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The EMC Effect and The Quest to High x Quark Distributions

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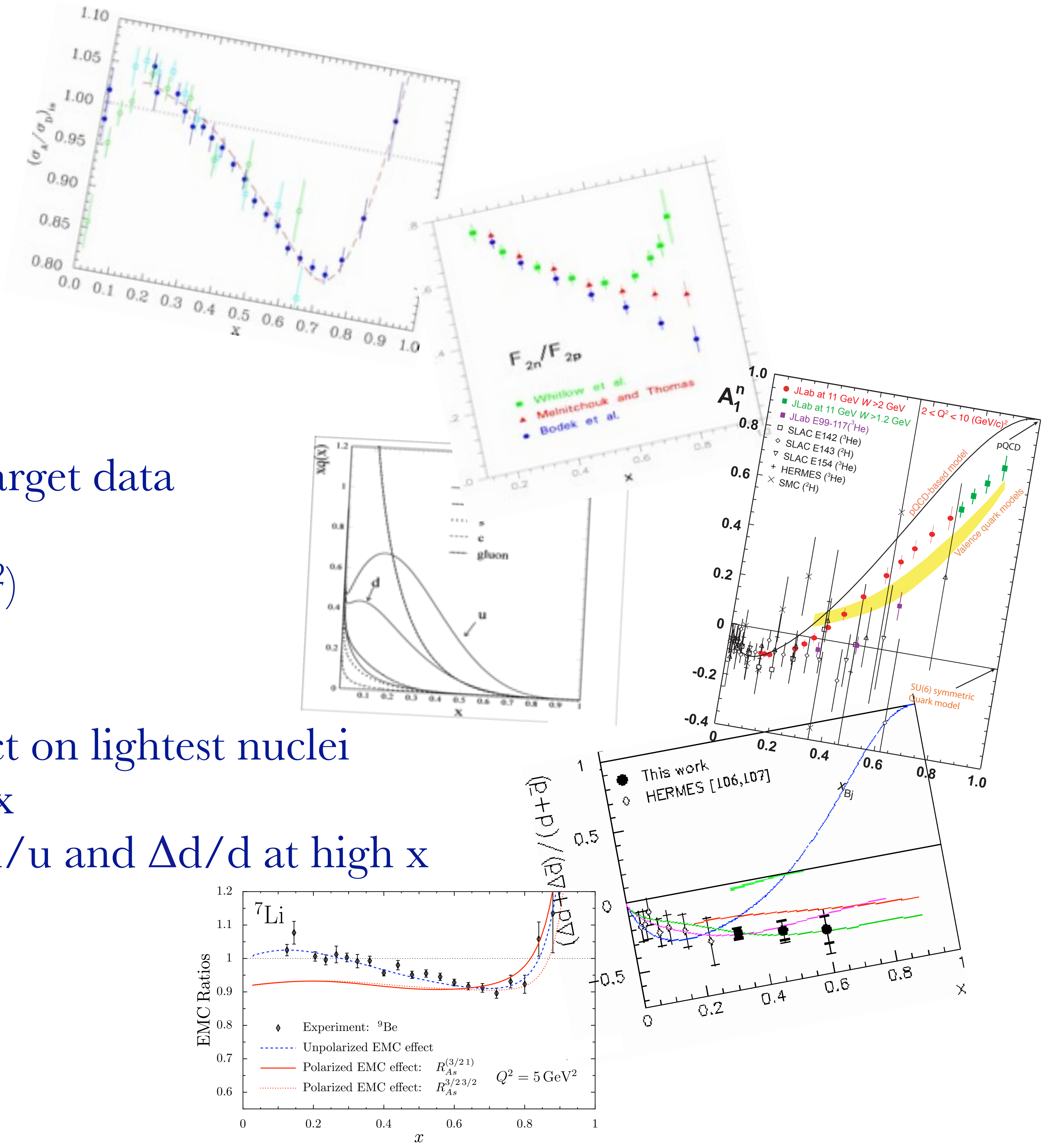
Argonne National Laboratory

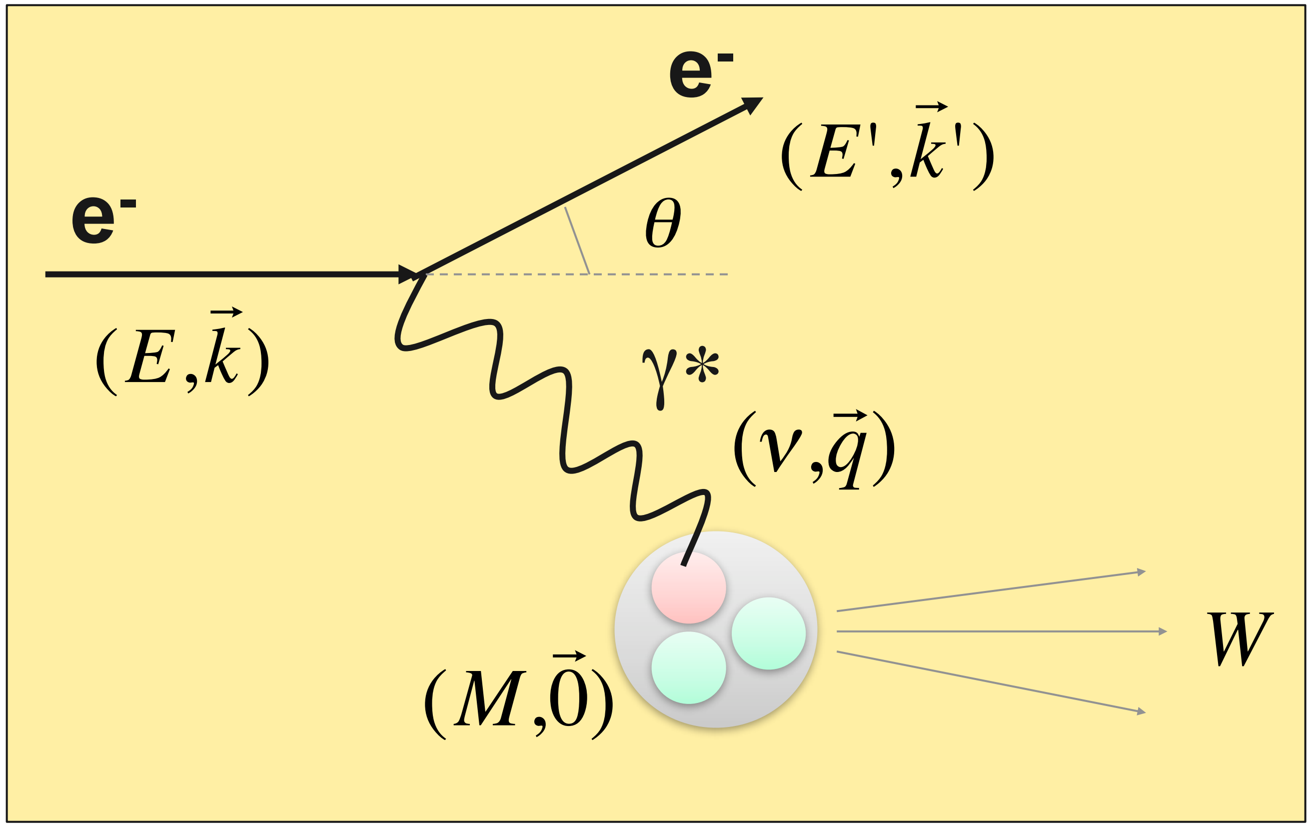
Hall C seminar
Jefferson Lab
April 9 2009

Outline

- The EMC effect
- JLab Hall C E03-103
- Coulomb Distortion
  - Effect on E03-103 heavy target data
  - Effect on World data
  - A-independence of $R(x,Q^2)$
- What's next ?
  - $F_2(^3H)/F_2(^3He)$: EMC effect on lightest nuclei
  - F2n/F2p and d/u at high x
  - A_1 proton and neutron: $\Delta u/u$ and $\Delta d/d$ at high x
- Summary and Outlook



The structure of the nucleon from inclusive



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

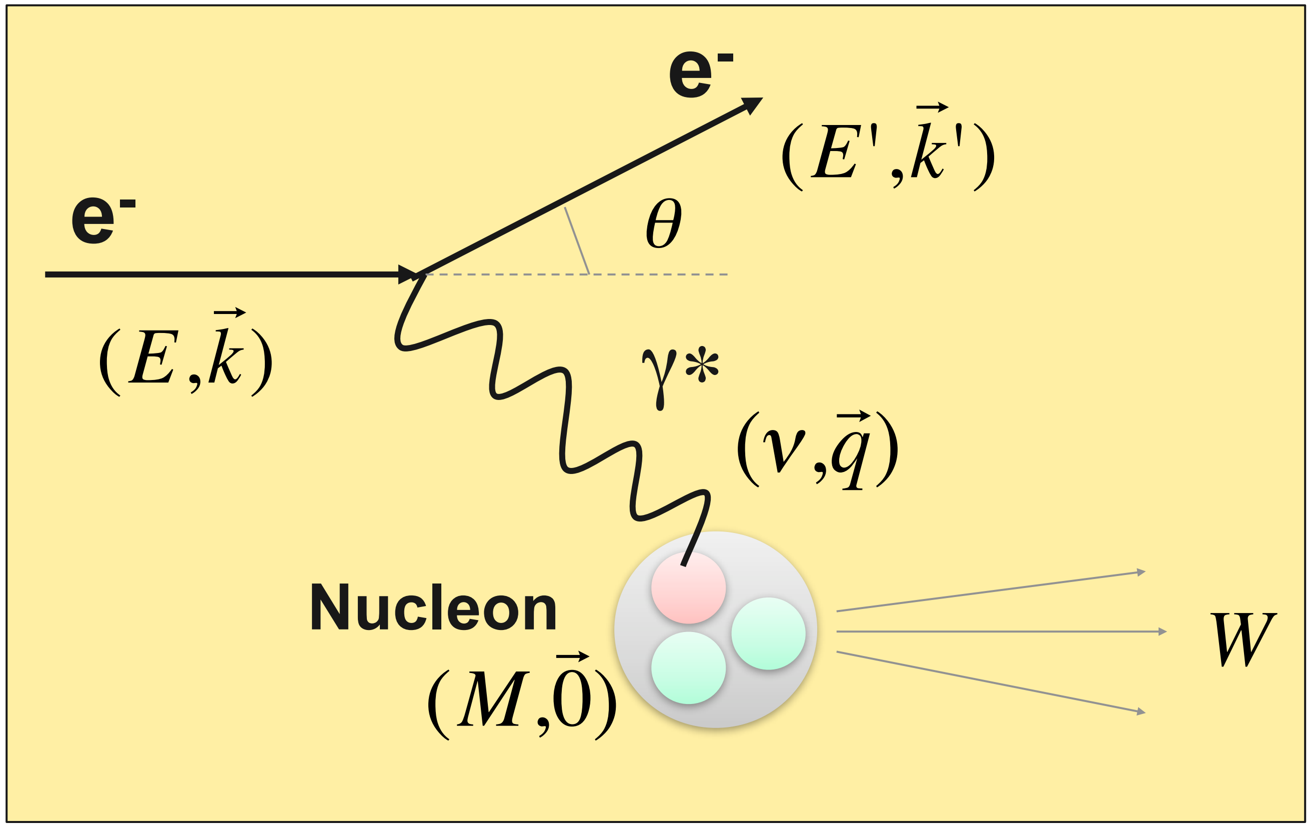
$$x = \frac{Q^2}{2M\nu}$$

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

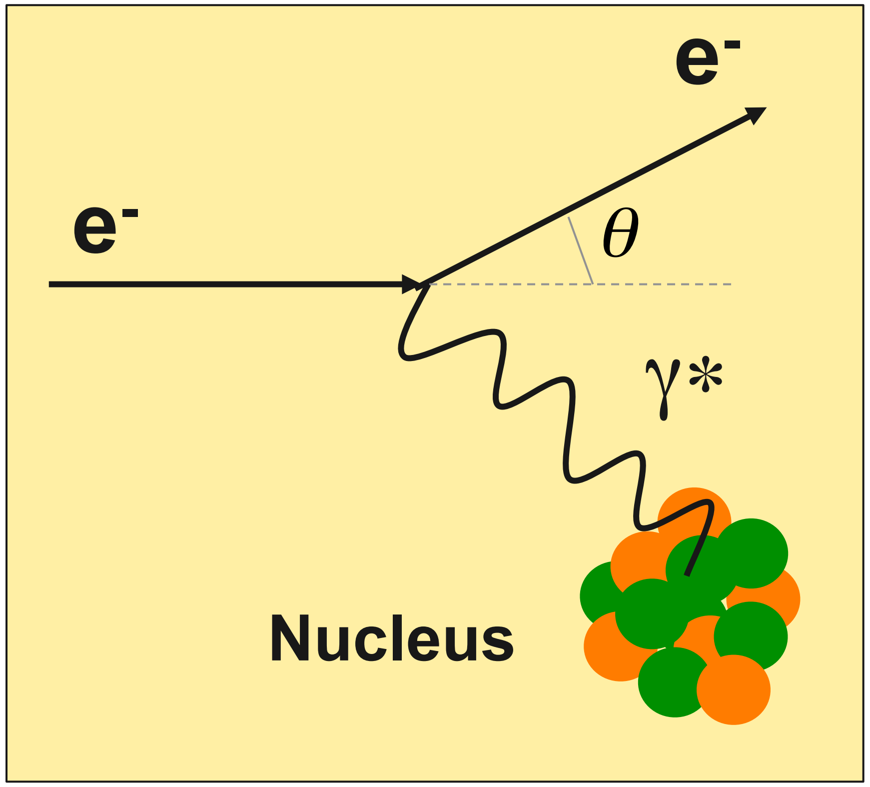
In the parton model:

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

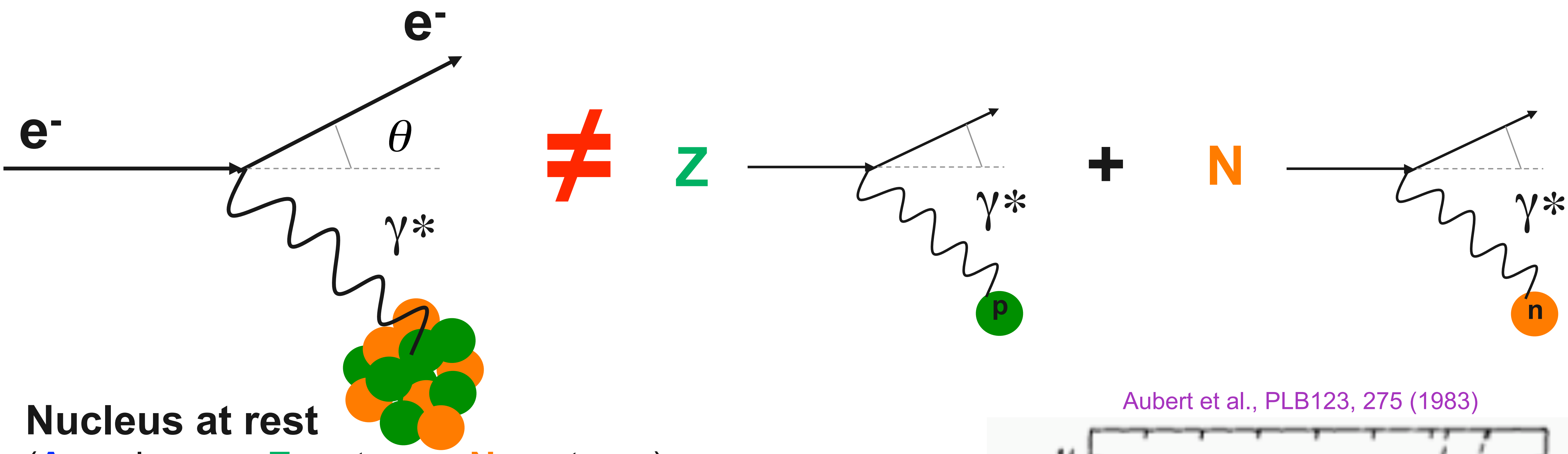
The quest for higher precision data



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

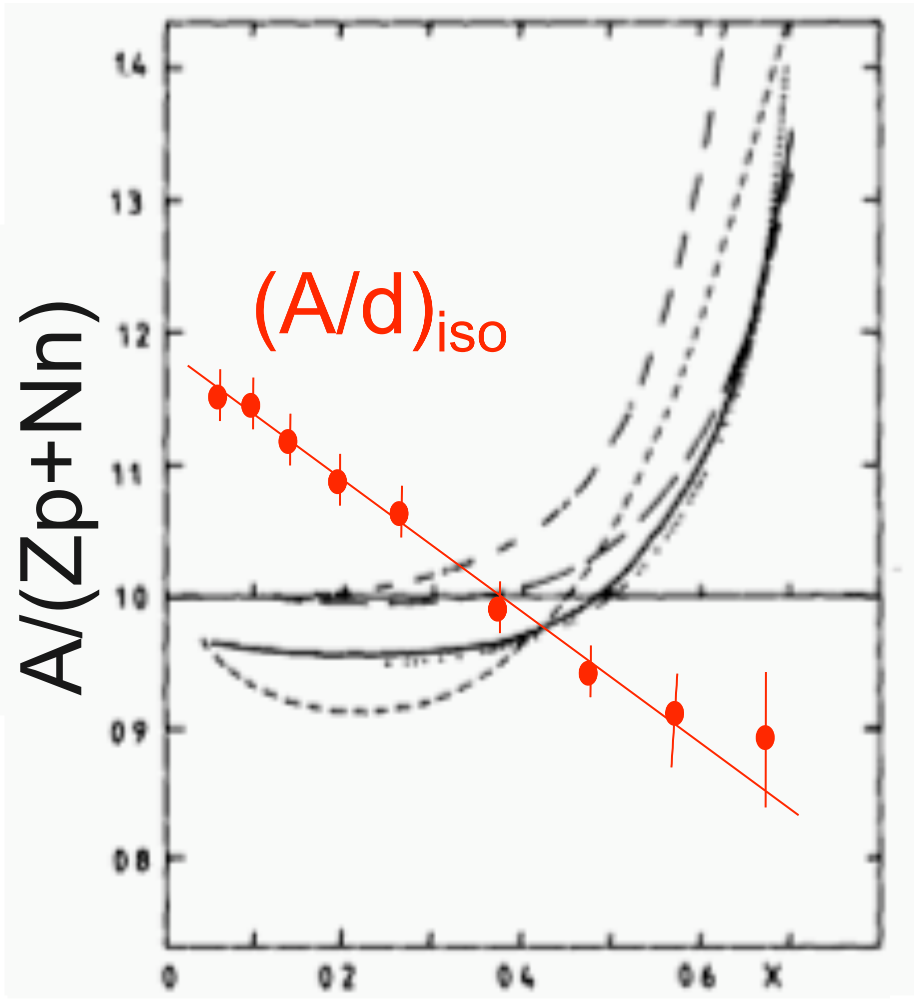


The EMC effect



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

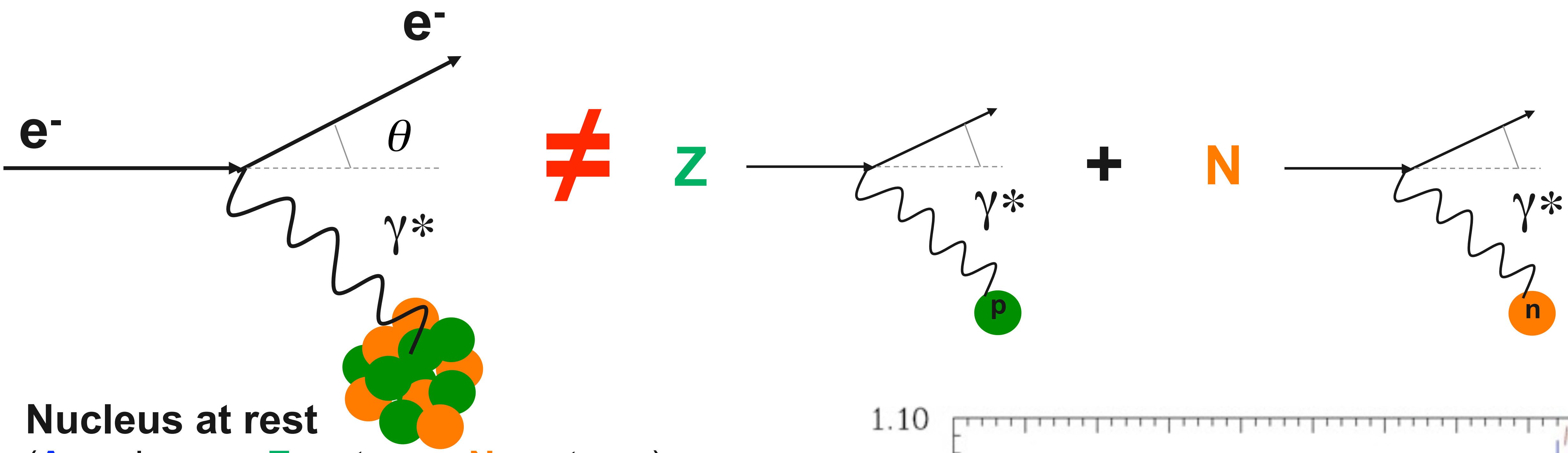
Aubert et al., PLB123, 275 (1983)



Nuclear structure:

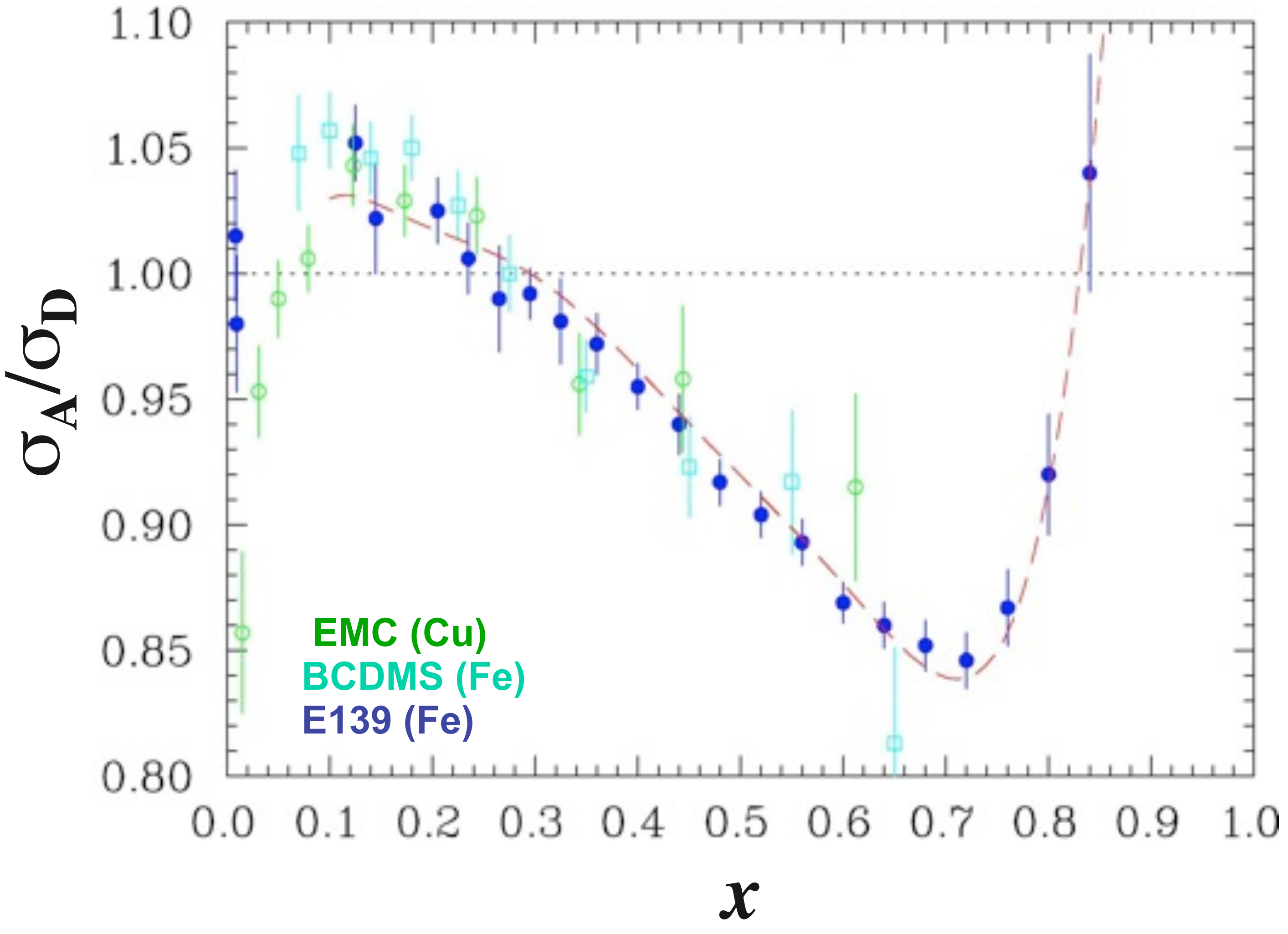
$$F_2^A \neq ZF_2^p + NF_2^n$$

The EMC effect



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

Effects found in several experiments at CERN, SLAC, DESY

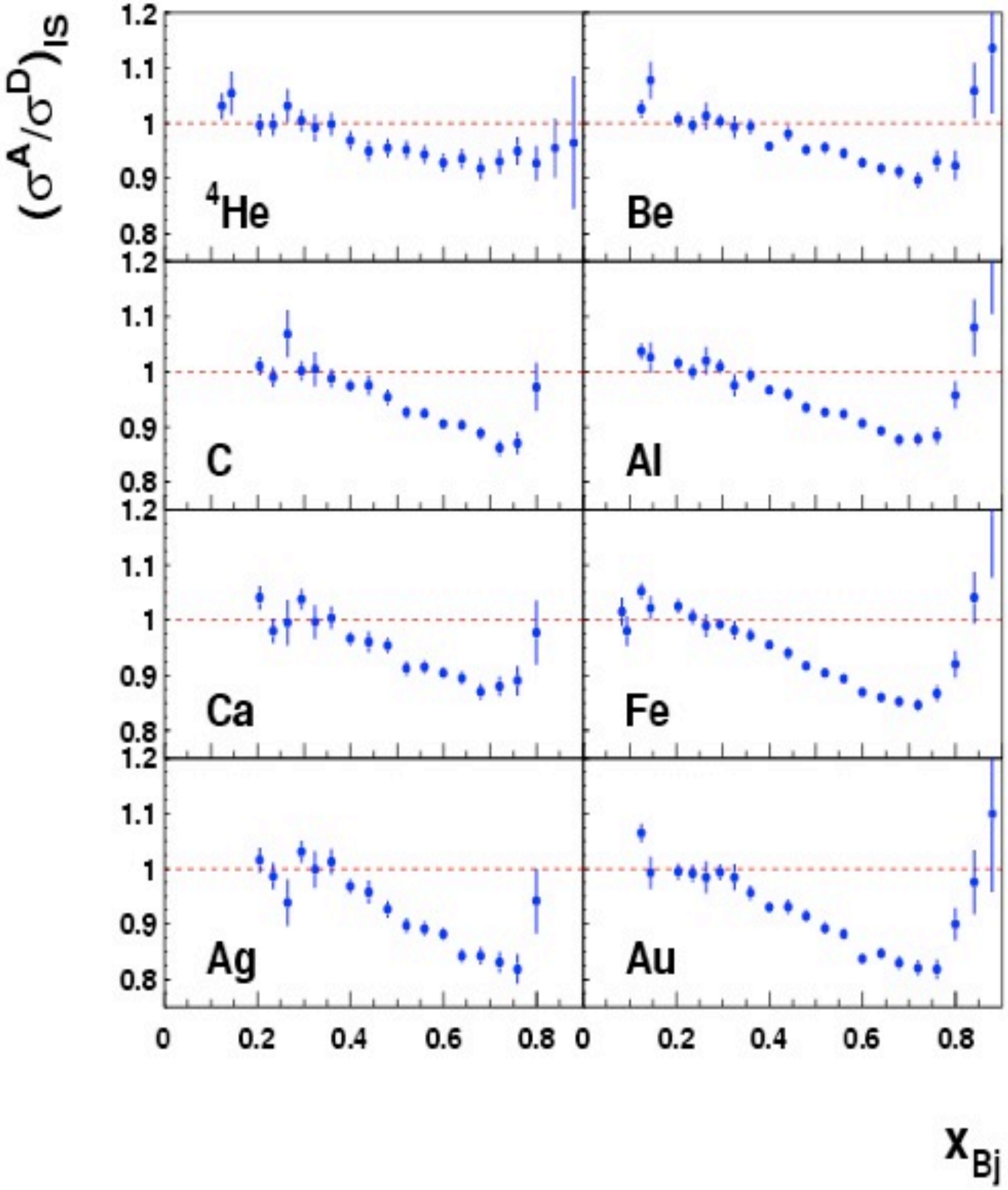


Existing EMC Data

SLAC E139:

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

J. Gomez et al, PRC49, 4348 (1994))



Nucleon only model

Assumptions on the nucleon structure function:

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

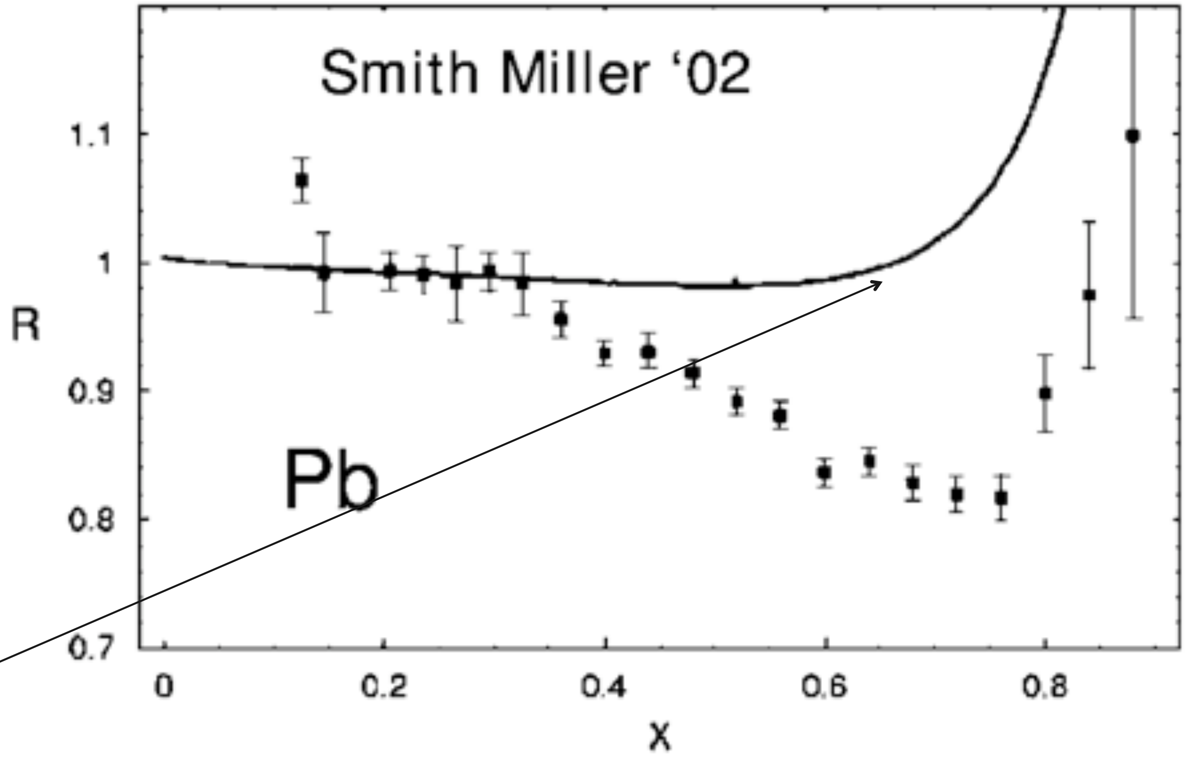
$$\frac{F_2^A(x_A)}{A} = \int_{x_A}^{A} dy \cdot f_N(y) F_2^N(x_A/y)$$

Fermi momentum << M$_{\text{nucleon}}$

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

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

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



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

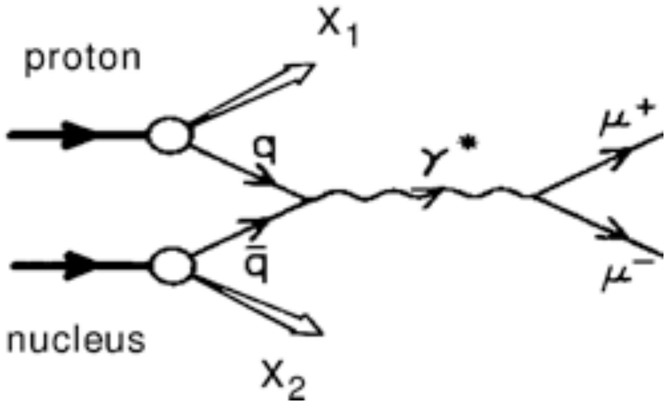
Nucleons and pions model

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

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

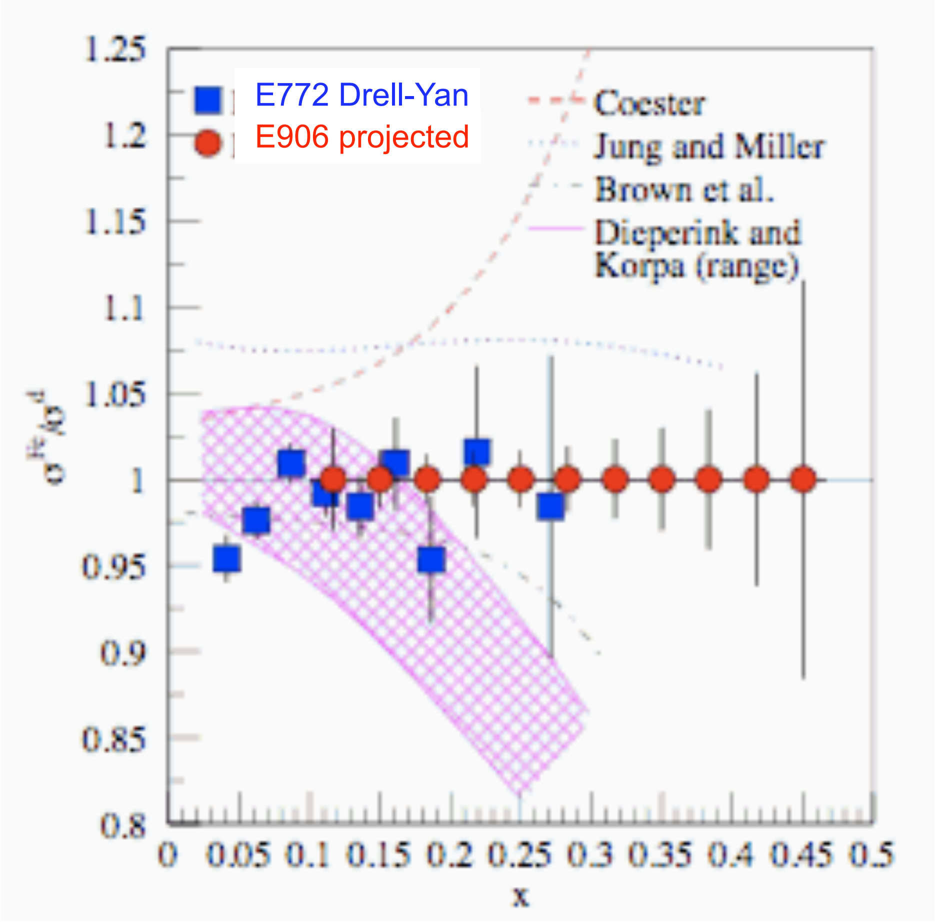
and using $P_\pi^+ / M_A = 0.04$ **is enough to reproduce the EMC effect**

