Experimental Overview of Past and Future Studies of the *EMC Effect*

Dave Gaskell - JLab

February 14, 2013

INT Workshop on Nuclear Structure and Dynamics at Short Distance

Outline

- Measurements of σ_A/σ_D
  - Early measurements
  - x, Q^2, nuclear dependence, universality
- JLab results and implications
  - EMC effect and local density
  - EMC-SRC connection
  - Flavor dependence
  - Nuclear dependence of $R=\sigma_L/\sigma_T$
- Summary

Quarks in the Nucleus

Typical nuclear binding energies
→ MeV while DIS scales → GeV

Naïve expectation:

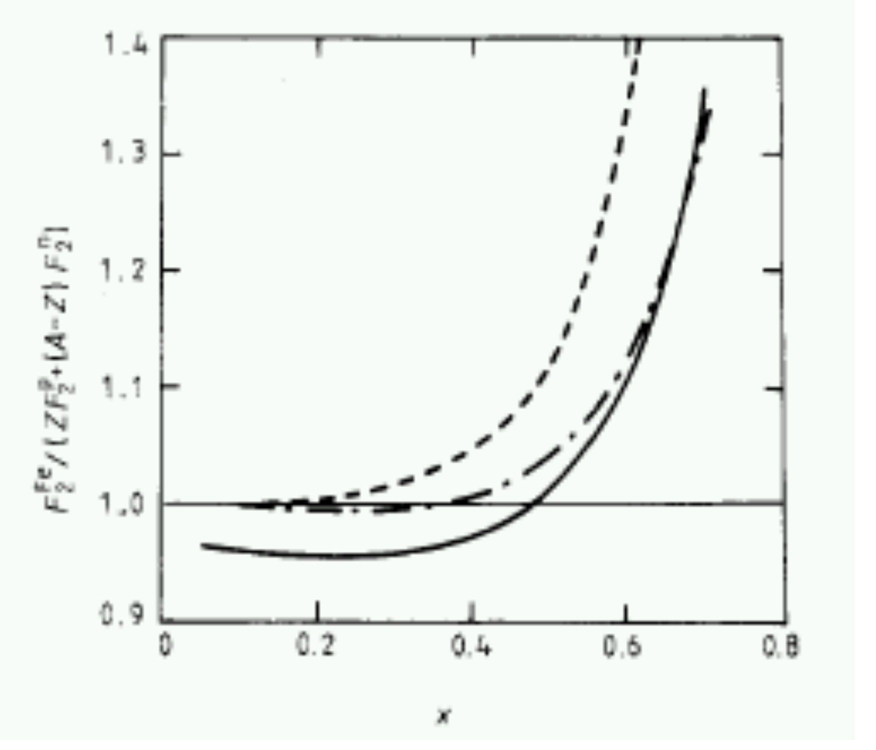
$$F_2^A(x) = ZF_2^p(x) + (A-Z)F_2^n(x)$$

More sophisticated approach includes effects from Fermi motion

$$F_2^A(x) = \sum_i \int_x^{M_A/m_N} dy f_i(y) F_2^N(x/y)$$

Quark distributions in nuclei were not expected to be significantly different (below x=0.6)

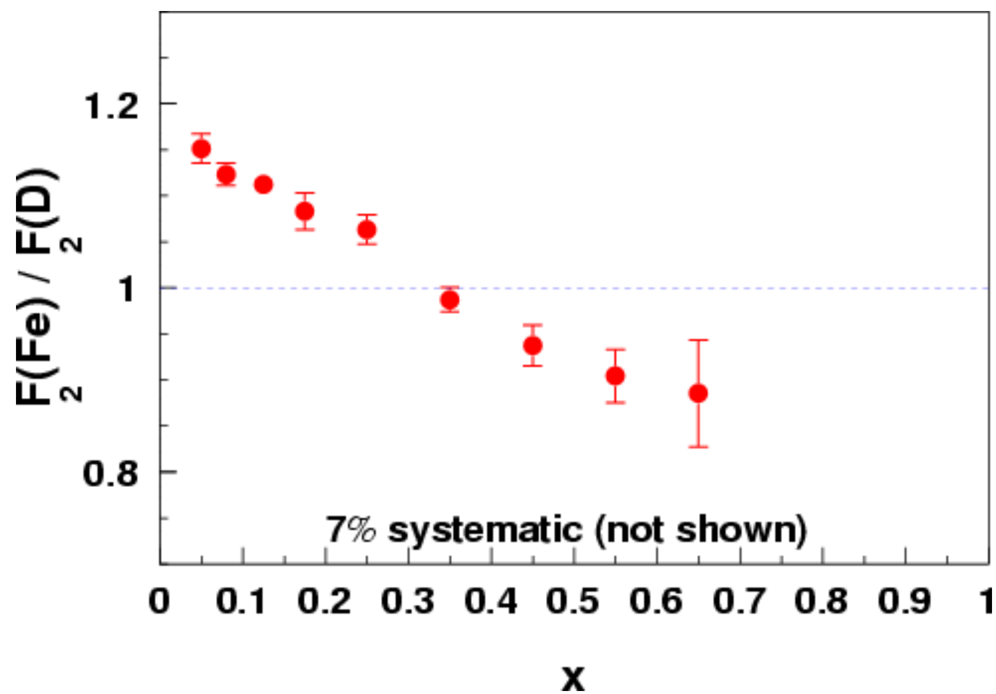
$$F_2^{Fe} / \left(ZF_2^p + (A-Z)F_2^n \right)$$



Bodek and Ritchie
PRD 23, 1070 (1981)

First Measurement of the EMC Effect

- First published measurement of nuclear dependence of F_2 by the European Muon Collaboration in 1983
- Observed 2 mysterious effects
  - Significant enhancement at small *x* → Nuclear Pions! (see my thesis)
  - Depletion at large *x* → the "EMC Effect"
- Enhancement at *x<0.1* later went away



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

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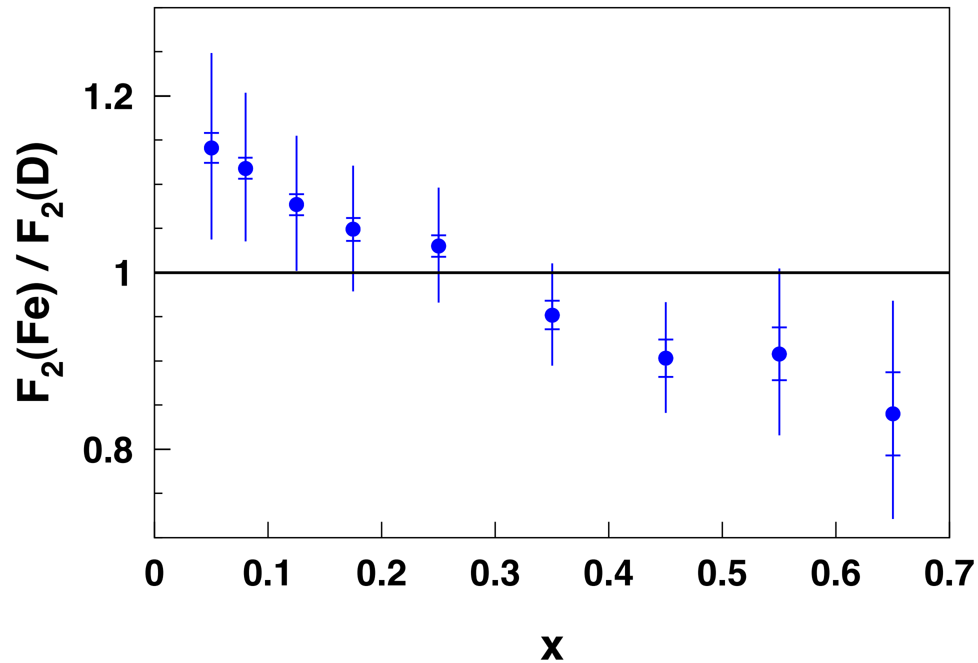


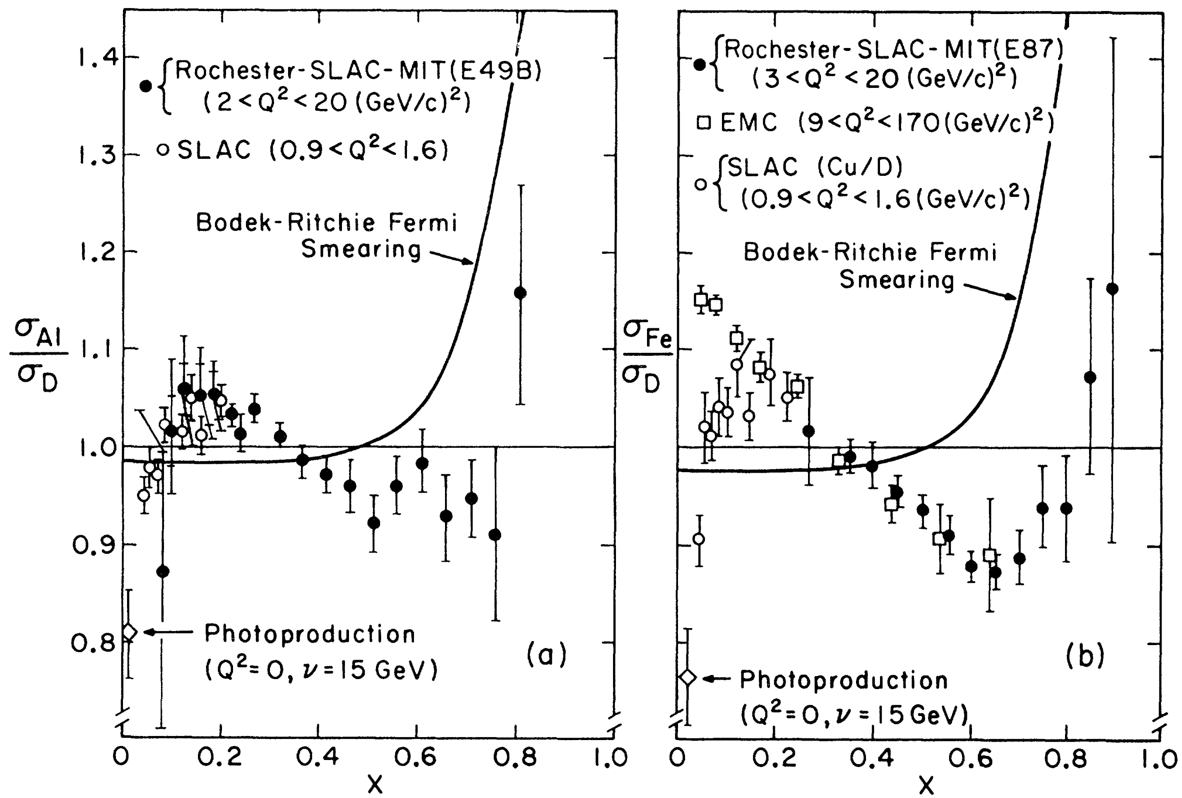
Aubert et al, Nucl. Phys. B293, 740 (1987)

Confirmation of the Effect

SLAC re-analysis of old solid target data used for measurements of cryotarget wall backgrounds

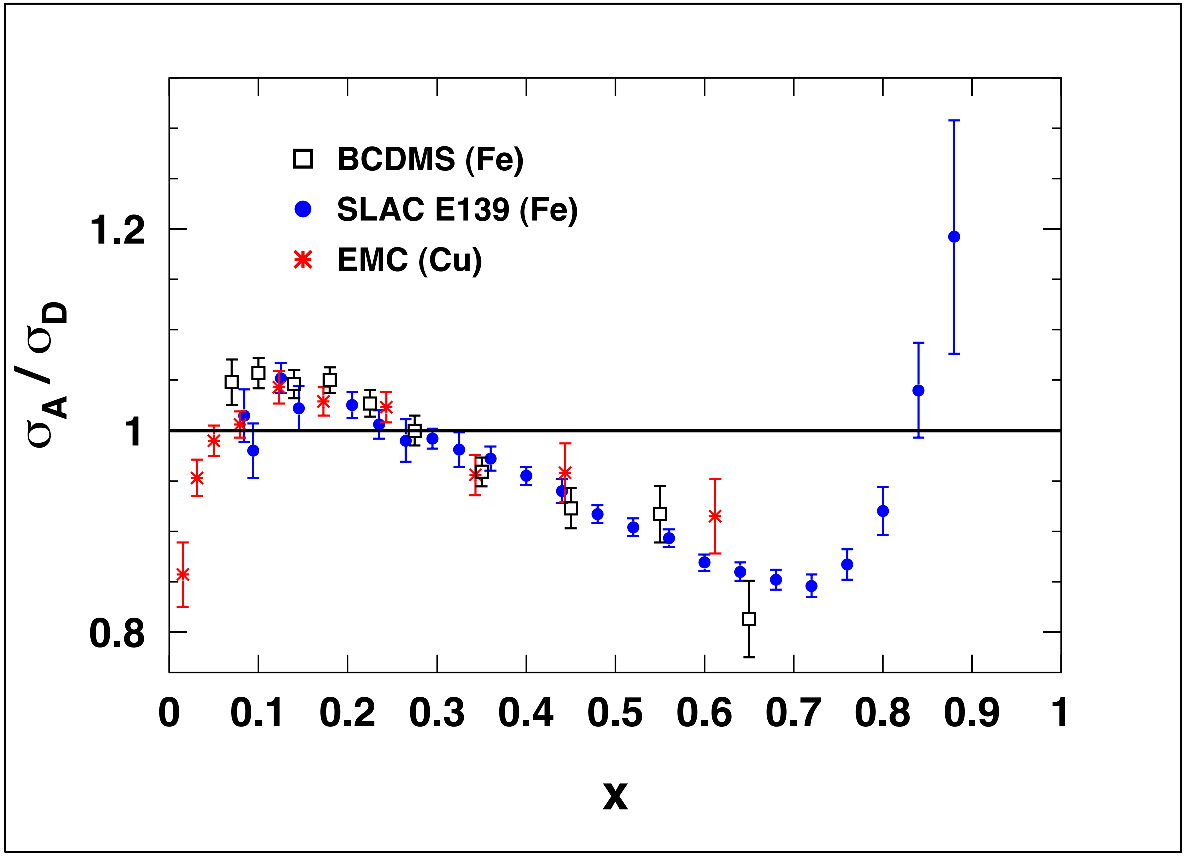
→Effect for *x>0.3* confirmed

→No large excess at very low *x*



Bodek et al, PRL 50, 1431 (1983) and PRL 51, 534 (1983)

Subsequent Measurements



A program of dedicated measurements quickly followed

The resulting data is remarkably consistent over a large range of beam energies and species

EMC Effect Measurements

Laboratory/ collaboration	Beam	Energy (GeV)	Target	Year
SLAC E139	e	8-24.5	***D***, ^{4}He, Be, C, Ca, Fe, Ag, Au	1994,1984
SLAC E140	e	3.75-19.5	***D***, Fe, Au	1992,1990
CERN NMC	μ	90	***^{6}Li***, ^{12}C, ^{40}Ca	1992
	μ	200	***D***, ^{4}He, C, Ca	1991, 1995
	μ	200	Be, ***C***, Al, Ca, Fe, Sn, Pb	1996
CERN BCDMS	μ	200	***D***, Fe	1987
	μ	280	***D***, N, Fe	1985
CERN EMC	μ	100-280	***D***, Cu	1993
	μ	280	***D***, C, Ca	1988
	μ	100-280	***D***, C, Cu, Sn	1988
	μ	280	H, ***D***, Fe	1987
	μ	100-280	***D***, Fe	1983
FNAL E665	μ	490	***D***, Xe	1992
	μ	490	***D***, Xe	1992
DESY HERMES	e	27	***D***, ^{3}He, N, Kr	2000, 2003
Jefferson Lab	e	6	***D***, ^{3}He, ^{4}He, Be, C, Cu, Au	2009
	e	6	***D***, C, Cu, Au	2004 (thesis)

Geesaman, Saito, and Thomas, Ann. Rev. Nucl. Sci. 45, 337 (1995) – updated by Gaskell

Nuclear dependence of structure functions

Experimentally, we measure cross sections (and the ratios of cross sections)

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 (E')^2}{Q^4 \nu}\left[F_2(\nu,Q^2)\cos^2\frac{\theta}{2} + \frac{2}{M\nu}F_1(\nu,Q^2)\sin^2\frac{\theta}{2}\right] \qquad F_2(x) = \sum_i e_i^2 x q_i(x)$$

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2}{2xF_1}\left(1 + 4\frac{M^2x^2}{Q^2}\right) - 1$$

In the limit $R_A = R_D$ →

$\sigma_A/\sigma_D = F_2^A/F_2^D$

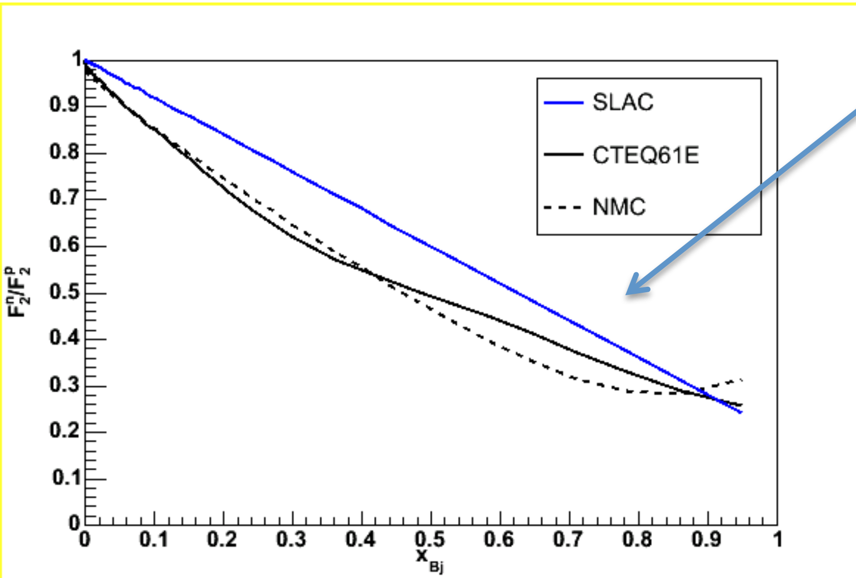
Experiments almost always display cross section ratios, σ_A/σ_D

→Often these ratios are labeled or called F_2^A/F_2^D

→ Sometimes there is an additional uncertainty estimated to account for the σ→F_2 translation. Sometimes there is not.

Isoscalar Corrections

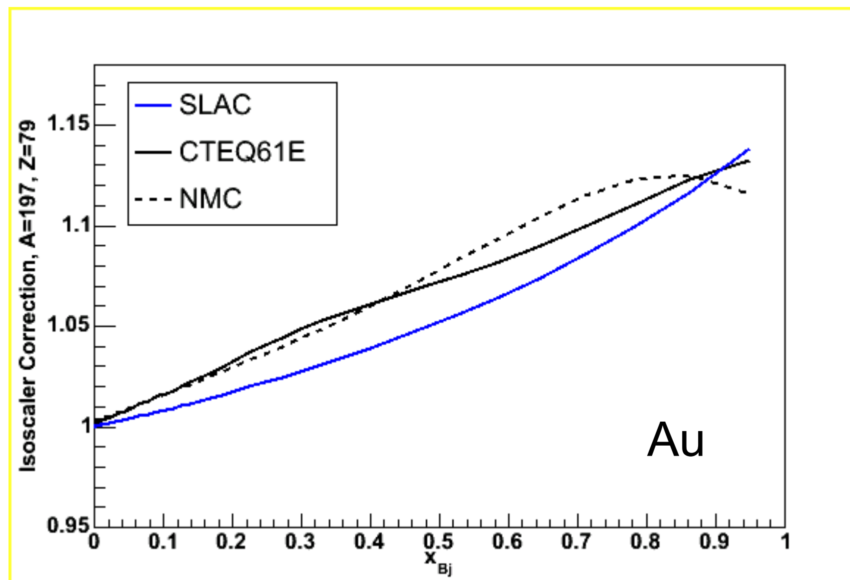
In the case of nuclei where N≠Z, need to remove the "trivial" change in nuclear cross section due to $\sigma_n \neq \sigma_p$
→ Different experiments often use slightly different parameterizations/estimates for this correction



