Argonne NATIONAL LABORATORY

... for a brighter future

New global study of the A-dependence of the EMC effect and the extrapolation to nuclear matter

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Work done in collaboration with:
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Outline

- **Introduction to the nucleon structure function and the EMC effect**

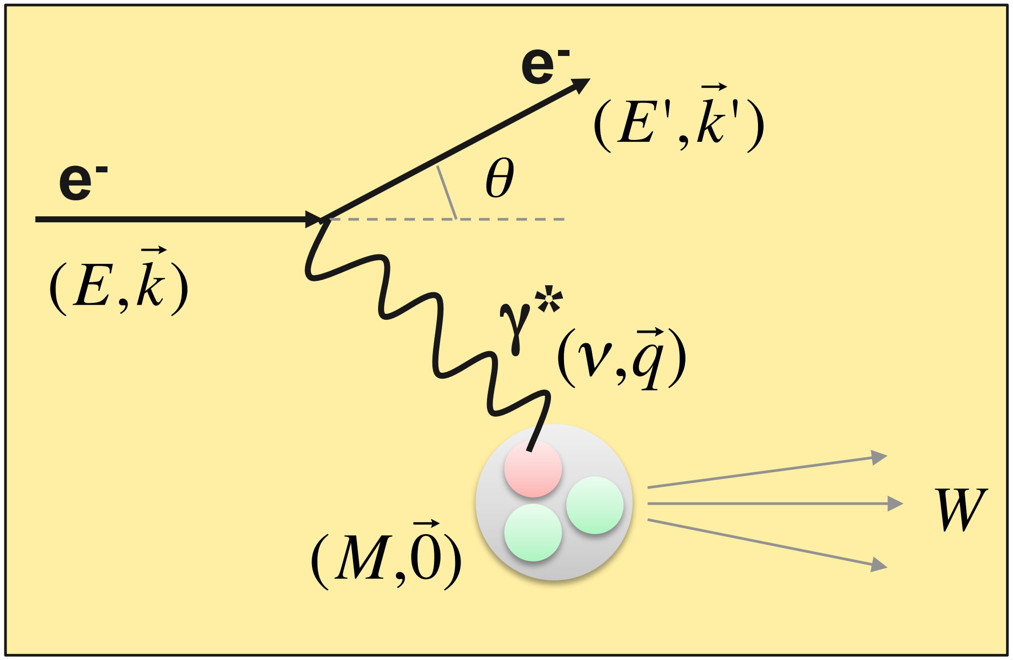
- **JLab E03-103 *close to final* results:**
  - ***Q^2-dependence study with Carbon***
  - ***Light nuclei***
  - ***Heavy nuclei and Coulomb distortion***

- **Global analysis**
  - ***Coulomb distortion***
  - ***Study of the A- and ρ-dependence***
  - ***New extrapolation to nuclear matter***

- **Summary and outlook**

The structure of the nucleon

Deep inelastic scattering ➔ probe the constituents of the nucleon: the quarks and the gluons



4-momentum transfer squared

$$Q^2 = -q^2 = 4EE'\sin^2\tfrac{\theta}{2}$$

Invariant mass squared

$$W^2 = M^2 + 2M\nu - Q^2$$

Bjorken variable

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

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\tfrac{\theta}{2}\right]$$

The structure of the nucleon

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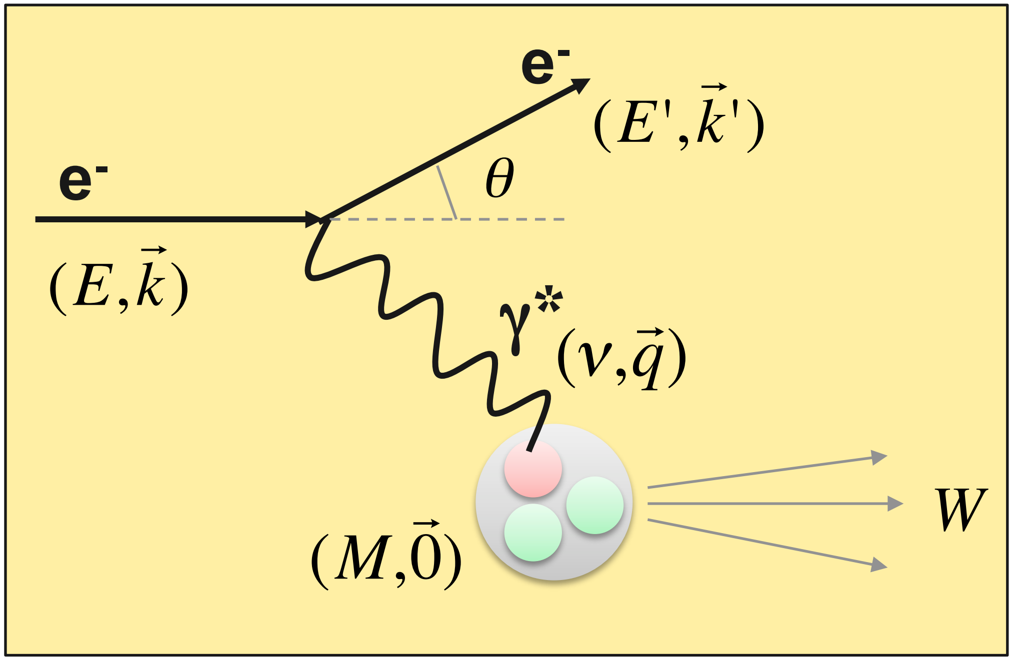


4-momentum transfer squared

$$Q^2 = -q^2 = 4EE'\sin^2\tfrac{\theta}{2}$$

Invariant mass squared

$$W^2 = M^2 + 2M\nu - Q^2$$

Bjorken variable

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

use to select DIS

~ momentum per quark

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\tfrac{\theta}{2}\right]$$

Structure functions in the parton model

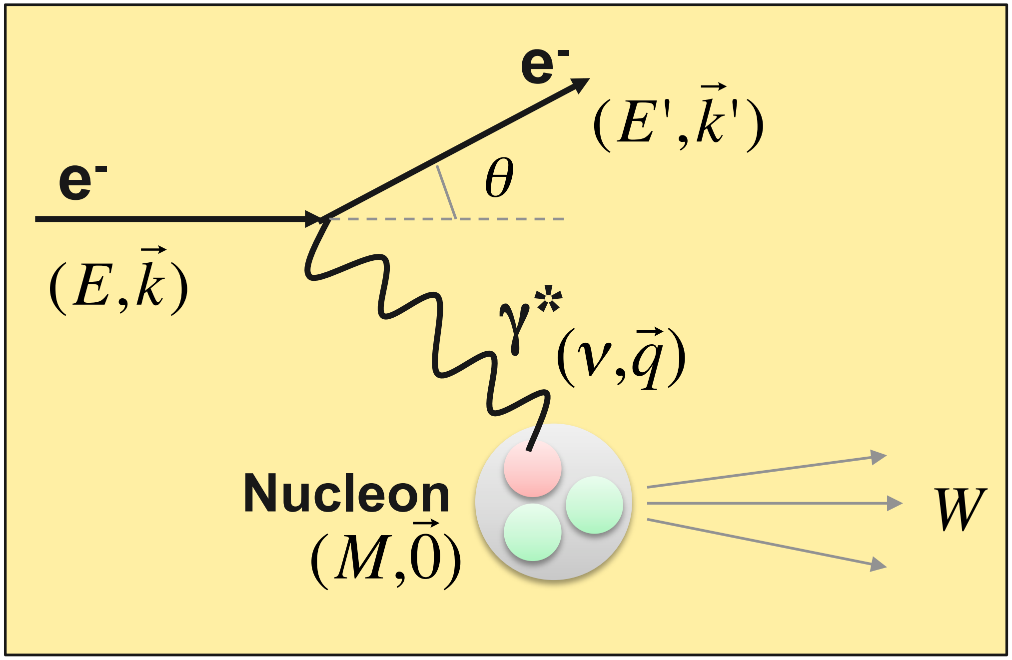
In the infinite-momentum frame, at high Q^2:

- no time for interactions between partons

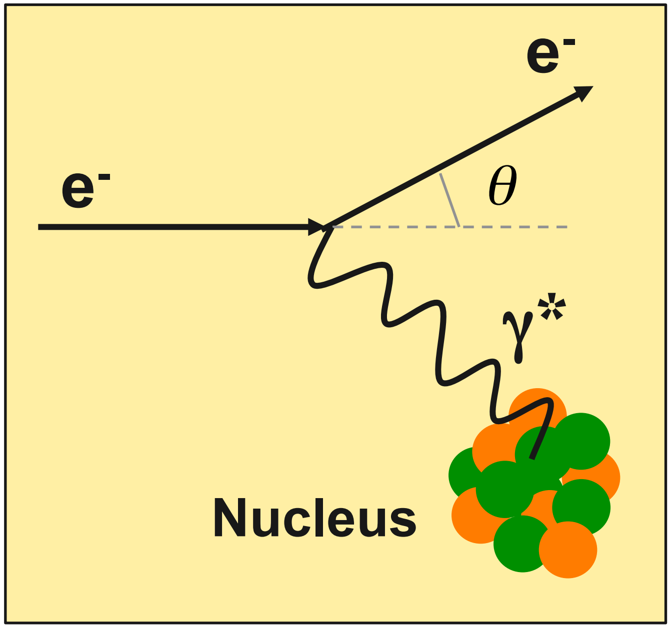
- Partons are point-like non-interacting particles: $\sigma_{\mathrm{Nucleon}} = \Sigma_i \, \sigma_i$

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 [q_i^{\uparrow}(x) + q_i^{\downarrow}(x)] = \frac{1}{2x} F_2(x)$$

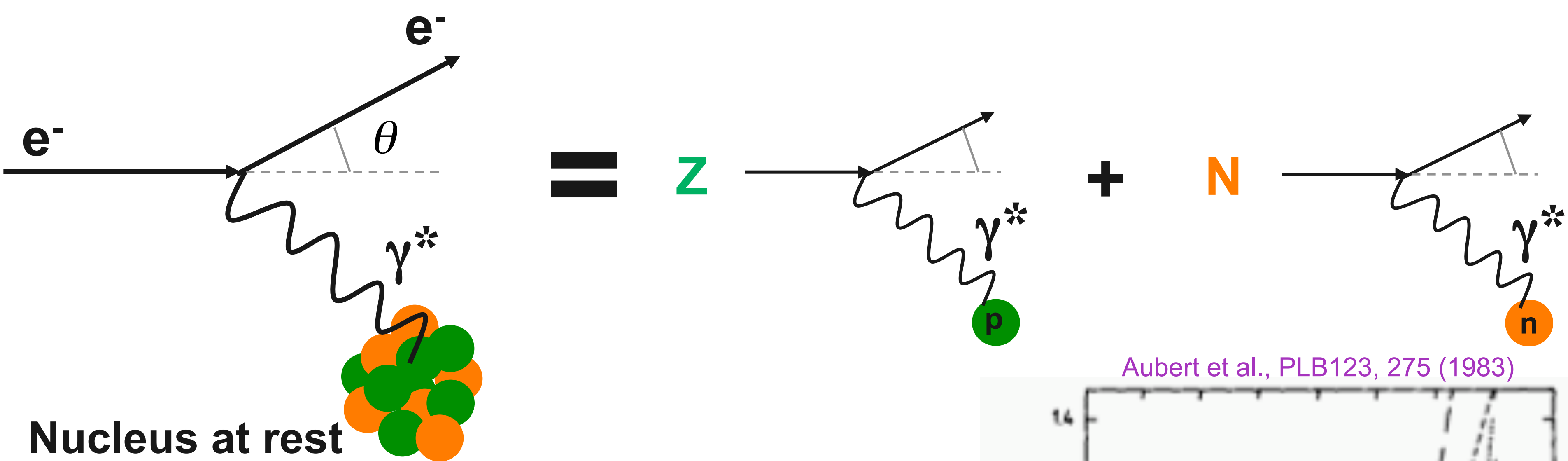
The quest for higher precision data



To increase the luminosity, physicists decided to use heavy nuclei to study the structure of the proton instead of a hydrogen target.



Discovery of the EMC effect



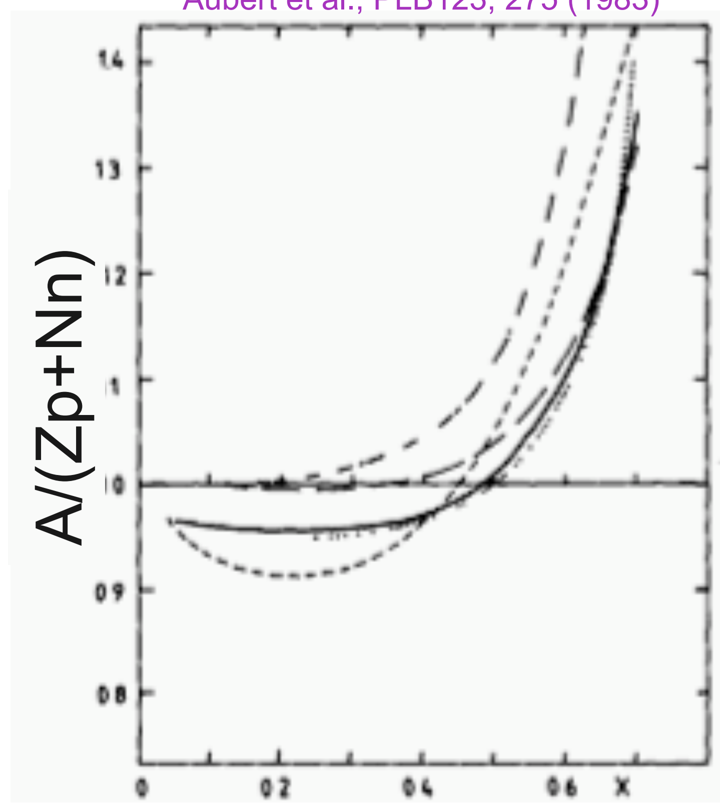
Nucleus at rest
(**A** nucleons = **Z** protons + **N** neutrons)

Theoretical prediction:

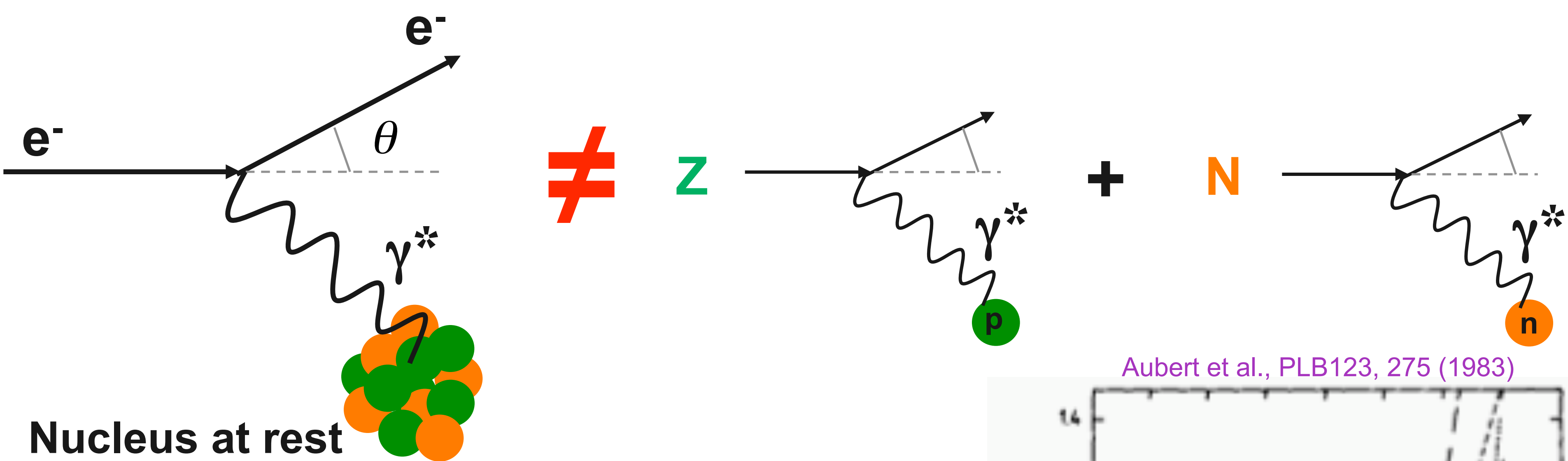
$$F_2^A = ZF_2^p + (A - Z)F_2^n$$

after corrections due to the motion of the nucleons in the nucleus (slowly moving nucleons weakly bound)

Aubert et al., PLB123, 275 (1983)



Discovery of the EMC effect

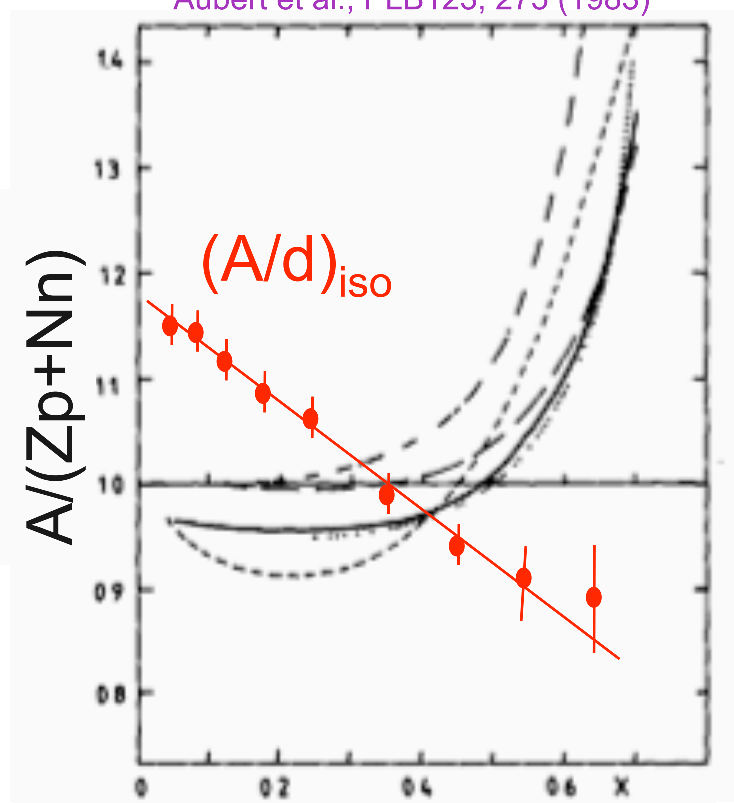


Nucleus at rest
(A nucleons = Z protons + N neutrons)

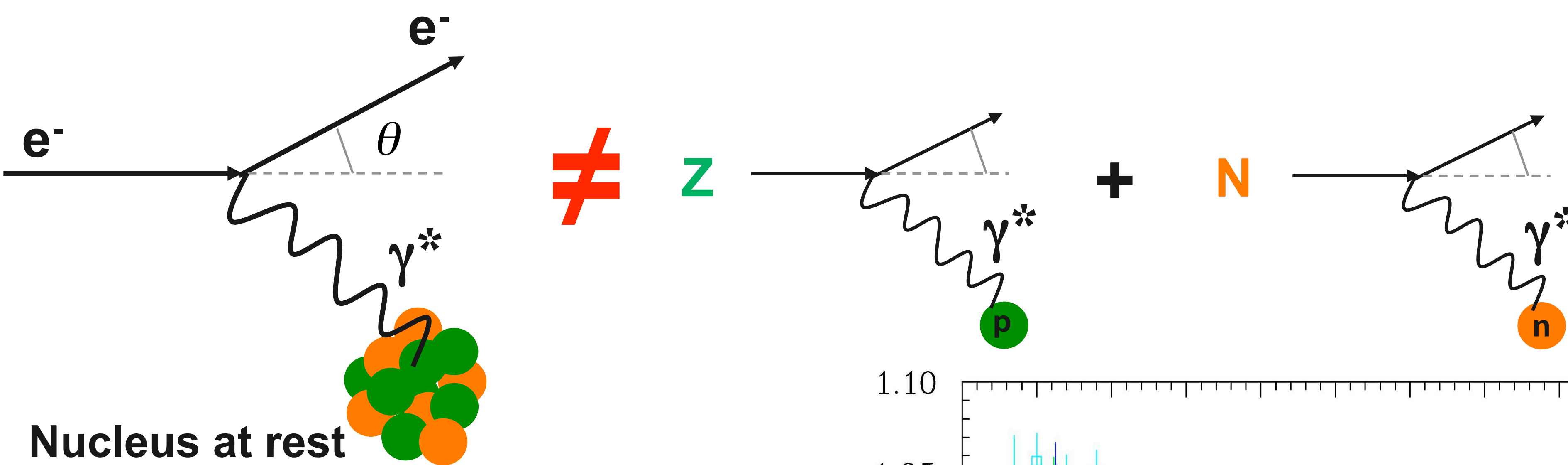
Nuclear structure:

$$F_2^A \neq ZF_2^p + NF_2^n$$

Aubert et al., PLB123, 275 (1983)

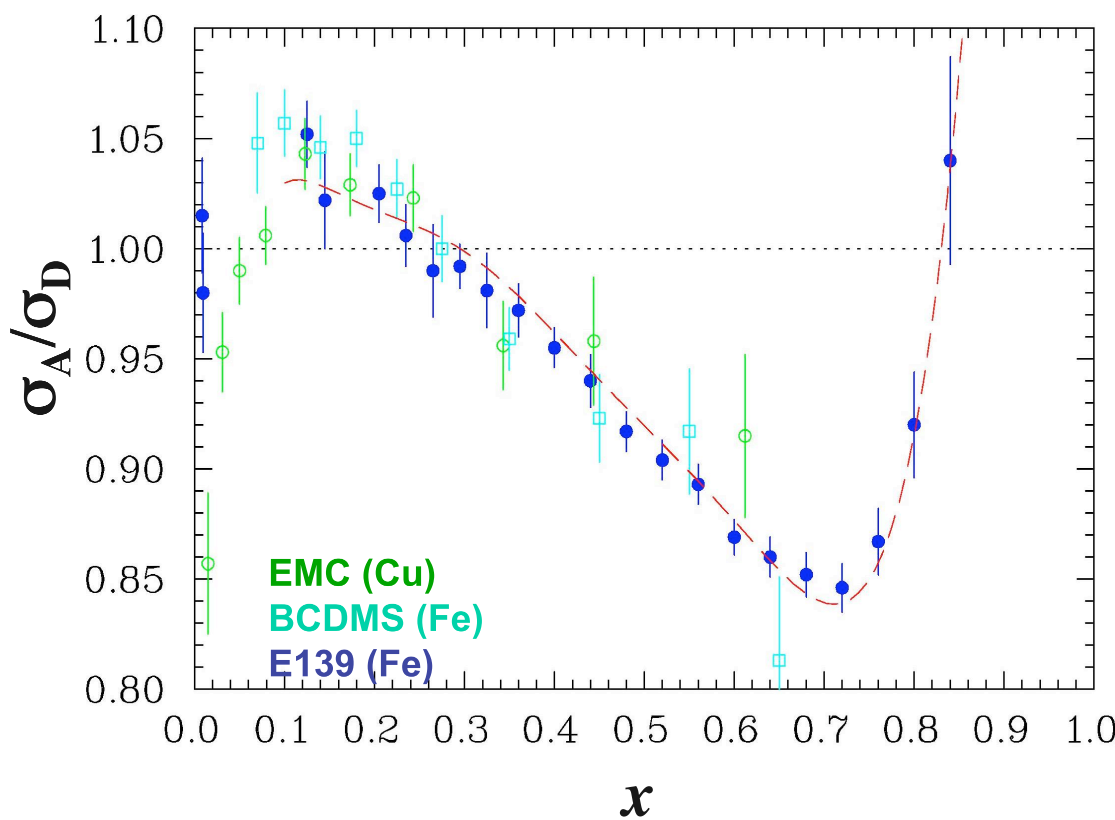


EMC effect confirmed



Nucleus at rest
(**A** nucleons = **Z** protons + **N** neutrons)

