Nuclear Partons at Large x: The EMC Effect

Light Ion Physics in the EIC Era

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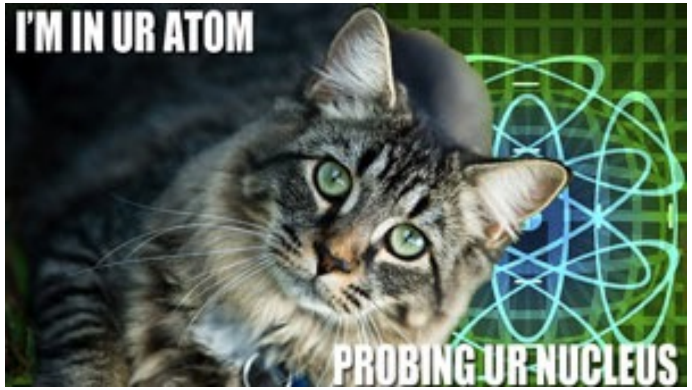
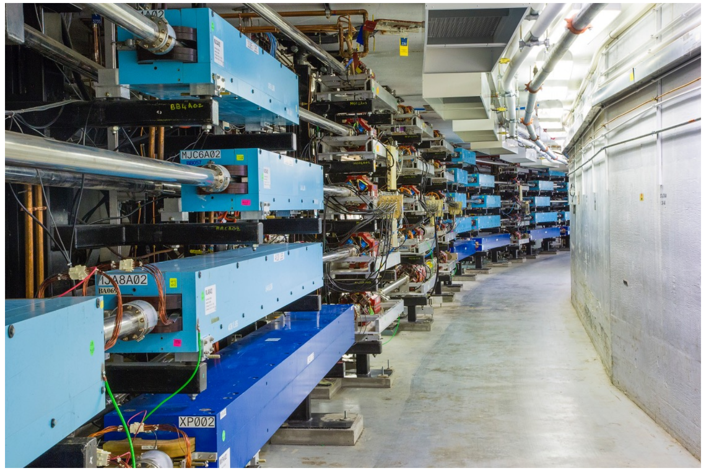
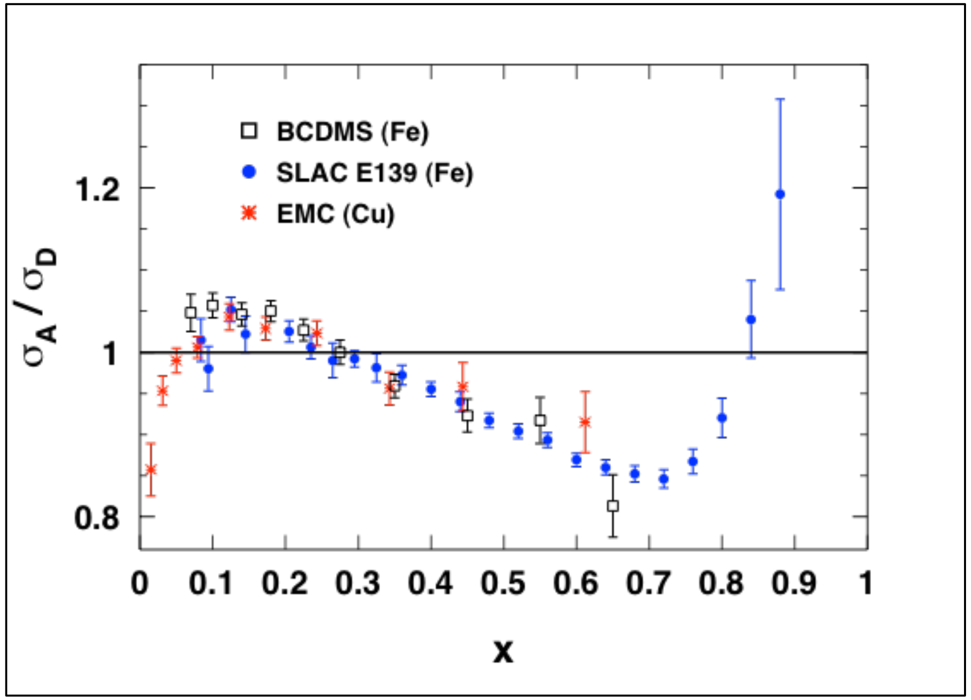
Jefferson Lab

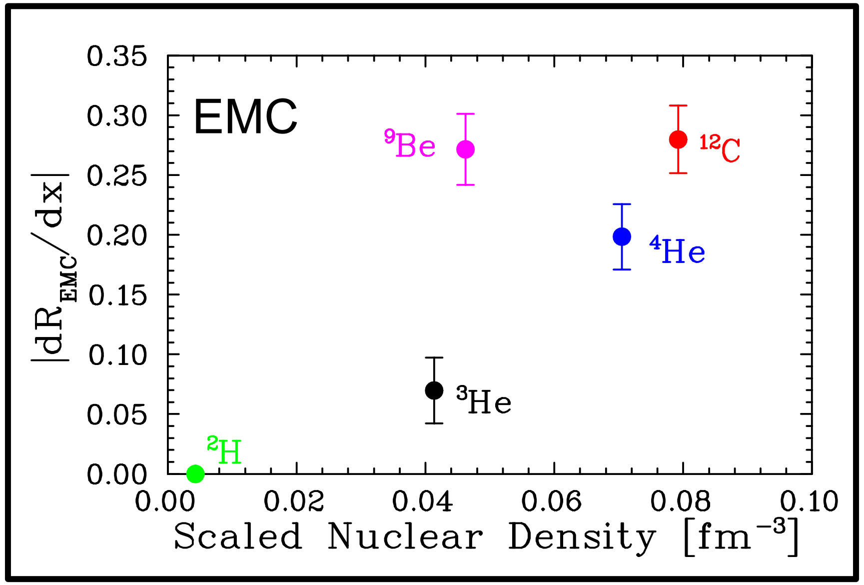
June 26-27, 2025

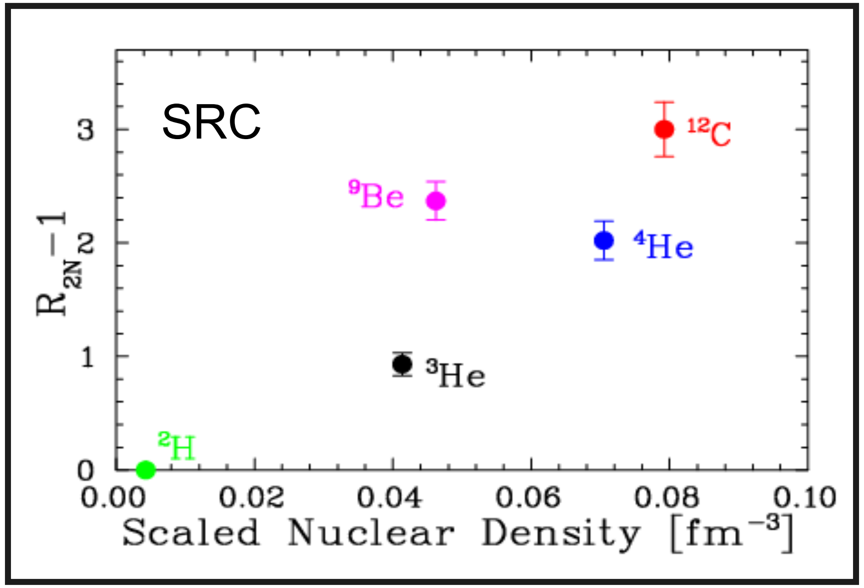




The EMC Effect and Local Density



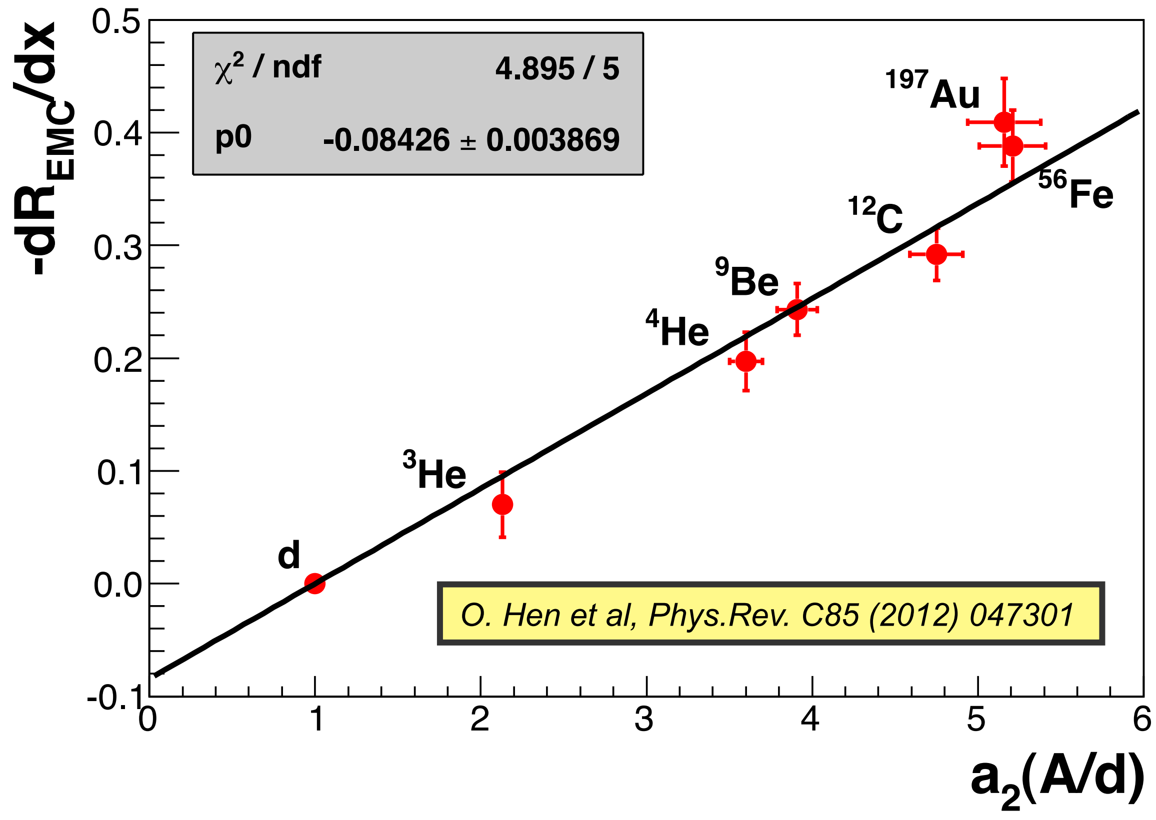




EMC Effect and Short-Range Correlations

Weinstein *et al* first observed linear correlation between size of EMC effect and Short-Range Correlation "plateau" using EMC and older SRC data

Correlation strengthened with addition of JLab 6 GeV SRC (beryllium) data



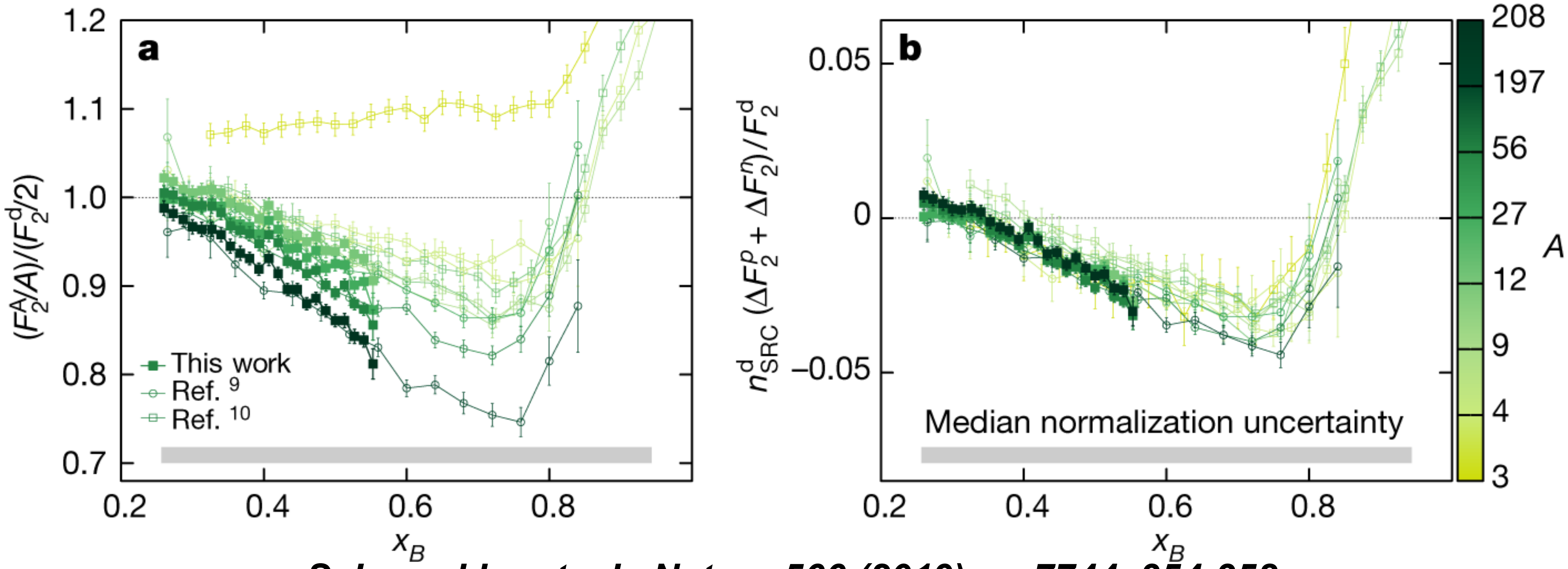
This result provides a ***quantitative*** test of level of correlation between the two effects, but does not provide a microscopic explanation for EMC Effect

Describing the EMC Effect with SRCs

One can model the EMC effect using contributions from unmodified (mean field nucleons) and modified nucleons in SRCs

$$
\begin{aligned}
F_2^{\mathrm{A}} &= \left(Z - n_{\mathrm{SRC}}^{\mathrm{A}}\right) F_2^p + \left(N - n_{\mathrm{SRC}}^{\mathrm{A}}\right) F_2^n + n_{\mathrm{SRC}}^{\mathrm{A}} \left(F_2^{p*} + F_2^{n*}\right) \\
&= Z F_2^p + N F_2^n + n_{\mathrm{SRC}}^{\mathrm{A}} \left(\Delta F_2^p + \Delta F_2^n\right)
\end{aligned}
$$

→ Existing EMC data can be described by universal function



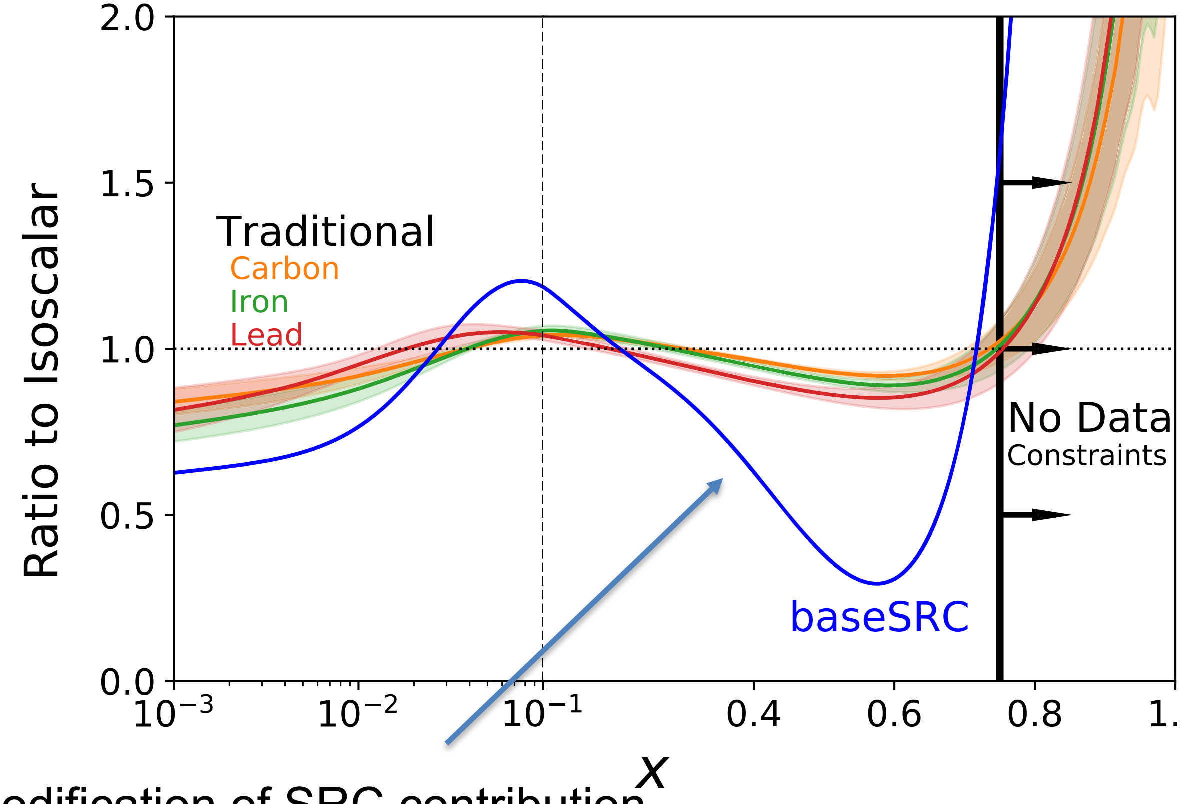
Nuclear PDFs and SRCs

Can also include SRC-based approach in global fits of nuclear PDFs

$$f_i^A(x,Q) = \frac{Z}{A}[(1-C_p^A)\times f_i^p(x,Q) + C_p^A \times f_i^{\mathrm{SRC}p}(x,Q)] + \frac{N}{A}[(1-C_n^A)\times f_i^n(x,Q) + C_n^A \times f_i^{\mathrm{SRC}n}(x,Q)].$$

Can break into contributions of unmodified mean-field contribution and modified SRC contribution

PDF fit works well, but this is a natural consequence of the originally observed correlation



Modification of SRC contribution

A. W. Denniston et al, Phys.Rev.Lett. 133 (2024) 15, 152502

EMC-SRC Correlation

What causes the detailed nuclear dependence to be the same?
→Common cause? Does one drive the other?