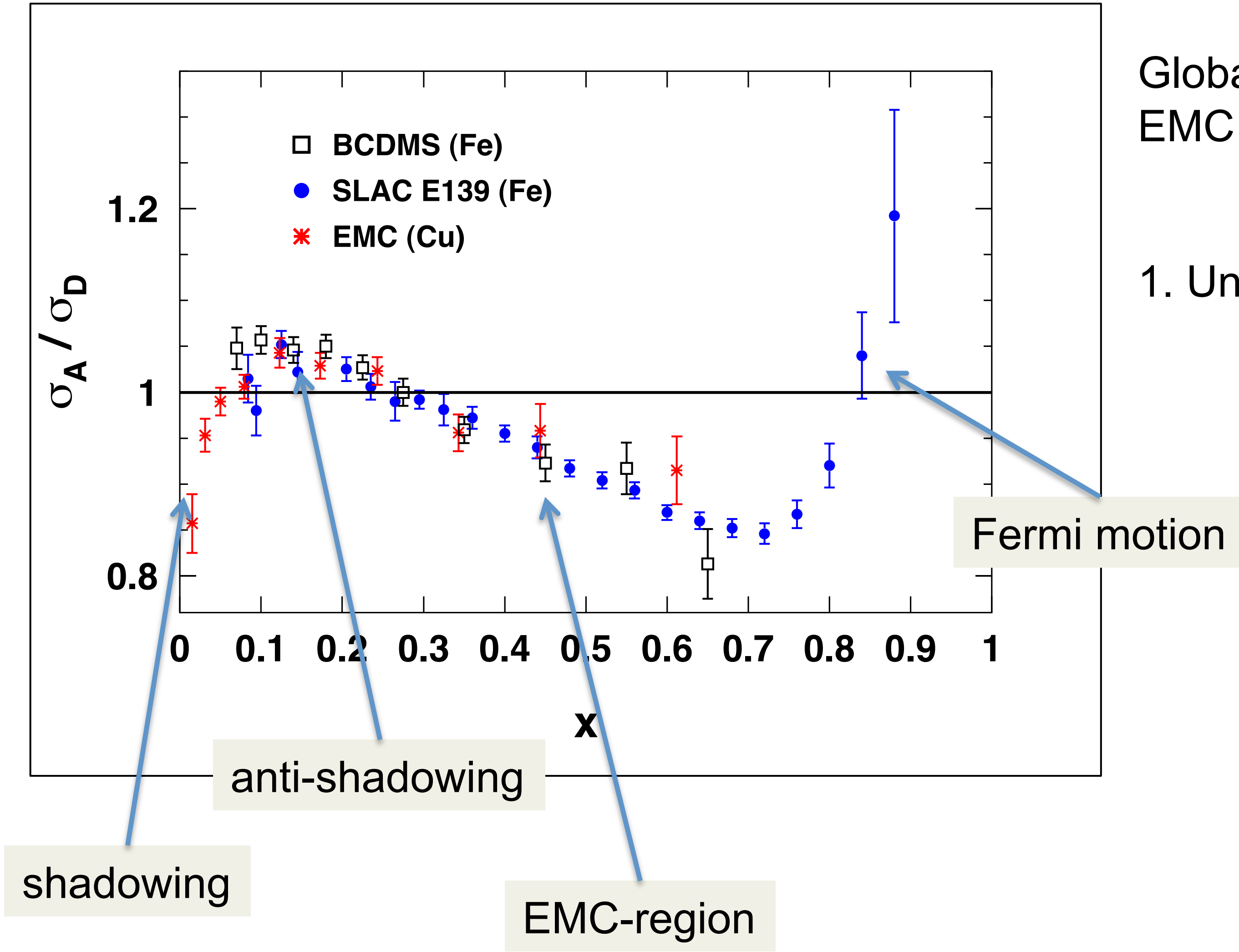
$$\frac{F_2^n}{F_2^p}$$

- SLAC param. *(1-0.8x)*
- CTEQ
- NMC fit

Isoscalar correction applied to data



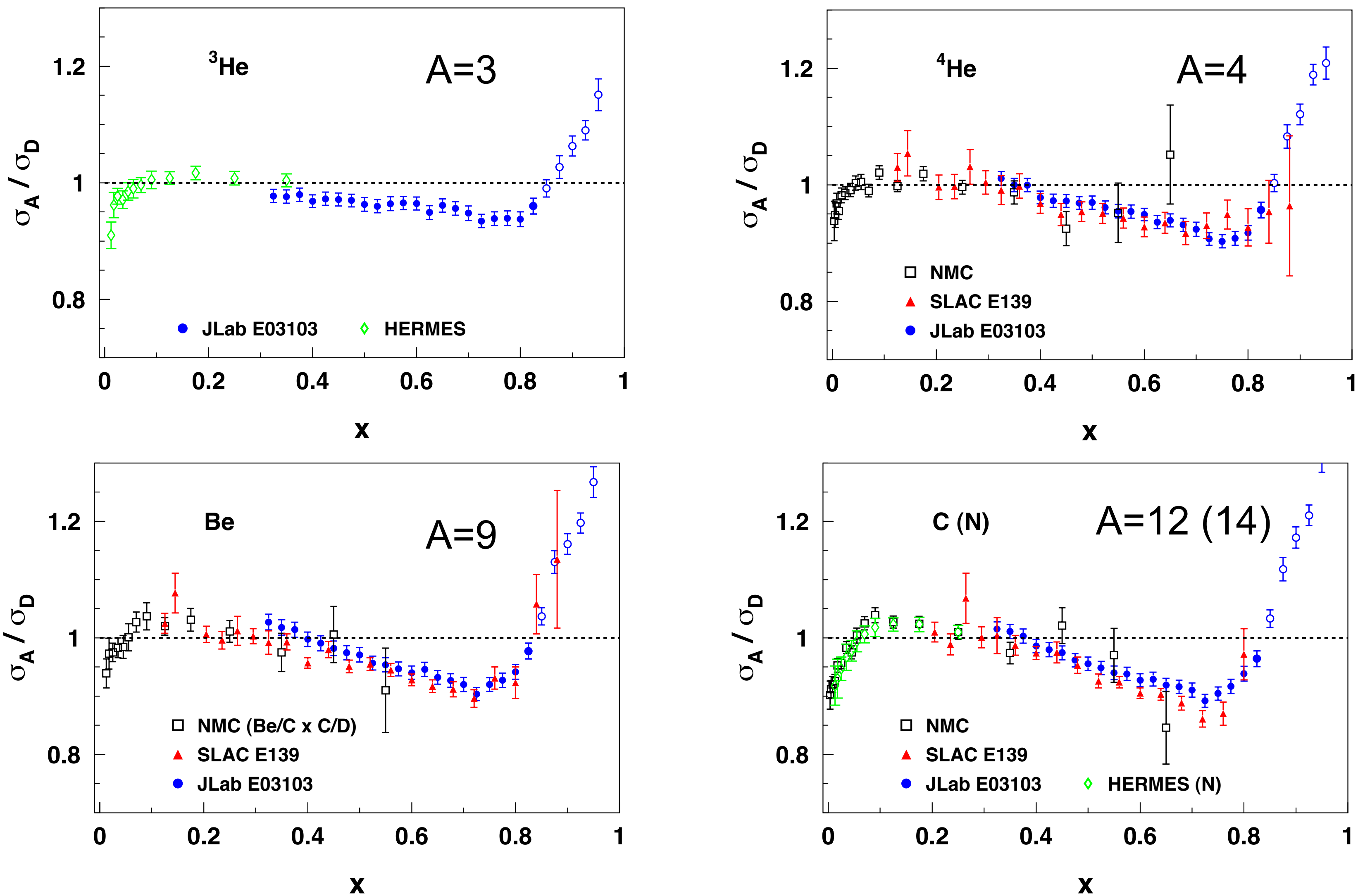
Properties of the EMC Effect



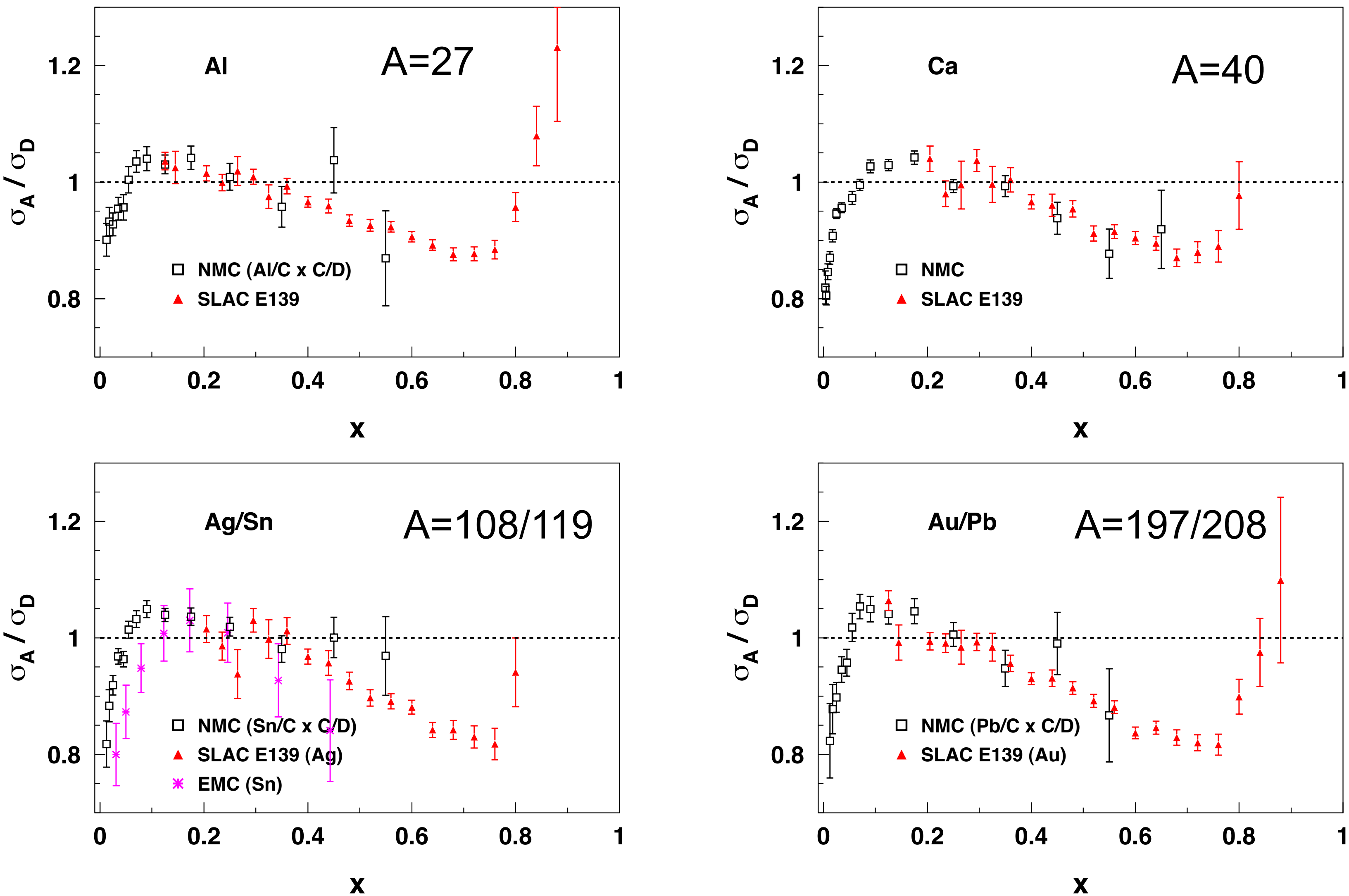
Global properties of the EMC effect

1. Universal x-dependence

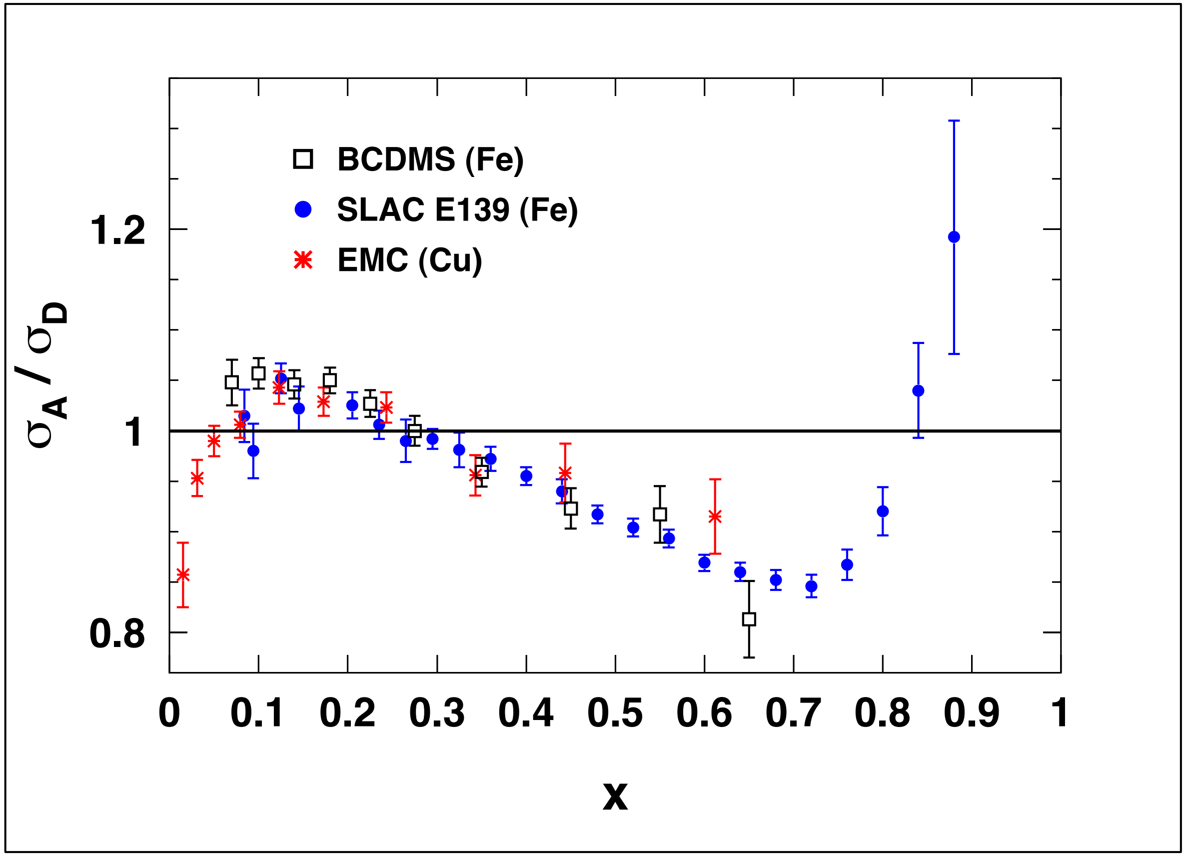
x Dependence



x Dependence



Properties of the EMC Effect



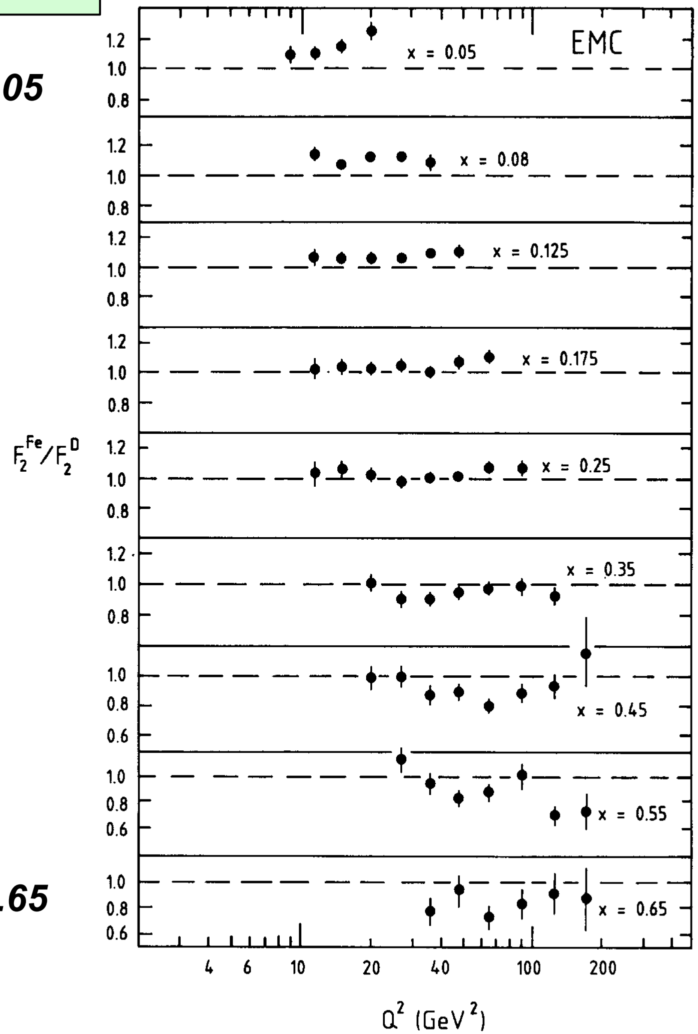
Global properties of the EMC effect

1. Universal x-dependence
2. Little Q^2 dependence*

Q^2 Dependence of the EMC Effect

EMC Q^2=10-200 GeV^2

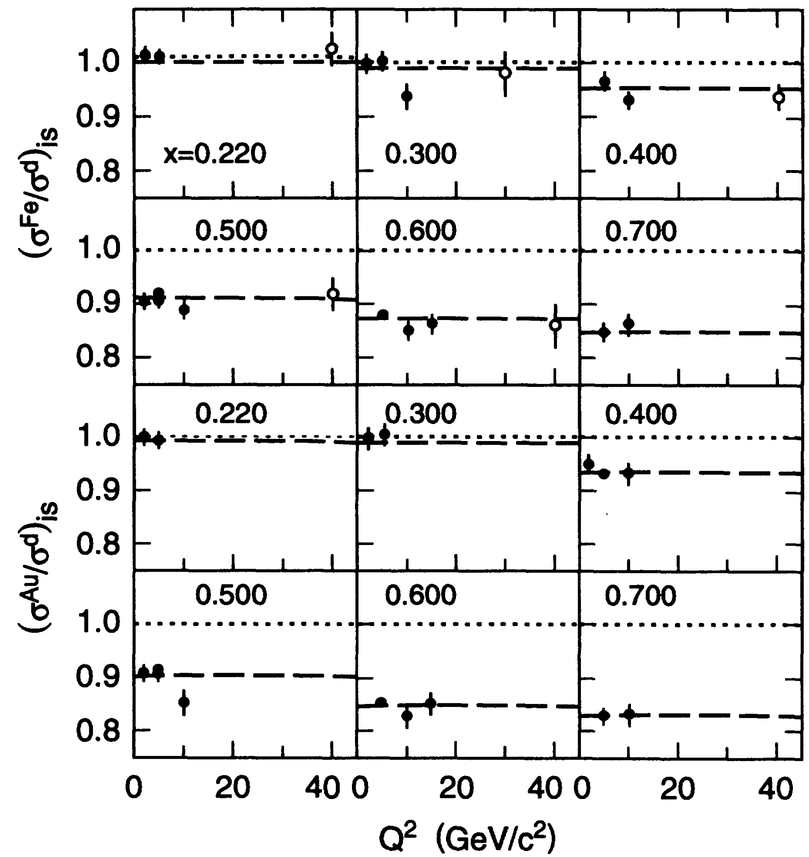
x=0.05



x=0.65

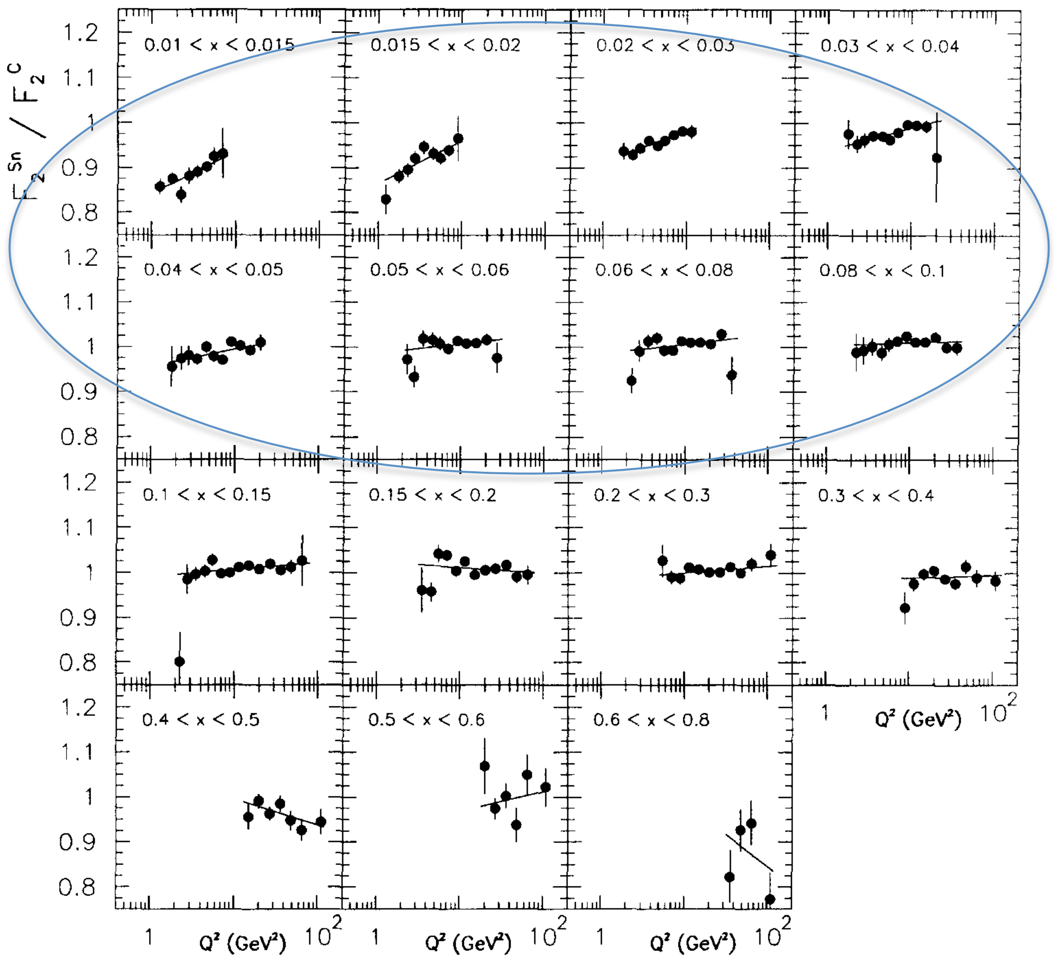
Aubert et al, Nucl. Phys. B293, 740 (1987)

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



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

(*) Q^2 Dependence of Sn/C

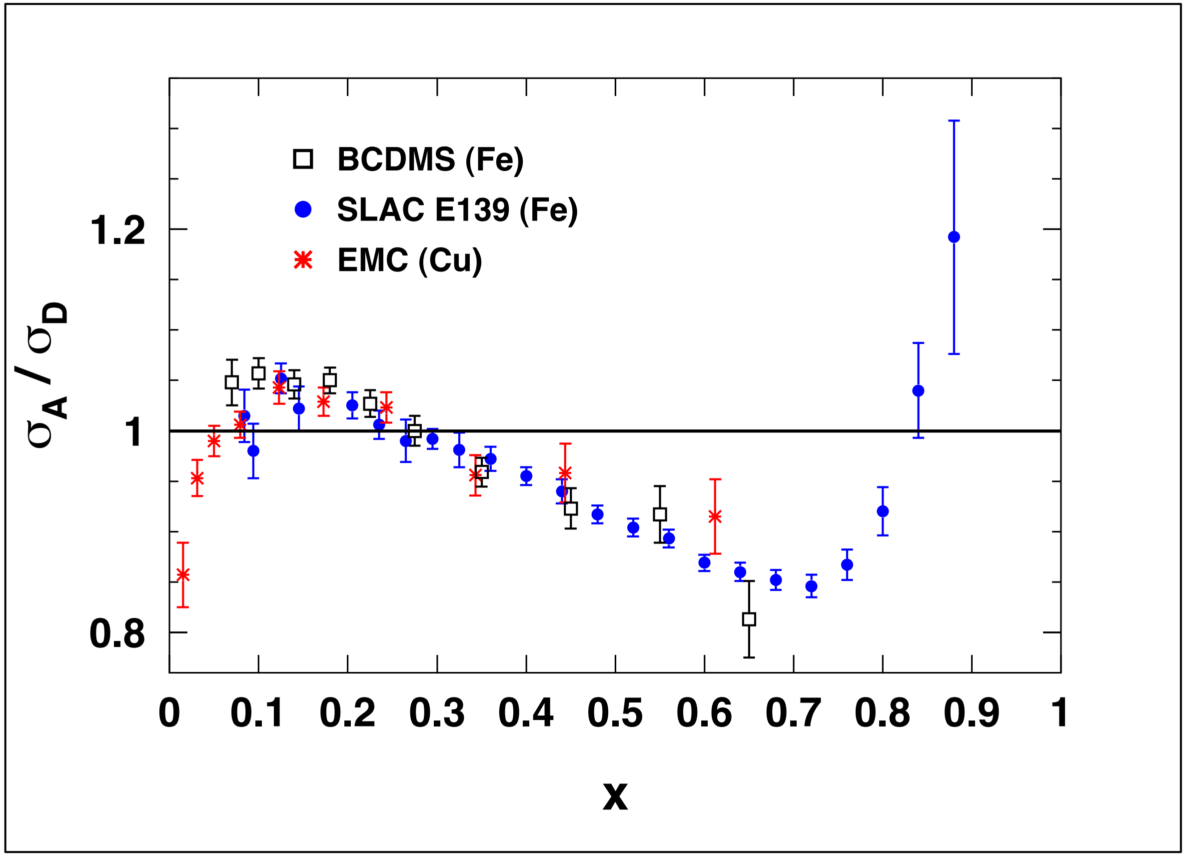


NMC measured non-zero Q^2 dependence in Sn/C ratio at low small x

→ This result is in some tension with other NMC C/D and HERMES Kr/D results

Arneodo et al, Nucl. Phys. B 481, 23 (1996)