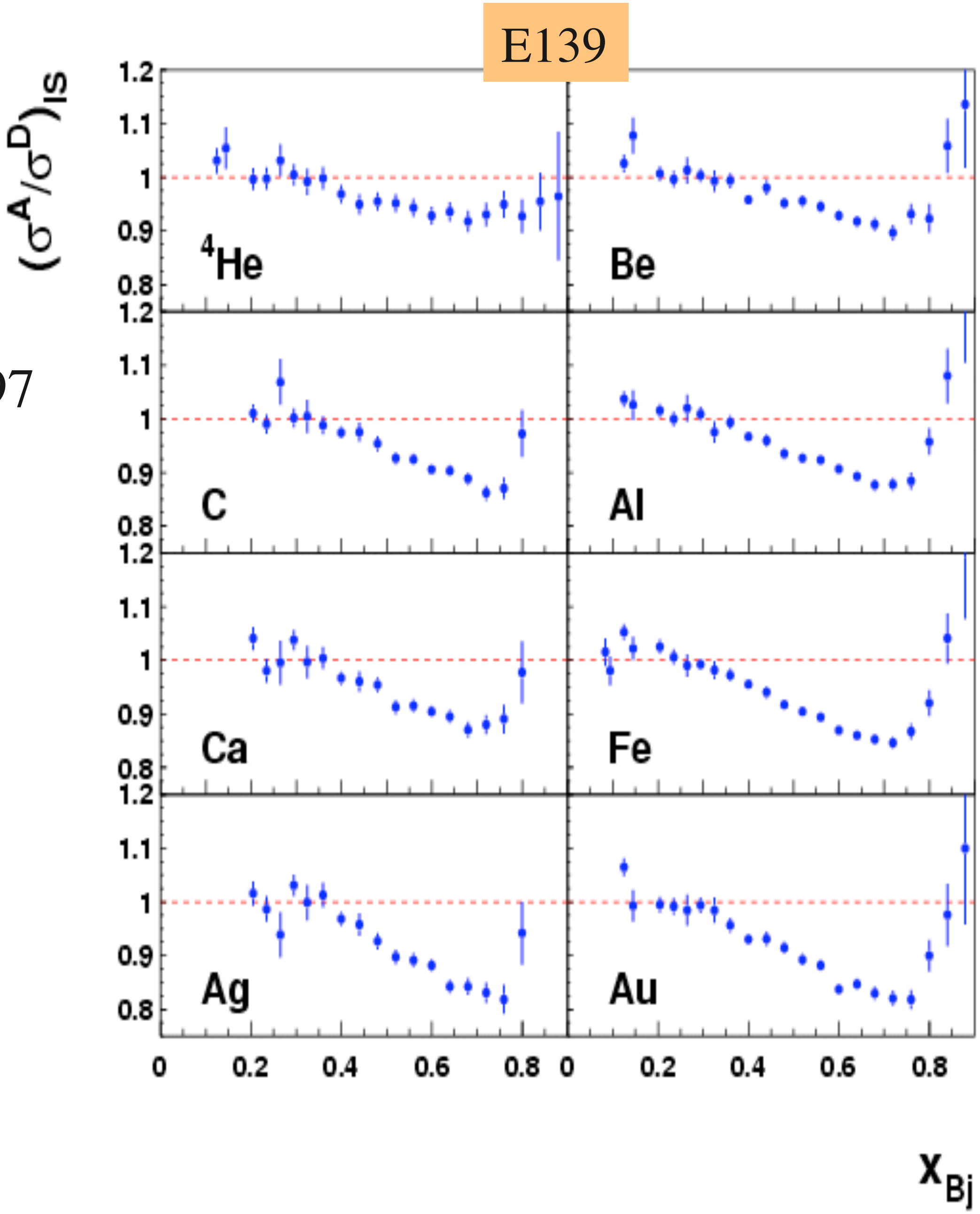
Effects found in several experiments at CERN, SLAC, DESY



Existing EMC Data

SLAC E139:

- Most complete data set: A=4 to 197
- Most precise at large *x*
  - → Q^2-independent
  - → universal shape
  - → magnitude dependent on A



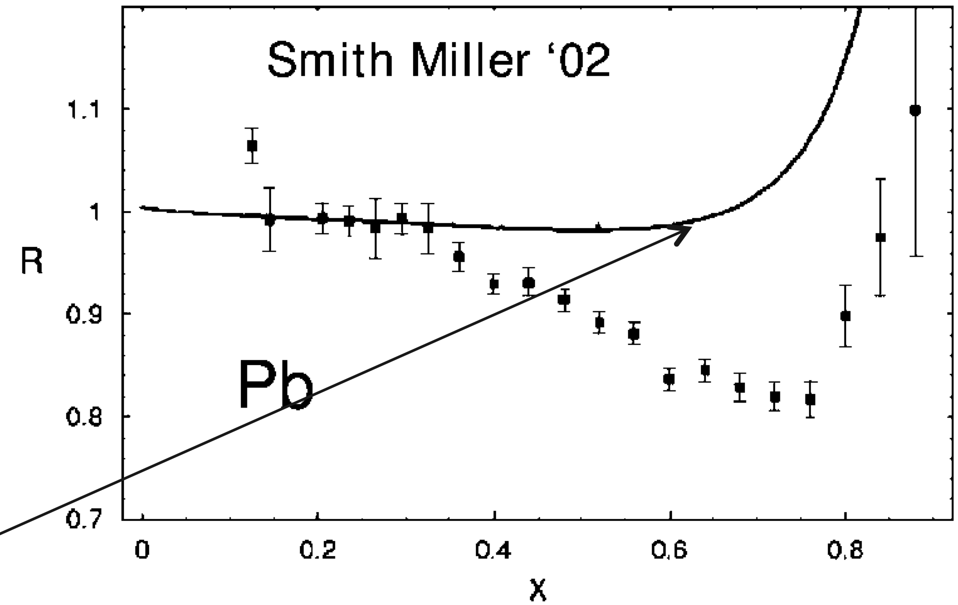
Nucleon only model

Assumptions on the nucleon structure function:

- *not modified in medium*
- *the same on and off the energy shell*

$$\frac{F_2^A(x_A)}{A} = \int_{x_A}^{A} dy \cdot f_N(y) F_2^N(x_A/y)$$

Smith & Miller,
PRC 65, 015211 and 055206 (2002)



Fermi momentum << $M_{nucleon}$

➔ $f_N(y)$ **is narrowly peaked and** $y \approx 1$

$$\frac{F_2^A}{A} \approx F_2^N$$ ➔ no EMC effect

"… some effect not contained within the conventional framework is responsible for the EMC effect." Smith & Miller, PRC 65, 015211 (2002)

Nucleons and pions model

Pion cloud is enhanced and pions carry an access of plus momentum:

$$P^+ = P_N^+ + P_\pi^+ = M_A$$

and using $P_\pi^+ / M_A = 0.04$ **is enough to reproduce the EMC effect**

But excess of nuclear pions ➔ enhancement of the nuclear sea

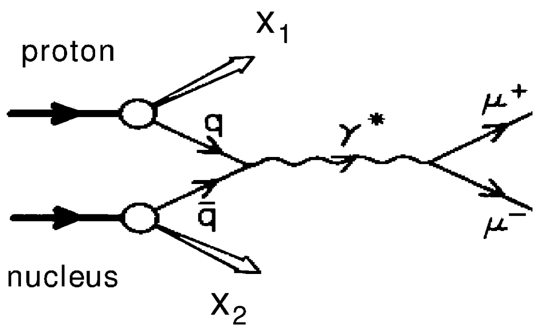
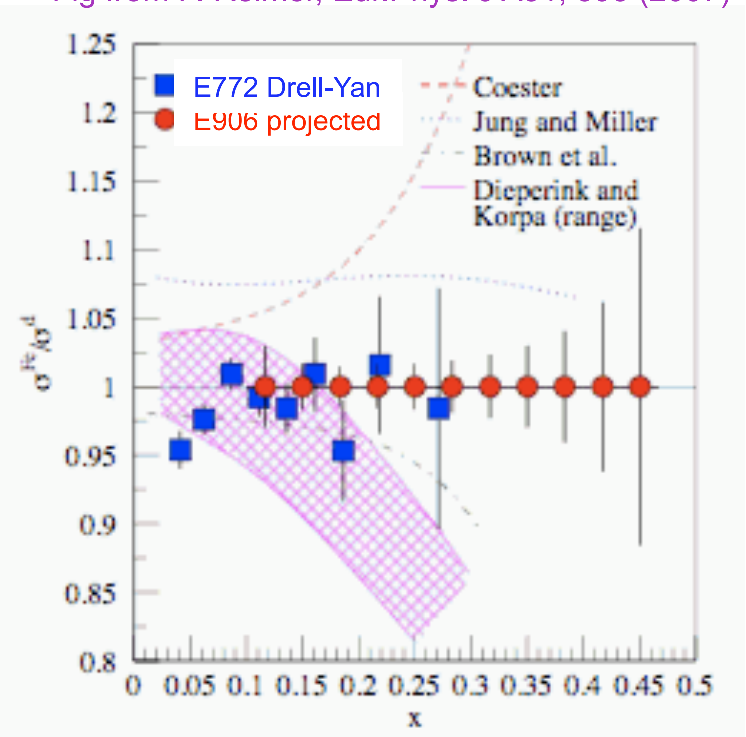


Fig from P. Reimer, Eur.Phys. J A31, 593 (2007)



But this enhancement was not seen in nuclear Drell-Yan reaction

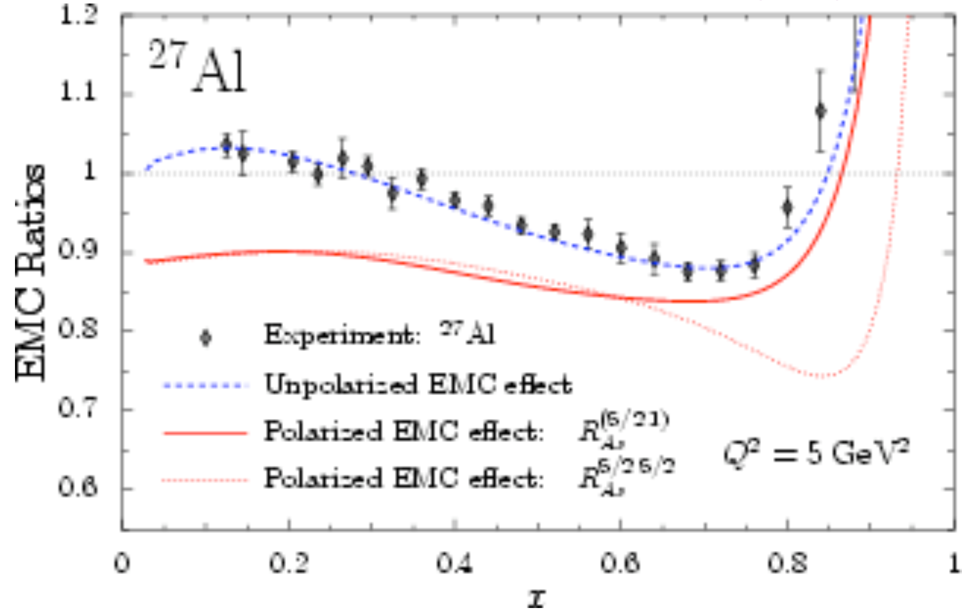
Another class of models

➔ **Interaction between nucleons**

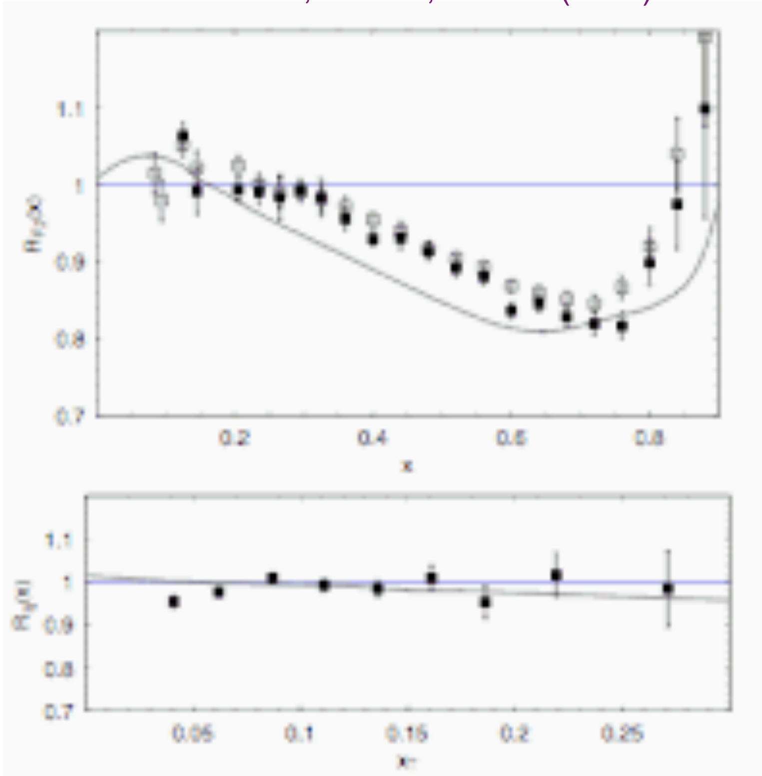
Model assumption:

nucleon wavefunction is changed by the strong external fields created by the other nucleons

Cloet, Bentz, and Thomas, PLB 642, 210 (2006)



Smith & Miller, PRL 91, 212301 (2003)



Model requirements:

- ***Momentum sum rule***
- ***Baryon number conservation***
- ***Vanishing of the structure function at x<0 and x>A***
- ***Should describe the DIS and DY data***

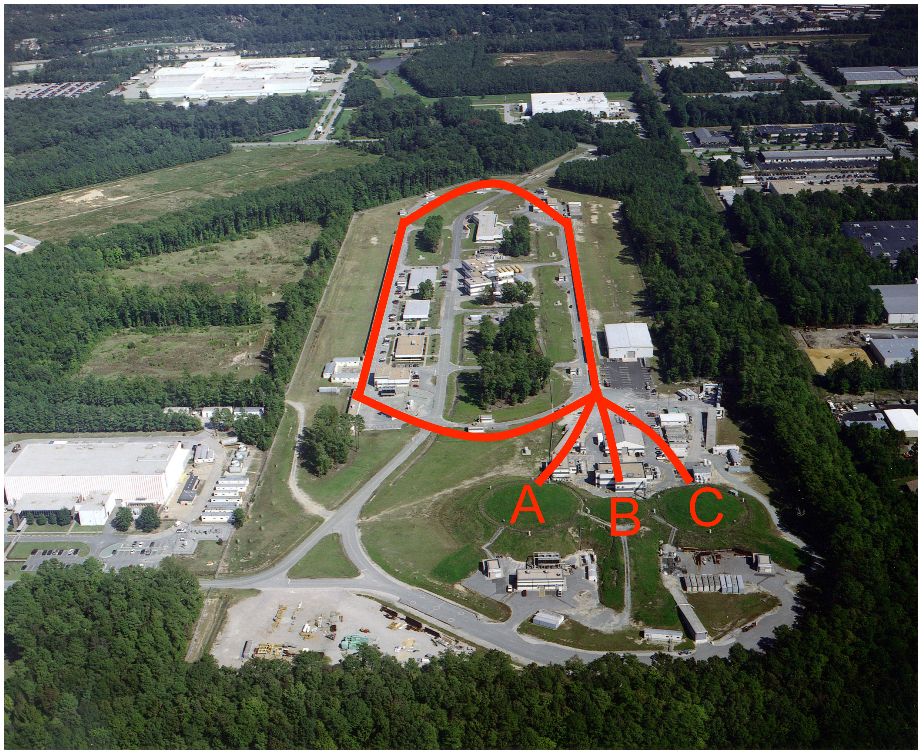
More data needed

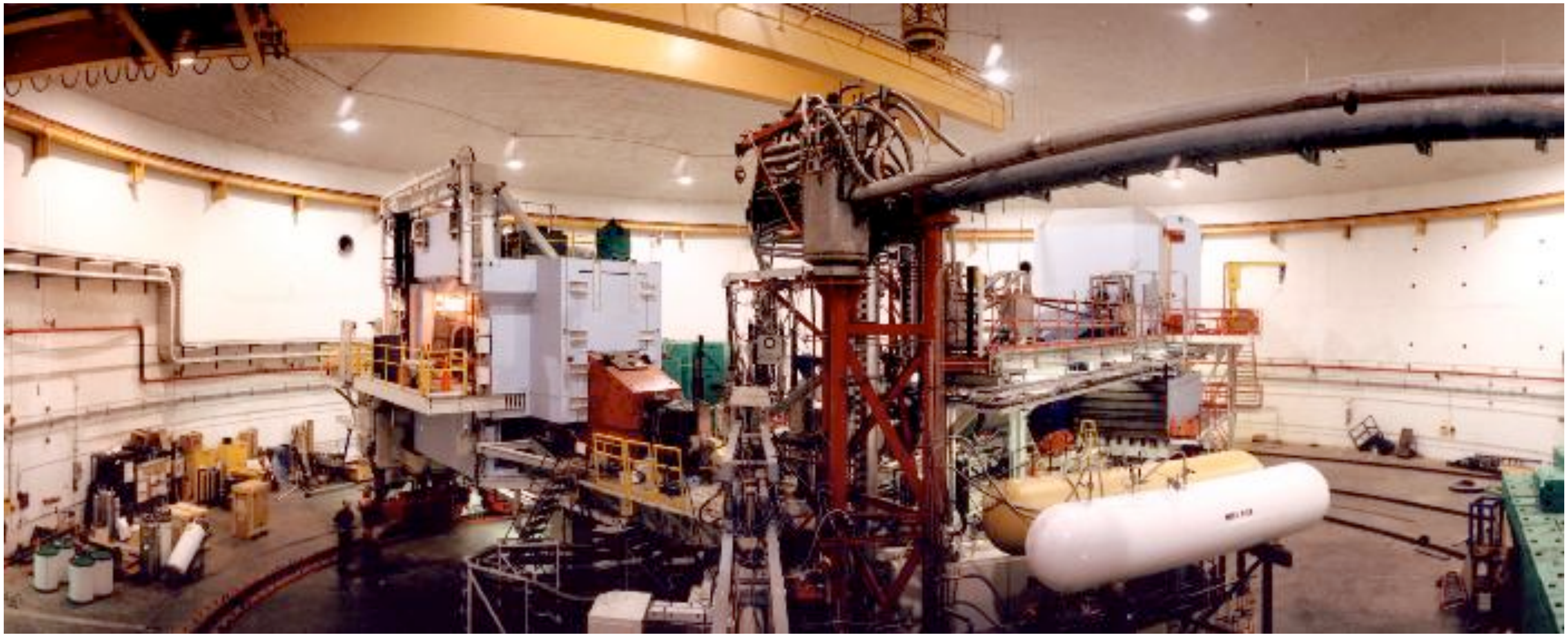
JLab E03-103 will improve with

- Higher precision data for ^{4}He
- Addition of ^{3}He data
- Precision data at large *x* for light and heavy nuclei

⇨ **Lowering Q^2 to reach high *x* region**

JLab and HallC





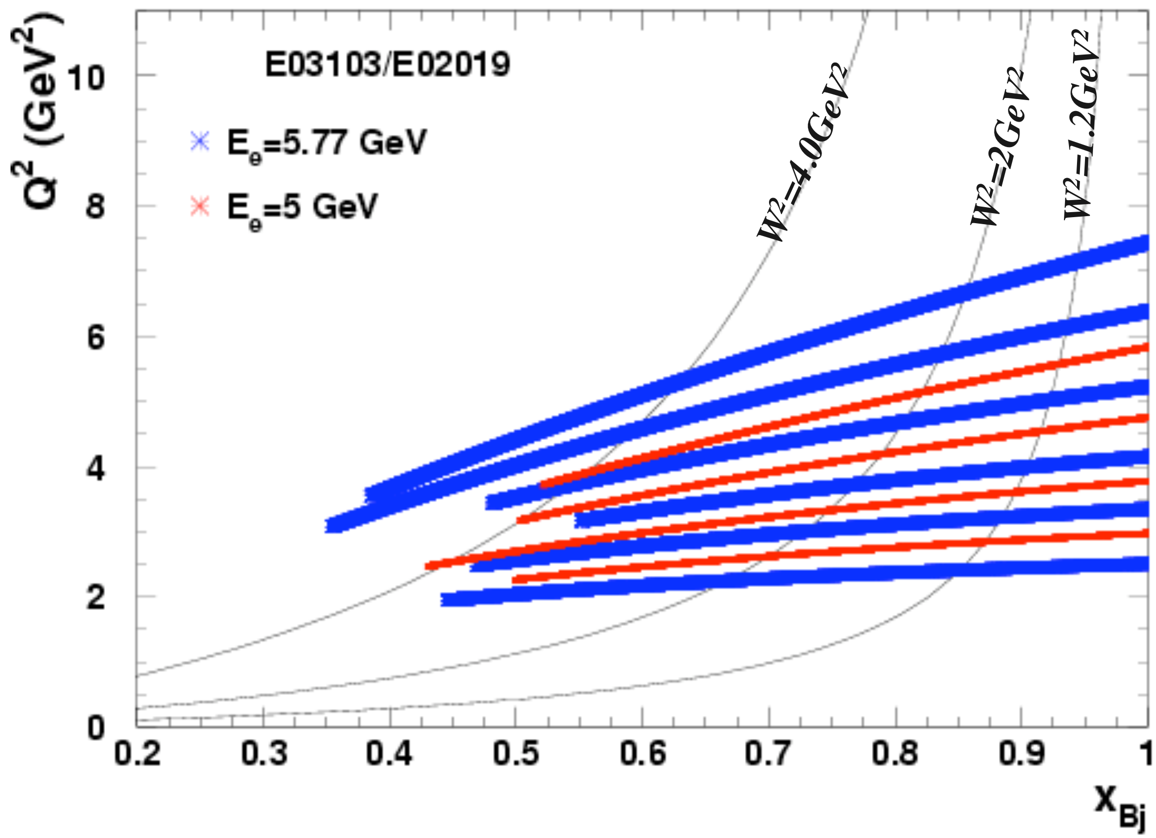
JLab Experiment E03-103

Spokespersons: D. Gaskell and J. Arrington
Post-doc: P. Solvignon
Graduate students: J. Seely and A. Daniel