Two hypotheses:

1. ***High virtuality***

→EMC effect driven by virtuality of nucleon – relative probability to have high-momentum nucleon

2. ***Local Density***

→ EMC effect driven by local density – nucleons are close together

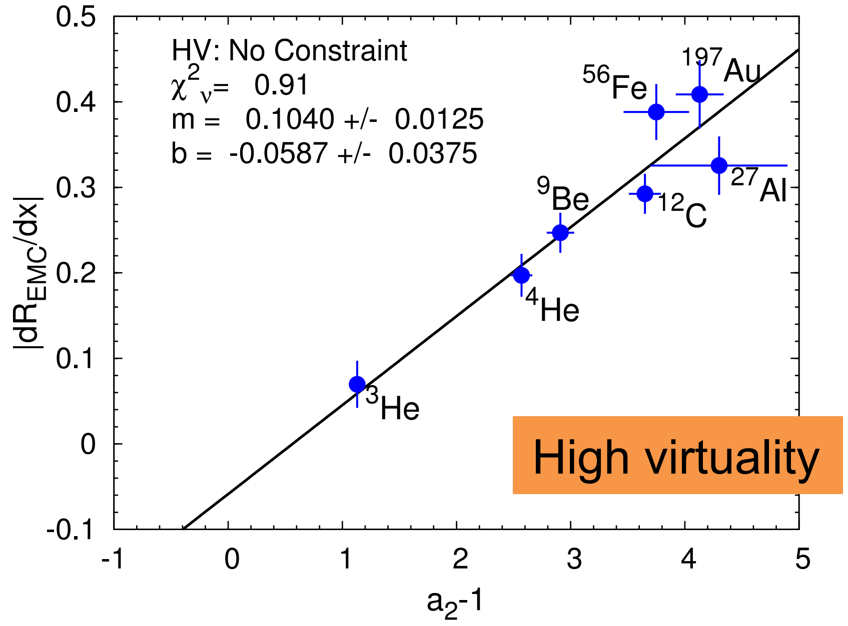
These hypotheses can be tested to looking at correlation vs. modified SRC variable

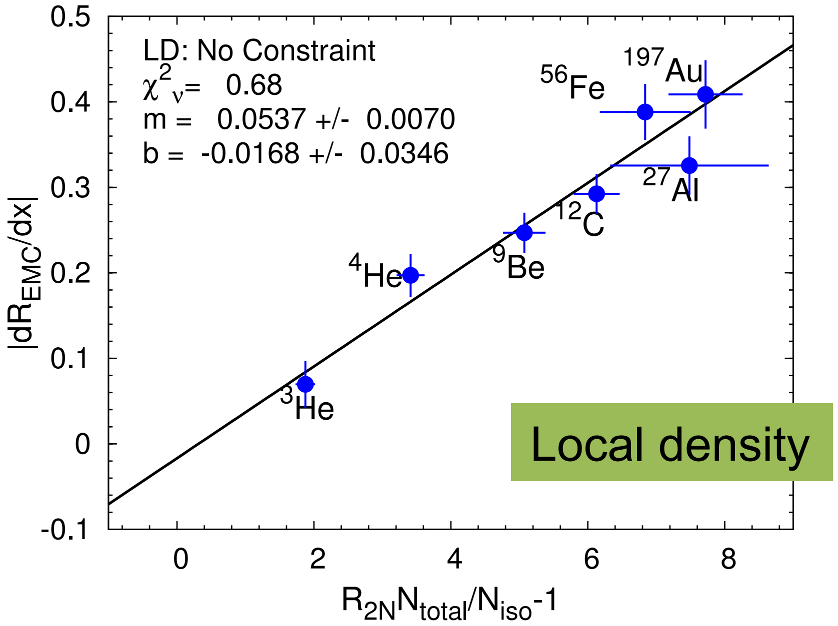
R_{2N} → a_2 corrected for CM motion of correlated pair → number of SRCs
a_2 → number of high-momentum nucleons coming from SRCs and pair motion

Neither picture ruled out by existing data

Nuclear Dependence of EMC and SRCs

Arrington et al, PRC 86, 065204 (2012)





a_2 ~ number of high momentum nucleons

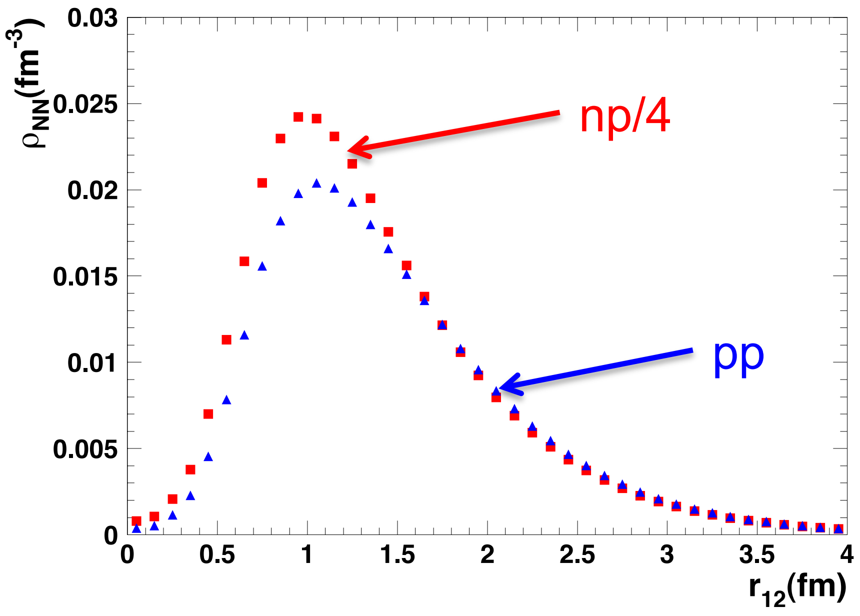
R_{2N} ~ number of nucleons "close" together

Detailed study of nuclear dependence of EMC effect and SRCs 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*

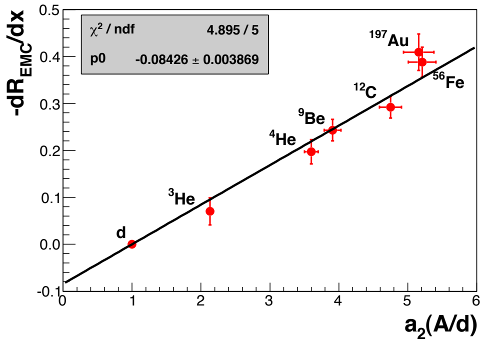
For $r_{12} < 1.7$ fm:

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

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

SRCs, the EMC Effect and Flavor Dependence



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

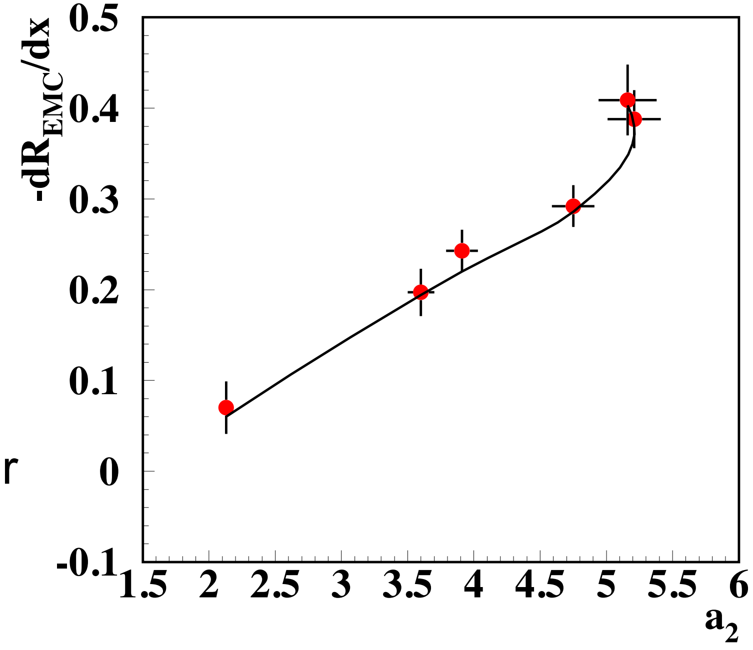
→The relative probability to find a high momentum proton is larger than for neutron for *N>Z* nuclei

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

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

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

Probability to find SRC

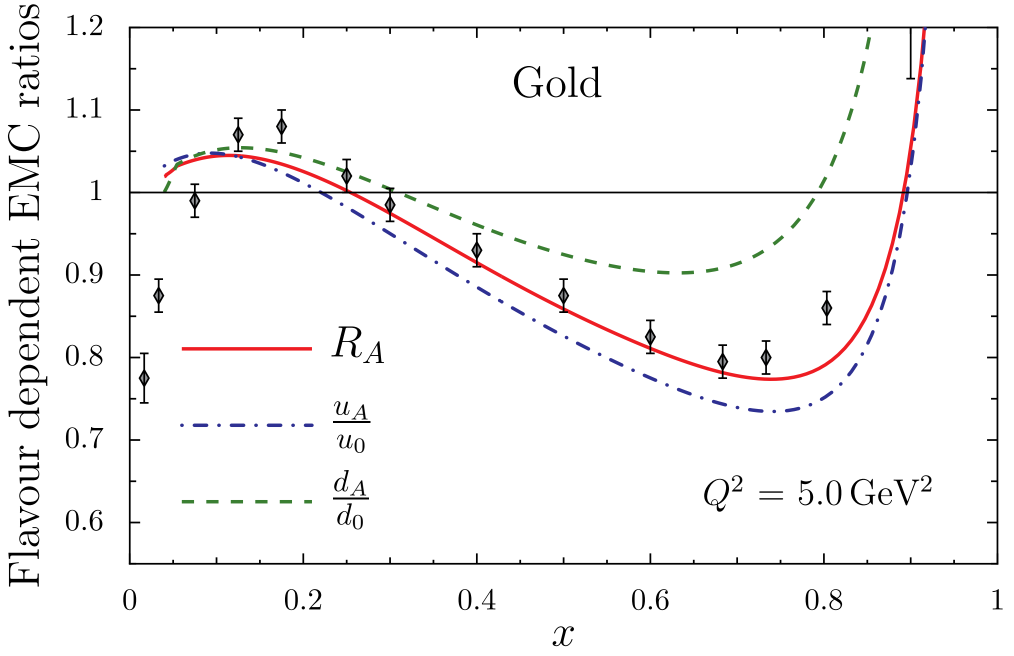


Under the assumption the EMC effect comes from "high virtuality" (high momentum nucleons), effect driven by protons (u-quark dominates) → similar flavor dependence is seen in some "mean-field" approaches

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

Flavor Dependence of the EMC Effect in Mean Field Approach

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



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

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

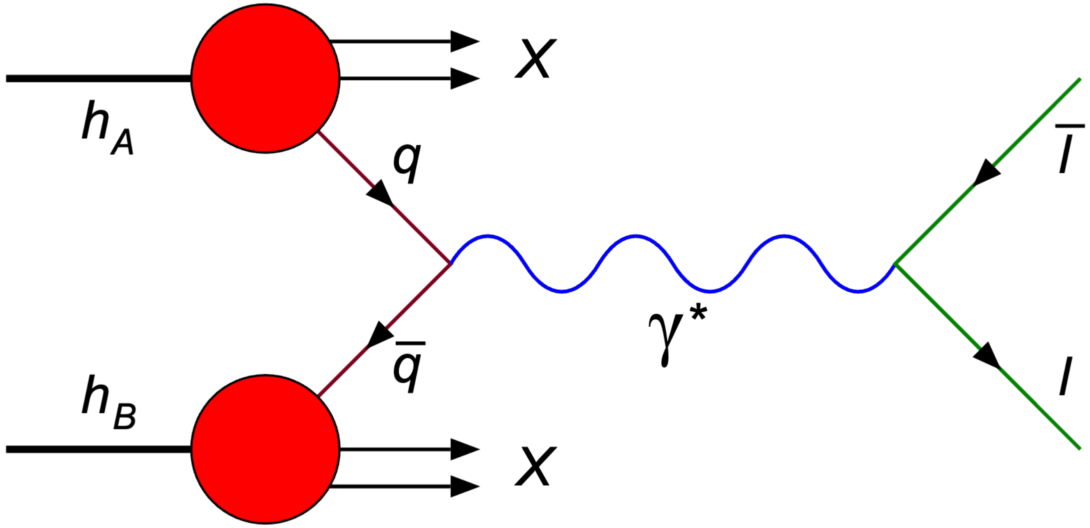
This model includes explicit quark degrees of freedom → nuclear dynamics included via shell model

Experimentally, this flavor dependence has not been observed directly

Flavor dependence could be measured using PVDIS, pion Drell-Yan, SIDIS, unpolarized EMC Effect…

Pion Drell-Yan

Drell-Yan reaction: quark from h_A annihilating with quark from h_b → virtual photon → lepton pair



Drell-Yan with pion beams provides access to flavor dependence of quark distributions

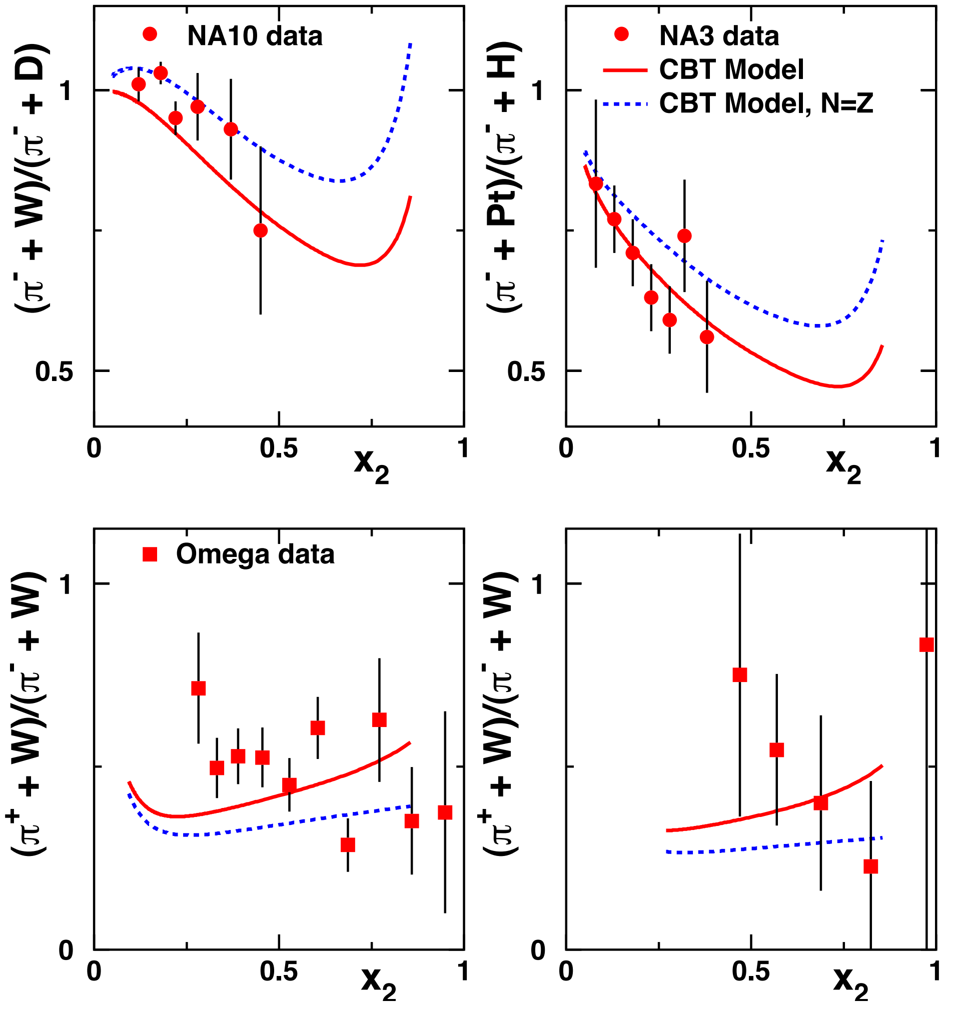
$$\frac{d\sigma_{\pi^\pm A}}{dx_\pi dx_2} = \frac{4\pi\alpha^2}{9sx_\pi x_2}\sum_q e_q^2[q_{\pi^\pm}(x_\pi)\bar{q}_A(x_2) + \bar{q}_{\pi^\pm}(x_\pi)q_A(x_2)]$$

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

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

$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + H)} \approx \frac{u_A(x)}{u_p(x)},$$

EMC Flavor Dependence: Pion Drell-Yan



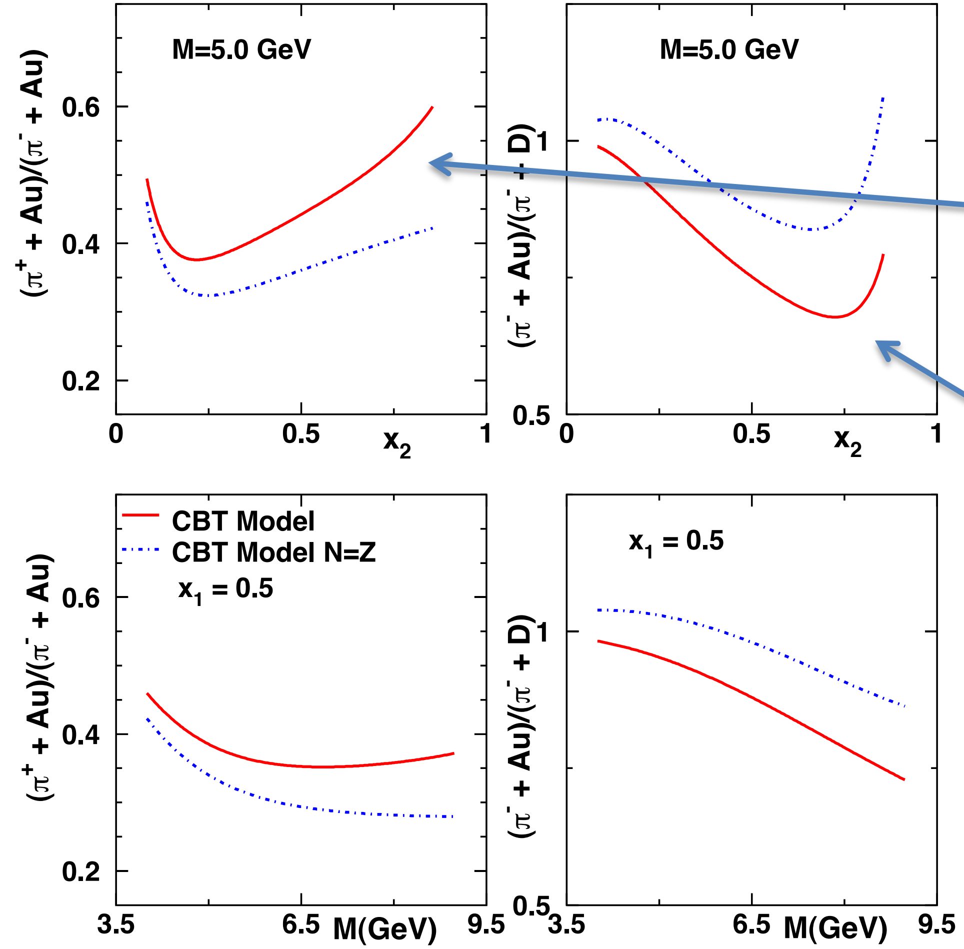
Experiment	Flavor Ind.	Flavor dep.
NA3	1.3	0.5
NA10	0.60	2.5
Omega (low Q^2)	6.2	3.2
Omega (high Q^2)	1.4	0.96

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

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

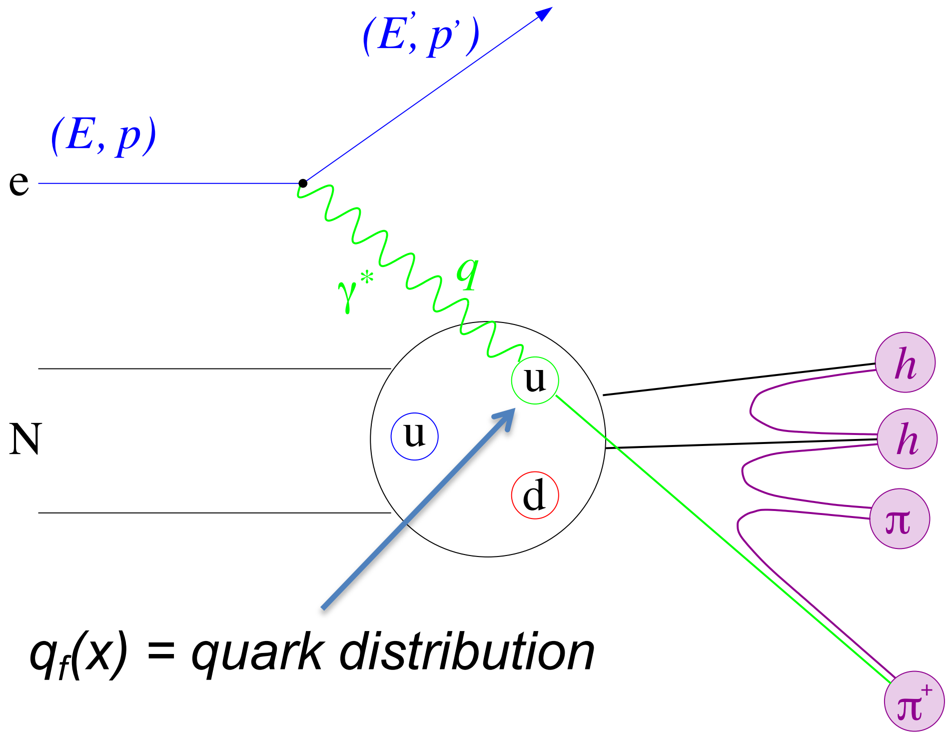
$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$