Properties of the EMC Effect

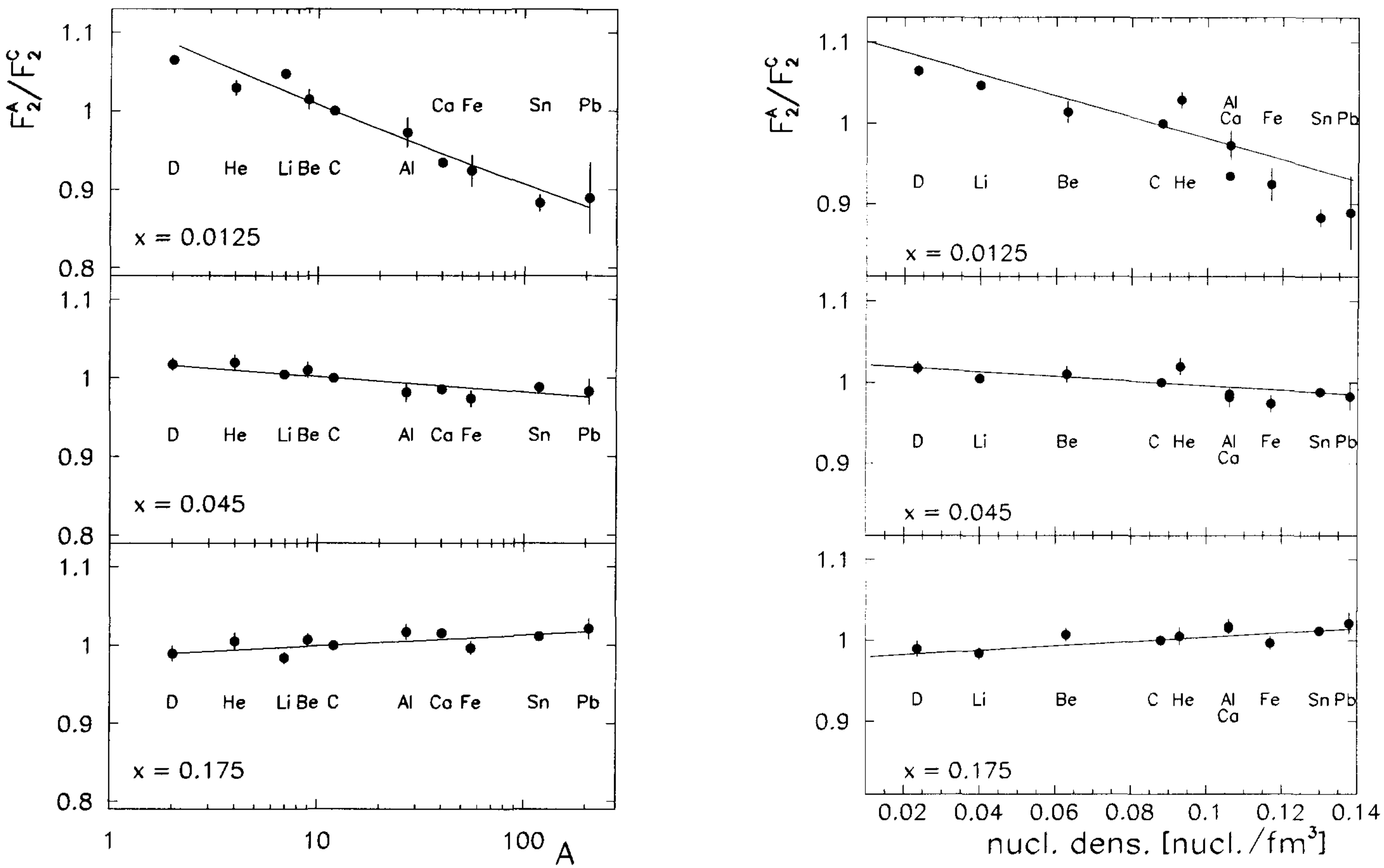


Global properties of the EMC effect

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

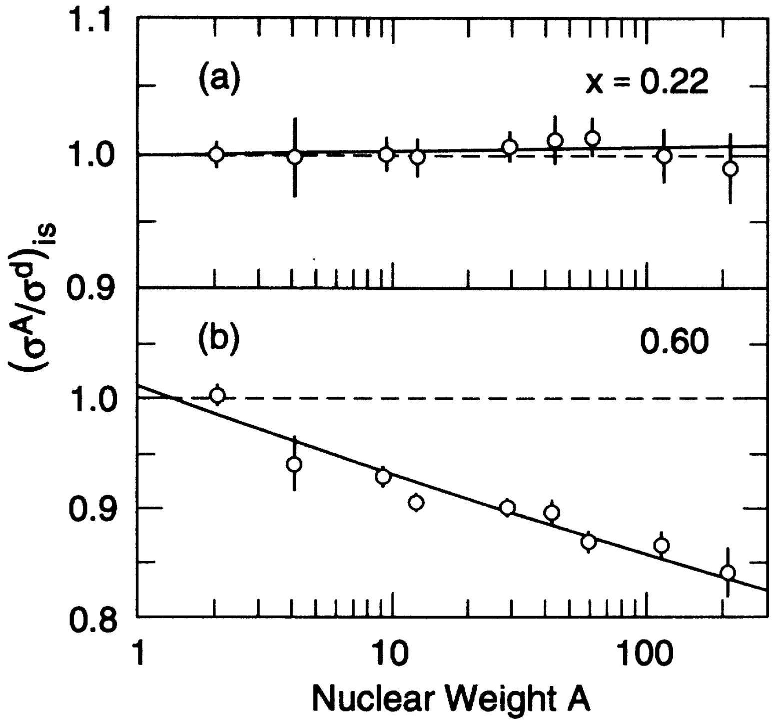
→ *Anti-shadowing region shows little nuclear dependence*

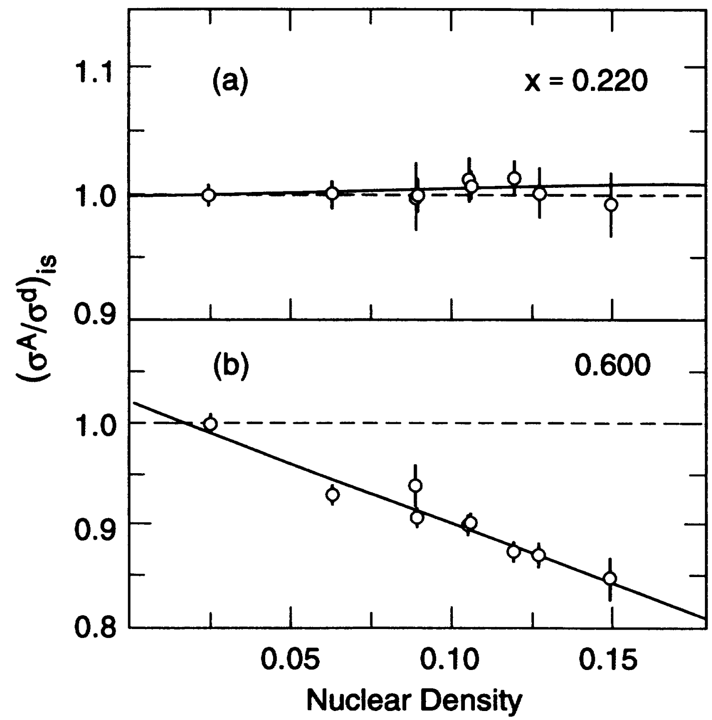
A-Dependence of EMC Effect



NMC: *Arneodo et al, Nucl. Phys. B 481, 3 (1996)*

A-Dependence of EMC Effect





$\rho = 3A/4\pi R_e^3$ $\quad R_e^2 = 5\langle r^2\rangle/3$

$<r^2>$=RMS electron scattering radius

SLAC E139: *Gomez et al, PRD 49, 4348 (1992)*

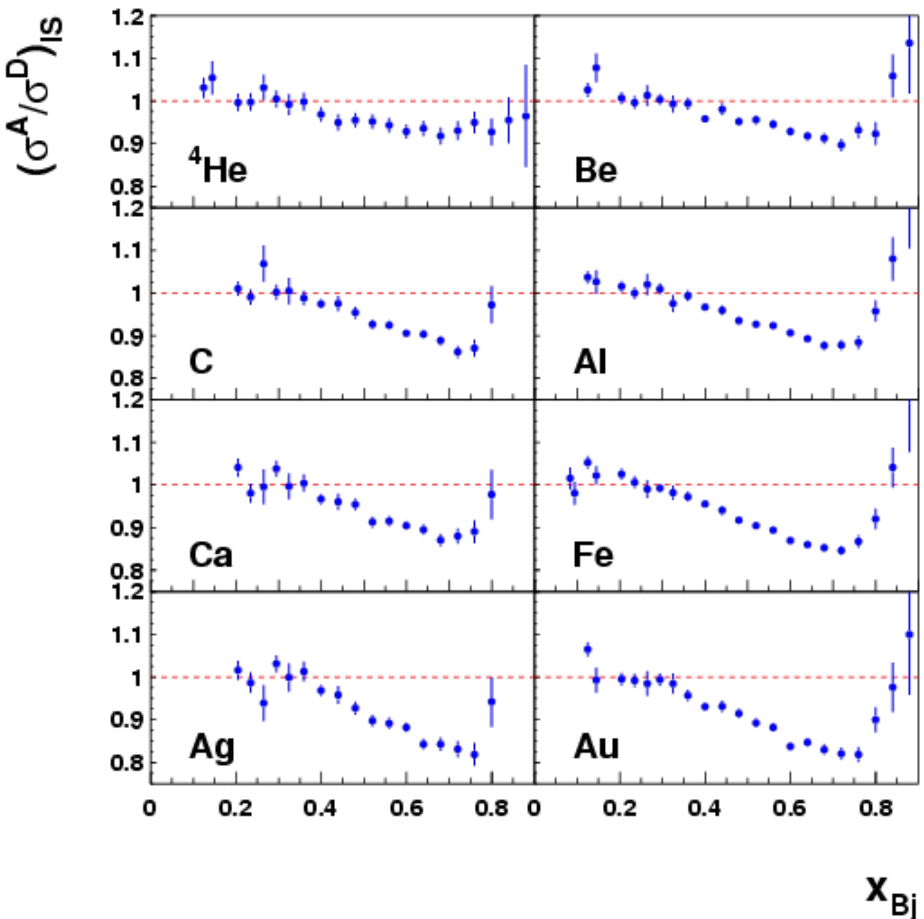
EMC Effect Measurements at Large x

SLAC E139 provided the most extensive and precise data set for *x*>*0.2*

Measured σ_A/σ_D for A=4 to 197
→ ^{4}He, ^{9}Be, C, ^{27}Al, ^{40}Ca, ^{56}Fe, ^{108}Ag, and ^{197}Au
→ Best determination of the *A* dependence
→ Verified that the *x* dependence was roughly constant

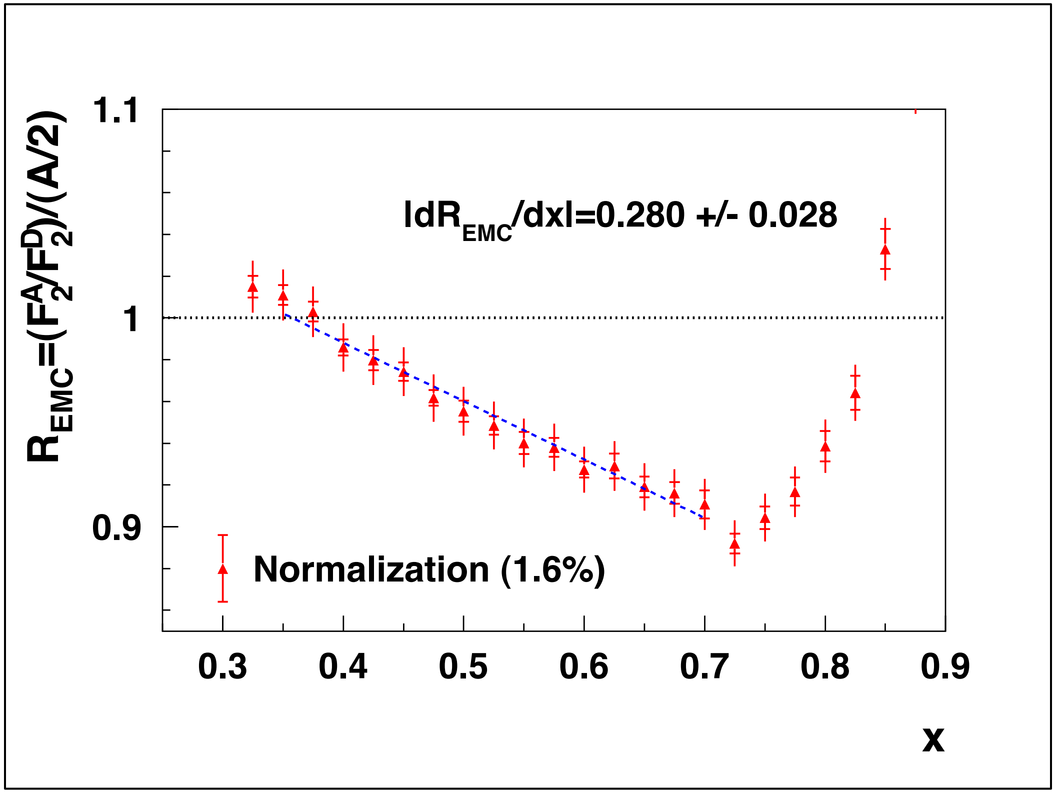
Building on the SLAC data
→ Higher precision data for ^{4}He
→ Addition of ^{3}He
→ Precision data at large *x*

SLAC E139



JLab E03103

E03103 in Hall C at Jefferson Lab ran Fall 2004
→ Measured EMC ratios for light nuclei (^{3}He, ^{4}He, Be, and C)
→ Results consistent with previous world data
→ Examined nuclear dependence a la E139



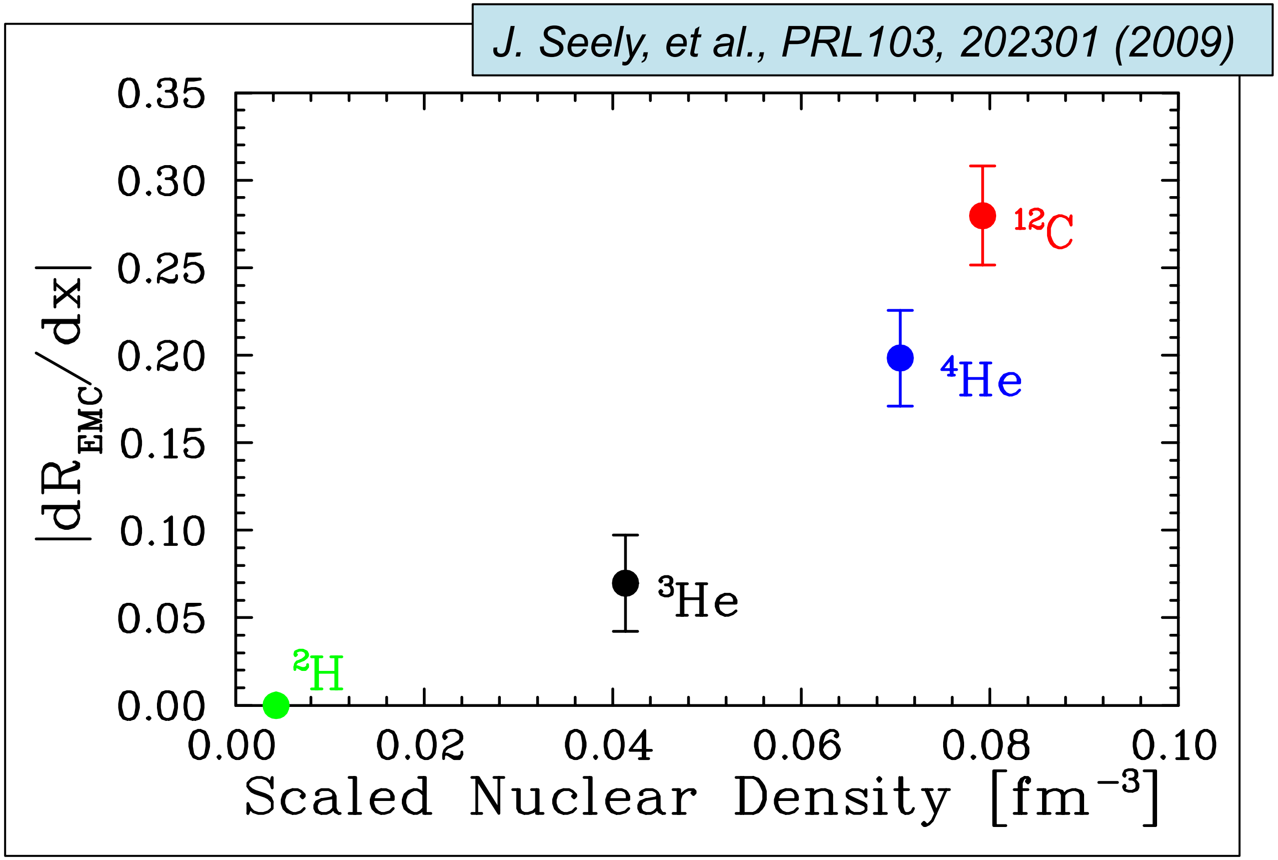
New definition of "size" of the EMC effect
→Slope of line fit from x=0.35 to 0.7

Definition assumes shape of the EMC effect is universal for nuclei
→Data *not inconsistent* with this assumption
→ Normalization errors mean we can only confirm this at 1-1.5% level

JLab E03103 Results

E03103 measured σ_A/σ_D for ^{3}He, ^{4}He, Be, C

→ ^{3}He, ^{4}He, C, EMC effect scales well with density



Scaled nuclear density = *(A-1)/A <ρ>*
→ remove contribution from struck nucleon

<ρ> from ab initio few-body calculations

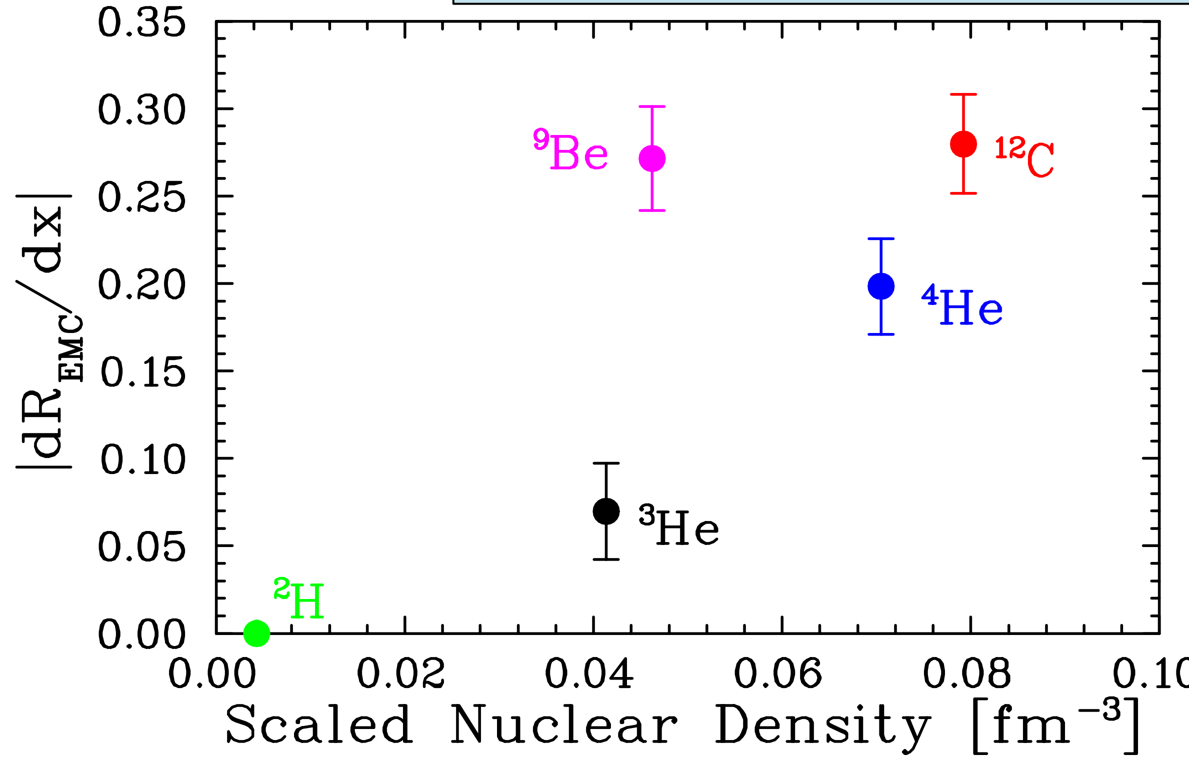
→ *[**S.C. Pieper and R.B. Wiringa**, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)]*

