


Figure from Bickerstaff and Thomas, J. Phys. G 15, 1523 (1989)
Calculation: Bodek and Ritchie PRD 23, 1070 (1981)

Properties of the EMC Effect

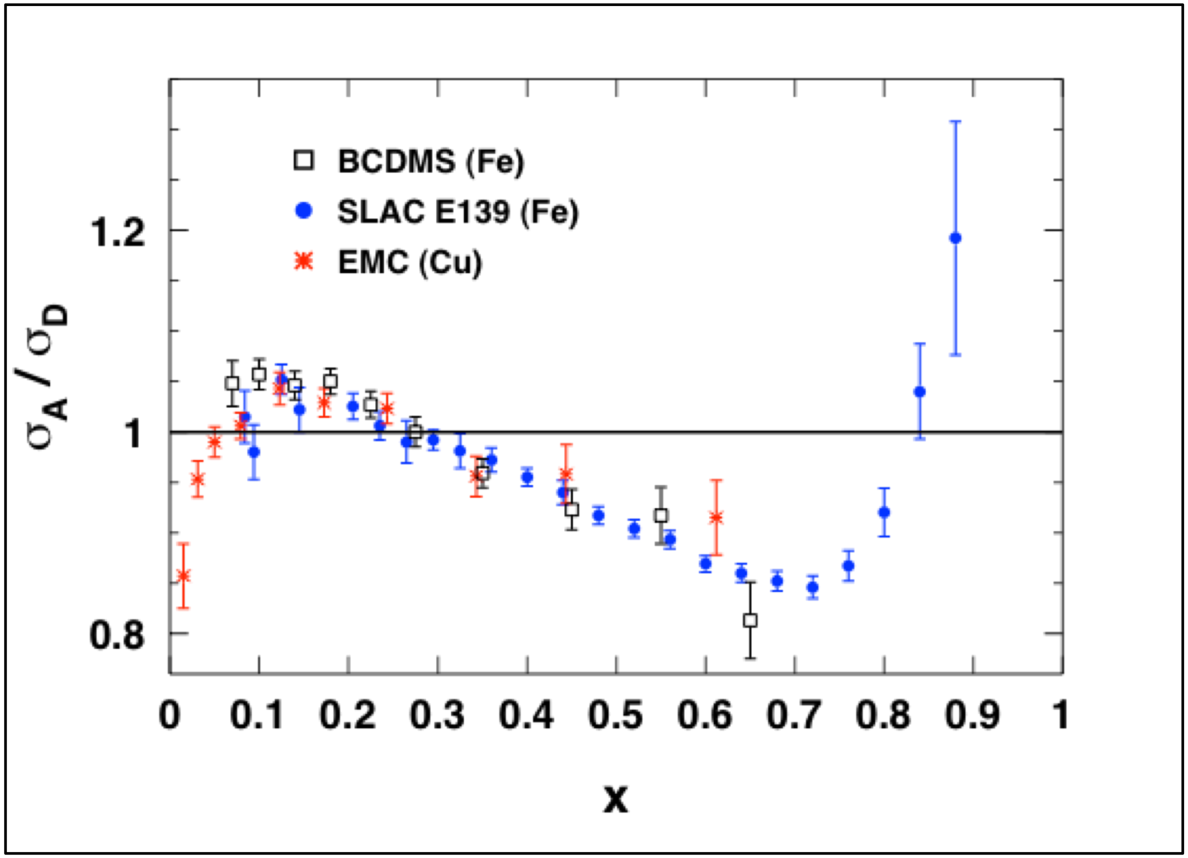


Global properties of the EMC effect

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

→ *Anti-shadowing region shows little nuclear dependence*

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*

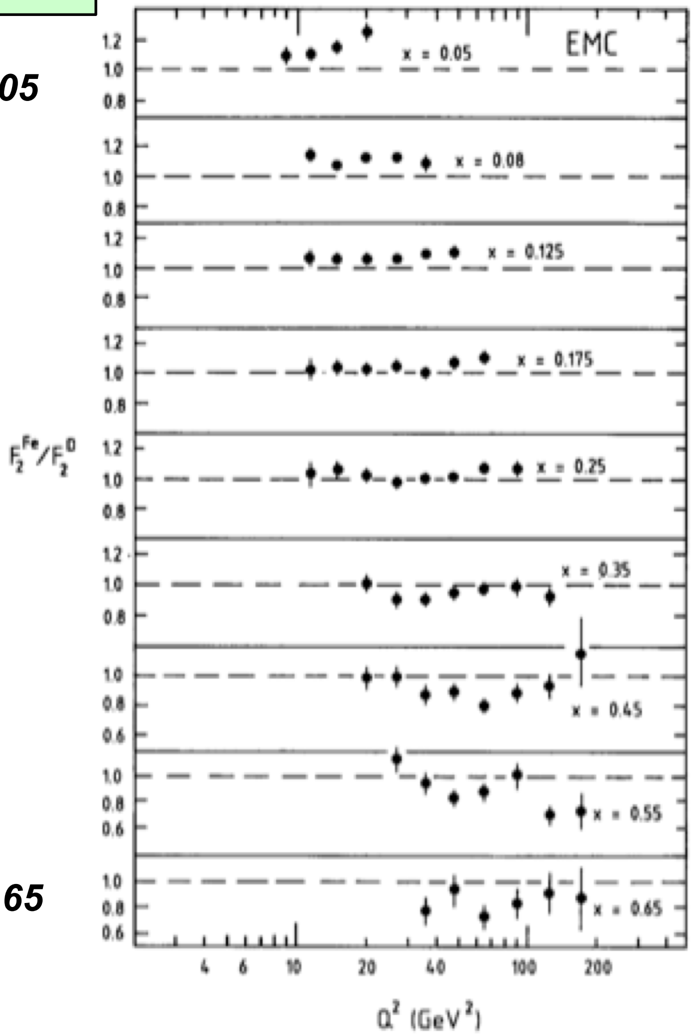
→ *Anti-shadowing region shows little nuclear dependence*