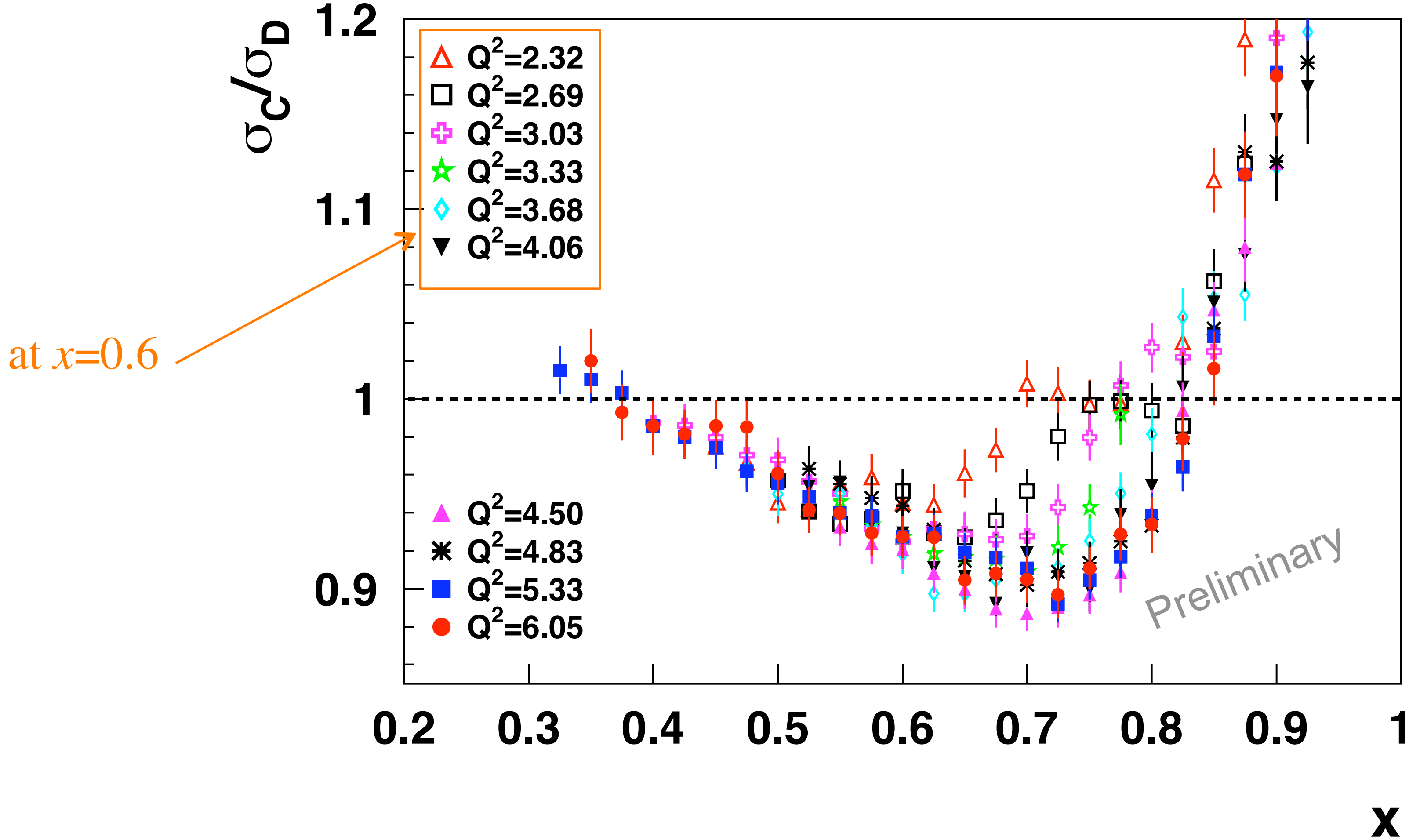
A(e,e') at 5.0 and 5.8 GeV in Hall C

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

- 10 angles to measure Q^2-dependence

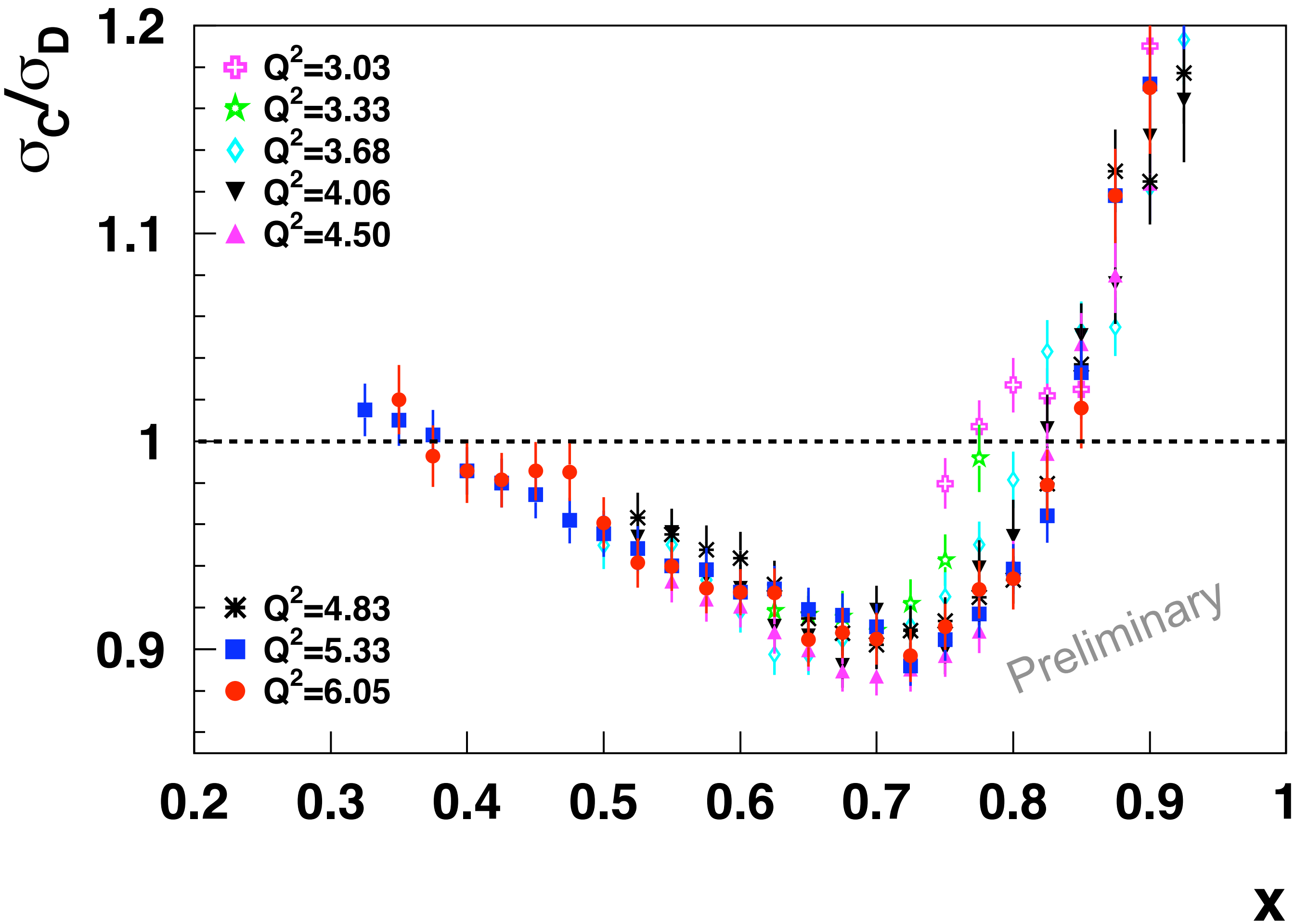


E03-103: Carbon EMC ratio and Q^2-dependence



Small angle, low Q^2 ➔ clear scaling violations for $x>0.6\text{-}0.7$

E03-103: Carbon EMC ratio and Q^2-dependence



At larger angles ➔ indication of scaling to very large x

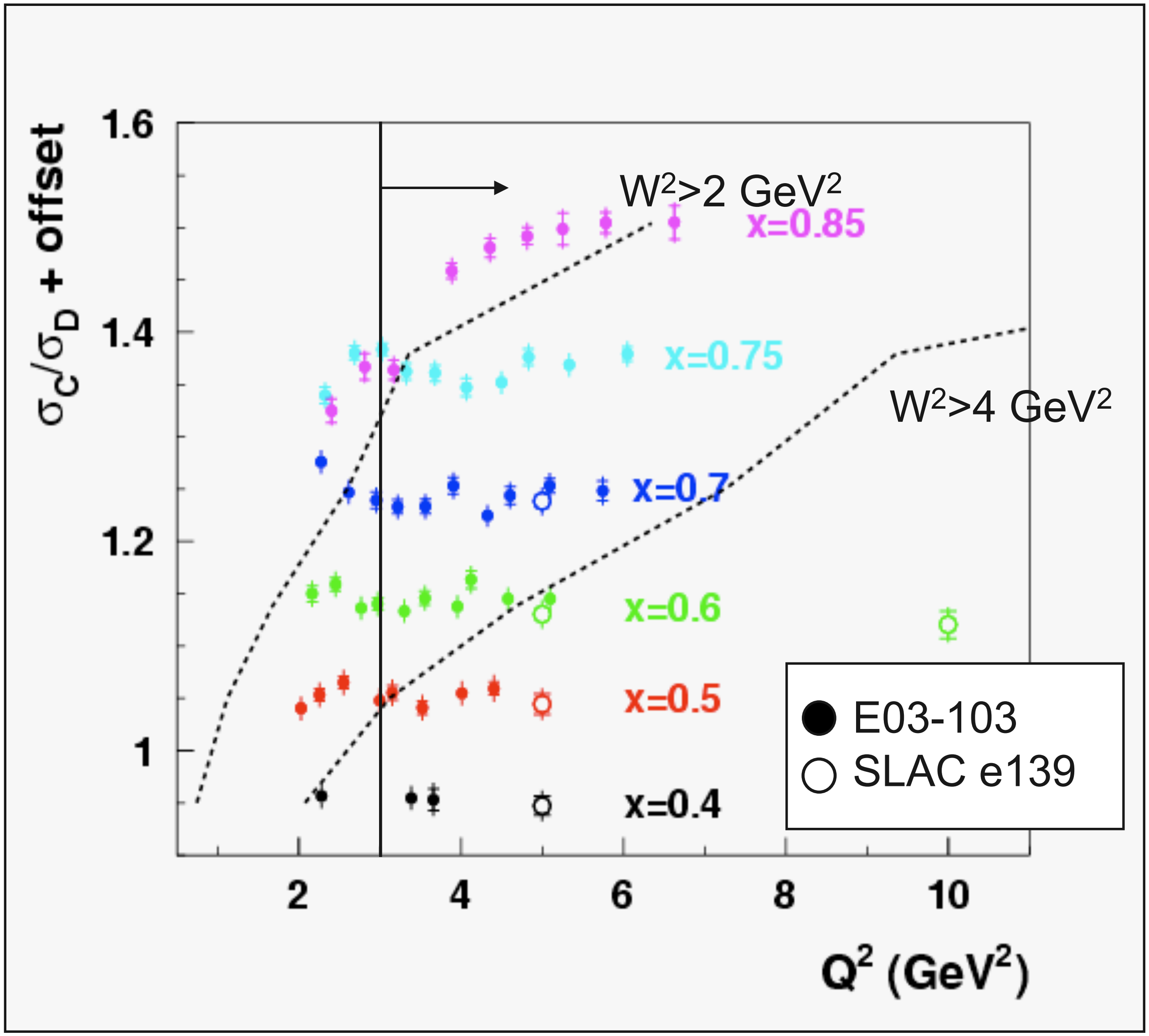
More detailed look at scaling

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

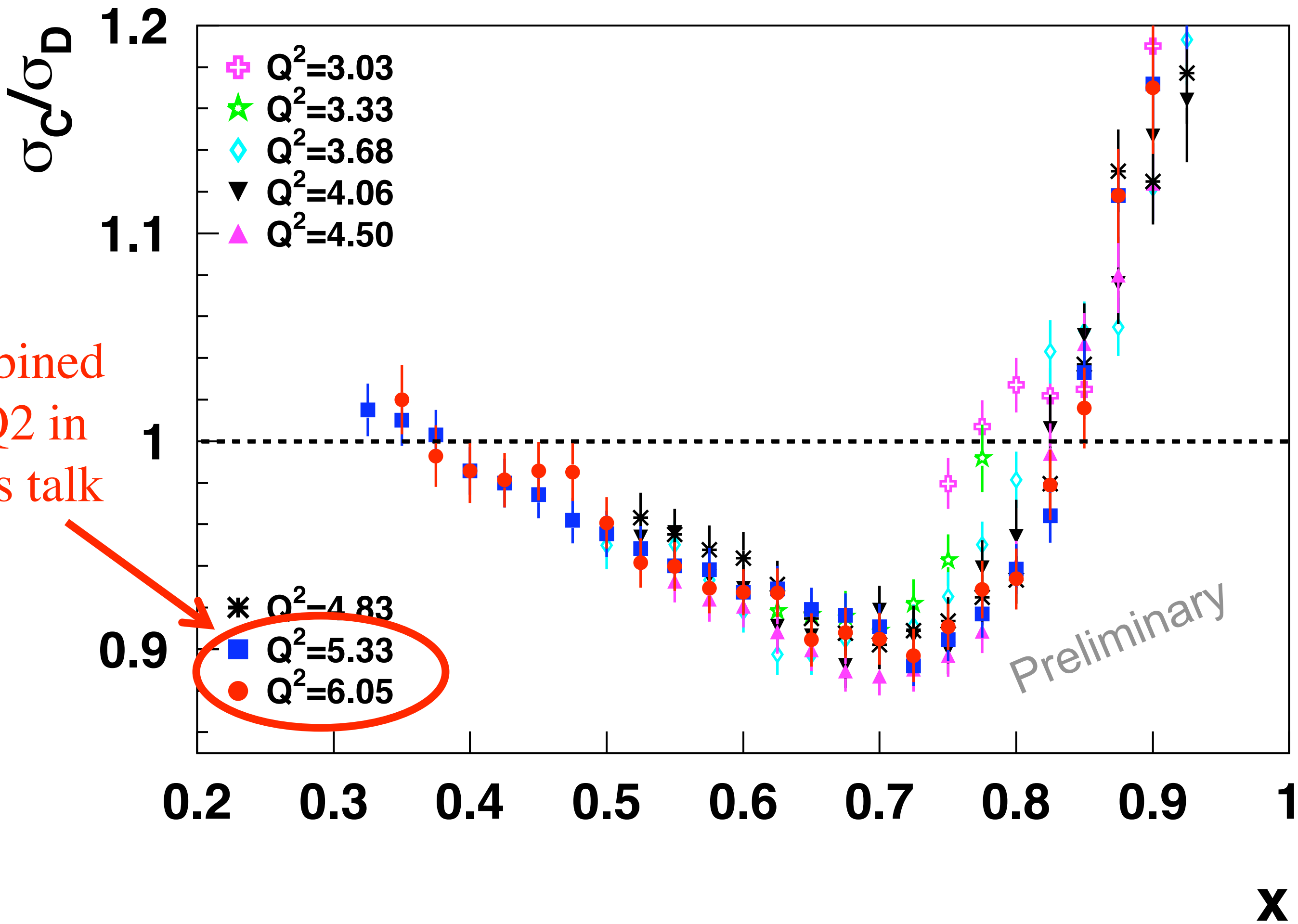
W^2>2 GeV^2
and
Q^2>3 GeV^2

limits E03-103 coverage to x=0.85

Note: Ratios at larger x will be shown, but could have small HT, scaling violation



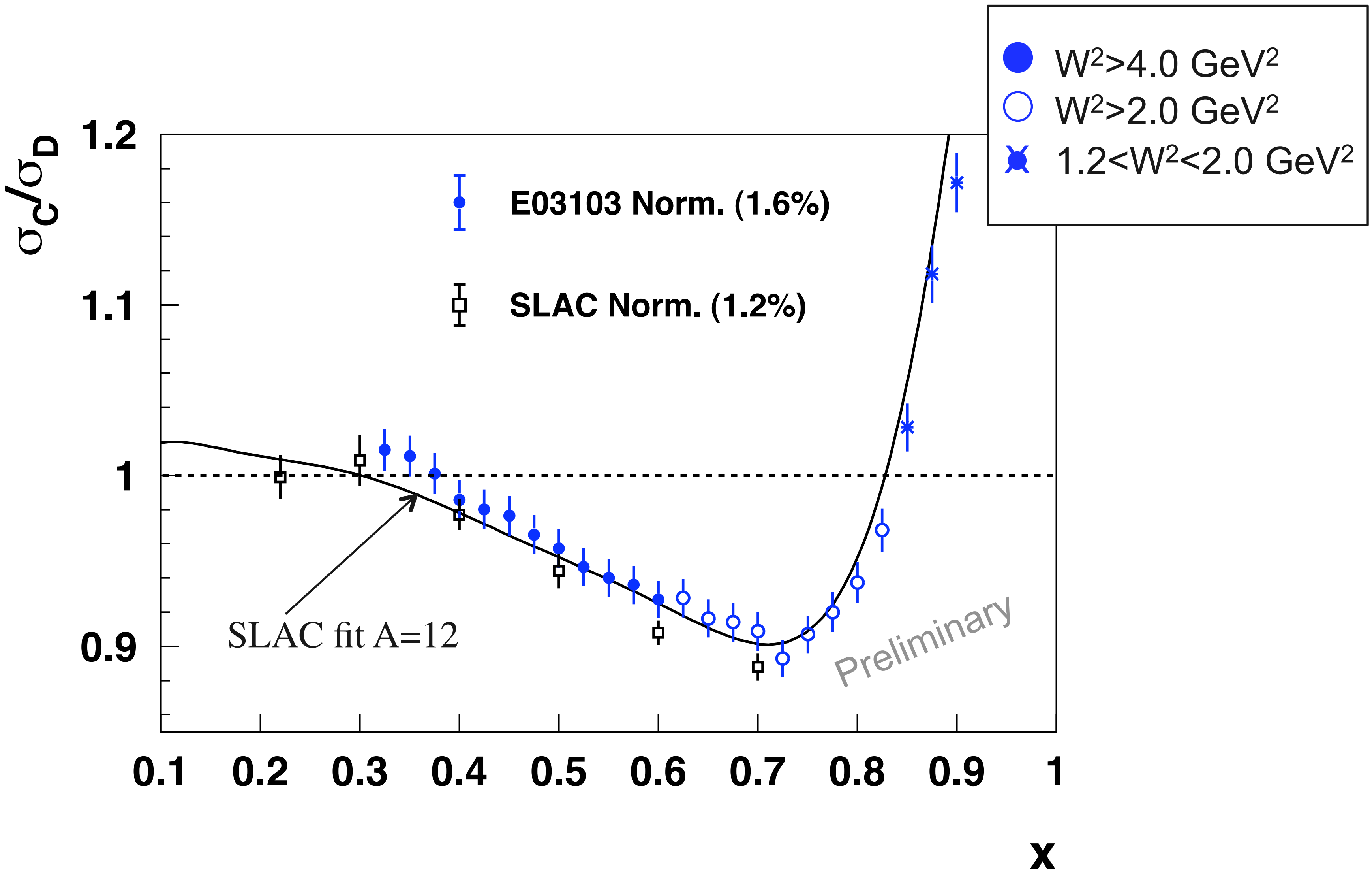
E03-103: Carbon EMC ratio and Q^2-dependence



Used the combined two highest Q2 in the rest of this talk

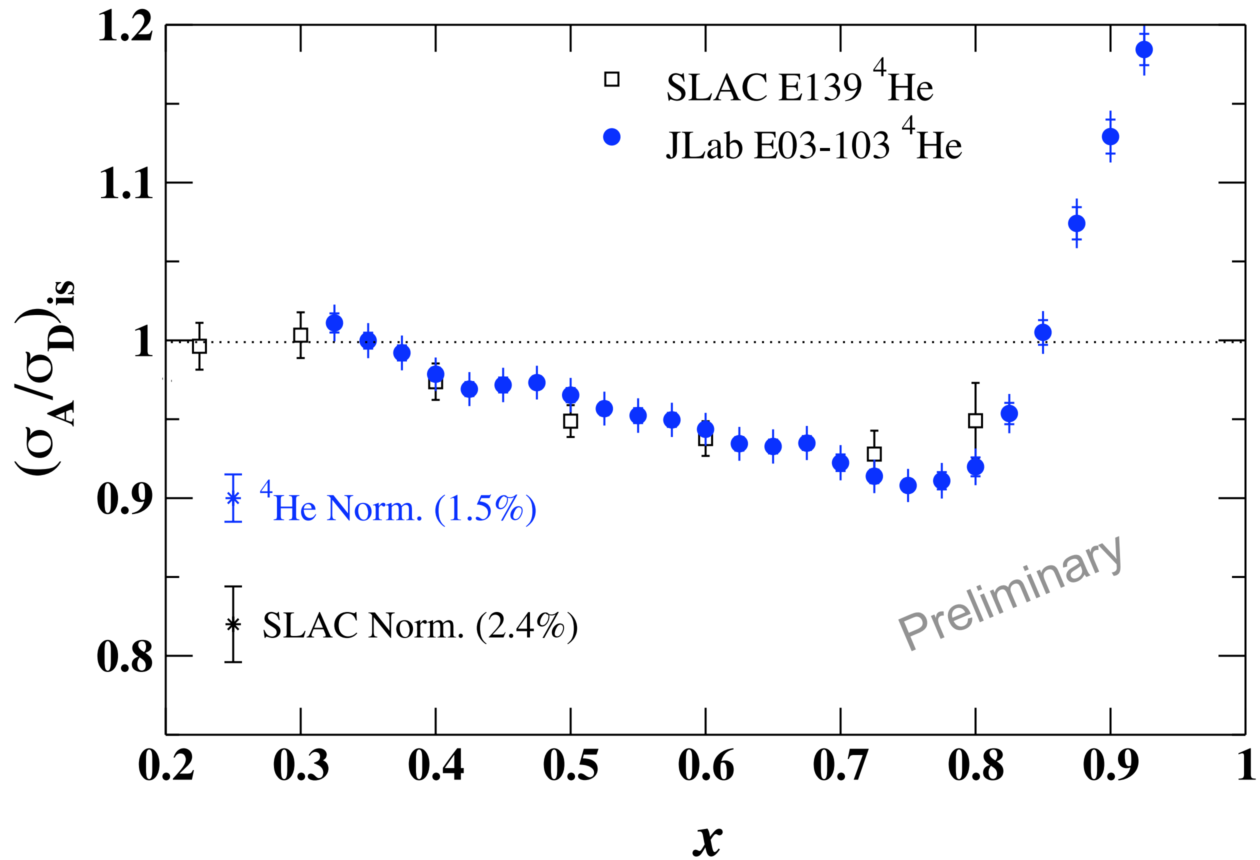
At larger angles ➔ indication of scaling to very large x