JLab E03103 Results

E03103 measured σ_A/σ_D for ^{3}He, ^{4}He, Be, C

→ ^{3}He, ^{4}He, C, EMC effect scales well with density
→ Be does not fit the trend

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



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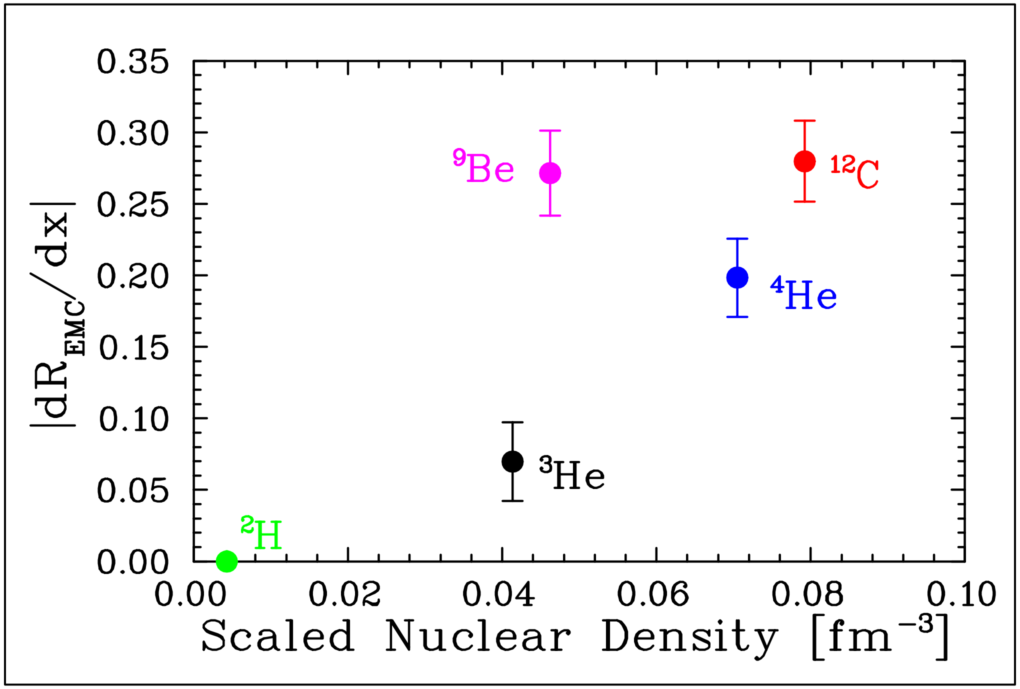
<ρ> from ab initio few-body calculations

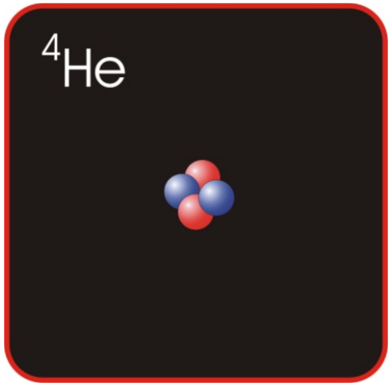
→ ***[S.C. Pieper and R.B. Wiringa**, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)]*

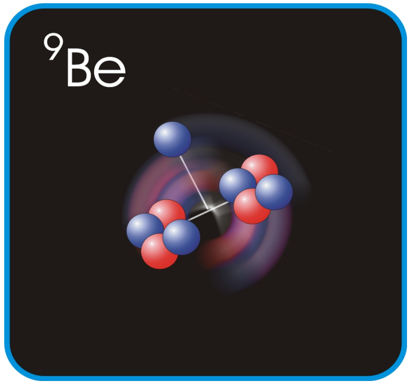
EMC Effect and Local Nuclear Density

^{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

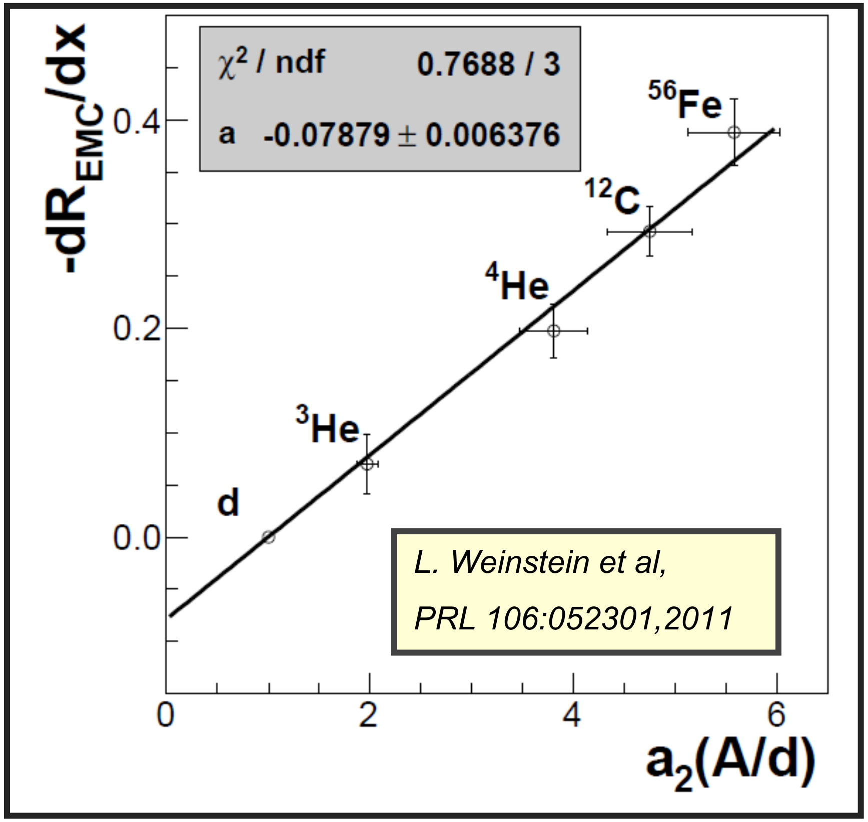






"Local density" is appealing in that it makes sense intuitively – can we make this more quantitative?

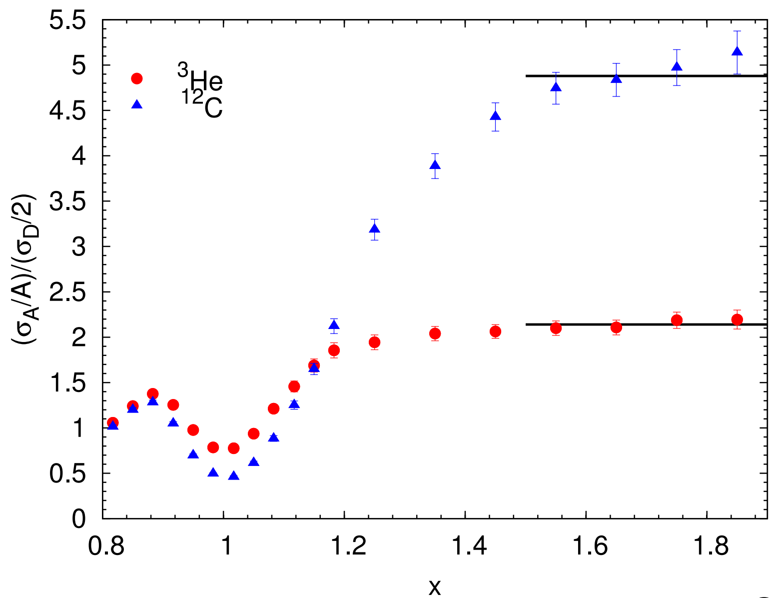
EMC Effect and Short Range Correlations



Weinstein et al observed linear correlation between size of EMC effect and Short Range Correlation "plateau"

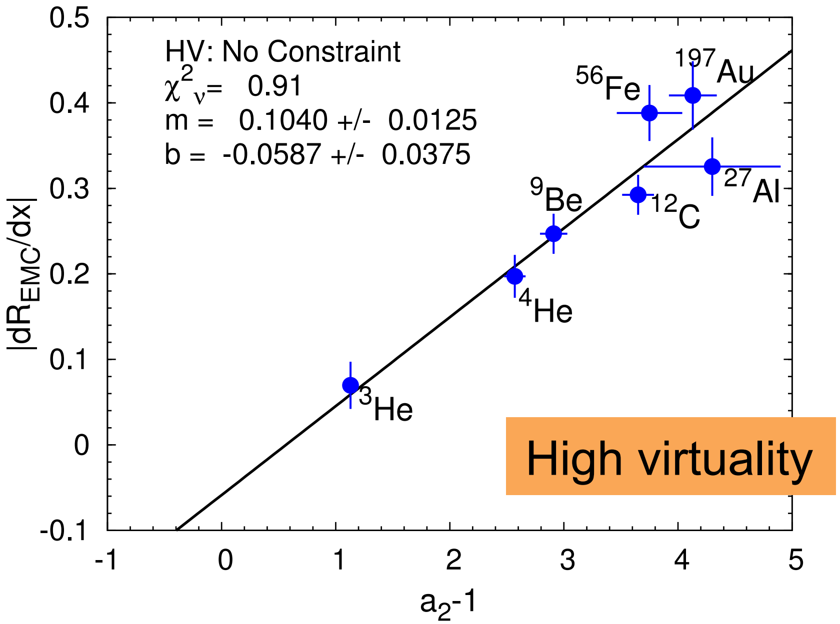
→Observing Short Range Correlations requires measurements at *x>1*
→ Reaction dynamics very different – DIS vs. QE scattering, why the same nuclear dependence?

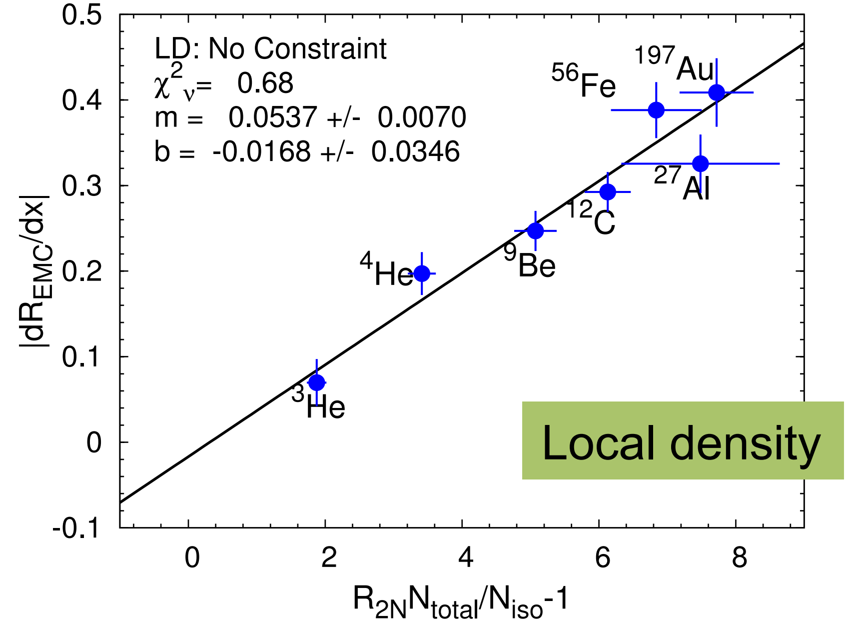
$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A)$$



Nuclear Dependence of EMC and SRCs

Arrington et al, PRC 86, 065204 (2012)





a_2 ~ number of high momentum nucleons

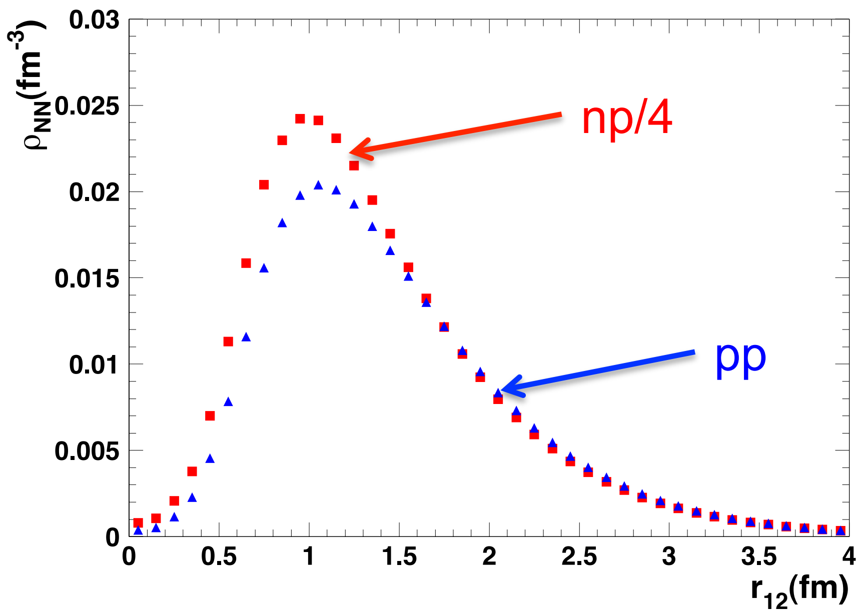
R_{2N} ~ number of nucleons "close" together

Detailed study of nuclear dependence of EMC effect and SRCs (see N. Fomin's talk from Monday) does not favor either picture

Can we distinguish between these two pictures via some new observable? → Flavor dependence of the EMC effect

Flavor dependence and SRCs

^{4}He 2-body density from



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

High momentum nucleons from SRCs emerge from tensor part of *NN* interaction <u>– *np* pairs dominate</u>

→ Probability to find 2 nucleons "close" together nearly the same for *np, nn, pp*

For $r_{12} < 1.7$ fm:

$$P_{pp} = P_{nn} \approx 0.8 P_{np}$$

If EMC effect due to ***high virtuality***, flavor dependence of EMC effect emerges naturally

→ If EMC effect from ***local density***, *np/pp/nn* pairs all contribute (roughly) equally

Flavor dependence and SRCs

High momentum nucleons in the nucleus come primarily from *np* pairs

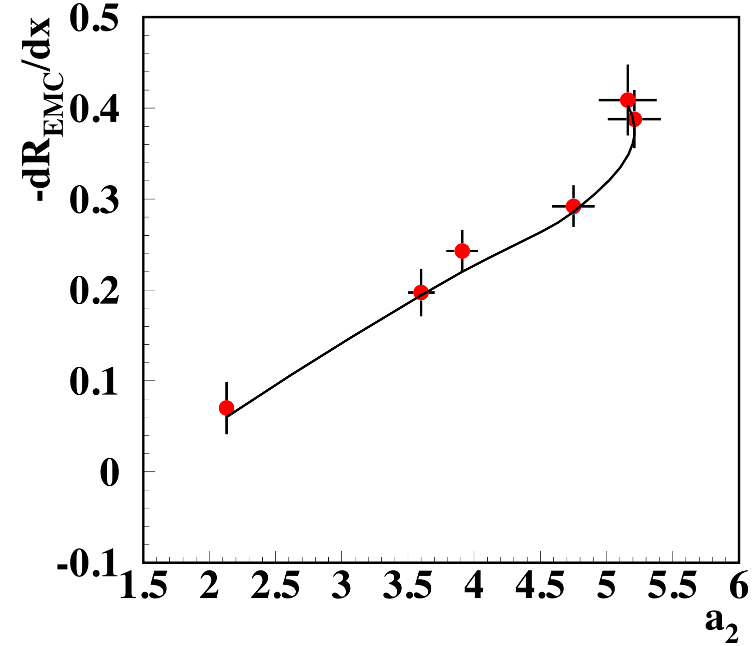
→The relative probability to find a high momentum proton is larger than for neutron for *N>Z* nuclei

$$n_p^A(p) \approx \frac{1}{2x_p} a_2(A,y) n_d(p) \qquad x_p = \frac{Z}{A}$$

$$n_n^A(p) \approx \frac{1}{2x_n} a_2(A,y) n_d(p) \qquad x_n = \frac{A-Z}{A}$$

Probability to find SRC

$$u_A = \frac{Z\tilde{u}_p + N\tilde{d}_p}{A} \qquad d_A = \frac{Z\tilde{d}_p + N\tilde{u}_p}{A}$$

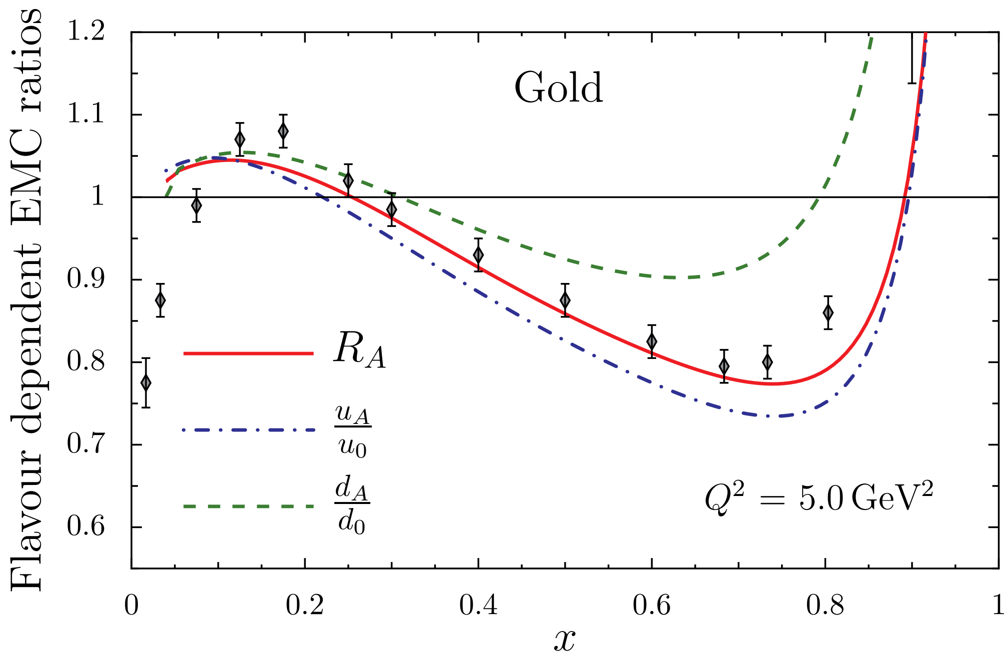


Under the assumption the EMC effect comes from "high virtuality" (high momentum nucleons), effect driven by protons (u-quark dominates) → similar flavor dependence is seen in some "mean-field" approaches

M. Sargsian, arXiv:1209.2477 [nucl-th] and arXiv:1210.3280 [nucl-th]

Flavor Dependence of the EMC Effect

Mean-field calculations predict a flavor dependent EMC effect for *N≠Z* nuclei



Cloët, Bentz, and Thomas, PRL 102, 252301 (2009)

Medium modified quark distributions

$$u_A = \frac{Z\tilde{u}_p + N\tilde{d}_p}{A} \qquad d_A = \frac{Z\tilde{d}_p + N\tilde{u}_p}{A}$$

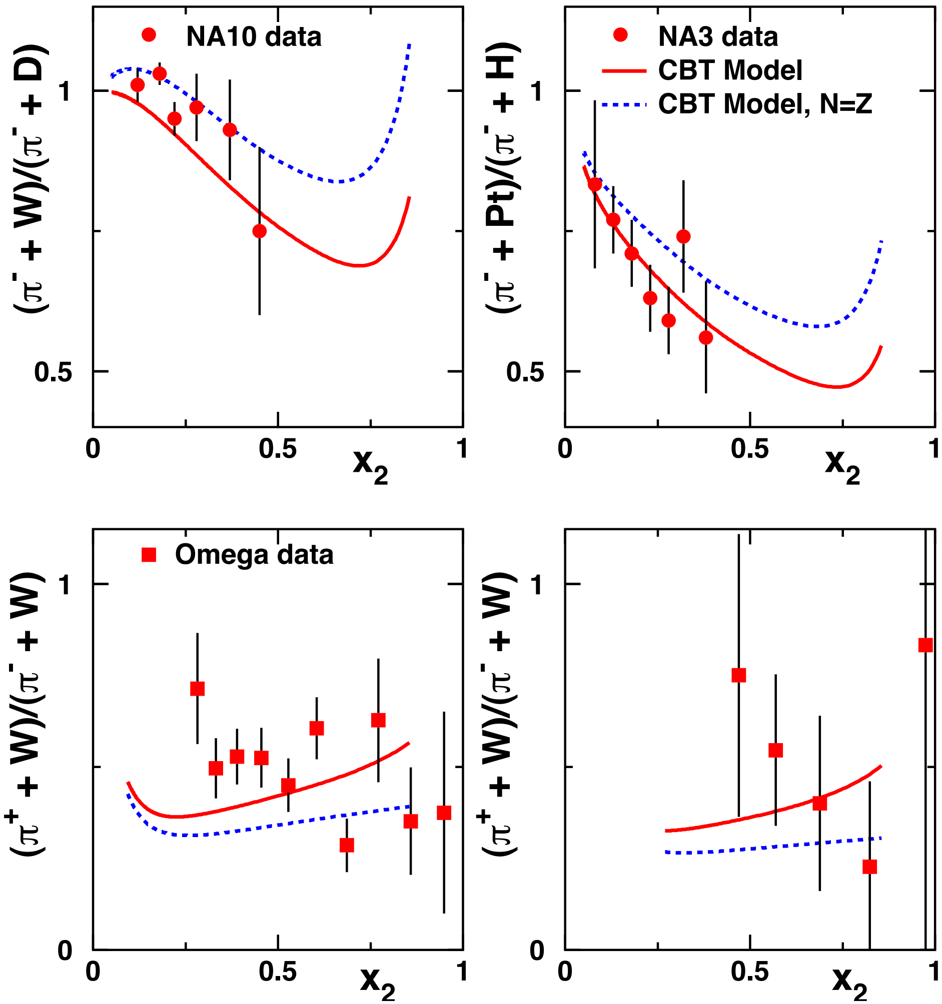
Free nucleon quark distributions

$$u_0 = \frac{Zu_p + Nd_p}{A} \qquad d_0 = \frac{Zd_p + Nu_p}{A}$$

Isovector-vector mean field (ρ) causes u (d) quark to feel additional vector attraction (repulsion) in *N≠Z* nuclei