But excess of nuclear pions ➔ enhancement of the nuclear sea



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

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



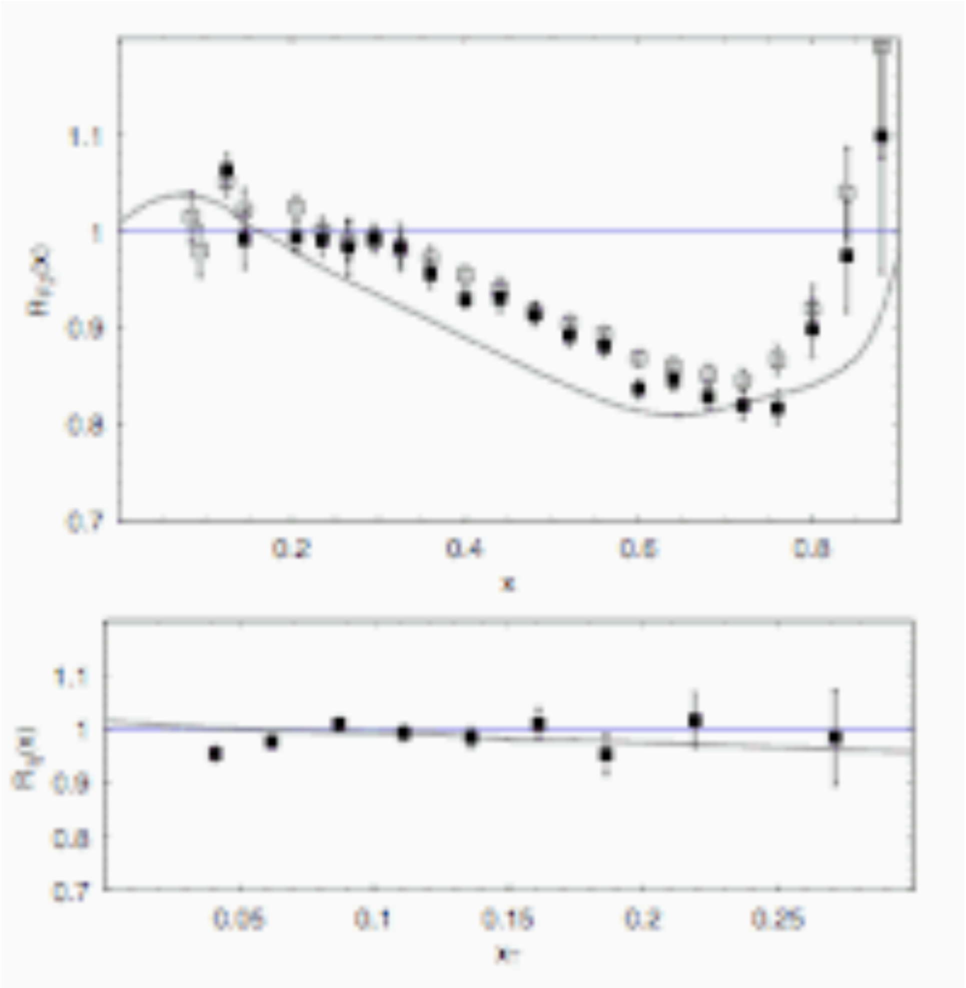
Another class of models

➔ **Interaction between nucleons**

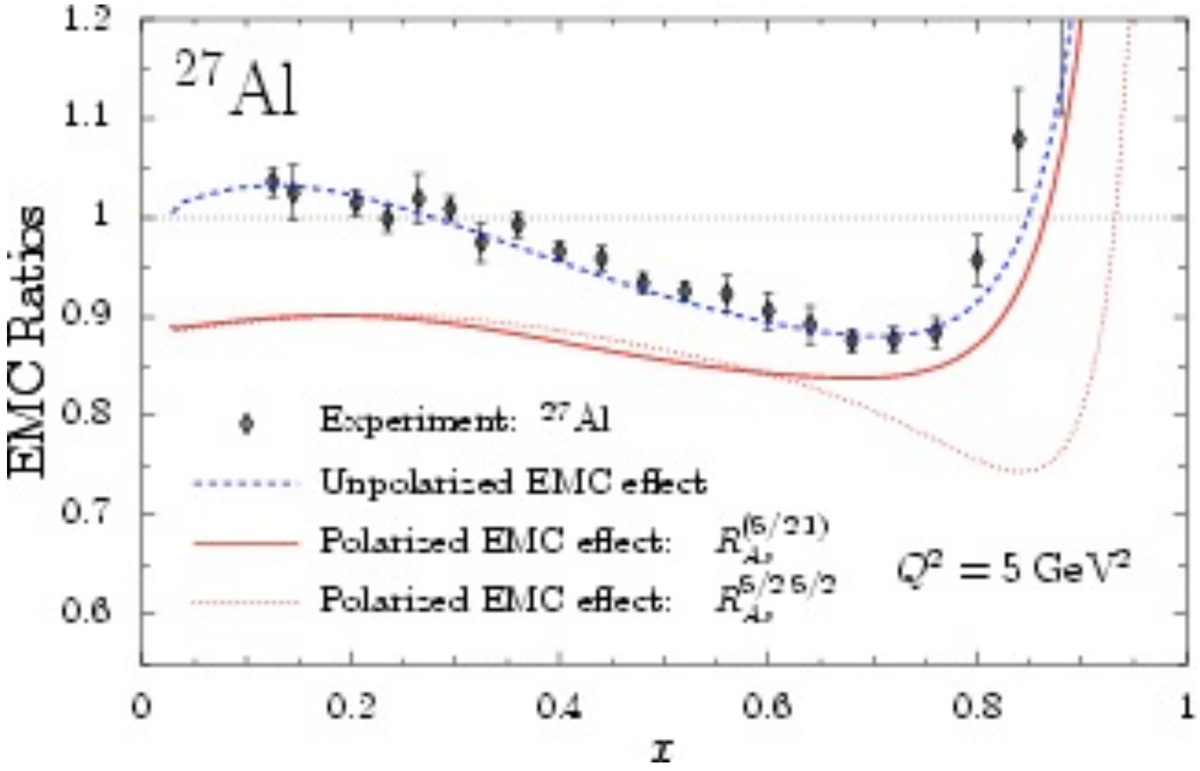
Model assumption:

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

Smith & Miller, PRL 91, 212301 (2003)



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



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*

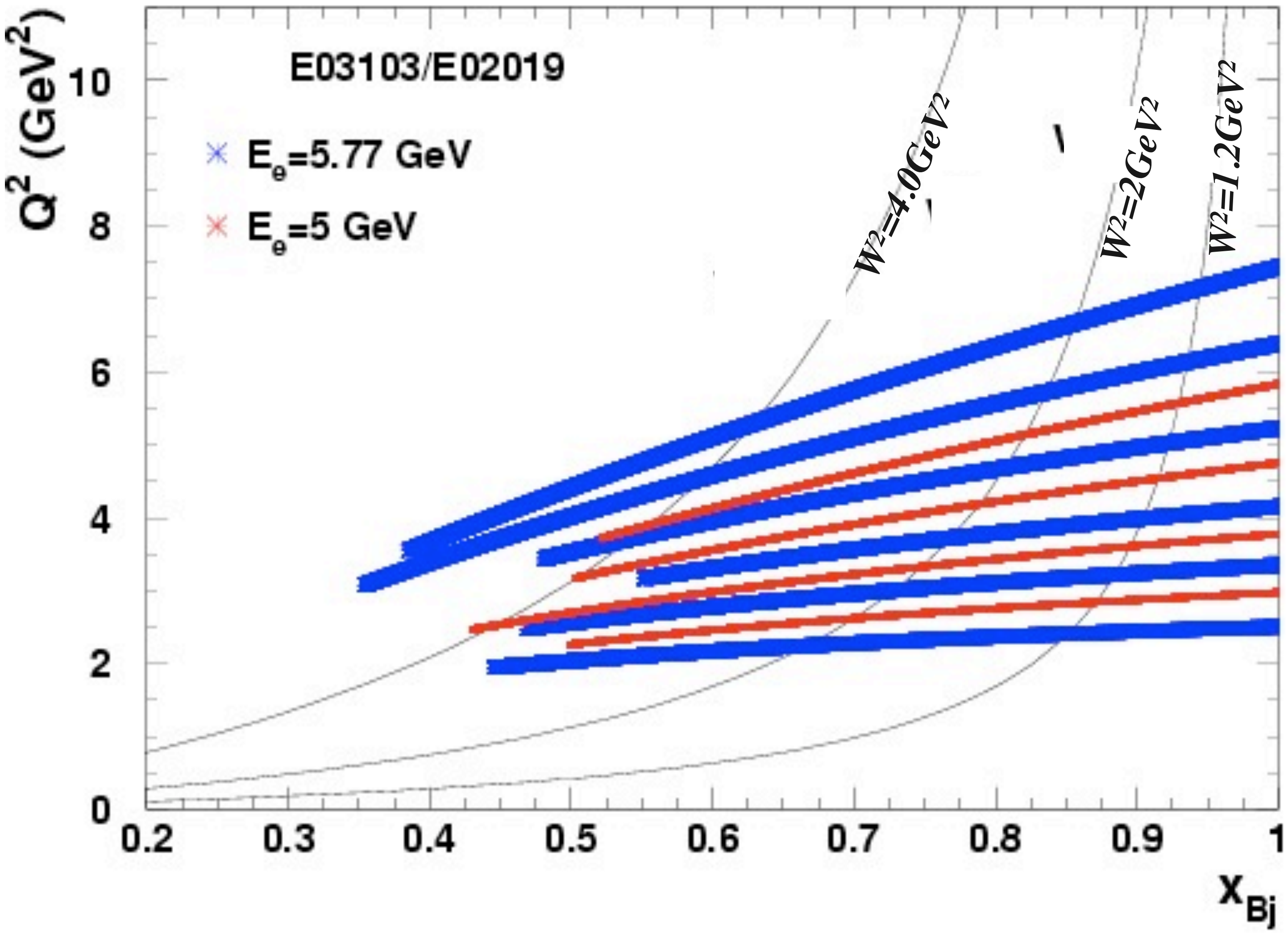
JLab Experiment E03-103

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

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

10 angles to measure Q^2-dependence

Targets: H, ^{2}H,
^{3}He, ^{4}He,
^{9}Be, ^{12}C,
^{63}Cu, ^{197}Au



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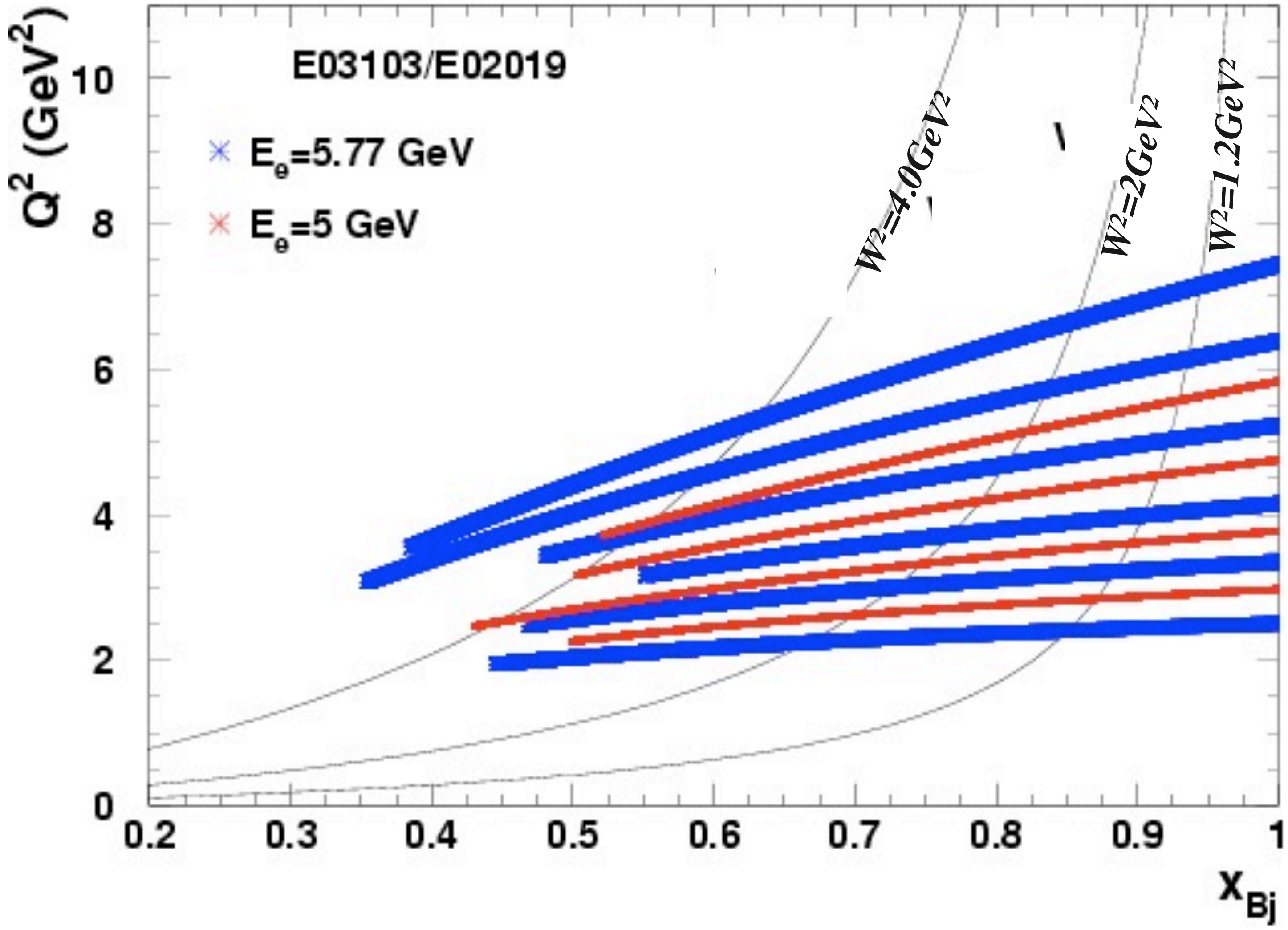
Isoscalar correction



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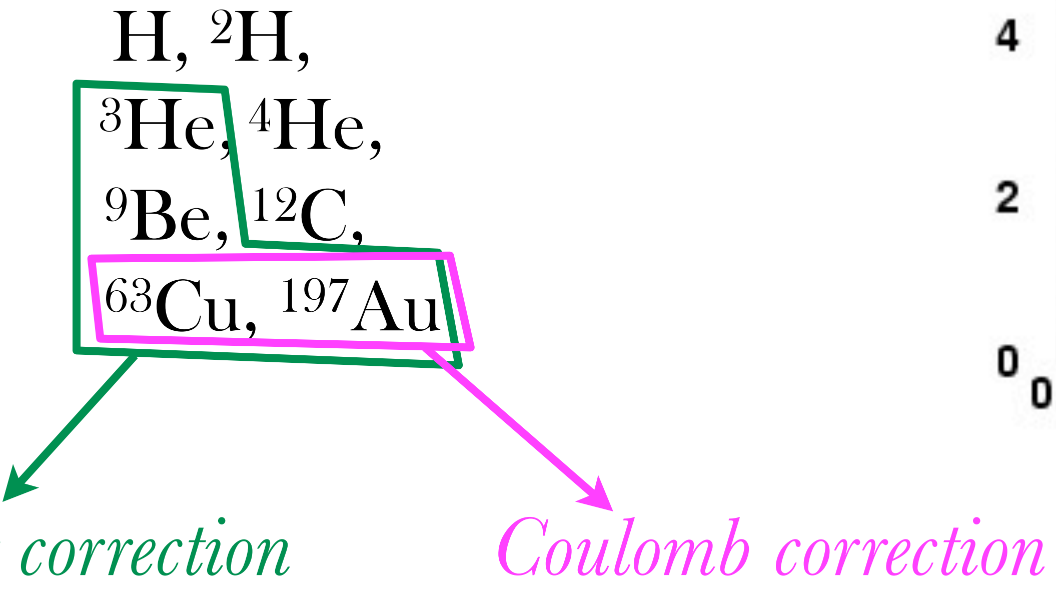

Targets: H, ^{2}H,
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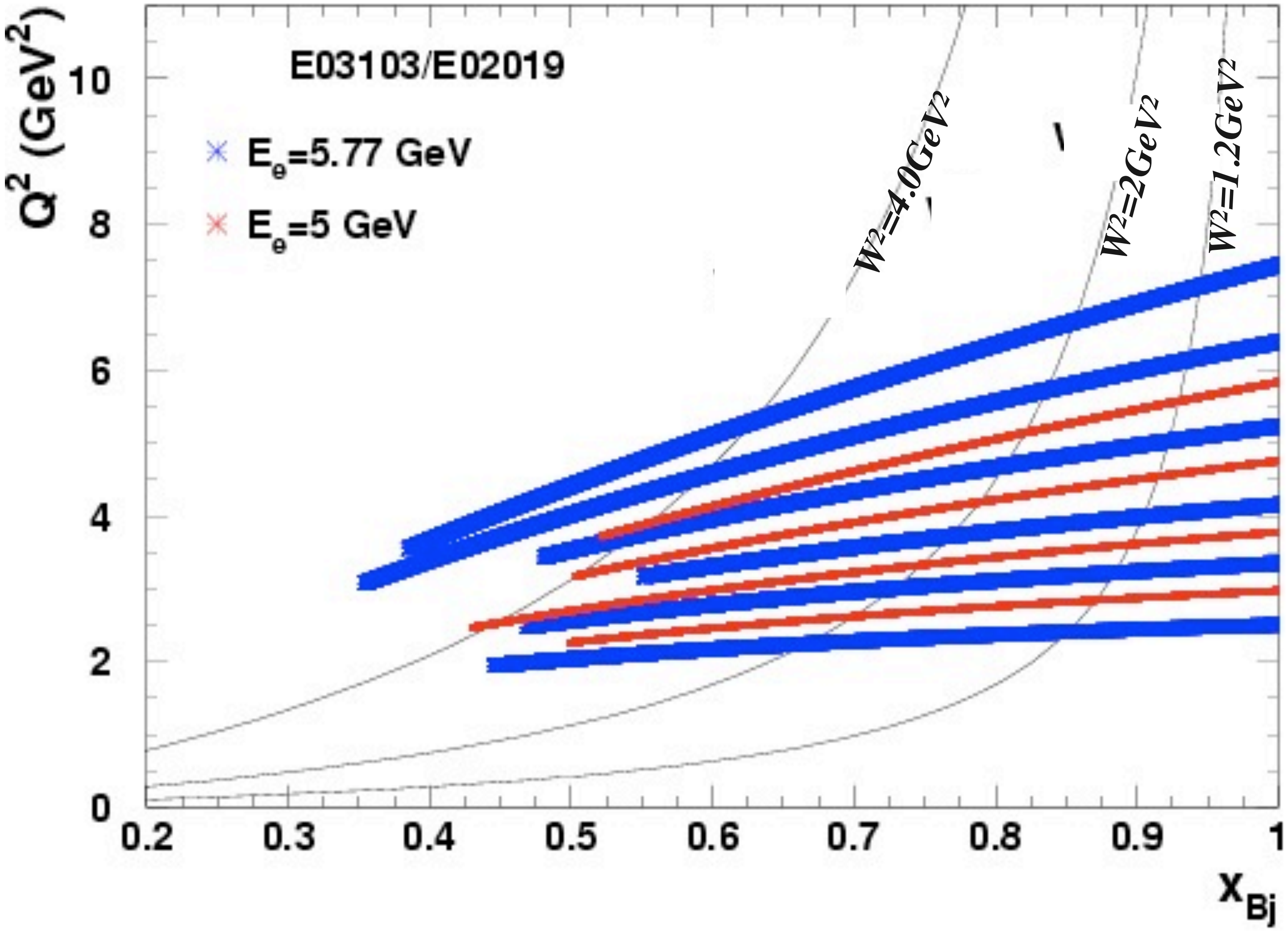
^{9}Be, ^{12}C,
^{63}Cu, ^{197}Au

Isoscalar correction

Coulomb correction



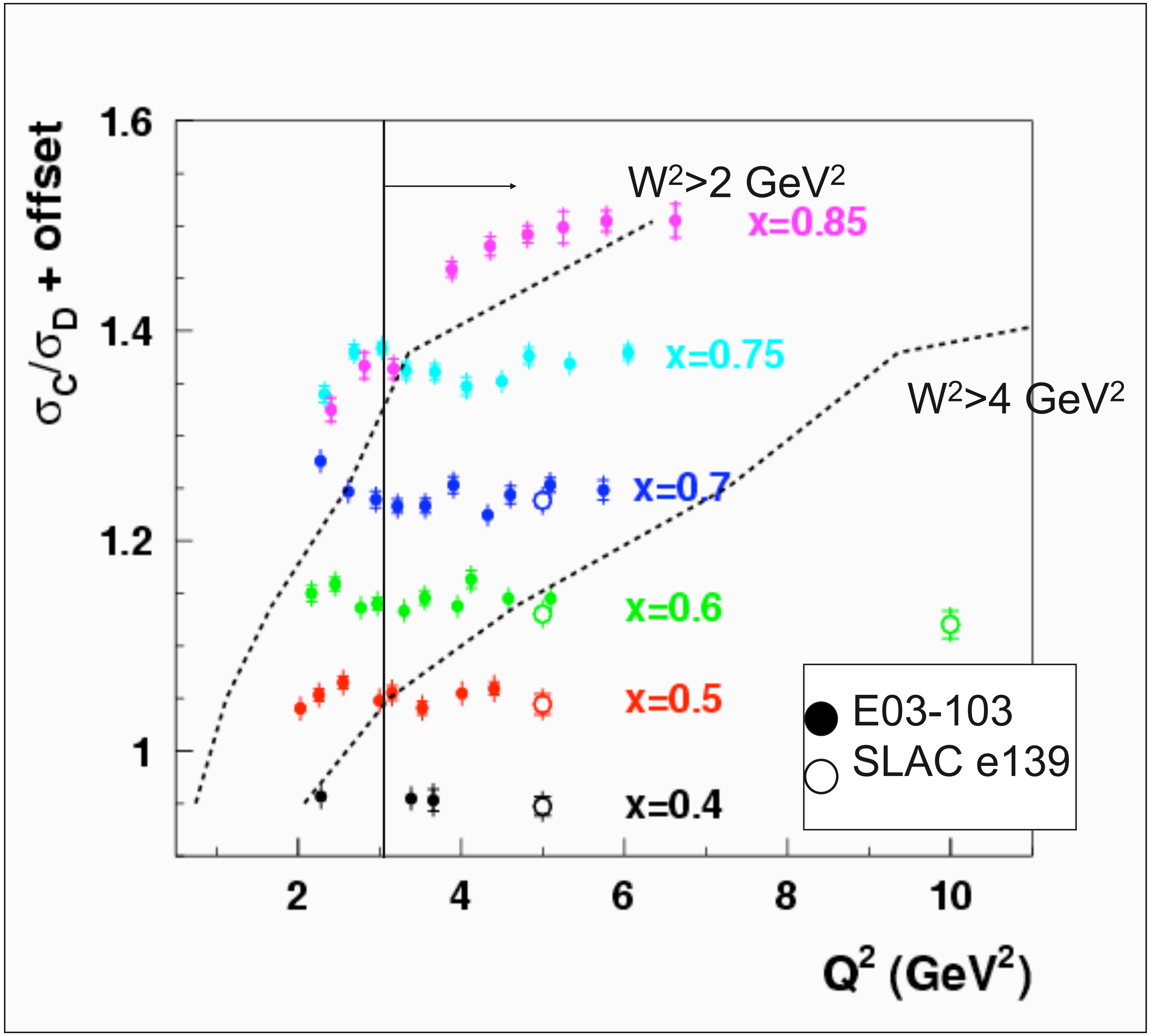
More detailed look at scaling

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 $x=0.85$

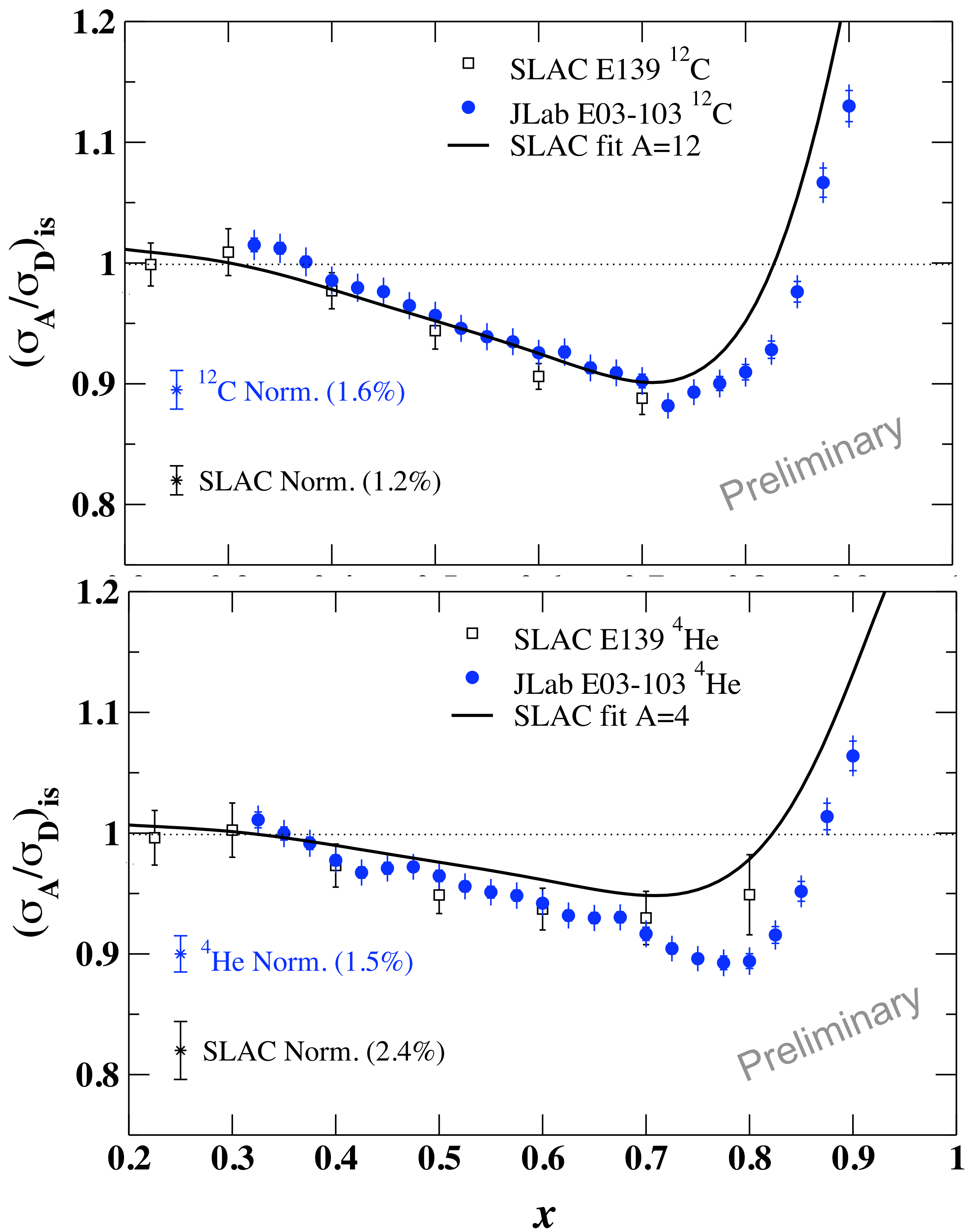
Note: Ratios at larger *x* will be shown, but could have small HT, scaling violation



E03-103: ^{12}C and ^{4}He EMC ratios

JLab results consistent with SLAC E139

→ Improved statistics and systematic errors



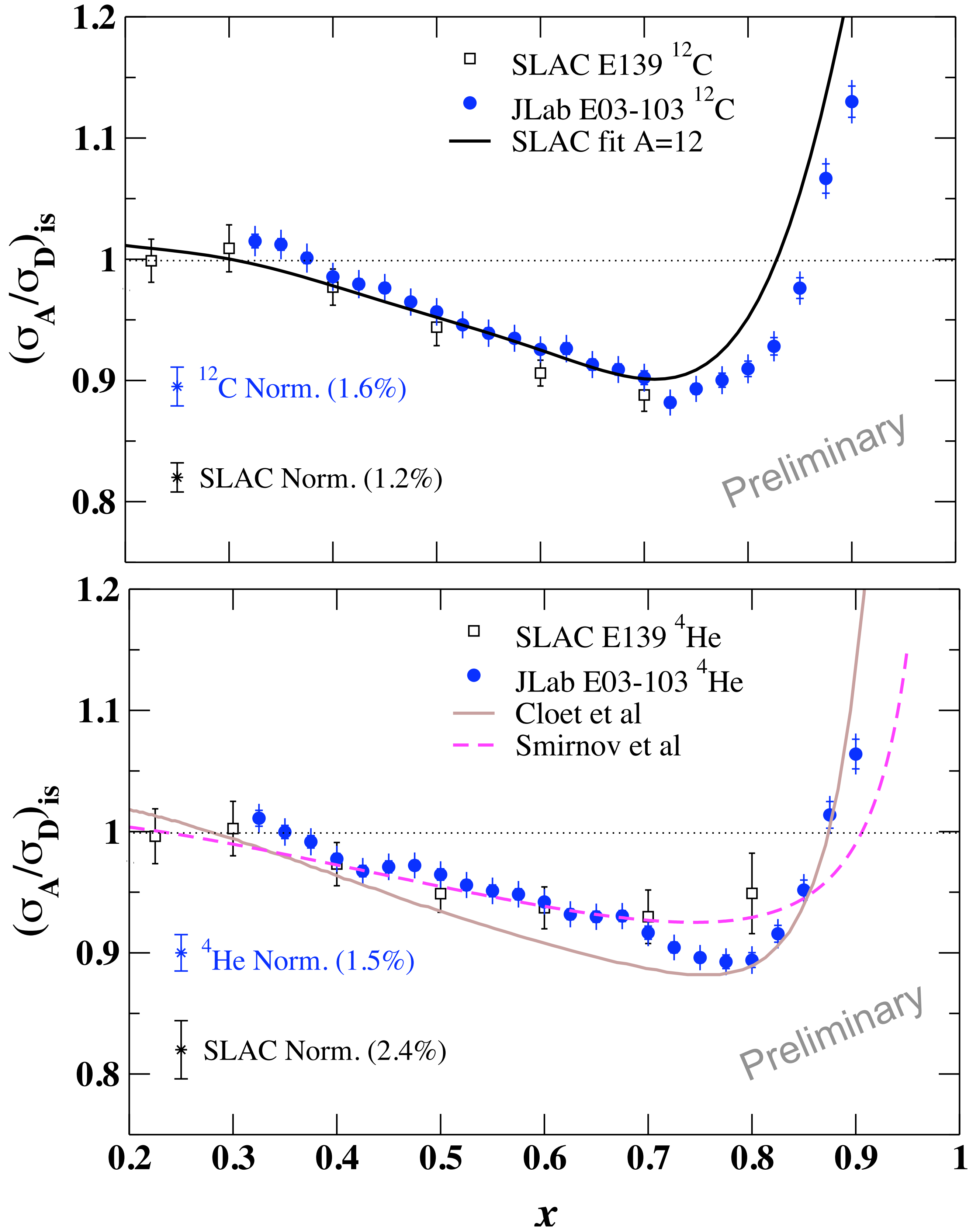
E03-103: ^{12}C and ^{4}He EMC ratios

JLab results consistent with SLAC E139

→ Improved statistics and systematic errors

Models shown do a reasonable job describing the data.

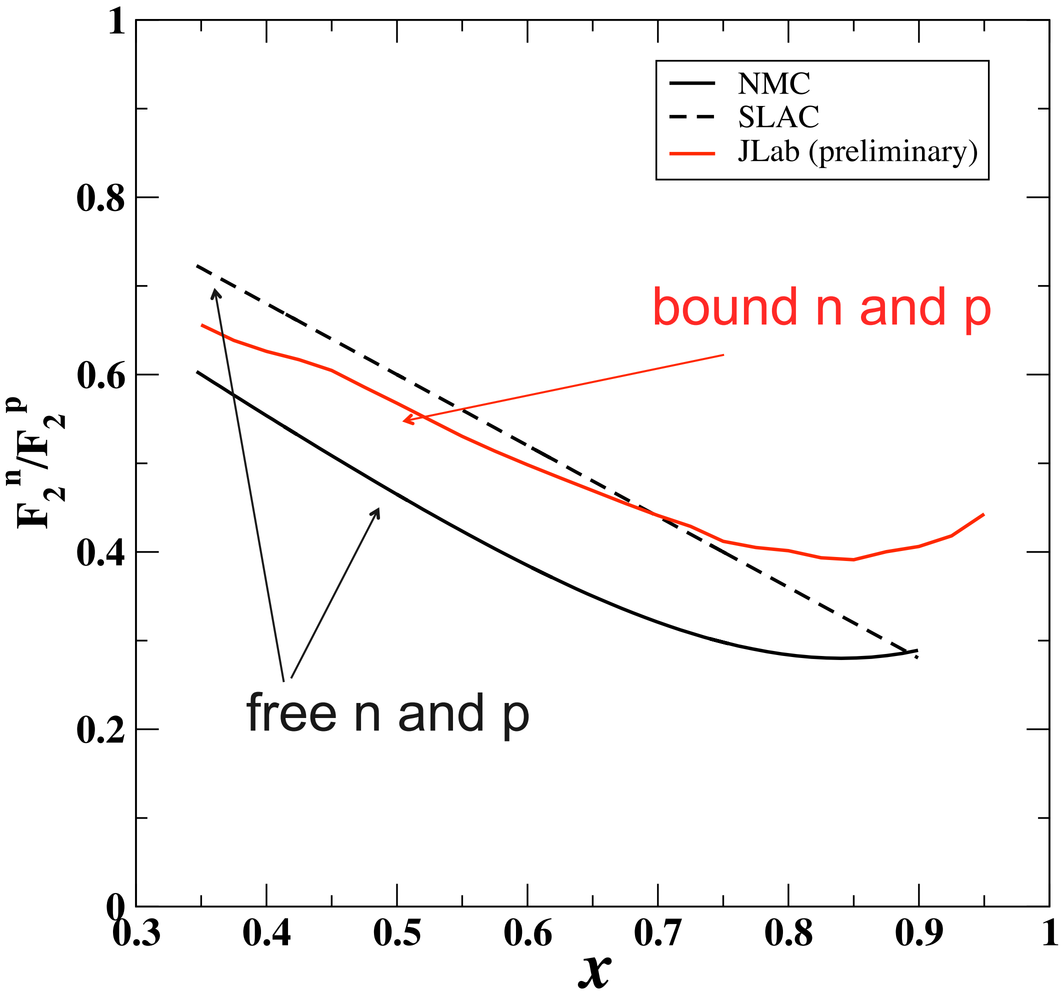
But very few real few-body calculations (most neglect structure, scale NM)