E03-103: Carbon EMC ratio



E03-103: ^4He EMC ratio

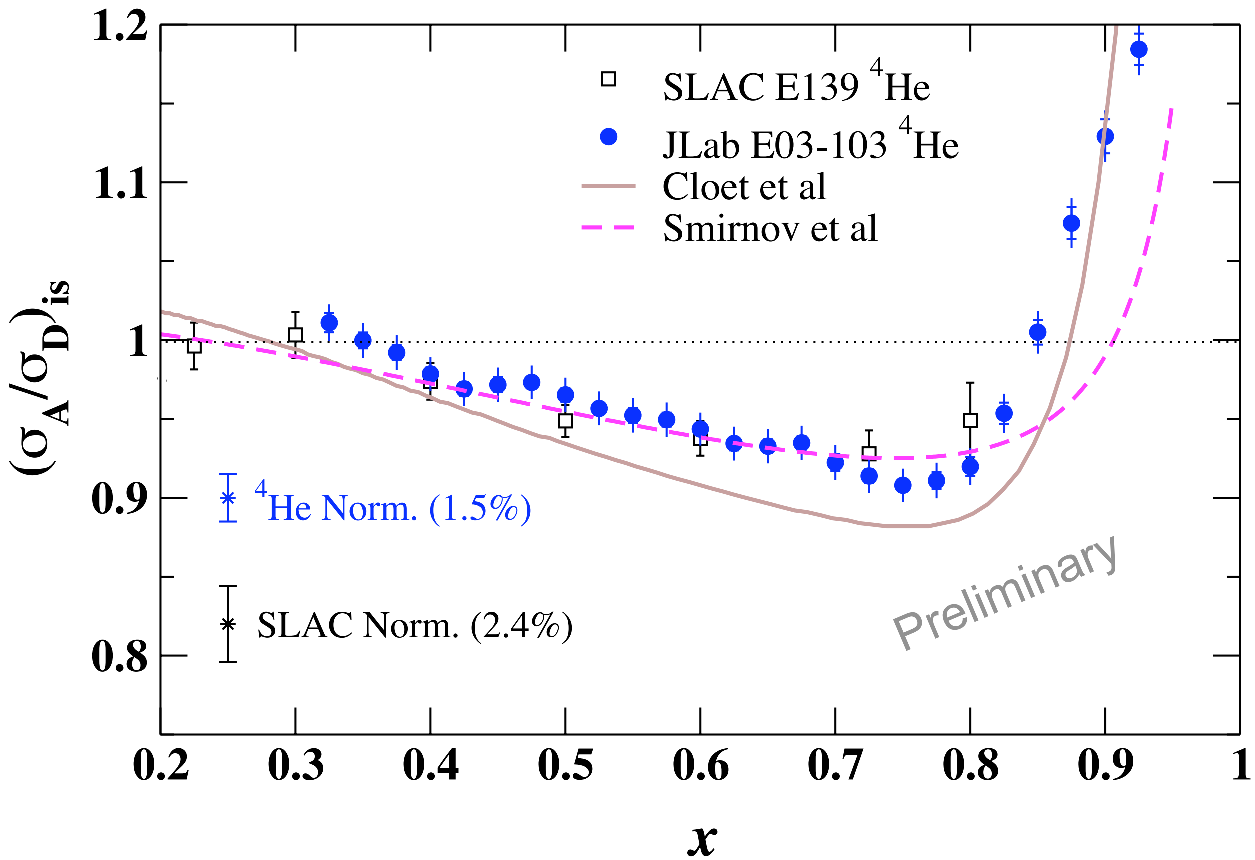
JLab results consistent with SLAC E139
→Improved statistics and systematic errors



E03-103: ^{4}He EMC ratio

JLab results consistent with SLAC E139
→Improved statistics and systematic errors

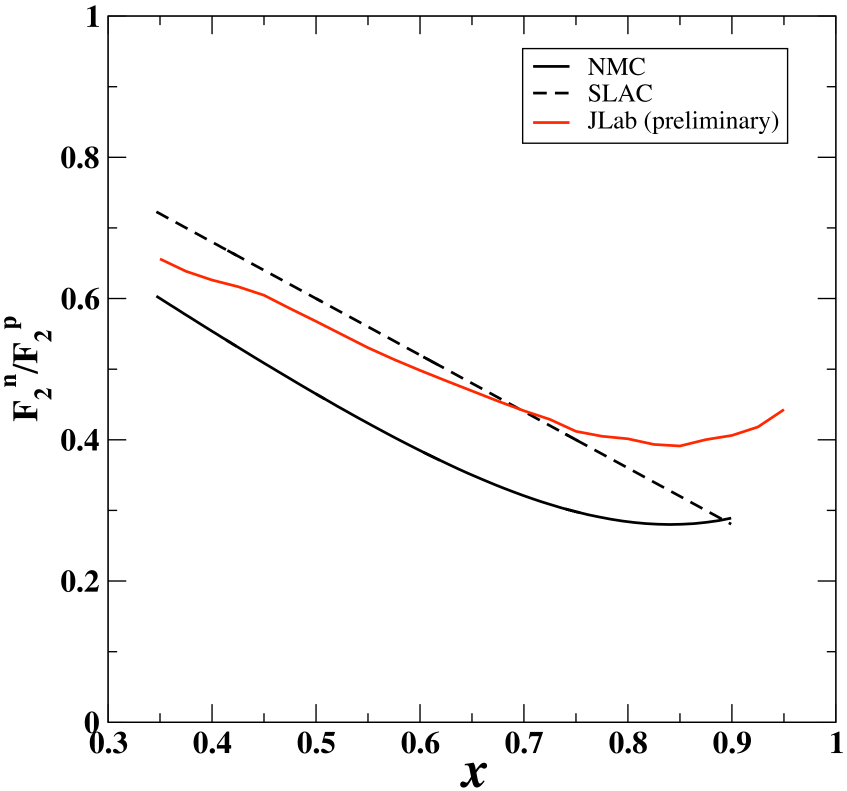
Models shown do a reasonable job describing the data, but very few real few-body calculations (most neglect structure, scale NM)



Isoscalar correction

$$R_{EMC} = \frac{\sigma_2^A / A}{\sigma_2^D / 2} \cdot \frac{(p+n)/2}{(Zp + Nn)/A}$$

Isoscalar correction



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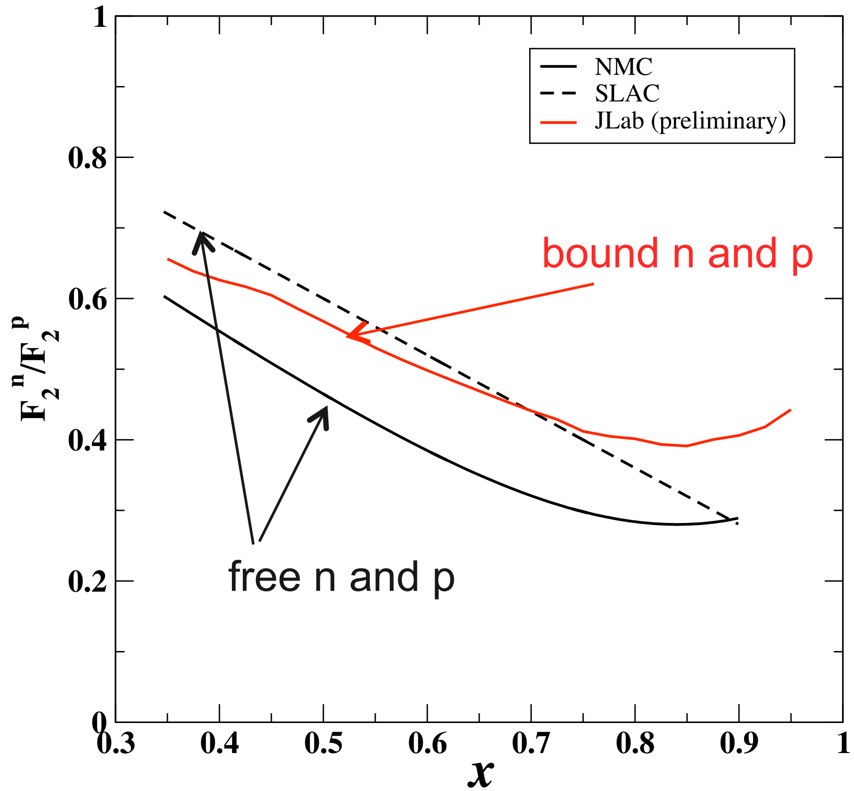
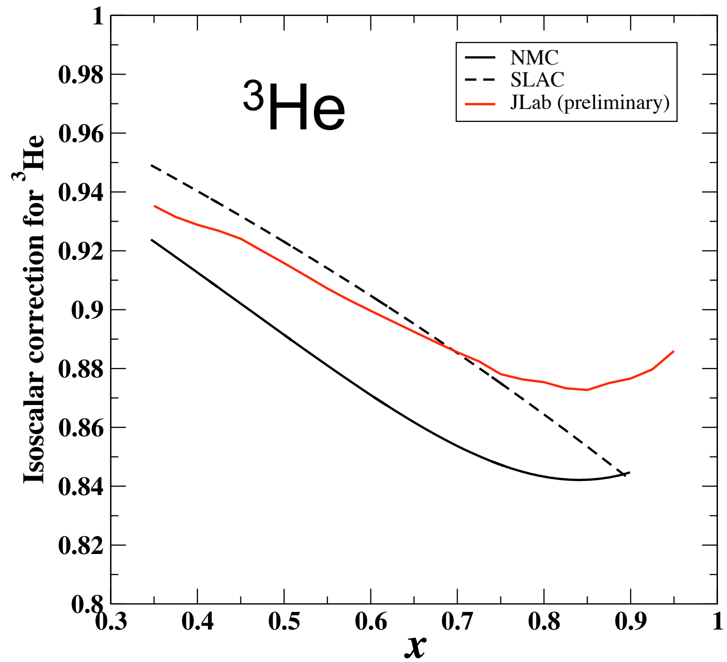
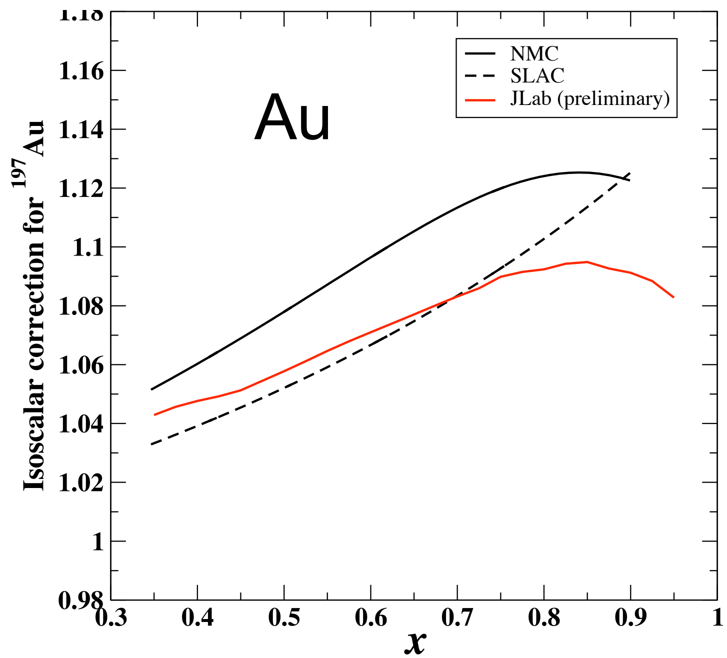
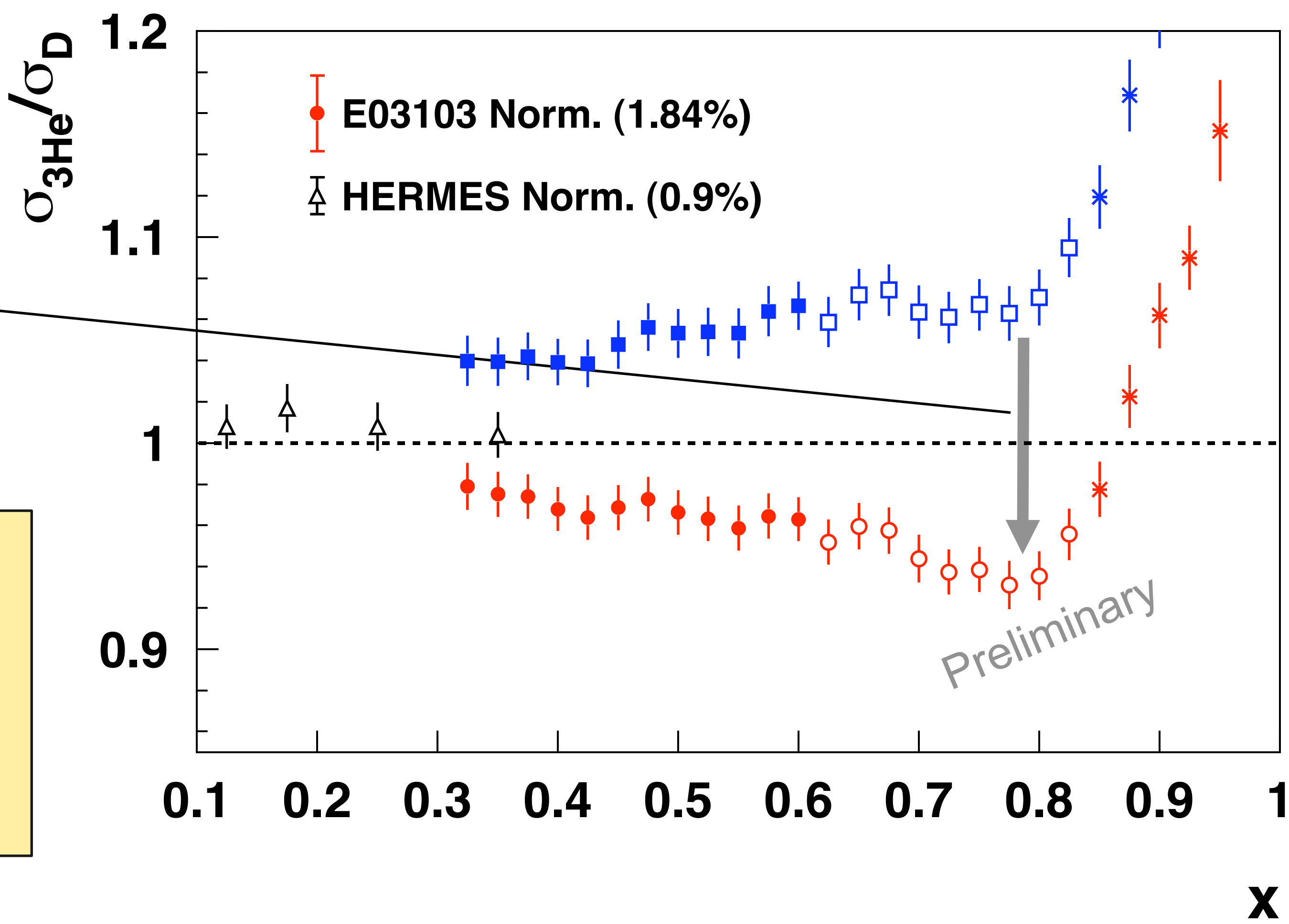
Isoscalar correction







E03-103: ^3He EMC ratio



Isoscalar correction done using ratio of bound neutron to bound proton at E03-103 kinematics

Coulomb distortions on heavy nuclei

Initial (scattered) electrons are accelerated (decelerated) in Coulomb field of nucleus with *Z* protons

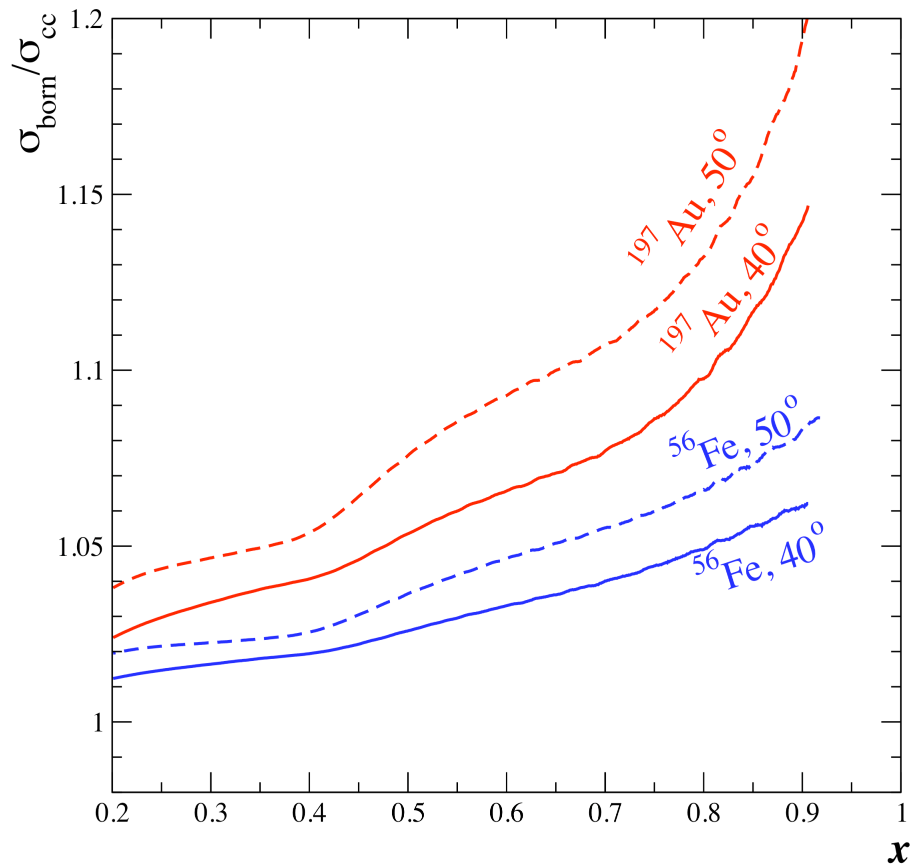
- Not accounted for in typical radiative corrections
- Usually, not a large effect at high energy machines
- Important for E'<<E (e.g. large θ, *x*)

E03-103 uses modified Effective Momentum Approximation (EMA)

Aste and Trautmann, Eur, Phys. J. A26, 167-178(2005)

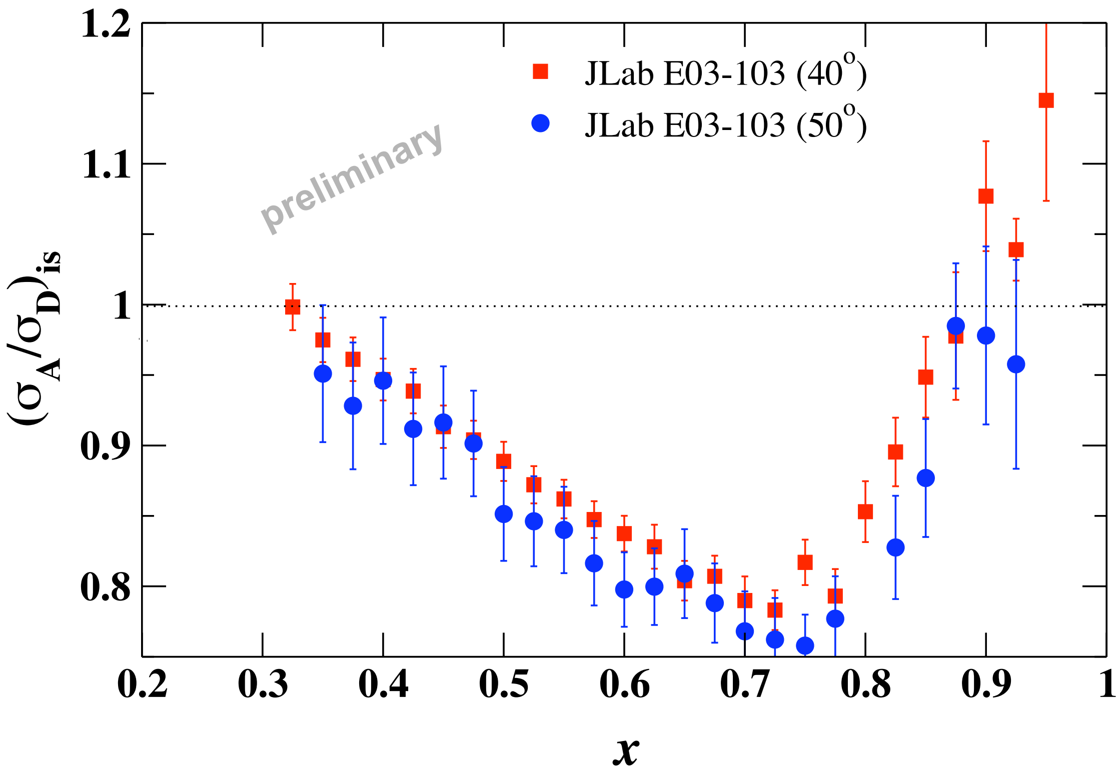
$$E \rightarrow E+\Delta$$
$$E' \rightarrow E'+\Delta$$

Δ ~ "boost in the Coulomb field" calibrated against lower E quasi-elastic cross sections