Experimentally, this flavor dependence has not been observed directly

EMC Flavor Dependence: Pion Drell-Yan



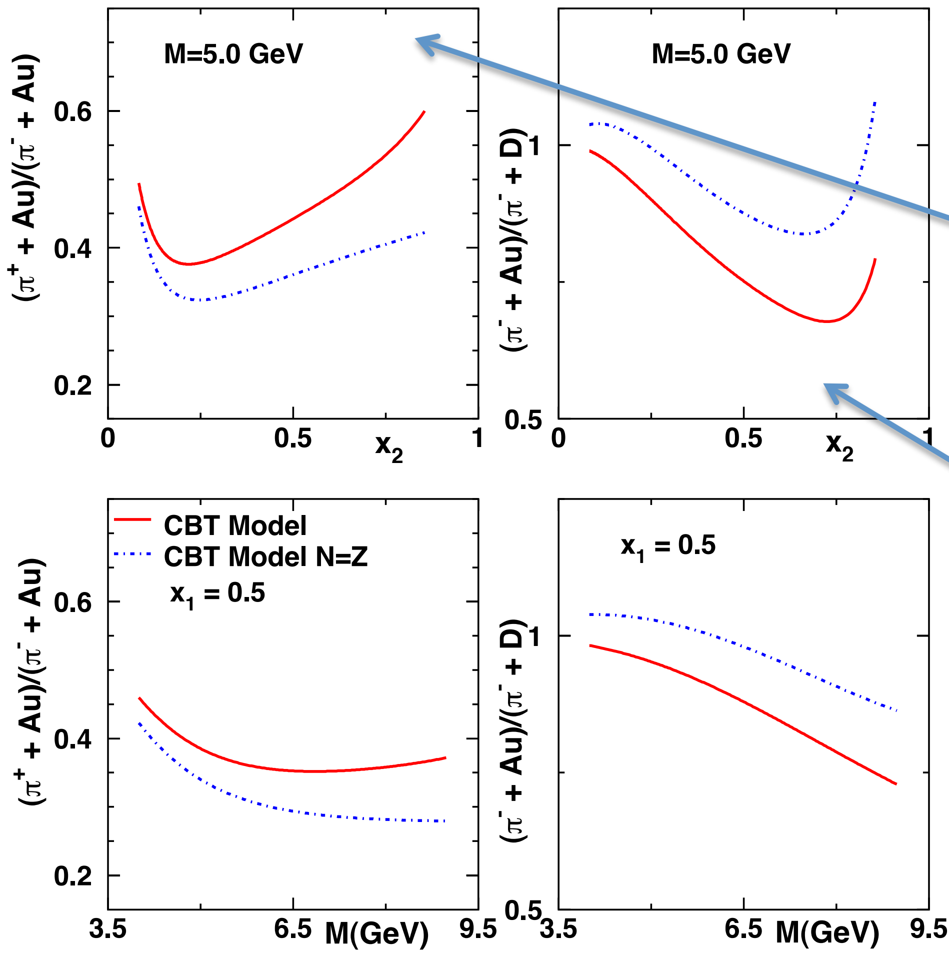
Experiment	Flavor Ind.	Flavor dep.
NA3	1.3	0.5
NA10	0.60	2.5
Omega (low Q^2)	6.2	3.2
Omega (high Q^2)	1.4	0.96

χ^2/DOF

Pion-induced Drell-Yan sensitive to potential flavor dependence, but existing data lack precision

Dutta, Peng, Cloët, DG, PRC 83, 042201 (2011)

Pion Drell-Yan at COMPASS



160 GeV pions on gold

$$\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)}$$

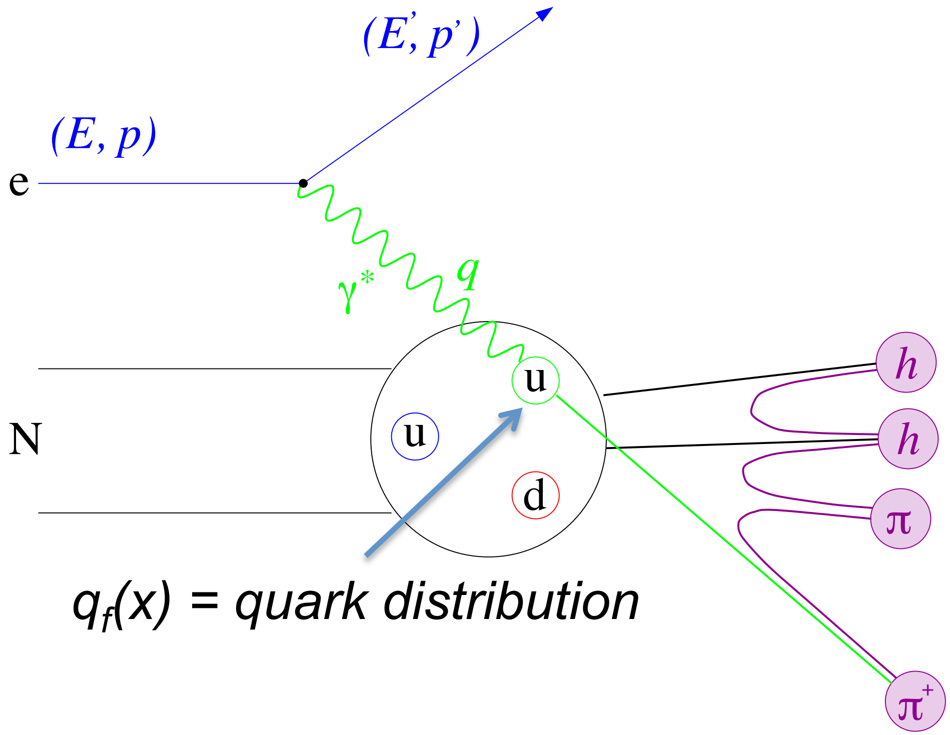
$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$

Dutta et al, PRC 83, 042201 (2011)

First measurements on NH3 (and nuclear targets) planned for 2014

$$\frac{d\sigma_{\pi^\pm A}}{dx_\pi dx_2} = \frac{4\pi\alpha^2}{9sx_\pi x_2} \sum_q e_q^2 [q_{\pi^\pm}(x_\pi)\bar{q}_A(x_2) + \bar{q}_{\pi^\pm}(x_\pi) q_A(x_2)]$$

Semi-Inclusive DIS



$q_f(x)$ = *quark distribution*

Assuming factorization holds, SIDIS acts as a "flavor tag" for struck quark
→ Similar to polarized quark distribution extractions

$D_f^h(z)$ – fragmentation function quark of flavor *f* → hadron *h*

$$\frac{d\sigma}{dx\,dQ^2\,dz} = \frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)} \left(\frac{d\sigma}{dx\,dQ^2}\right)$$

x = fraction of proton momentum carried by quark
$z = E_{hadron}/\nu$

Semi-Inclusive DIS

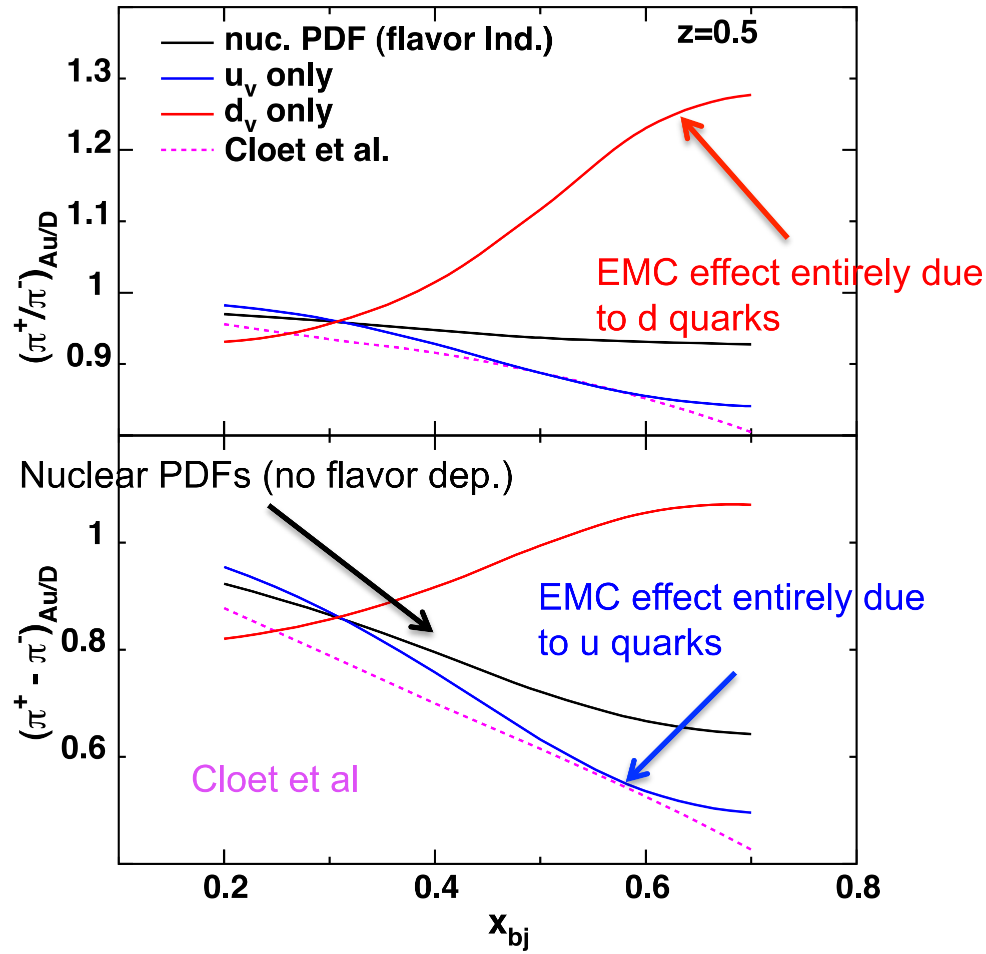
Extract flavor dependence via semi-inclusive pion yields from gold and deuterium

Super-ratio

$$\frac{Y_{Au}^{\pi^+}/Y_{Au}^{\pi^-}}{Y_D^{\pi^+}/Y_D^{\pi^-}}$$

Difference ratio

$$\frac{Y_{Au}^{\pi^+} - Y_{Au}^{\pi^-}}{Y_D^{\pi^+} - Y_D^{\pi^-}}$$



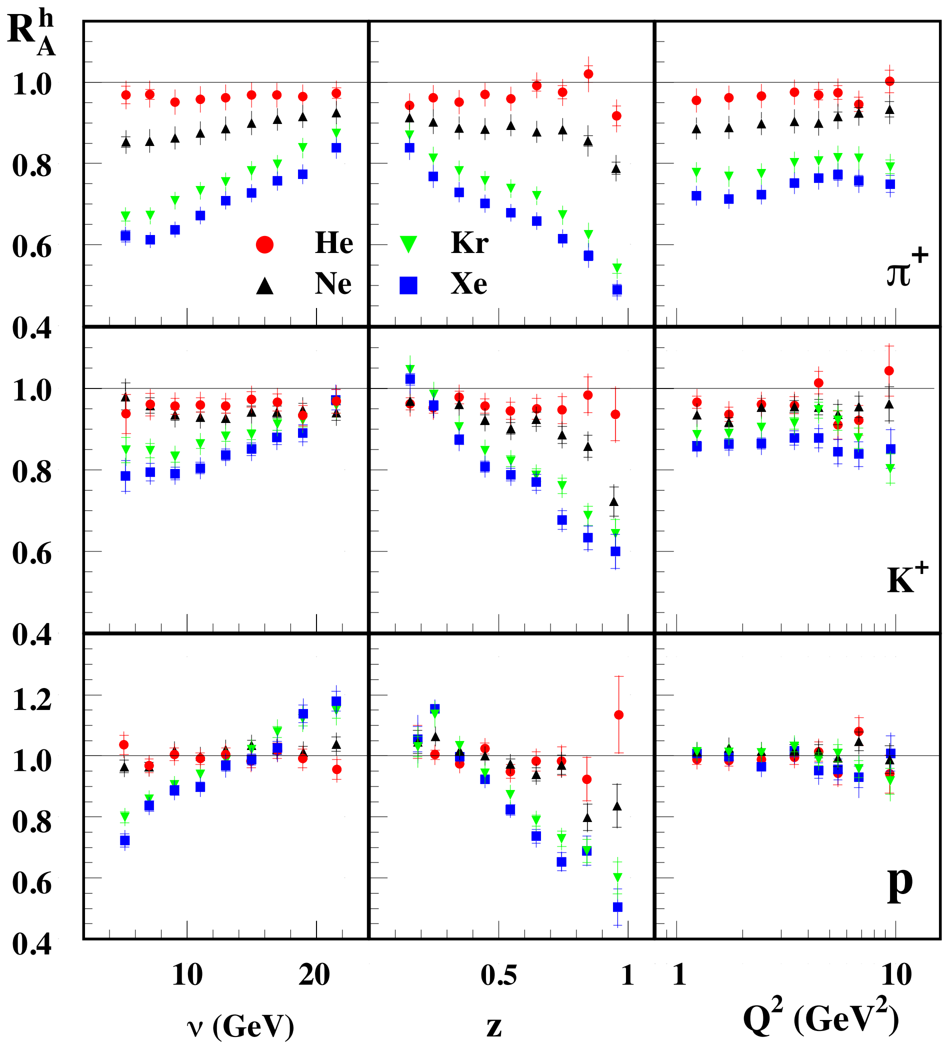
Toy model:

u_V only: EMC effect due to modification of u_A only

d_V only: EMC effect due to modification of d_A only

F_2^A unchanged

SIDIS - Interpretability



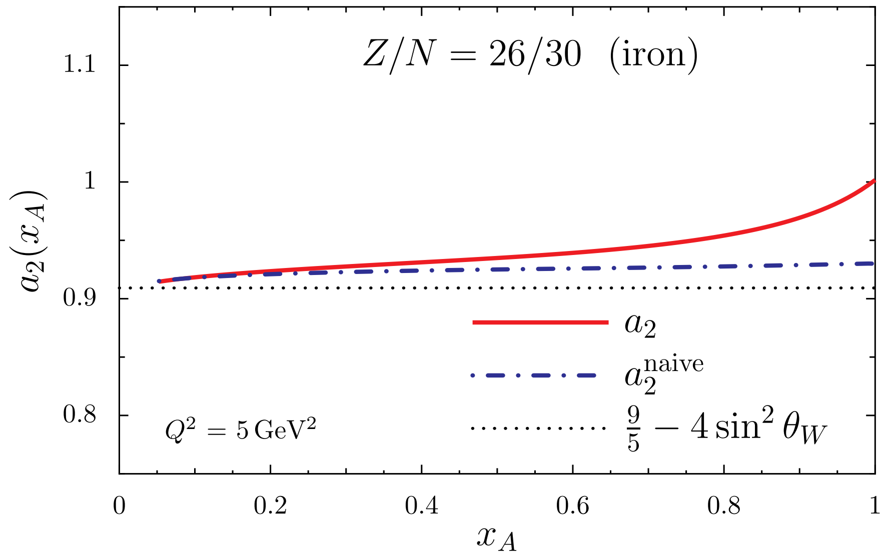
$$R_h^A(z,\nu) = \frac{\left(\frac{1}{\sigma_e}\frac{d\sigma}{dz d\nu}\right)_A}{\left(\frac{1}{\sigma_e}\frac{d\sigma}{dz d\nu}\right)_D}$$

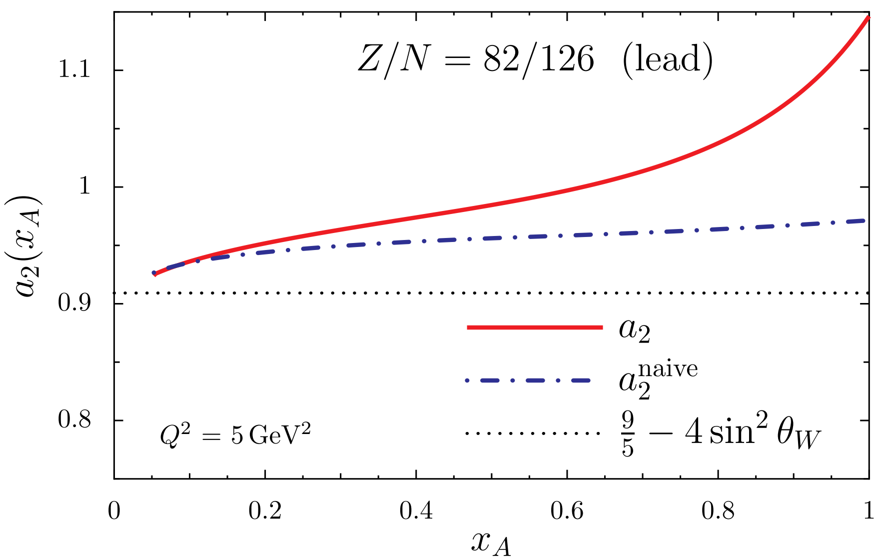
Hadronization is modified in the nuclear medium
→ Probability for quark *f* to form hadron *h* changes
→ Depends on *A*, hadron kinematics

Complicates interpretation of SIDIS measurements of flavor dependence if effect different for π^+ and π^-

→ This can be checked with measurements at *x=0.3* (no EMC effect)

Parity Violating DIS





Flavor dependence of EMC effect can also be explored via parity violating DIS

$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{em}}\left[a_2(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right]$$

suppressed

quark weak vector couplings

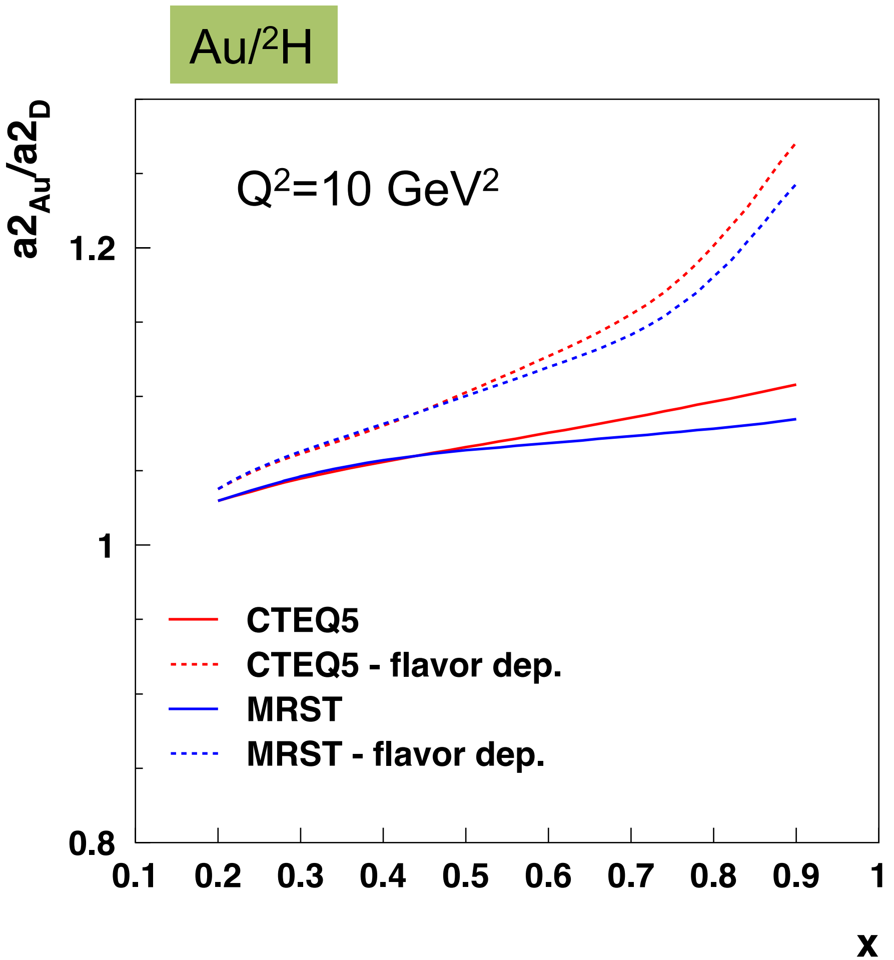
$$a_2(x) = \frac{2\sum_q e_q g_V^q\left[q_A(x) + \bar{q}_A(x)\right]}{\sum_q e_q^2\left[q_A(x) + \bar{q}_A(x)\right]}$$

Avoids complications due to hadronization issues

CBT model predicts 5% effect at x=0.6

Cloët, Bentz, and Thomas, PRL 109, 182301 (2012)

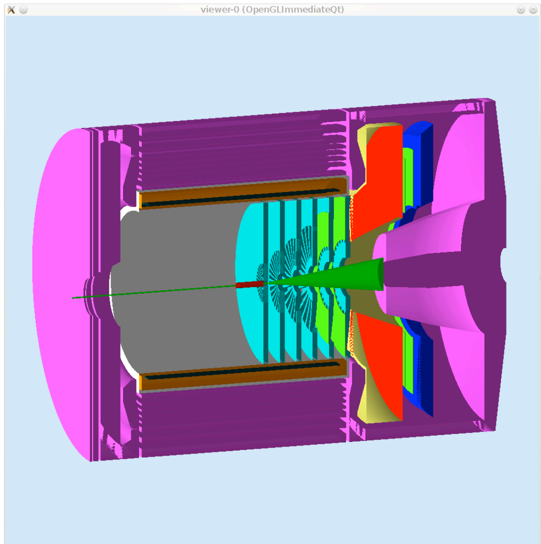
Measuring Flavor Dependence with PVDIS



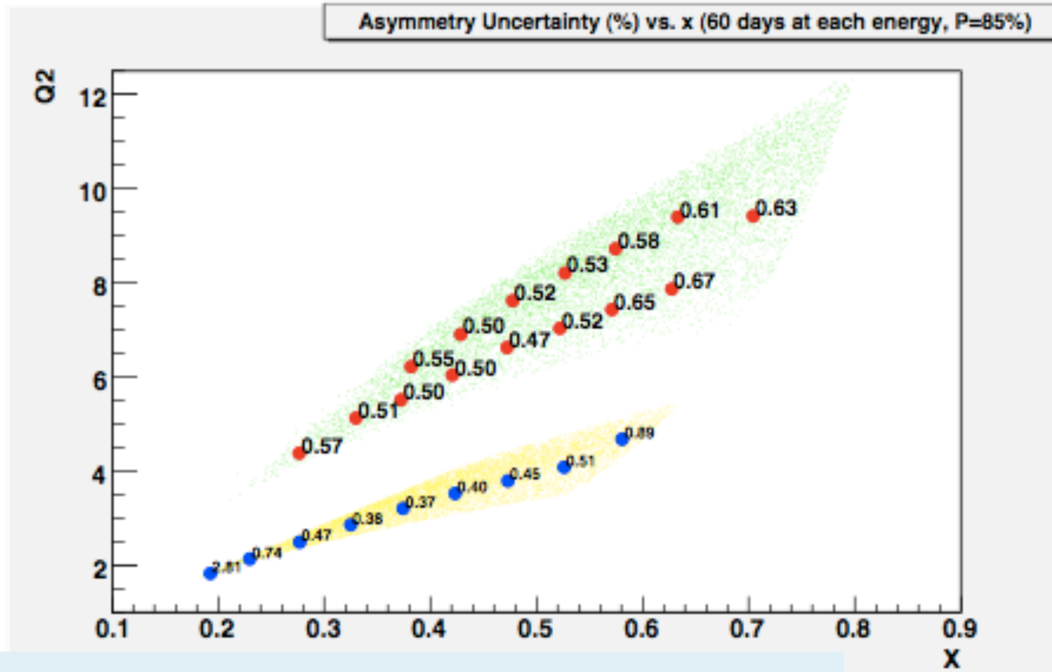
Experimentally – simpler to measure super-ratio
→Certain systematics are reduced (beam polarization)
→Less sensitivity to absolute value of weak vector couplings