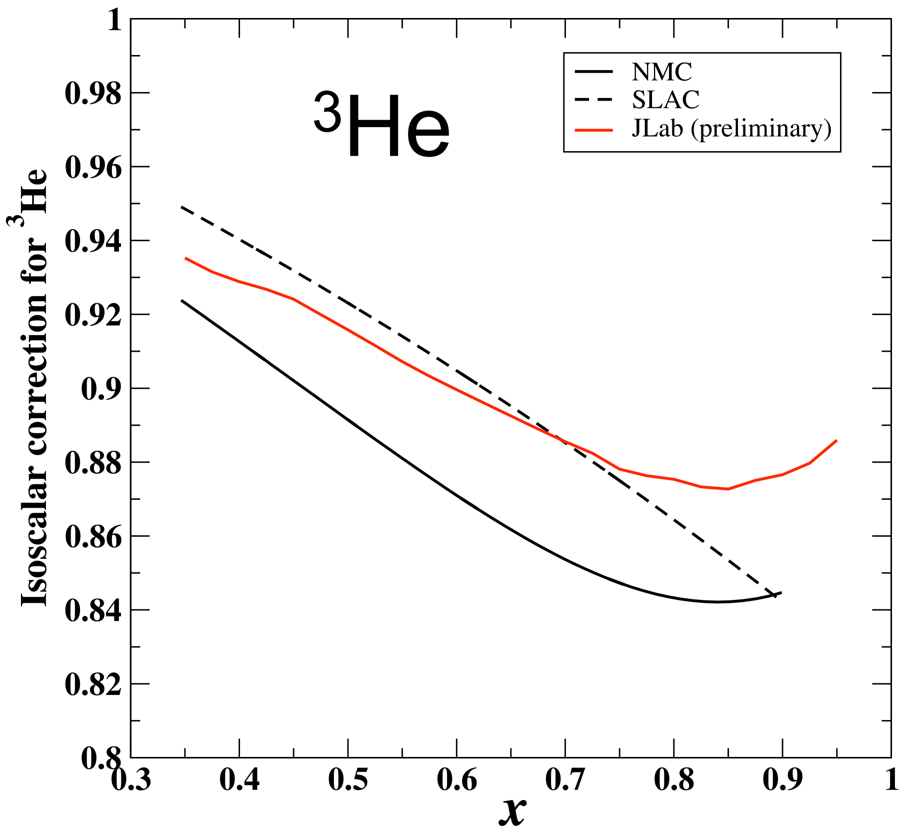


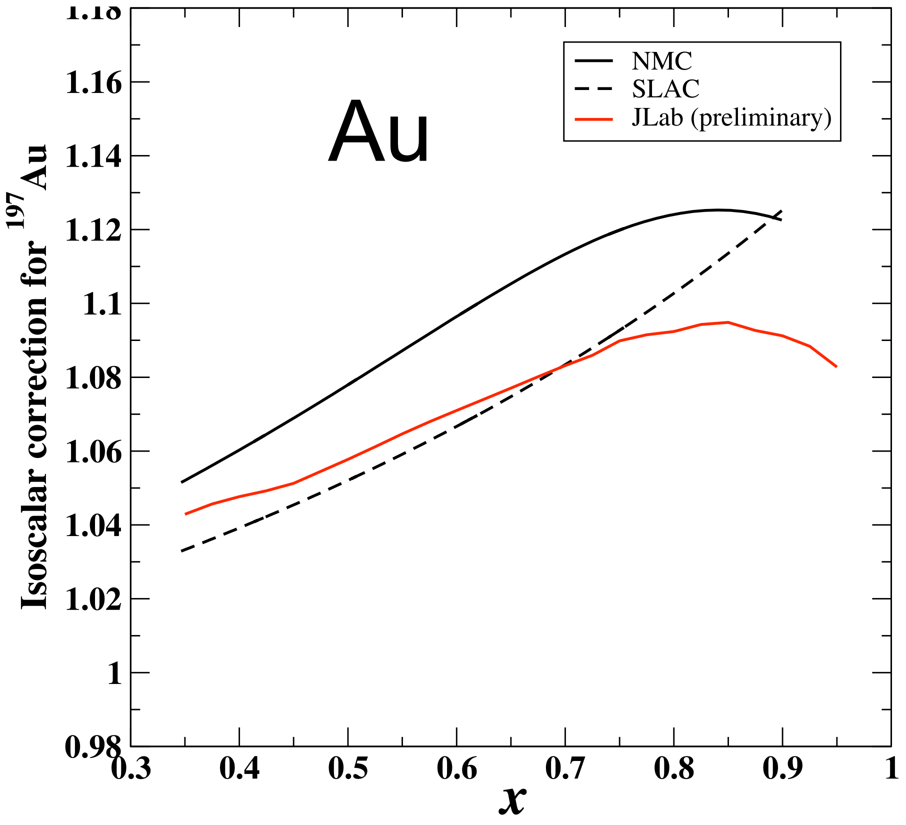
Isoscalar correction

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

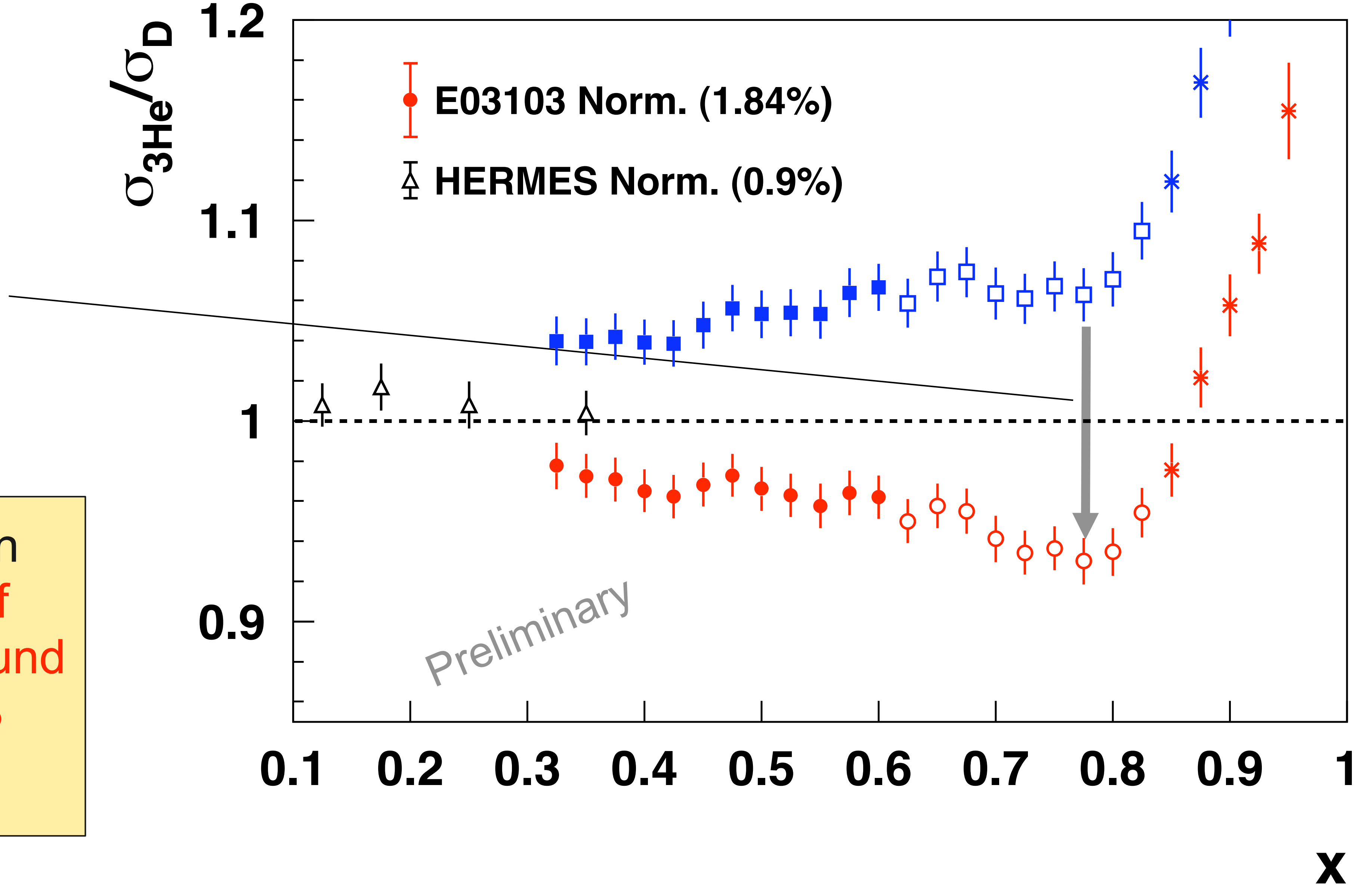
Isoscalar correction







E03-103: ^{3}He EMC ratio

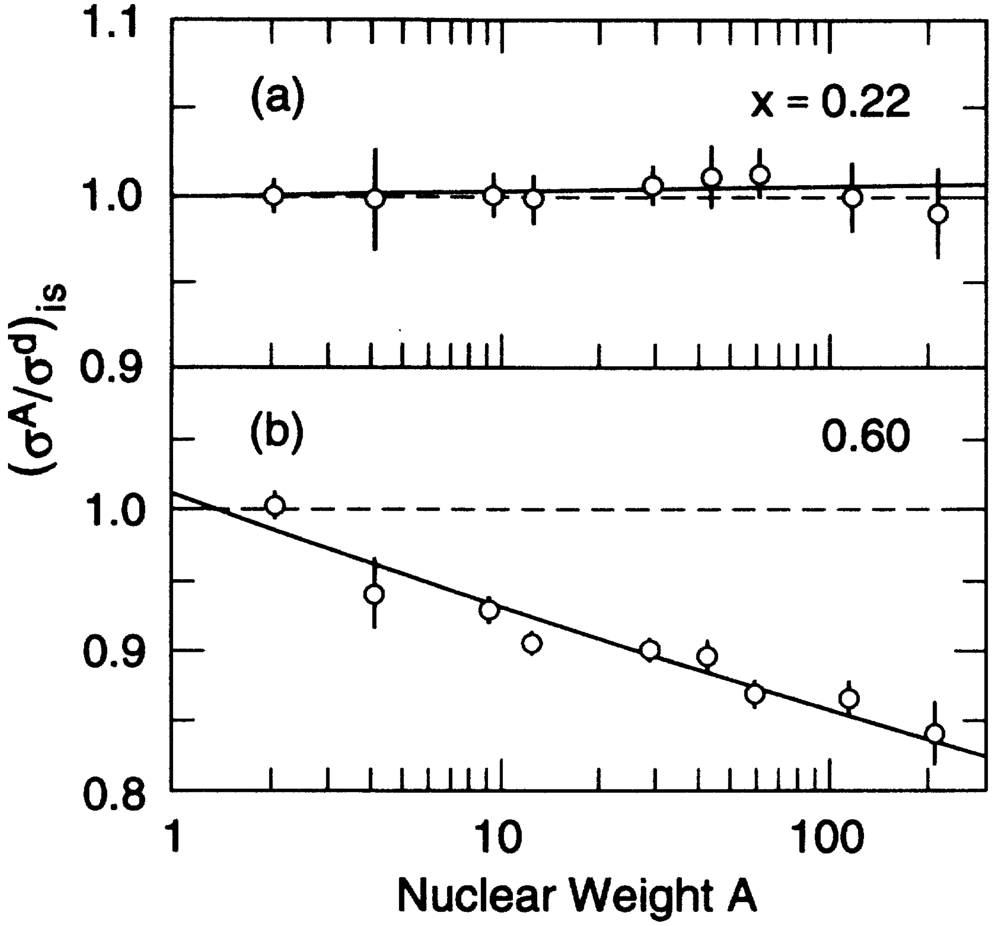


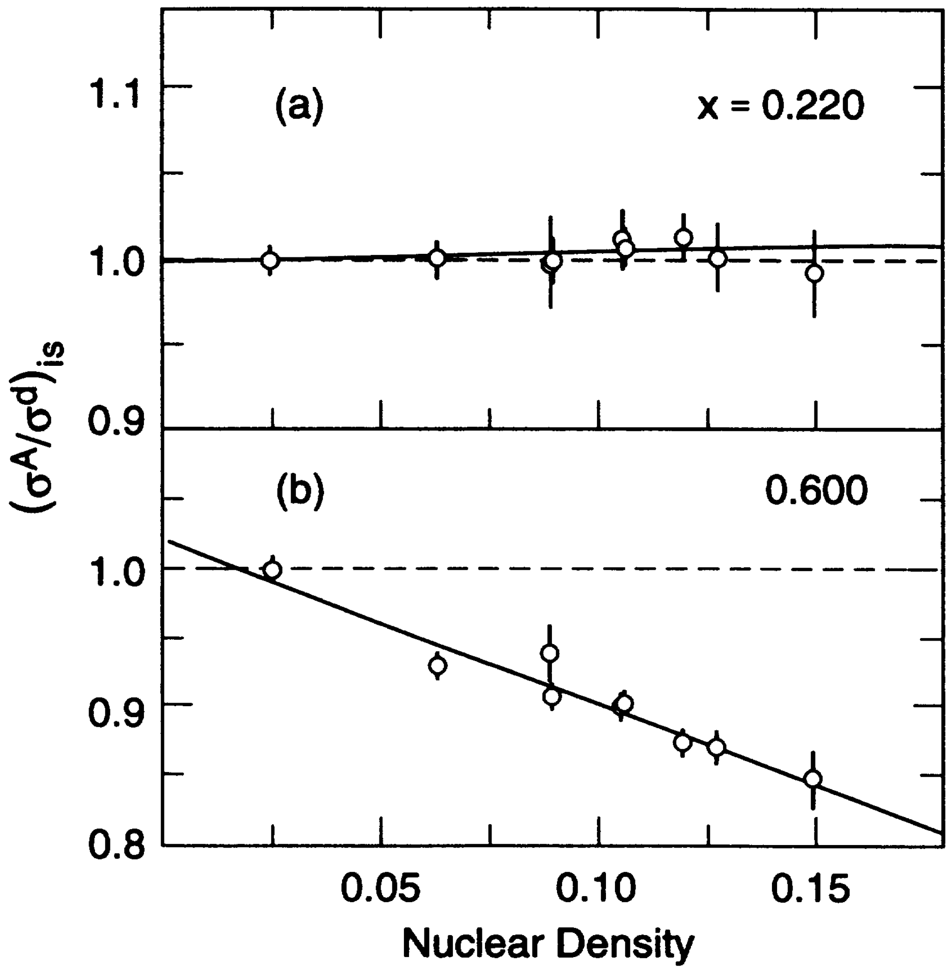
Large proton excess correction

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

A or ρ-dependence ?

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





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

A or ρ-dependence ?

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

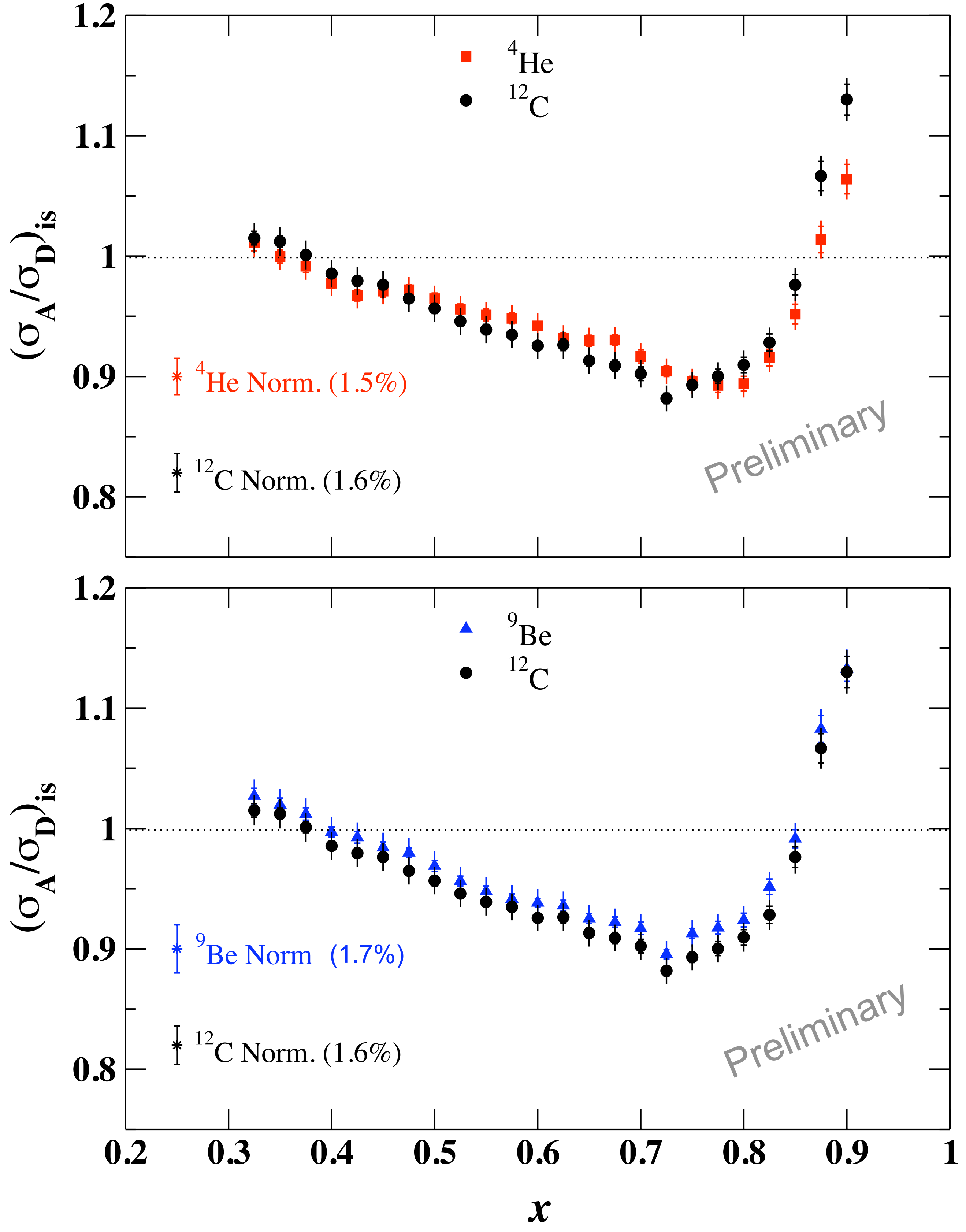
ρ(^{4}He) ~ ρ(^{12}C)

EMC effect: ρ–dependent

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

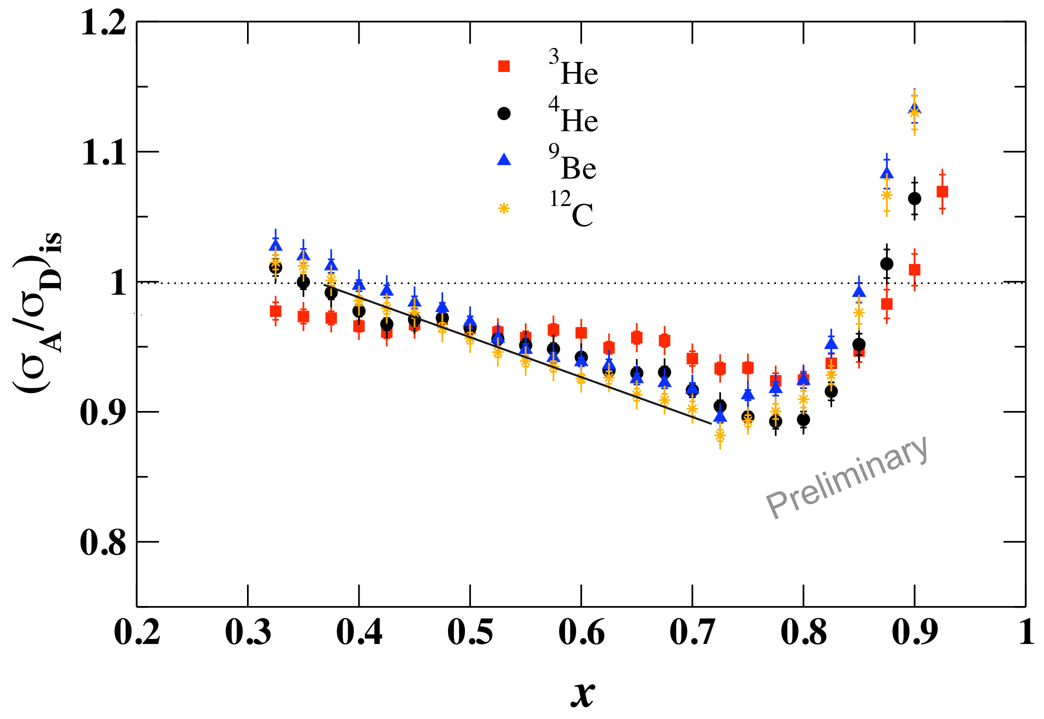
ρ(^{9}Be) << ρ(^{12}C)

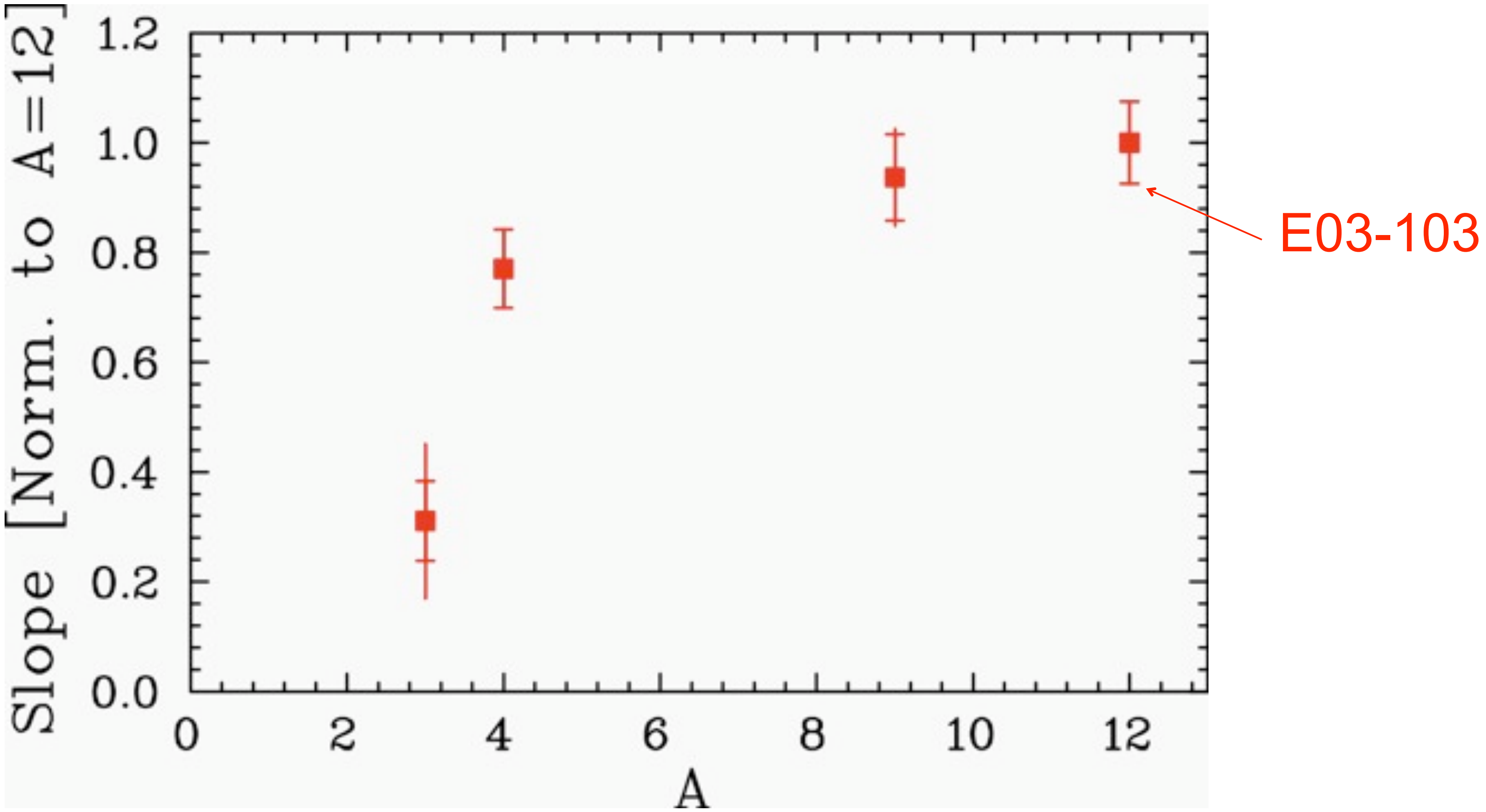
EMC effect: A-dependent



A or ρ-dependence ?

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





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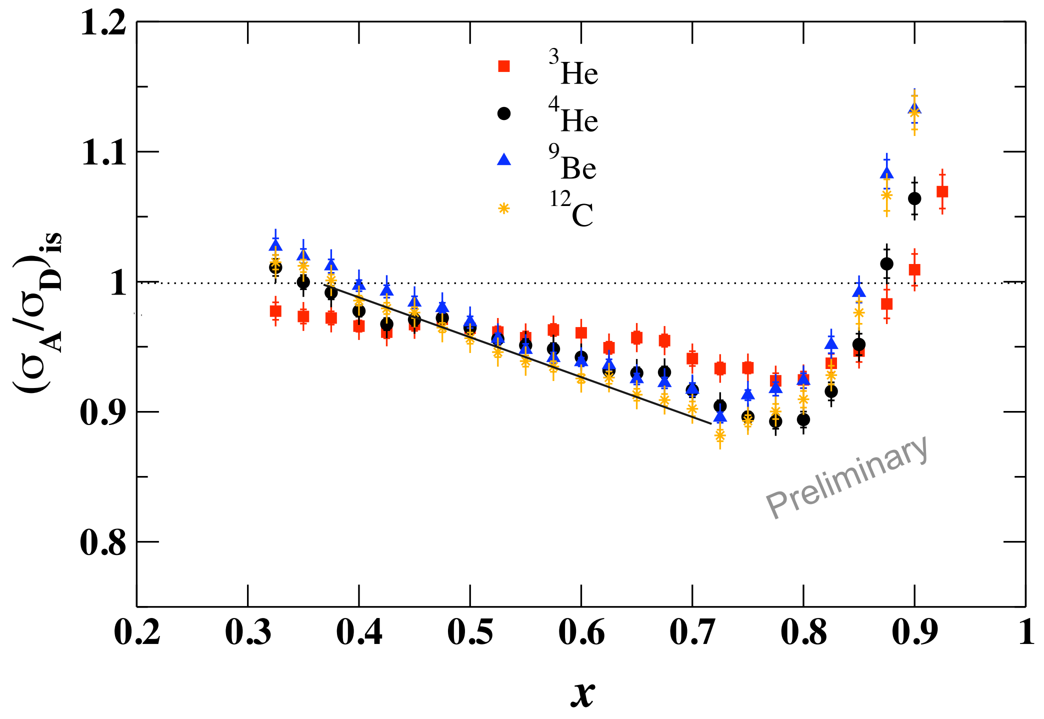

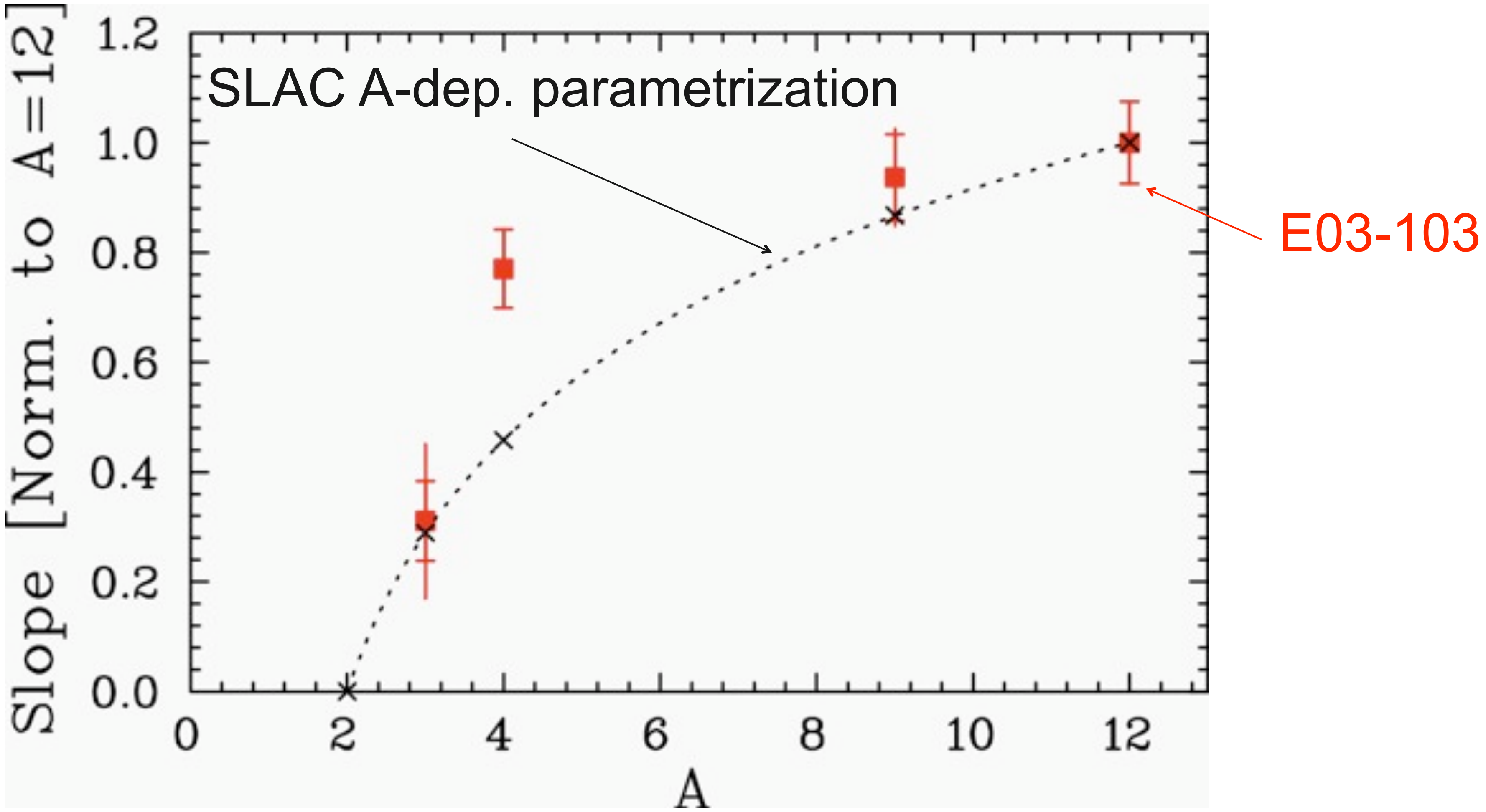

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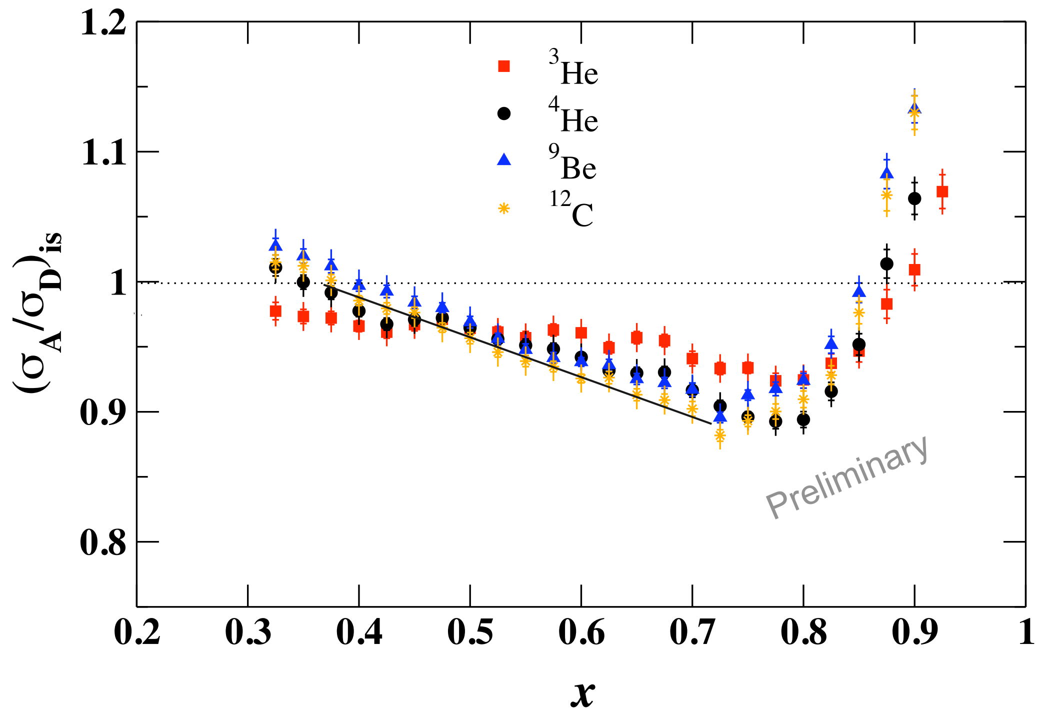
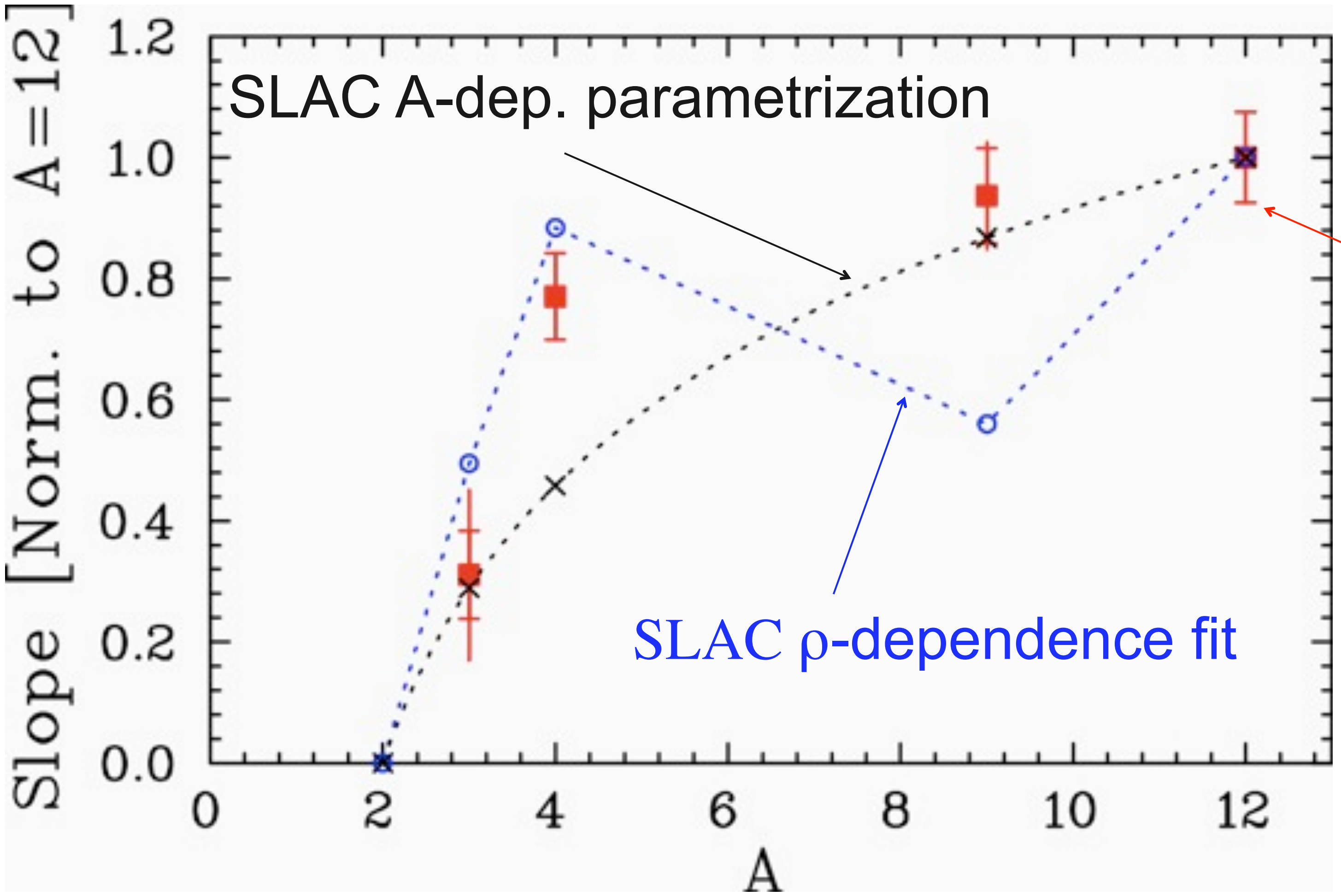


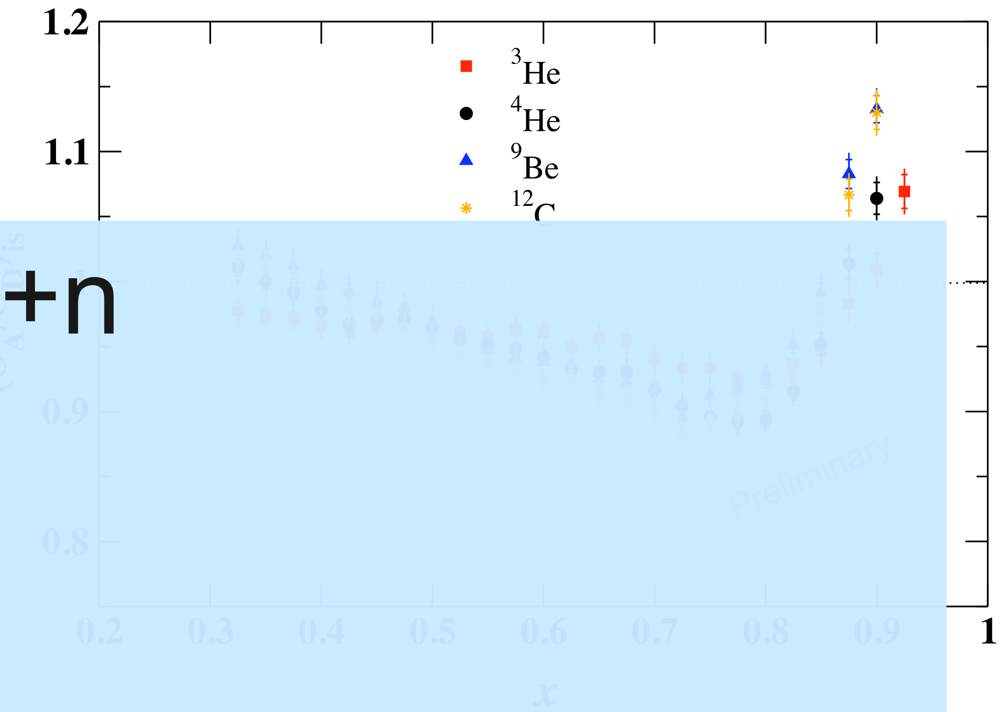


SLAC A-dep. parametrization

E03-103

SLAC ρ-dependence fit

A or ρ-dependence ?



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

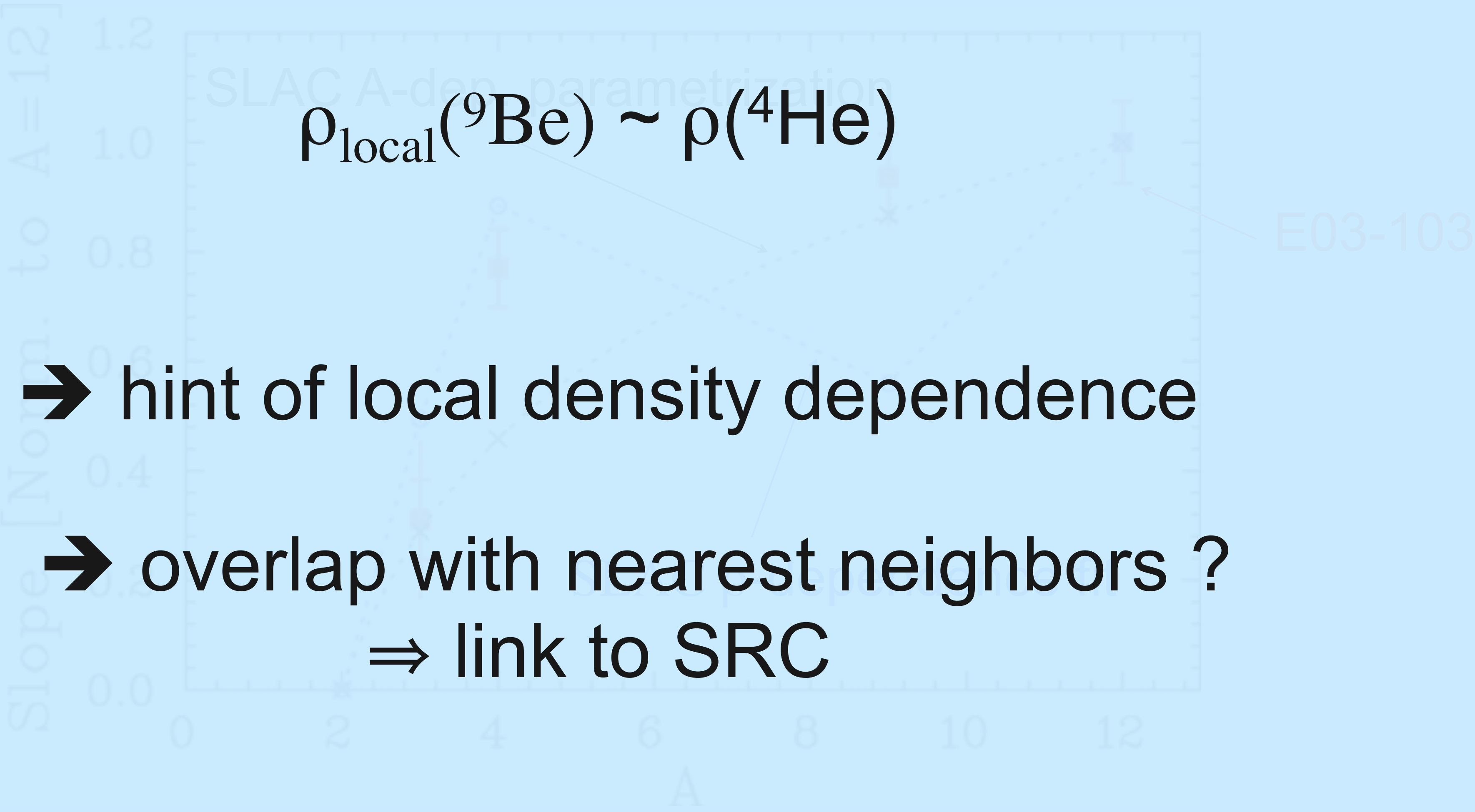
^{9}Be ~ 2α-cluster+n

🡇

<ρ> small

but

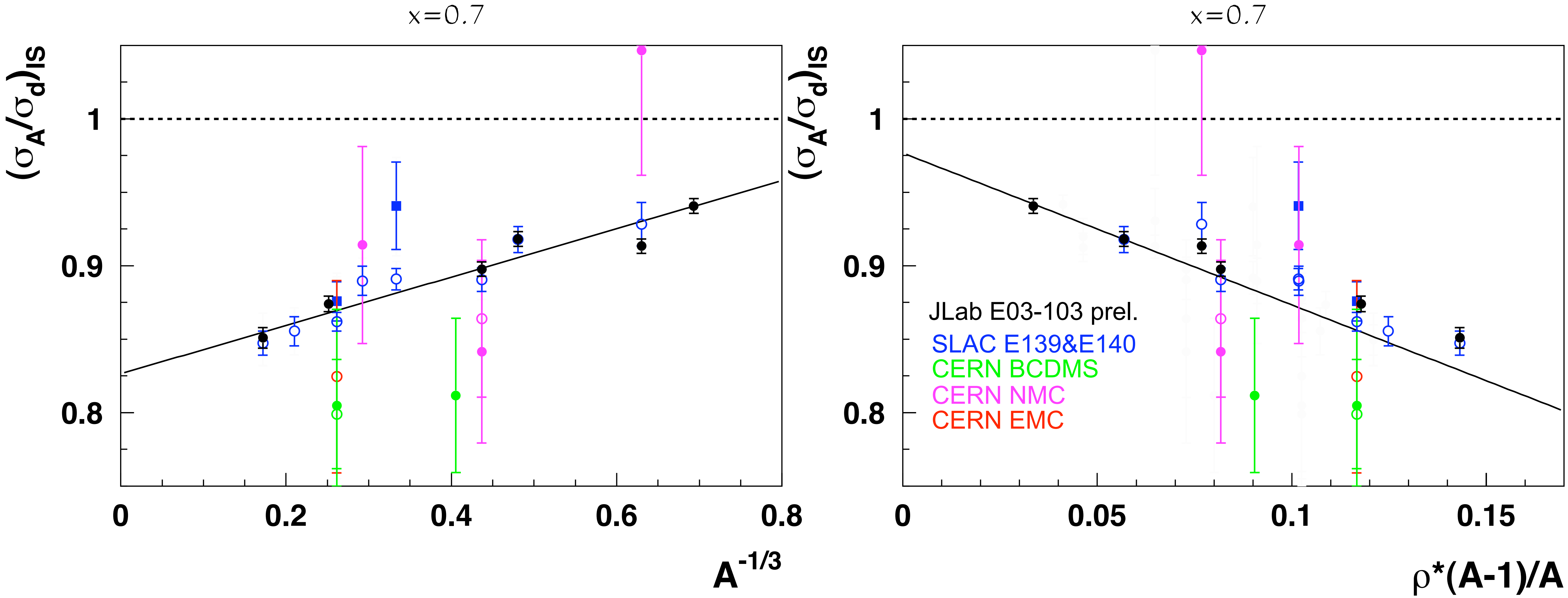
$\rho_{local}(^9\text{Be}) \sim \rho(^4\text{He})$



➔ hint of local density dependence

➔ overlap with nearest neighbors ?
⇒ link to SRC

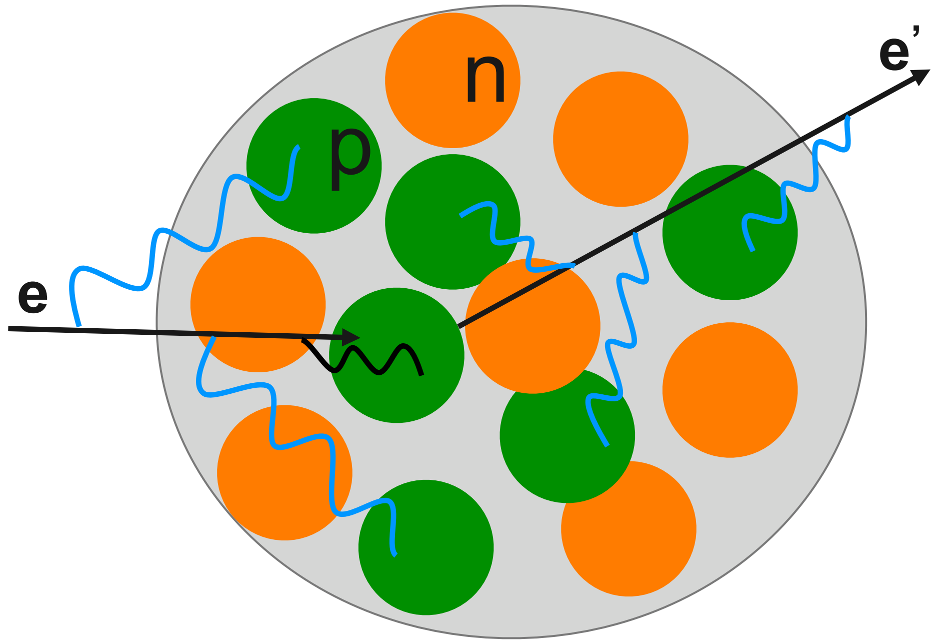
A or ρ-dependence ?