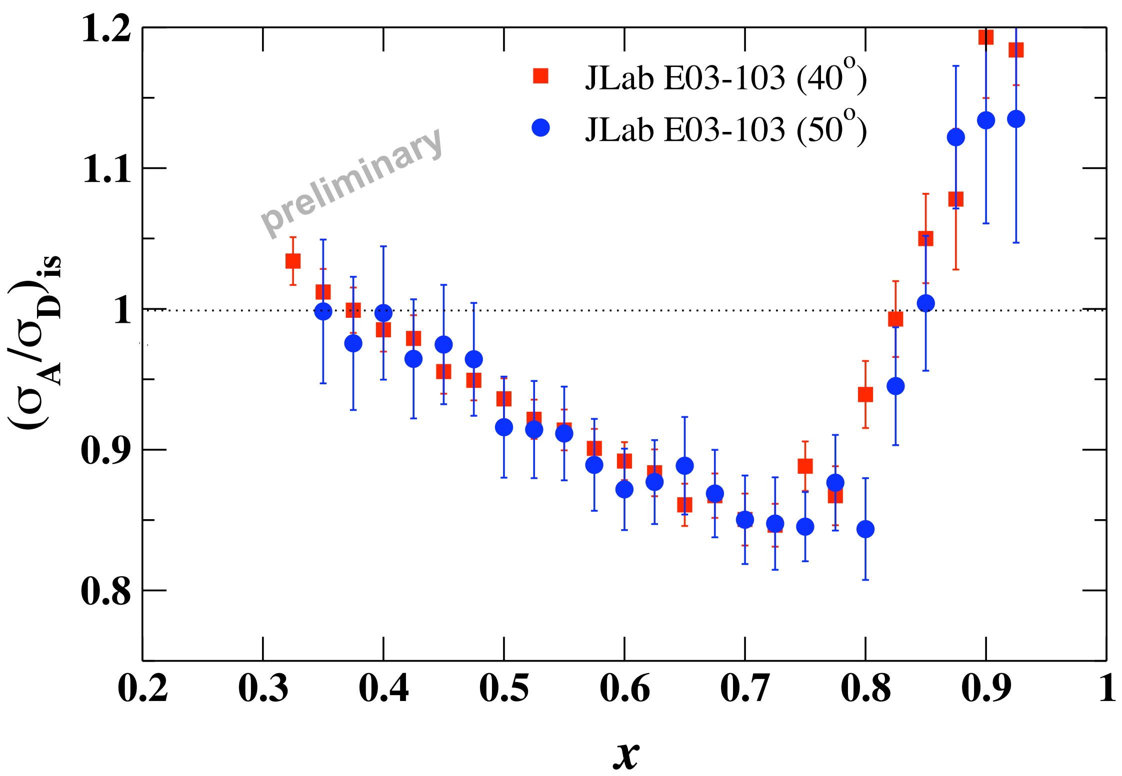
E03-013 heavy target results

Before coulomb corrections

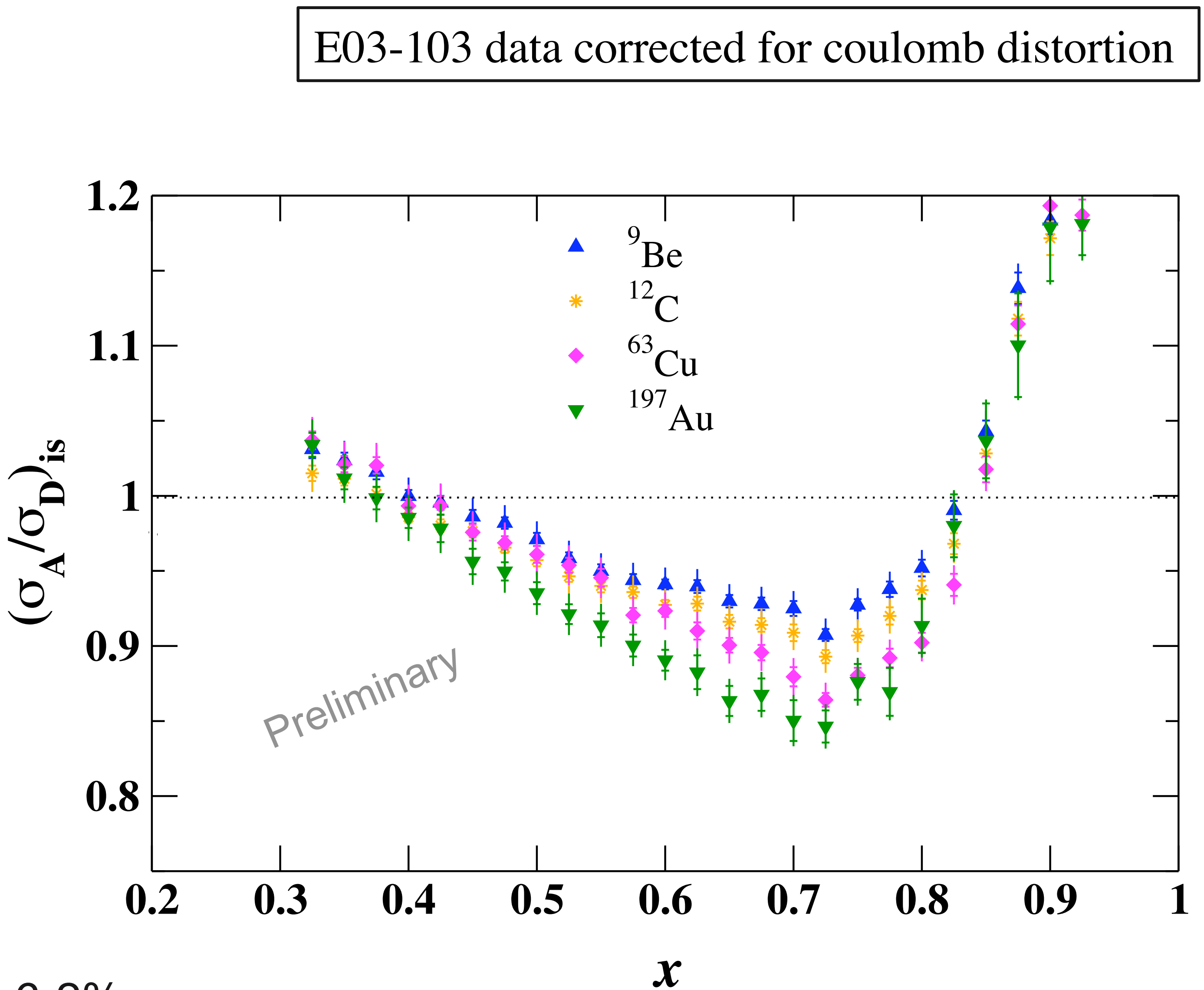


E03-013 heavy target results

After coulomb corrections



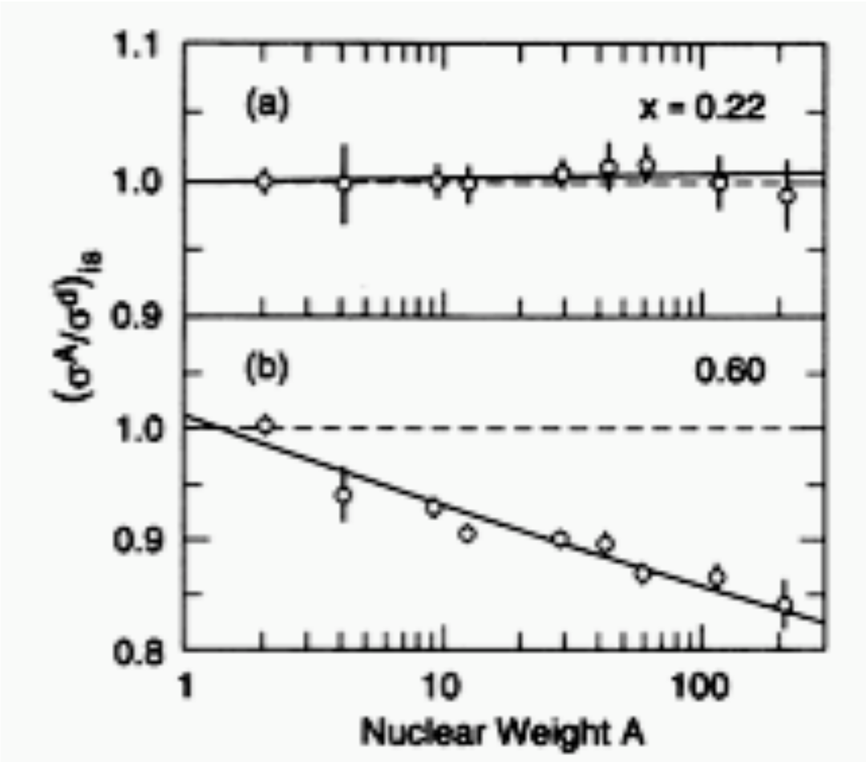
E03-103: EMC effect in heavy nuclei

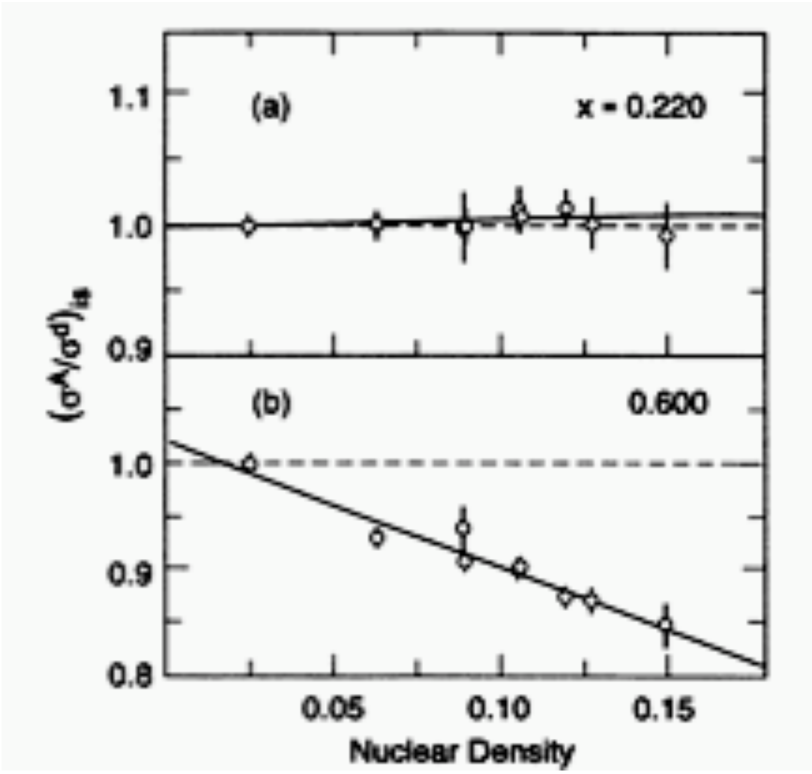


Scale errors: 1.6-2%

A or density dependence ?

Figs from J. Gomez, PRC49, 4348 (1994))





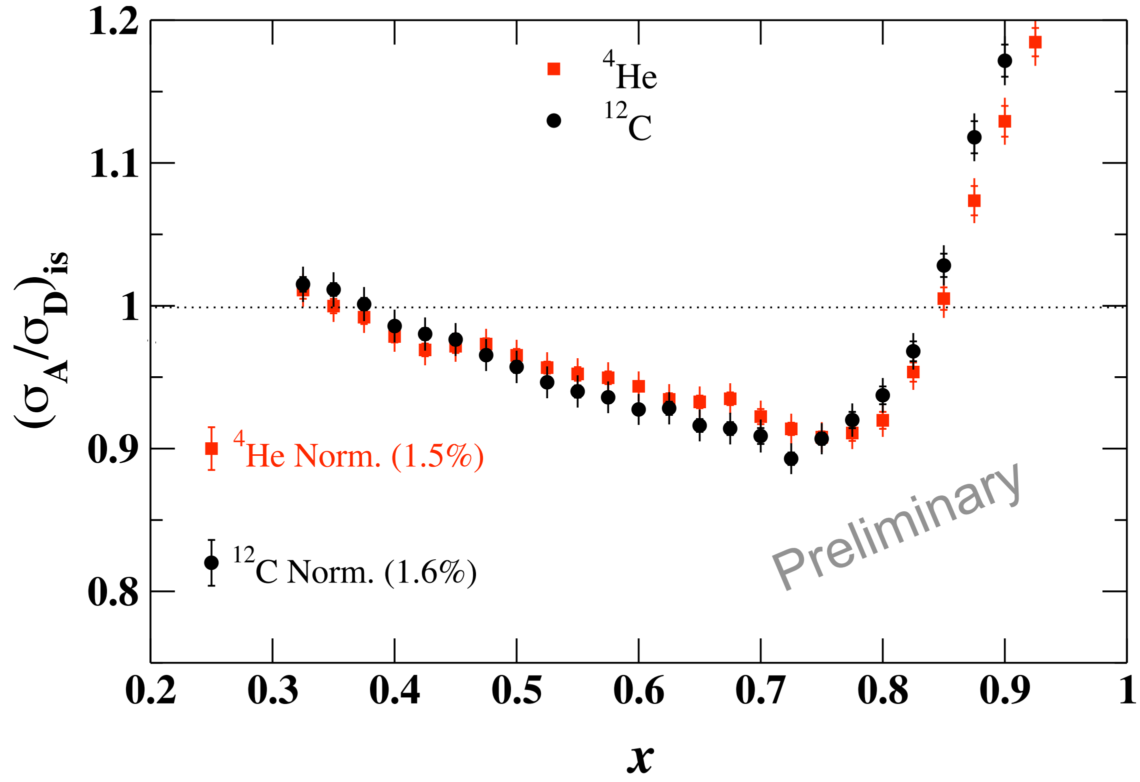
Density calculated assuming a uniform sphere of radius: R_e $(r=3A/4pR_e^3)$

A or density dependence ?

Magnitude of the EMC effect for C and ^{4}He very similar, and

$\rho(^4He) \sim \rho(^{12}C)$

EMC effect: ρ−dependent
(A-dep. ➔ factor of 2)



A or density dependence ?

Magnitude of the EMC effect for C and ^{4}He very similar, and

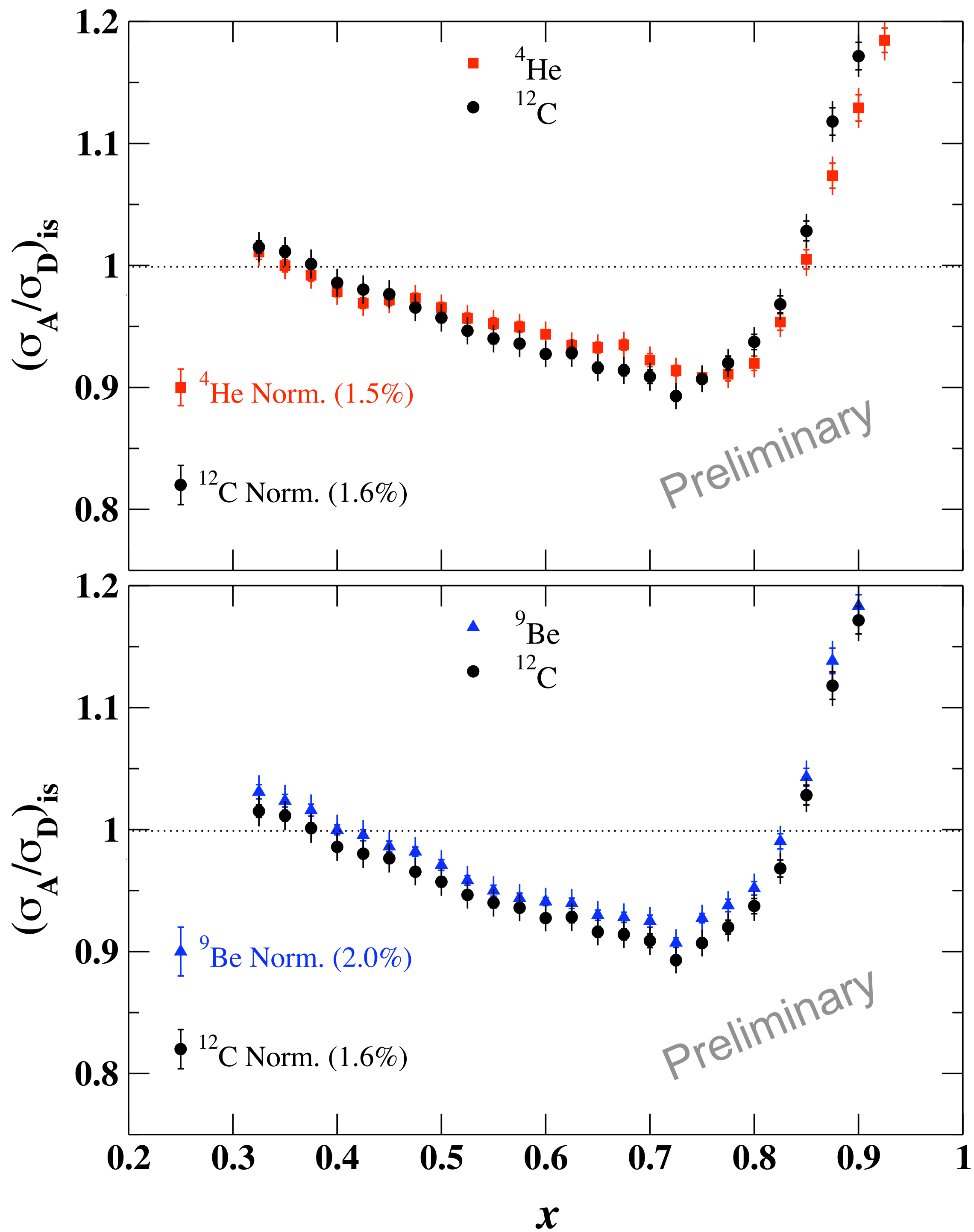
$\rho(^4\text{He}) \sim \rho(^{12}\text{C})$

EMC effect: ρ−dependent
(A-dep. ➔ factor of 2)

Magnitude of the EMC effect for C and ^{9}Be very similar, but

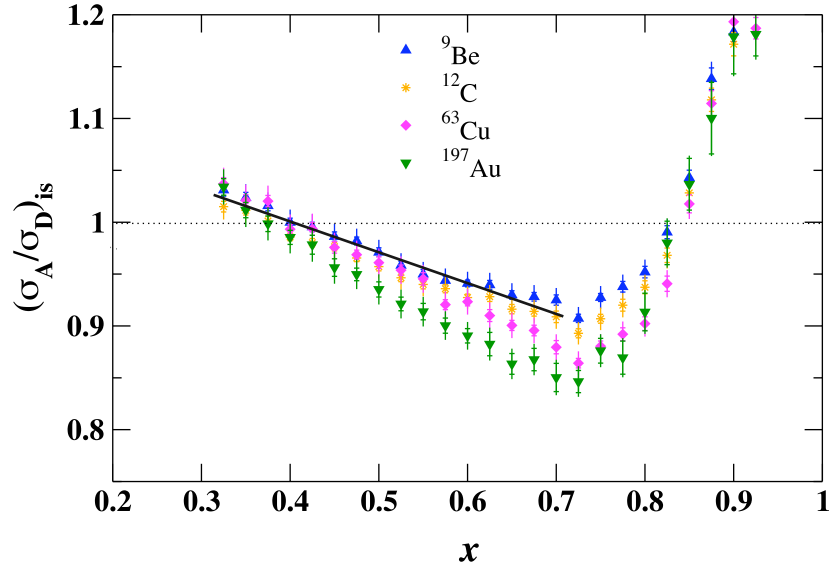
$\rho(^9\text{Be}) << \rho(^{12}\text{C})$

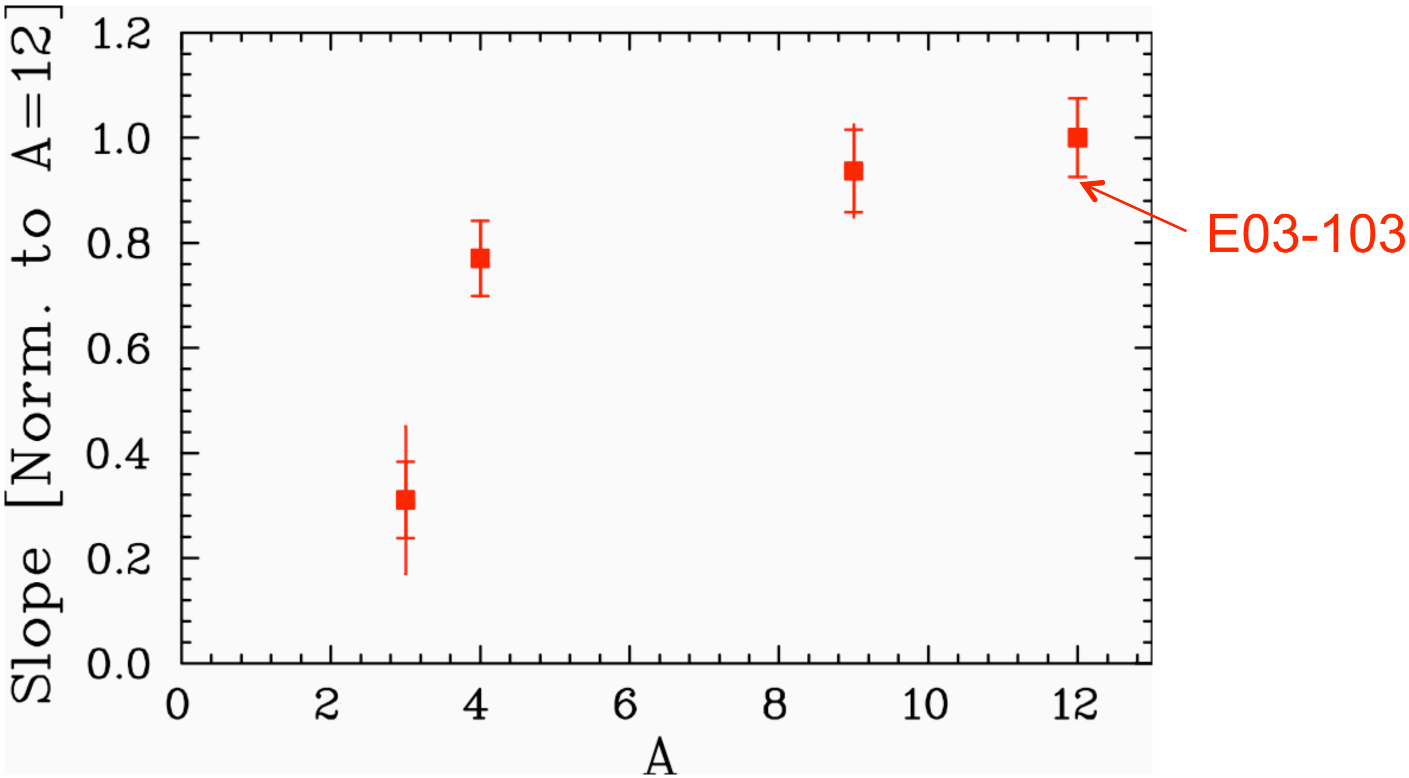
EMC effect: A-dependent
(ρ-dep. ➔ factor of 2)



A or density dependence ?