Note that even the "no flavor dependence" calculation not identically 1.0
→ Must compare experimental result to the "naïve" estimate
→ Naïve estimate has some dependence on nucleon PDFs
→ May be non-negligible contribution to uncertainty

PVDIS at JLab



New solenoidal spectrometer



Proposed kinematic coverage and statistical precisions

SOLID experiment at JLab (P. Souder, spokesperson) – use PVDIS to look for physics beyond Standard Model, *d/u* at large *x*

→awarded 169 days for H and D running

→no time for solid target running (flavor dependent EMC) requested yet

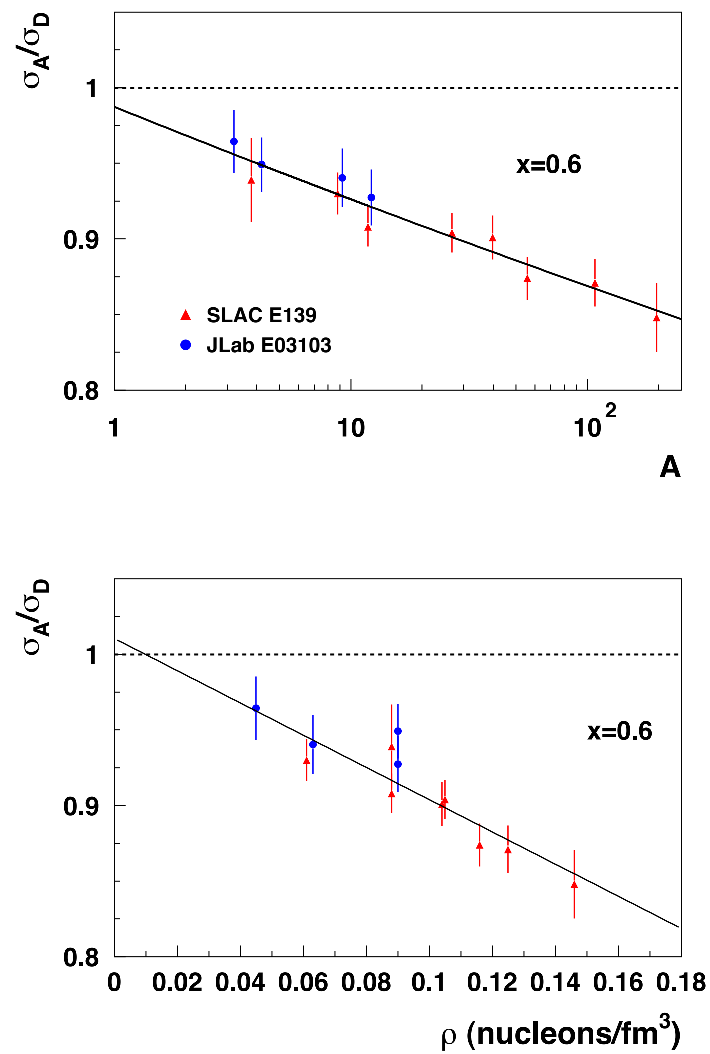
Flavor Dependence with inclusive DIS

Several alternatives for accessing flavor dependence of EMC effect

→Pion DY @ COMPASS: sufficient statistical precision at large x?
→SIDIS @ JLab: hadron attenuation and factorization concerns
→PVDIS @ JLab: SOLID experiment requires significant $, long time scale

Would like something "easy" that can be done on a short time scale

Inclusive DIS on nucleus with same *A* and ρ but different ratio *N/Z*



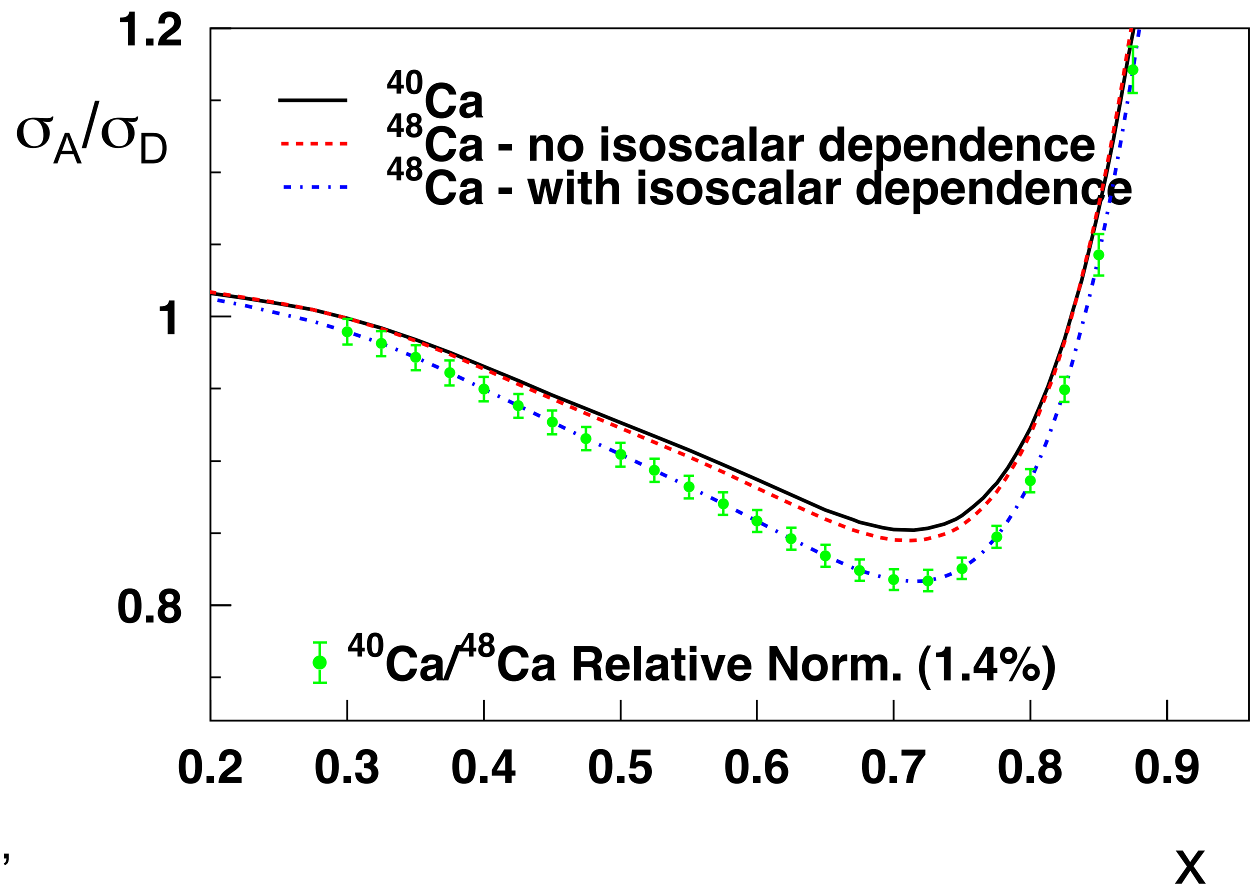
Flavor dependence from ^{40}Ca and ^{48}Ca

CBT model predicts a ~3% effect for ^{48}Ca at *x=0.6*
→*N/Z = 1.4*

Assuming no flavor dependence, difference between ^{40}Ca and ^{48}Ca should be less than < 1%

Will be measured at JLab @ 12 GeV

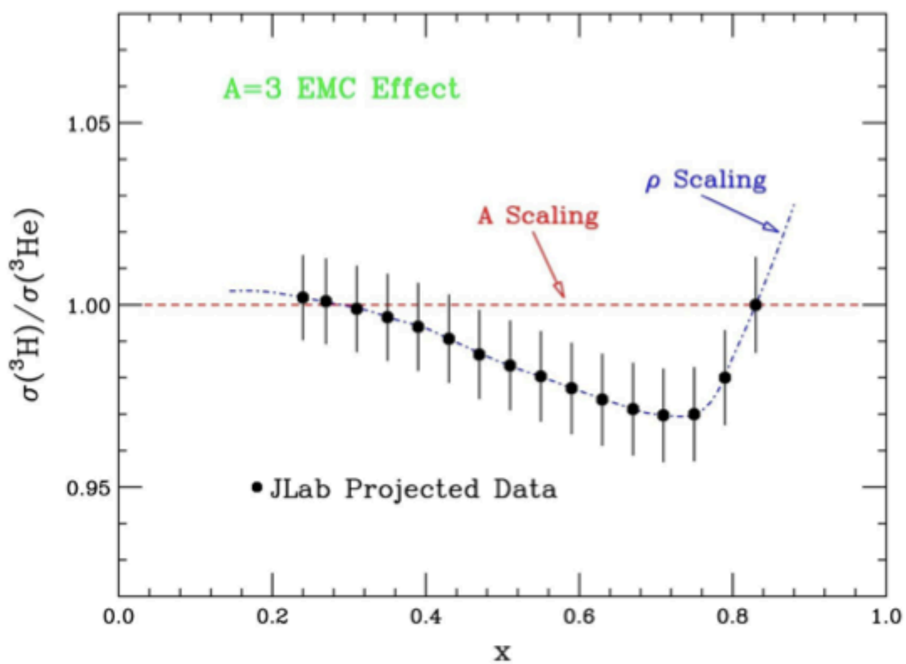
E12-10-008
Spokespersons: Arrington, Gaskell, Daniel

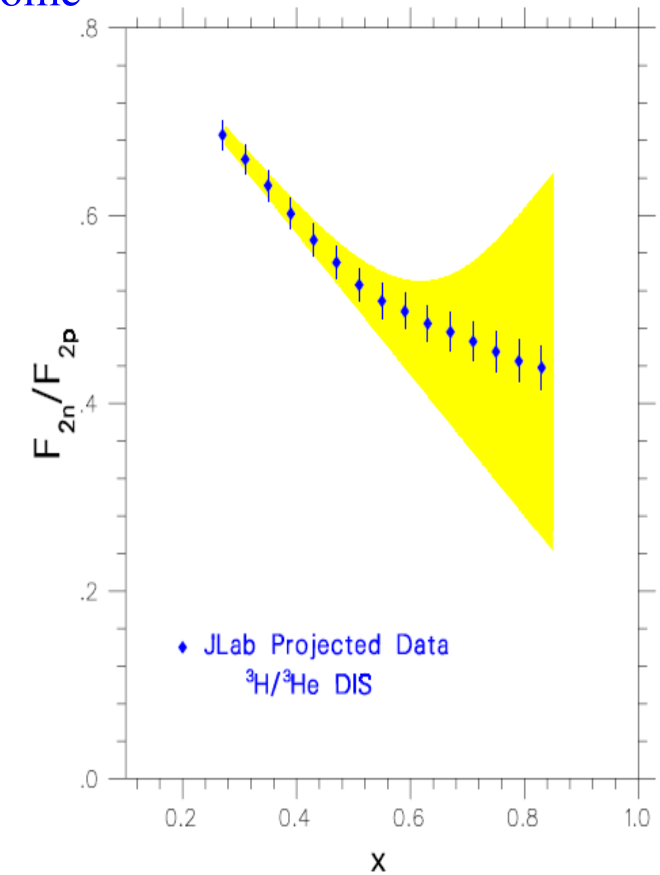


E12-06-118: The MARATHON experiment

Spokespeople: G. Petratos, J. Gomez, R. Holt, R. Ransome

EMC effect with A=3 mirror nuclei



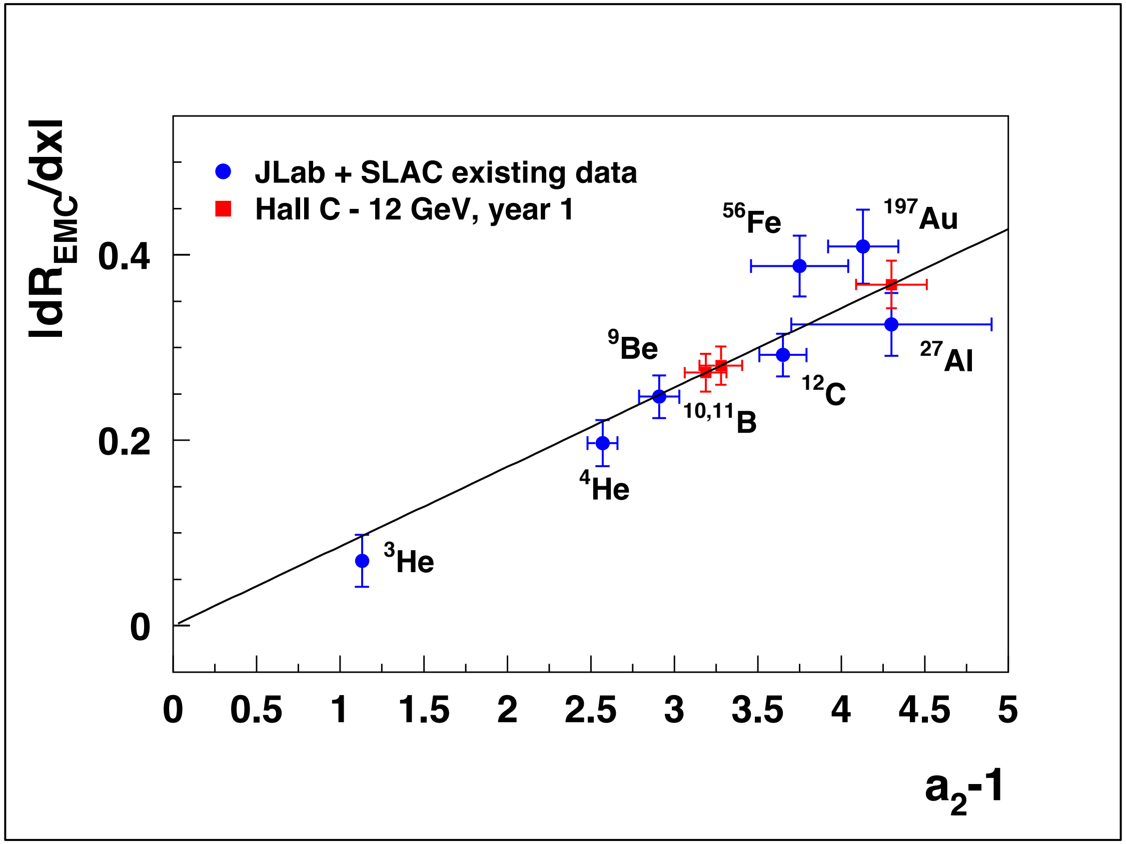


→ "Free" n/p (d/u) ratios extracted using "known" corrections to difference in EMC effect in ^{3}He/^{3}H; additional flavor dependence could impact extraction

E12-10-008 and E12-06-105

Hall C experiments will provide more inclusive data
→E12-06-105 *x>1*
→E12-10-008 *EMC Effect*

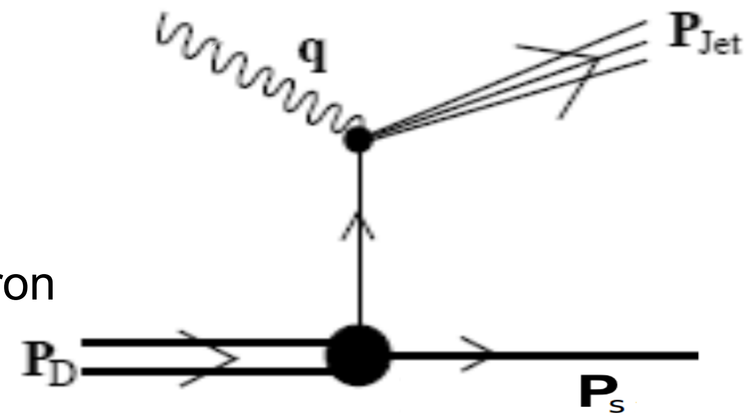
Will provide additional data on light and medium-heavy targets
→^{2}H, ^{3}He, ^{4}He
→^{6}Li, ^{7}Li, Be, ^{10}B,^{11}B, C
→Al, ^{40}Ca, ^{48}Ca, Cu

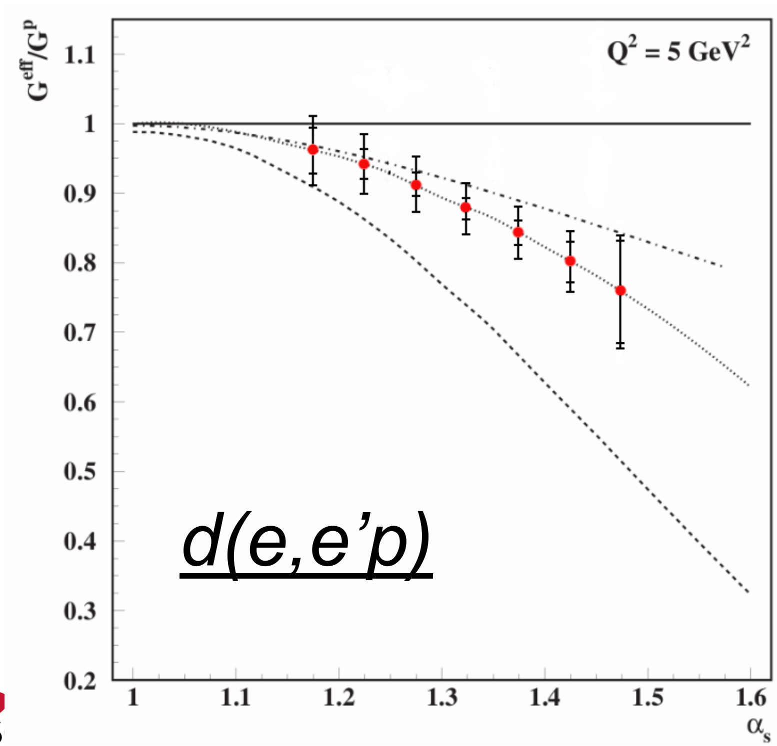


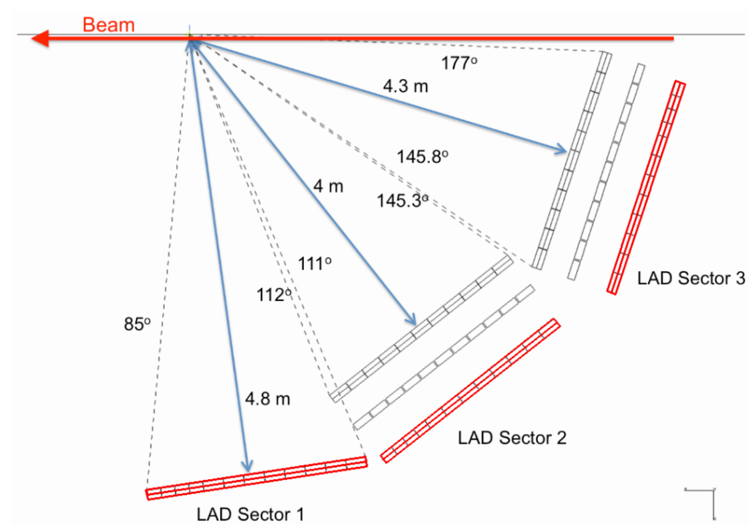
First running in Hall C after completion of 12 GeV Upgrade will include a few days for EMC/x>1 measurements on ^{10}B, ^{11}B, and Al (parasitic)

E12-11-107: In-Medium Structure Functions

Measure structure function of high momentum nucleon in deuterium by tagging the spectator
→Final state interactions cancelled by taking double ratios
→Requires new, large acceptance proton/neutron detector at back angles







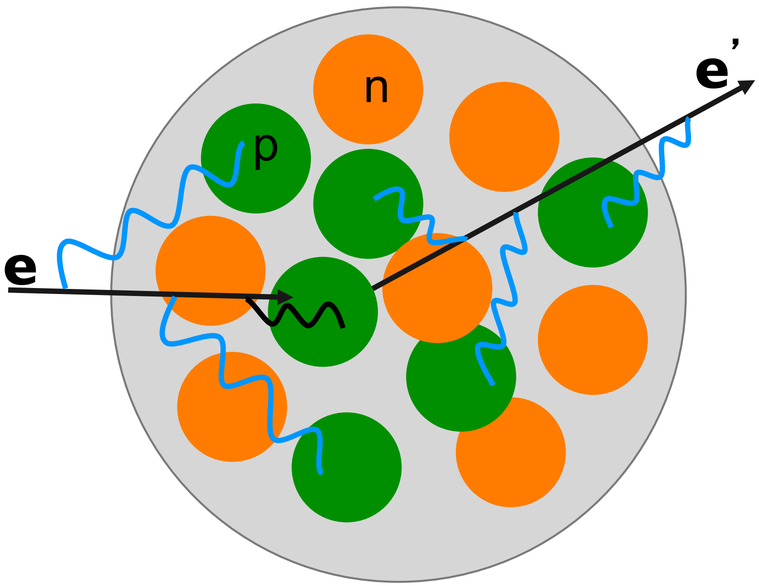
Spokespersons: O. Hen, L. Weinstein, S. Gilad, S. Wood

Light to Heavy Nuclei

- New JLab data, new method of characterizing “size” of EMC effect gave insight into nuclear dependence of EMC effect.
  - Same dependence observed for A/D ratios at x>1
  - Correlation between EMC effect and SRCs
  - Local density vs. high virtuality → flavor dependence?
- Some interesting effects have also been observed for heavy targets

JLab E03103 – Heavy Targets

E03-103 also measured EMC ratios for Cu and Au – analysis at the relatively low 6 GeV beam energy complicated by ***Coulomb Corrections***



Electrons scattering from nuclei can be accelerated/decelerated in the Coulomb field of the nucleus