Dutta et al, PRC 83, 042201 (2011)

Unfortunately, COMPASS has not produced results on this observable → (low statistics) → Planned for AMBER

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

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*

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

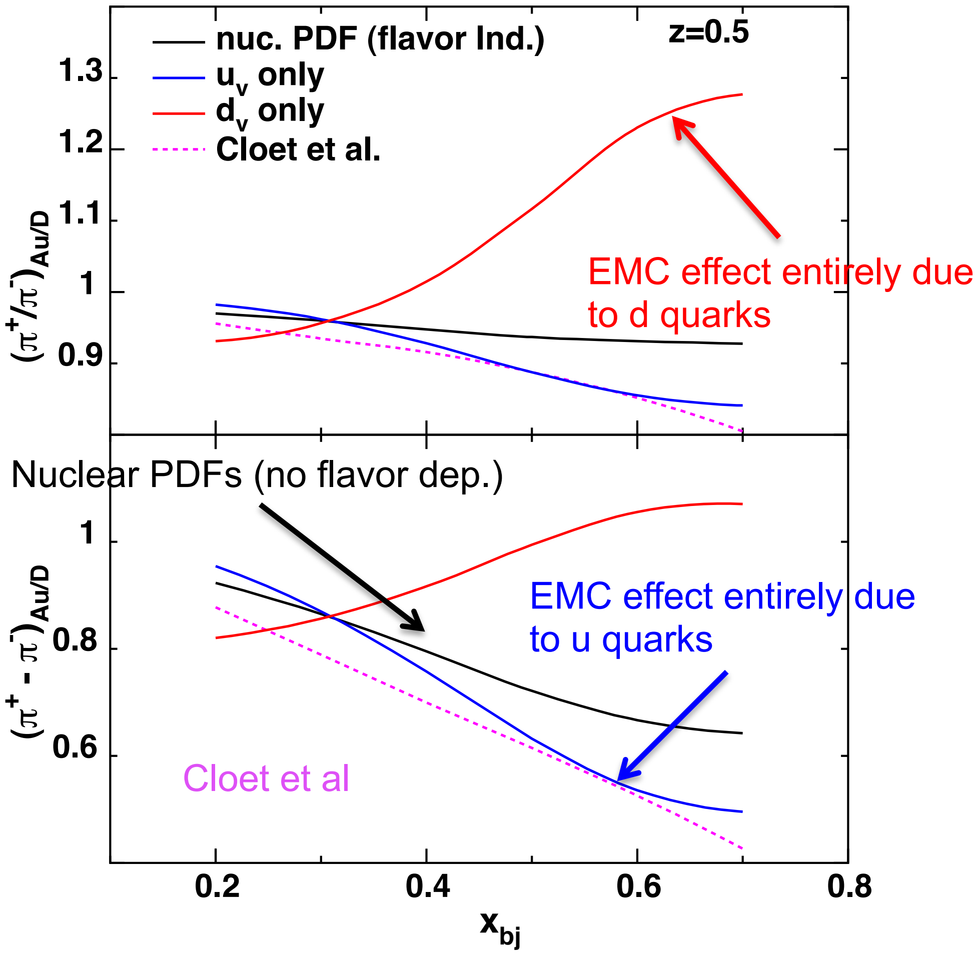
x = fraction of proton momentum carried by quark
$z = E_{hadron}/\nu$

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

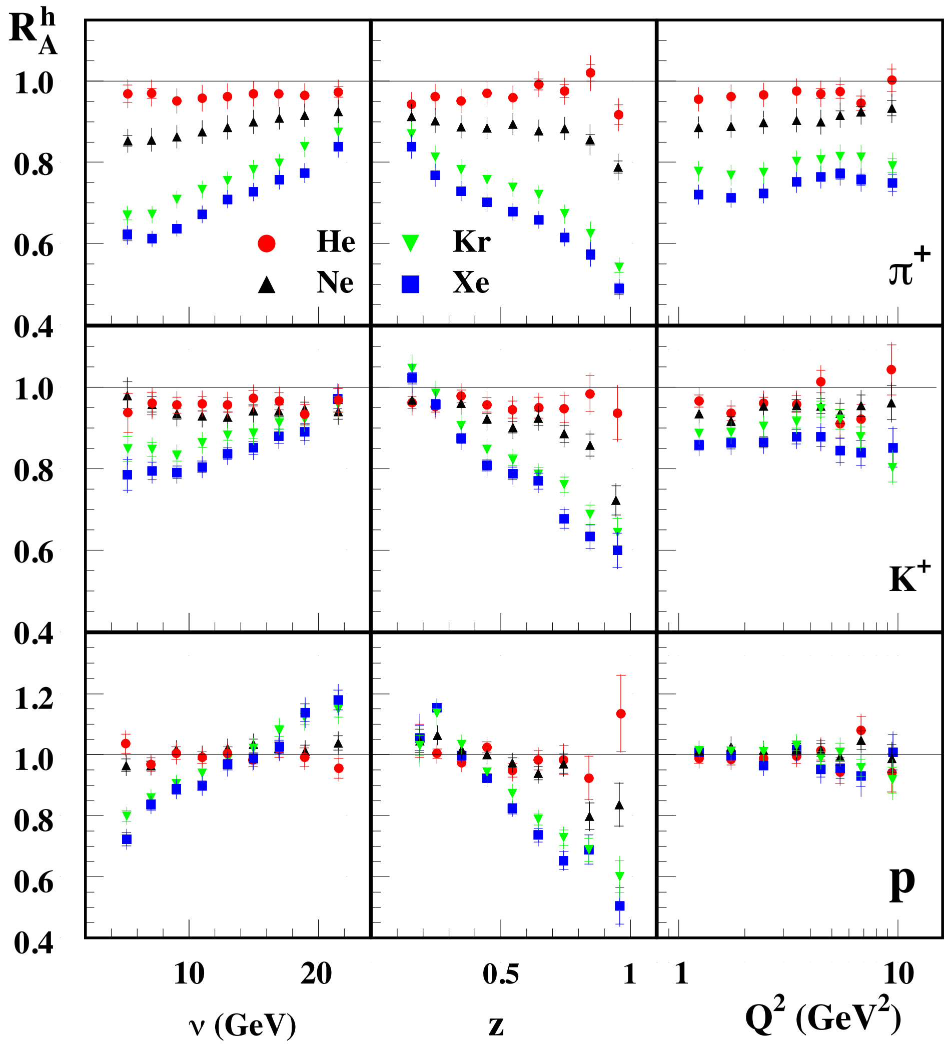


Toy model:
u_V only: EMC effect due to modification of u_A only
d_V only: EMC effect due to modification of d_A only

F_2^A unchanged

Jefferson Lab

SIDIS - Interpretability



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

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 could possibly be checked with measurements at *x=0.3* (no EMC effect)

Hadron attenuation effects should be smaller at EIC!

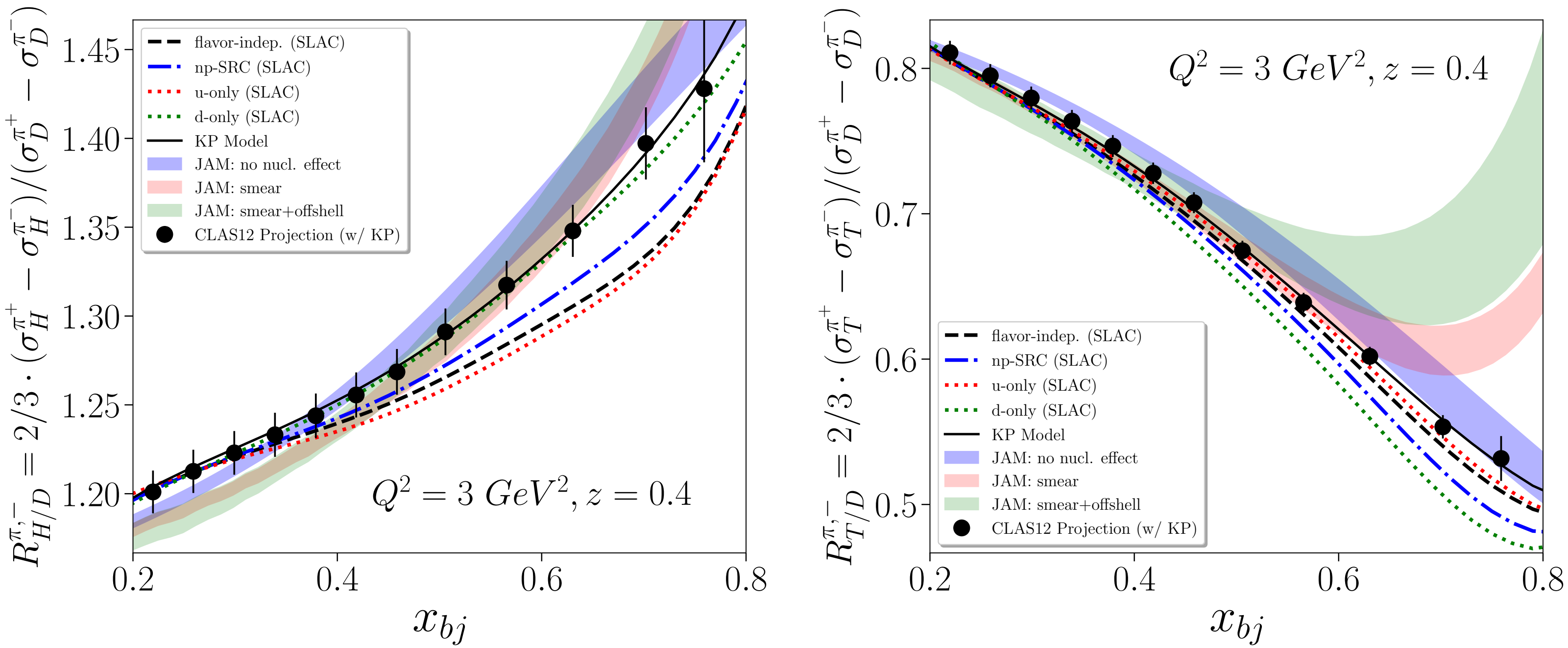
SIDIS with A=3 Nuclei

Can also explore flavor dependence with light nuclei with very different N/Z ratios:

^{3}He: N/Z = 0.5
^{3}H: N/Z = 2

Expected effects due to hadron attenuation much smaller

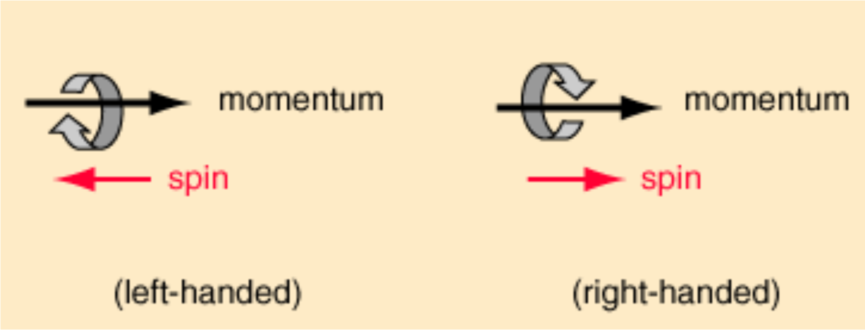
Requires tritium target



Conditionally approved experiment in Hall B:
"Semi-Inclusive Deep Inelastic Scattering Measurement of A=3 Nuclei with CLAS12 in Hall B"
Spokespersons: L. Weinstein*, O. Hen, D. Dutta, D. Gaskell, D. Meekins, D. Nguyen, J. West, Z. Ye

Parity violating electron scattering

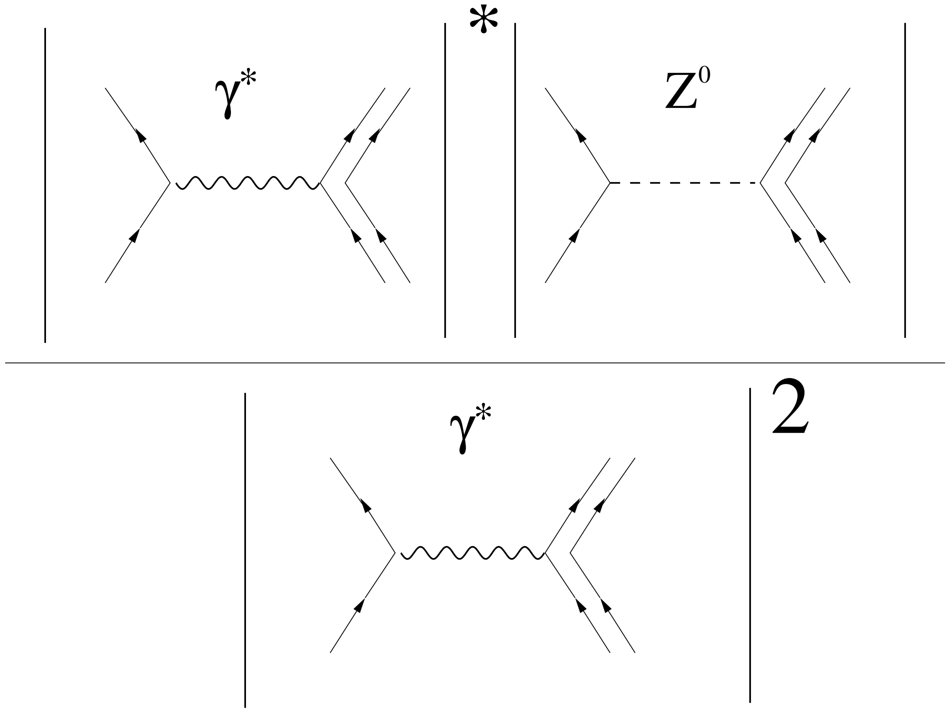
Electron beam at JLab is highly polarized → electron spins preferentially oriented in one direction



In DIS, the electromagnetic interaction is independent of electron spin → parity conserving

DIS can also proceed via the weak interaction → parity violating, but highly suppressed

The asymmetry is sensitive to the interference between EM and Weak contributions
→ Coupling for weak interactions for a given quark flavor not the same as electromagnetic



Flavor Dependence from PVDIS

$$A_{PV} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right]$$

Suppressed by small values of C_2, y-factor

$$a_1(x) = 2\frac{\sum C_{1q} e_q (q+\bar{q})}{\sum e_q^2 (q+\bar{q})}$$

C_{1u}=-0.19, C_{1d}=0.34

Expanding about u_A=d_A limit, neglecting sea quarks:

$$a_1(x) \approx \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+}$$

$$q^\pm = q(x) \pm \bar{q}(x)$$

PVDIS directly sensitive to difference in up and down quark distributions in nuclei

Flavor Dependence from PVDIS

$$A_{PV} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2} a_3(x)\right]$$

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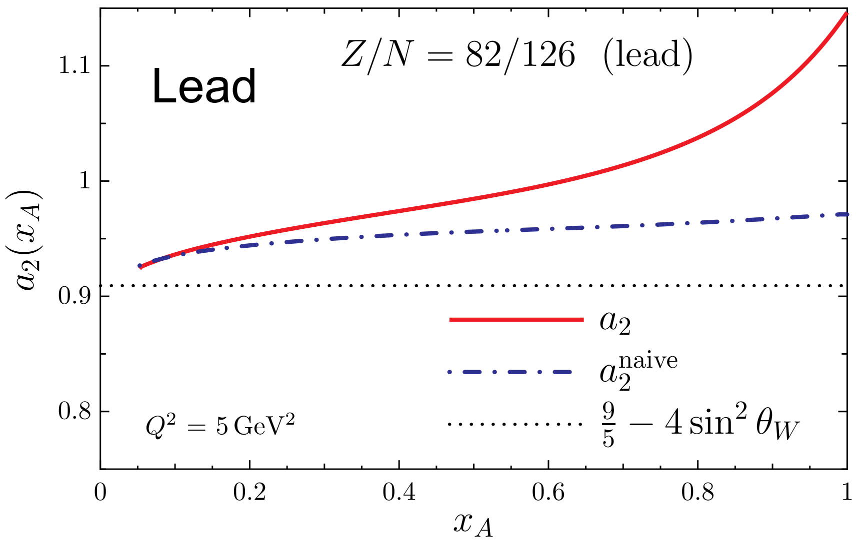
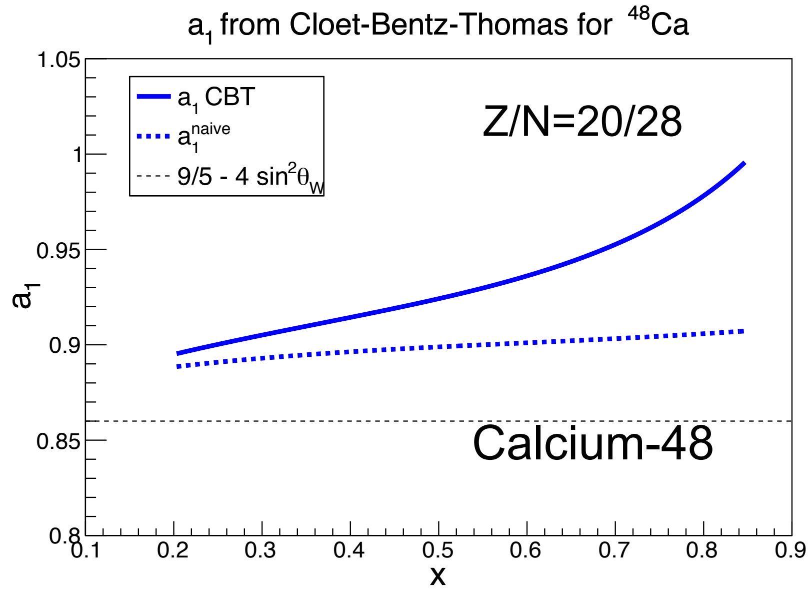