- ☐ Improved density calculation (calculated with density distributions from R. Wiringa and S. Pieper).
- ☐ Apply coulomb distortion correction.
- ☐ In progress: review of n/p corrections in world data
- ☐ Target mass correction to be looked at.

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

Coulomb distortion



Exchange of one or more (soft) photons with the nucleus, in addition to the one hard photon exchanged with a nucleon

Incident (scattered) electrons are accelerated (decelerated) in the Coulomb well of the nucleus.

Opposite effect with positrons

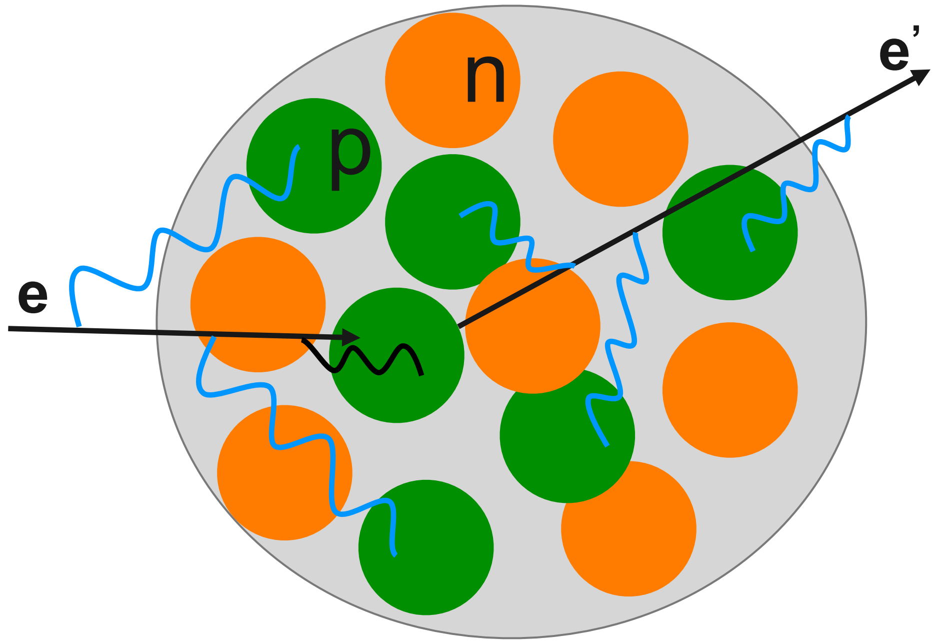
$$\xcancel{\sigma_{tot}^{PWBA} = \sigma_{Mott}\, S_{tot}^{PWBA}(|\vec{q}|, \omega, \theta)}$$

⇨

σ_{tot}^{DWBA}

- Focusing of the electron wave function
- Change of the electron momentum

Coulomb distortion



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- Change of the electron momentum

Effective Momentum Approximation (EMA)

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

$$\left.\begin{array}{l} E \rightarrow E + \bar{V} \\ E_p \rightarrow E_p + \bar{V} \end{array}\right\} Q_{eff}^2 = 4(E+\bar{V})(E_p+\bar{V})\sin^2(\frac{\theta}{2})$$

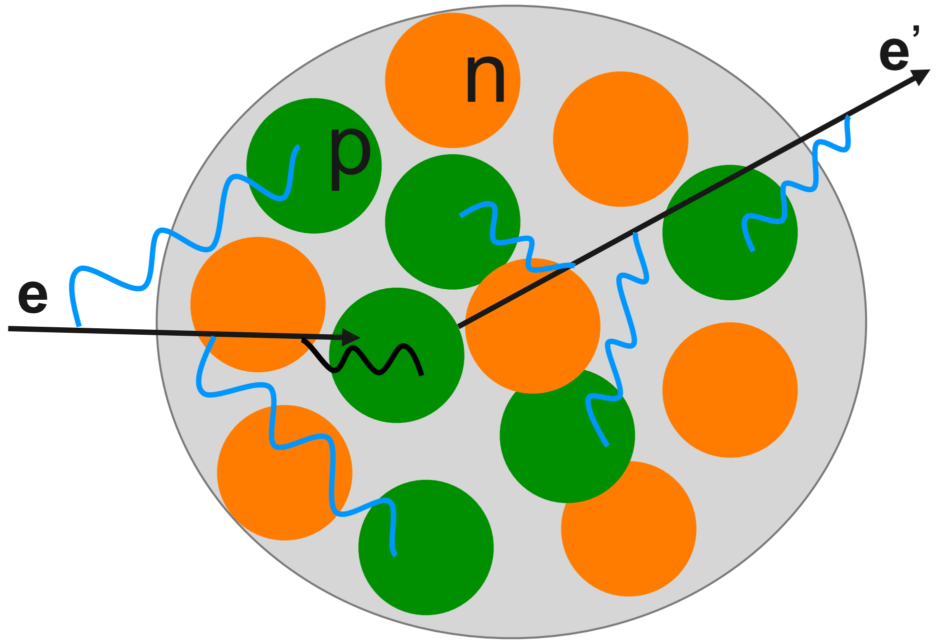
$$S_{tot}^{PWBA}(|\vec{q}|,\omega,\theta) \longrightarrow S_{tot}^{PWBA}(|\vec{q}_{eff}|,\omega,\theta)$$

$$\sigma_{Mott}^{eff} = 4\alpha^2\cos^2(\theta/2)(E_p+\bar{V})^2/Q_{eff}^4$$

$$F_{foc}^{i} = \frac{E+\bar{V}}{E}$$

$$\boxed{\sigma_{tot}^{CC} = (F_{foc}^{i})^2 \cdot \sigma_{Mott}^{eff} \cdot S_{tot}^{PWBA}(|\vec{q}_{eff}|,\omega,\theta)}$$

Coulomb distortion



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σ_{tot}^{DWBA}

- Focusing of the electron wave function
- Change of the electron momentum

Effectiv $\omega, \theta)$

Aste and T

Q_{eff}^4

E → E

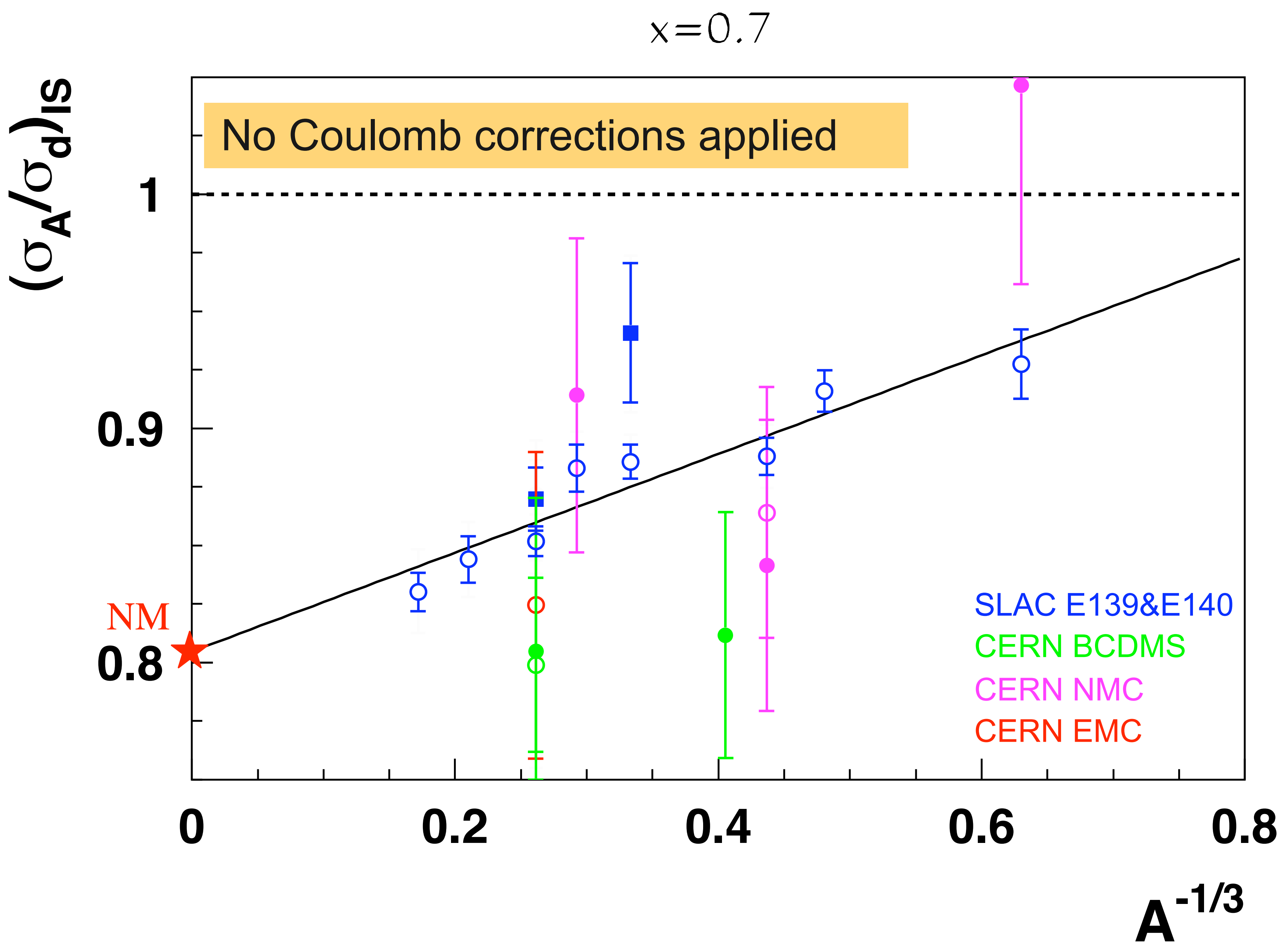
$E_p \to E_p + V$

One-parameter model depending only on the effective potential seen by the electron on average.

Coulomb potential established in Quasi-elastic scattering regime !

Extrapolation to nuclear matter

Exact calculations of the EMC effect exist for light nuclei and for nuclear matter.



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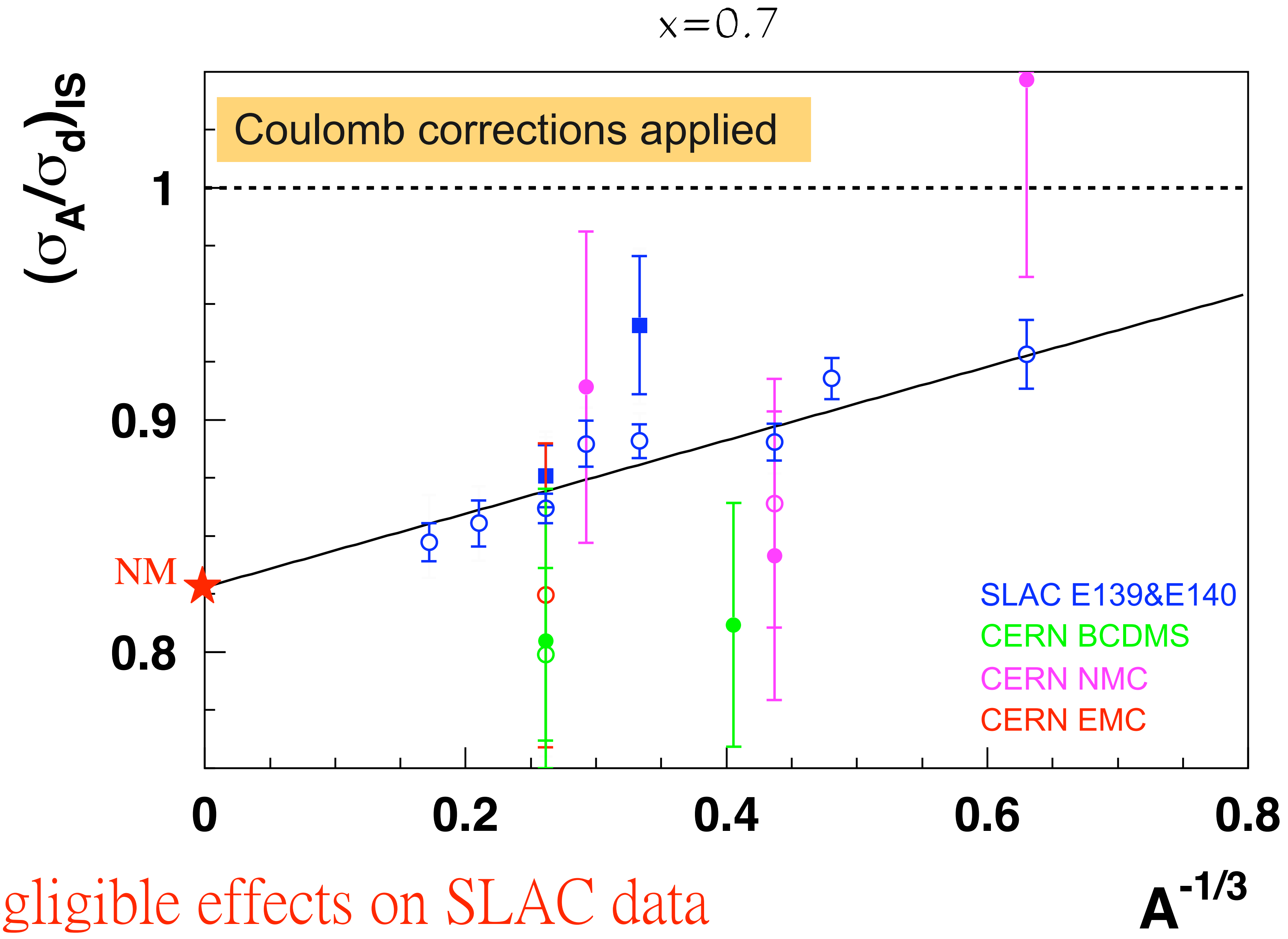

Non-negligible effects on SLAC data

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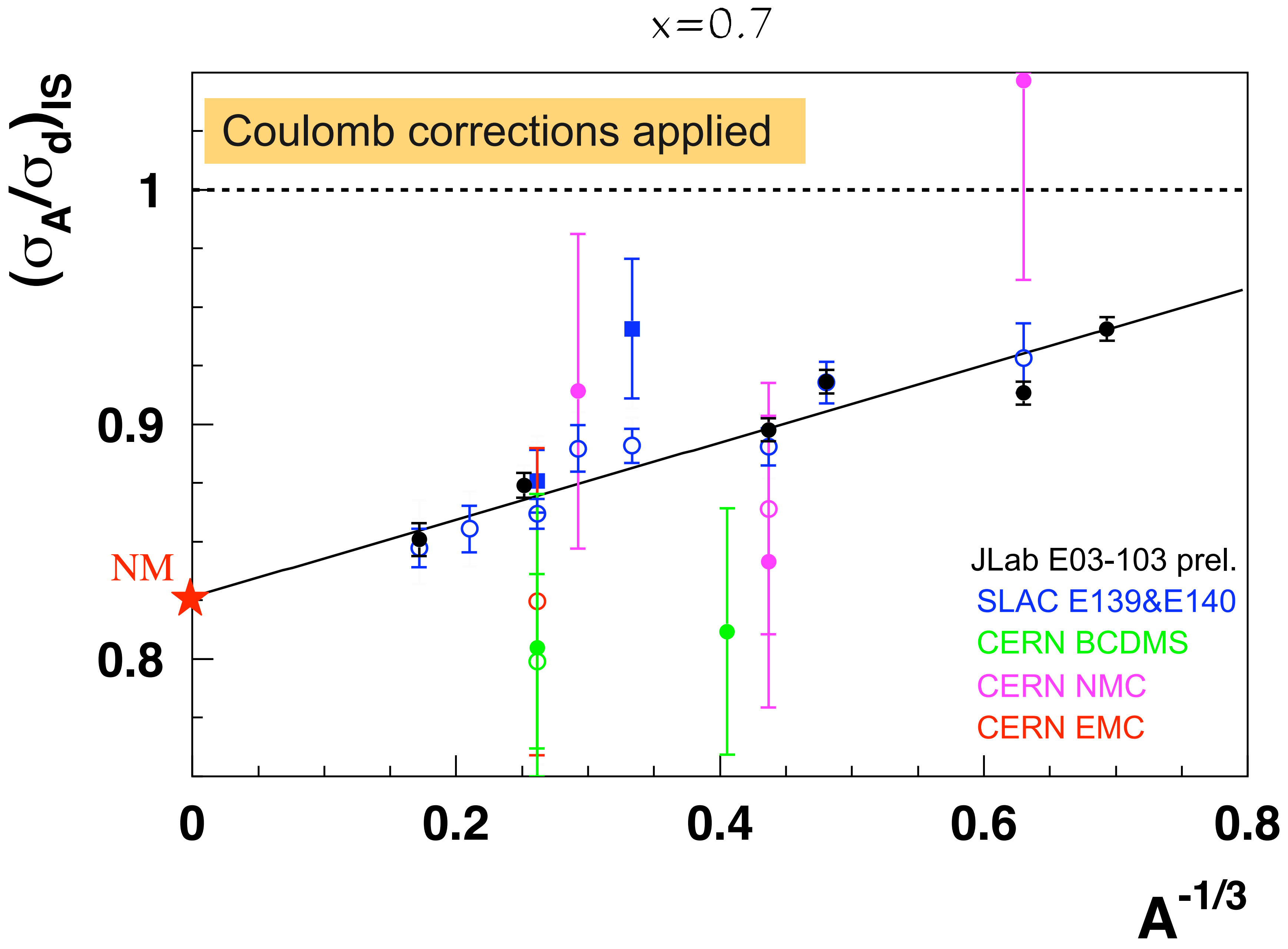


$R(x, Q^2)$

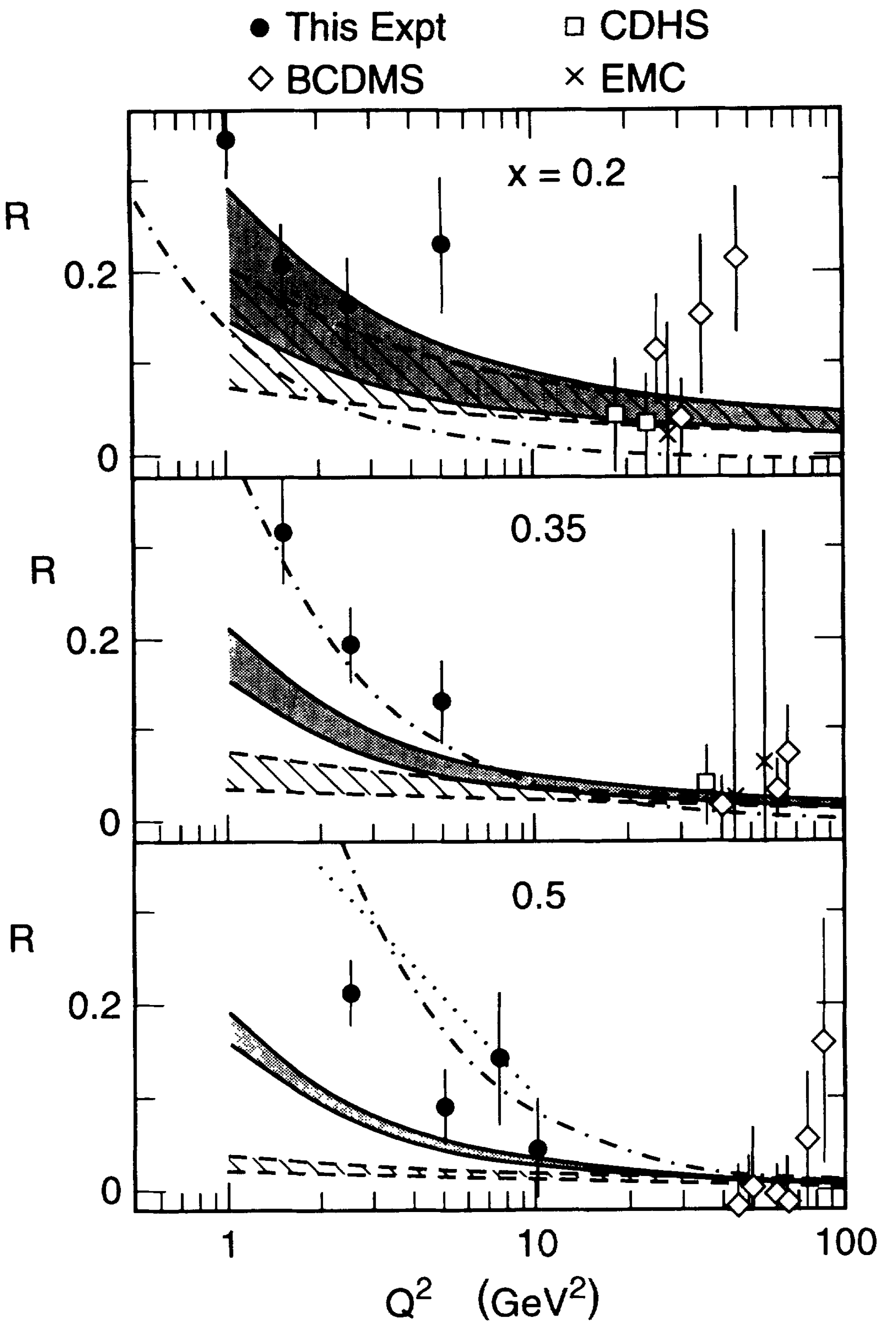
$$\frac{d\sigma}{d\Omega dE'} = \Gamma\left[\sigma_T(x,Q^2) + \varepsilon\sigma_L(x,Q^2)\right]$$

$$\boxed{R(x,Q^2) = \frac{\sigma_L(x,Q^2)}{\sigma_T(x,Q^2)}}$$

In a model with:

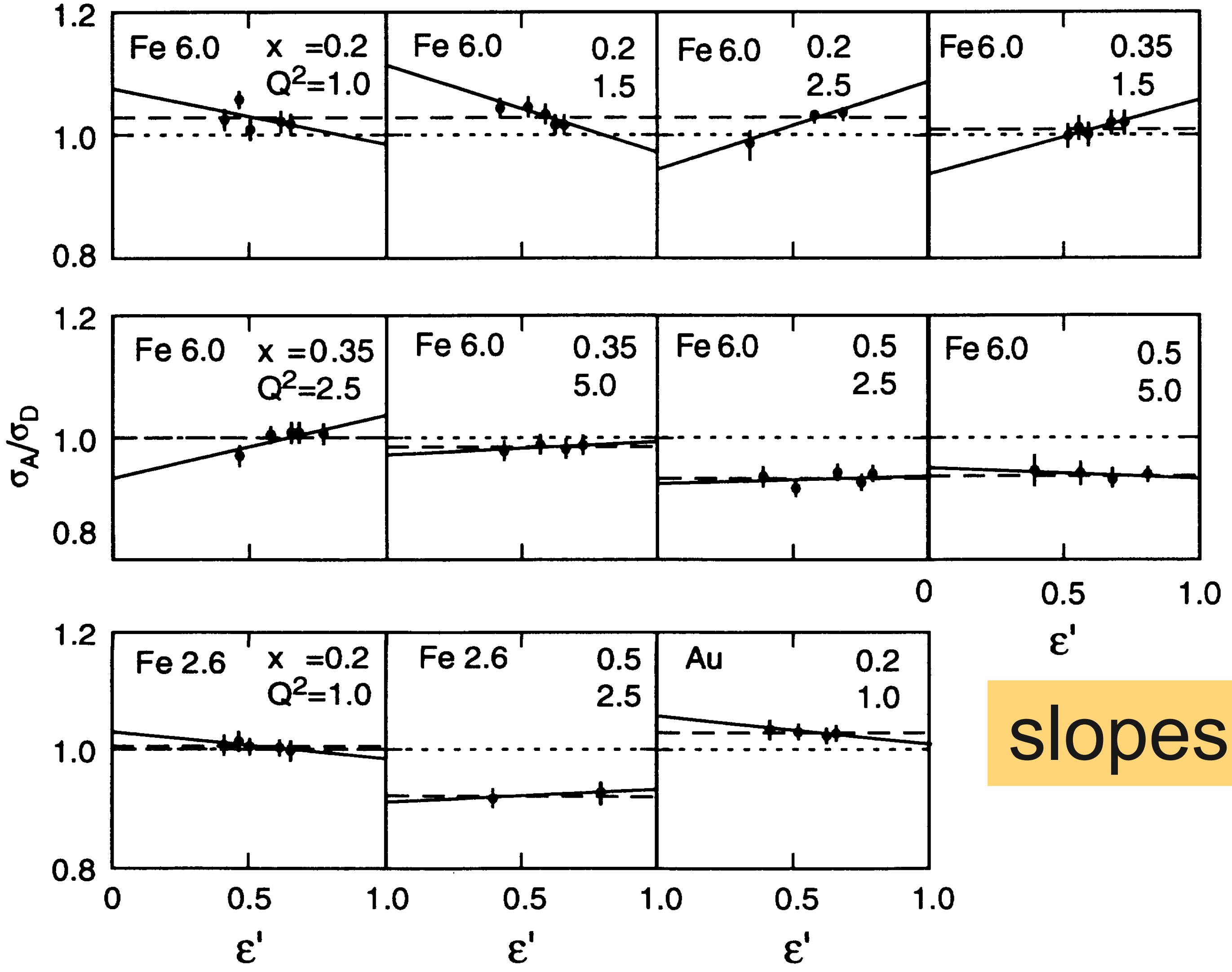
a) spin-1/2 partons: R should be small and decreasing rapidly with Q^2

b) spin-0 partons: R should be large and increasing with Q^2



Dasu et al., PRD49, 5641(1994)

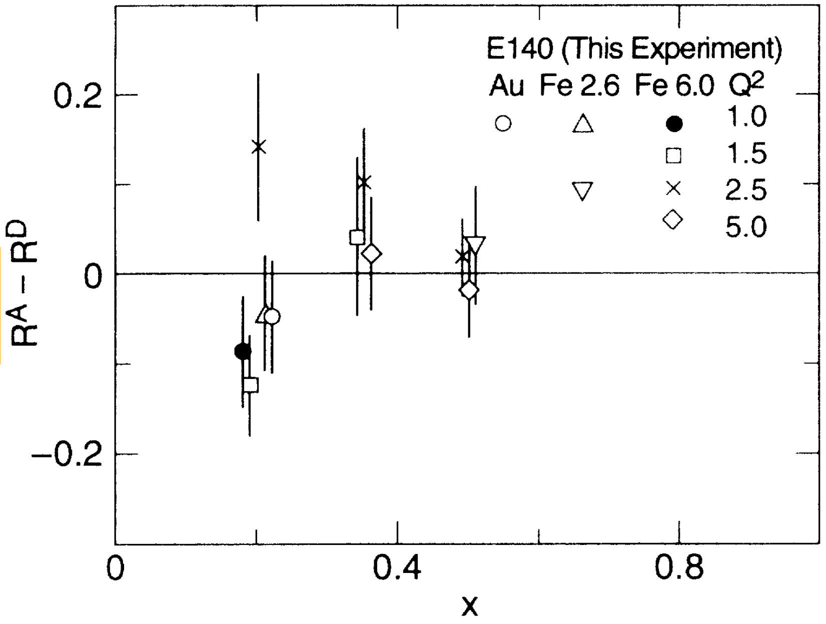
Access to nuclear dependence of R



Dasu et al., PRD49, 5641(1994)

FIG. 13. The fits to the differential cross section ratio σ_A/σ_D versus $\epsilon' = \epsilon/(1+R^D)$ are shown for each (x, Q^2) point. The errors on the cross section include statistical and point-to-point systematic contributions added in quadrature.

slopes ⇒ R_A-R_D

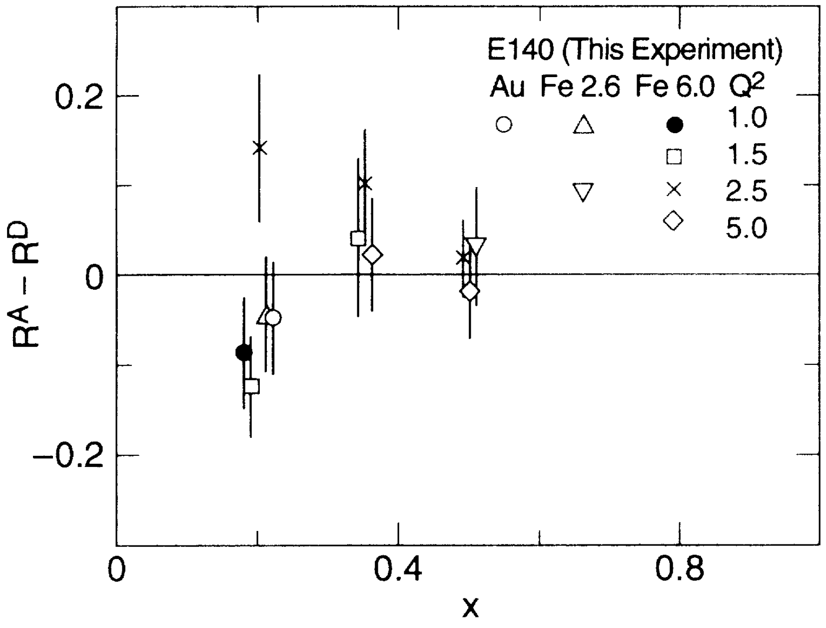


⇐ R_A-R_D=0

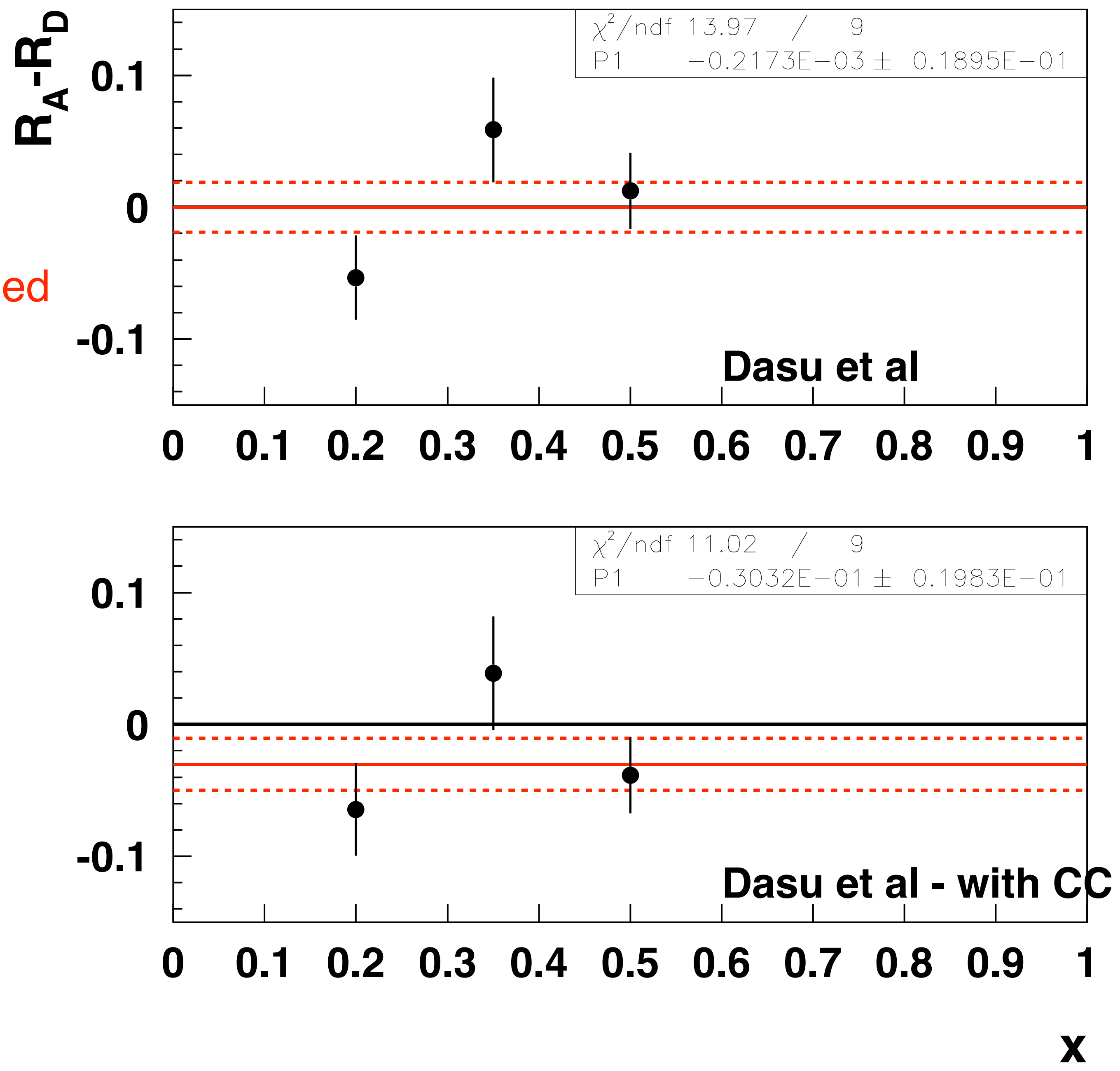
Nuclear higher twist effects and spin-0 constituents in nuclei: same as in free nucleons