Fit of the EMC ratio for 0.3<x<0.7
and look at A-dependence of the slope





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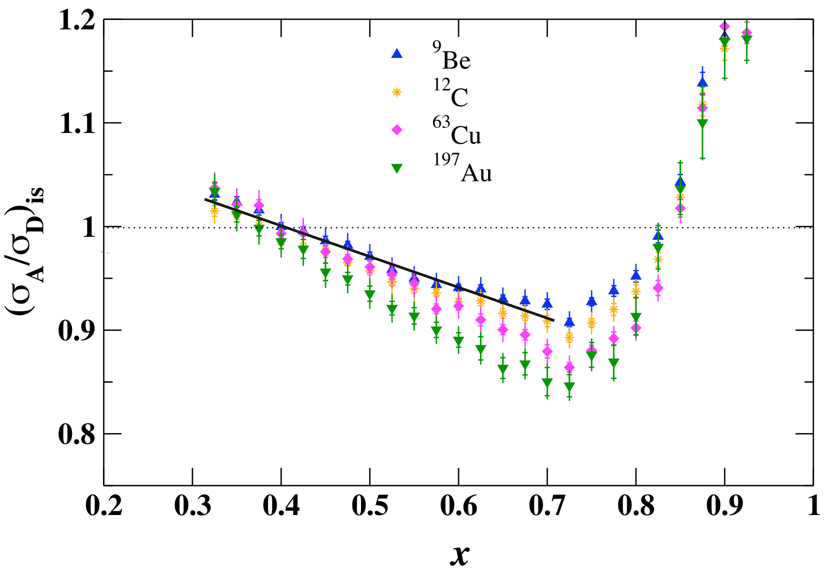

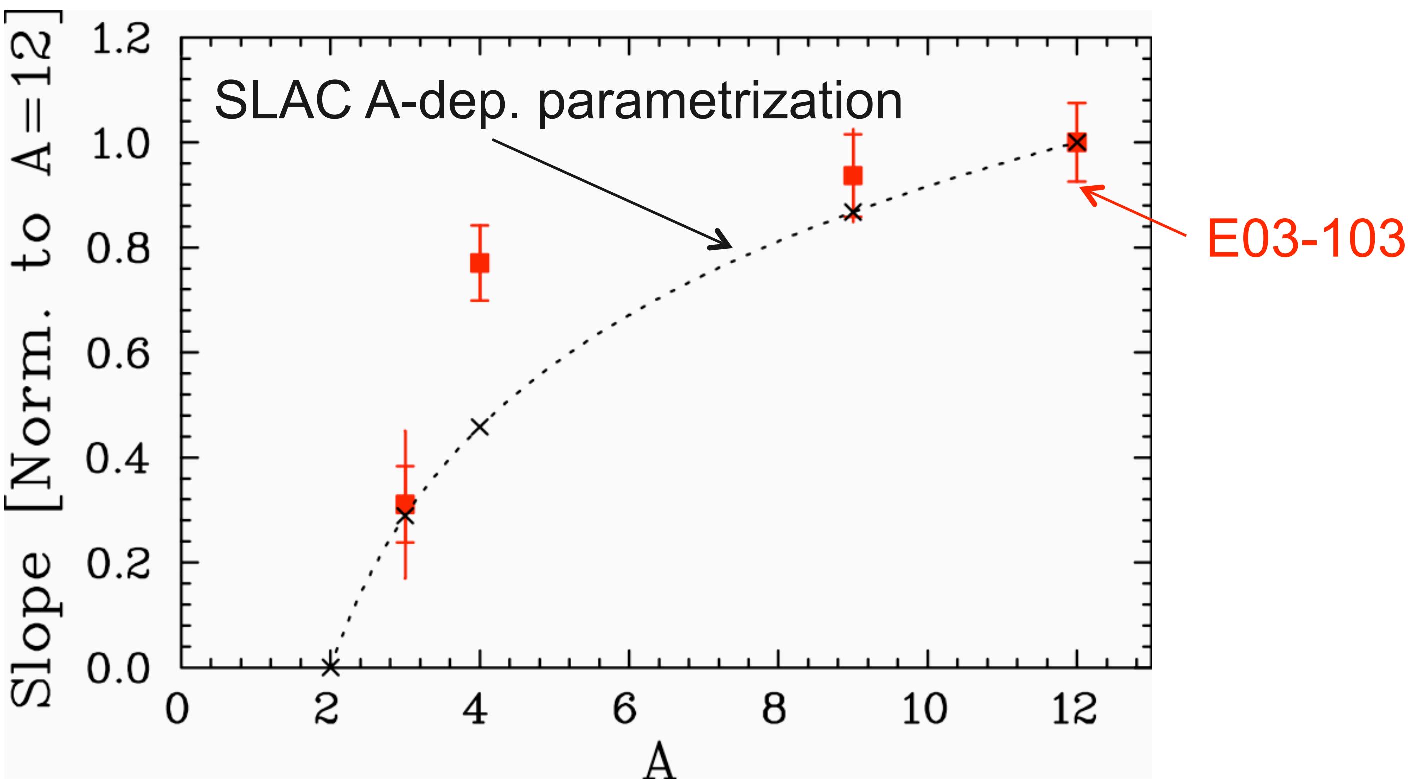

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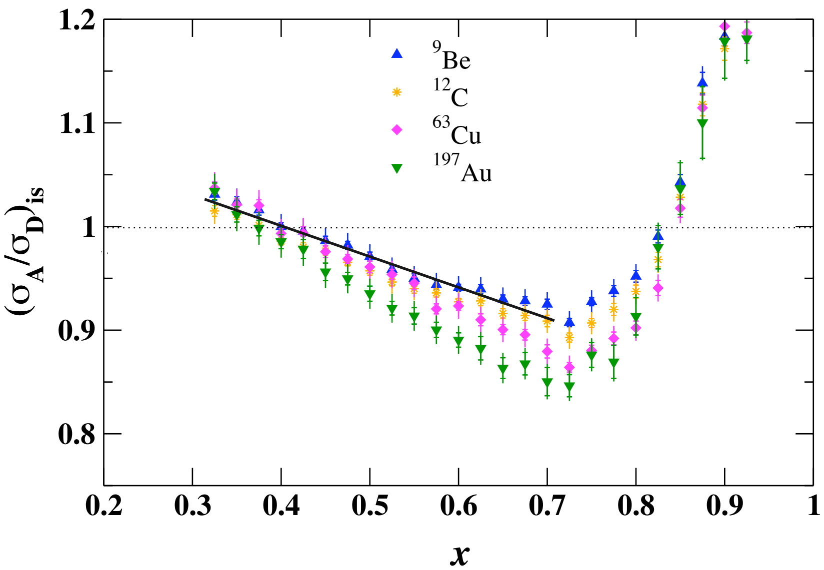
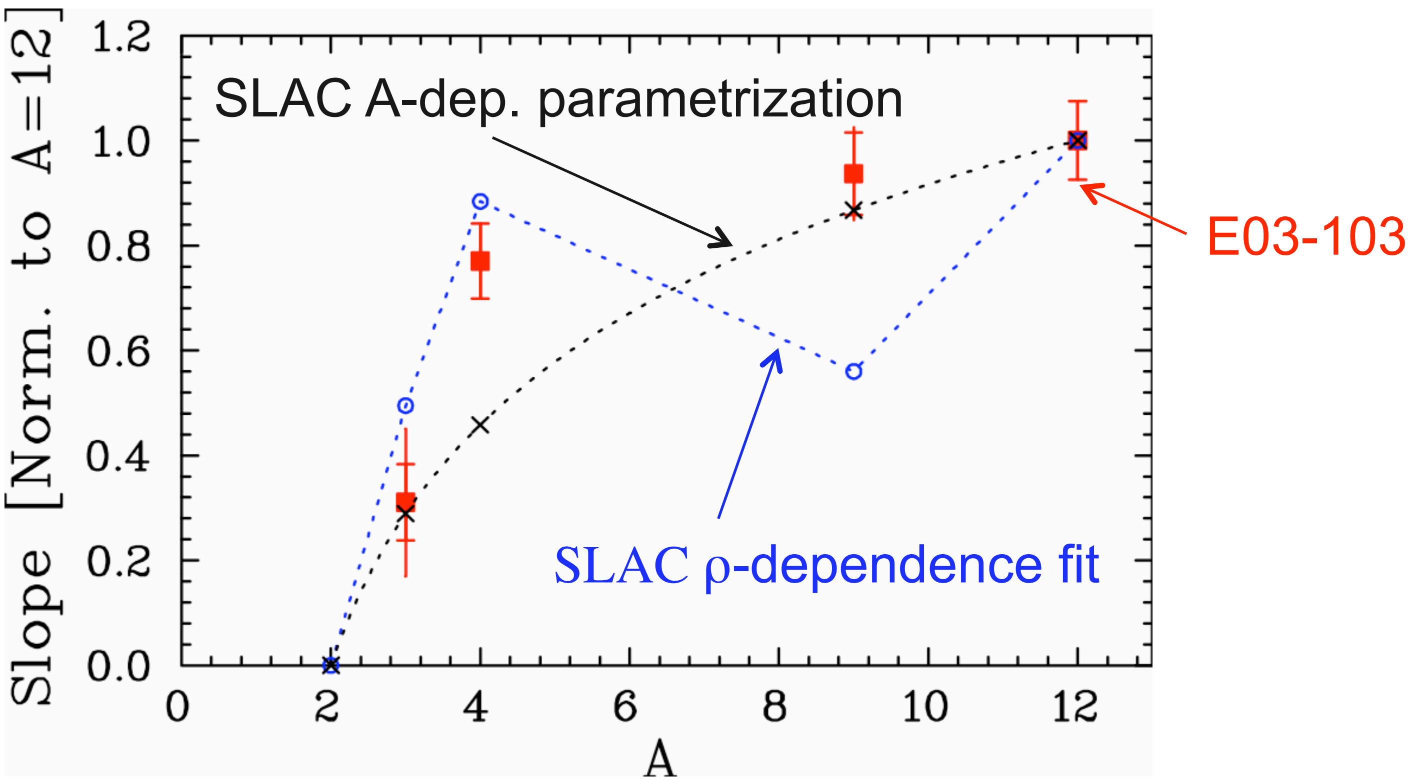




A or density dependence ?

^{9}Be ~ 2α-cluster+n

↓

<ρ> small

but

$\rho_{local}(^{9}Be) \sim \rho(^{4}He)$

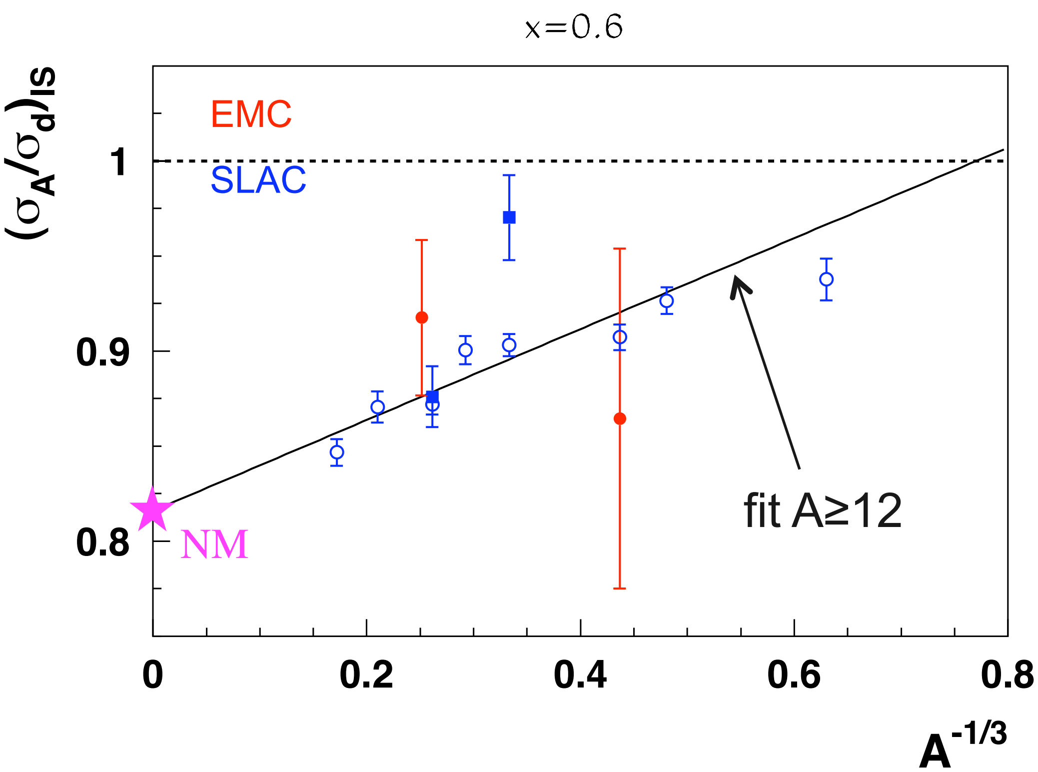
➔ hint of local density dependence

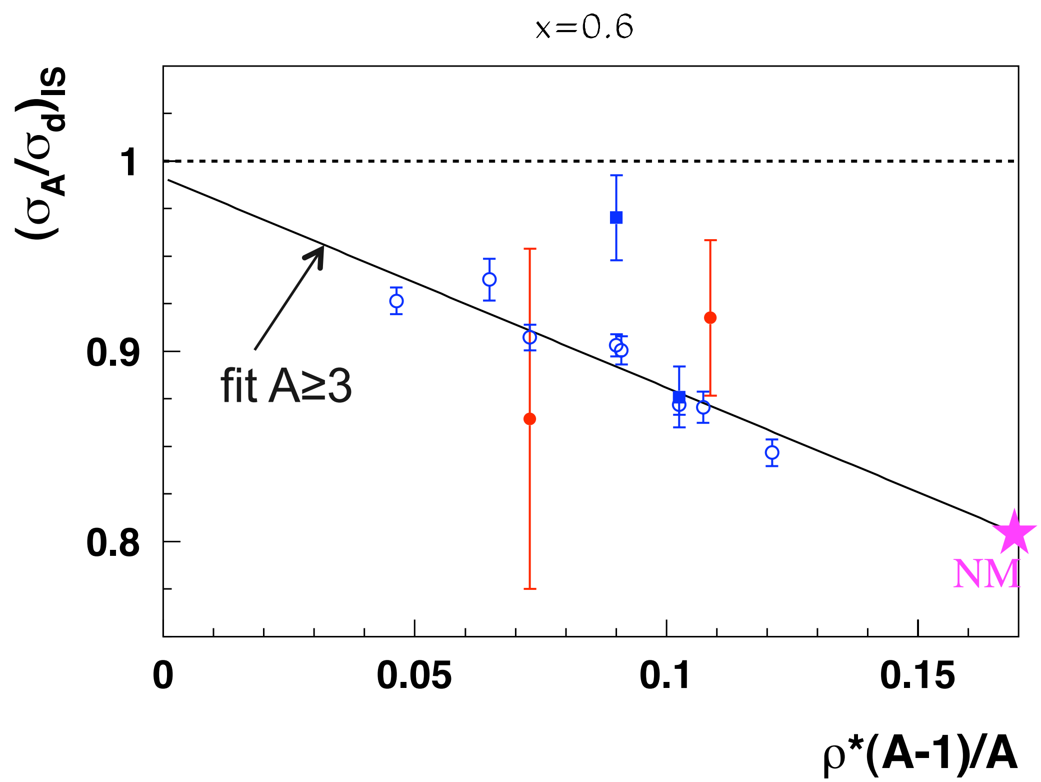
➔ overlap with nearest neighbors ?

World data re-analysis

Experiments	E (GeV)	A	x-range	Pub. 1st author
CERN-EMC	280	56	0.050-0.650	Aubert
		12,63,119	0.031-0.443	Ashman
CERN-BCDMS	280	15	0.20-0.70	Bari
		56	0.07-0.65	Benvenuti
CERN-NMC	200	4,12,40	0.0035-0.65	Amaudruz
	200	6,12	0.00014-0.65	Arneodo
SLAC-E61	4-20	9,27,65,197	0.014-0.228	Stein
SLAC-E87	4-20	56	0.075-0.813	Bodek
SLAC-E49	4-20	27	0.25-0.90	Bodek
SLAC-E139	8-24	4,9,12,27,40,56,108,197	0.089-0.8	Gomez
SLAC-E140	3.7-20	56,197	0.2-0.5	Dasu
DESY-HERMES	27.5	3,14,84	0.013-0.35	Airapetian

Extrapolation to nuclear matter

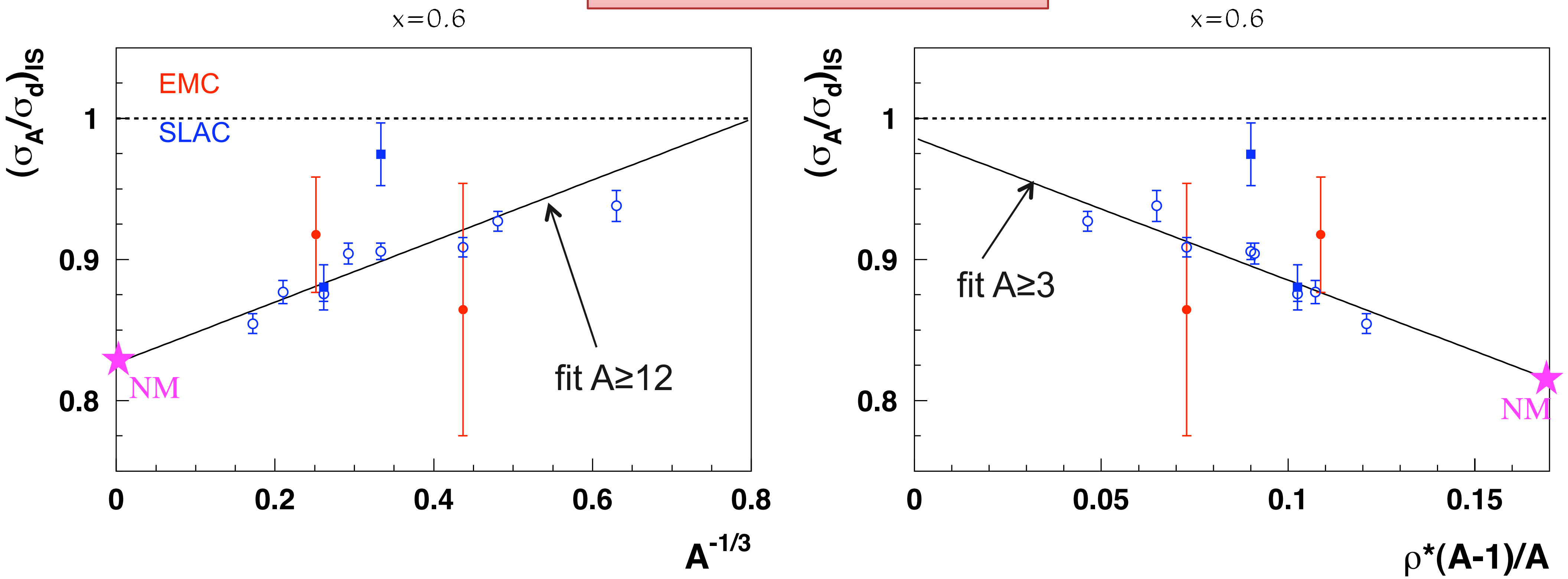




- Improved density calculation (calculated with density distributions from R. Wiringa and S. Pieper)

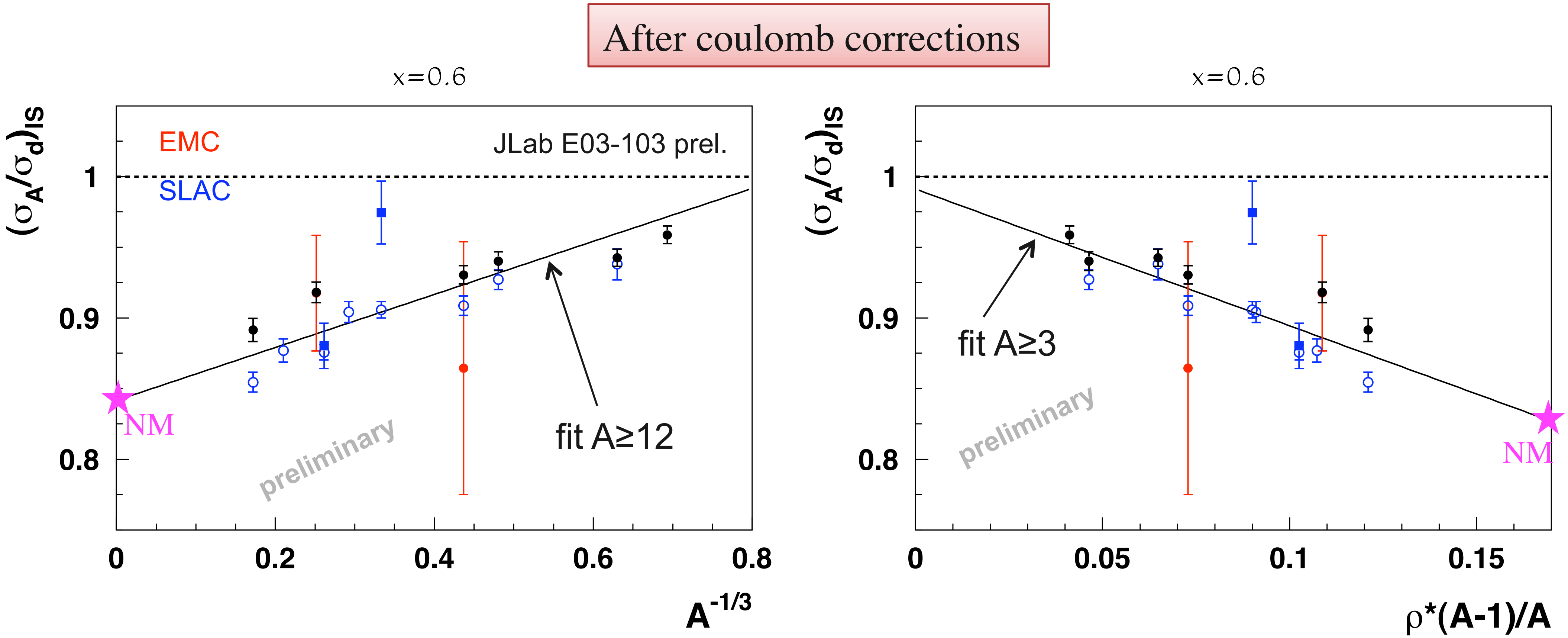
Extrapolation to nuclear matter

After coulomb corrections



- Improved density calculation (calculated with density distributions from R. Wiringa and S. Pieper)
- Apply coulomb distortion correction

Extrapolation to nuclear matter

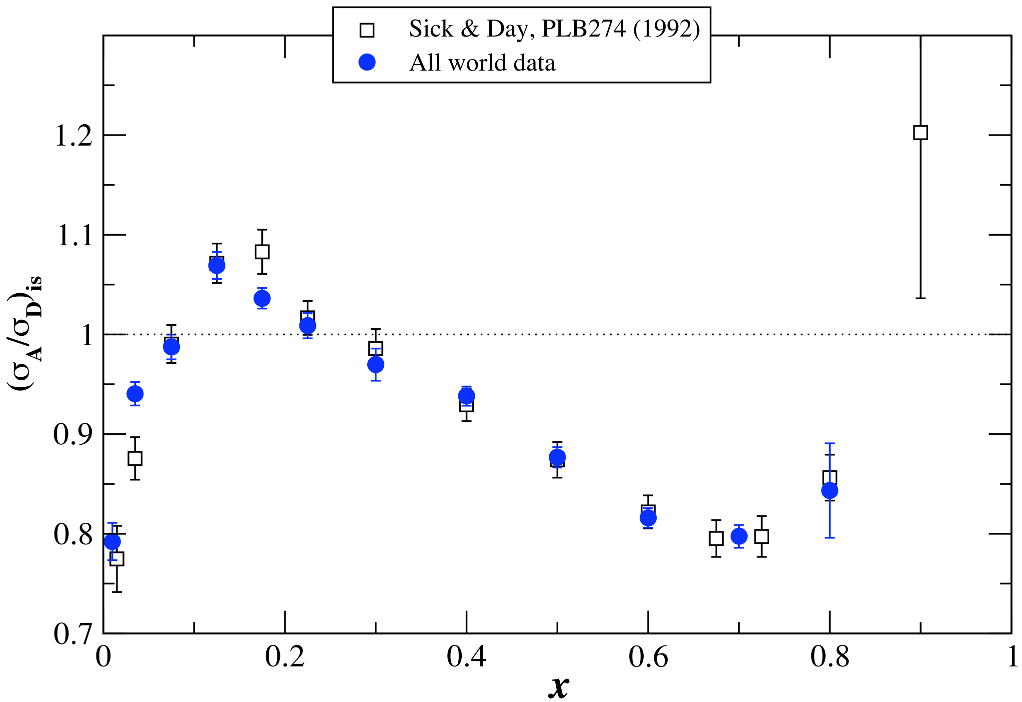


- Improved density calculation (calculated with density distributions from R. Wiringa and S. Pieper).
- Apply coulomb distortion correction.
- In progress: n/p at large Q^2 and low x, and large x and large Q^2.
- Target mass correction to be looked at.