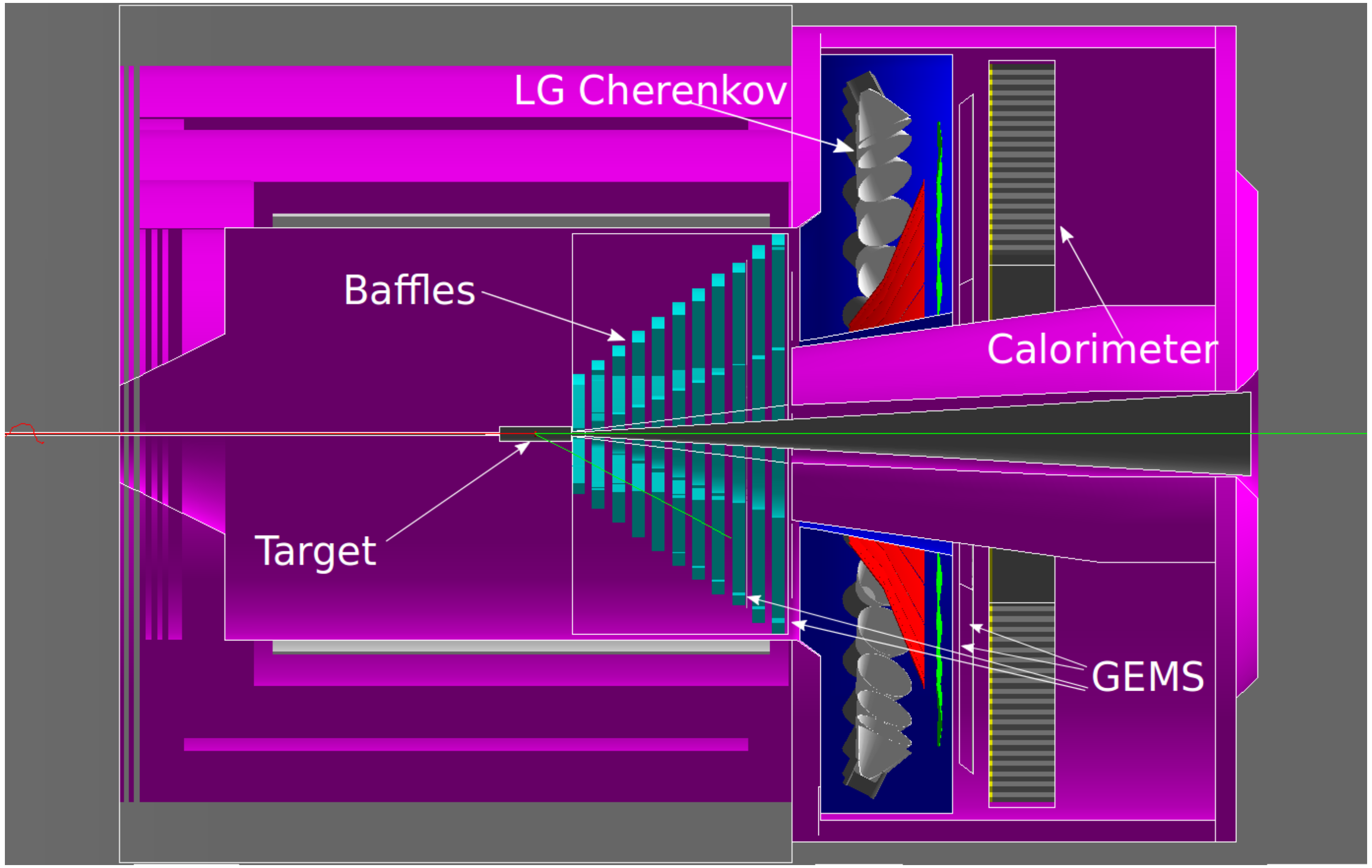


Cloët, Bentz, and Thomas, PRL 109, 182301 (2012)

PVEMC with SoLID

High precision measurement possible with proposed SoLID spectrometer in Hall A

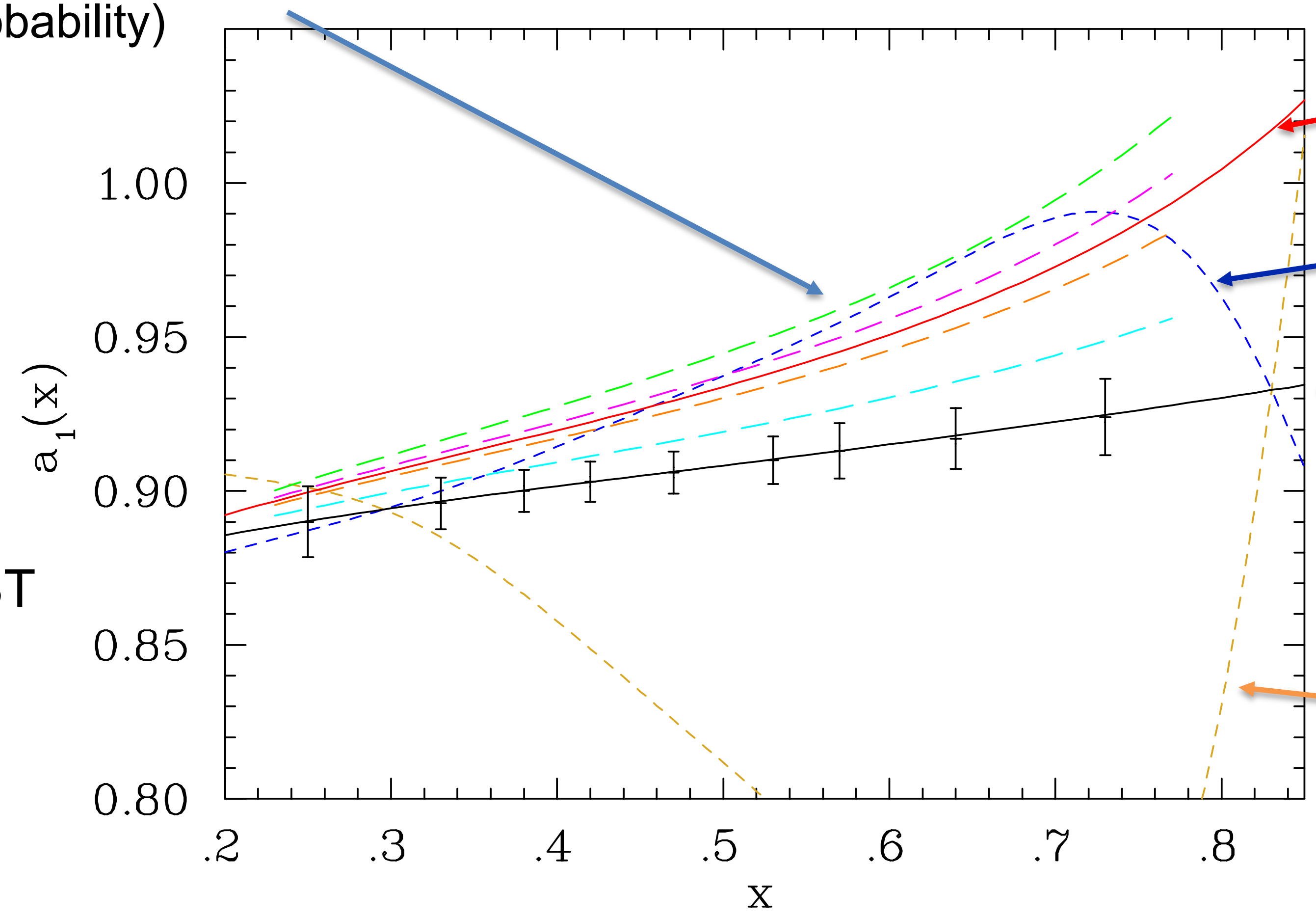
Two proposed SoLID configurations:
1. PVDIS → planned measurements on proton and deuteron
2. SIDIS/J/ψ



PVEMC measurement requires target with N ≠Z and large EMC effect
→ ^{48}Ca satisfies both requirements with smaller radiation length than heavier targets (e.q., gold or lead)

Projections - Sensitivity

Scaling models (p>300 MeV, kinetic energy, average density, overlap probability)



CBT Model

Up only

No flavor dependence

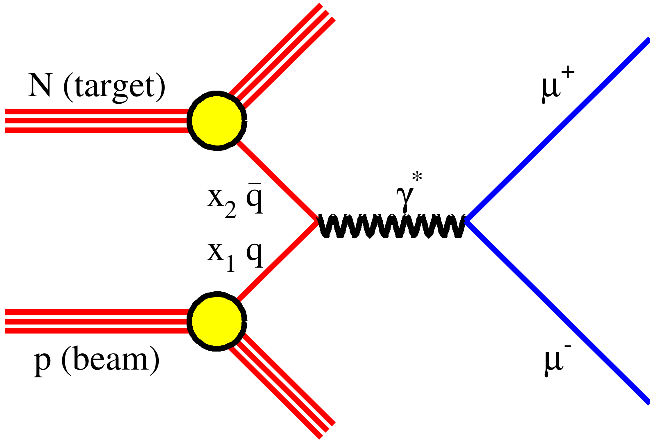
Down only

8σ sensitivity to CBT model (neglecting normalization uncertainty)

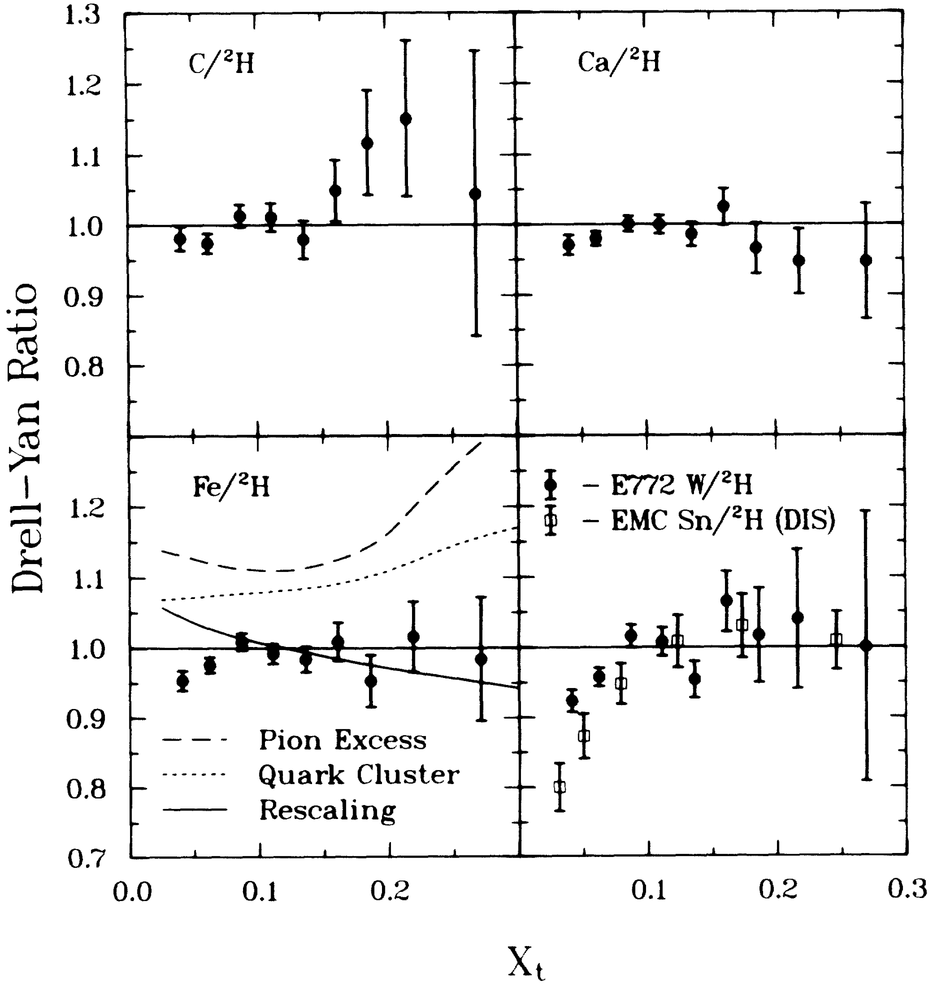
C12-22-002: Conditionally approved to run in Hall A using SoLID (50 days)

What about anti-quarks?

- Most models of the EMC effect ignore anti-quarks



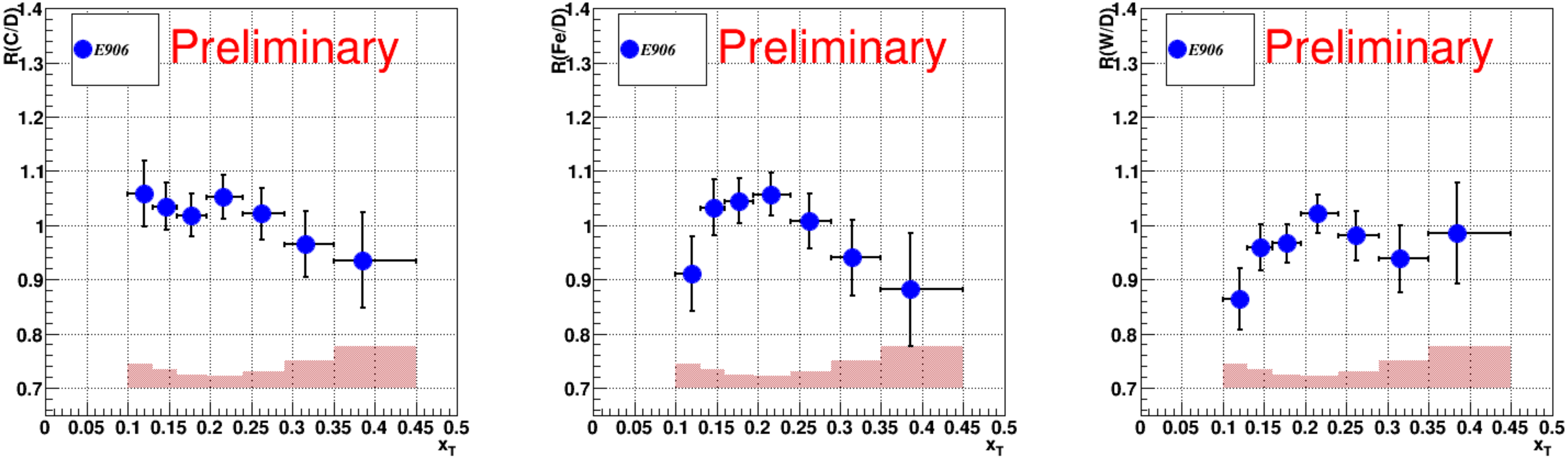
- The "pion excess" picture suggests that the anti-quark distributions should be enhanced in nuclei
  - Measured using Drell-Yan reaction by E772 at Fermilab
- Significant contributions from nuclear pions ruled out
- Limited x range



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

E906 (SEAQUEST) should provide improved precision at larger x

SEAQUEST results



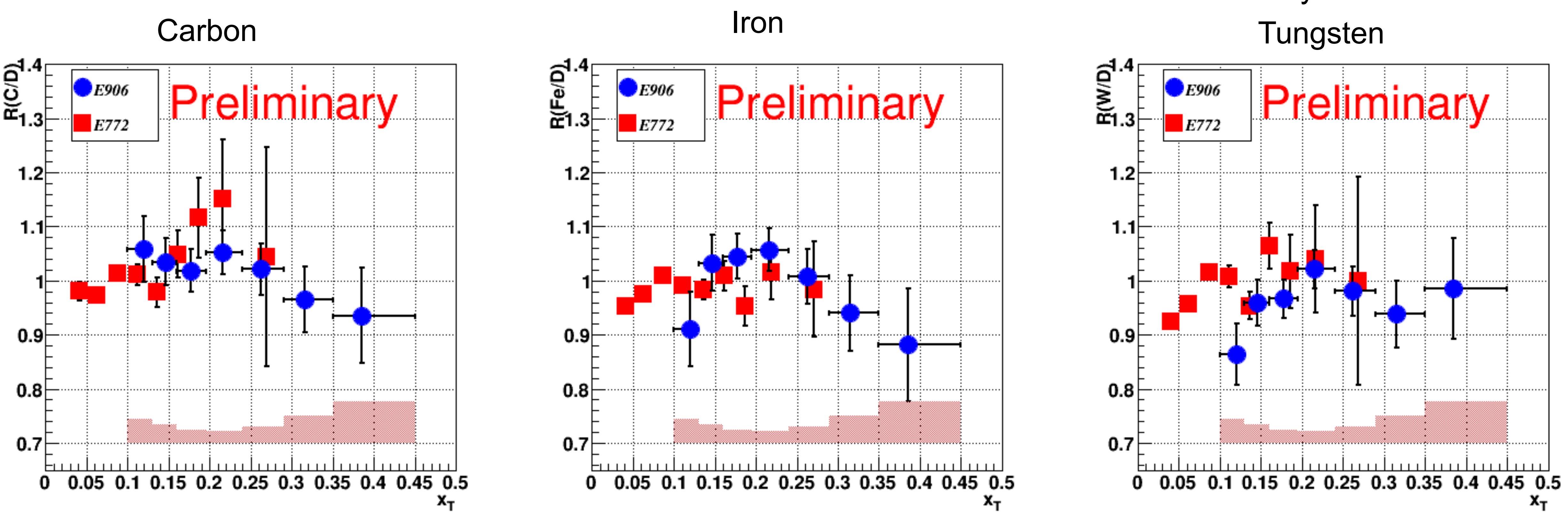
- No enhancement seen as in the case of a pion excess model!
- EMC like behavior is displayed but results are consistent with 1

Slide courtesy Arun Tadepalli

SEAQUEST Comparison with E772

Slide courtesy Arun Tadepalli

*E772 systematics not shown



- No enhancement seen as in the case of a pion excess model!
- EMC like behavior is displayed but results are consistent with 1
- Basically in agreement with E772 results in the overlap region

Further Studies of the EMC Effect via Inclusive Target Ratios?

EMC effect has been studied extensively via A/D ratios – what more can we learn?

→Additional light and heavy nuclei
→Light nuclei allow use of "exact" nuclear wave functions
→Explore EMC-SRC connection via A dependence at ~ fixed N/Z, N/Z dependence at ~ fixed A
→Flavor dependence from inclusive measurements?

JLab E12-10-008: More detailed study of Nuclear Dependence

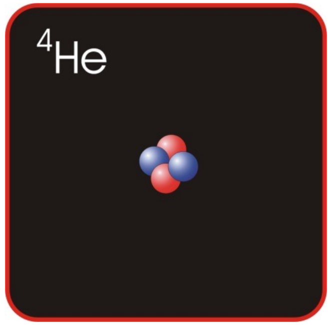
Spokespersons: J. Arrington, A. Daniel, N. Fomin, D. Gaskell

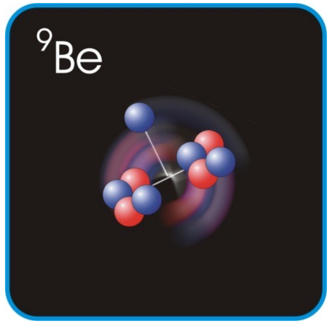
E03-103: EMC at 6 GeV

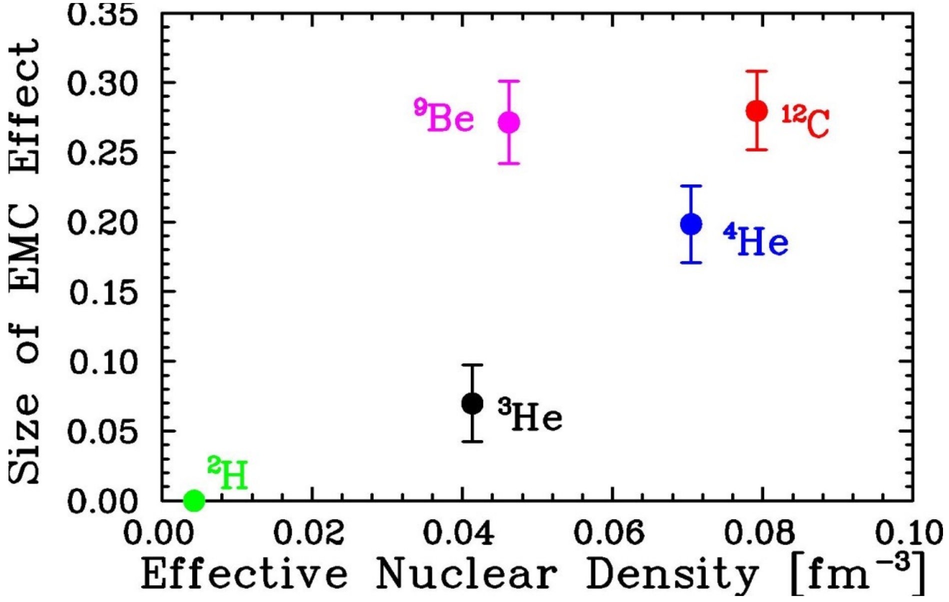
→ Focused on light nuclei

→ Large EMC effect for ^{9}Be

→ Local density/cluster effects?