Access to nuclear dependence of R

Dasu et al., PRD49, 5641(1994)



re-analysized

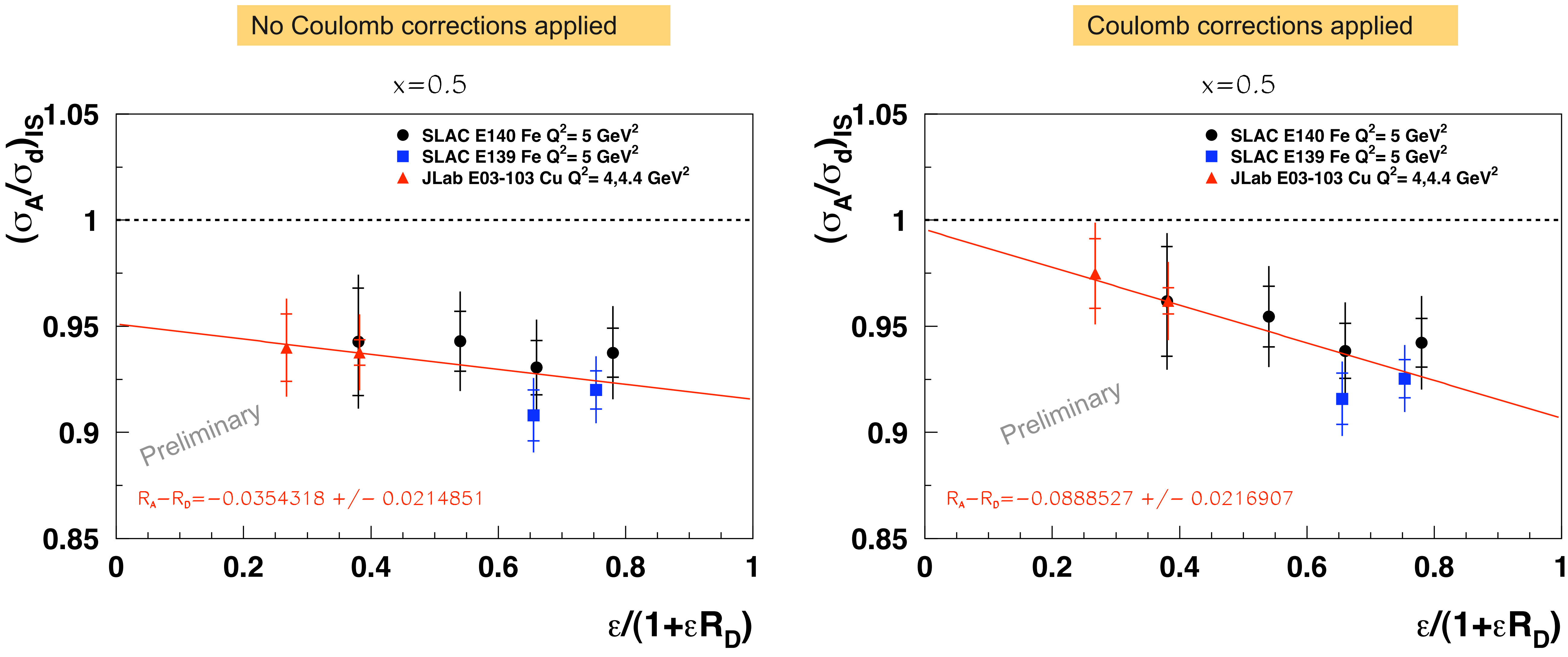


A non-trivial effect in R_A-R_D arises after applying Coulomb corrections

Access to nuclear dependence of R

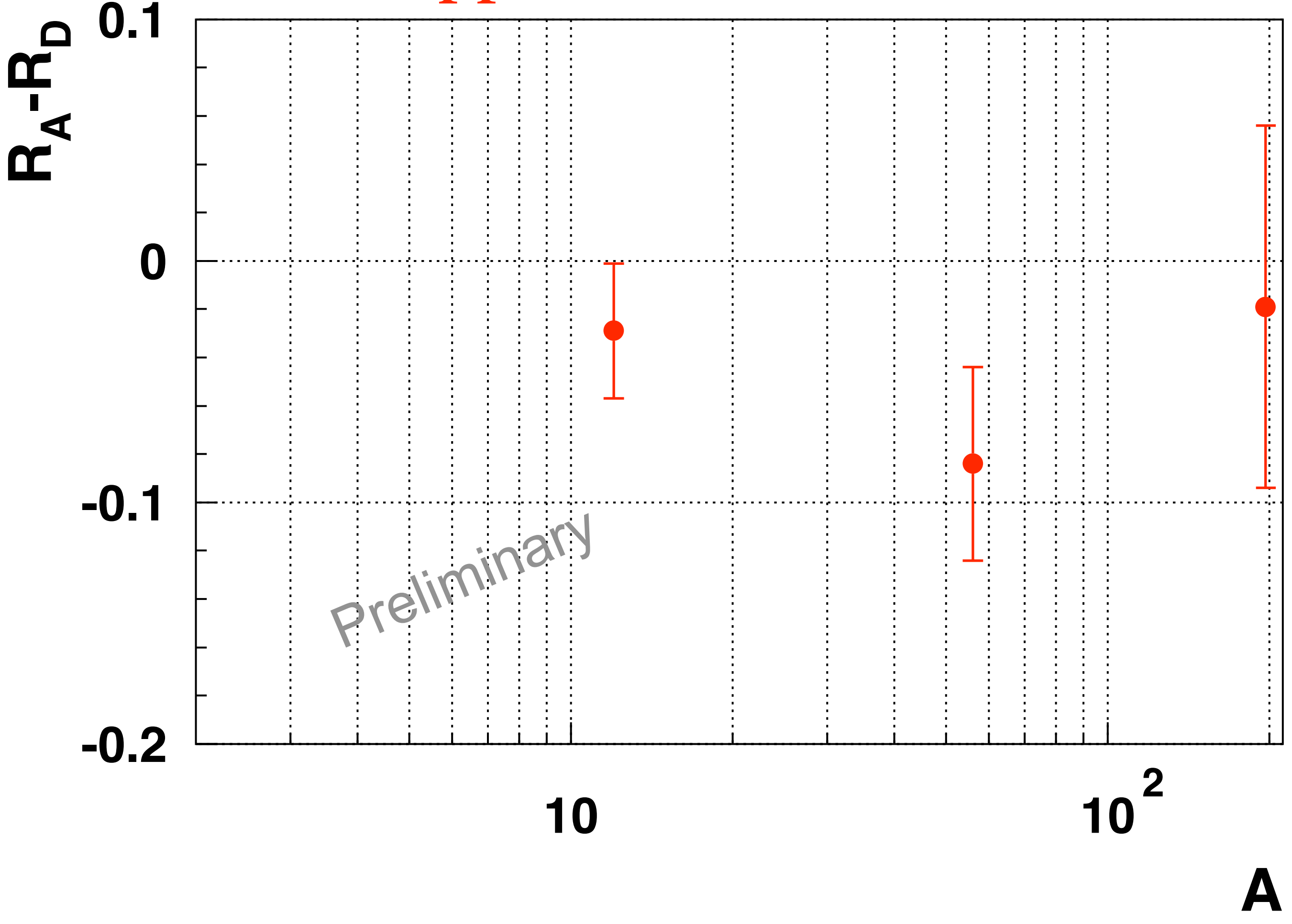
New data from JLab E03-103: access to lower ε

Iron-Copper



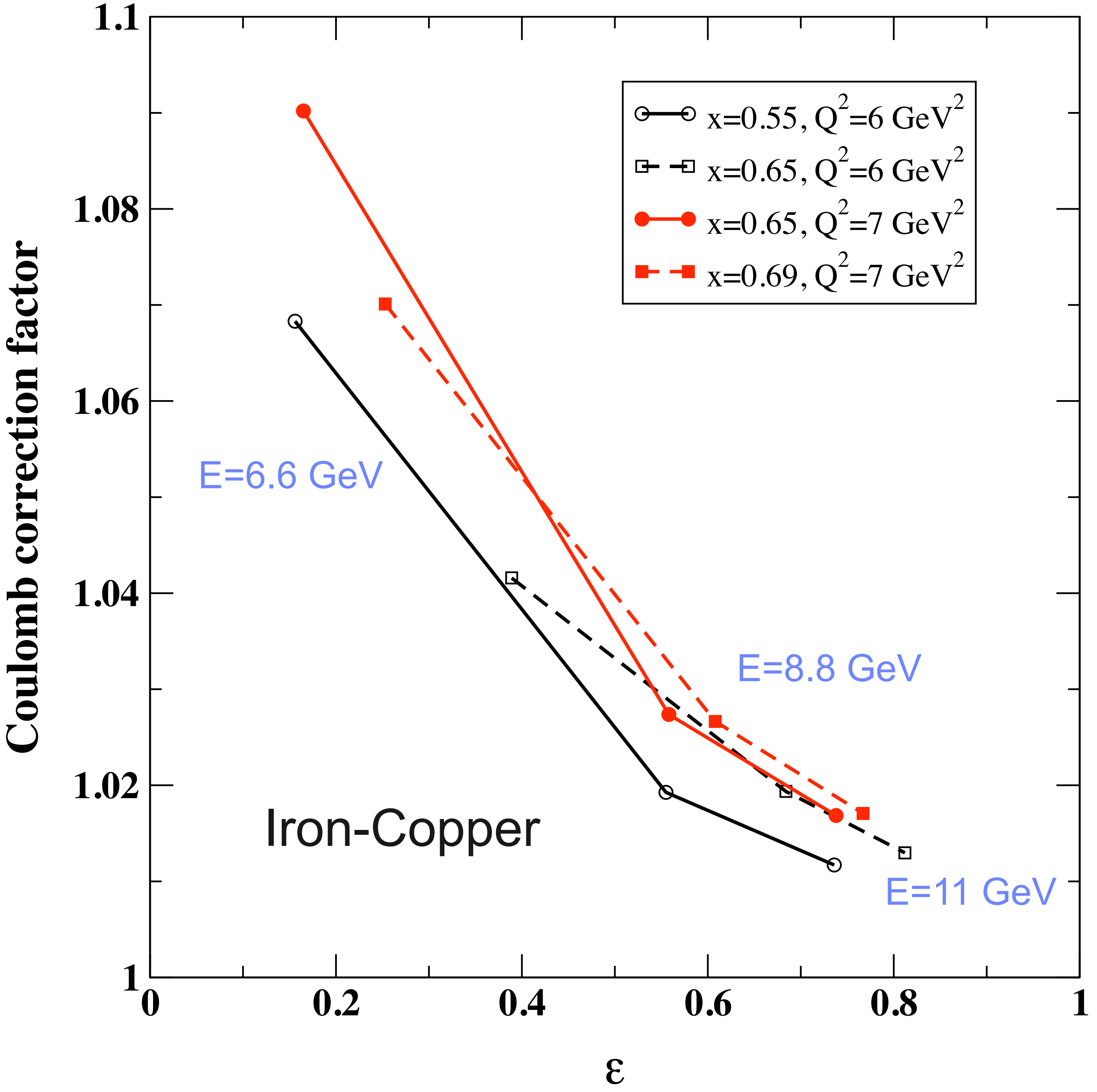
Access to nuclear dependence of R

Hint of an A-dependence in R in Copper-Iron



After taking into account the normalization uncertainties from each experiment

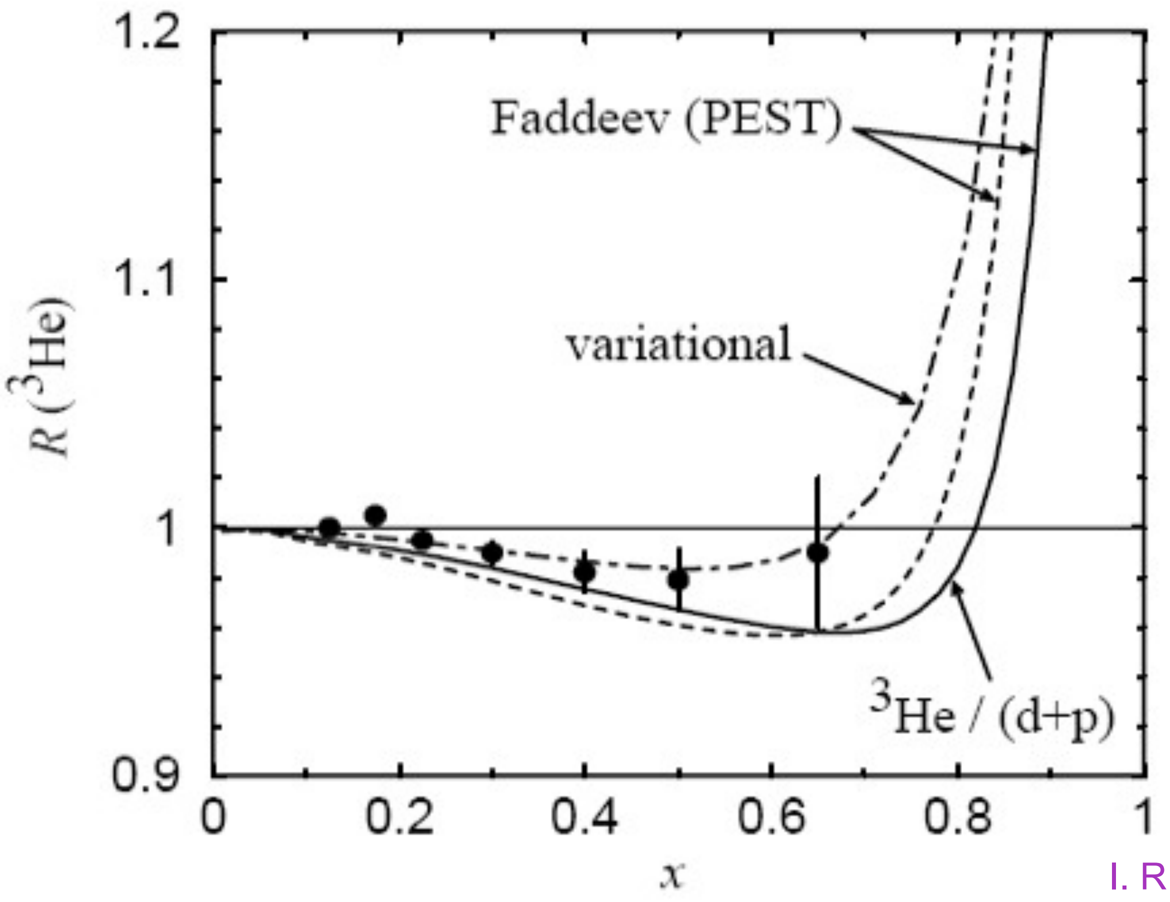
The ε -dependence of the Coulomb distortion has effect on the extraction of R in nuclei



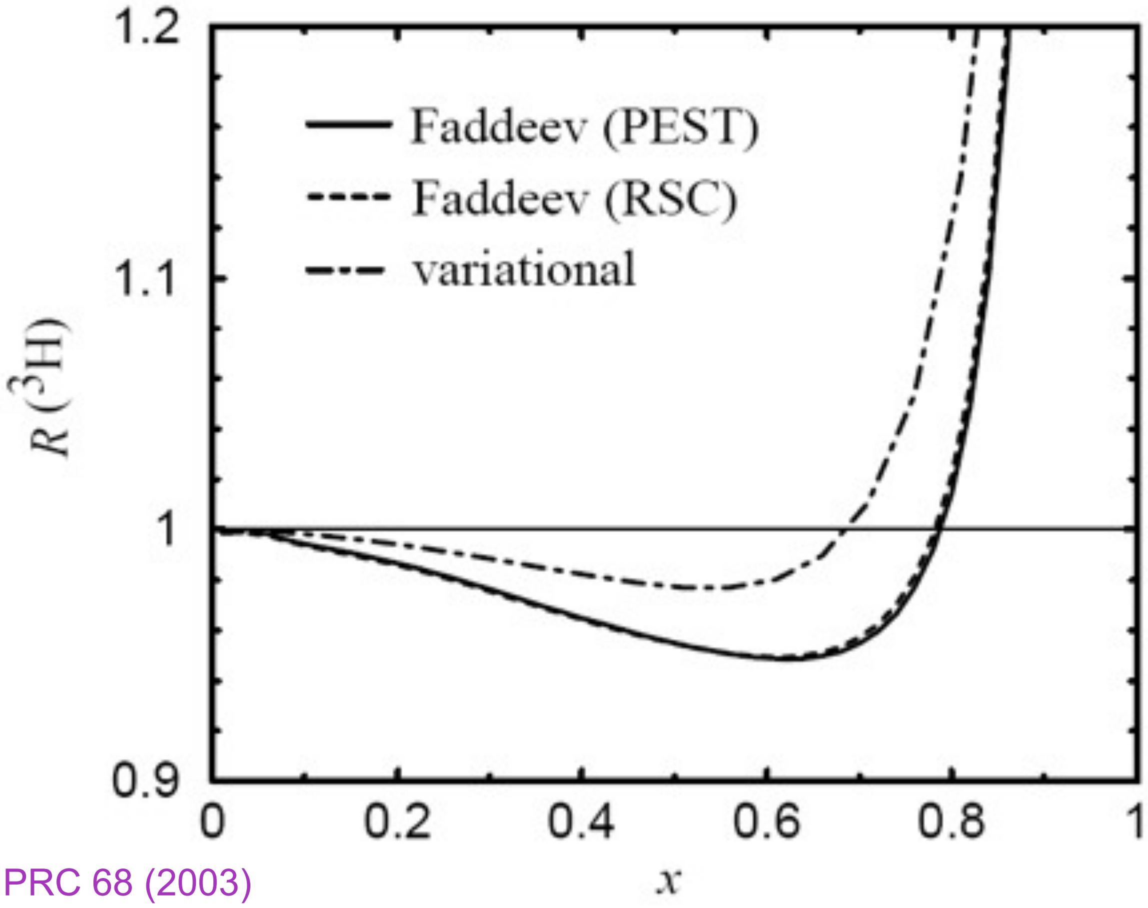
What's next ?

The EMC effect in ^{3}H and ^{3}He

$$R(^3He) = \frac{F_2^{^3He}}{2F_2^p + F_2^n}$$



$$R(^3H) = \frac{F_2^{^3H}}{F_2^p + 2F_2^n}$$



I. R. Afnan *et al*, PRC 68 (2003)

Ratio of ^{3}He, ^{3}H: JLab E12-06-118

A way to get access to F_2^n

- Measure F_2's and form ratios:

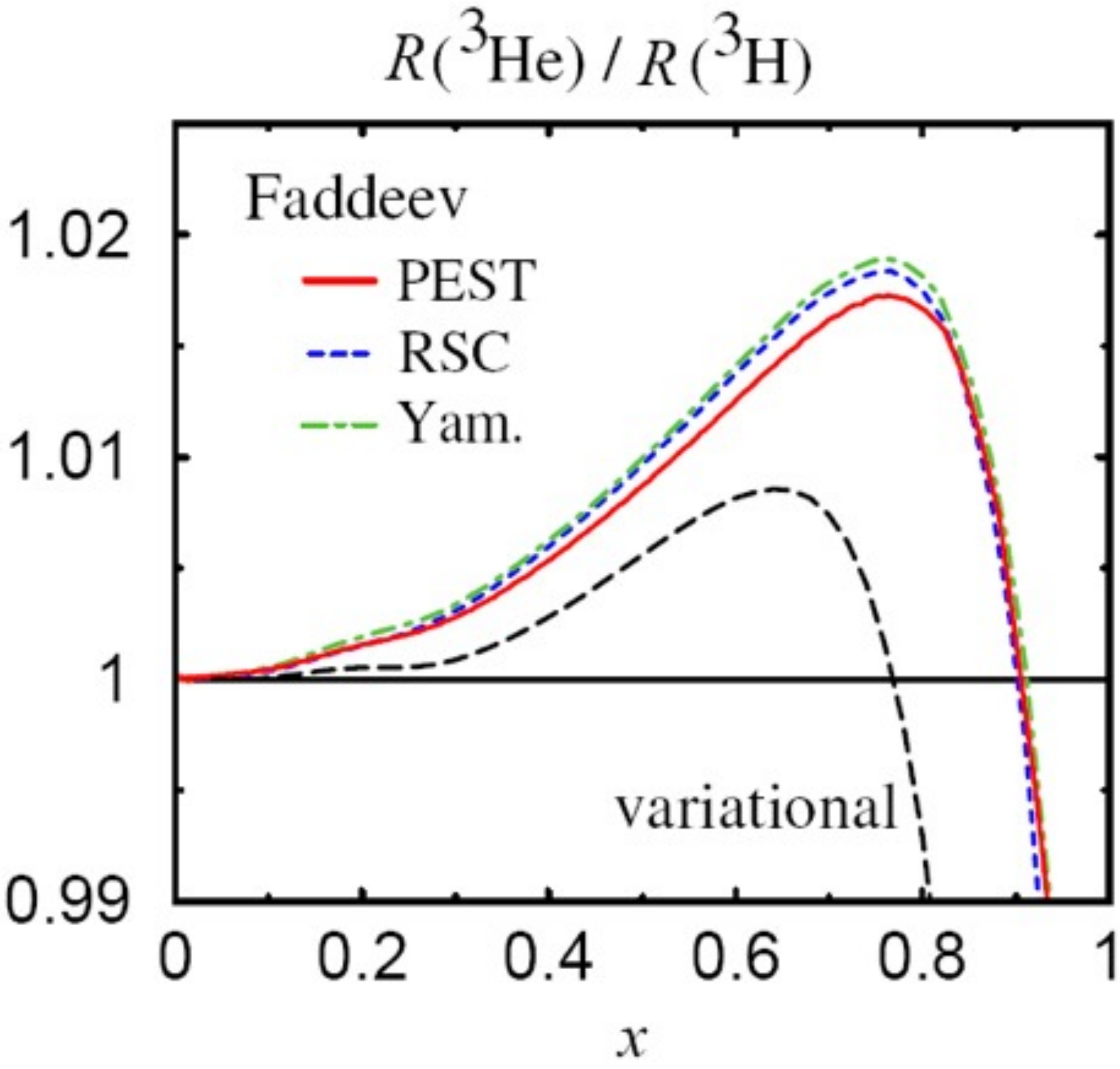
$$R(^3He) = \frac{F_2^{^3He}}{2F_2^p+F_2^n},\ R(^3H) = \frac{F_2^{^3H}}{F_2^p+2F_2^n}$$

- Form "super-ratio", r, then

$$\frac{F_2^n}{F_2^p} = \frac{2r - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - r}$$

where $r \equiv \frac{R(^3He)}{R(^3H)}$

I. Afnan et al, PRC 68 (2003)



Why is the F_2^n/F_2^p ratio so interesting?

SU(6)-symmetric wave function of the proton in the quark model (spin up):

$$|p\uparrow\rangle = \frac{1}{\sqrt{18}}\left(3u\uparrow[ud]_{S=0} + u\uparrow[ud]_{S=1} - \sqrt{2}u\downarrow[ud]_{S=1} - \sqrt{2}d\uparrow[uu]_{S=1} - 2d\downarrow[uu]_{S=1}\right)$$

- *u and d quarks identical, N and Δ would be degenerate in mass.*
- *In this model: d/u = 1/2, F_2^n/F_2^p = 2/3.*

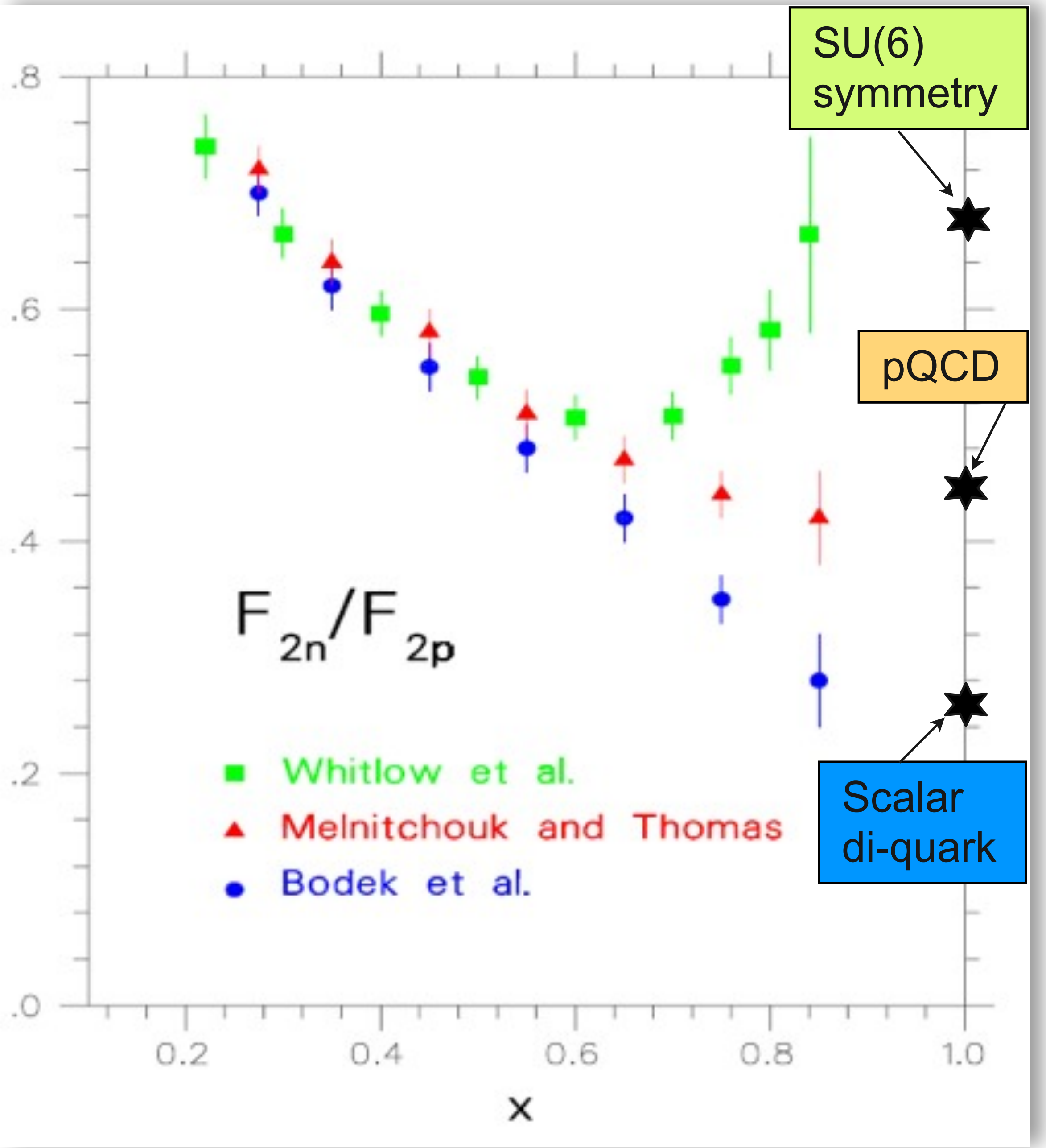
pQCD: helicity conservation (q↑↑p)

=> d/u =2/(9+1) = 1/5, F_2^n/F_2^p = 3/7 for x ->1

SU(6) symmetry is broken: N-Δ Mass Splitting

- *Mass splitting between S=1 and S=0 diquark spectator.*
- *symmetric states are raised, antisymmetric states are lowered (~300 MeV).*
- *S=1 suppressed*

=> d/u = 0, F_2^n/F_2^p = 1/4, for x -> 1

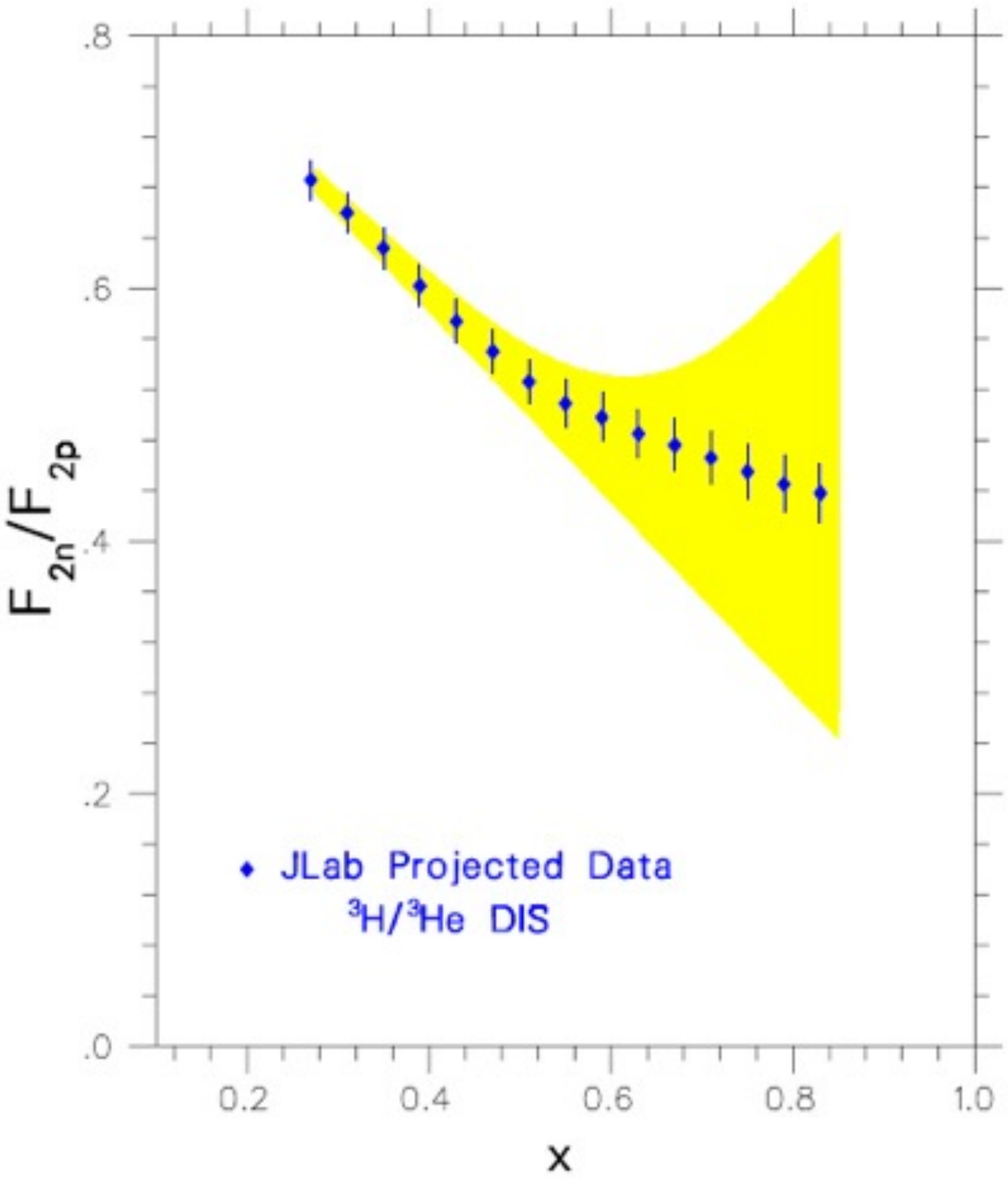


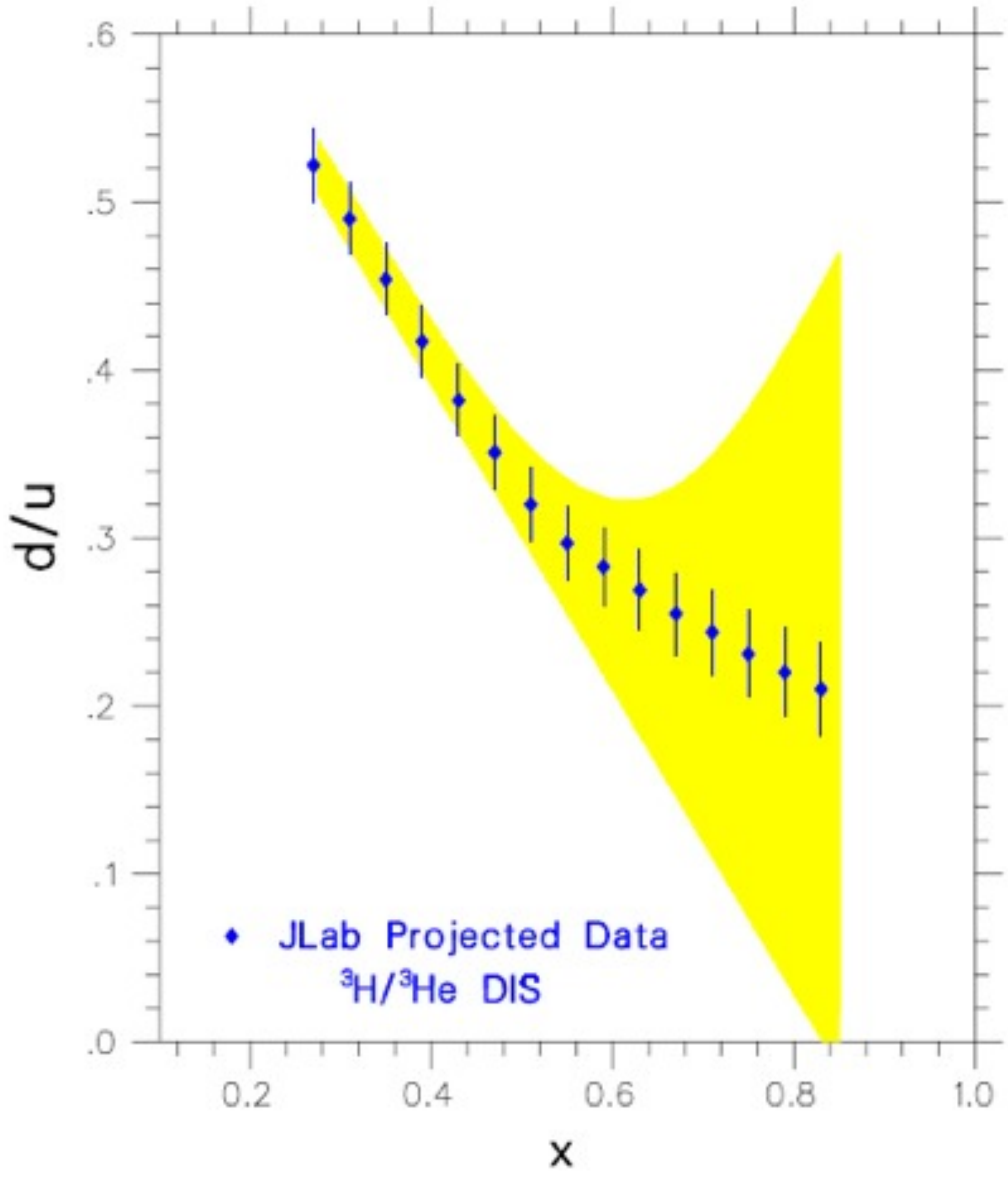
SU(6) symmetry

pQCD

Scalar di-quark

E12-06-118 Projected Results

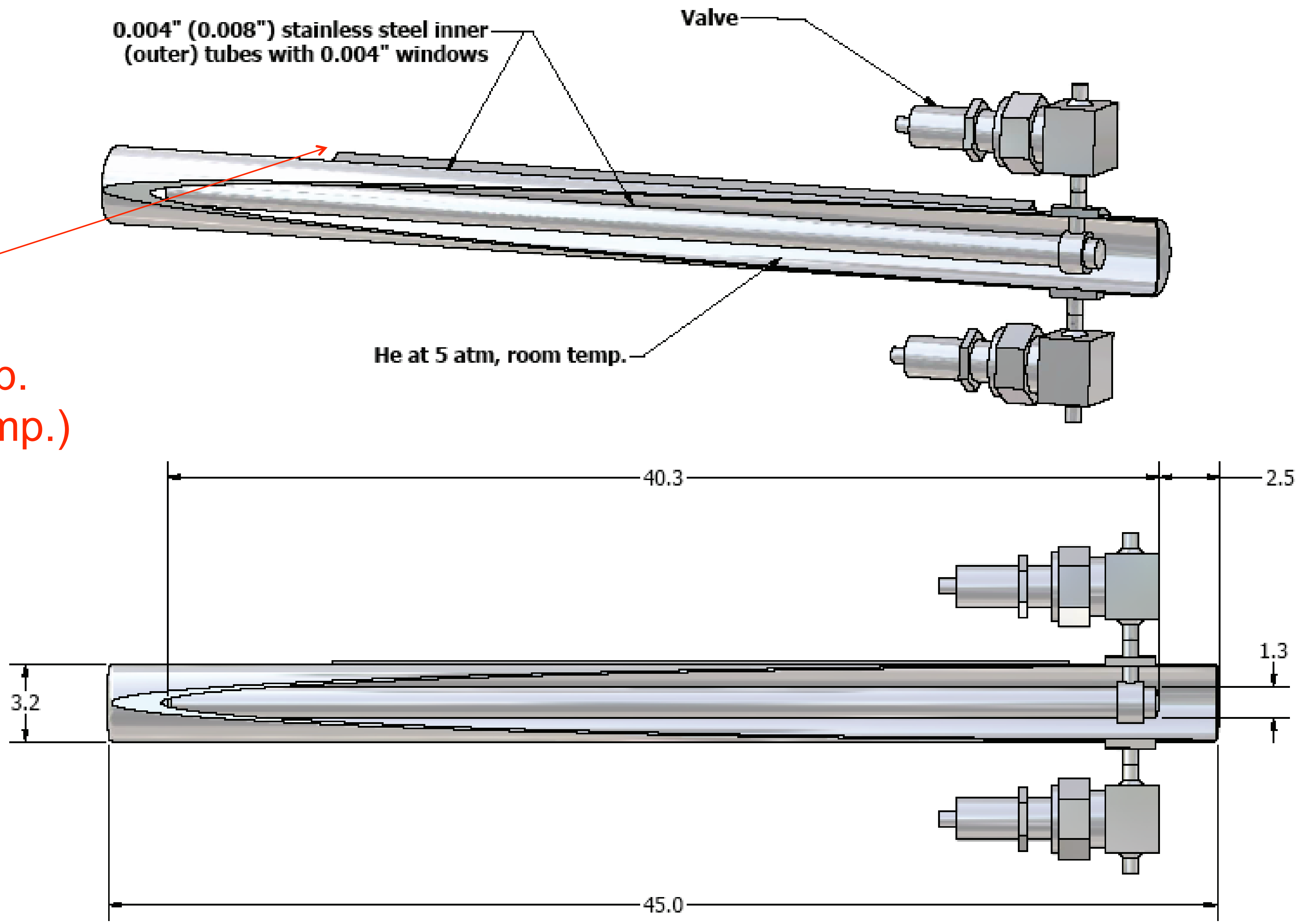




- PAC30: “conditionally approved”
- 5000 Ci T target, 31 days
- JLab E12-06-118, G. Petratos, J. Gomez, R. J. Holt, R. Ransome *et al*

The tritium target conceptual design

E. J. Beise (U. of Maryland), R. J. Holt (Argonne), W. Korsch (U. of Kentucky),
T. O'Connor (Argonne), G. G. Petratos (Kent State U.), R. Ransome (Rutgers U.),
P. Solvignon (Argonne), and B. Wojtsekhowski (Jefferson Lab)
Tritium Target Task Force



$^3H_2$ at 10 atm, room temp.
(or ^3He at 20 atm, room temp.)