→ Nuclear structure functions evolve with Q^2 in same way as nucleon

Q^2 Dependence of the EMC Effect

EMC Q^2=10-200 GeV^2

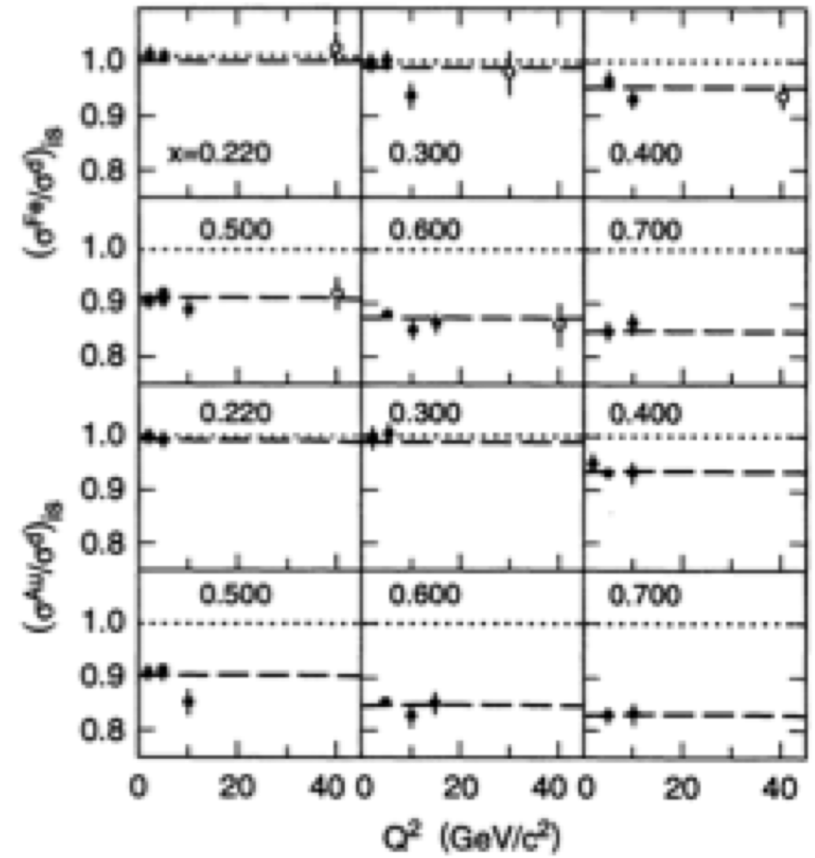
x=0.05



x=0.65

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

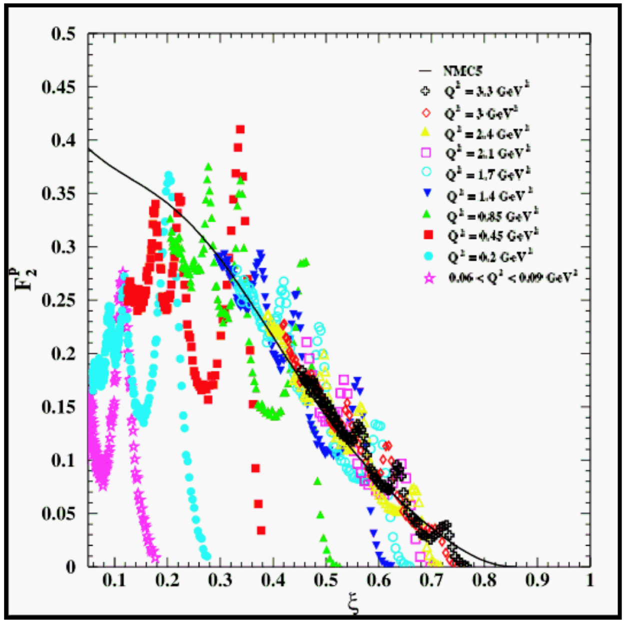
SLAC E139 Q^2=1-10 GeV^2

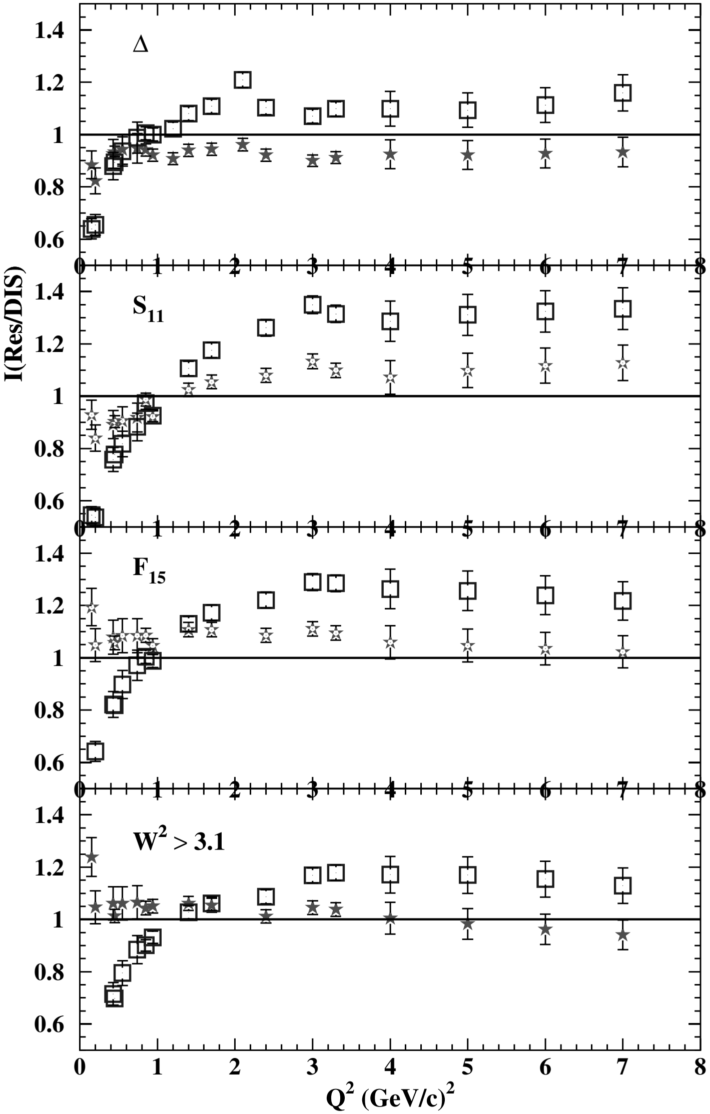


Gomez et al, Phys. Rev. D 49, 4348 (1994)

Quark-Hadron Duality in Nucleons

I. Niculescu et al., PRL85:1182 (2000)





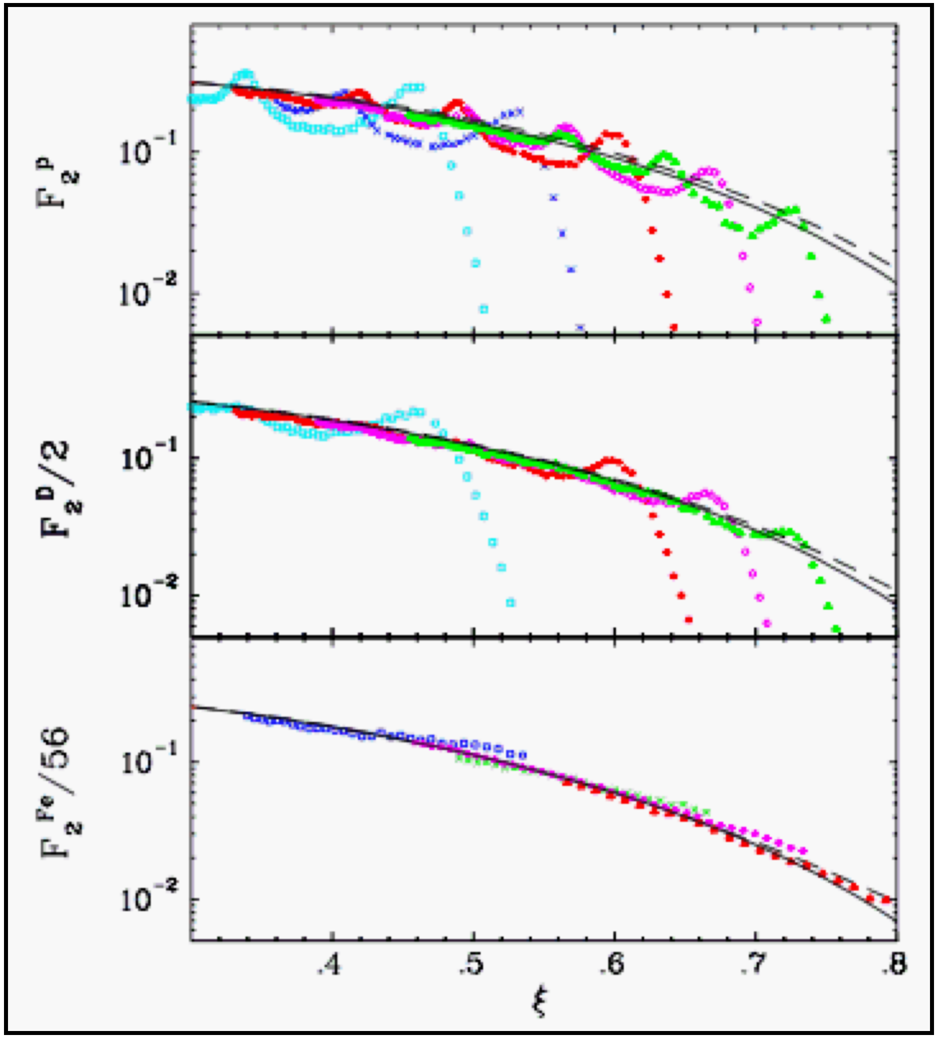
→ Resonance region structure functions oscillate around smooth, DIS curve

→ Quantitative agreement between DIS/resonance F_2 when integrating over distinct regions in W^2

Quark-Hadron Duality in Nuclei

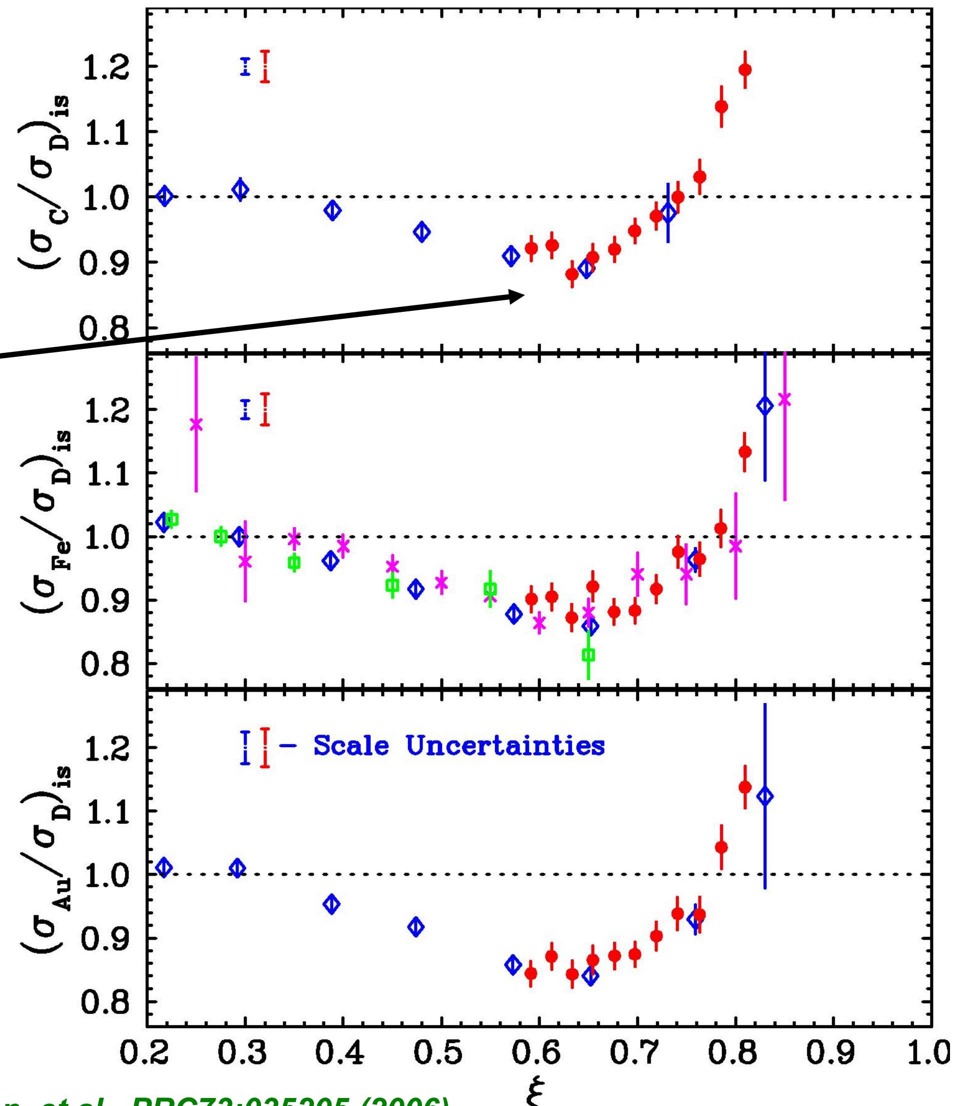
- Free nucleon
  - average over resonance region = DIS scaling limit
- Bound nucleon
  - Fermi motion does the averaging for us
  - Resonances much less prominent in nuclear structure functions
- Nuclear structure functions appear to "scale" to lower Q^2 than their free nucleon counterparts with no explicit resonance averaging