→ This effect is NOT part of the hadronic structure of the nucleus we wish to study

→ Important to remove/correct for apparent changes in the cross section due to Coulomb effects

In a very simple picture – Coulomb field induces a change in kinematics in the reaction

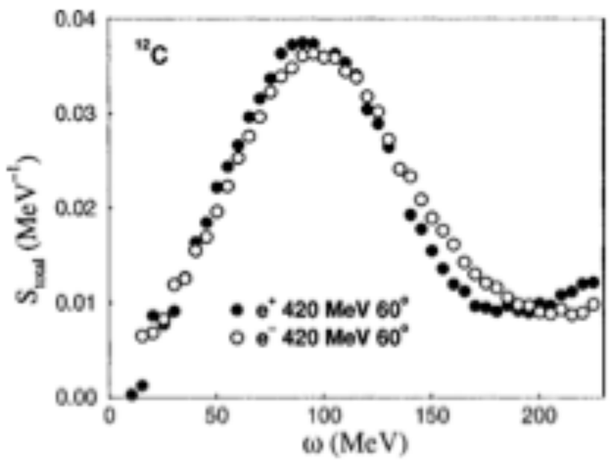
$$E_e \rightarrow E_e + V_0$$

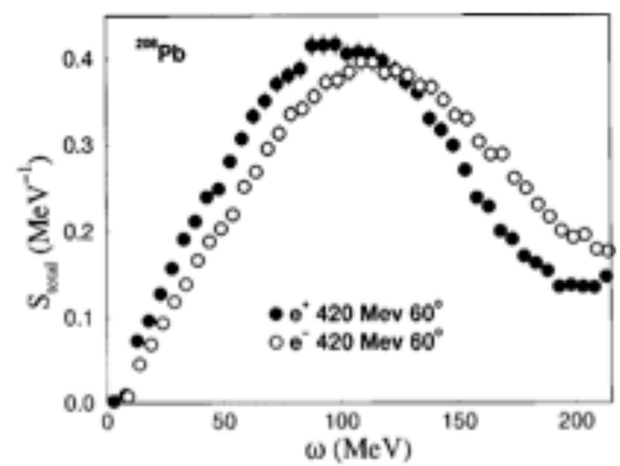
$$E_e' \rightarrow E_e' - V_0$$

$$V_0 = 3\alpha(Z-1)/2R$$ ← *Electrostatic potential energy at center of nucleus*

Coulomb Corrections in QE Processes

Importance of Coulomb Corrections in quasi-elastic processes well known





Gueye et al., PRC60, 044308 (1999)

Distorted Wave Born Approximation calculations are possible – but difficult to apply to experimental cross sections

→Instead use ***E***ffective ***M***omentum ***A***pproximation (***EMA***) tuned to agree with DWBA calculations

EMA: $E_e \rightarrow E_e + V_0$ $E_e' \rightarrow E_e' - V_0$ with "focusing factor" $F^2 = (1-V_0/E)$

$V_0 \rightarrow (4/5)V_0$, $V_0=3\alpha(Z-1)/2R$ V_0 = 10 MeV for Cu, 20 MeV for Au

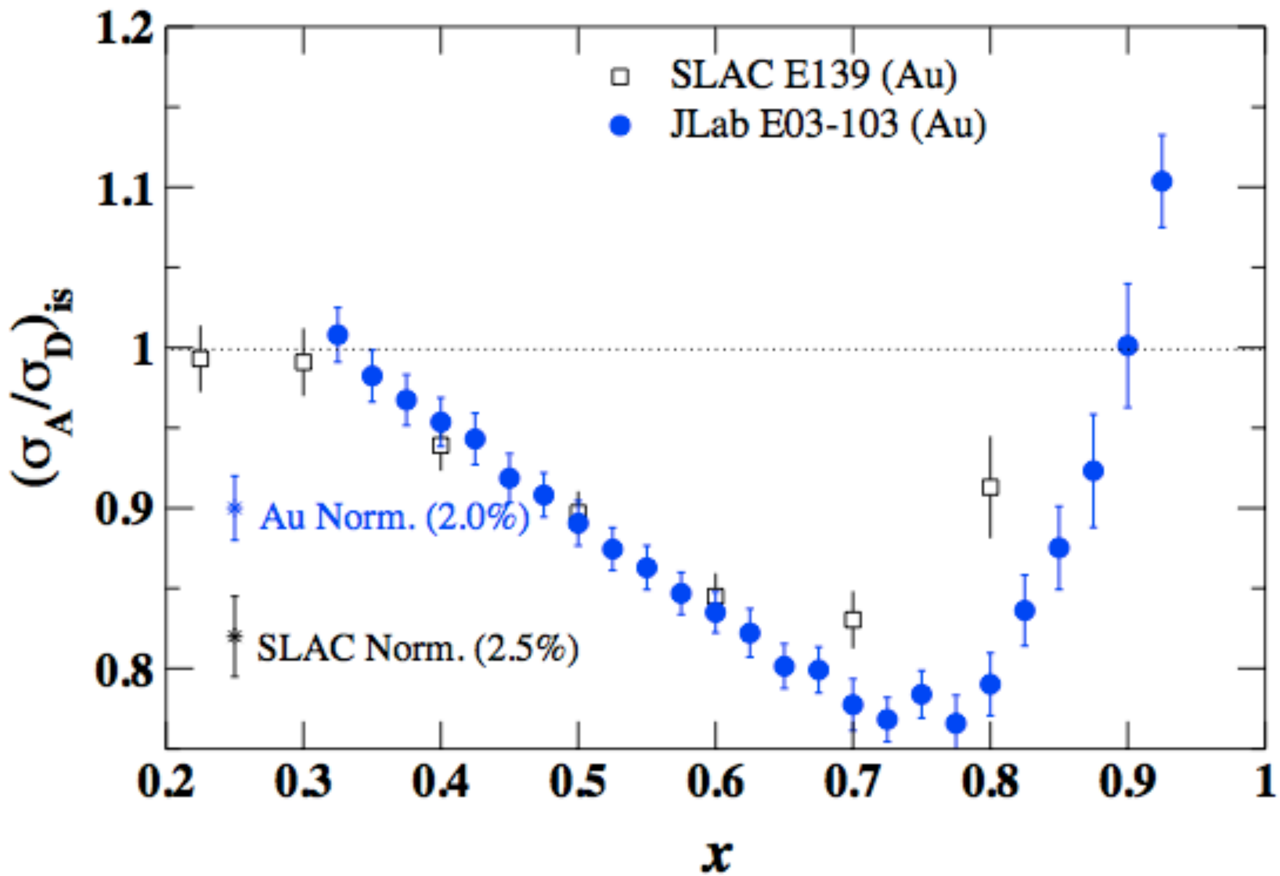
[Aste et al, Eur.Phys.J.A26:167-178,2005, Europhys.Lett.67:753-759,2004]

E03103: EMC Effect in Gold

σ_A/σ_D for Gold
A=197 Z=79

<u>SLAC E-139</u>
E_e ~ 8-25 GeV
E_e' ~4-8 GeV

<u>JLab E03-103</u>
E_e ~ 6 GeV
E_e' ~1-2 GeV



No Coulomb Corrections applied

E03103: EMC Effect in Gold

σ_A/σ_D for Gold
A=197 Z=79

<u>SLAC E-139</u>
E_e ~ 8-25 GeV
E_e' ~4-8 GeV

<u>JLab E03-103</u>
E_e ~ 6 GeV
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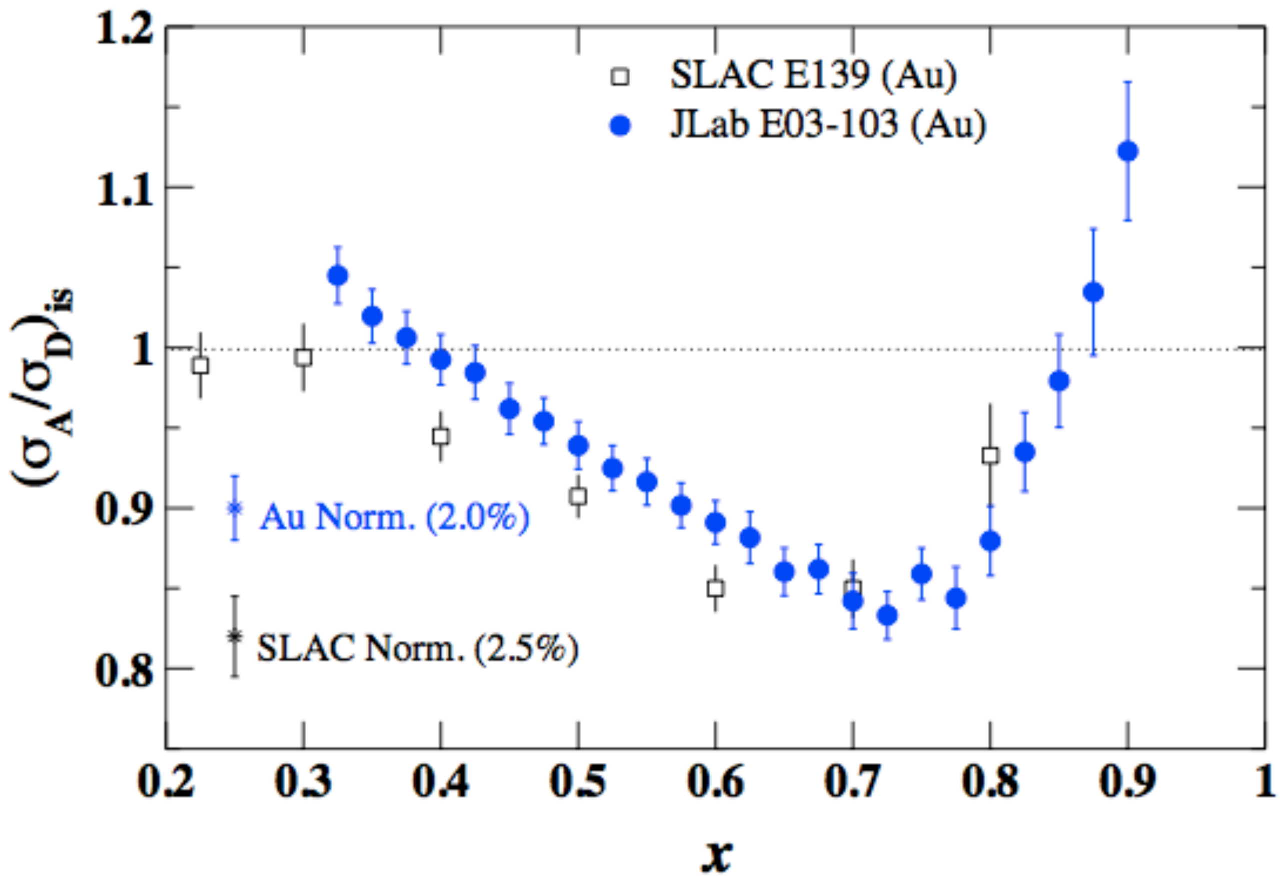


with Coulomb Corrections (both data sets)

R_A-R_D

E03103 shows good agreement with E139 data for smaller *A*
→ agreement not as good for heavier targets. Why?

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 (E')^2}{Q^4 \nu}\left[F_2(\nu,Q^2)\cos^2\frac{\theta}{2} + \frac{2}{M\nu}F_1(\nu,Q^2)\sin^2\frac{\theta}{2}\right]$$

$F_2(x) = \sum_i e_i^2 x q_i(x)$ ← Quark distribution functions

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

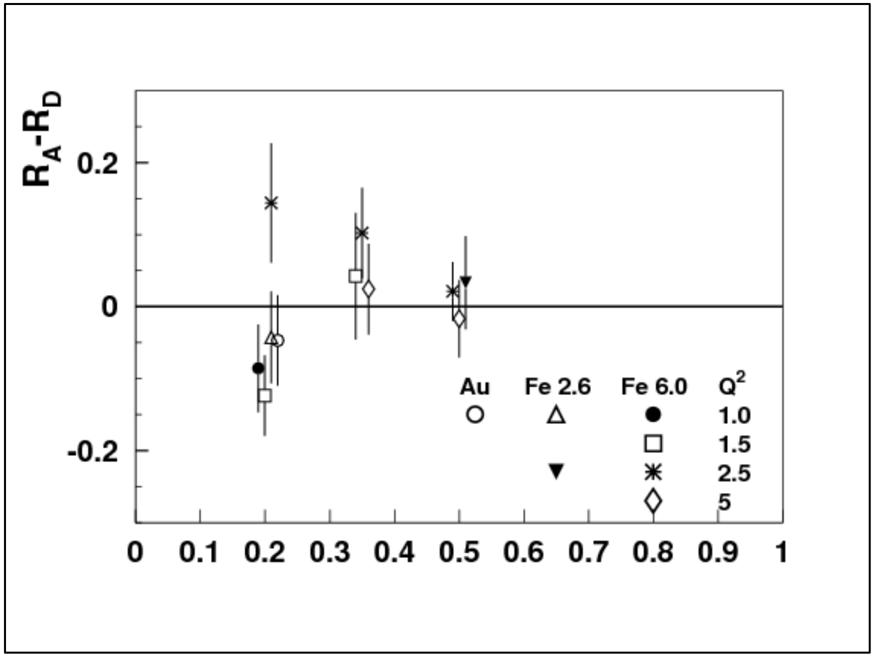
$F_1 \,\alpha\, \sigma_T$ F_2 linear combination of σ_T and σ_L

Measurements of EMC effect often assume $\sigma_A/\sigma_D = F_2^A/F_2^D$
→ this is true if $R=\sigma_L/\sigma_T$ is the same for A and D

E139 data mostly at large ε – JLab data at small ε → if RA ≠ RD, this might explain the difference

→ Motivated us to re-examine earlier experiments that measured nuclear dependence of *R*

SLAC E140: R_A-R_D



E140 measured ε dependence of cross section ratios σ_A/σ_D for

x=0.2, 0.35, 0.5
Q^2 = *1.0, 1.5, 2.5, 5.0* GeV^2
Iron and Gold targets

$R_A - R_D$ consistent with zero within errors

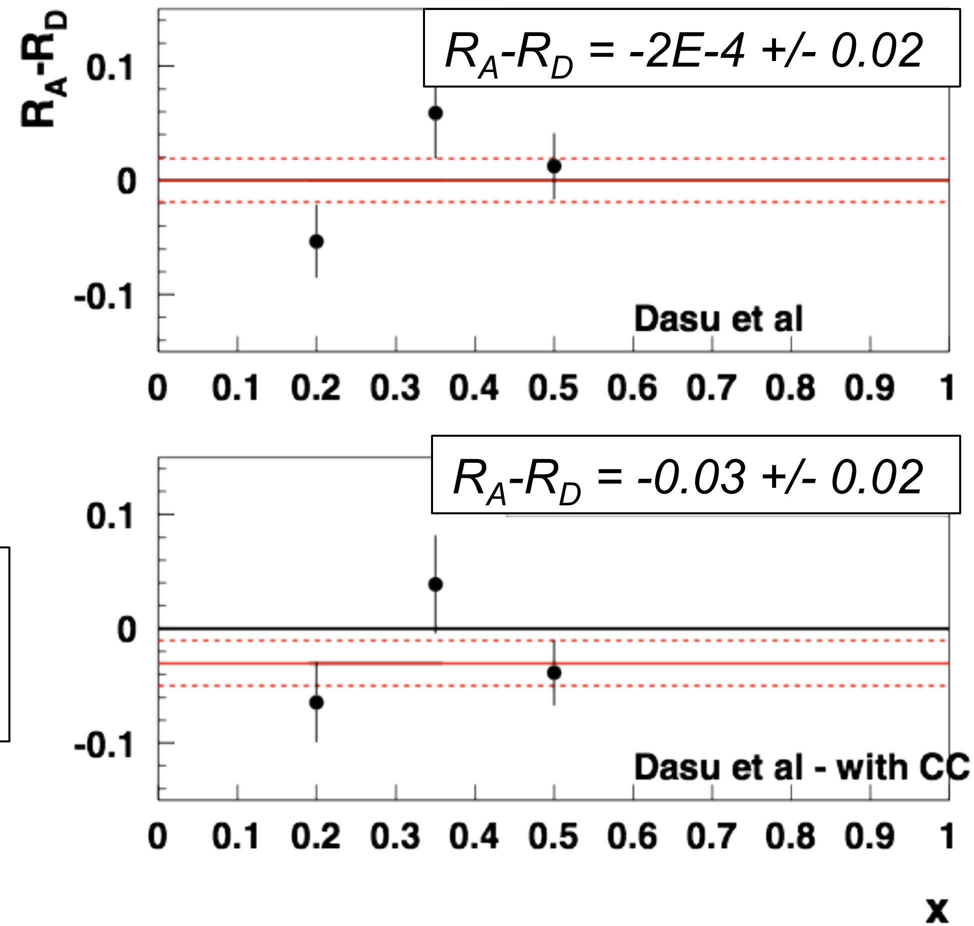
[E140 Phys. Rev. D 49 5641 (1993)]

No Coulomb corrections were applied

Large ε data: E_e ~ *6-15* GeV E_e' ~ *3.6-8* GeV
Low ε data: E_e ~ *3.7-10* GeV **E_e' ~ 1-2.6 GeV**

R_A-R_D: E140 Re-analysis

Re-analyzed E140 data using Effective Momentum Approximation for published "Born"-level cross sections
→ Total consistency requires application to radiative corrections model as well



Including Coulomb Corrections yields result 1.5 σ from zero when averaged over ***x***

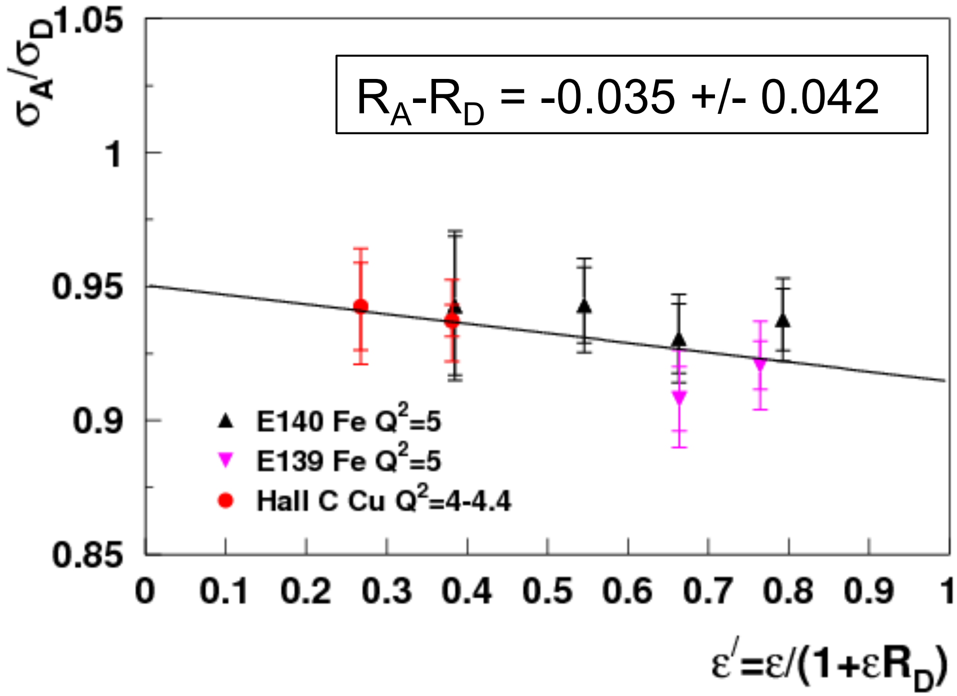
R_A-R_D at *x=0.5*

Interesting result from E140 re-analysis motivated more detailed study
→ *x=0.5*, Q^2=*5* GeV^2

→ Include E139 Fe data
→ Include JLab data
Cu, Q^2=*4-4.4* GeV^2

Normalization uncertainties between experiments treated as extra point-to-point errors

No Coulomb Corrections → combined analysis still yields R_A-R_D ~ 0



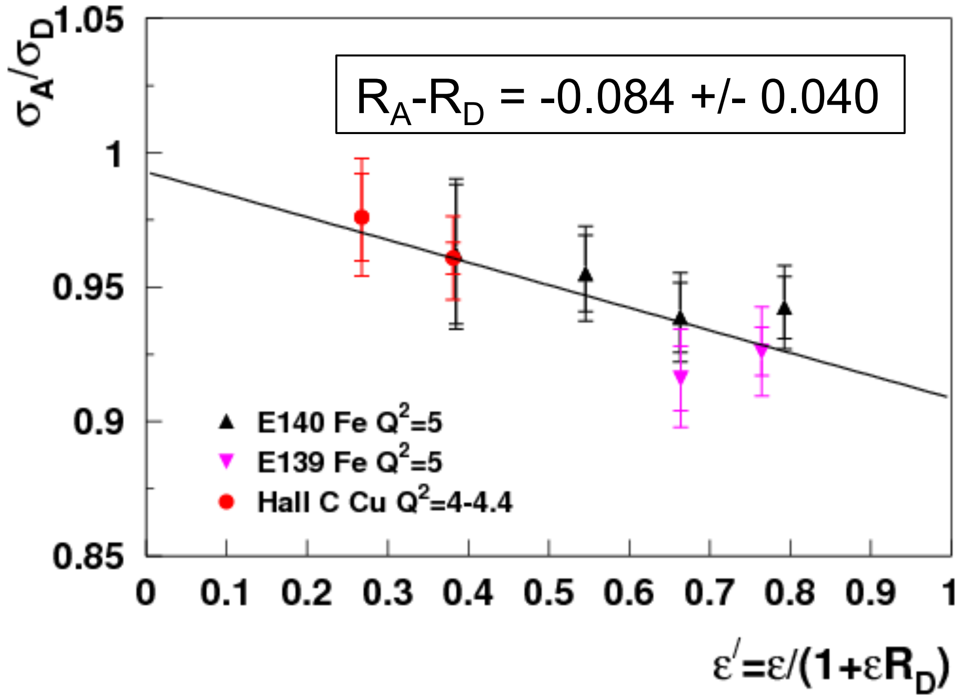
No Coulomb Corrections

R_A-R_D at $x=0.5$

Interesting result from E140 re-analysis motivated more detailed study
→ $x=0.5$, $Q^2=5$ GeV^2