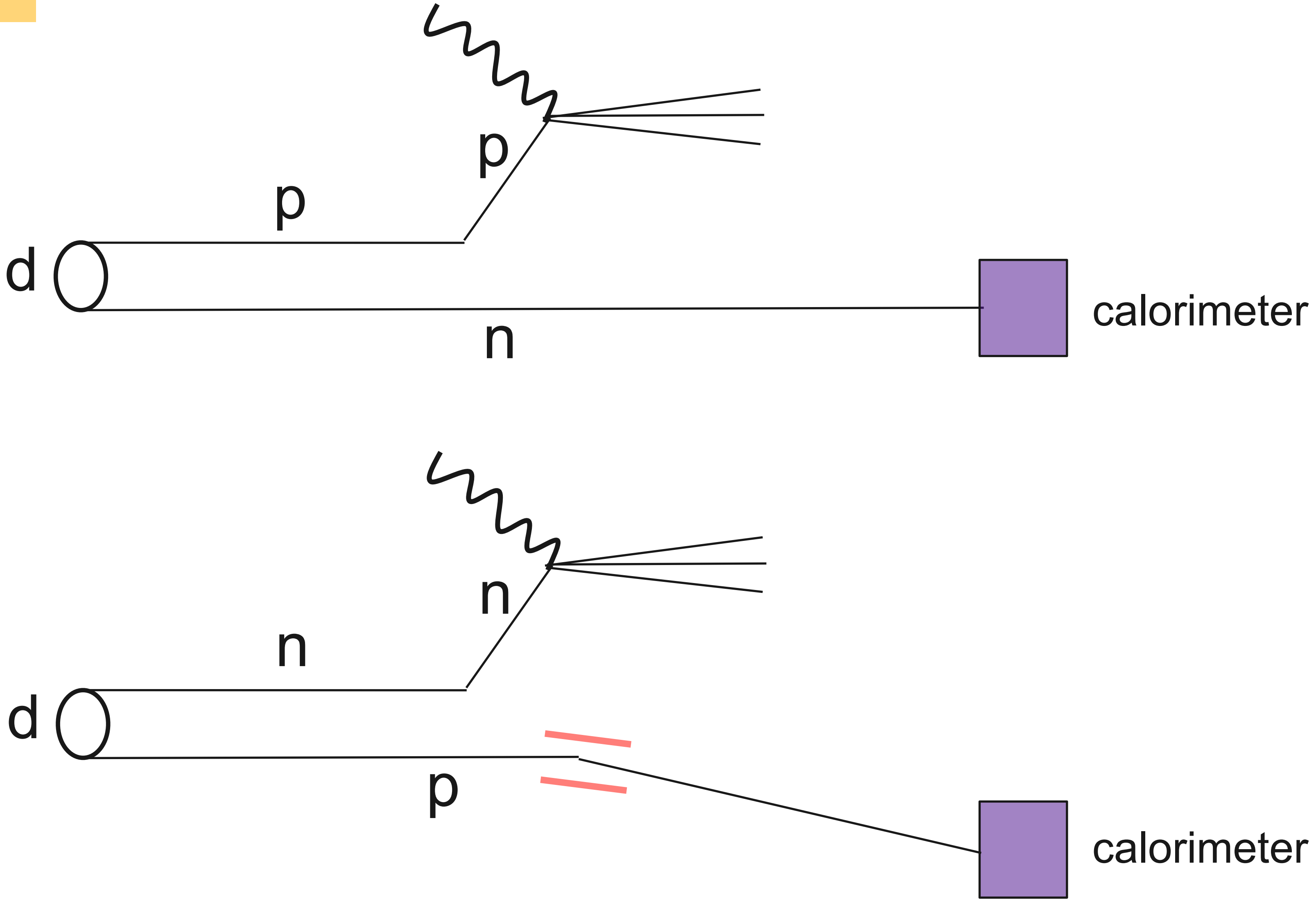
- ❖ Closed double-cell system
- ❖ Density: 2.5mg/cm^3
- ❖ Target length/diameter: 40cm/1.25cm
- ❖ Activity ~ 1500 Ci
- ❖ He for heat conduction

What about a measurement at the EIC ?

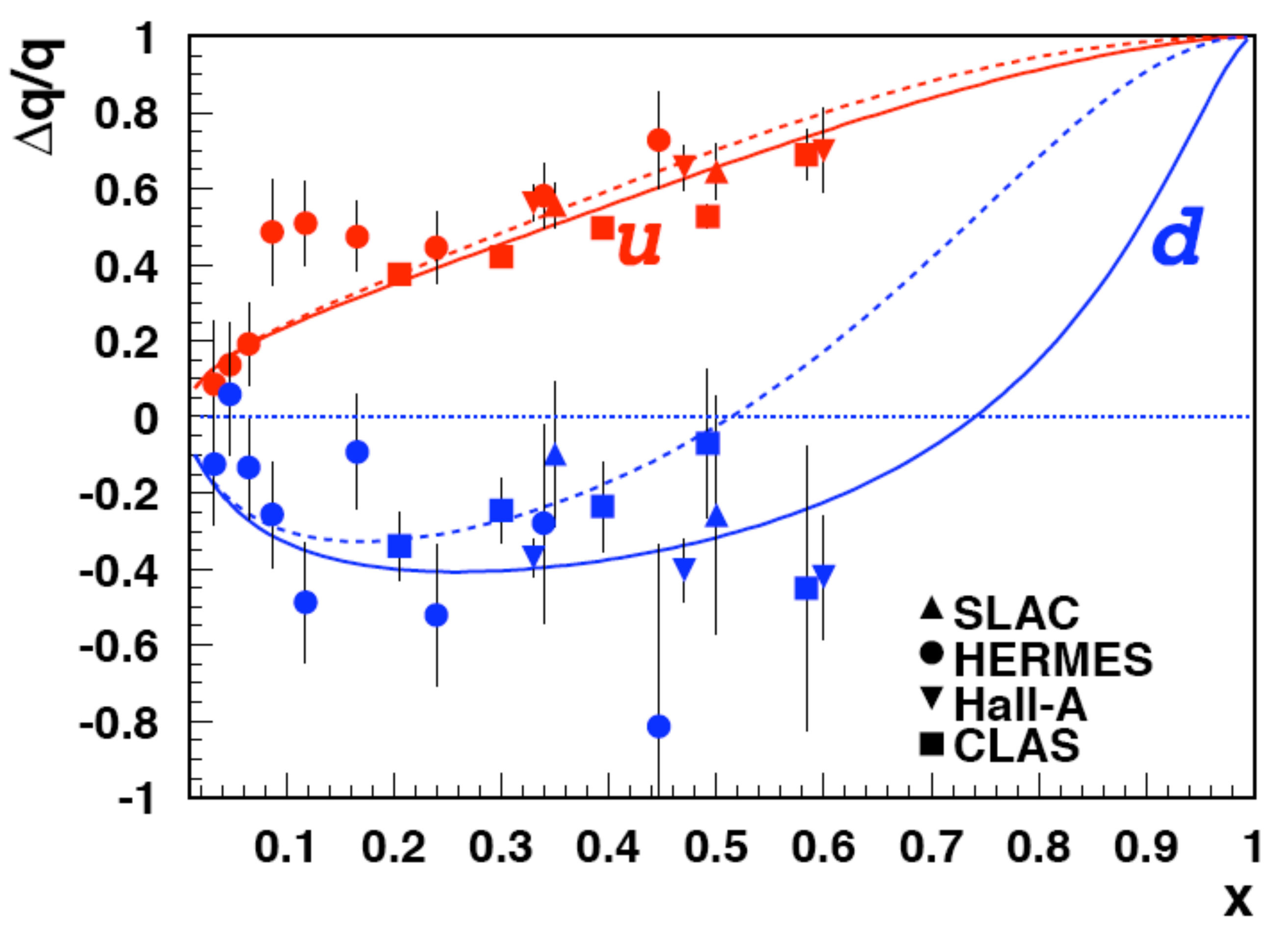
F2n/F2p at EIC:

high W so no need to worry about target mass correction

$e^- \rightarrow \Leftarrow$ d



Polarized quark distributions



In the parton model:

$$F_1(x) = \frac{1}{2}\Sigma_i e_i^2[q_i(x)]$$

$$g_1(x) = \frac{1}{2}\Sigma_i e_i^2[\Delta q_i(x)]$$

At high Q^2, $A_1 = g_1/F_1$ and:

$$\frac{g_1^n}{F_1^n} = \frac{\Delta u + 4\Delta d}{u+4d}$$

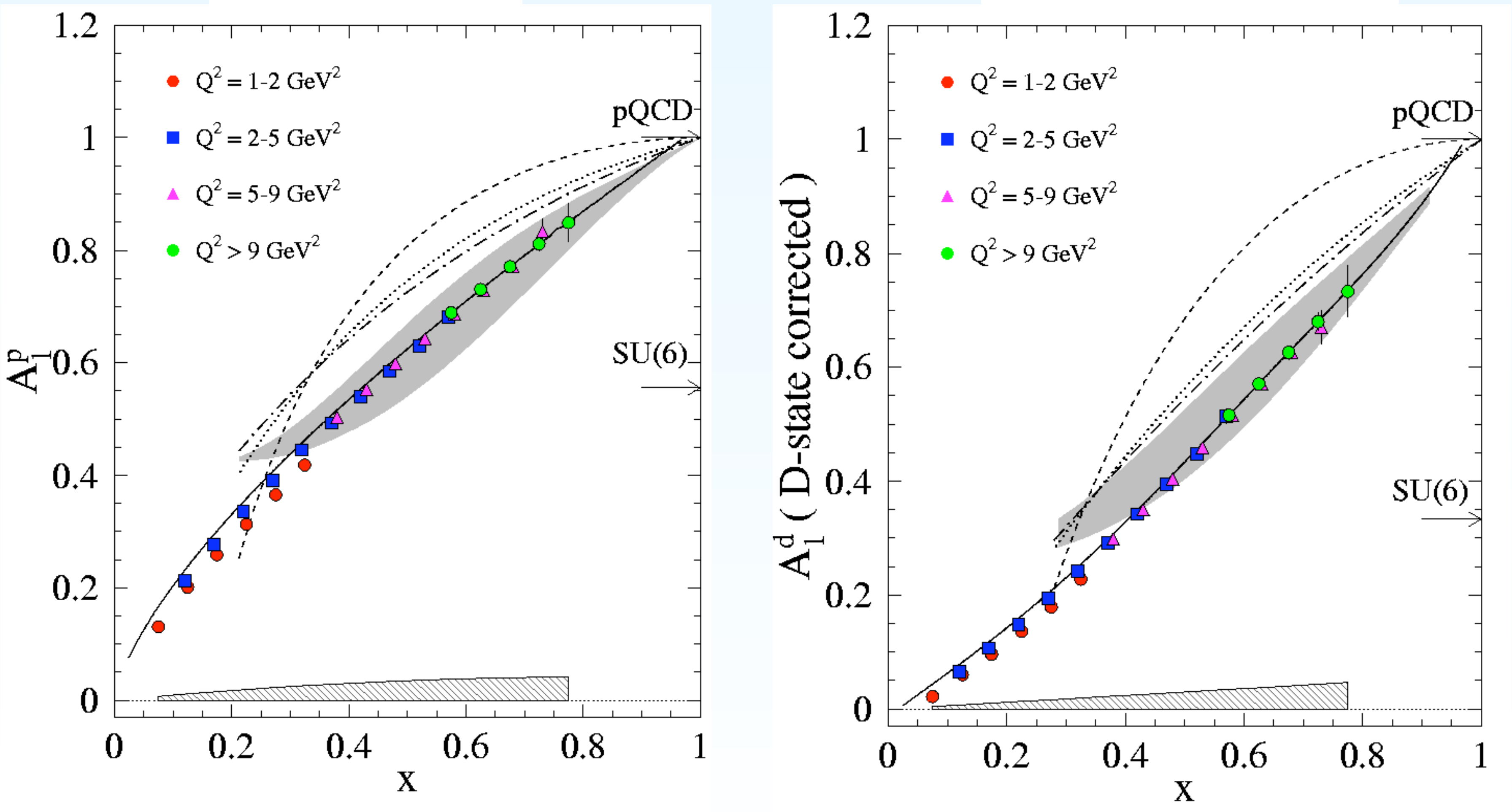
$$\frac{g_1^p}{F_1^p} = \frac{4\Delta u + \Delta d}{4u+d}$$

$$\frac{\Delta u}{u} = \frac{4}{15}\frac{g_1^p}{F_1^p}(4+\boxed{\frac{d}{u}}) - \frac{1}{15}\frac{g_1^n}{F_1^n}(1+4\boxed{\frac{d}{u}})$$

$$\frac{\Delta d}{d} = \frac{4}{15}\frac{g_1^n}{F_1^n}(4+1/\boxed{\frac{d}{u}}) - \frac{1}{15}\frac{g_1^p}{F_1^p}(1+4/\boxed{\frac{d}{u}})$$

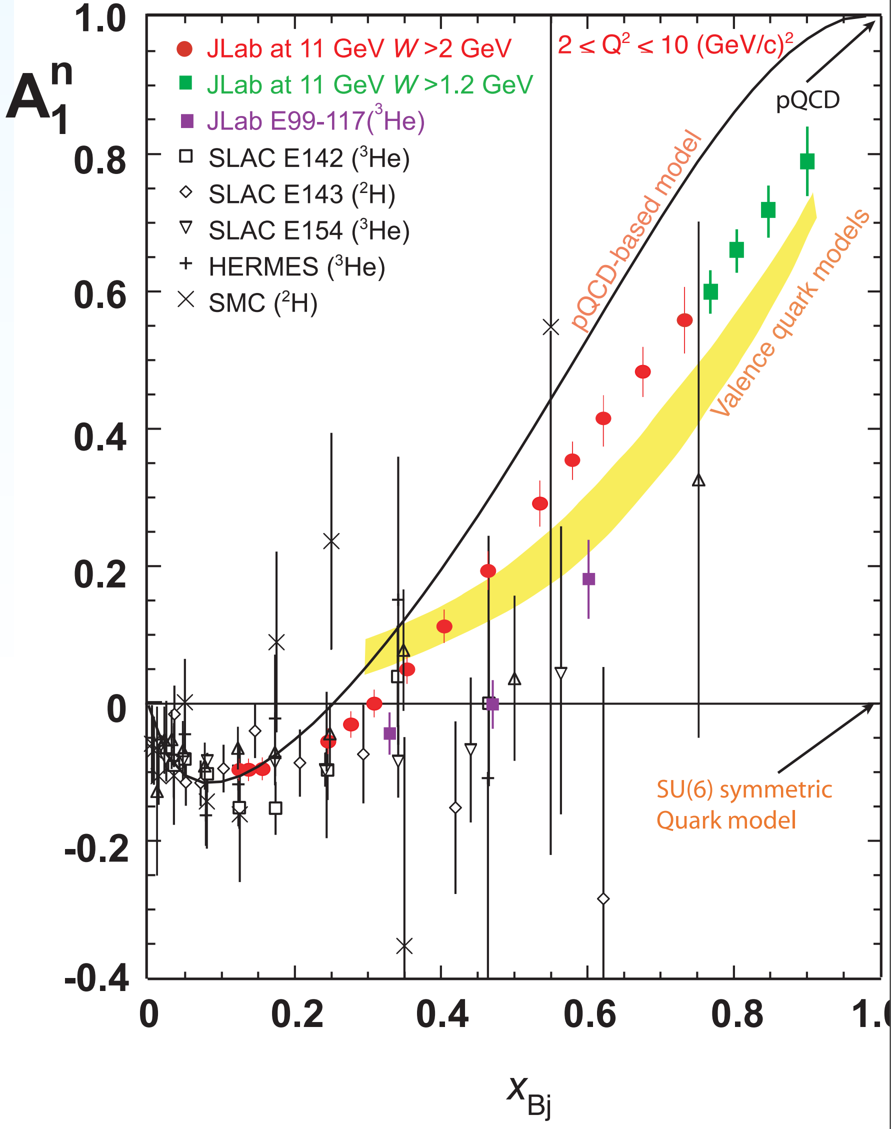
Planned A_1 measurement at JLab 12 GeV

Proton W > 2; $Q^2 > 1$ Deuteron



E12-06-109 in Hall B

E12-06-110 in Hall C



$$A_1^n = \frac{F_2^{3He}[A_1^{3He} - 2\frac{F_2^p}{F_2^{3He}} P_p A_1^p (1-\frac{0.014}{2P_p})]}{P_n F_2^n (1+\frac{0.056}{P_n})}$$

Summary

JLab experiment E03-103 brings a wealth of new results:

- Light nuclei:
    - *contain key information on the EMC effect*
    - *hint of local density dependence of the EMC effect*
    - *can be compared to realistic calculations*

- Heavy nuclei and Coulomb distortion:
    - *affects the extrapolation to nuclear matter which is key for comparison with theoretical calculations*
    - *has a real impact on the A-dependence of R: clear ε-dependence*
    - *need a measurement of the amplitude of the effect in the inelastic regime*

Outlook

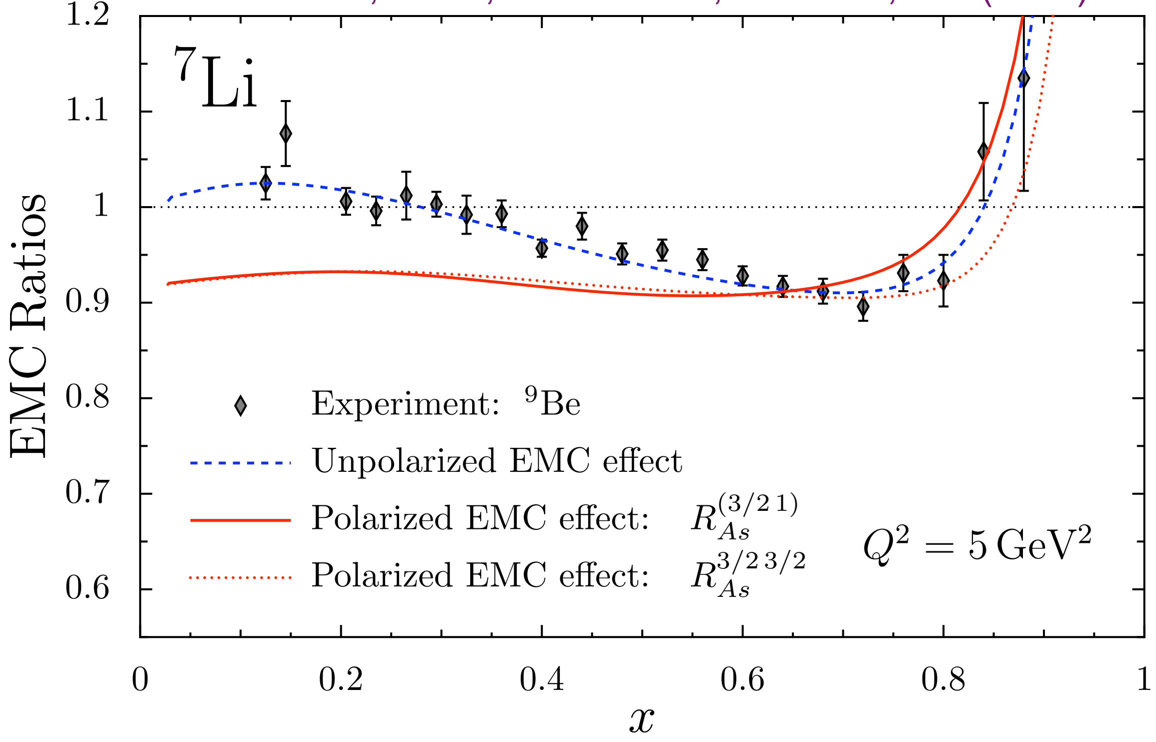
- ☐ $F_2(^3He)/F_2(^3H)$: Hall A E12-06-118
  - EMC effect in light nuclei
  - n/p at high x in DIS
  - getting to the d-quark distribution

--> important for extraction of Δu/u and Δd/d from measurement of A_1^n at high x

- ☐ Coulomb distortion measurement in DIS: require a positron beam

- ☐ Polarized EMC

- ☐ EIC: F2n/F2p from e^--^2H collisions

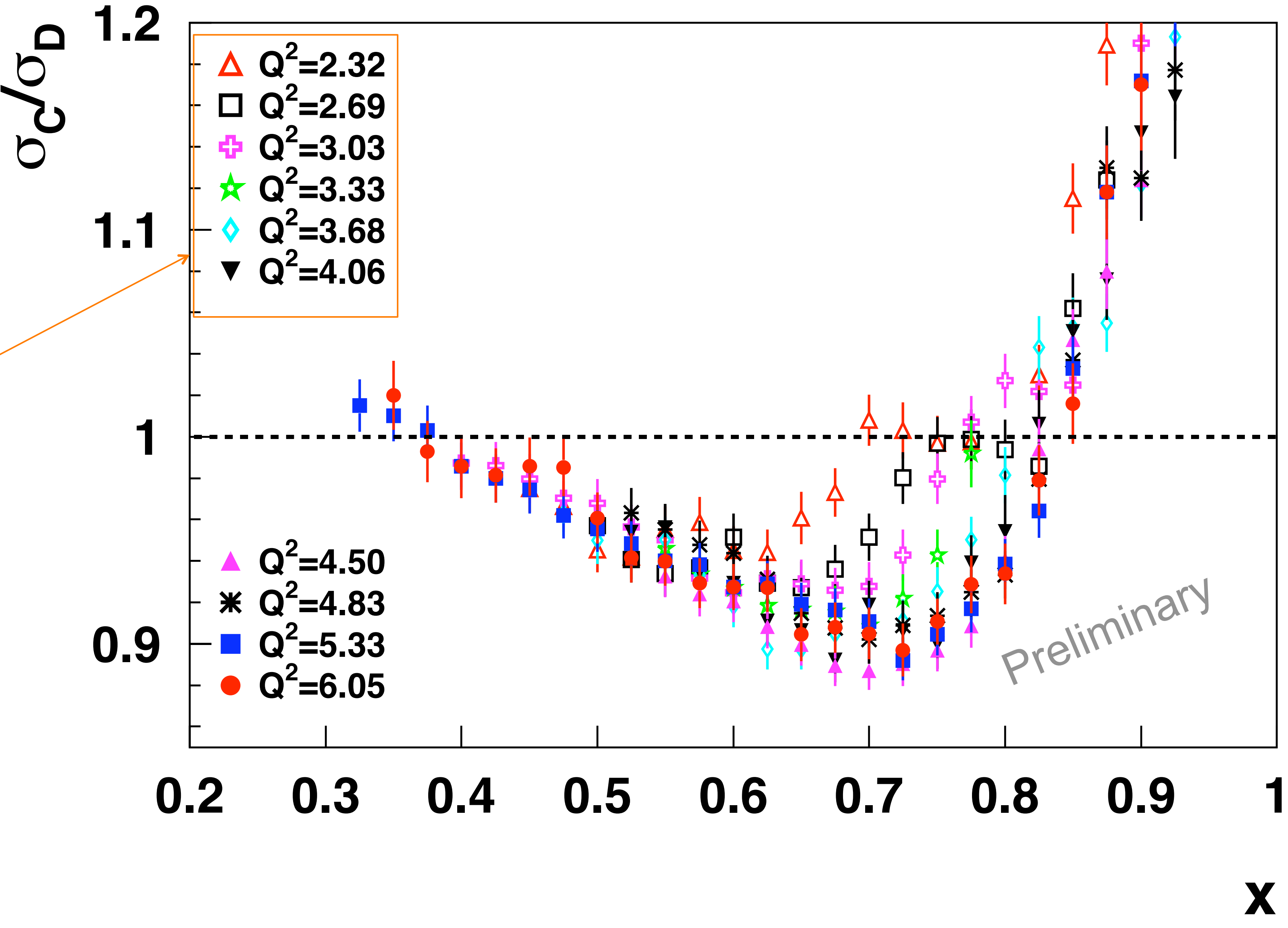


Cloet, Bentz, and Thomas, PLB 642, 210 (2006)

Extra slides

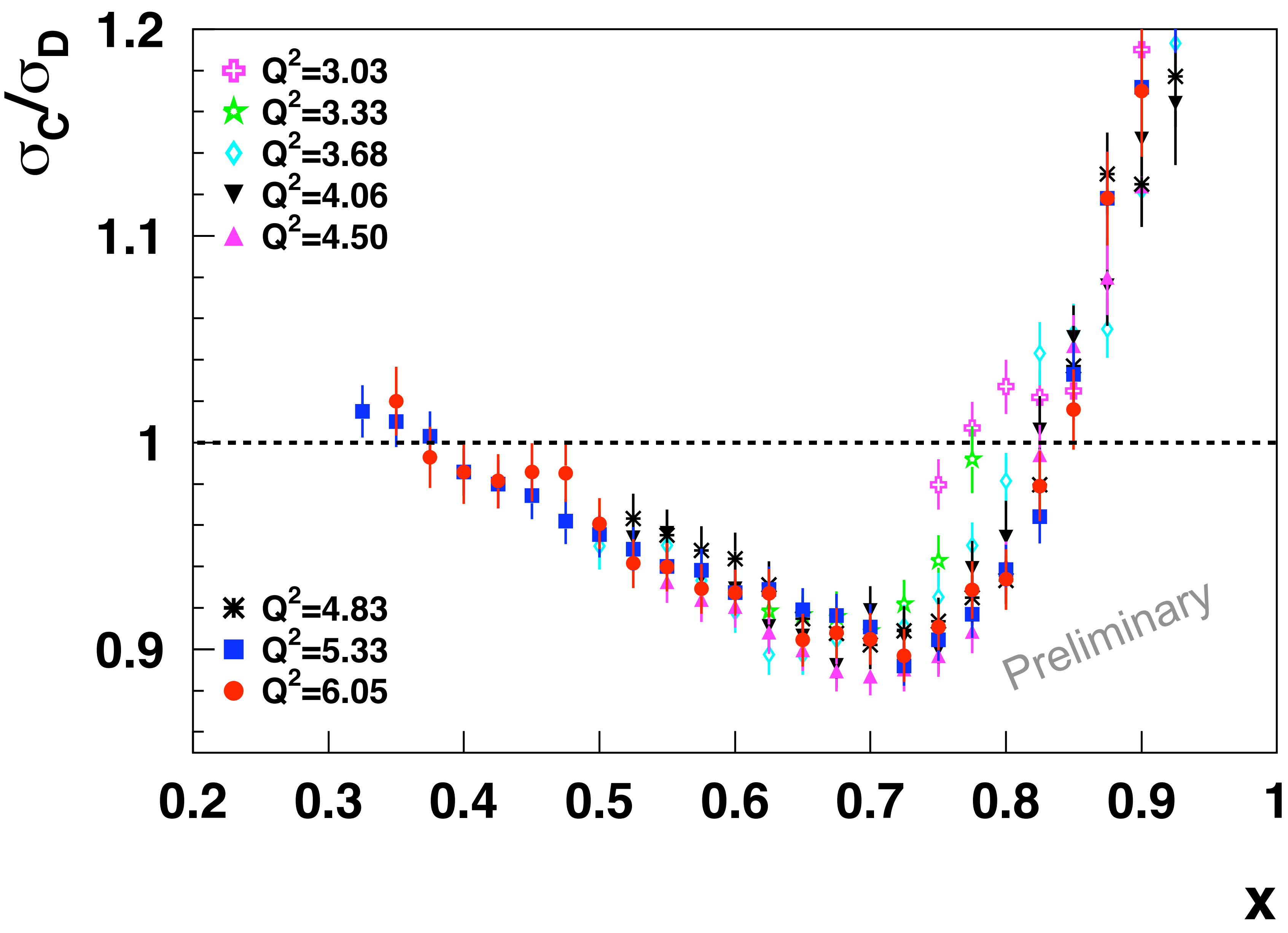
E03-103: Carbon EMC ratio and Q^2-dependence

at x=0.6



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

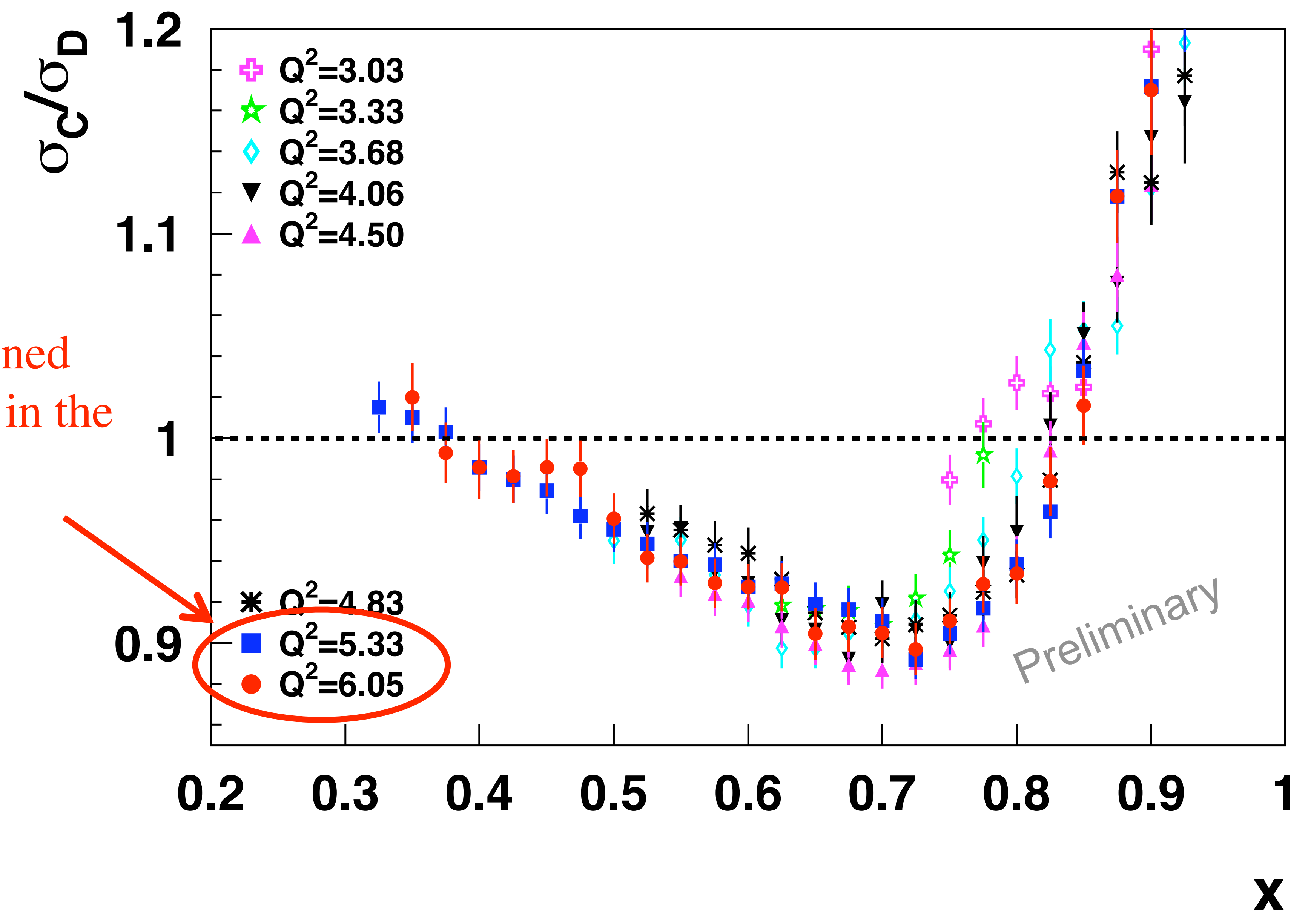
E03-103: Carbon EMC ratio and Q^2-dependence



At larger angles ➔ indication of scaling to very large *x*

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

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



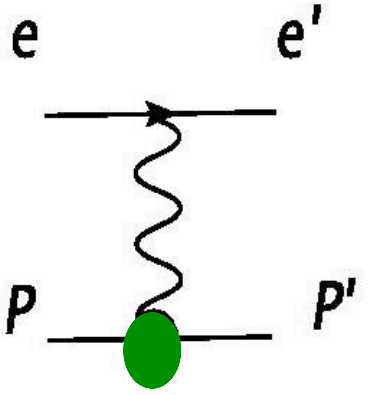
At larger angles ➔ indication of scaling to very large *x*

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

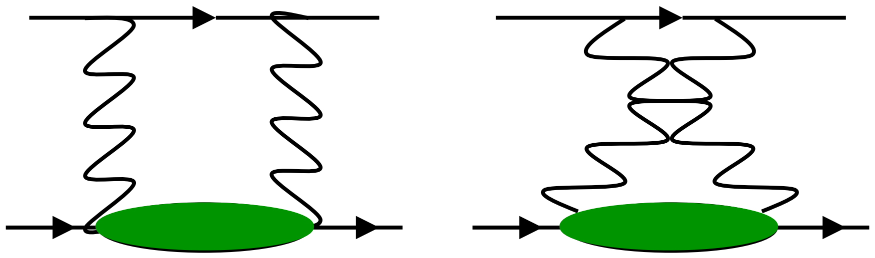
Coulomb distortion and two-photon exchange

OPE



TPE

Exchange of 2 (hard) photons with a single nucleon

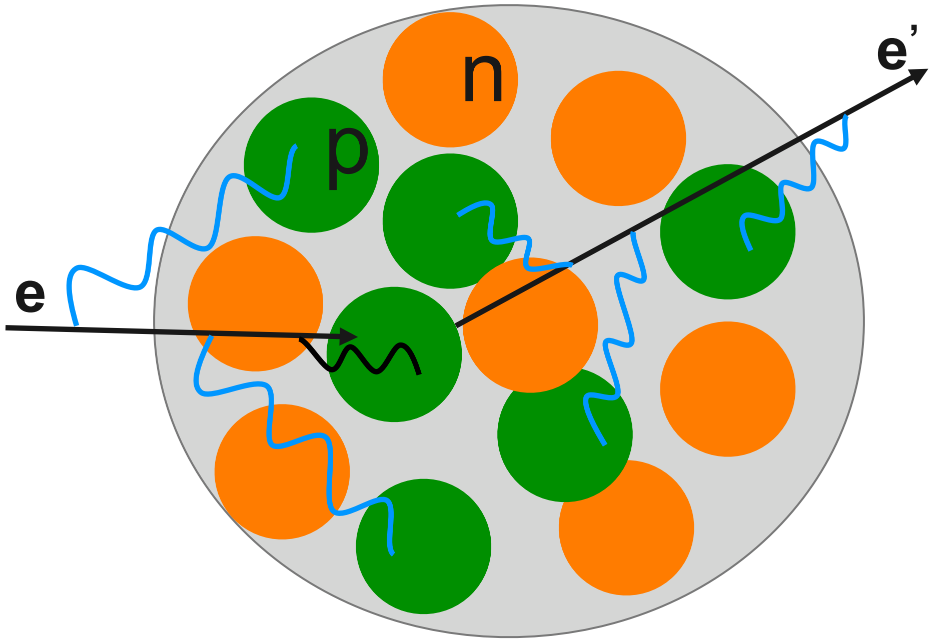


Coulomb distortion

Exchange of one or more (soft) photons with the nucleus, in addition to the one hard photon exchanged with a nucleon

Incident (scattered) electrons are accelerated (decelerated) in the Coulomb well of the nucleus.

Opposite effect with positrons



How to correct for Coulomb distortion ?

$$\xcancel{\sigma_{tot}^{PWBA} = \sigma_{Mott}\, S_{tot}^{PWBA}(|\vec{q}|, \omega, \theta)}$$ ⇨

σ_{tot}^{DWBA}

- Focusing of the electron wave function
- Change of the electron momentum

Effective Momentum Approximation (EMA)

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

$$\left.\begin{array}{l} E \rightarrow E + \bar{V} \\ E_p \rightarrow E_p + \bar{V} \end{array}\right\} \quad Q_{eff}^2 = 4(E + \bar{V})(E_p + \bar{V})\sin^2(\frac{\theta}{2})$$

<u>1st method</u>

$$S_{tot}^{PWBA}(|\vec{q}|, \omega, \theta) \longrightarrow S_{tot}^{PWBA}(|\vec{q}_{eff}|, \omega, \theta)$$

<u>2nd method</u>

$$S_{tot}^{PWBA}(|\vec{q}|, \omega, \theta) \longrightarrow S_{tot}^{PWBA}(|\vec{q}_{eff}|, \omega, \theta)$$

$$\sigma_{Mott}^{eff} = 4\alpha^2 \cos^2(\theta/2)(E_p + \bar{V})^2 / Q_{eff}^4$$

$$F_{foc}^{i} = \frac{E + \bar{V}}{E}$$

$$\boxed{\sigma_{tot}^{CC} = \sigma_{Mott} \cdot S_{tot}^{PWBA}(|\vec{q}_{eff}|, \omega, \theta)} \quad \Leftrightarrow \quad \boxed{\sigma_{tot}^{CC} = (F_{foc}^{i})^2 \cdot \sigma_{Mott}^{eff} \cdot S_{tot}^{PWBA}(|\vec{q}_{eff}|, \omega, \theta)}$$

How to correct for Coulomb distortion ?

$$\cancel{\sigma_{tot}^{PWBA} = \sigma_{Mott}\, S_{tot}^{PWBA}(|\vec{q}|, \omega, \theta)}$$ ⇨

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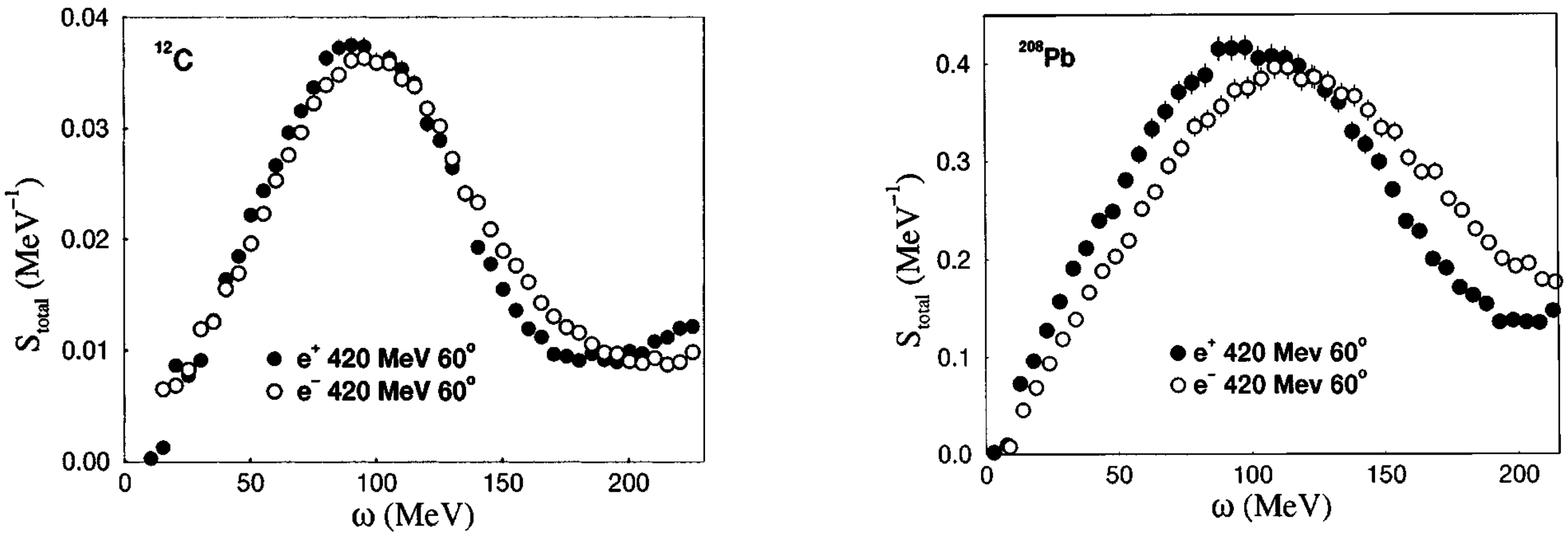
One-parameter model depending only on the effective potential seen by the electron on average.