J. Arrington, et al., PRC73:035205 (2006)



EMC Effect in Resonance Region

JLab E89-008:
Q^2 ~ 4 GeV^2
1.3<W^2<2.8 GeV^2
data in the resonance region
→ In region of overlap agrees well with DIS data



Subsequent Hall C data taken at higher Q^2, tested scaling with precise measurement of Q^2-dependence

J. Arrington, et al., PRC73:035205 (2006)

JLab Experiment E03-103

Measurement of the EMC Effect in light nuclei (^{3}He and ^{4}He) and at large *x*

→^{3}He, ^{4}He amenable to calculations using “exact” nuclear wave functions

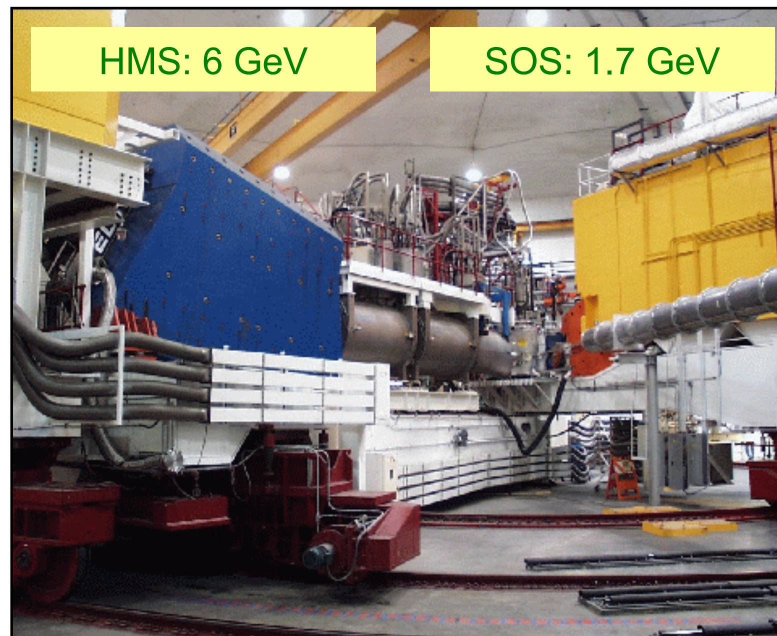
→ **Large *x*** dominated by binding, conventional nuclear effects

A(e,e’) at *5.77* GeV in Hall C at JLAB (with E02-019, *x>1*)

Targets: H, ^{2}H, ^{3}He, ^{4}He,
Be, C, Cu, Au

Six angles to measure Q^2 dependence

Spokespersons: DG and J. Arrington
Graduate students: J. Seely and A. Daniel

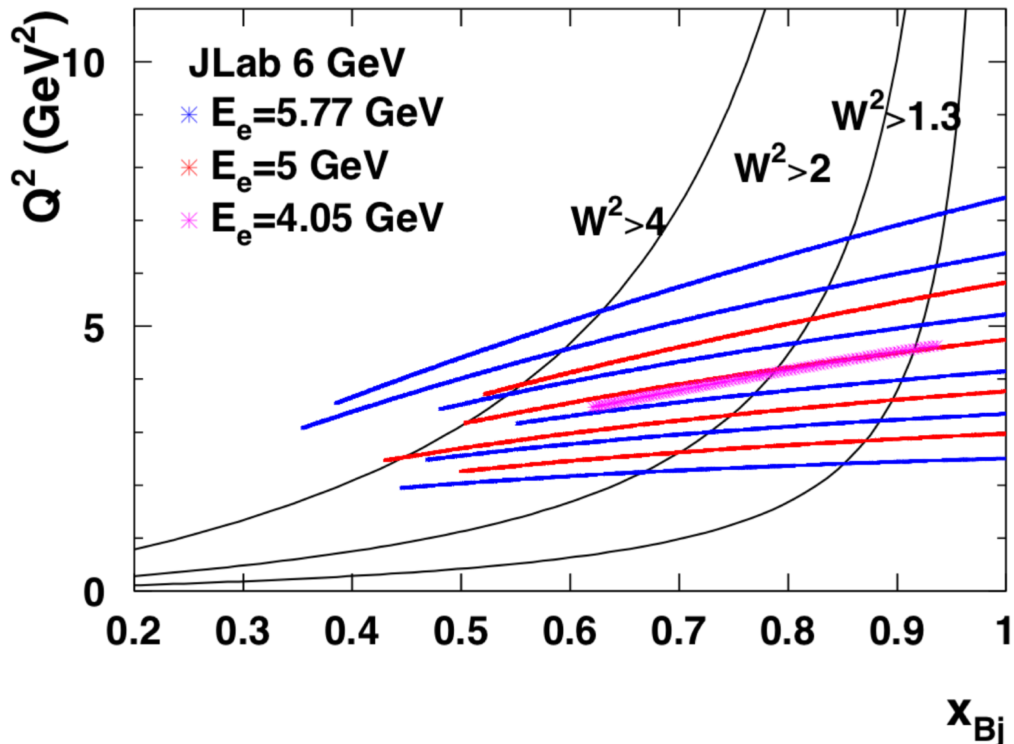


Deep Inelastic Scattering at low W

Canonical DIS regime:

$Q^2 > 1$ GeV^2 ***AND***
$W^2 > 4$ GeV^2

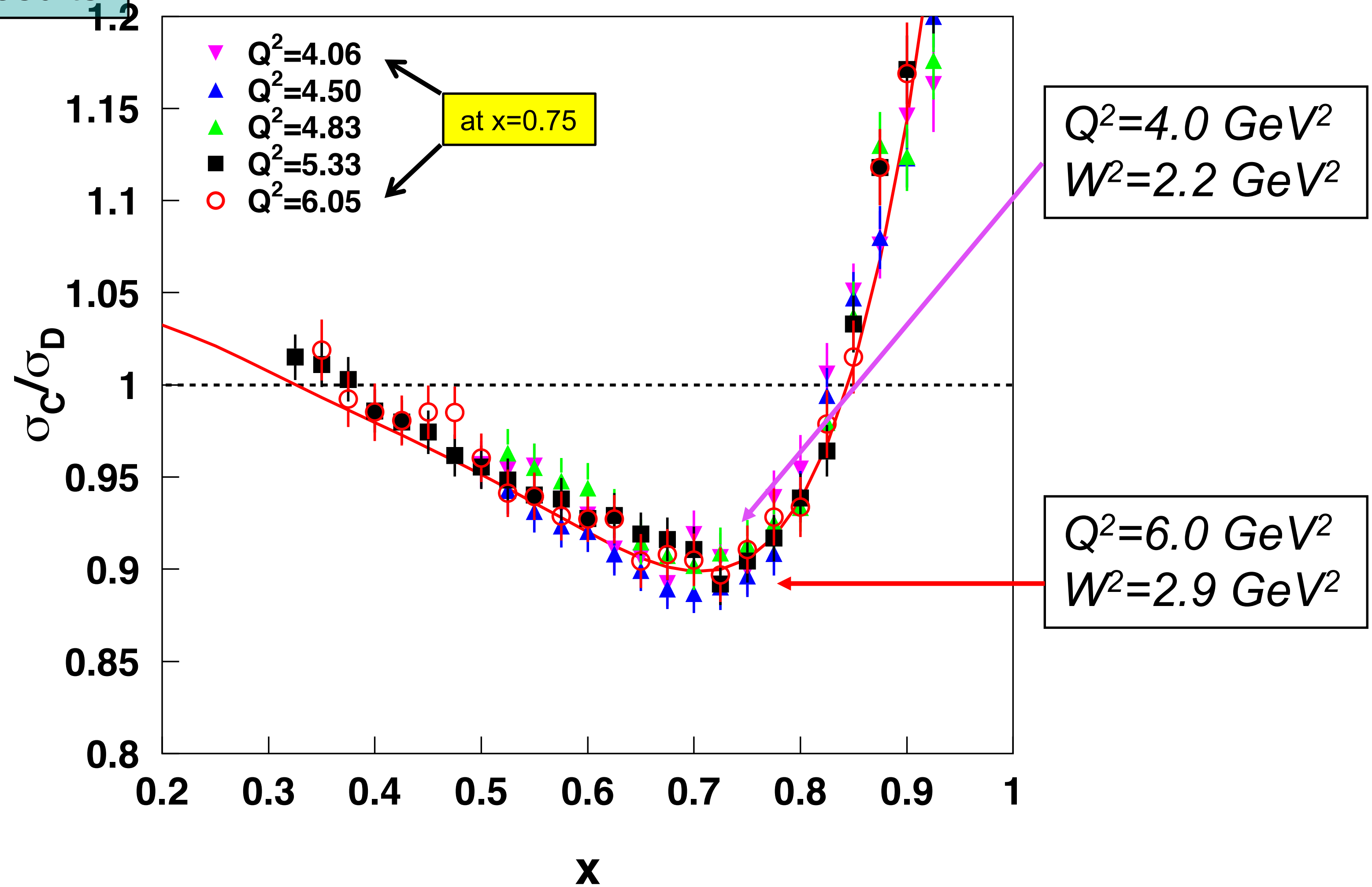
At JLab 6 GeV, access to large Q^2, and $W^2>4$ GeV^2 up to $x=0.6$