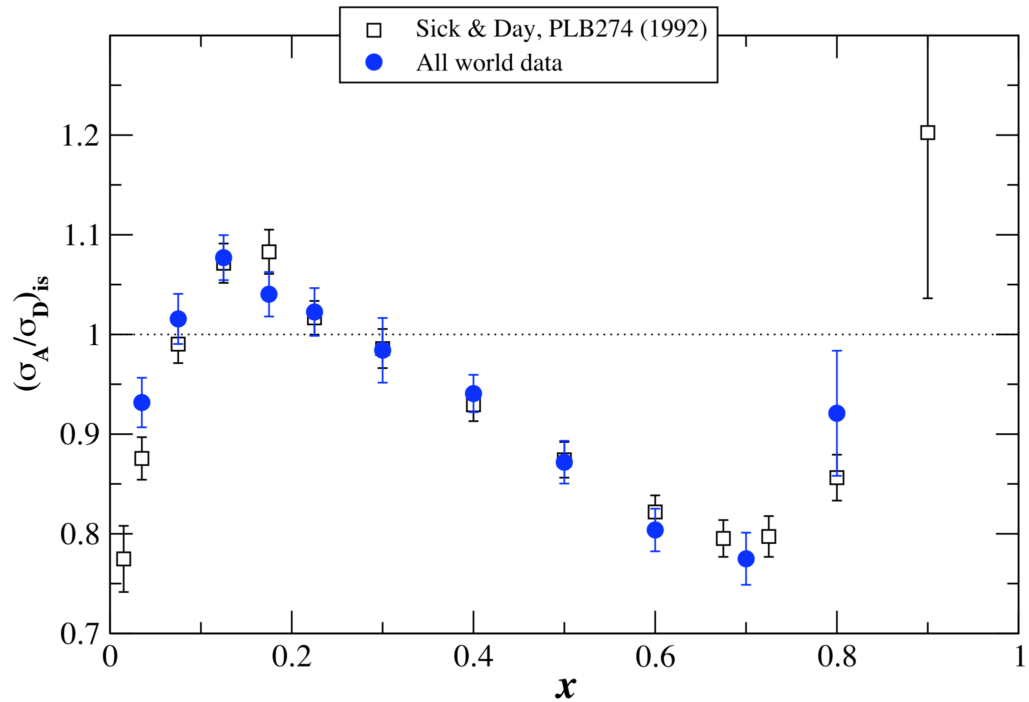
Note: n/p correction is also A-dependent !

EMC effect in nuclear matter

From $A^{-1/3}$ dependence



From ρ-dependence



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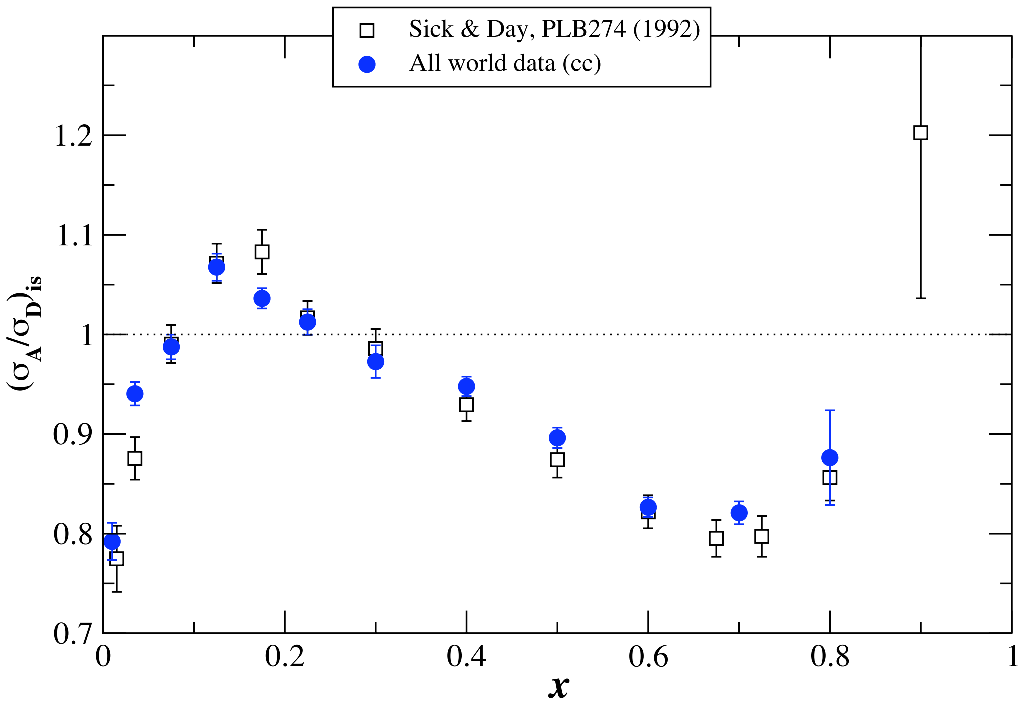

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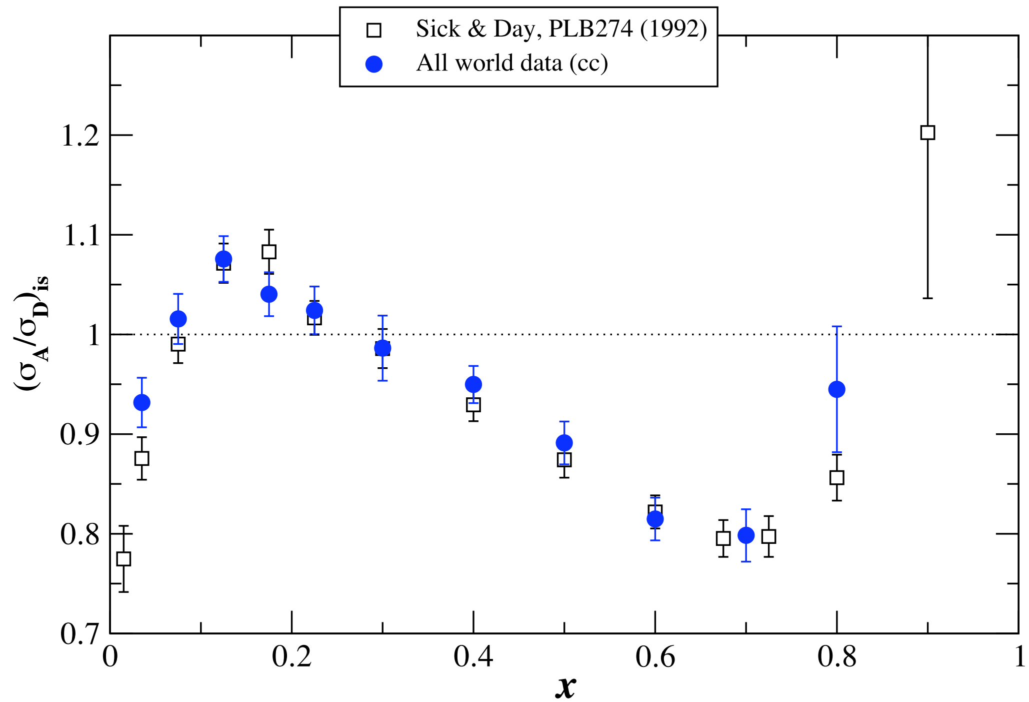

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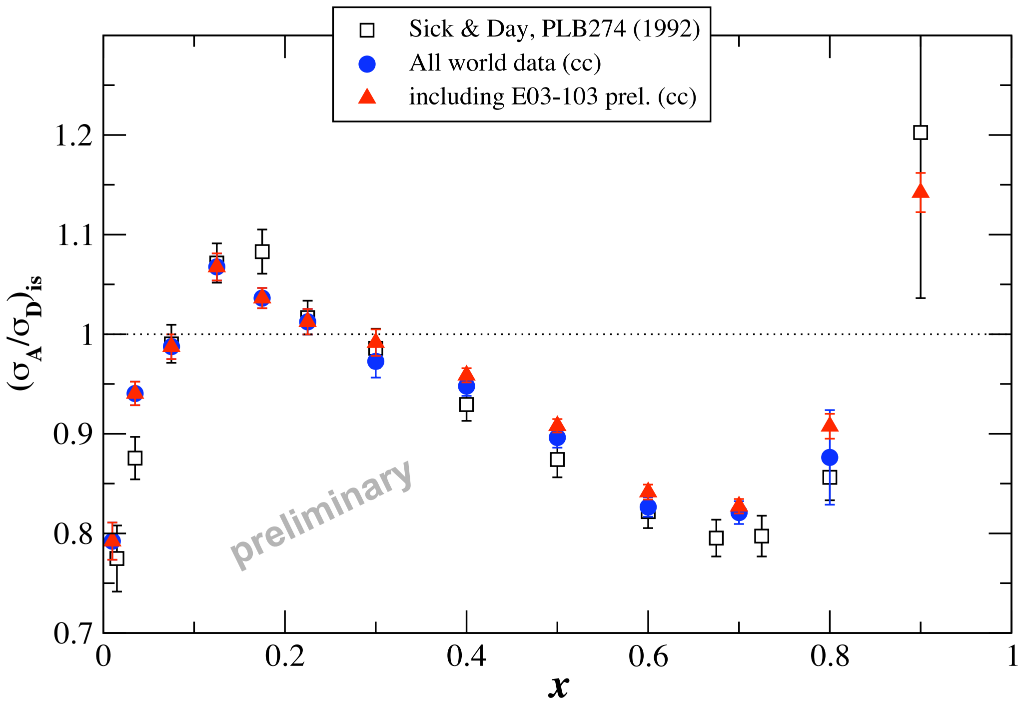
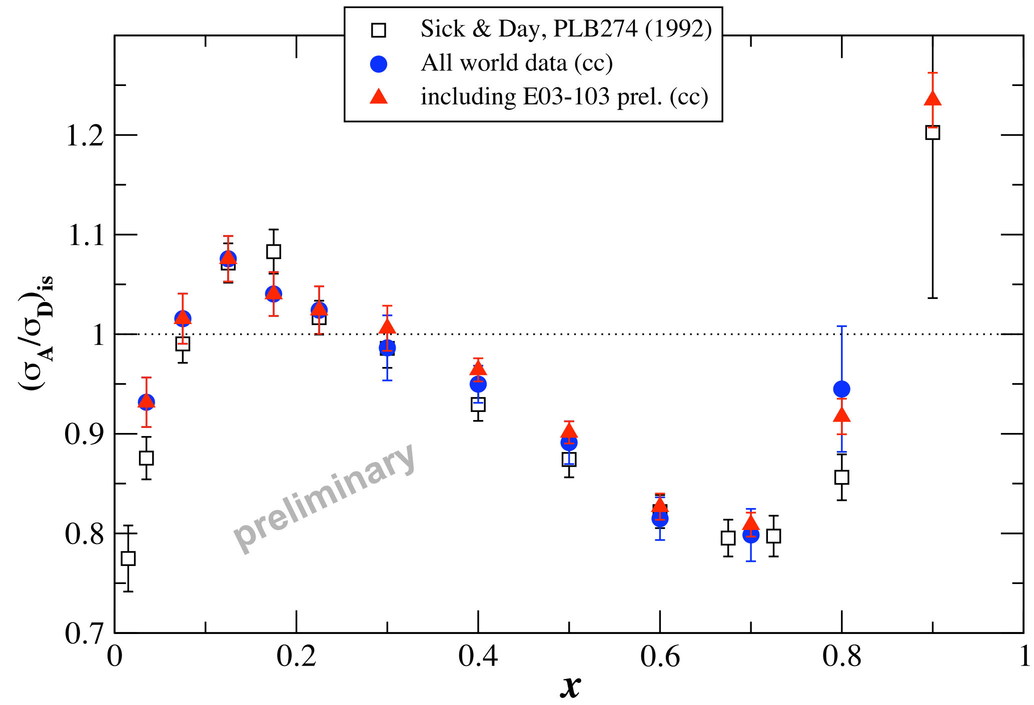


From ρ-dependence



EMC effect in nuclear matter

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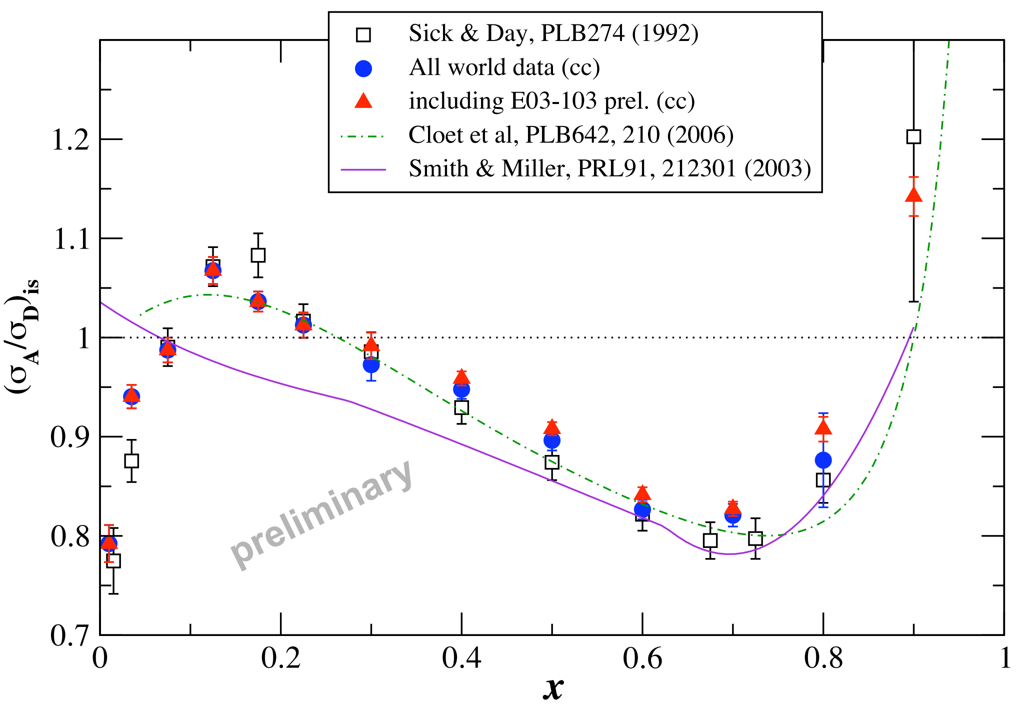
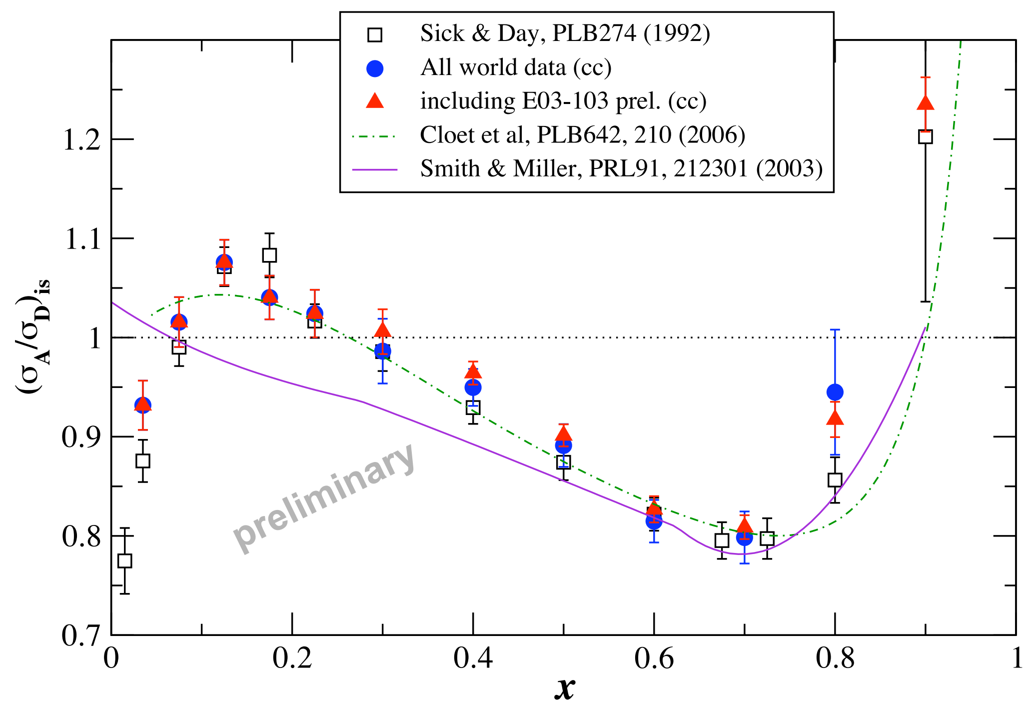


From ρ-dependence



Summary

- JLab E03-103 provides:
  - Precision nuclear structure ratios for light nuclei
  - Access to large x EMC region for ^{3}He $\rightarrow$ ^{197}Au

- Preliminary observations:
  - Scaling of the structure function ratios for W<2GeV down to low Q^2
  - First measurement of the EMC effect in ^{3}He: very sensitive to isoscalar correction
  - Similar large x shape of the structure function ratios for A>3

- In progress:
  - Coulomb correction systematics
  - Nuclear density calculations
  - Smeared n/p at correct kinematics and for each nucleus
  - Target mass correction

Outlook

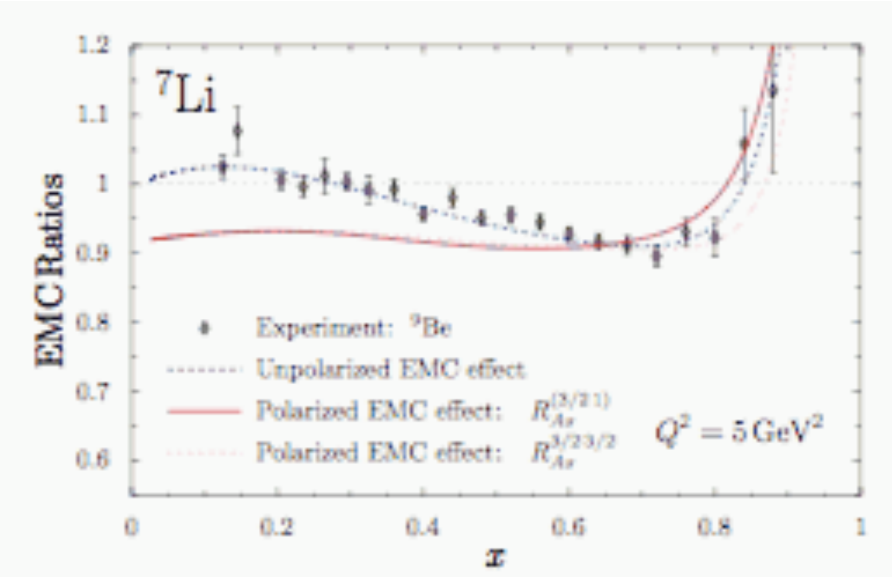
- New JLab data (light nuclei and high x precision) indicate:
  - ✓ the need to go beyond the simple A- or ρ-based fits
  - ✓ the importance of detailed calculations with real n/p input

- Updated/new extrapolation to the EMC effect in nuclear matter

- Important to understand EMC effect for neutrinos experiments.