S_{tot}^{PWB}

$$F^i_{foc} = \frac{E+\bar{V}}{E}$$

$$\boxed{\sigma_{tot}^{CC} = \sigma_{Mott} \cdot S_{tot}^{PWBA}(|\vec{q}_{eff}|, \omega, \theta)} \Leftrightarrow \boxed{\sigma_{tot}^{CC} = (F^i_{foc})^2 \cdot \sigma^{eff}_{Mott} \cdot S_{tot}^{PWBA}(|\vec{q}_{eff}|, \omega, \theta)}$$

Coulomb distortion measurements in quasi-elastic scattering



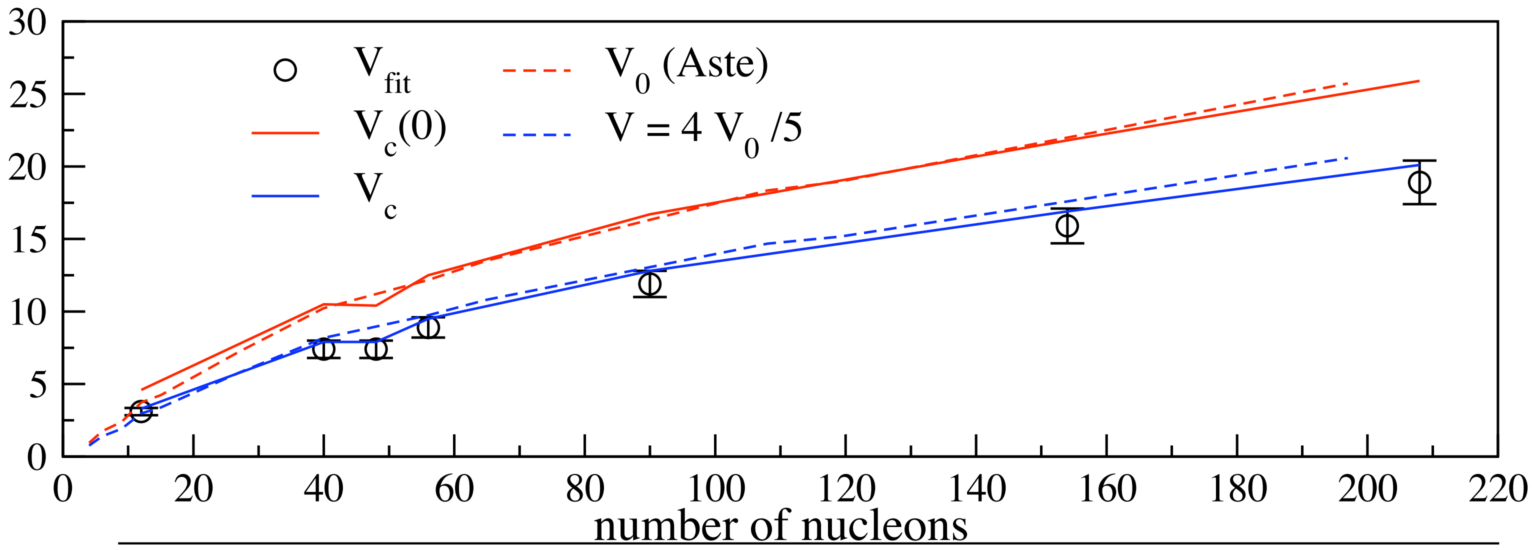
Gueye *et al.*, PRC60, 044308 (1999)

$$\tilde{k} = k - V(z)$$

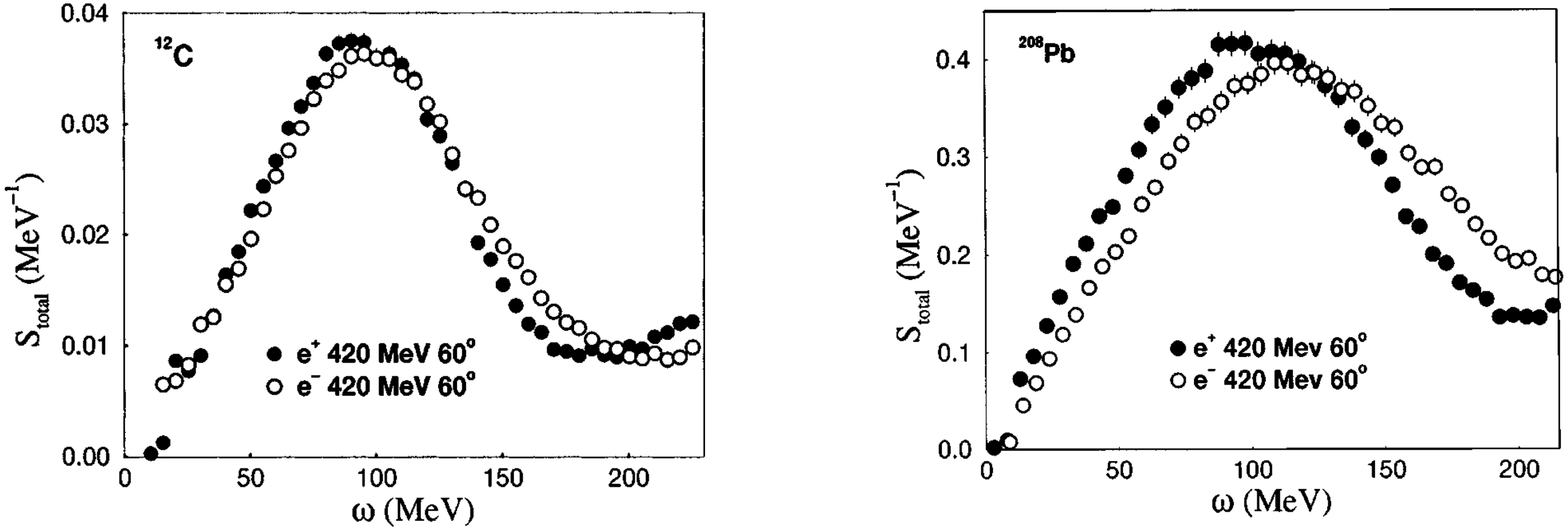
$$V(r) = -\frac{3\alpha(Z-1)}{2R} + \frac{\alpha(Z-1)}{2R}\left(\frac{r}{R}\right)^2$$

$$R = 1.1A^{1/3} + 0.86A^{-1/3}$$

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



Coulomb distortion measurements in quasi-elastic scattering



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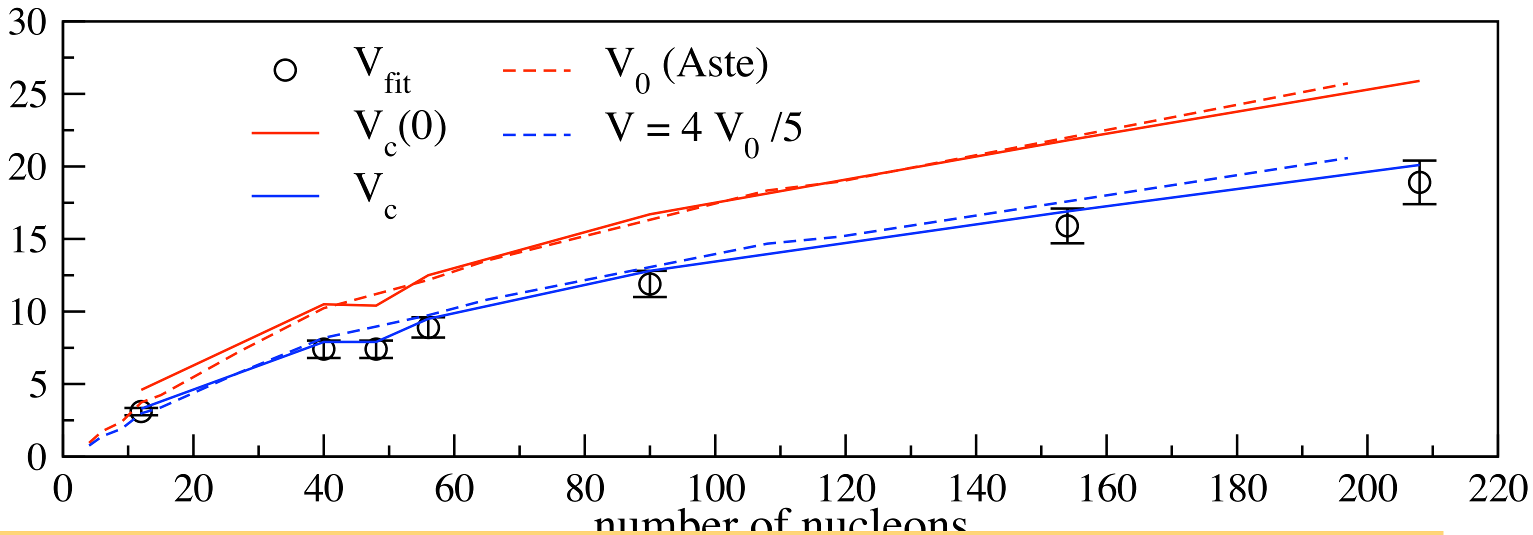
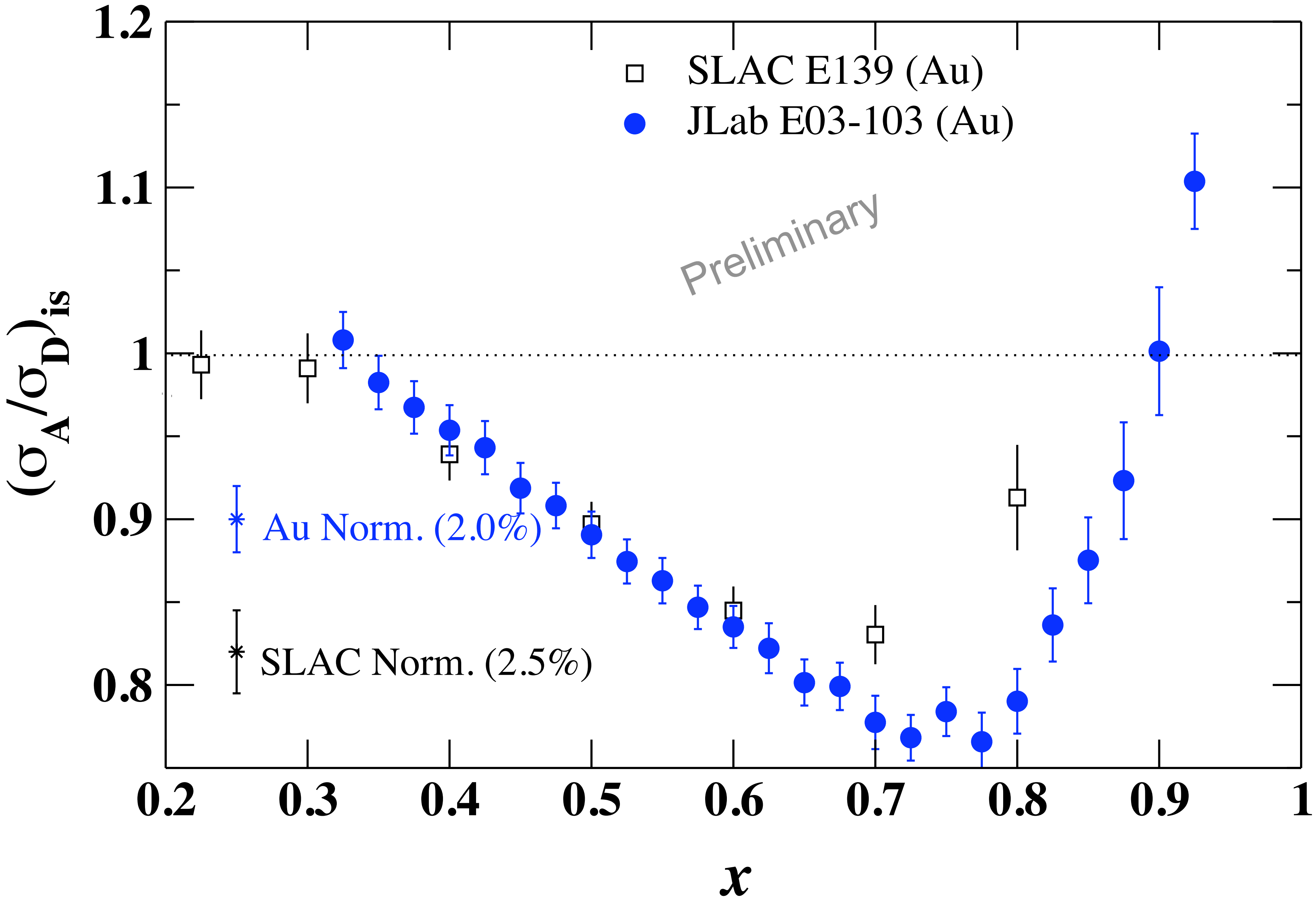


Coulomb potential established in Quasi-elastic scattering regime !

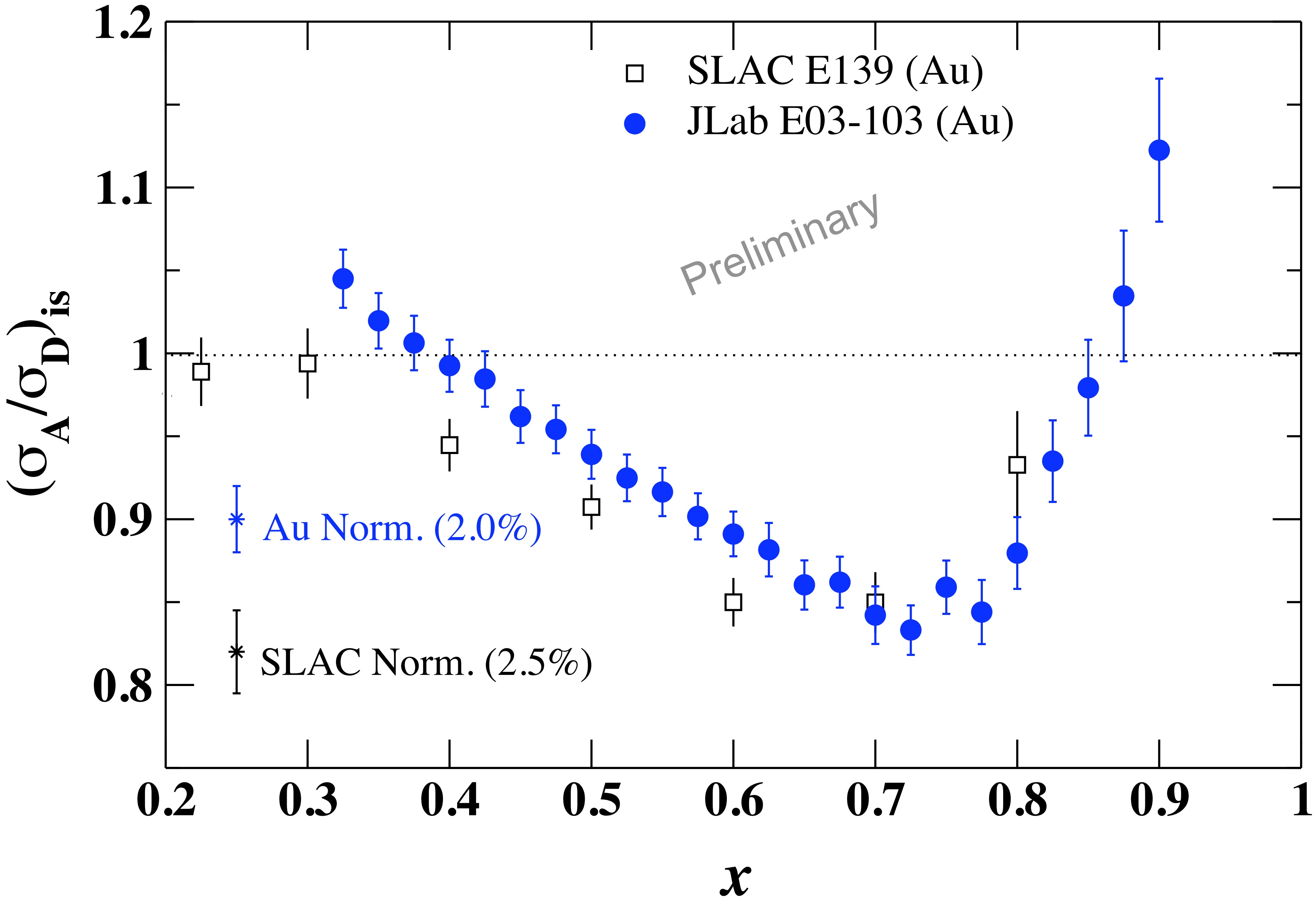
E03-103 heavy target results

no Coulomb corrections applied



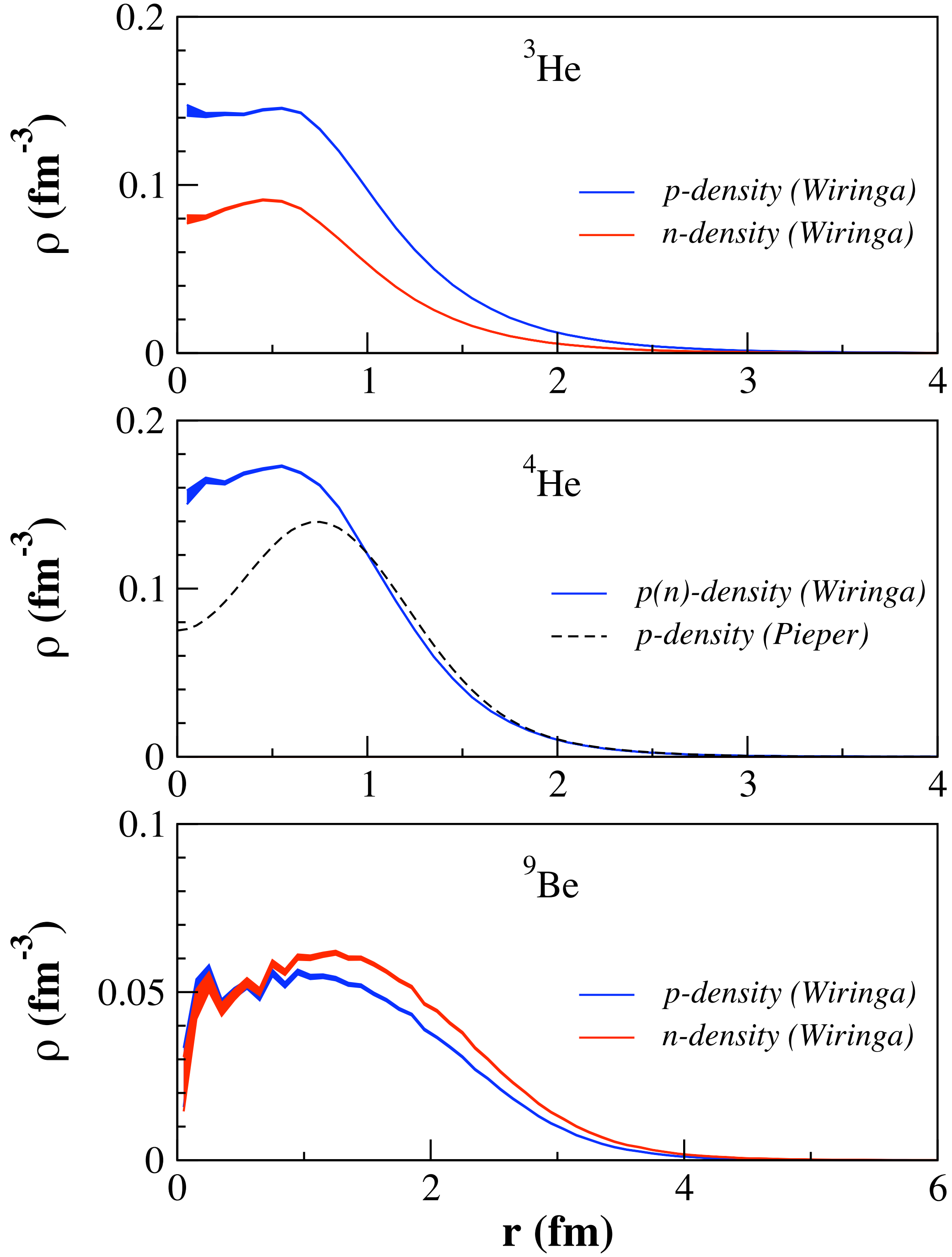
E03-103 heavy target results

Coulomb corrections applied

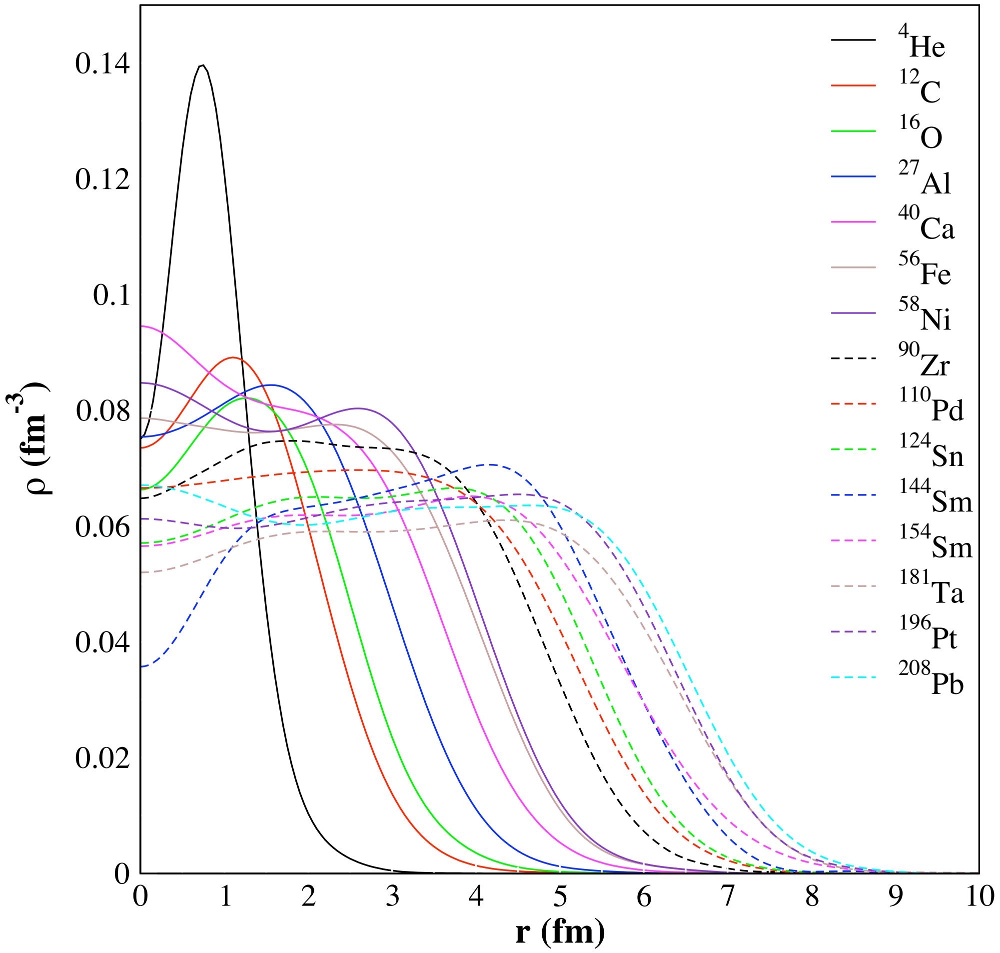


Density calculations

Calculation from R. Wiringa & S. Pieper



Calculation from S. Pieper



Average density:

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

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

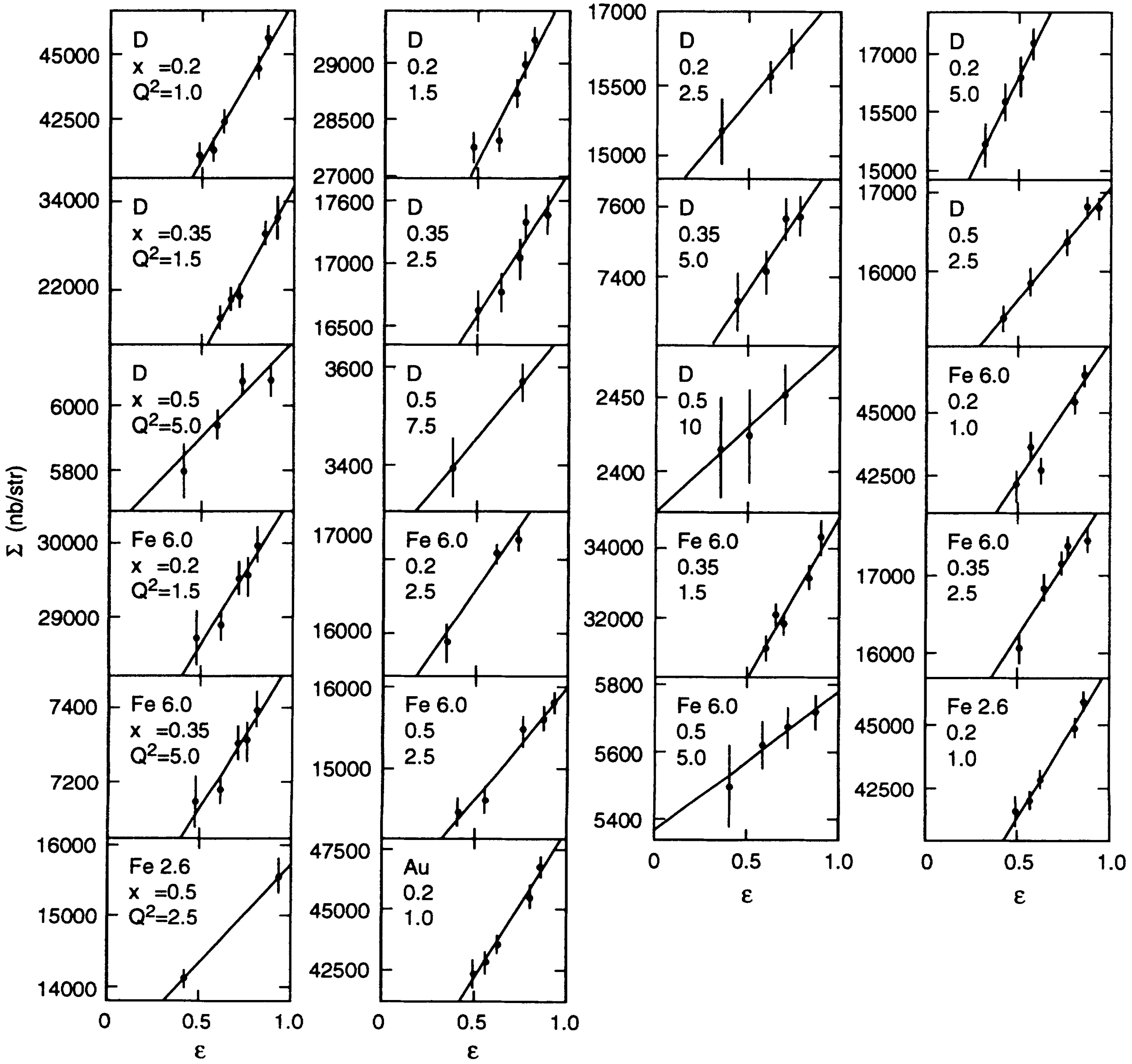
with $r_{eff} = \sqrt{\langle r \rangle^2 + 0.9^2}$

$R(x,Q^2)$

$$\frac{d\sigma}{d\Omega dE'} = \Gamma\left[\sigma_T(x,Q^2) + \varepsilon\sigma_L(x,Q^2)\right]$$

$$\boxed{R(x,Q^2) = \frac{\sigma_L(x,Q^2)}{\sigma_T(x,Q^2)}}$$

Dasu et al., PRD49, 5641(1994)



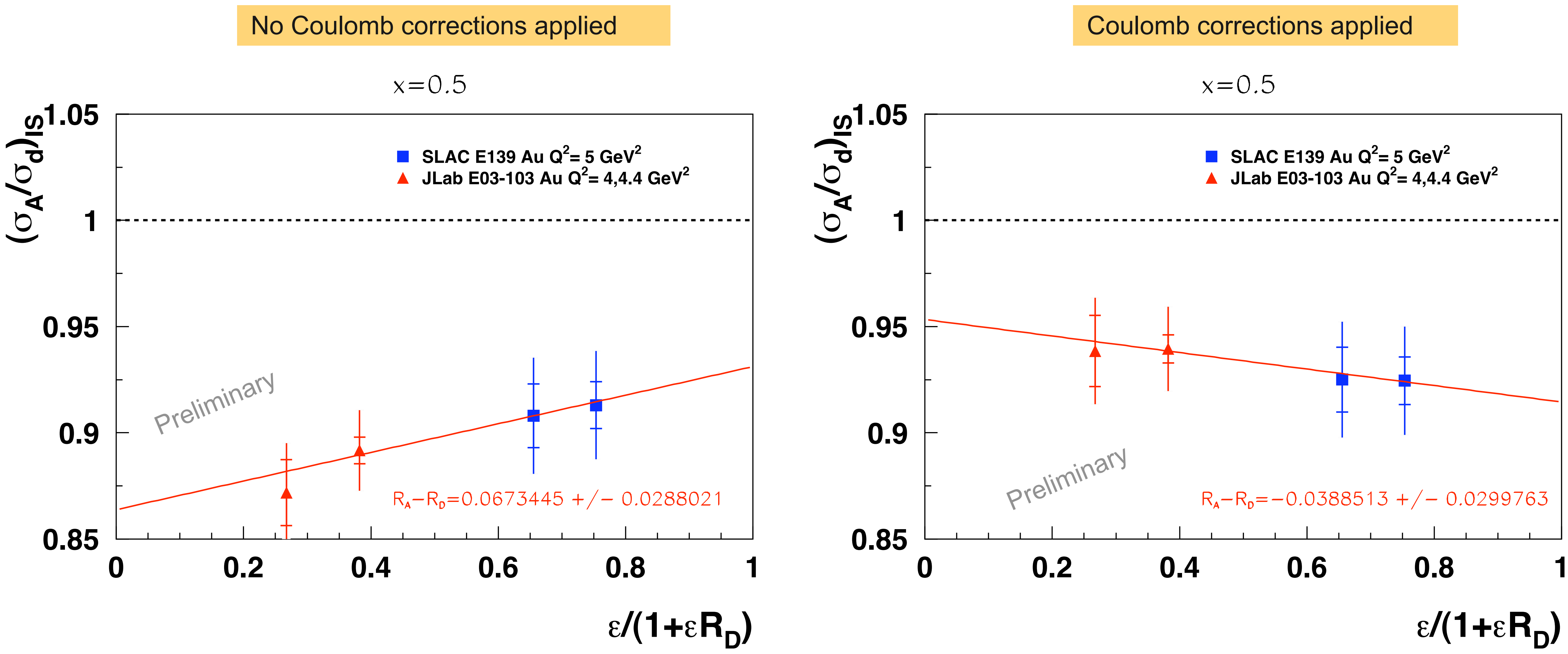
TPE can affect the ε dependence (talk of E. Christy on Thursday)

Coulomb Distortion could have the same kind of impact as TPE, but gives also a correction that is A-dependent.

Access to nuclear dependence of R

New data from JLab E03-103: access to lower ε

Gold



No Coulomb corrections applied

Coulomb corrections applied

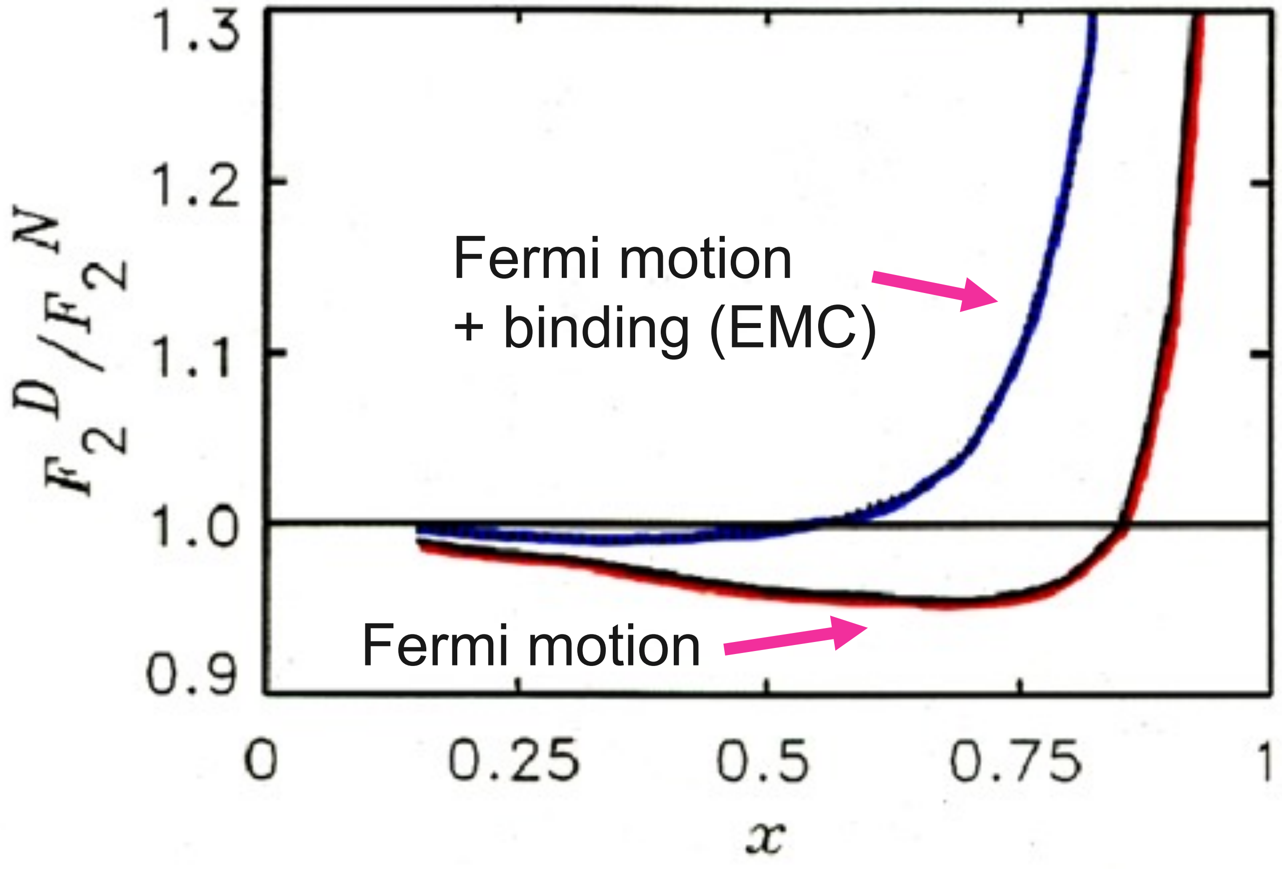
Why don't we know the ratio at high x?

The deuteron is used as "poor person's" neutron target.

$$F_2^D = \frac{1}{2}\sum_N \int_x^{M_D/M} dy\rho(y)F_2^N\left(\frac{x}{y}, Q^2\right) + \delta^{off}F_2^D$$

Off-shell

Probability of N of momentum y
(Fermi smearing + binding)



- Subtract off-shell corr from deuteron data
- Smear the proton data and subtract
- Remainder is smeared neutron struc fn.
- Unsmear the neutron structure function

$$F_2^n = S_n(F_2^{D(conv)} - \tilde{F}_2^p)$$

- Iterate

A. W. Thomas and W. Melnitchouk, NP A 631 (1998) 296

Large x is essential for particle physics

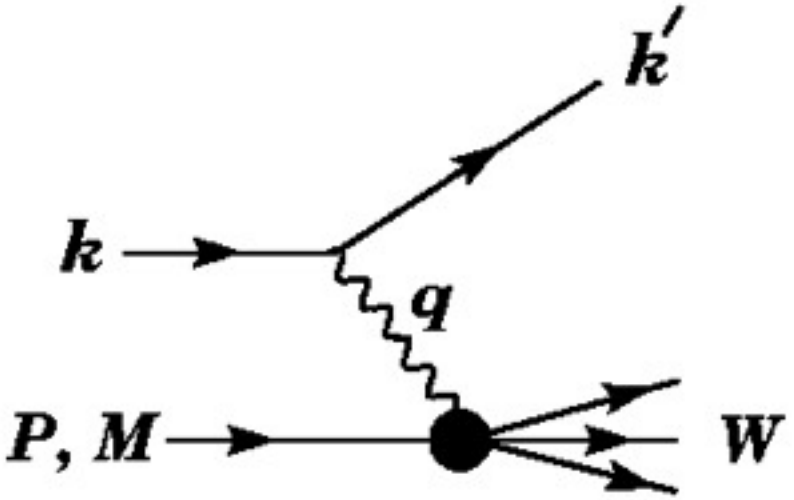
- **Parton distributions at large x are important input into simulations of hadronic background at colliders, *eg* the LHC.**
  - High x at low Q^2 evolves into low x at high Q^2.
  - Small uncertainties at high x are amplified.

- **HERA anomaly: (1996): excess of neutral and charged current events at $Q^2 > 10{,}000$ GeV^2**
  - Leptoquarks
  - ~0.5% larger u(x) at x > 0.75

    S. Kuhlmann et al, PLB 409 (1997)

LHC era is approaching.

Why do we need high energy electrons?