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

E12-10-008: EMC effect at 12 GeV

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

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

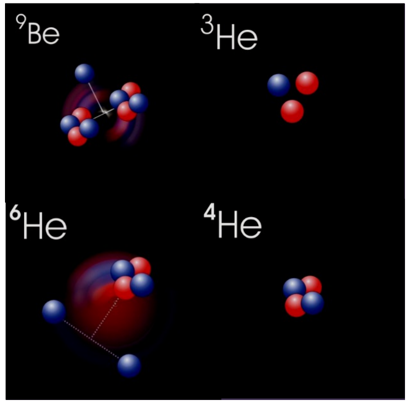
→ Heavy nuclei include ^{40}Ca, ^{48}Ca and Cu and additional heavy nuclei of particular interest for EMC-SRC correlation studies

JLab: E12-10-008 (EMC) and E12-06-105 (x>1) – Exploring the EMC-SRC Connection

- Both experiments use wide range of nuclear targets to study impact of cluster structure, separate mass and isospin dependence on SRCs, nuclear PDFs
- Experiments will use a common set of targets to provide more information in the EMC-SRC connection

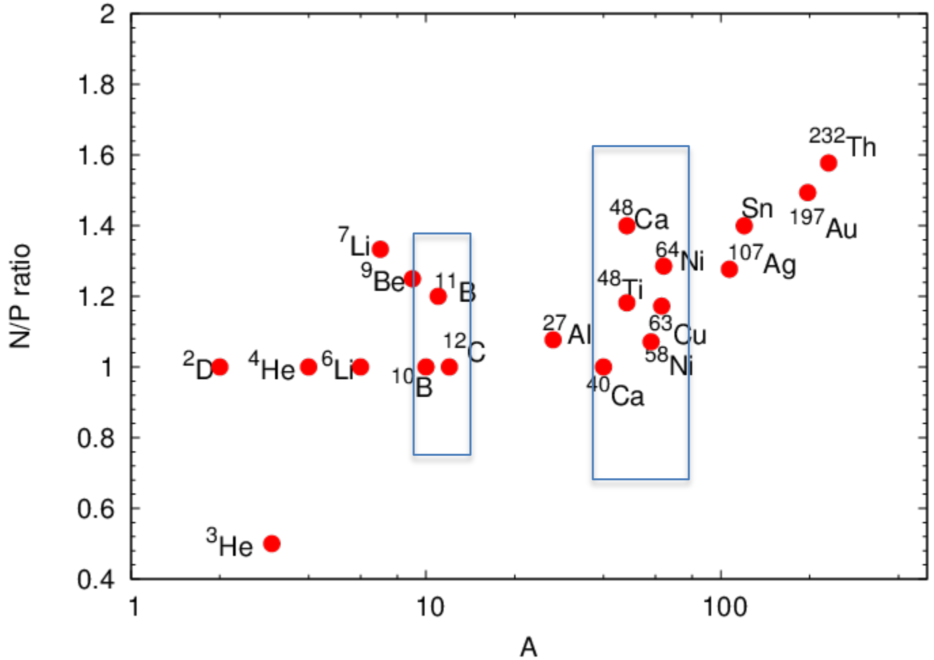
Light nuclei: Reliable calculations of nuclear structure (e.g. clustering)

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



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

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



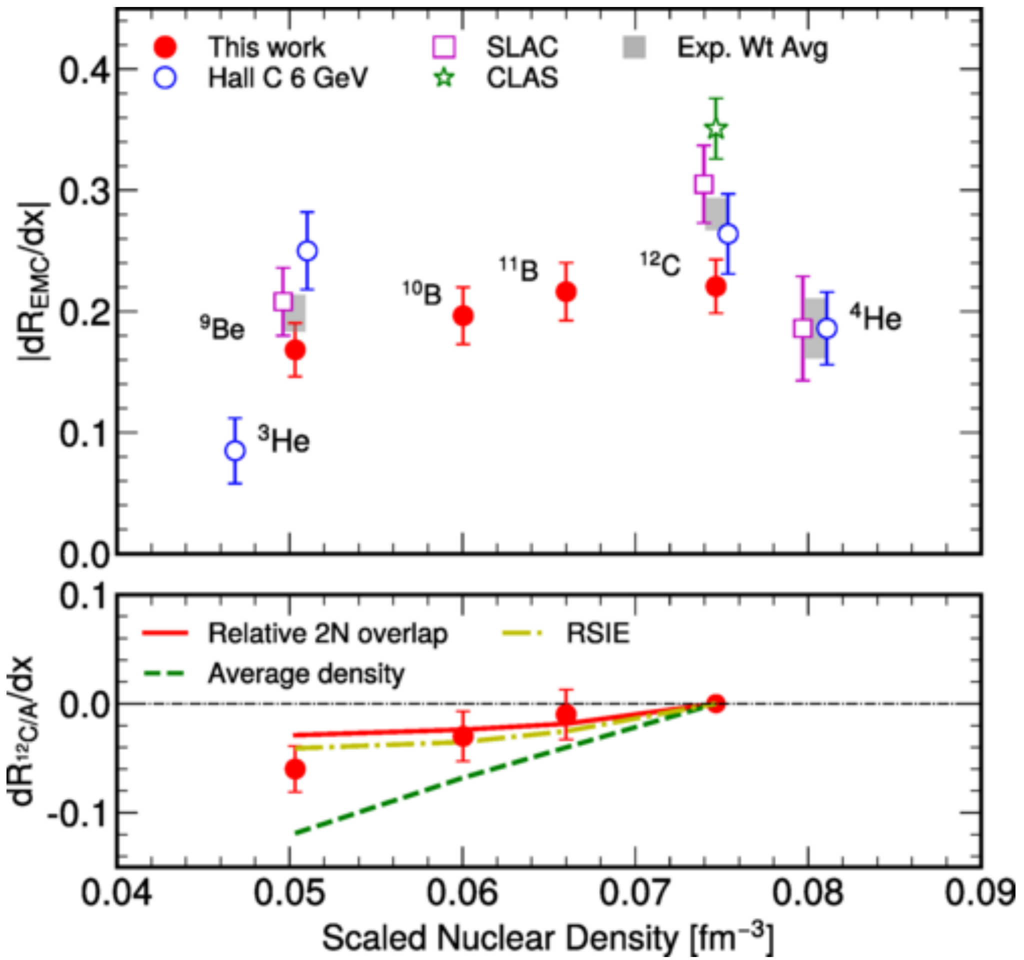
EMC Effect in ^{10}B and ^{11}B

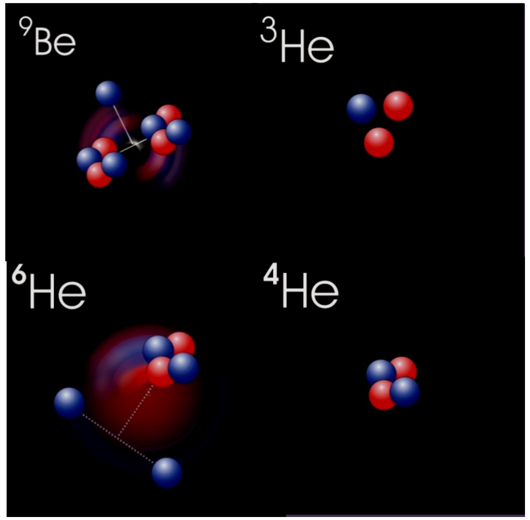
A few days of the allocated time E12-10-008 used in 2018 to help commission the new Hall C equipment after 12 GeV upgrade

EMC Effect in ^{10}B and ^{11}B found to be similar to ^{4}He, ^{9}Be, ^{12}C

→ Both boron isotopes have significant α cluster structure like ^{9}Be and ^{12}C

→ Reinforces "local density" picture





EMC Effect in ^{10}B and ^{11}B

A few days of the allocated time E12-10-008 used in 2018 to help commission the new Hall C equipment after 12 GeV upgrade

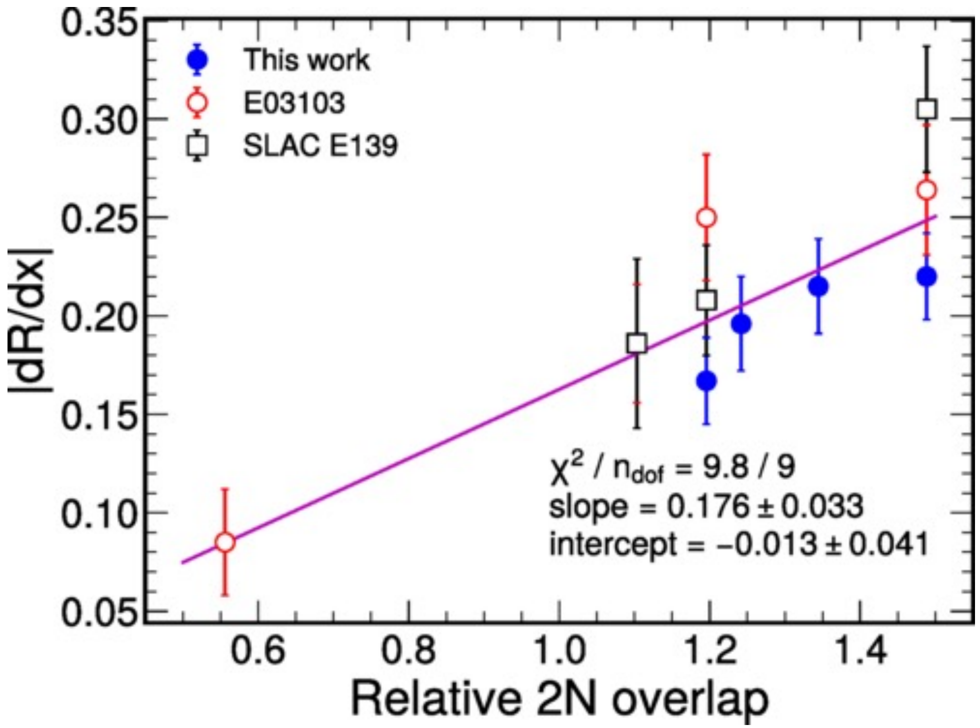
EMC Effect in ^{10}B and ^{11}B found to be similar to ^{4}He, ^{9}Be, ^{12}C

→ Both boron isotopes have significant α cluster structure like ^{9}Be and ^{12}C

→ Reinforces "local density" picture

Can also define the "relative 2-nucleon overlap"

$$O_{rel} = \langle O_N \rangle - \langle O_D \rangle$$



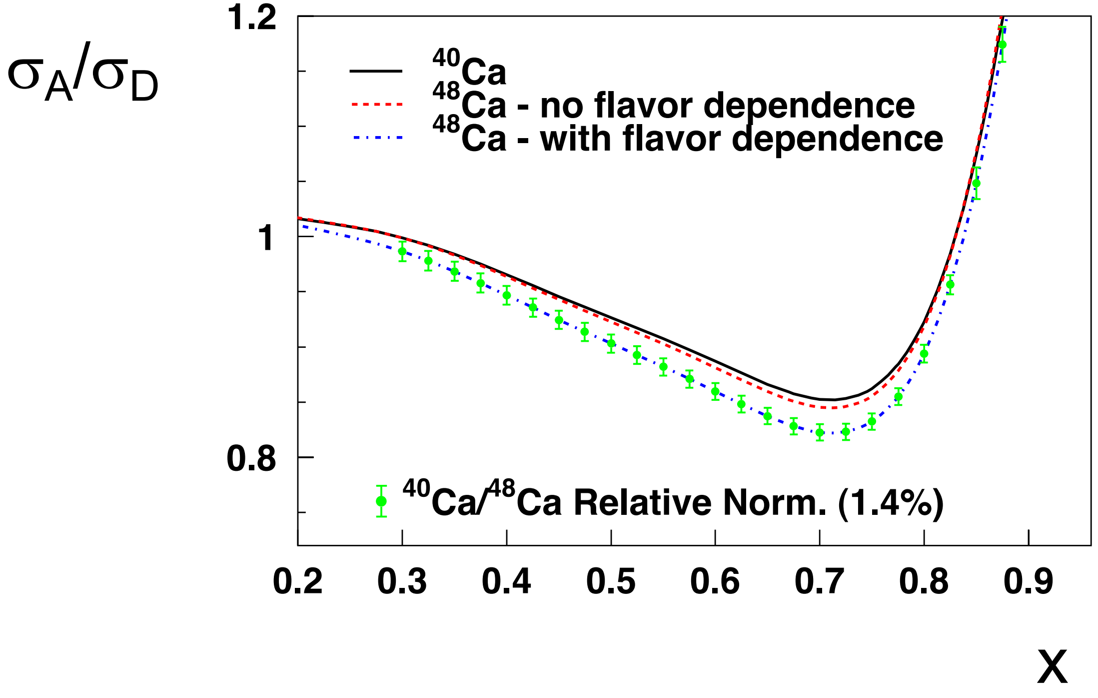
Derived from probability to find 2 nucleons "close" to each other

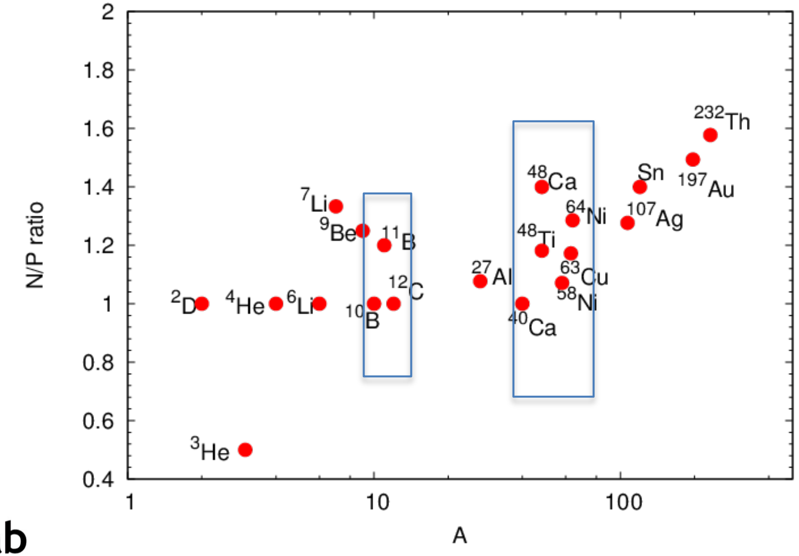
Flavor dependence from Inclusive ^{40}Ca and ^{48}Ca

Measure inclusive EMC effect for similar A, different N/Z

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

If there is no flavor dependence, difference between ^{40}Ca and ^{48}Ca should be less than 1% (SLAC E139 A-dependent parametrization)





E12-10-008 expands on this idea by measuring several nuclei with similar A, but varying N/Z

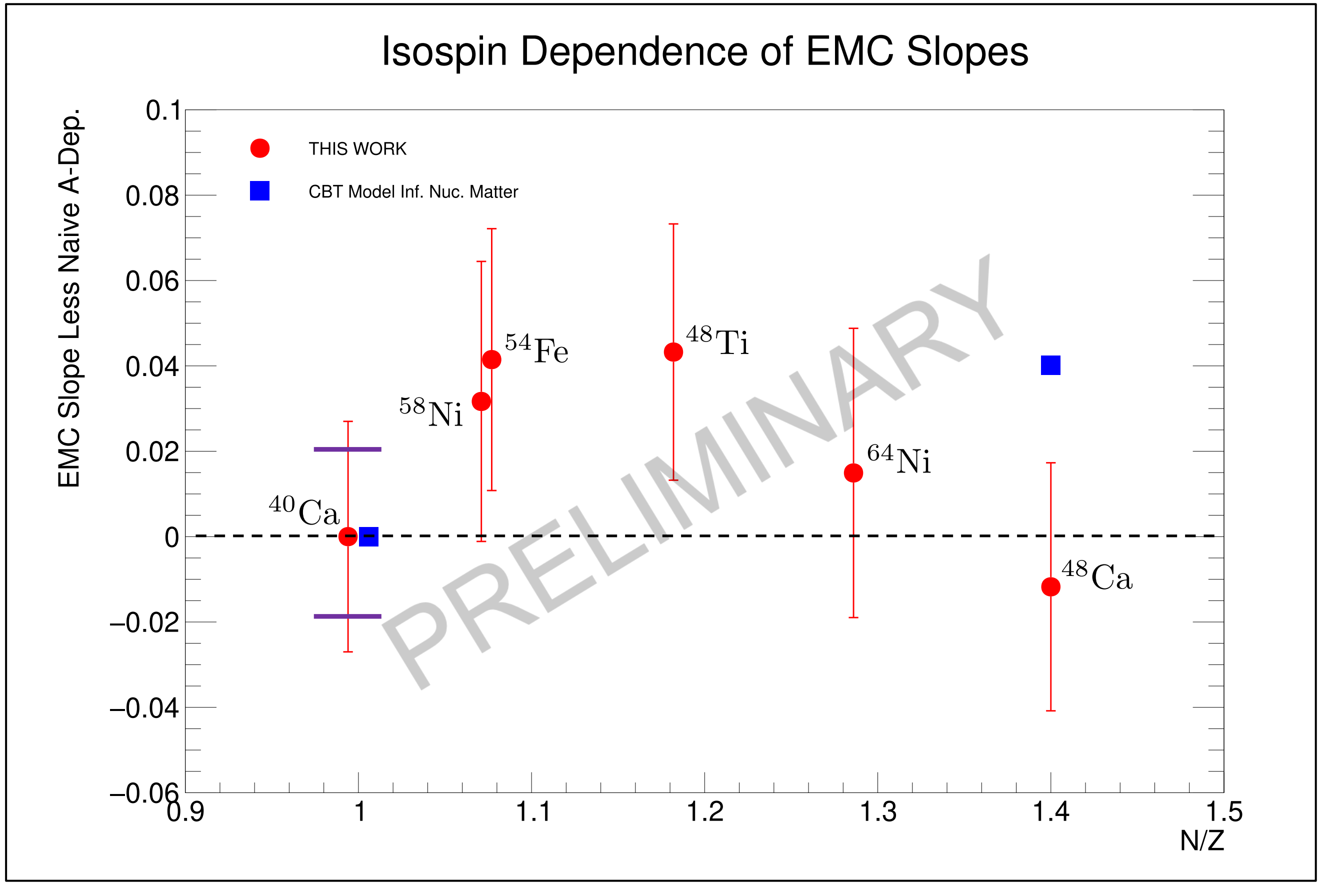
Preliminary Extraction of N/Z Dependence

Cameron Cotton (UVa) focused on study of N/Z dependence of EMC Effect

→ Extracted size of EMC Effect for ^{40}Ca, ^{48}Ca, ^{48}Ti, ^{58}Ni, ^{64}Ni, ^{54}Fe
→ Removed A-dependence of EMC Effect using fit to isoscalar nuclei
→ Compared A>40 nuclei relative to ^{40}Ca

Model from Cloët, Bentz, and Thomas would result in larger EMC Effect for ^{48}Ca→ results suggest little or no difference

Trend vs. N/Z also not understood

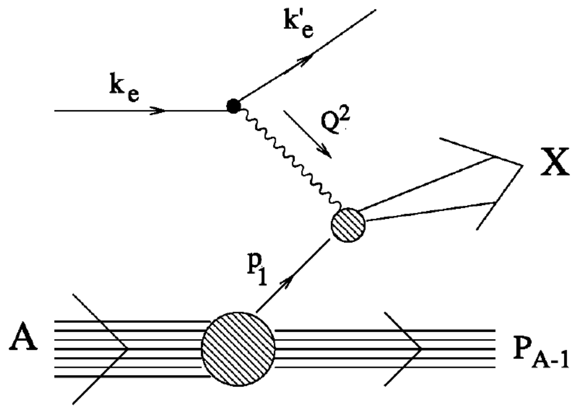


Ratios above all relative to deuterium → there is a correlated error that should be removed
→ Purple error bar = estimated uncertainty after removing correlated piece