→ Include E139 Fe data
→ Include JLab data
Cu, $Q^2=4$-4.4 GeV^2

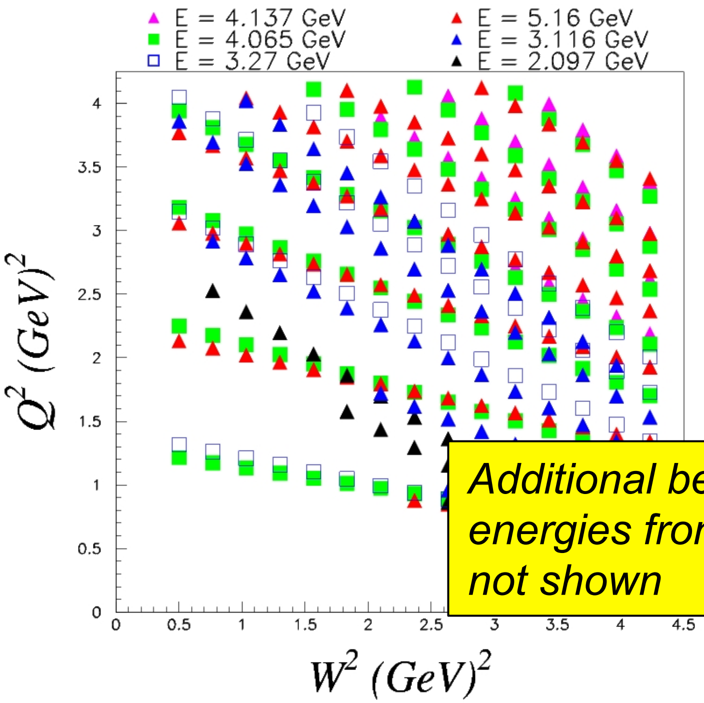
Normalization uncertainties between experiments treated as extra point-to-point errors



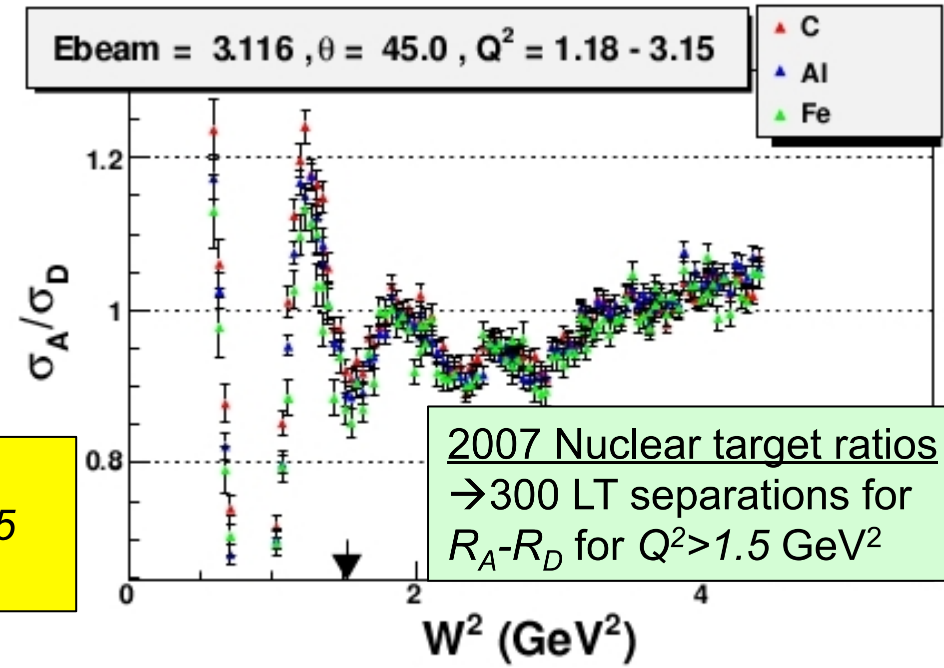
with Coulomb Corrections

Application of Coulomb Corrections → R_A-R_D 2 σ from zero

JLab Hall C E02-109/E04-001/E06-009



Additional beam energies from 2005 not shown

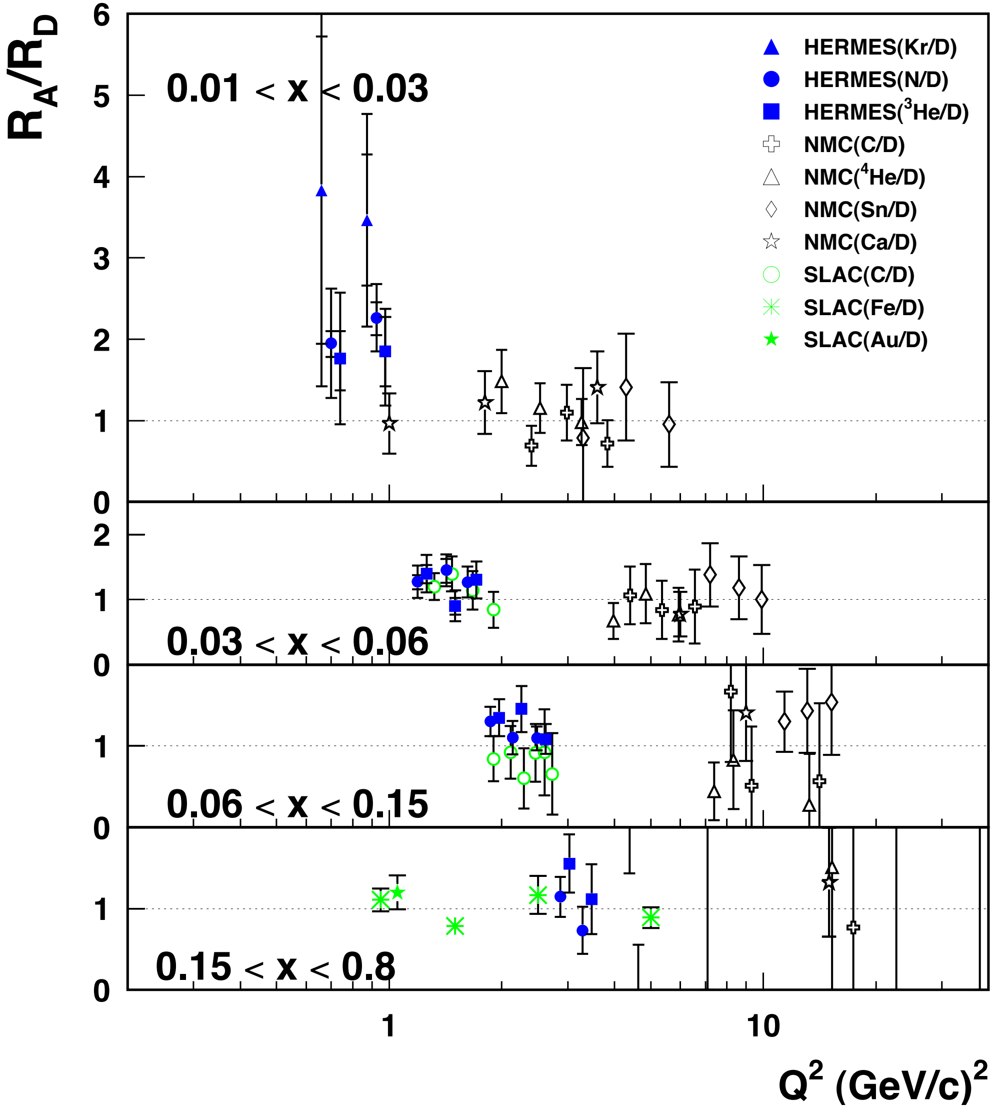


<u>2007 Nuclear target ratios</u>
→300 LT separations for R_A-R_D for Q^2>1.5 GeV²

→ Precision extraction of separated structure functions on D, Al, C, Fe/Cu
→ Search for nuclear effects in F_L, R
→ Neutron and p-n moment extractions (compare to lattice calculations)
→ Allow study of quark-hadron duality for neutron, nuclei separated structure functions

F_2, F_L, R on Deuterium and heavier targets

World Data on R_A/R_D



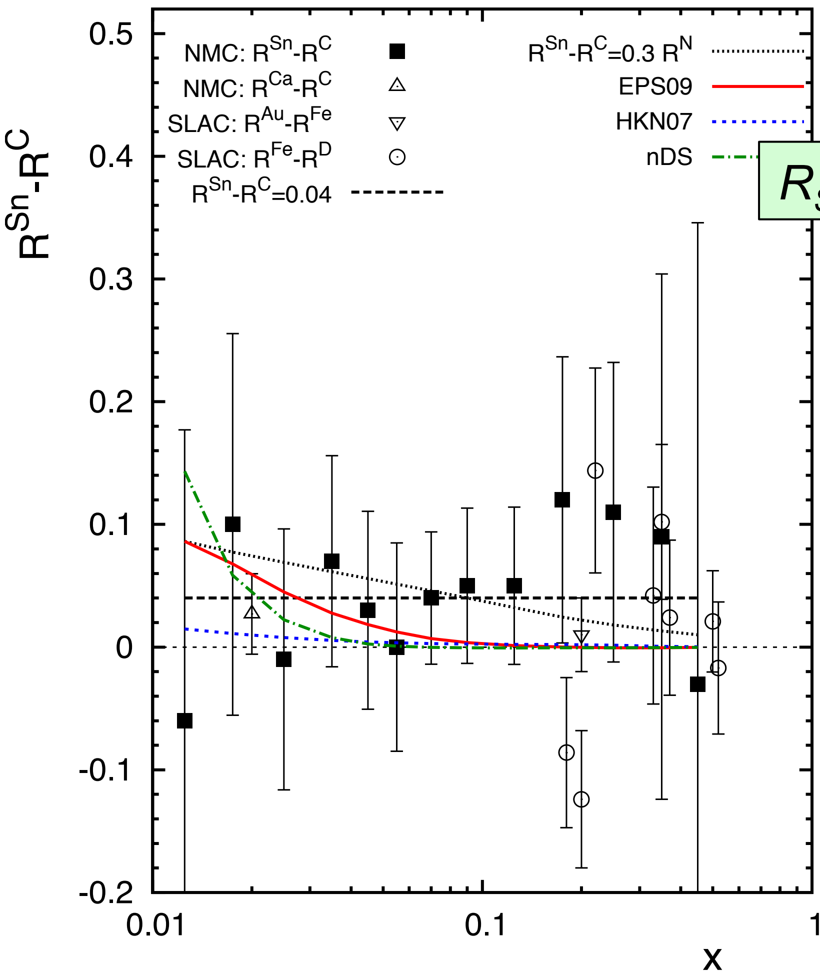
SLAC E140: *PRD 49, 5641 (1994)*
R_A-R_D for Fe, Au
Only true Rosenbluth separated data

NMC:
Phys. Lett. B 294, 120 (1992)
R_{Ca}-R_C
Nucl. Phys. B 481, 23 (1996)
R_{Sn}-R_C
Multiple beam energies, R_A-R_C extracted using Q^2 dep. fit at fixed x

HERMES:
Phys Lett. B 567, 339 (2003)
R_A/R_D for Kr, N, ^{3}He
Fit ε dependence at fixed x for single beam energy (changing Q^2)

Other Hints of non-zero R_A-R_D

NMC results for R_{Sn}-R_C systematically larger than zero



$R_{Sn} - R_C$ = 0.040 +/- 0.026 (stat) +/- 0.020 (sys)

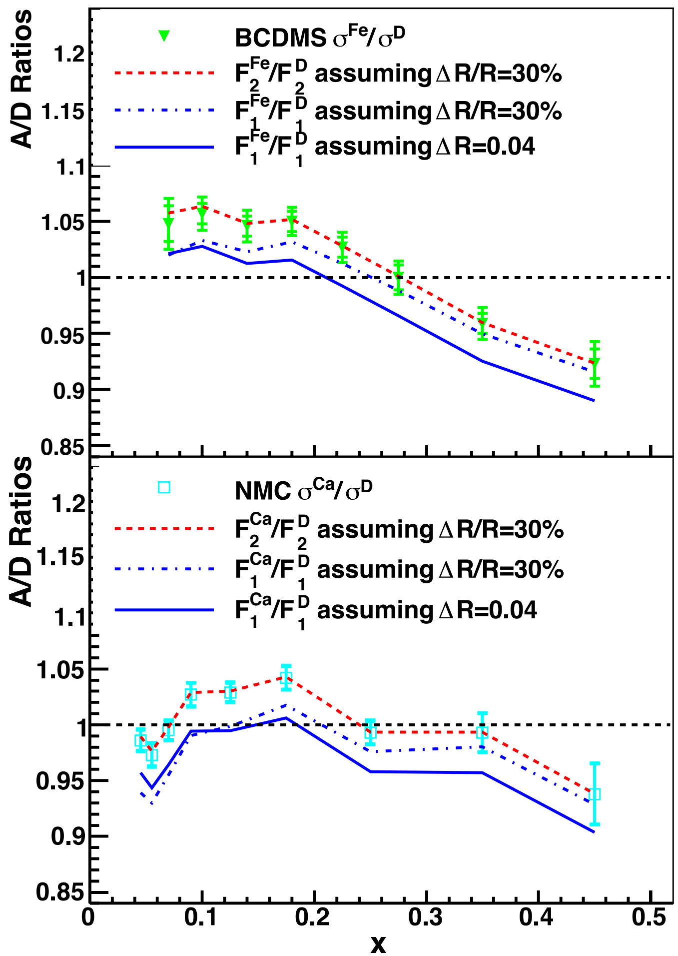
→Averaged over x=0.0125 – 0.45
→$\langle Q^2 \rangle$ = 10 GeV^2

What are the consequences for A/D ratios for F_1 and F_2 if this is true?

V. Guzey et al, PRC 86 045201 (2012)

Jefferson Lab

Consequences of R_A-R_D >0



$$\frac{\sigma_A}{\sigma_D} = \frac{F_1^A(x)}{F_1^D(x)} \left[1 + \frac{\epsilon(R_A - R_D)}{1 + \epsilon R_D} \right]$$

F_1 ratio purely transverse

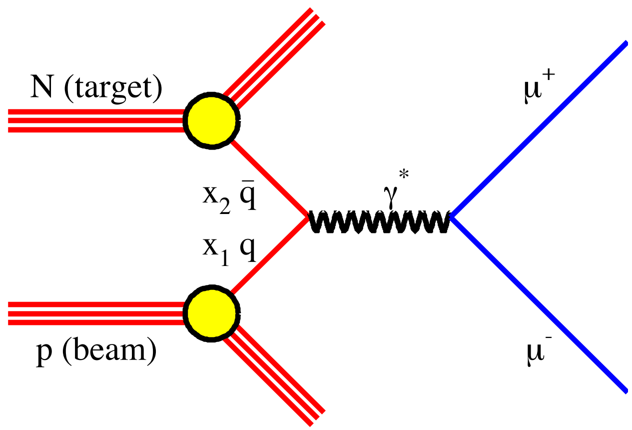
Anti-shadowing disappears for F_1 ratio, remains for F_2

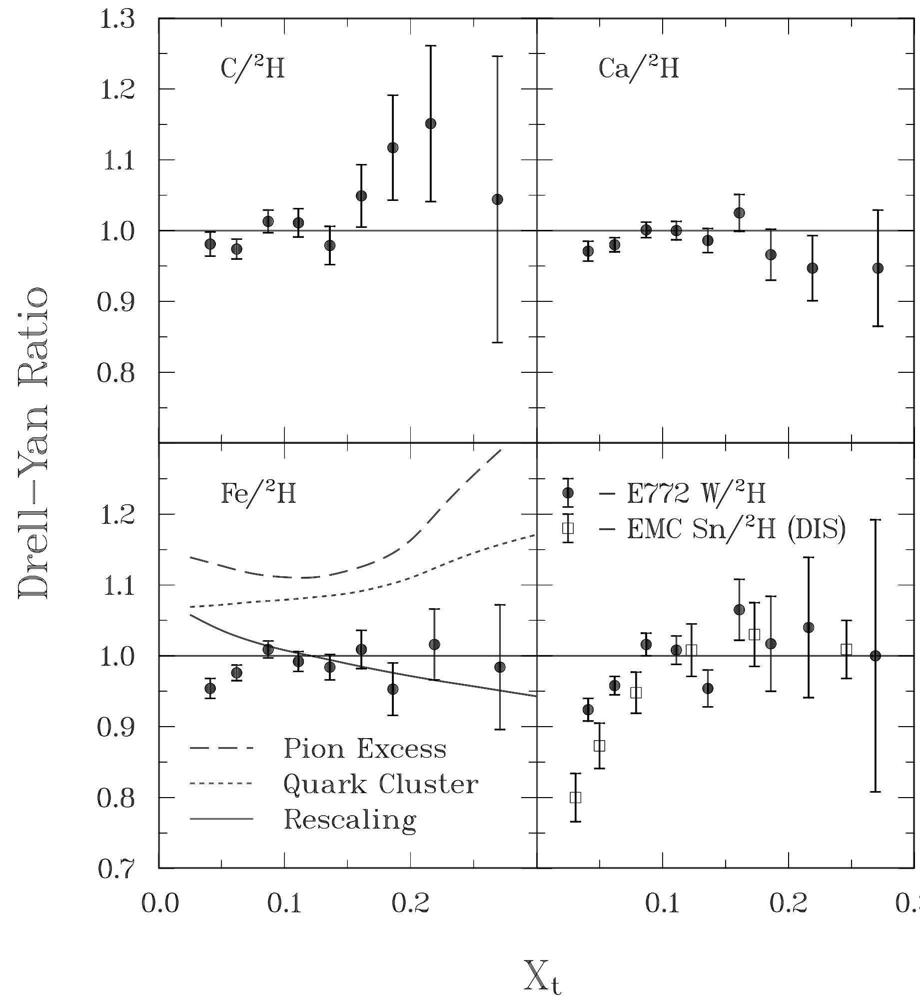
Anti-shadowing from longitudinal photons?

More discussion in Thia Keppel's talk next week

V. Guzey et al, PRC 86 045201 (2012)

A Dependence of Anti-quark Distributions

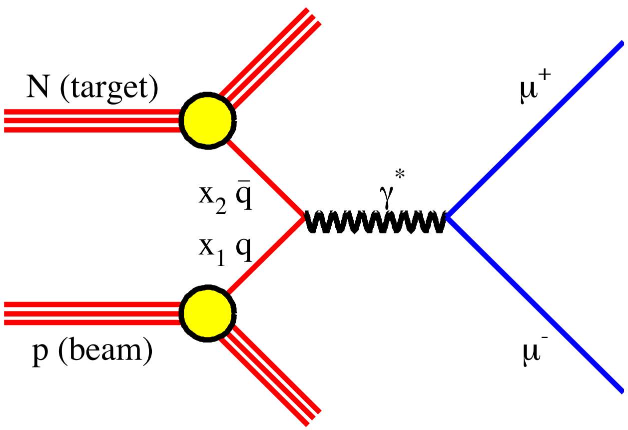


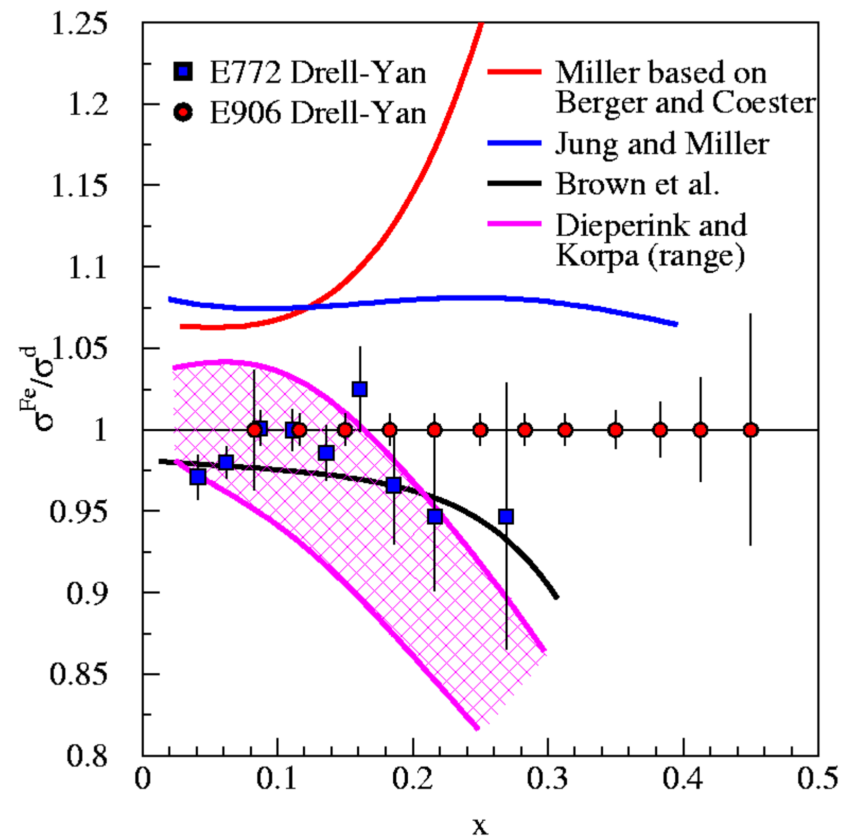


- Drell-Yan process sensitive to anti-quark distributions in the target
- E772 measured no *A* dependence over limited *x* range, with limited precision
- E906 will measure up to *x=0.4*

D.M. Alde et al., PRL**64:** 2479 (1990)

A Dependence of Anti-quark Distributions





- Drell-Yan process sensitive to anti-quark distributions in the target
- E772 measured no *A* dependence over limited *x* range, with limited precision
- E906 will measure up to *x=0.4*

E906 underway …

Nuclear Dependence of *R*

- Conventional wisdom was that there was little or no difference between R in heavy nuclei and free nucleon
- Recent JLab data suggests R_A-$R_D < 0$ at large x
  - Alternatively, Coulomb Corrections are not under control
  - Better calculations and/or experimental tests needed
- Re-examination of high energy NMC data suggests R_A-$R_D>0$
  - How can this be consistent with JLab + SLAC data?
  - Q^2 dependent? Problems with either data set?
- More data is needed – a systematic study over large range of Q^2 and x

Summary

- The EMC effect has been with us for 30 years and motivated intense experimental (and theoretical) study
- Amazingly, it seems there is still much to learn
  - What is the link between SRCs and the EMC effect?
  - Does the EMC effect depend on quark flavor?
  - Does $\sigma_A/\sigma_D = F_2^A/F_2^D$ for all x and Q^2
- Many of these questions will be addressed at JLab after the 12 GeV upgrade
- Issues I did not discuss
  - Polarized EMC effect
  - Low x measurements → EIC
  - Several other processes that aim to quantify the modification of nucleons in the nucleus