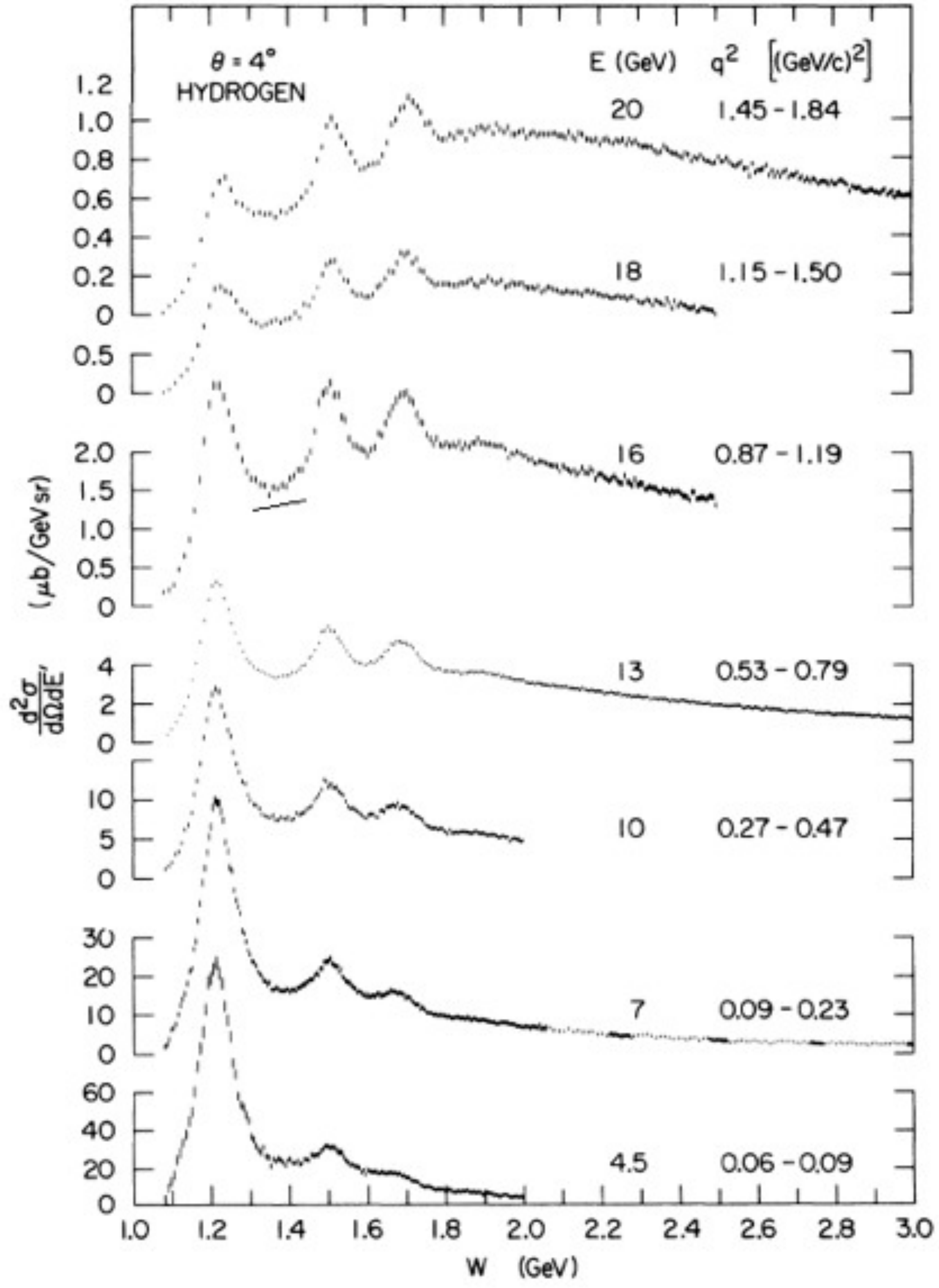
$$Q^2 > 1\ \mathrm{GeV}^2$$
$$W\ > 2\ \mathrm{GeV}$$

$$W^2 = (p+q)^2 = M^2 + 2M\nu - Q^2$$

$$W^2 = M^2 + \frac{1-x}{x}Q^2$$

eg. if x =0.9, then $Q^2 = 27\ \mathrm{GeV}^2$

Practical limit at JLab12: x = 0.8



S. Stein *et al*, PRD 12 (1975)

Ratio: Neutron to Proton Structure Function

- Proton structure function:

$$F_2^p = x\left[\tfrac{4}{9}(u+\bar{u}) + \tfrac{1}{9}(d+\bar{d}) + \tfrac{1}{9}(s+\bar{s})\right]$$

- Neutron structure function (isospin symmetry): $u_p(x) = d_n(x) \equiv u(x)$

$$F_2^n = x\left[\tfrac{4}{9}(d+\bar{d}) + \tfrac{1}{9}(u+\bar{u}) + \tfrac{1}{9}(s+\bar{s})\right]$$

- Ratio:

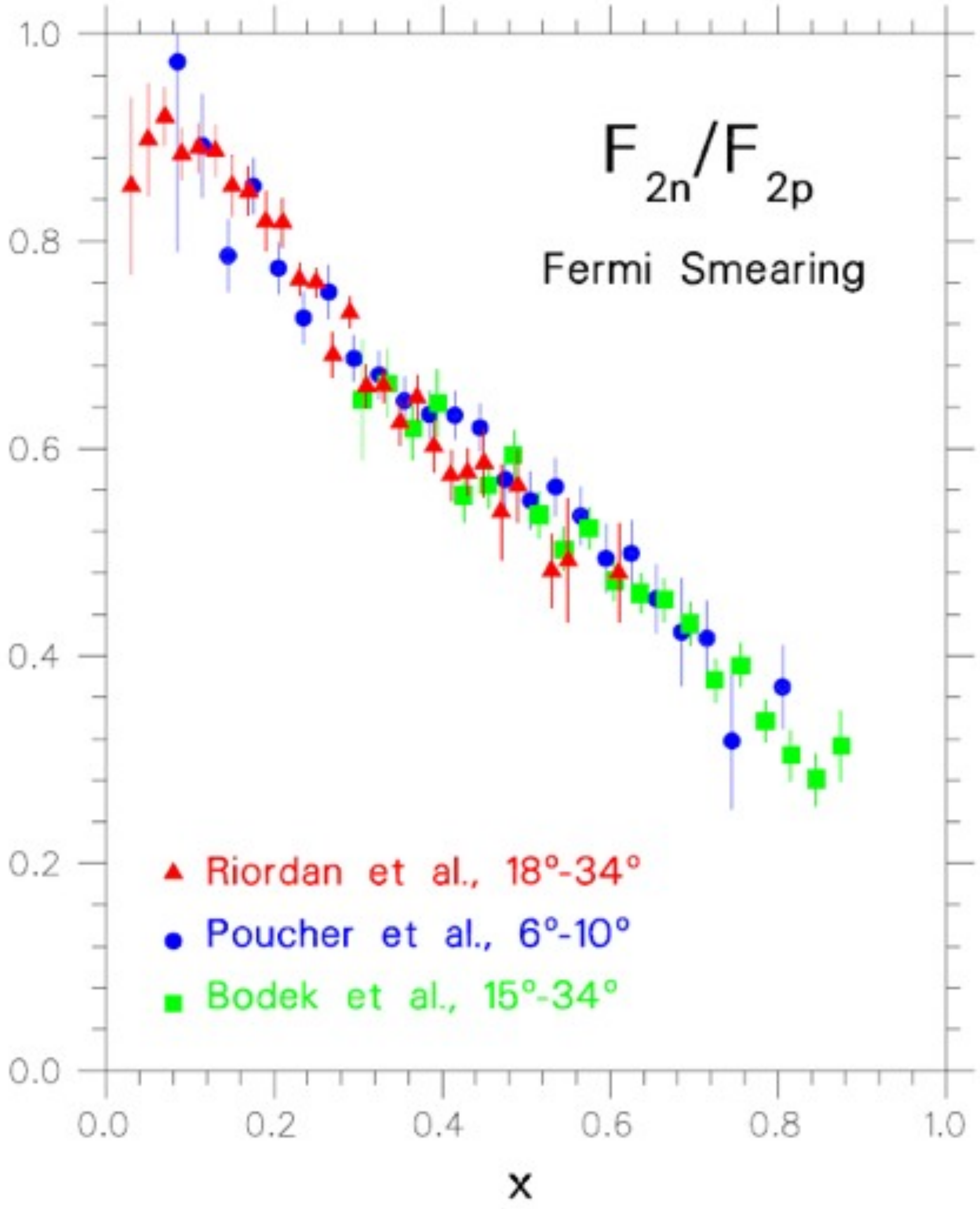
$$\frac{F_2^n}{F_2^p} = \frac{u+\bar{u}+4(d+\bar{d})+s+\bar{s}}{4(u+\bar{u})+d+\bar{d}+s+\bar{s}}$$

- Nachtmann inequality:

$$\frac{1}{4} \le \frac{F_2^n}{F_2^p} \le 4$$

- Focus on high x:

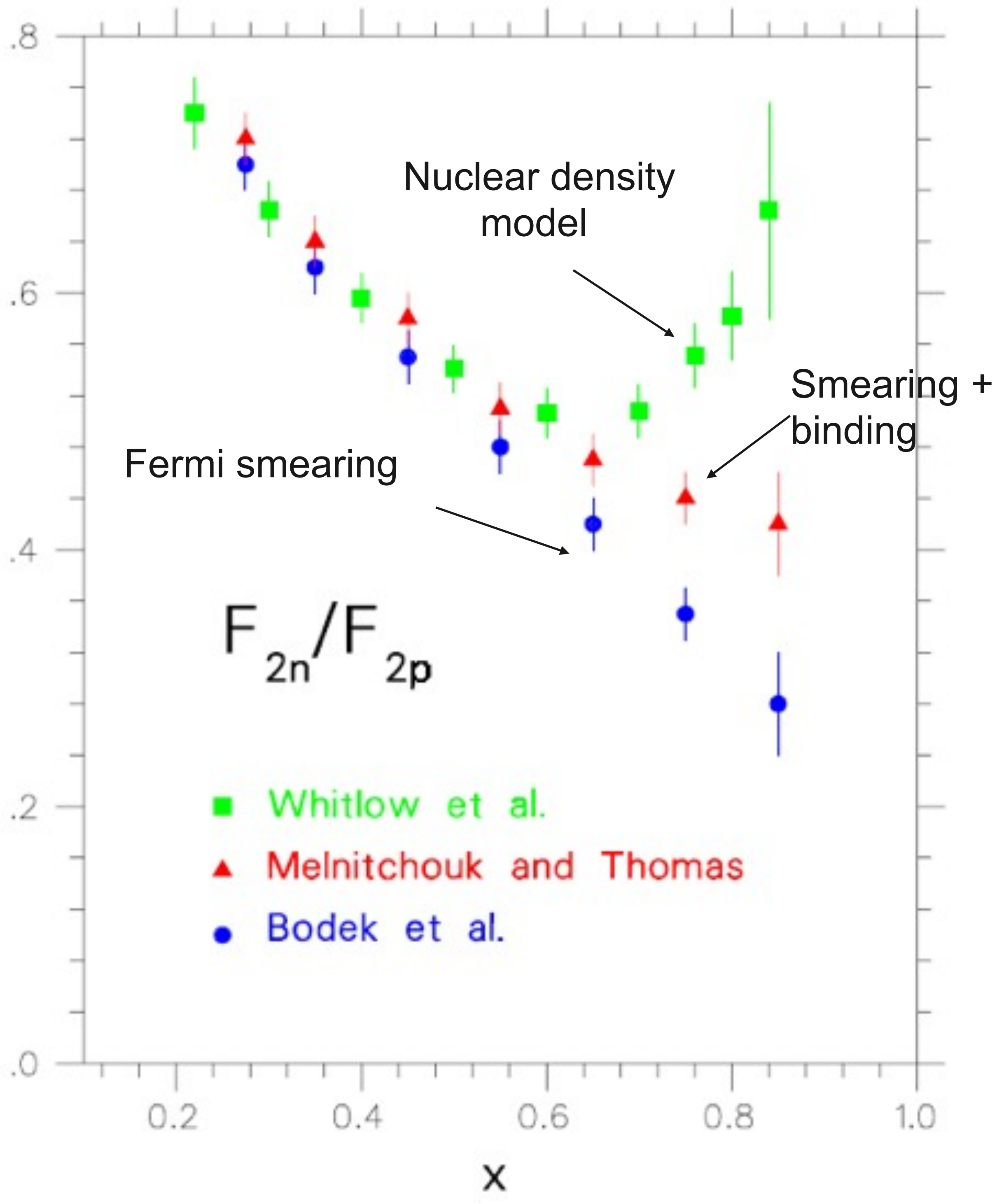
$$\frac{F_2^n}{F_2^p} = \frac{[1+4(d/u)]}{[4+(d/u)]}$$



Structure Function Ratio Problem

$$F_2^d(x,Q^2) = \int dy \rho(y)[F_2^p(x/y,Q^2)+F_2^n(x/y,Q^2)]$$

$$\frac{F_2^d}{F_2^p+F_2^n} = 1 + \frac{\rho_d}{\rho_A-\rho_d}\left[\frac{F_2^A}{F_2^d} - 1\right]$$



Nuclear density model

Smearing + binding

Fermi smearing

Structure Function Ratio Problem

- Convolution model

$$F_2^d(x,Q^2) = \int dy \rho(y)[F_2^p(x/y,Q^2) + F_2^n(x/y,Q^2)]$$

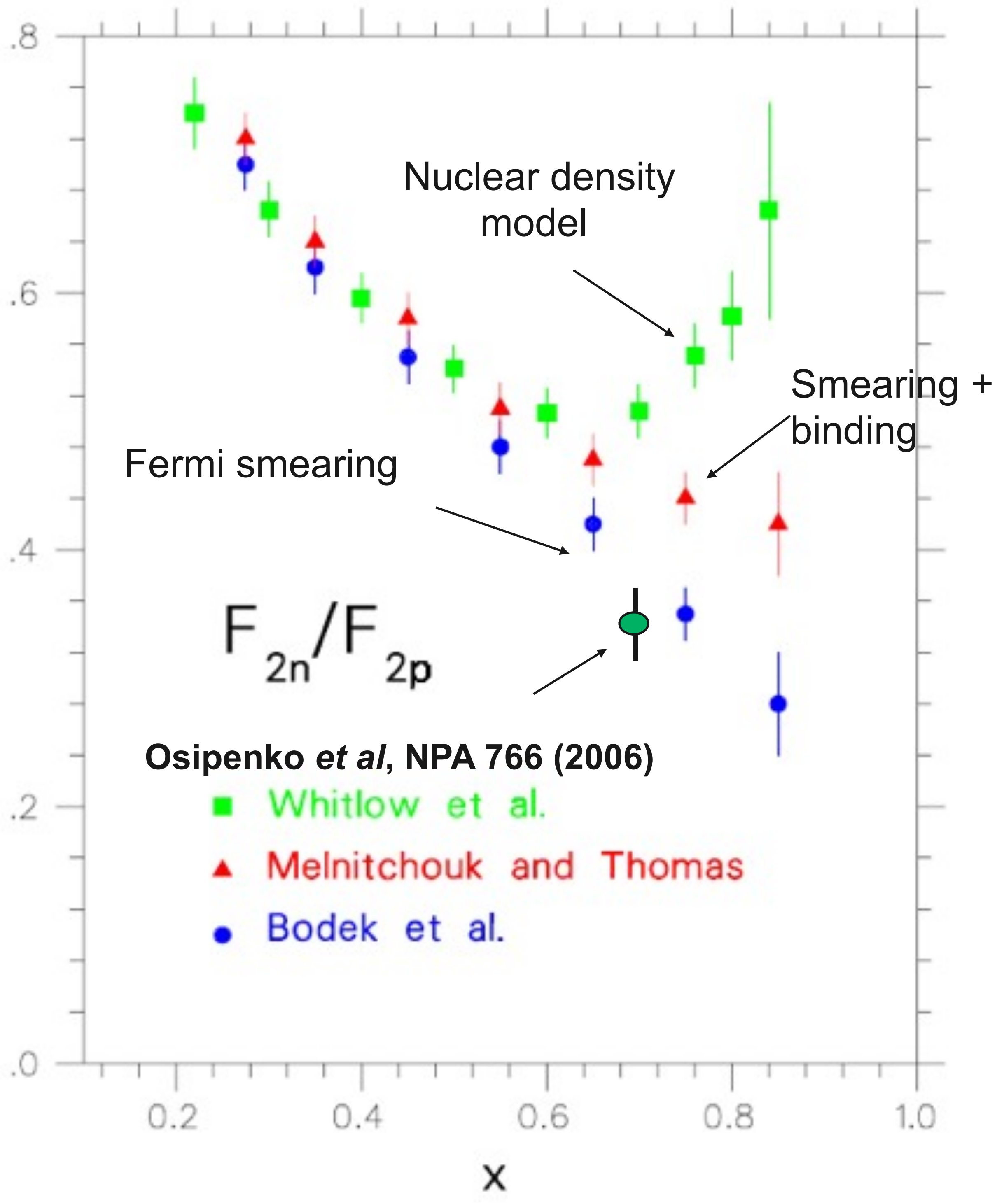
  - ρ(y) accounts for Fermi motion and binding, covariant deuteron wave function

    Melnitchouk and Thomas (1996)

- Nuclear density model:
  - EMC effect for deuteron scales with nuclear density.

$$\frac{F_2^d}{F_2^p+F_2^n} = 1 + \frac{\rho_d}{\rho_A-\rho_d}\left[\frac{F_2^A}{F_2^d} - 1\right]$$ 8)

- Theoretical efforts haven't clarified the situation. New experiments and theoretical works are necessary.



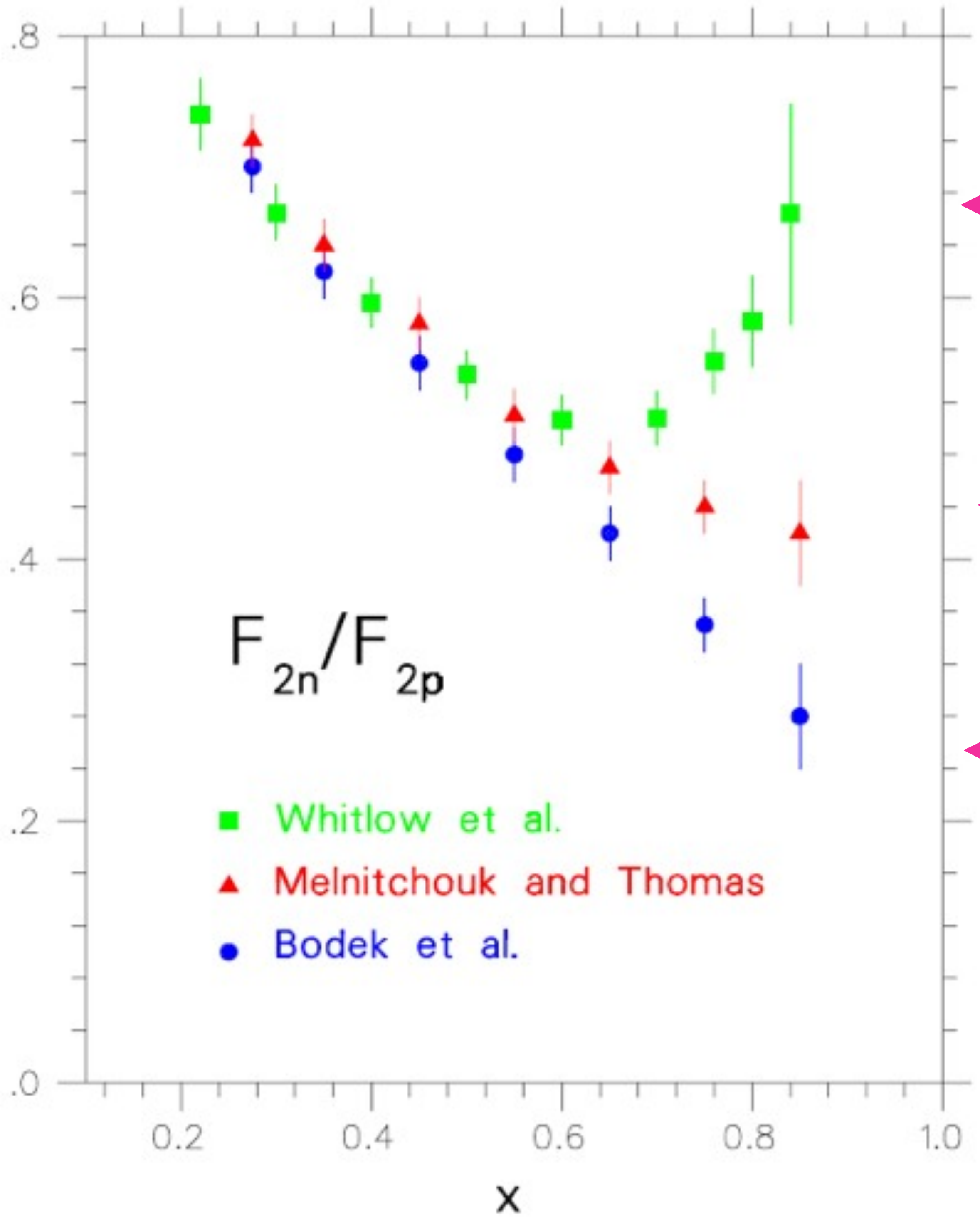
Nuclear density model

Smearing + binding

Fermi smearing

Osipenko *et al*, NPA 766 (2006)

Structure Function Ratio



SU(6) symmetry

pQCD

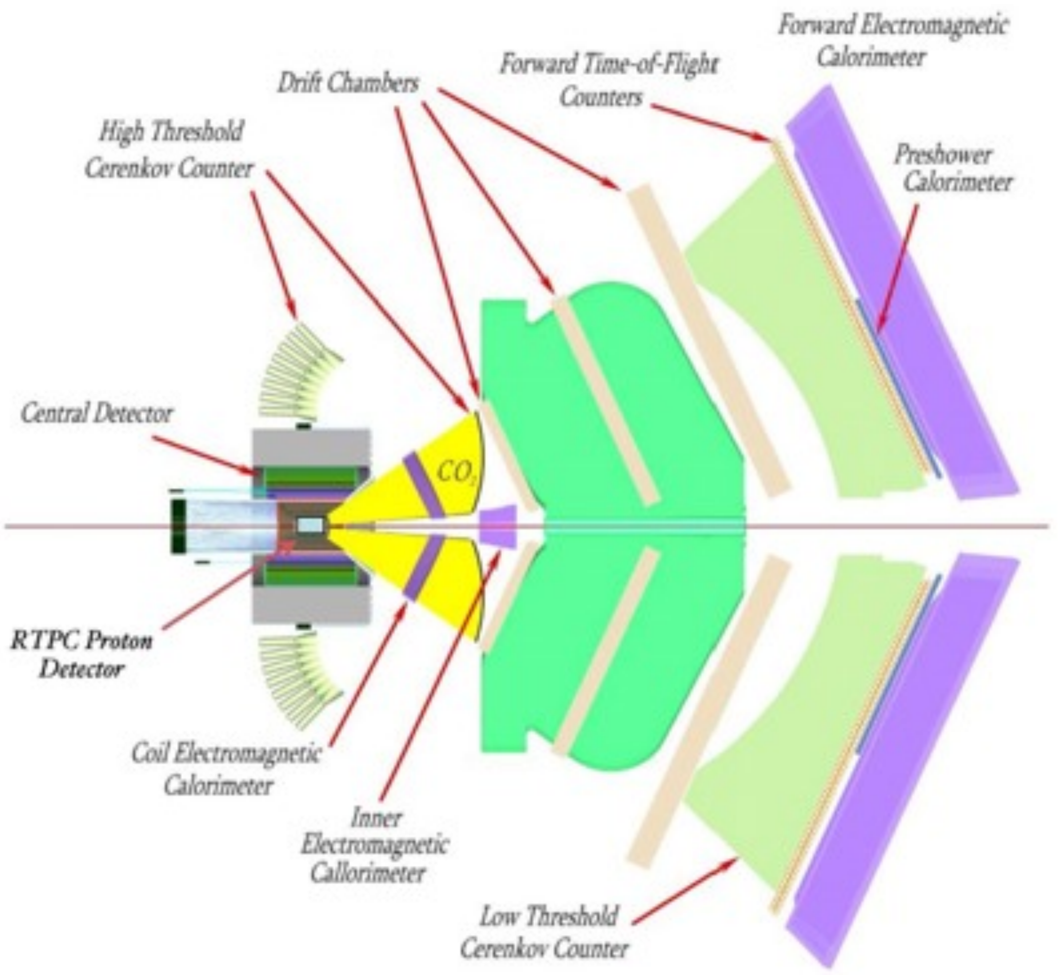
Scalar di-quark

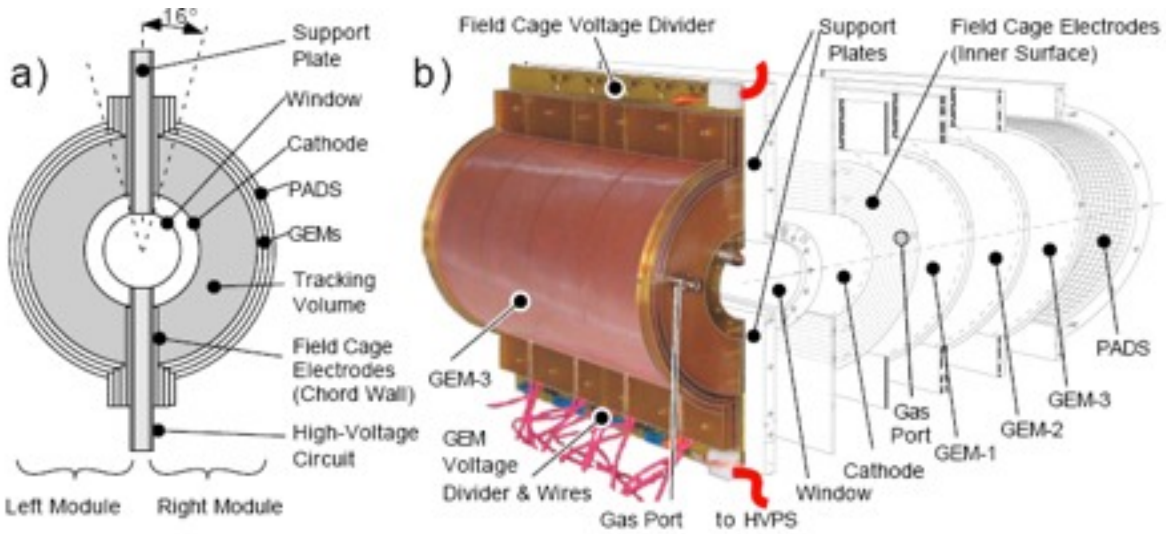
Reviews:

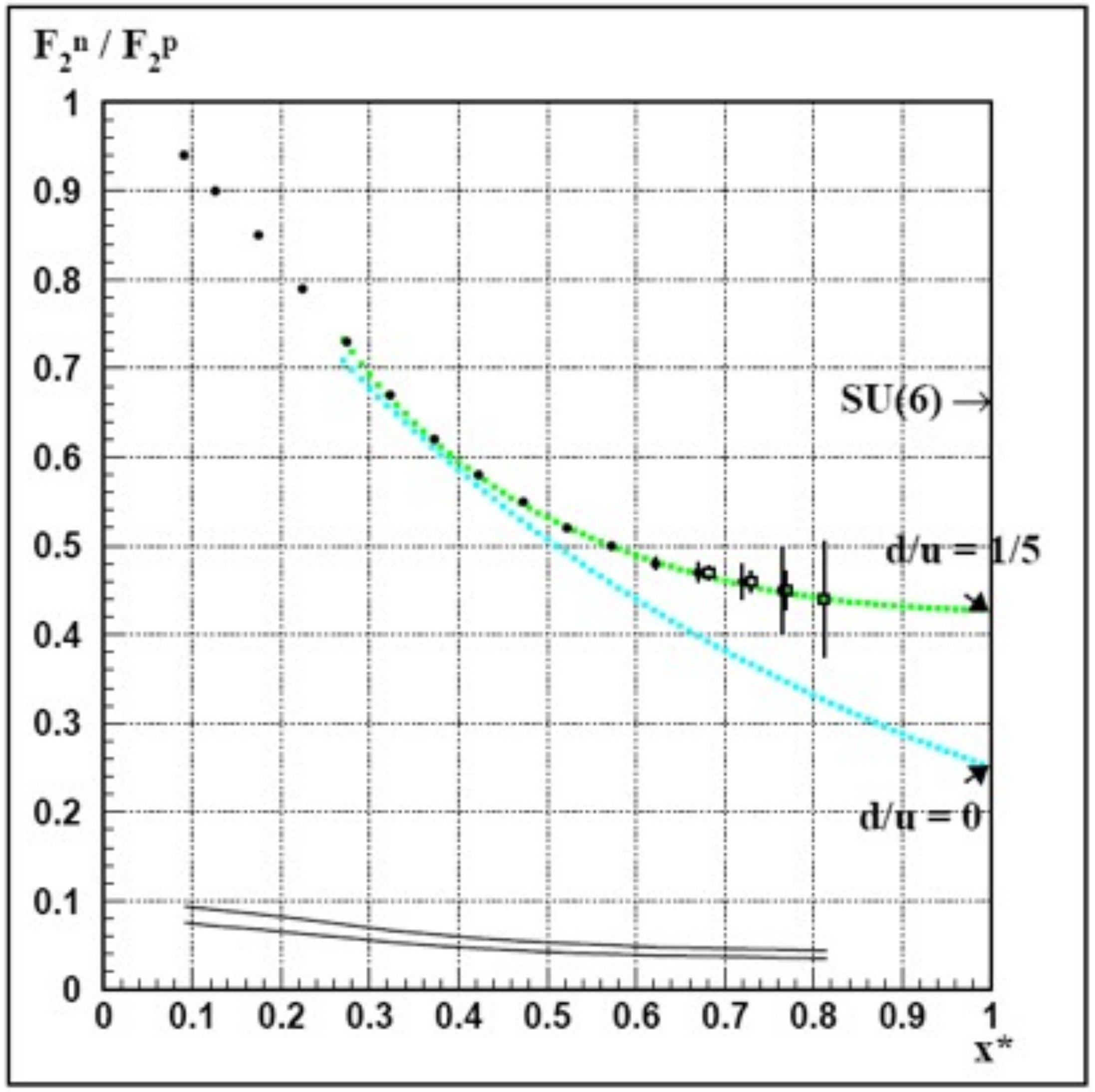
N. Isgur, PR**D 59** (1999),
S Brodsky et al NP **B441** (1995),
W. Melnitchouk and A. Thomas PL **B377** (1996) 11.

Craig Roberts: “a top priority”

Tagged Neutron in the Deuteron – BONUS + CLAS12

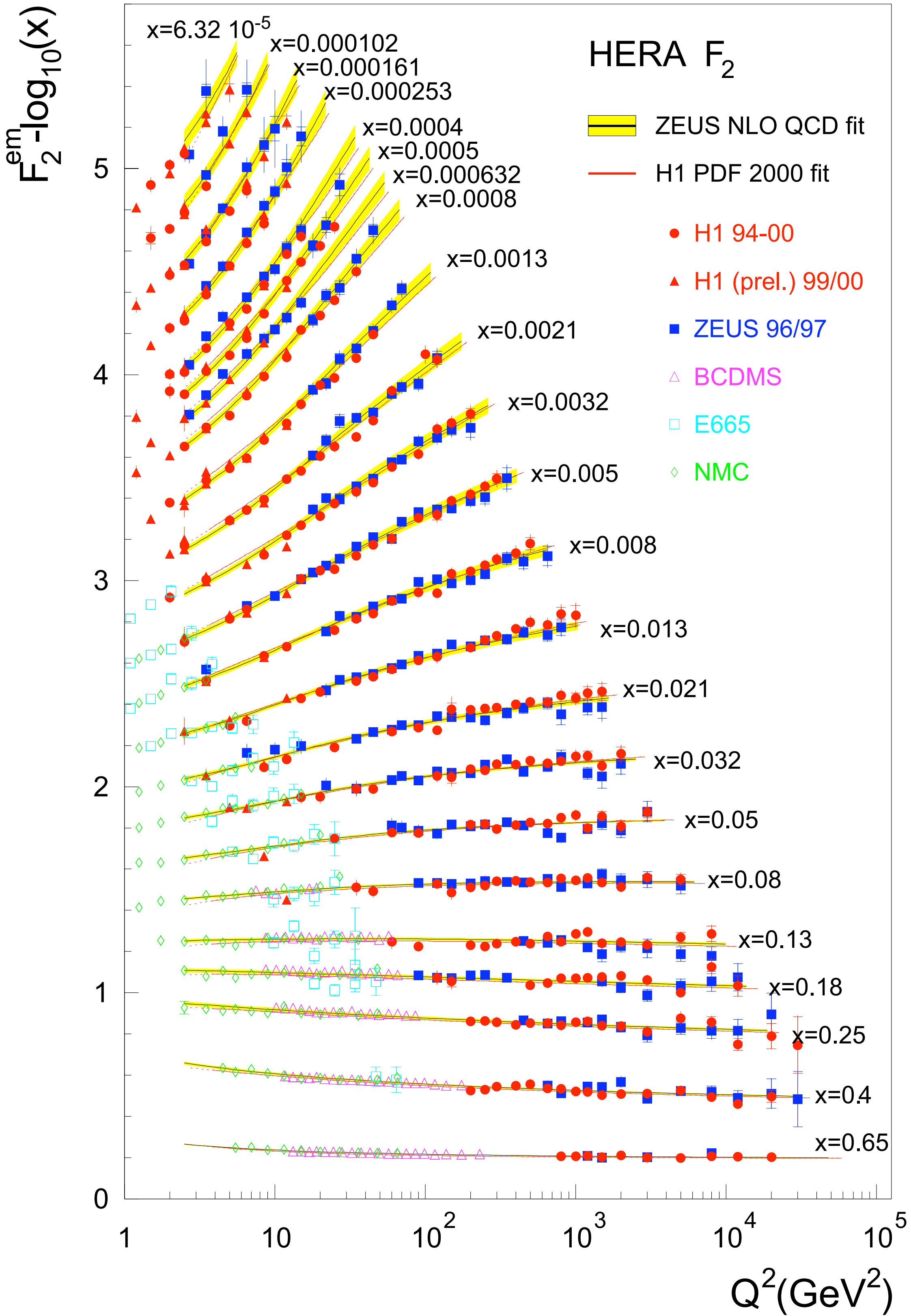


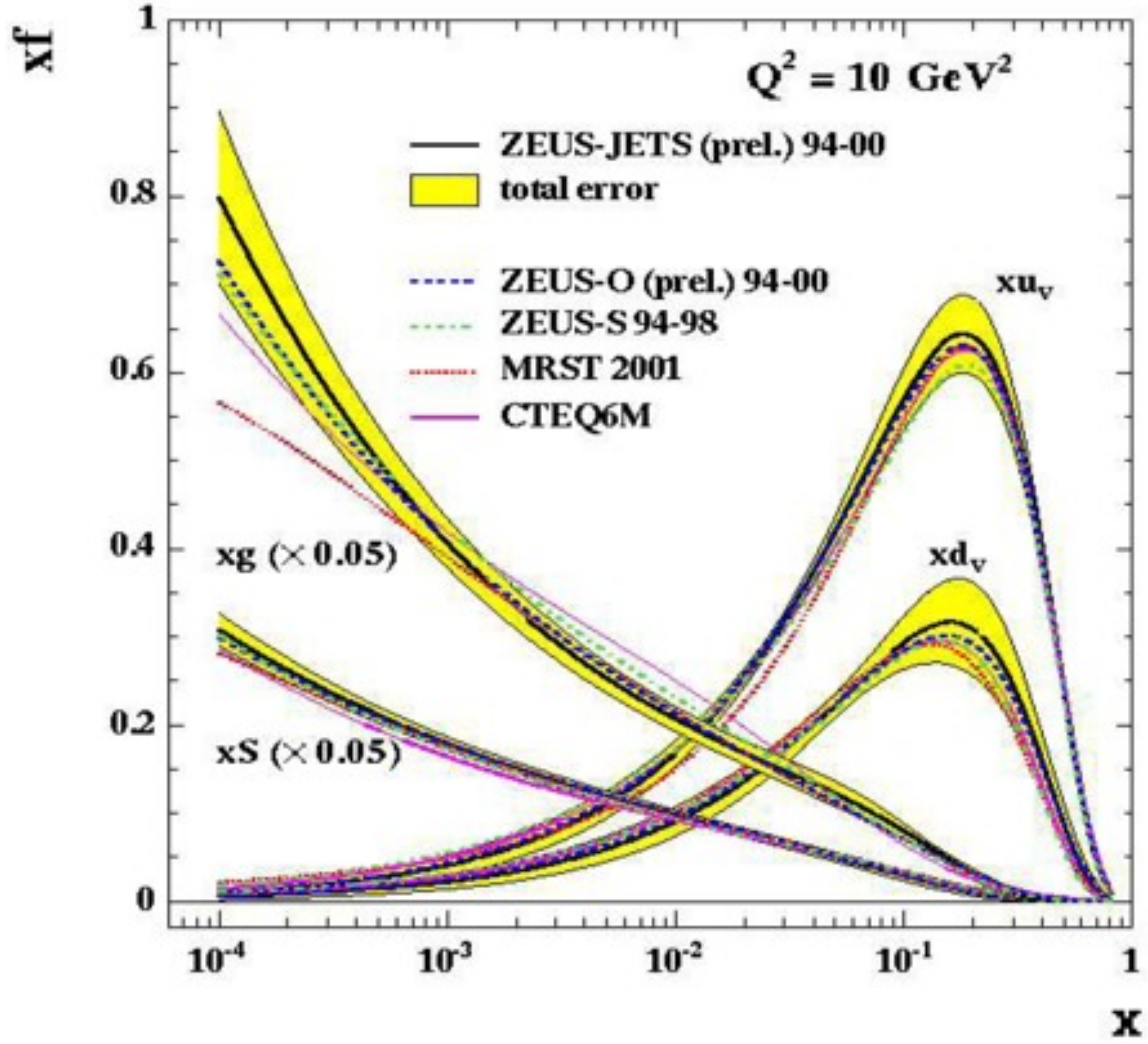




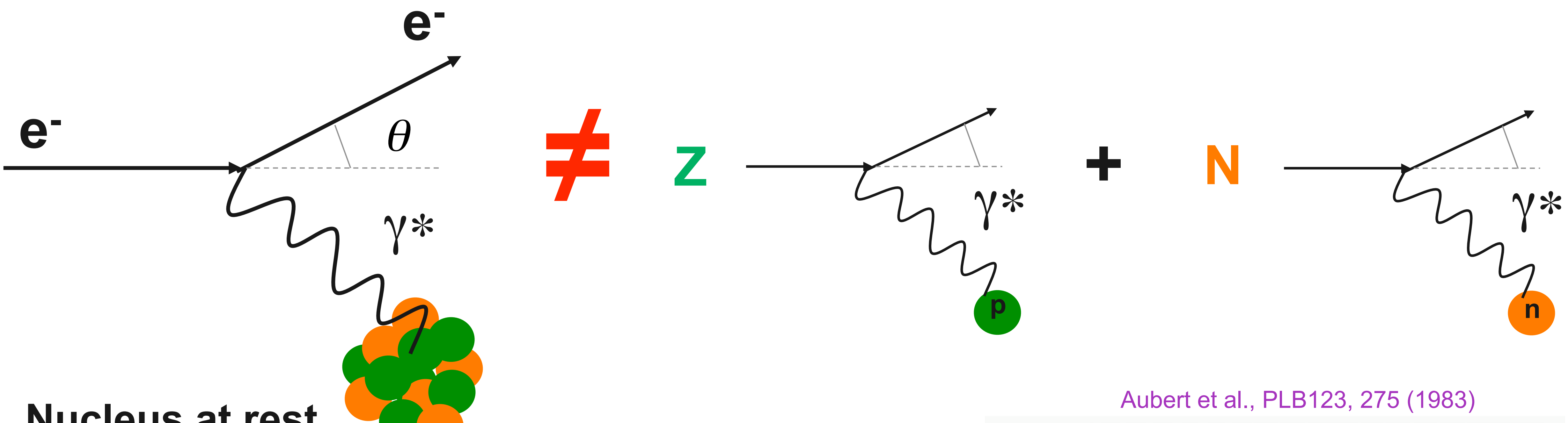
- PAC30: “conditionally approved”
- JLab E12-06-113, S. Bueltmann, H. Fenker, M. Christy, C. Keppel *et al*

F2p and parton distributions





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)