Spectator Tagging and the EMC Effect

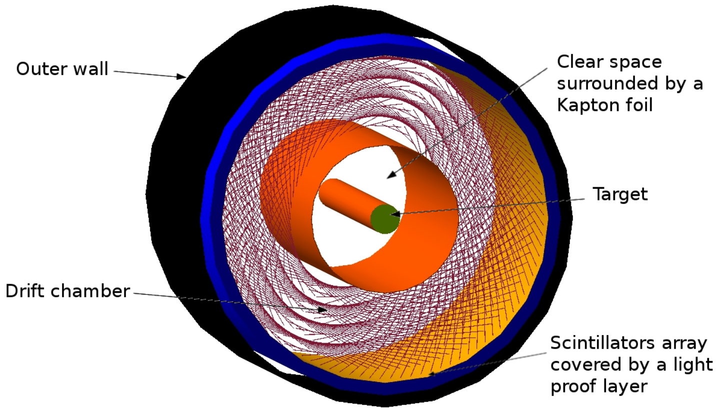
Spectator tagging can be used to determine the kinematics of the struck nucleon

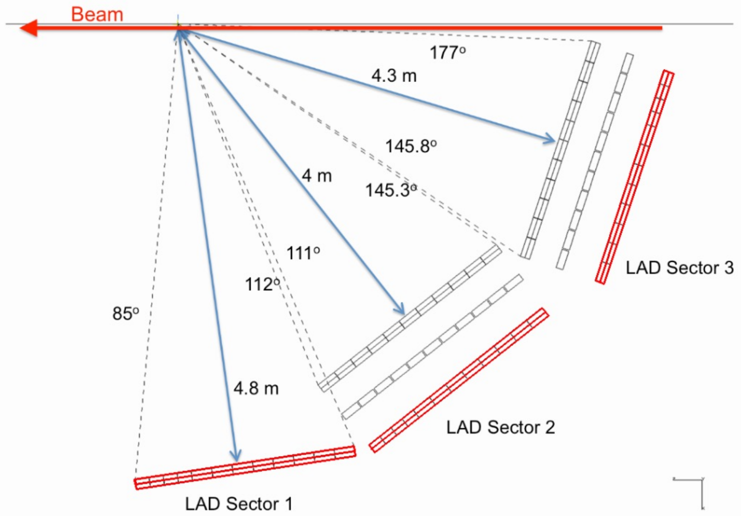
2 complementary programs of ”tagged EMC” measurements at JLab



1. Low energy recoil detector for reconstructing residual, recoiling nucleus

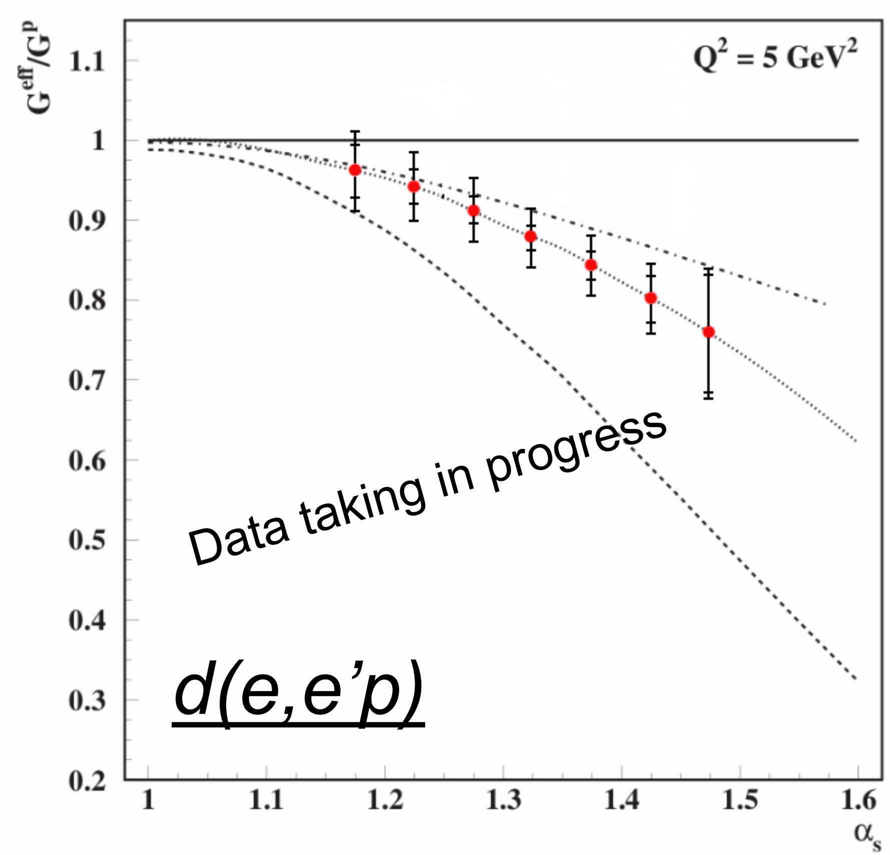
2. Backward angle proton/neutron detectors to sample high momentum (hundreds of MeV) nucleons

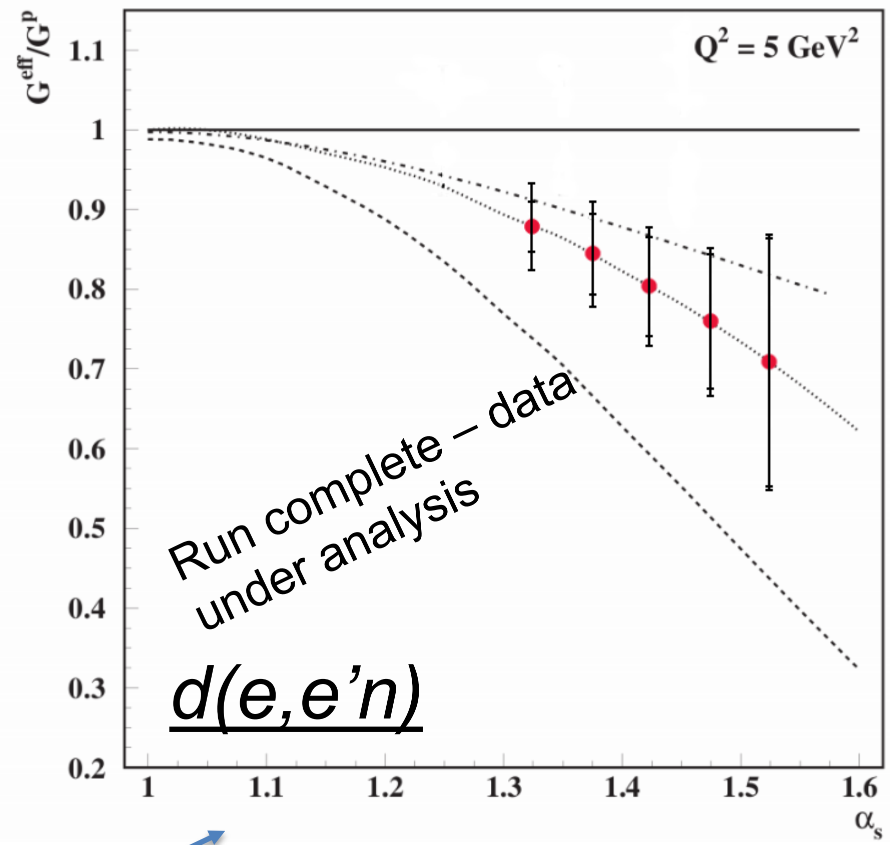




Spokespersons: O. Hen, L. Weinstein, S. Gilad, S. Wood. H. Hakobyan

E12-11-107 (Hall C) and E12-11-003a (Hall B)





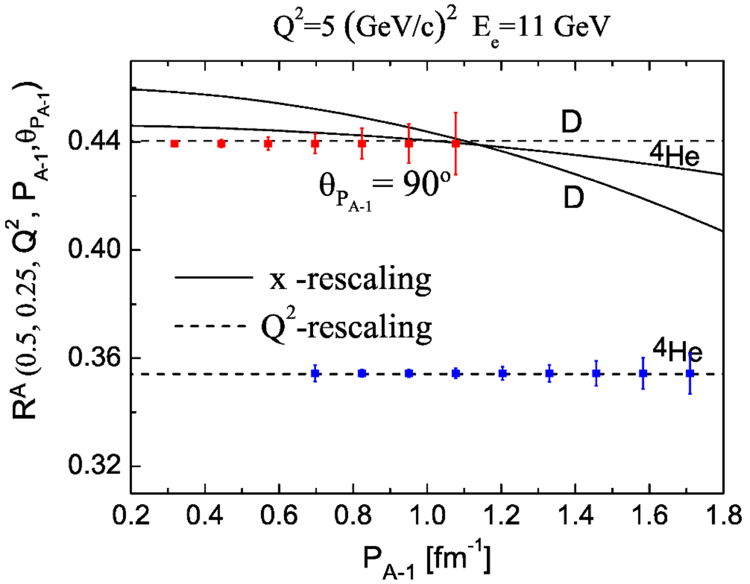
Nucleon virtuality: $\alpha_s = (E_s - p_s^z)/m_s$

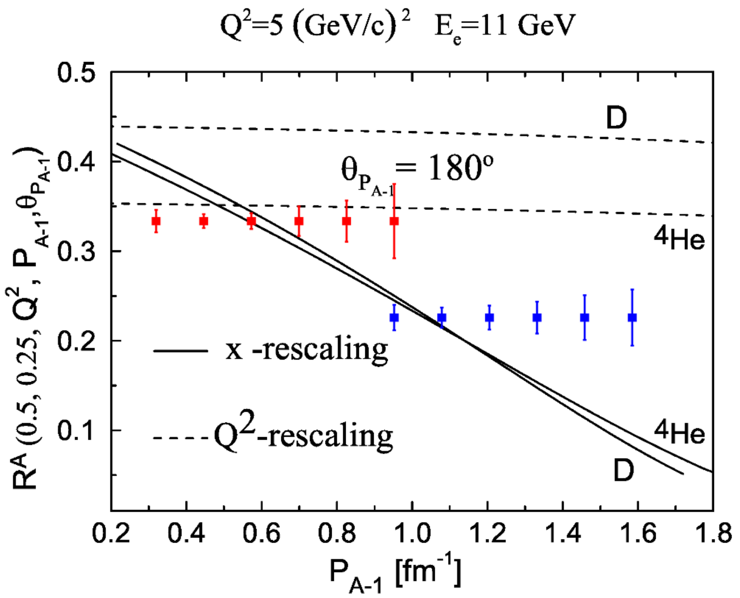
Measure structure function of high momentum nucleon in **deuterium** by tagging the spectator

→Take ratio of yield at large x (EMC region) to low x (no EMC expected)

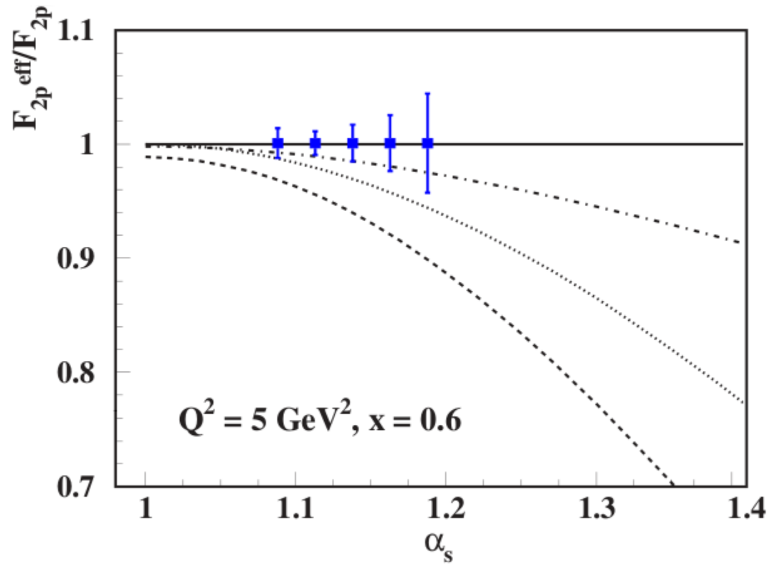
→Requires new, large acceptance proton/neutron detectors at back angles

ALERT Program in Hall B





$$R^A(x_B, x'_B, Q^2, |\vec{P}_{A-1}|) \equiv \frac{\sigma_1^A(x_B, Q^2, |\vec{P}_{A-1}|, z_1^{(A)}, y_A)}{\sigma_1^A(x'_B, Q^2, |\vec{P}_{A-1}|, z_1^{(A)}, y_A)},$$



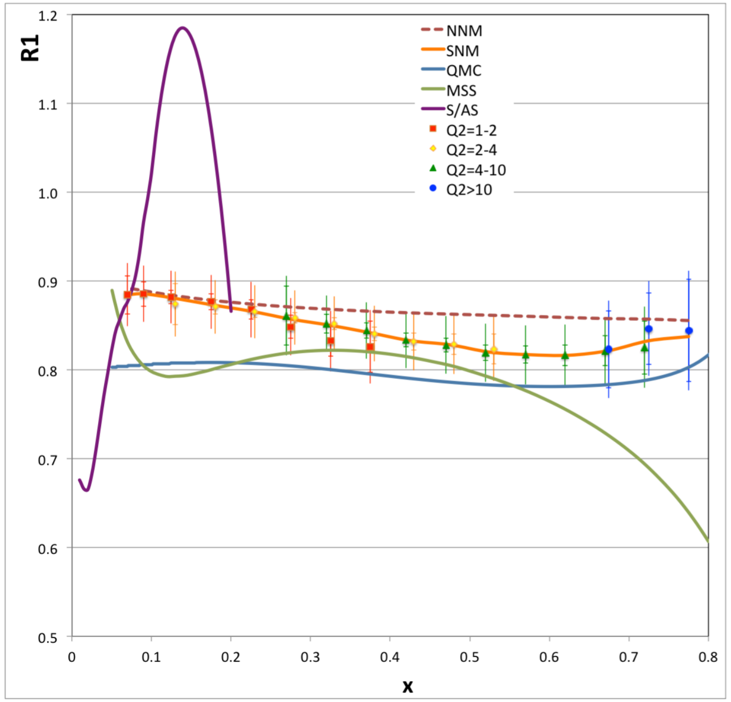
Low energy recoil detector gives high precision at low to moderate virtuality

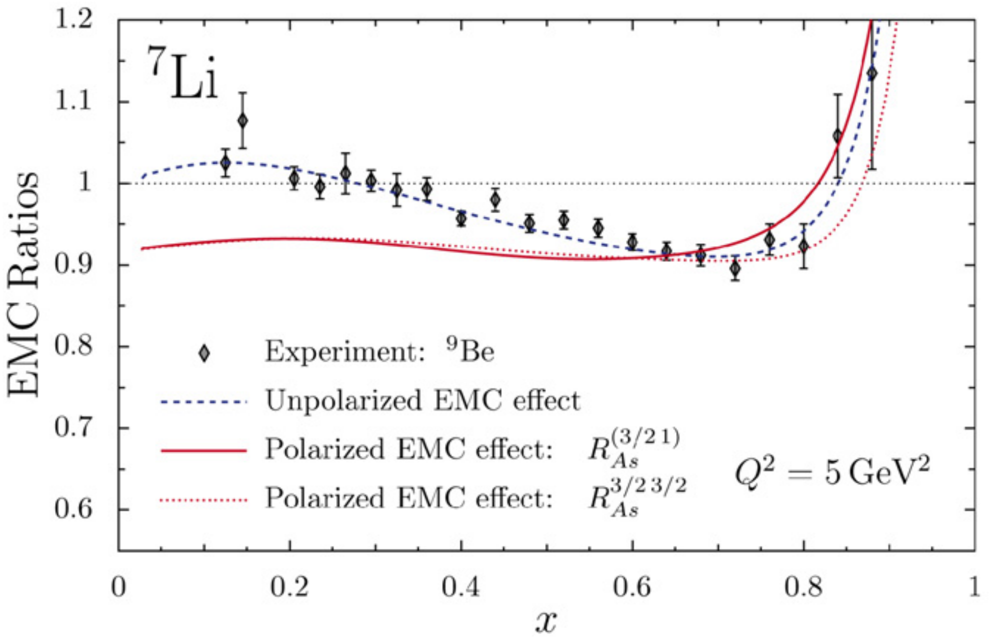
→ Significant difference between "*x*-rescaling" (binding) and Q^2 rescaling models

Polarized EMC Effect

Similar to unpolarized DIS, can define nuclear ratio for polarized structure functions

$$R = \frac{F_2^A}{ZF_2^p + (A-Z)F_2^n} \qquad R = \frac{g_{1A}}{P_p g_{1p} + P_n g_{1n}}$$





Cloët, Bentz, and Thomas, Phys. Lett. B 642 (2006) 210–217

JLab E12-14-001 in Hall B will use ^{7}LiD solid polarized target

Polarized EMC effect provides another possible handle on connection to SRCs
→ Smaller fraction of polarized nucleons involved in SRCs

Intermediate conclusions

- Connection between EMC Effect and SRCs and theory developments have suggested new avenues of investigation
  - Tagged EMC measurements
  - Investigation of flavor dependence (valence)
    - Several methods → preliminary Hall C results
  - Spin-dependent EMC effect

Nuclear dependence of structure functions

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

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

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

$$\frac{\sigma_A}{\sigma_D} = \frac{F_2^A(1+\epsilon R_A)(1+R_D)}{F_2^D(1+R_A)(1+\epsilon R_D)}$$

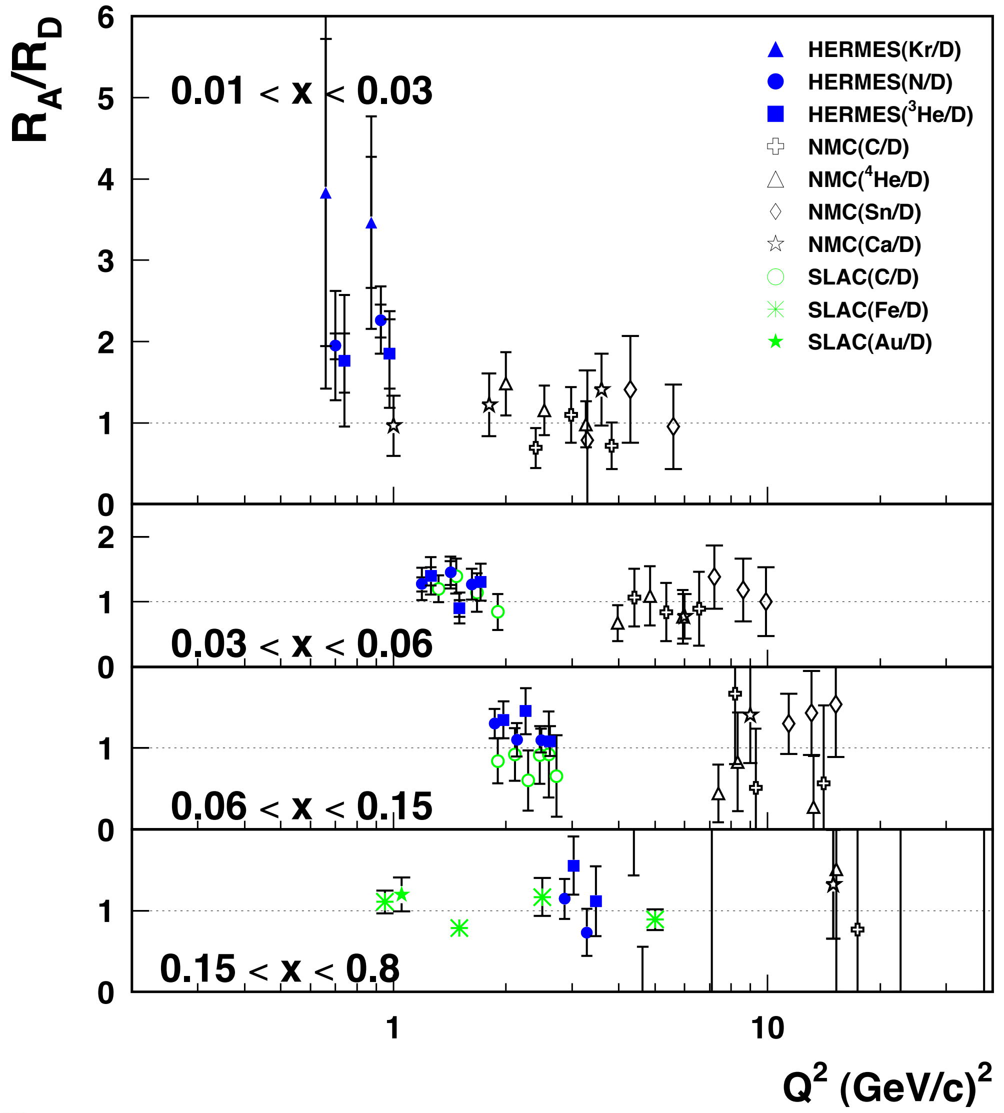
In the limit $R_A = R_D$ or ε=1 → $\boxed{\sigma_A/\sigma_D = F_2^A/F_2^D}$

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 $\sigma \rightarrow F_2$ translation. Sometimes there is not.