- At $x>0.6$, we are in the "resonance region", but Q^2 is still large
- Are we really sensitive to quarks in this regime?
  - Test by checking Q^2 dependence of (carbon) ratios and structure functions

Carbon/^{2}H Ratio and Q^2 Dependence

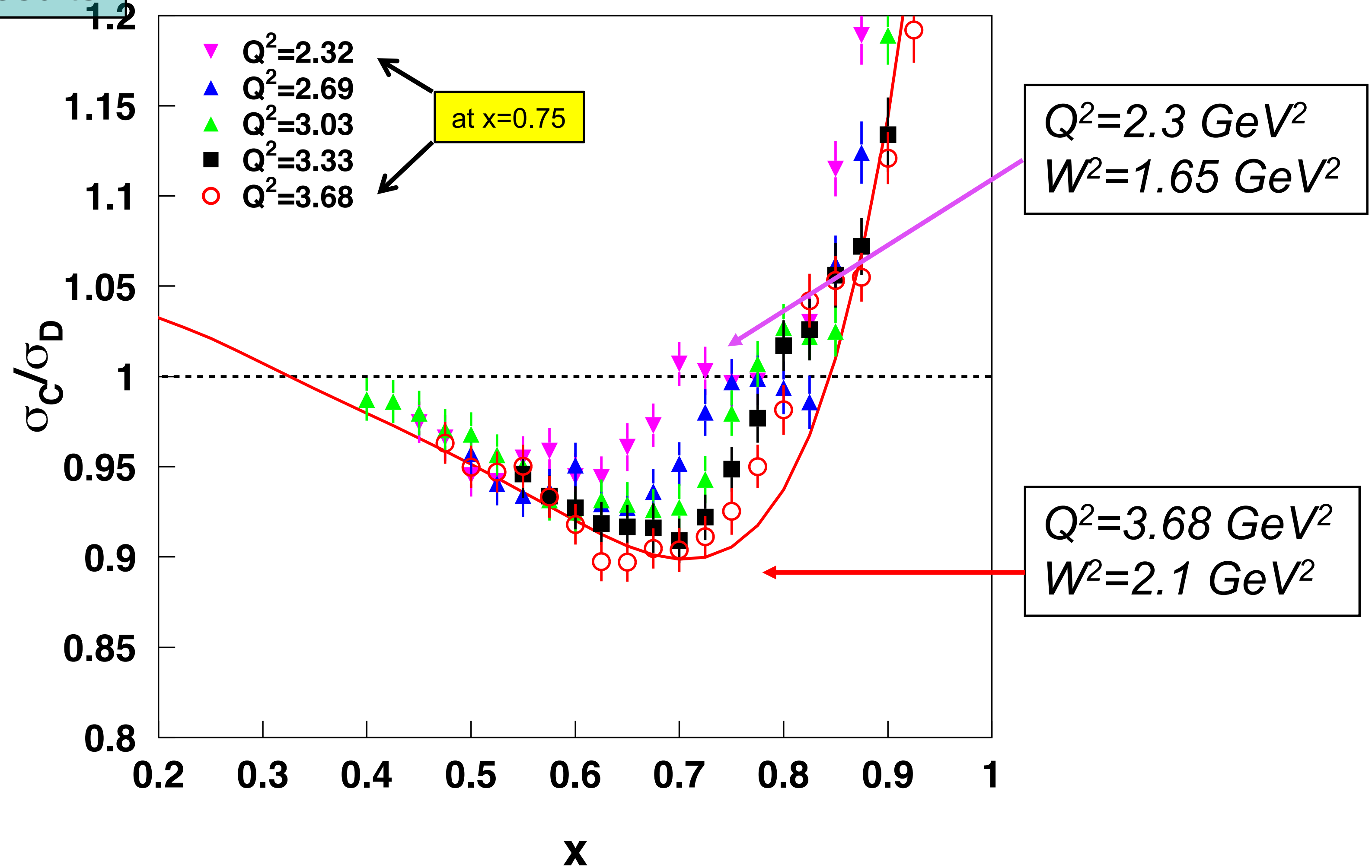
E03-103 Results



At larger angles (Q^2) the ratio appears to scale to very large *x*
→ $W^2 > 2$ GeV^2 and $Q^2 > 3$ GeV^2

Carbon/^{2}H Ratio and Q^2 Dependence

E03-103 Results



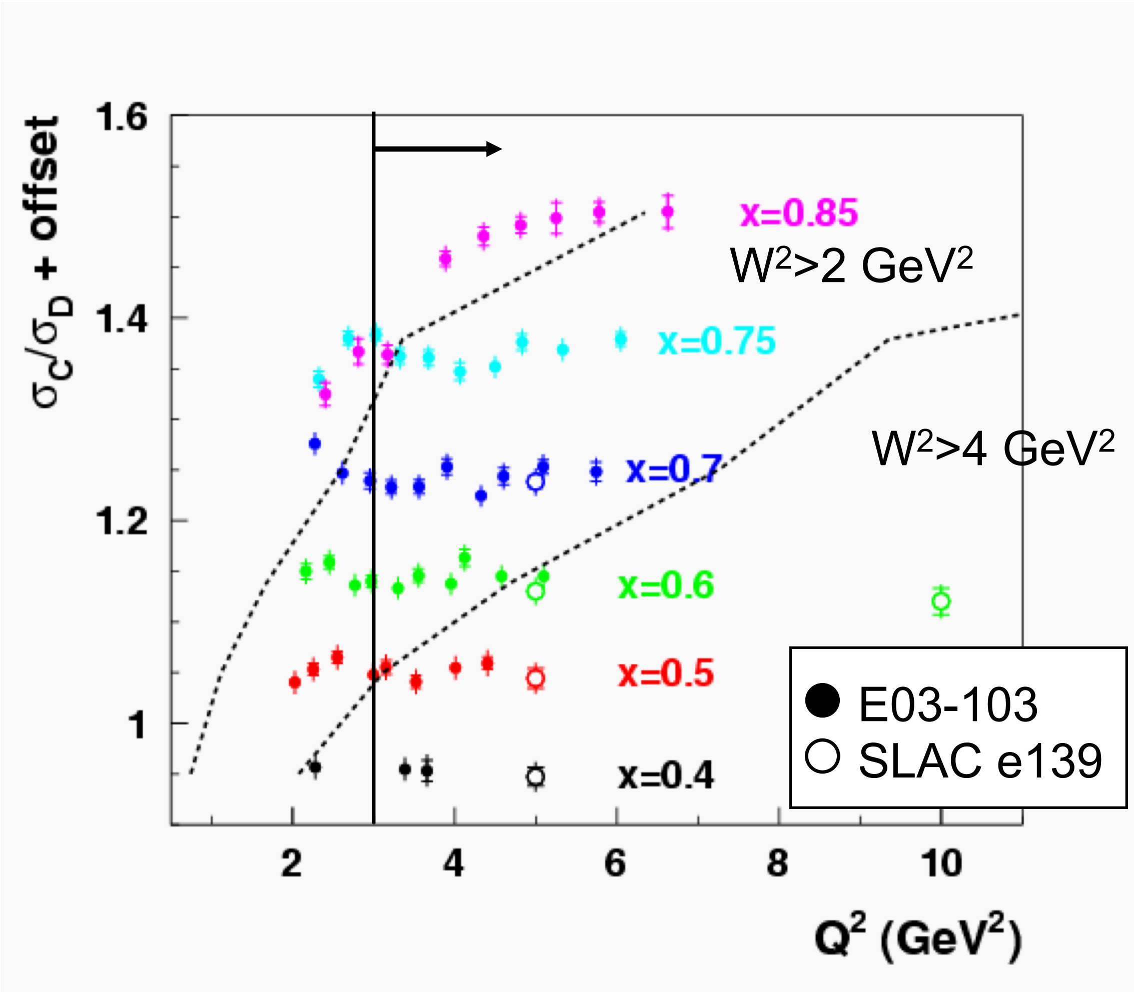
Clear deviation from scaling at W^2<2.2 GeV^2