- Future related measurements:
  - ^{3}H and ^{3}He (n/p in nuclei) at Jlab 12 GeV
  - JLab BONUS (6 and 12 GeV) → free n/p
  - First measurement of the polarized EMC effect first test

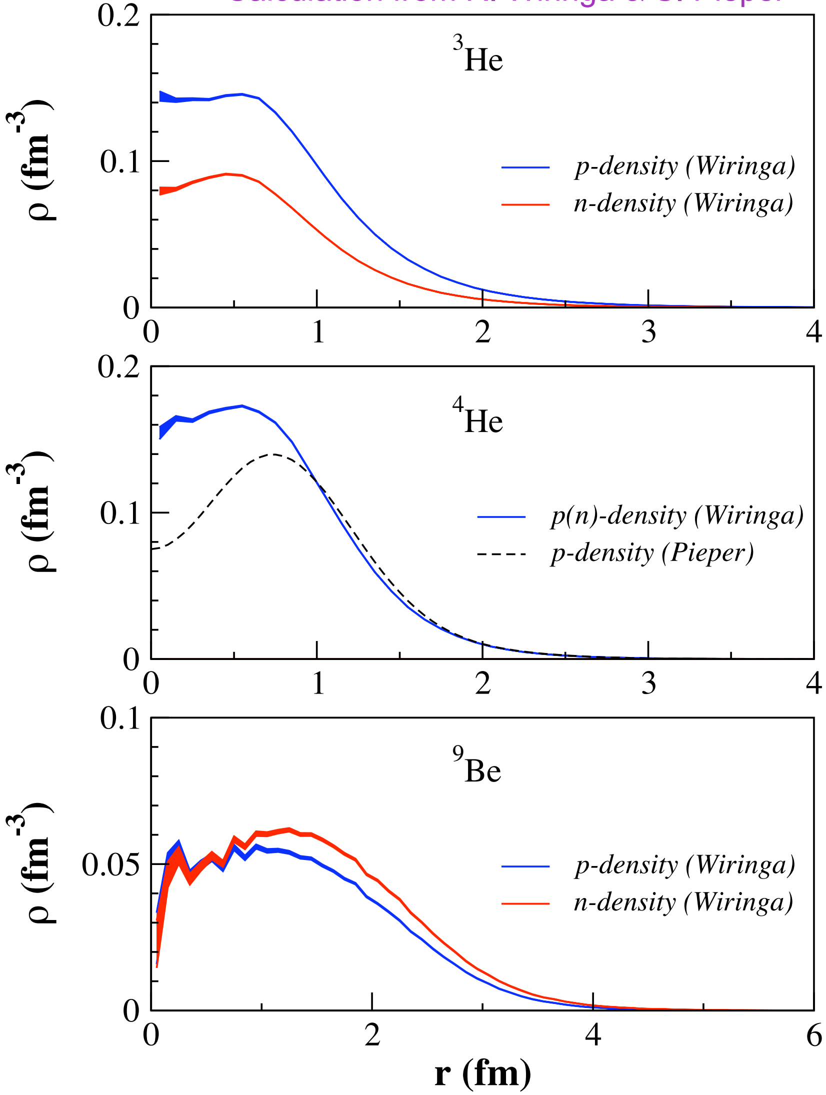
Cloet, Bentz, and Thomas, PLB 642, 210 (2006)



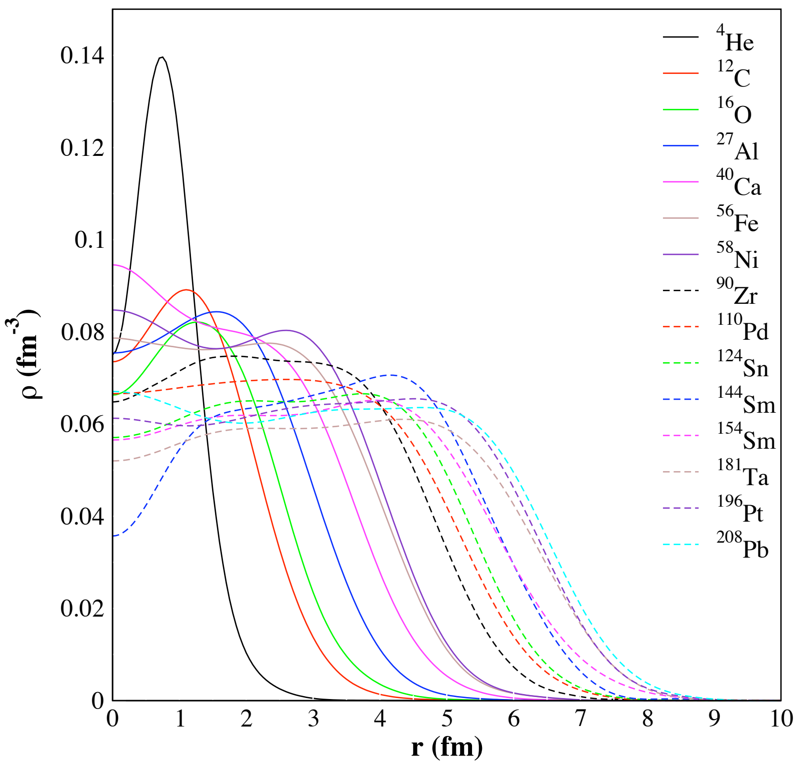
Back-ups

Density calculations

Calculation from R. Wiringa & S. Pieper



Calculation from S. Pieper



Average density:

$$\langle \rho_{n,p} \rangle = \frac{\int \rho_{n,p}^2 d^3 r}{\int \rho_{n,p} d^3 r}$$

$$\langle \rho_p \rangle + \langle \rho_n \rangle = \langle \rho_A \rangle \xrightarrow{\text{finite proton size correction}} \langle \rho_A \rangle \cdot \left(\frac{\langle r \rangle}{r_{eff}} \right)^3$$

with $r_{eff} = \sqrt{\langle r \rangle^2 + 0.9^2}$

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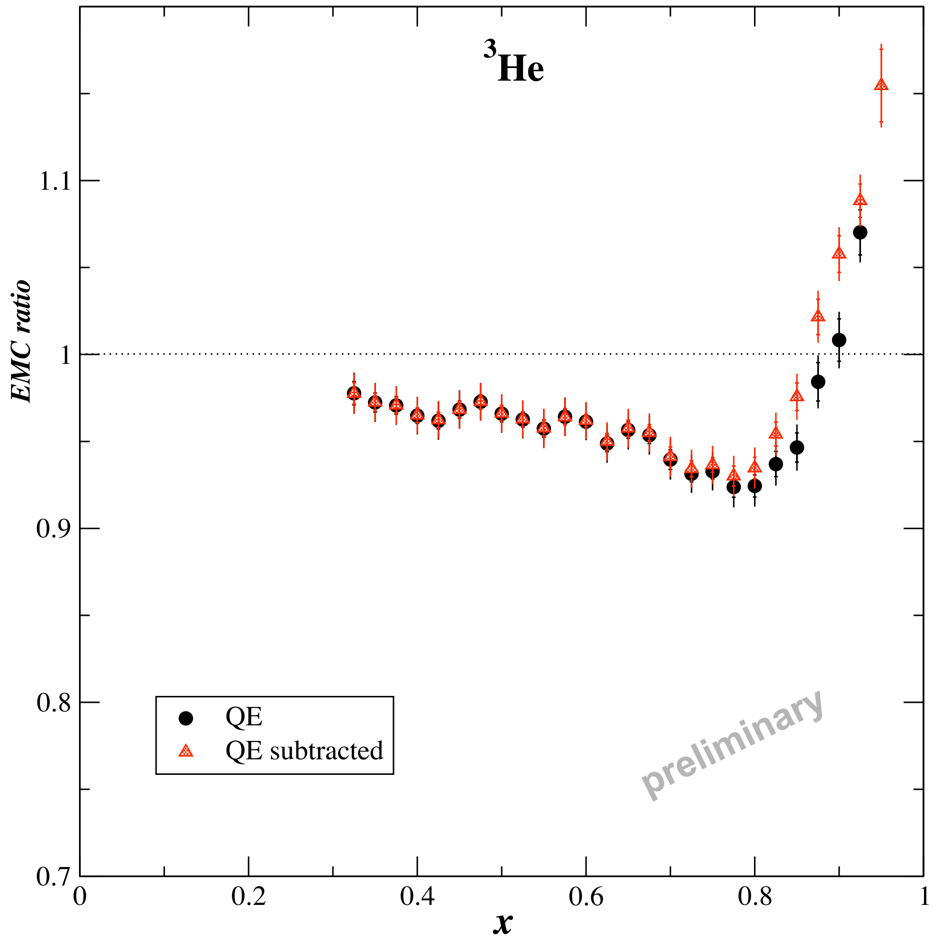
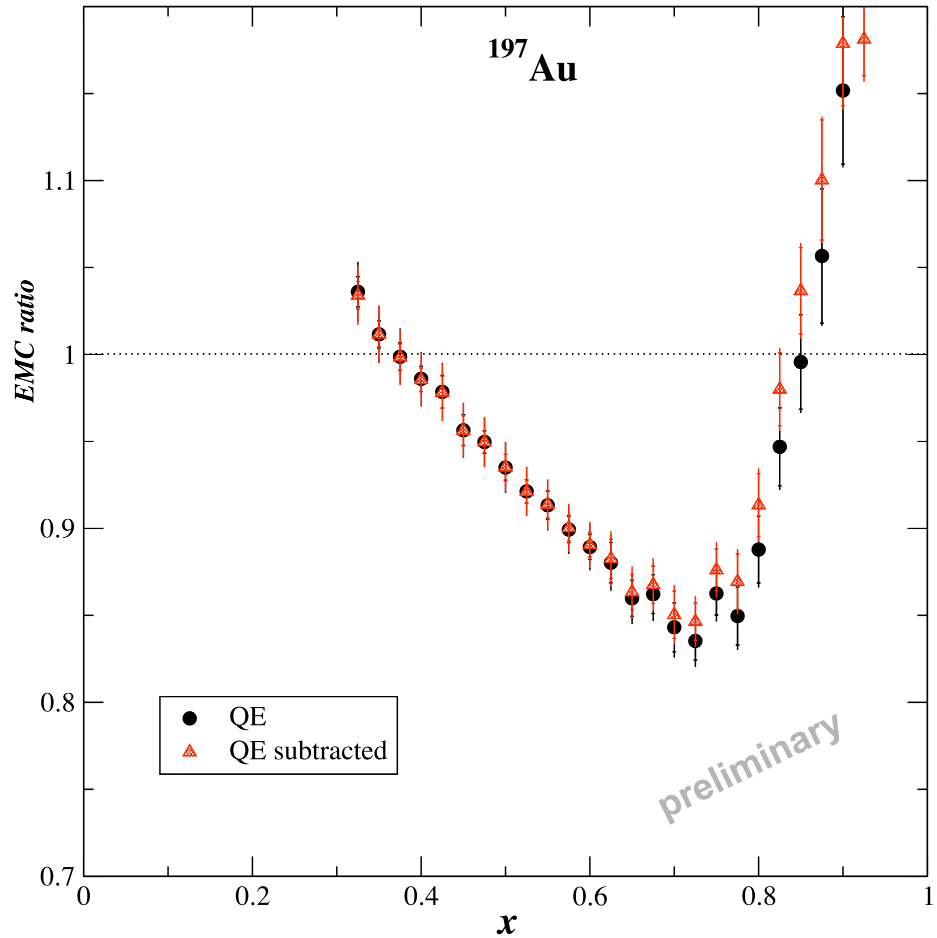
E03-103: QE subtraction effect



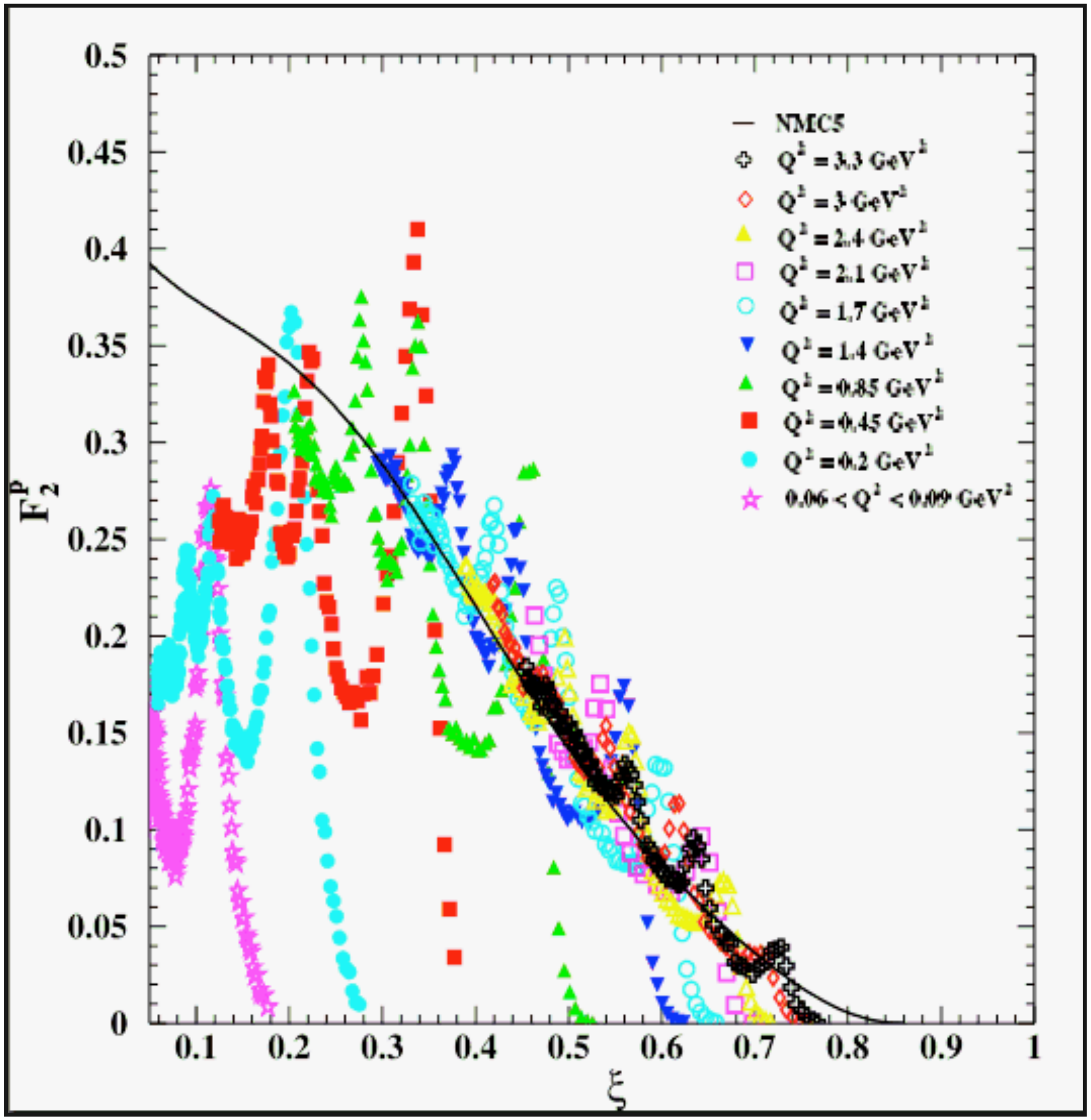


Quark-hadron duality

First observed by Bloom and Gilman in the 1970's on F_2:

Scaling curve seen at high Q^2 is an accurate average over the resonance region at lower Q^2

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



Quark-hadron duality

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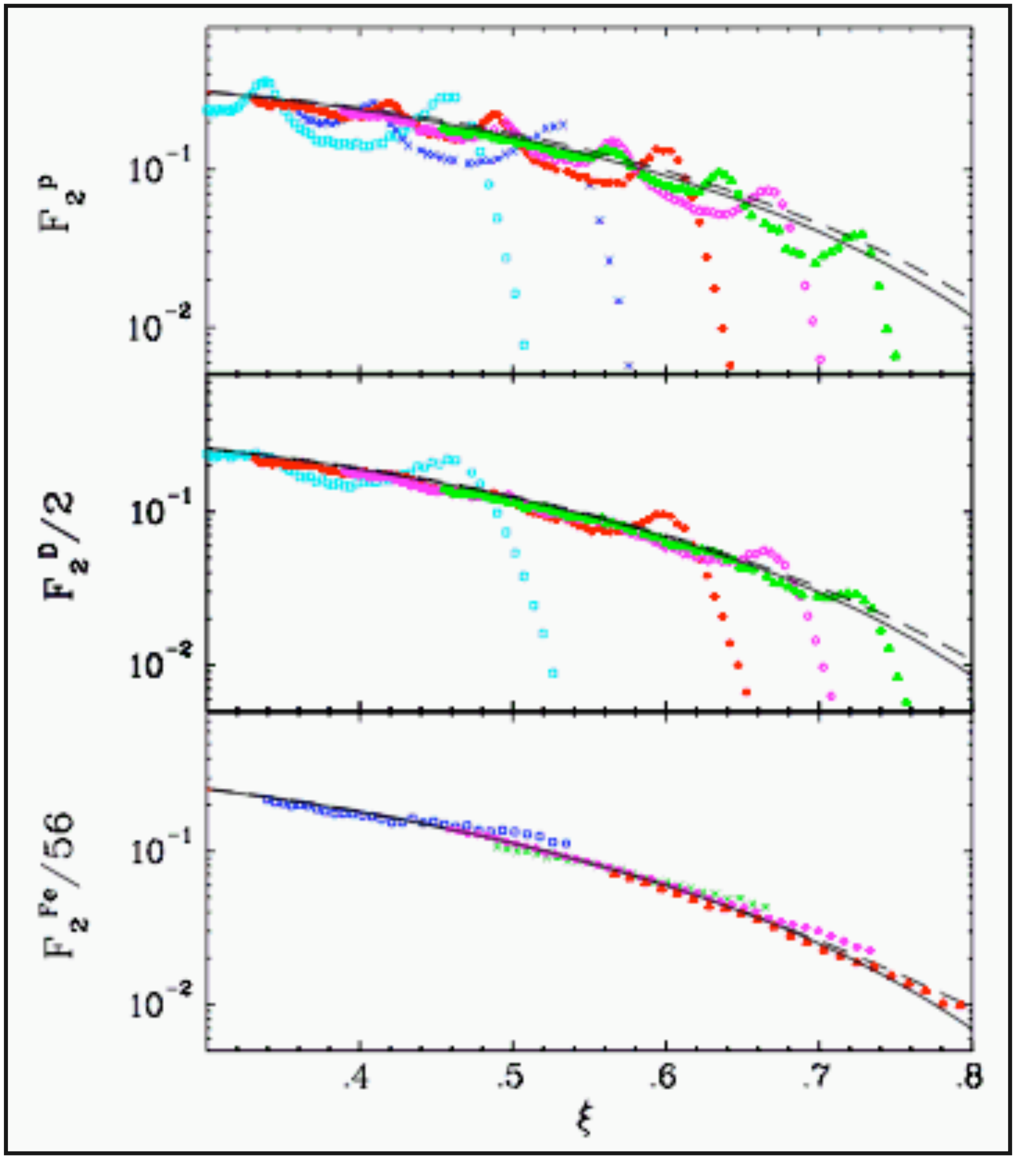
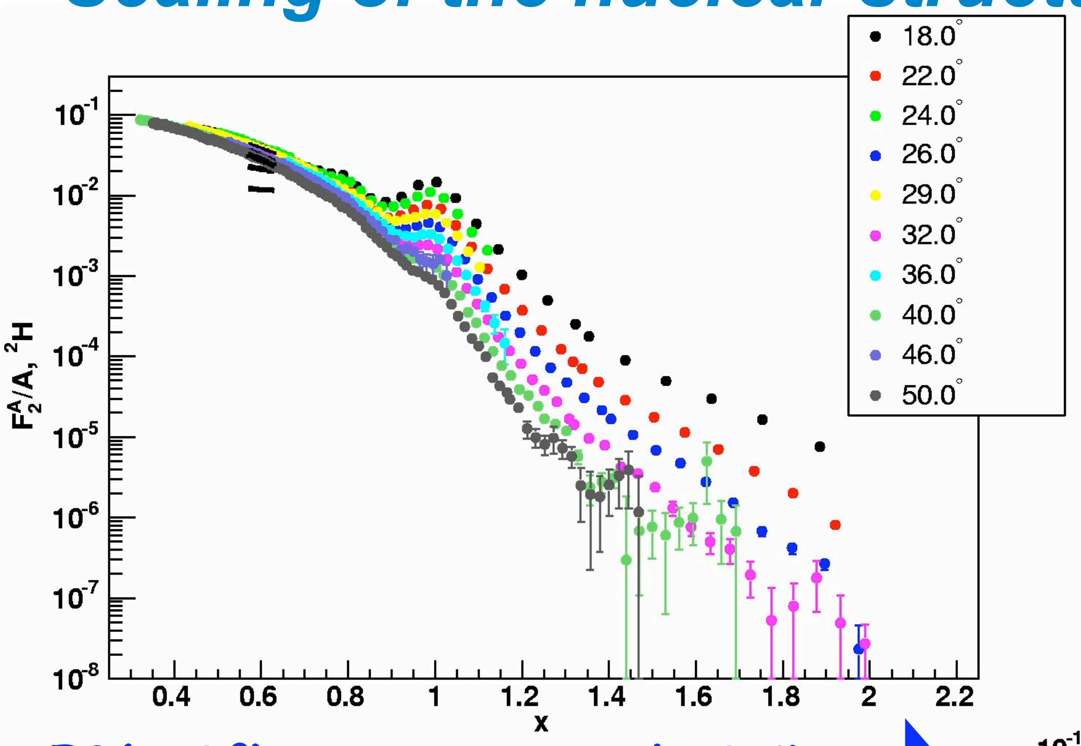
Scaling curve seen at high Q^2 is an accurate average over the resonance region at lower Q^2

In nuclei, the averaging is in part done by the Fermi motion.

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



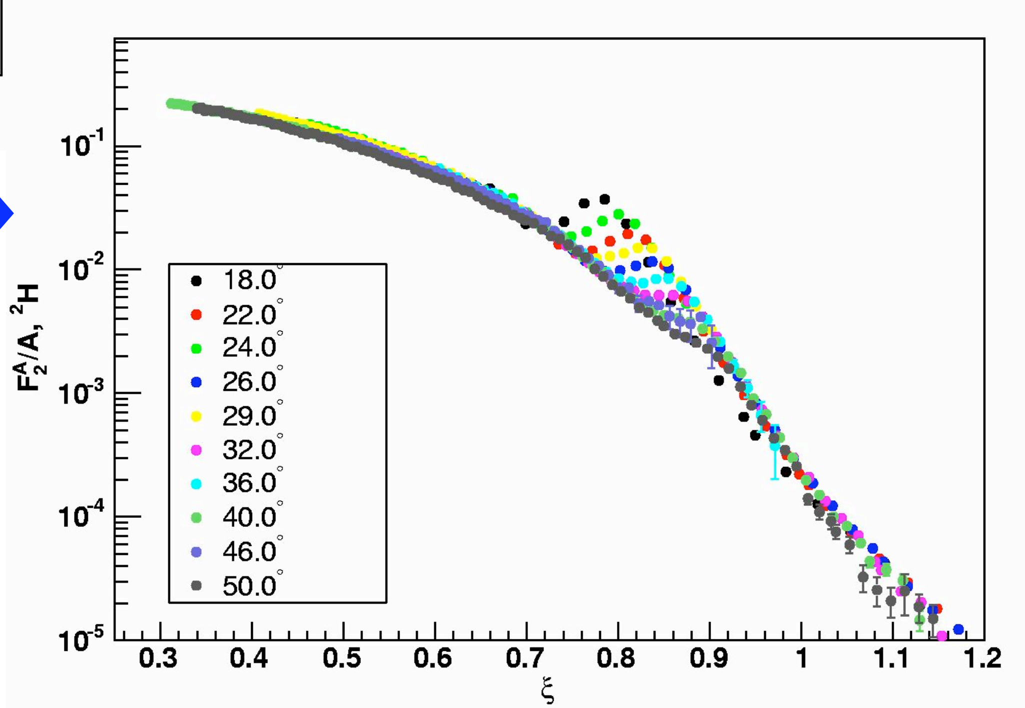
Scaling of the nuclear structure functions



$F_2(x,Q^2)$ consistent with QCD evolution in Q^2 for low x values (x<0.5)

Huge scaling violations at large x (especially for x>1)

F2(ξ,Q^2) consistent with QCD evolution in Q^2 to much larger ξ values



Scaling violations are mostly the "target-mass" corrections (plus a clear contribution from the QE peak)

→ Nearly independent of A

E03-103: Experimental details

Main improvement over SLAC due to improved ^{4}He targets:

Source of uncertainty	SLAC E139	JLab E03-103
Statistics	1.0-1.2%	0.5-0.7%
*Density fluctuations	1.4%	0.4%
Absolute density	2.1%	1.0% (1.5% for ^{3}He)

* - *size* of correction is 8% at 4 uA vs. 4% at 80 uA

Main drawback is lower beam energy:

Requires larger scattering angle to reach same Q^2

→ Larger π^- contamination

→ Large charge-symmetric background

→ Larger Coulomb distortion corrections