World Data on R_A/R_D

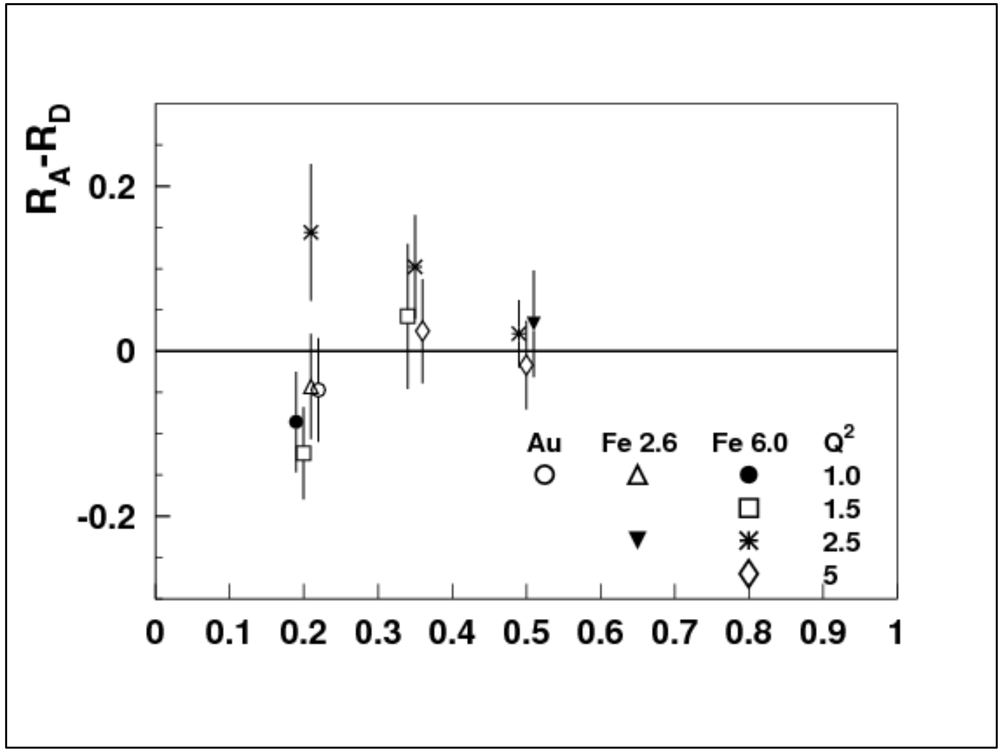


<u>SLAC E140:</u> *PRD 49, 5641 (1994)*
R_A-R_D for Fe, Au
Only true Rosenbluth separated data

<u>NMC:</u>
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***

<u>HERMES:</u>
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*)

SLAC E140: R_A-R_D



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

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

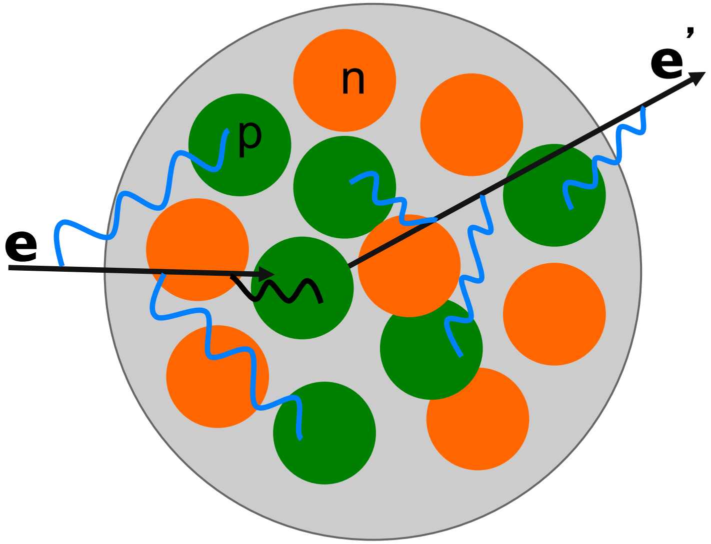
x=0.2, 0.35, 0.5
Q^2 = 1.0, 1.5, 2.5, 5.0 GeV^2
Iron and Gold targets

$R_A - R_D$ consistent with zero within errors

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**

Coulomb Distortion in Heavy Nuclei



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

→ This effect is in general **NOT** included in most radiative corrections procedures

→ *Coulomb Corrections are perhaps more appropriately described in terms of multi-photon exchange, but Coulomb Corrections provide convenient shorthand*

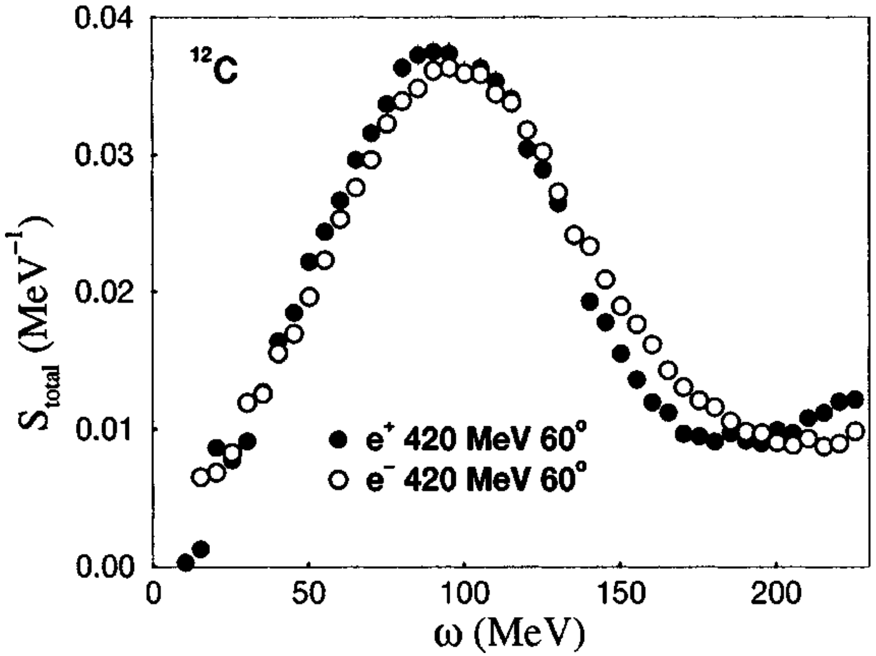
- Well-known effect in QE scattering - relevant particularly for Coulomb sum rule
- Can be calculated in QE using DWBA → experimentalists use Effective Momentum Approximation (EMA) to apply corrections to data
- Comparisons of EMA with detailed DWBA calculations resulted in "improved EMA"

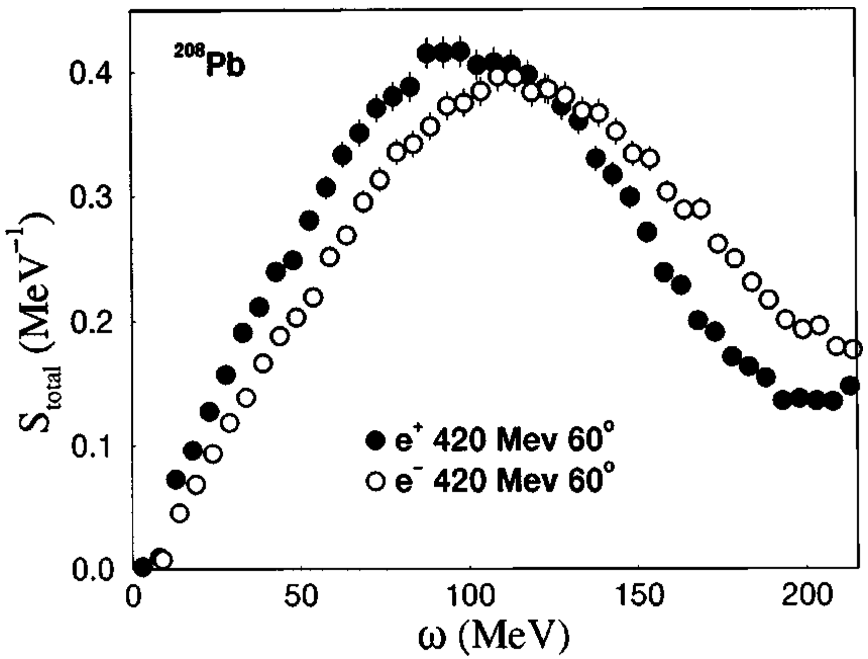
$$E_e \rightarrow E_e + V_0 \qquad E_e' \rightarrow E_e' + V_0 \quad \text{with "focusing factor"} \quad F^2 = (1+V_0/E_e)^2$$

$$V_0 \rightarrow (0.7\text{-}0.8)V_0, \quad V_0 = 3\alpha(Z-1)/2R$$

[Aste et al, Nucl. Phys. A, 806:191-215 (2008) Eur.Phys.J.A26:167-178,2005, Europhys.Lett.67:753-759,2004]

Electron-Positron Comparisons in QE Scattering





Gueye et al., PRC60, 044308 (1999)

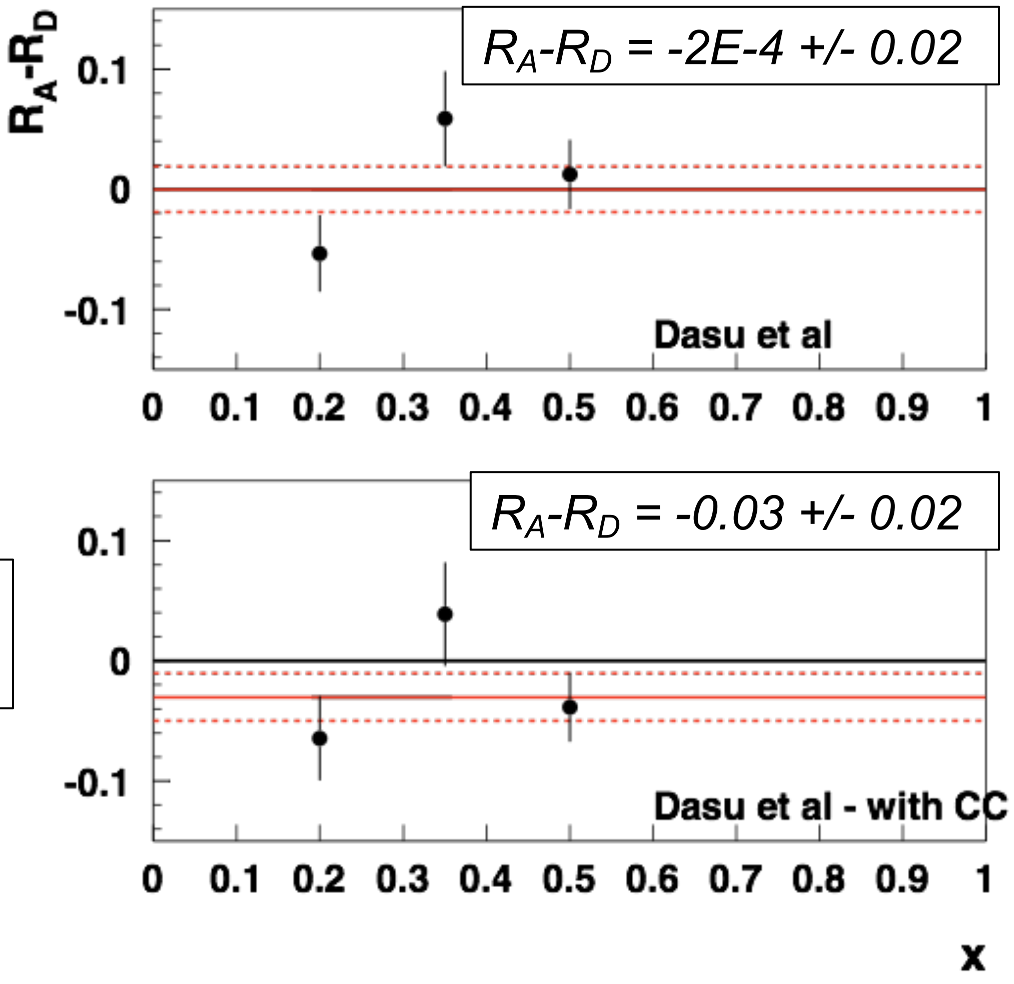
- Comparisons of electron and positron scattering have been performed in QE scattering
- Were used to fit V_0 in context of EMA
- V_0 = 10 MeV for Fe, 20 MeV for Fe

Coulomb Corrections in Inelastic Scattering

- E. Calva-Tellez and D.R. Yennie, Phys. Rev. D 20, 105 (1979)
  - Perturbative expansion in powers of strength of Coulomb field
  - Effect of order → $-\frac{Z\alpha}{12}\frac{(Q^2)^2}{\nu^2}\frac{(E_e+E'_e)}{E_eE'_e} < r >$
  - "For any reasonable kinematics, this is completely negligible" → plugging in JLab/SLAC kinematics, this is not true!
- B. Kopeliovich et al., Eur. Phys. J. A 11, 345 (2001)
  - Estimates non-zero effect using Eikonal approximation → applies estimates to vector meson production, not DIS
- O. Nachtmann, Nucl. Phys. B 18, 112 (1970)
  - Coulomb Corrections for neutrino reactions
  - DWBA calculation that results in modifications to structure functions → "at most 5%" effects for energies > 1 GeV
  - Final state particle only, not directly applicable to electron/positron scattering

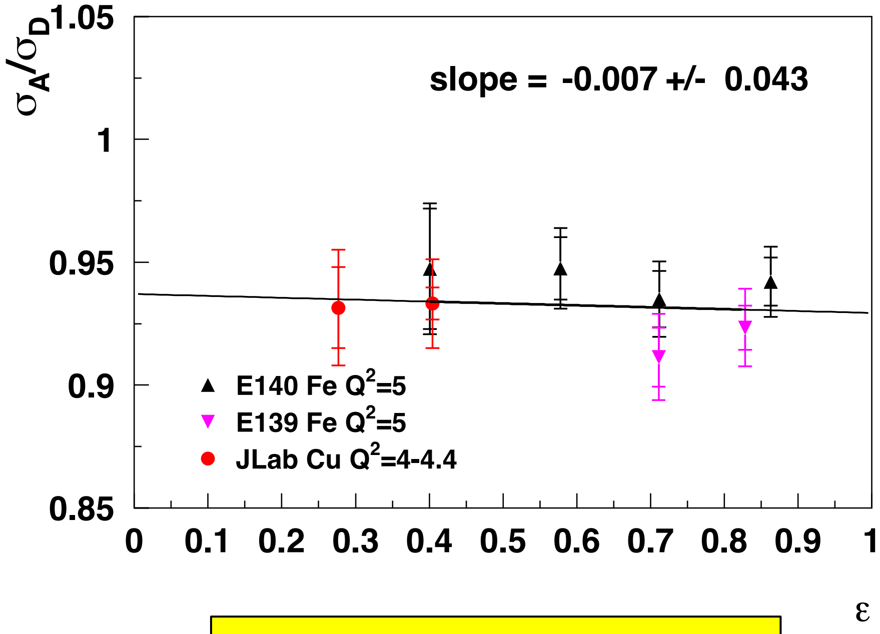
R_A-R_D: E140 Re-analysis

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

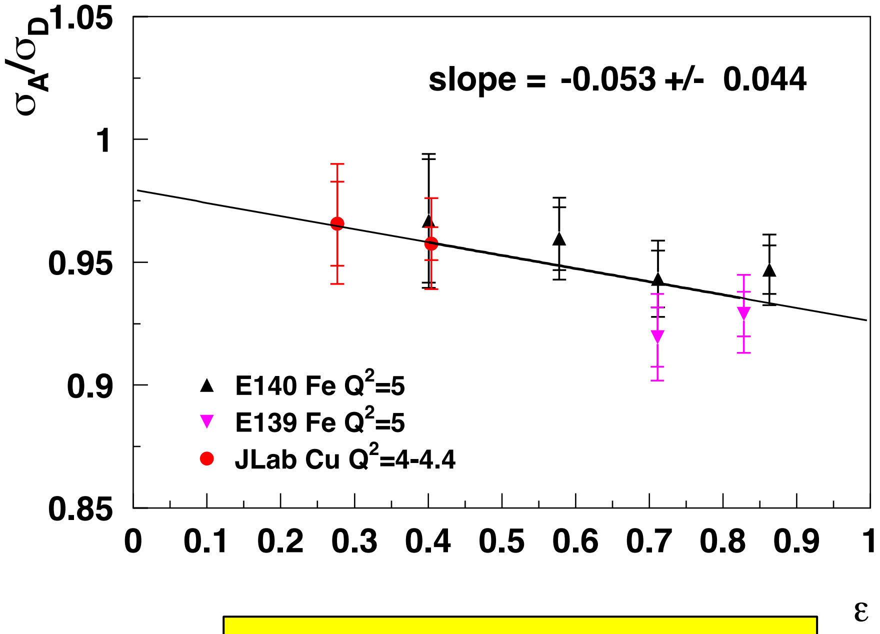


Including Coulomb Corrections yields result 1.5 σ from zero when averaged over ***x***

R_A-R_D at $x=0.5$ (combined analysis)