More detailed look at scaling of C/D ratios

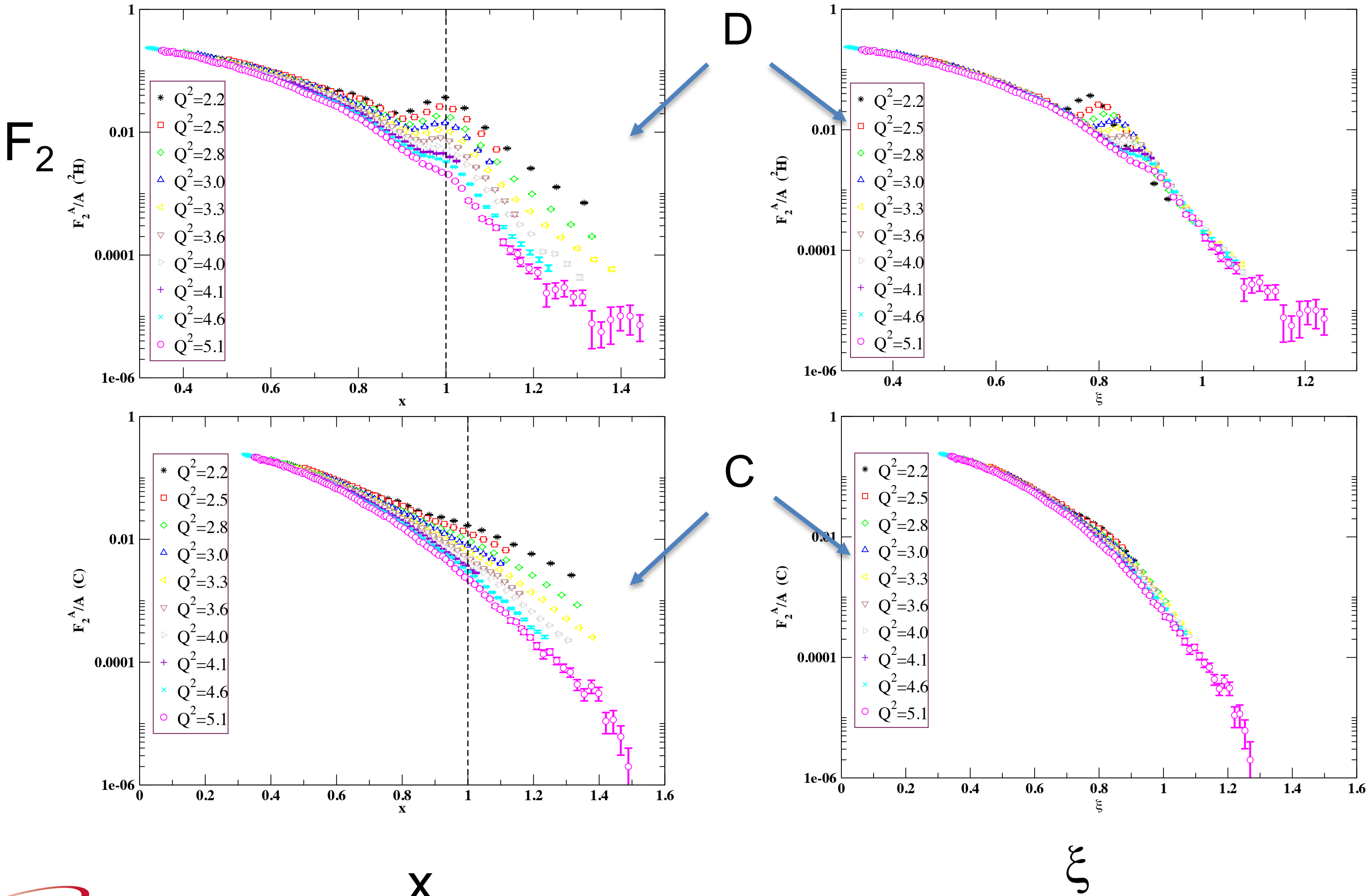
C/D ratios at fixed x are Q^2 independent for

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

For E03-103, this extends to $x=0.85$



Structure Functions

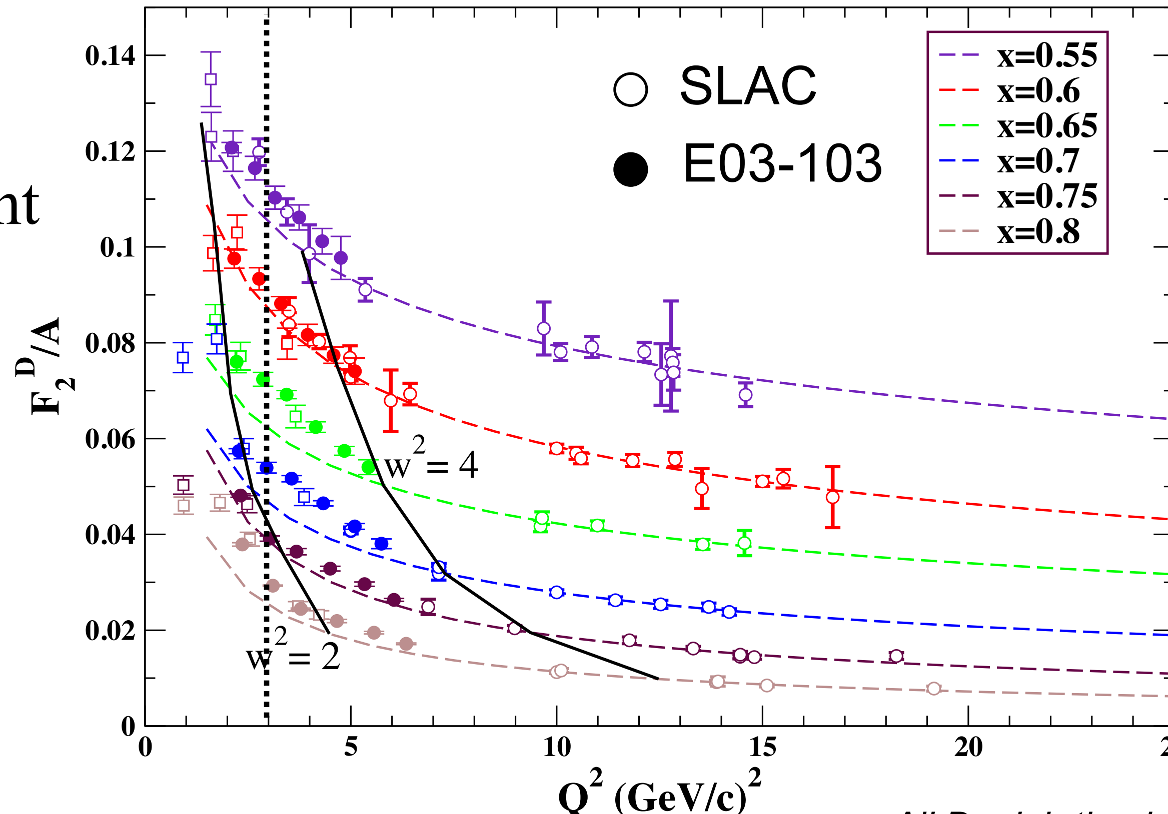


Scaling of F_2^D – Fixed x

Scaling:

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

Curves fit to large Q^2 SLAC data → compared to JLab data at lower Q^2



Aji Daniel -thesis

Although target ratios scale down to Q^2=3 GeV^2, for W^2>2 GeV^2, F_2 shows deviations from logarithmic scaling

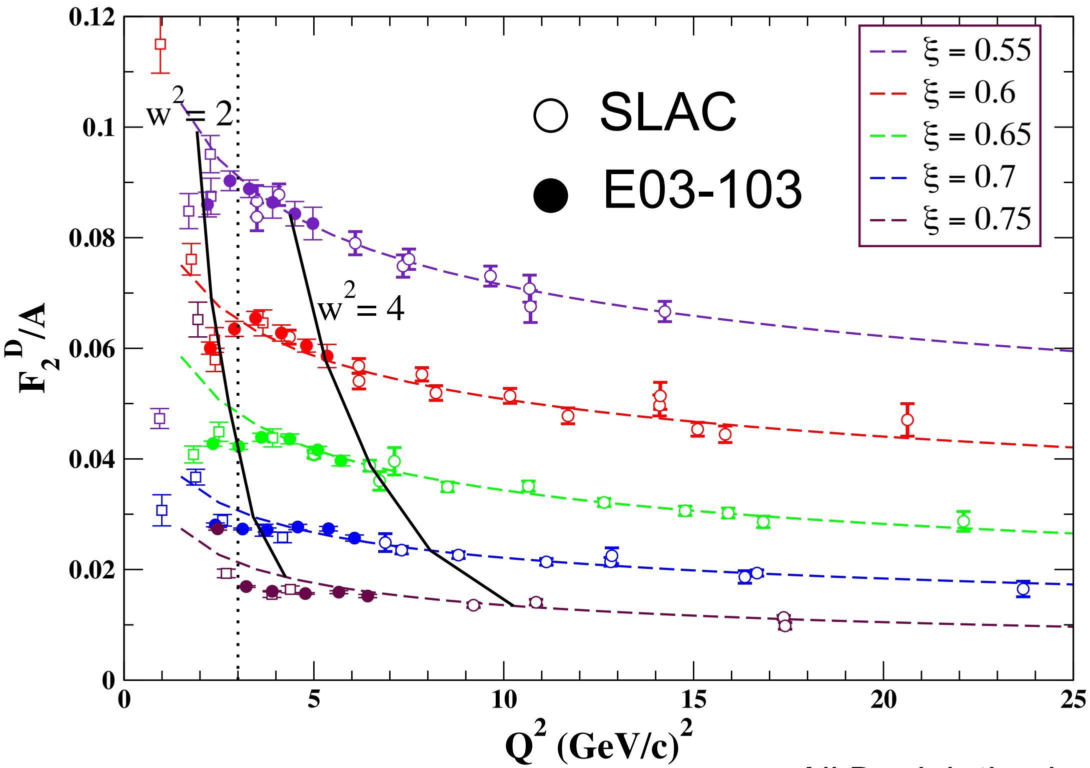
Jefferson Lab

Scaling of F_2^D – Fixed ξ

Scaling:

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

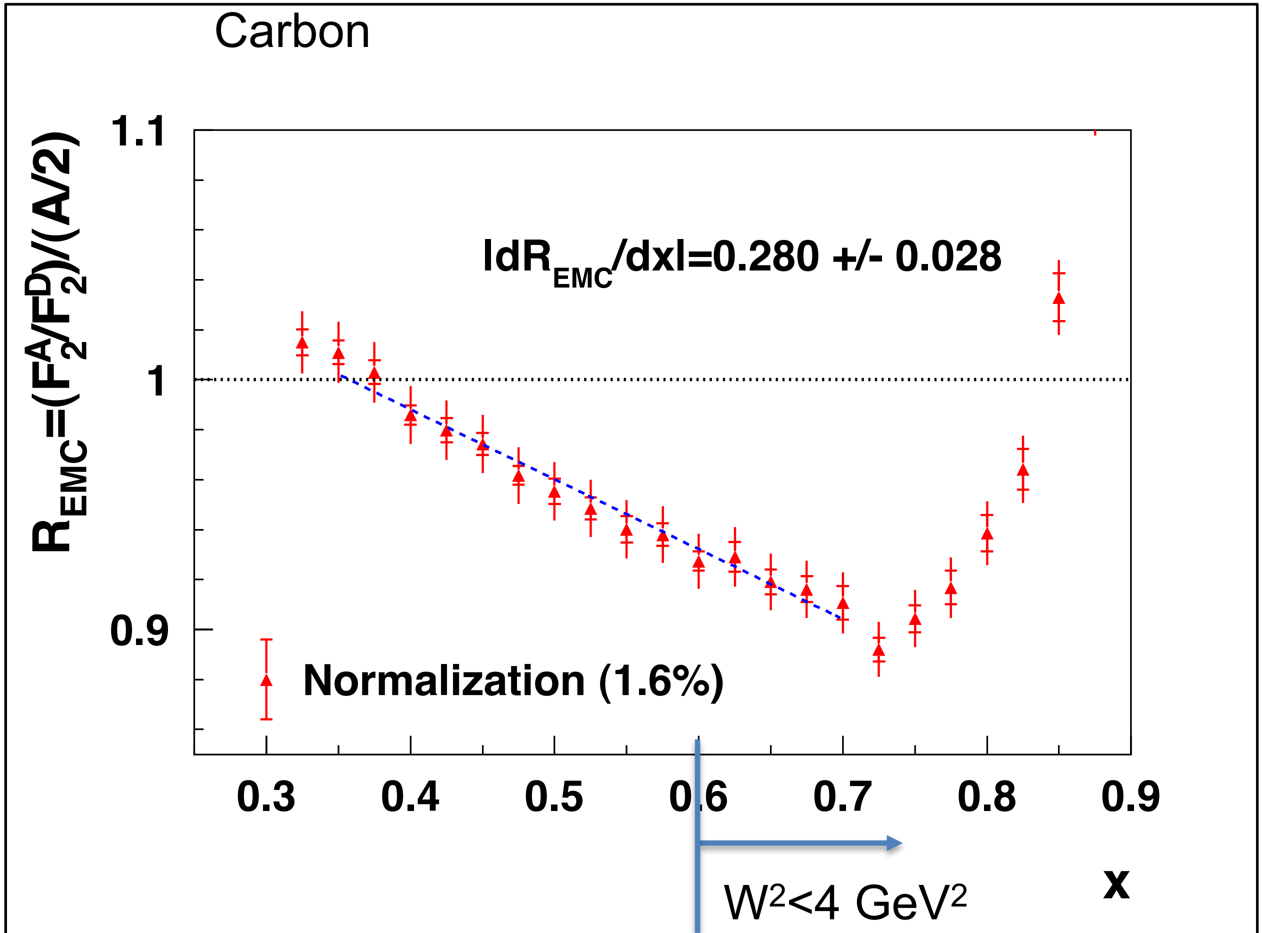
Curves fit to large Q^2 SLAC data → compared to JLab data at lower Q^2



Aji Daniel -thesis

Looking at Q^2 dependence for fixed ξ, structure functions shows improved scaling

JLab E03-103 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

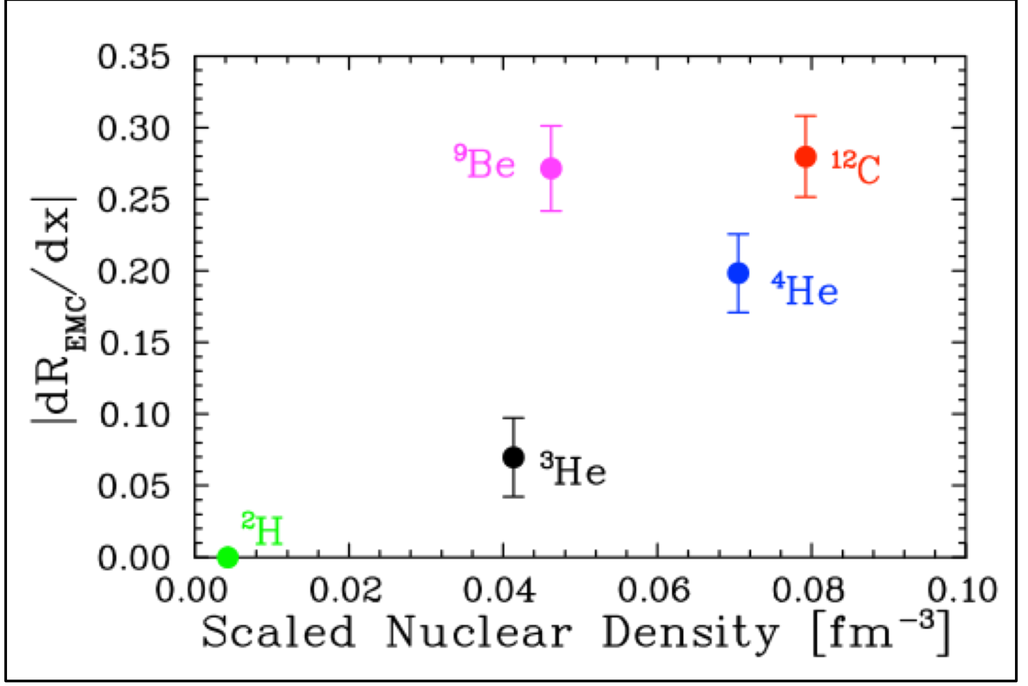
Assumes shape is universal for all nuclei

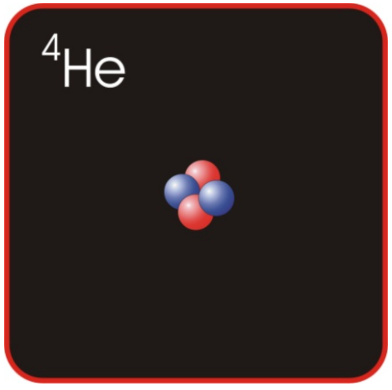
→Normalization uncertainties a much smaller relative contribution

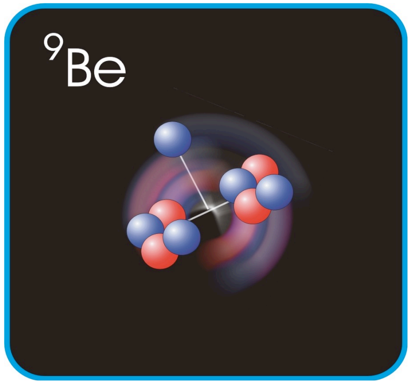
E03103 Results: EMC Effect and Local Nuclear Density

^{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 we see similar behavior in other nuclei?

E12-10-008: EMC effect in light→ heavy nuclei

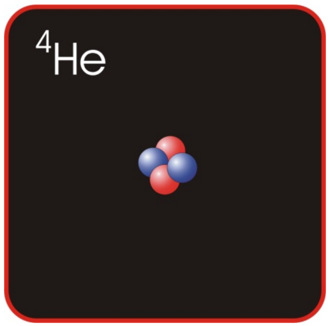
Spokespersons: J. Arrington, A. Daniel, N. Fomin, D. Gaskell

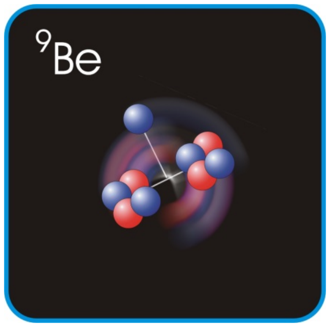
E03-103: EMC at 6 GeV

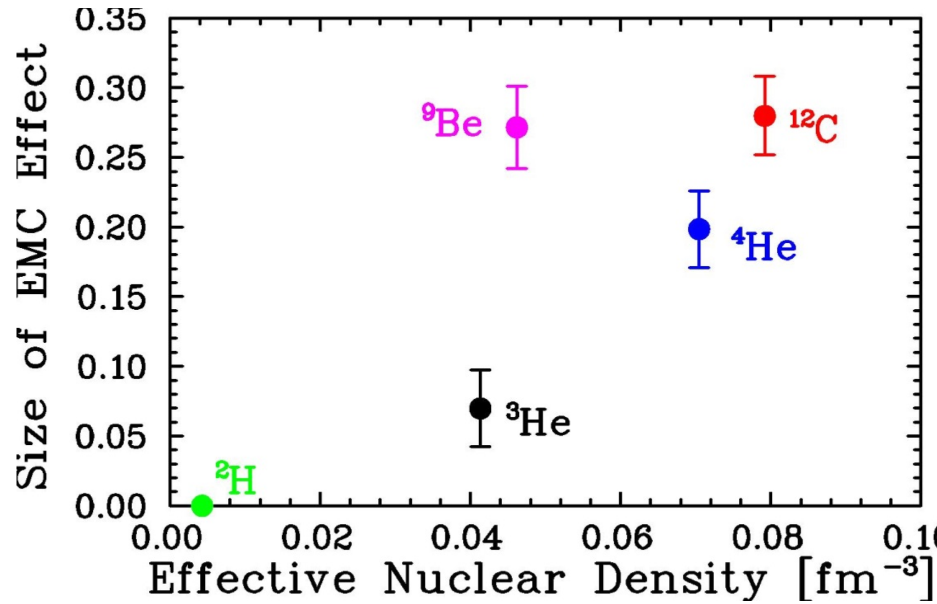
→ Focused on light nuclei

→ Large EMC effect for ^{9}Be

→ Local density/cluster effects?







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

E12-10-008: EMC effect at 12 GeV

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

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

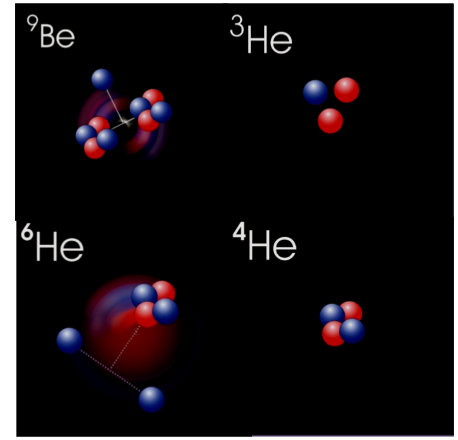
→ Heavy nuclei include ^{40}Ca, ^{48}Ca and Cu and additional heavy nuclei of particular interest for EMC-SRC correlation studies

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

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

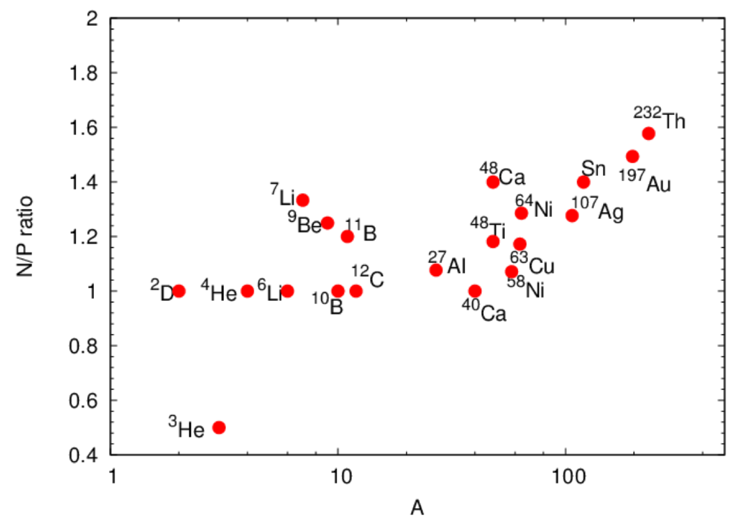
- Both experiments use wide range of nuclear targets to study impact of cluster structure, separate mass and isospin dependence on SRCs, nuclear PDFs

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



- Experiments will use a common set of targets to provide more information in the EMC-SRC connection

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



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

E12-10-008: Commissioning running

→ Ran with E12-10-002 at part of commissioning experiment run to make some initial EMC effect measurements

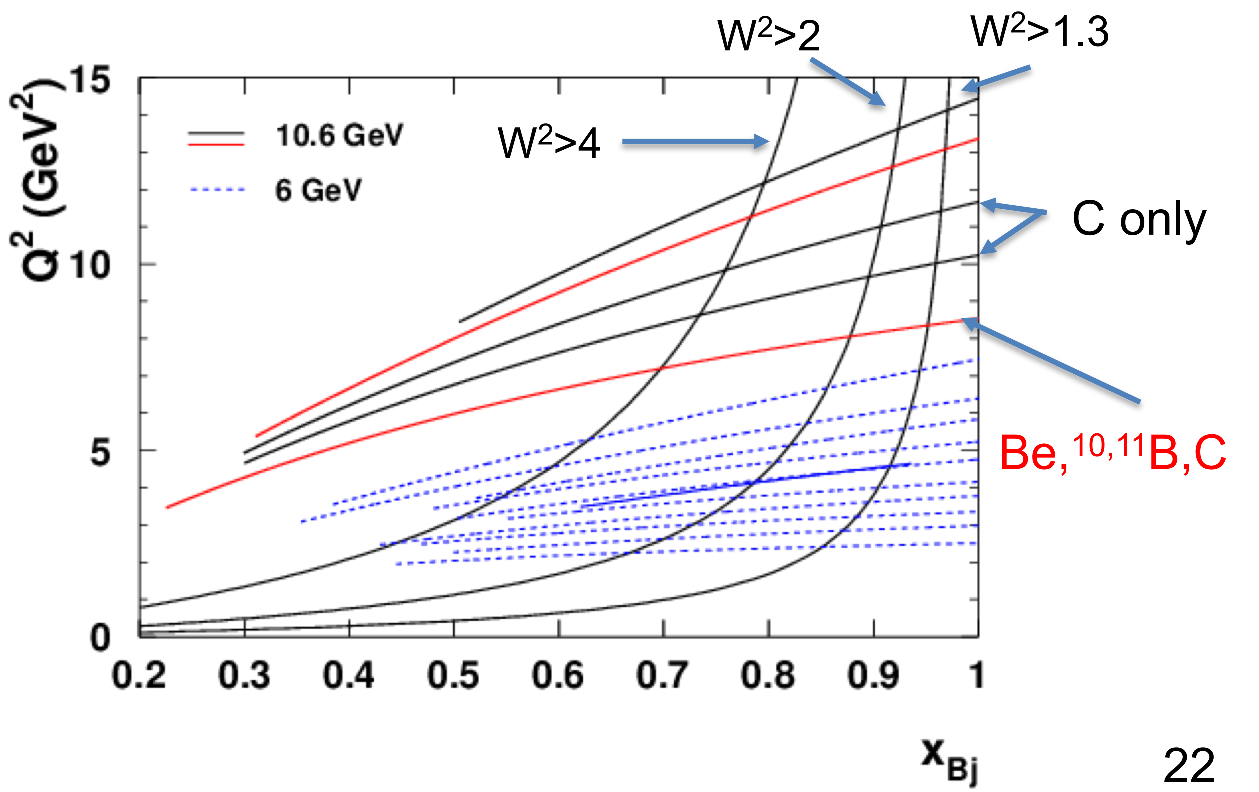
→ ~2 days used to:

1. Measure Q^2 dependence of EMC effect over range of x to check scaling of EMC ratio → carbon target
2. Obtain data on a few light nuclei at a single Q^2/angle (^{9}Be, ^{10}B, ^{11}B, C)

Full experiment:

→ All targets at 21 degrees, smaller subset at 35 degrees

→ 25,29,40 degrees used for Q^2 dependence tests w/Carbon

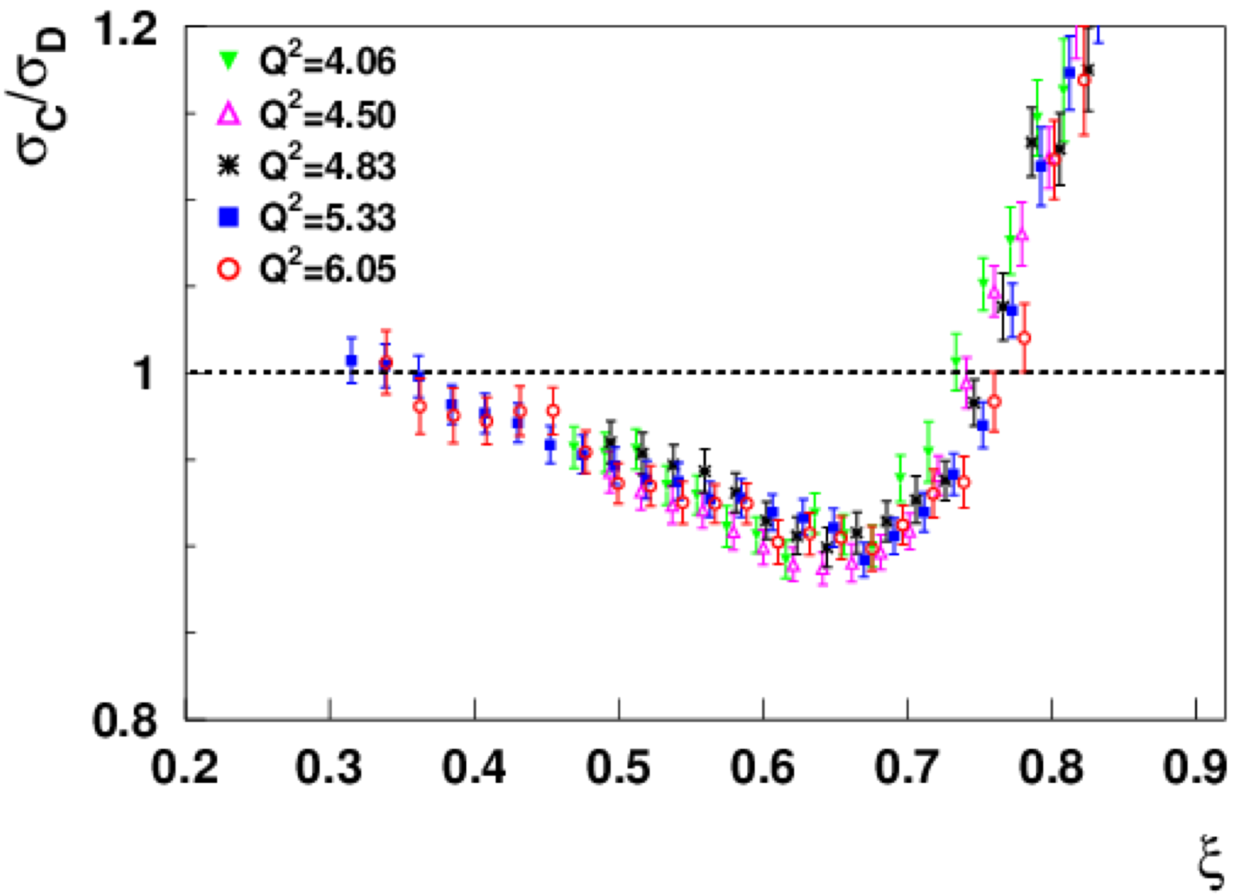


Summary

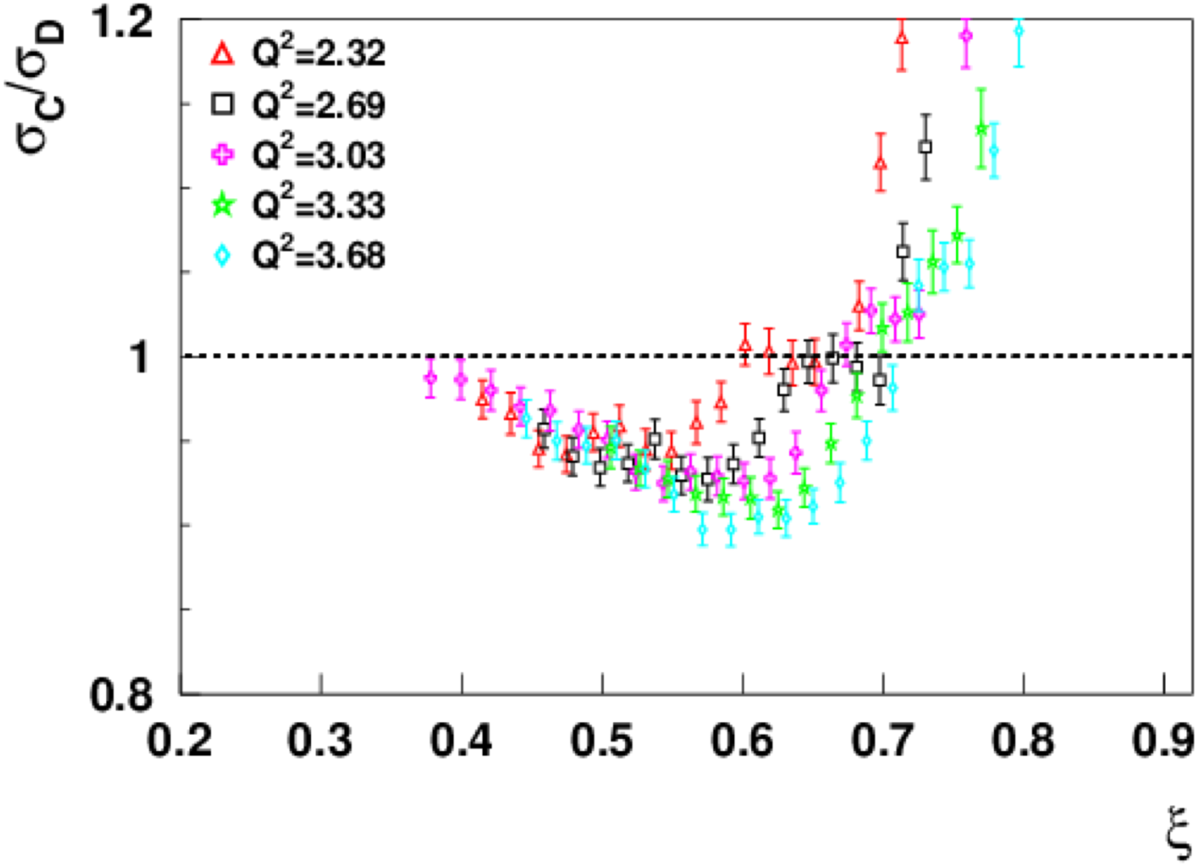
- Nuclear structure function ratios (EMC effect) appear to show scaling down to W^2=2 GeV^2 for Q^2>3 GeV^2 → consequence of duality + Fermi smearing in nucleus
  - Apparent scaling does not work as well for individual structure functions, unless studied as function of ξ
- Allows access to EMC effect measurements to rather large x (0.85) at 6 GeV beam energies
  - Larger x should be accessible with JLab 12 GeV measurements
  - Will ratios for W^2<2 GeV^2 scale at larger Q^2
- Precise EMC Effect measurements at large x provide test of the wave functions used in EMC effect calculations
- Applicability of duality (or not) in nuclear structure functions also relevant for neutrino experiments → Monte Carlo models

EXTRA

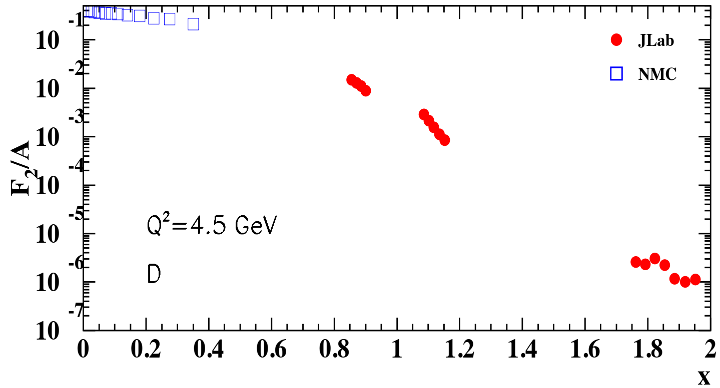
Carbon/^{2}H Ratio and Q^2 Dependence

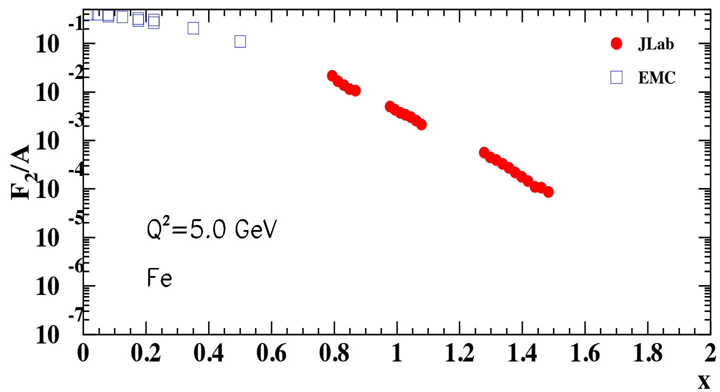


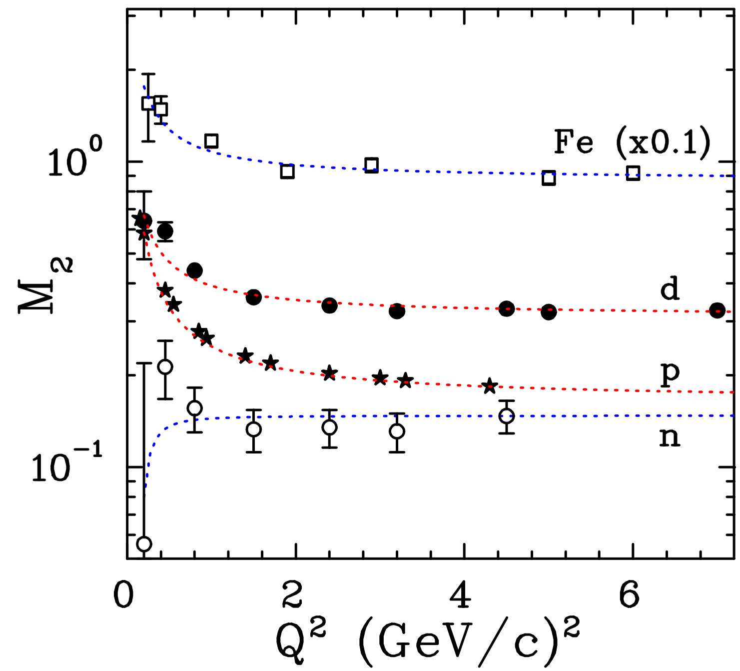
Carbon/^{2}H Ratio and Q^2 Dependence



Moments of Nuclear Structure Functions







Low Q^2, large x data used to calculate Cornwall-Norton moments

$$M_2(Fe) = Z \times M_2(p) + (A - Z) \times M_2(n)$$

*I. Niculescu, et al, PRC**73**,035205(2006)*