No Coulomb Corrections



with Coulomb Corrections

PRC 104(6):065203, 2021

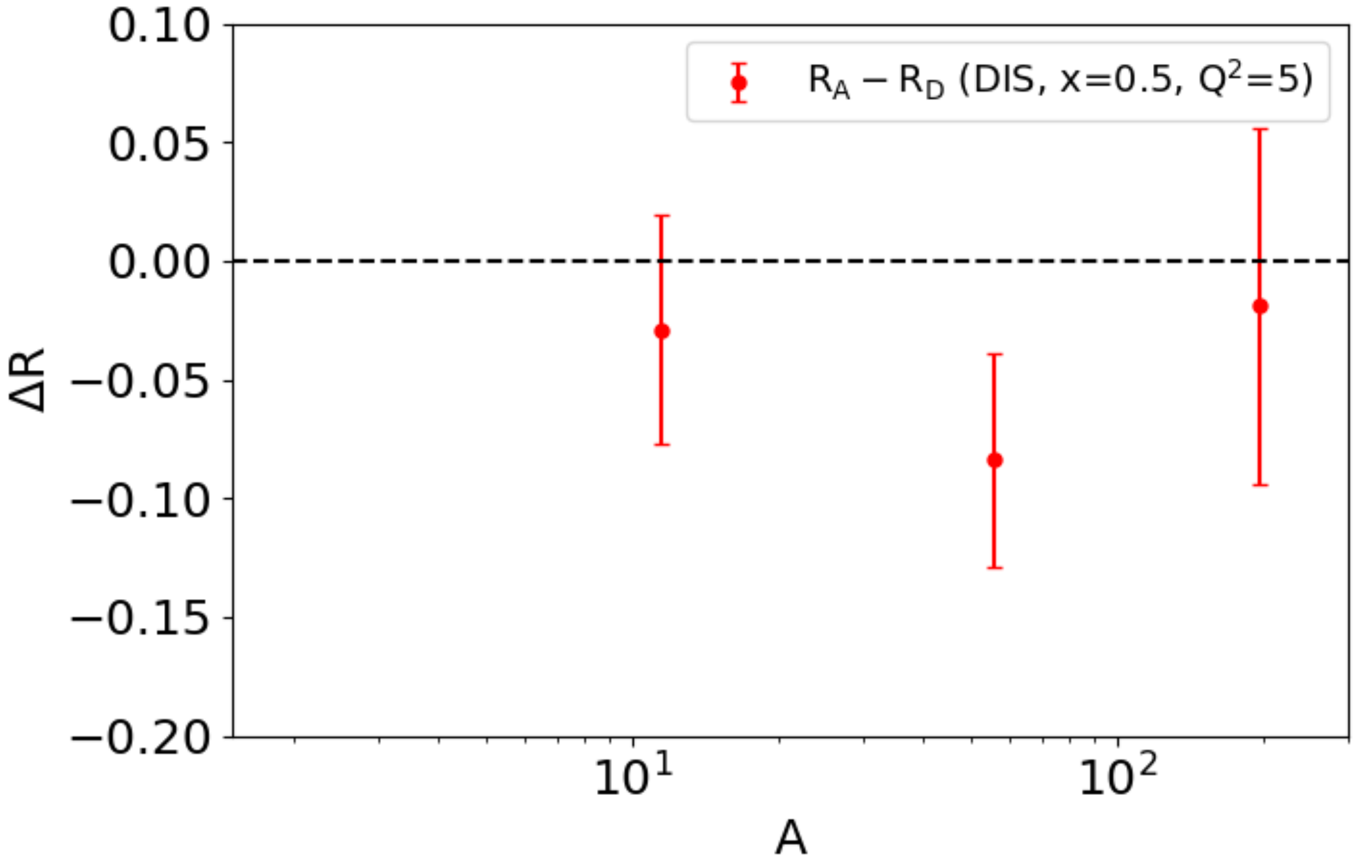
Combined analysis of SLAC E139, E140 and JLab 6 GeV data for Fe/Cu at $x=0.5$, $Q^2\sim5\ GeV^2$

Nuclear Dependence of R

Combined fit to SLAC E139, E140, and JLab E03103 data
→ Examined A-dependence of R_A-R_D at x=0.5, Q^2=5 GeV^2

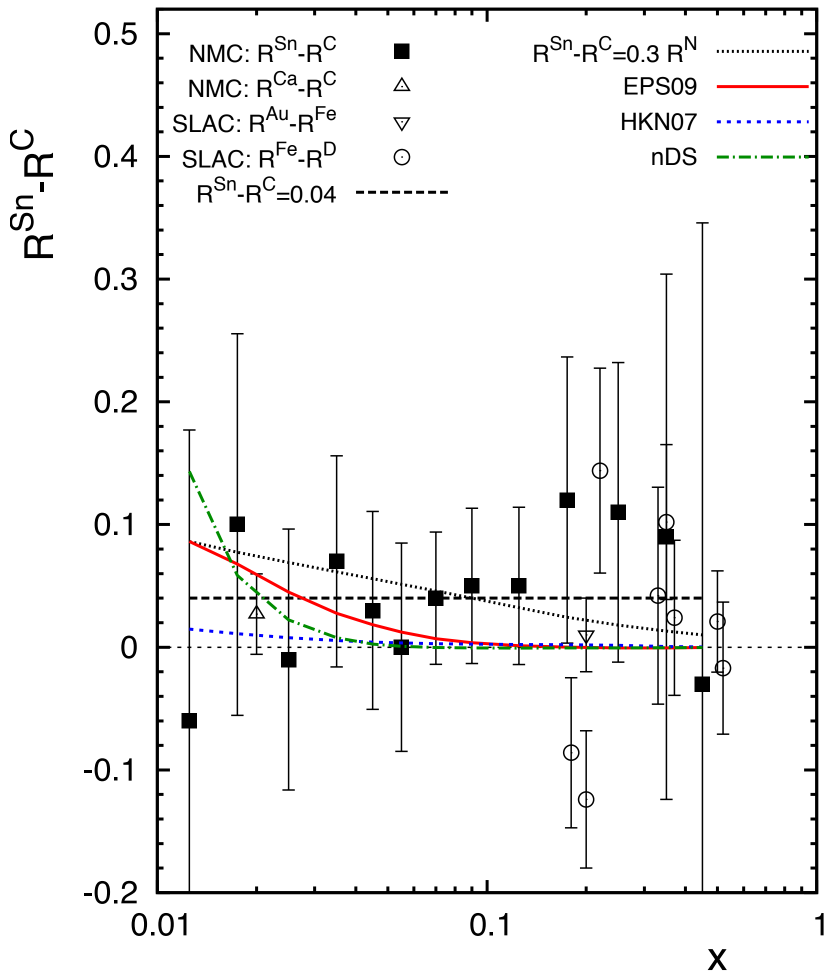
Data lack precision to make definitive conclusion

→ More data required!



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

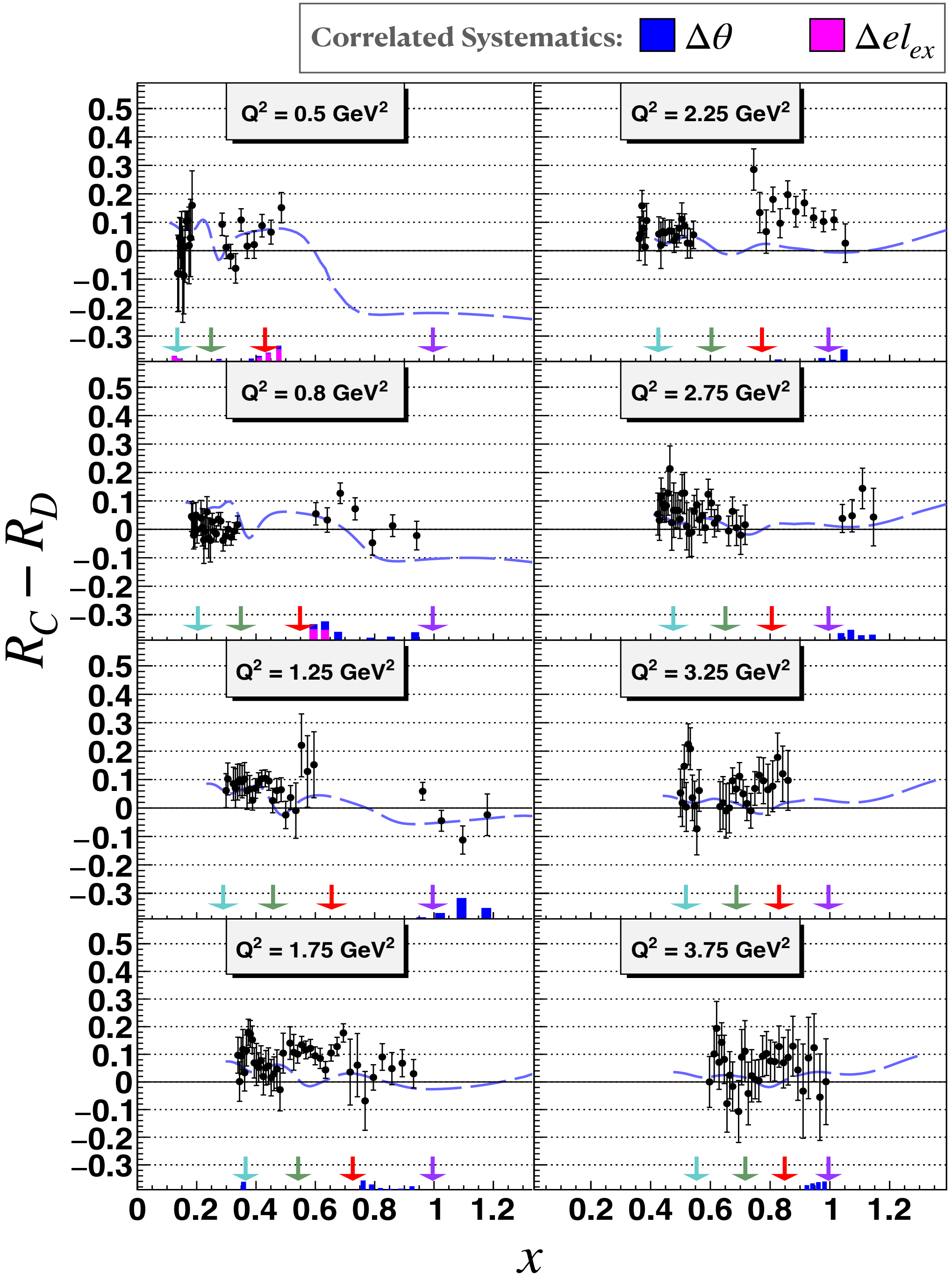
Other Hints of non-zero R_A-R_D

Hall C measurements in resonance region indicate R_A-R_D>0

→ Combined analysis in DIS region suggests R_A-R_D<0 in DIS region

→ Hall C measurement has some DIS coverage as well

Measurements inconsistent?



S. Alsalmi et al, 2501.13316 [nucl-ex]

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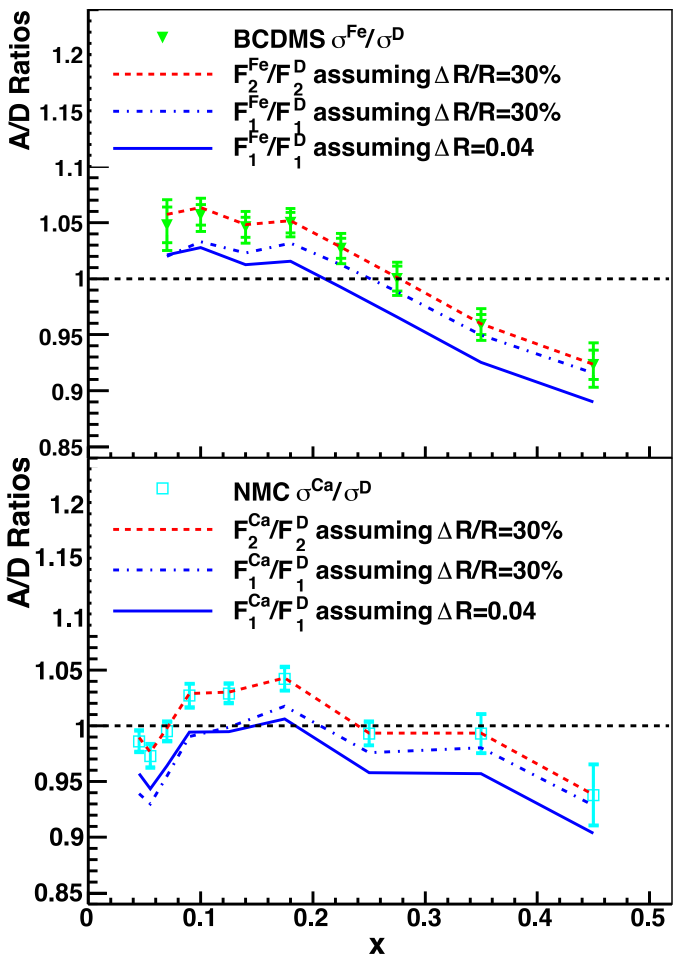
Consequences of R_A-R_D >0



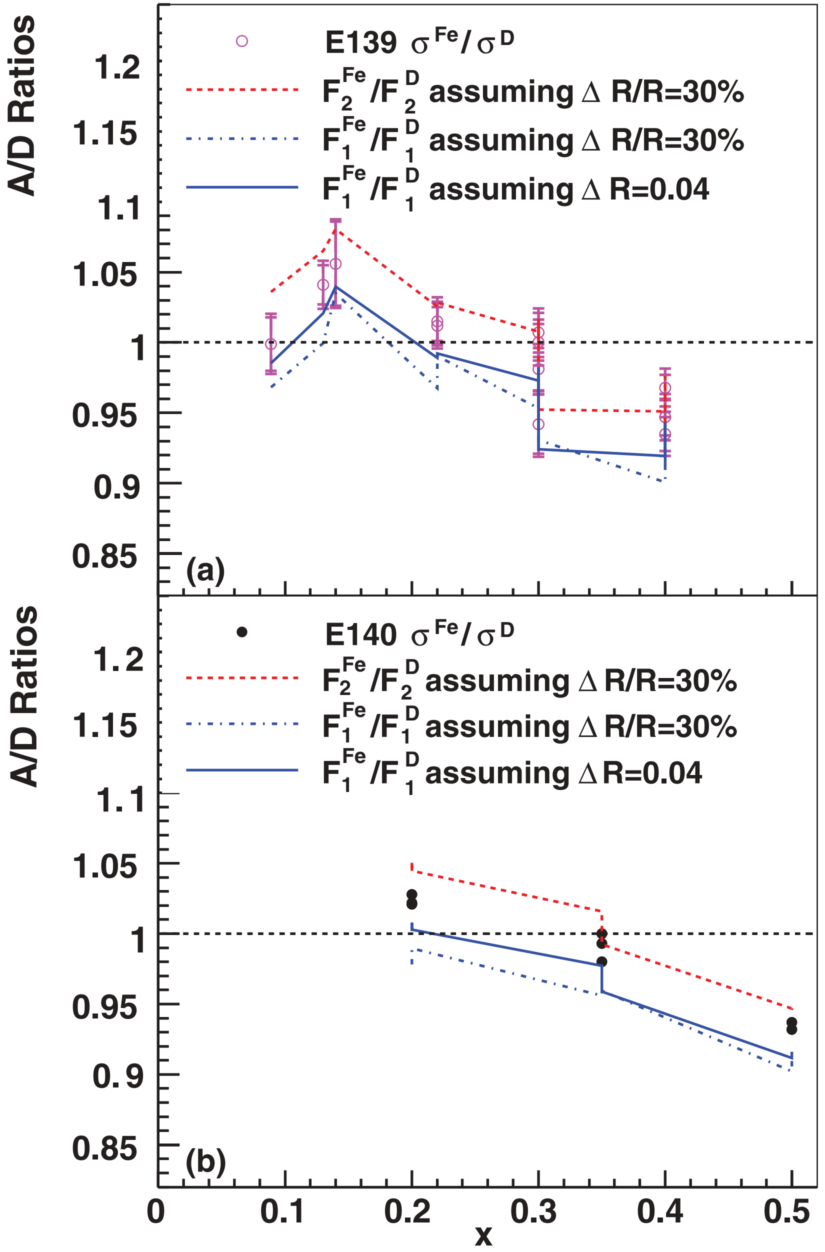
$$\frac{\sigma_A}{\sigma_D} = \frac{F_1^A(x)}{F_1^D(x)} \left[1 + \frac{\epsilon(R_A - R_D)}{1 + \epsilon R_D} \right]$$

F_1 ratio purely transverse

Anti-shadowing disappears for F_1 ratio, remains for F_2

Anti-shadowing from longitudinal photons?

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



Consequences of R_A-R_D >0

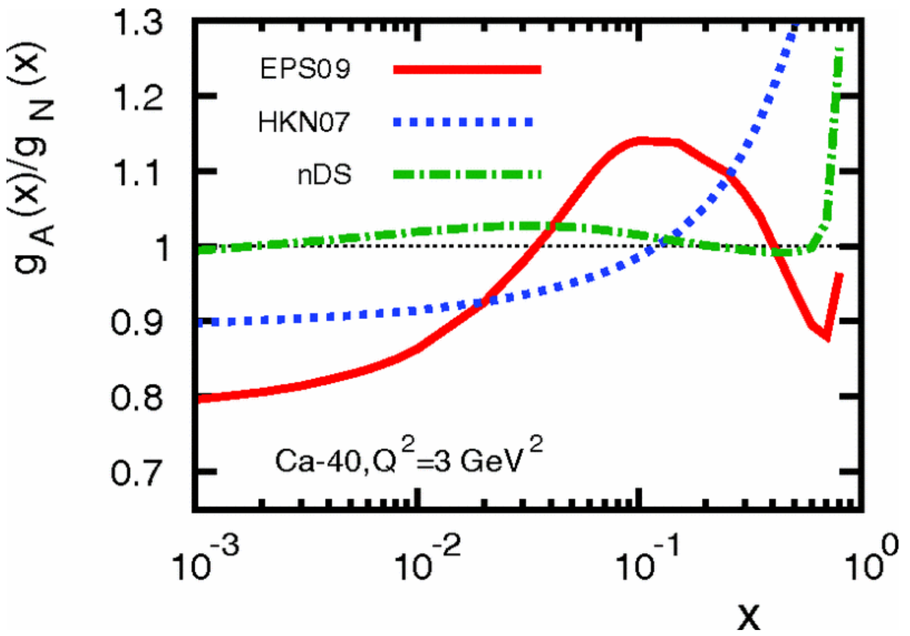
$$\frac{\sigma_A}{\sigma_D} = \frac{F_1^A(x)}{F_1^D(x)}\left[1 + \frac{\epsilon(R_A - R_D)}{1+\epsilon R_D}\right]$$

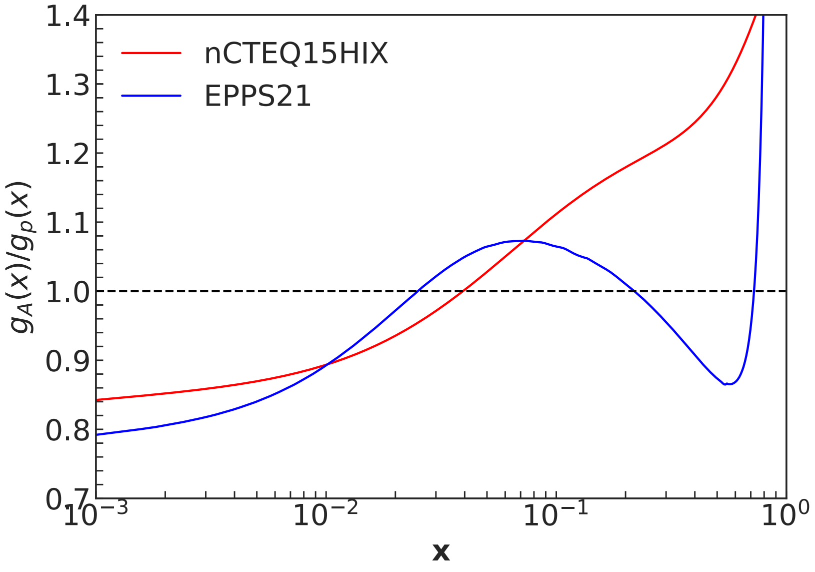
F_1 ratio purely transverse

- Anti-shadowing disappears for F_1 ratio, remains for F_2
- Anti-shadowing from longitudinal photons?
- ***Non-trivial change to EMC ratio at larger x***
- Parton model: $R=4\langle k_T^2\rangle/Q^2$
    - $\langle k_T^2\rangle$ smaller for bound nucleons?
      [*A. Bodek, PoS DIS2015 (2015) 026*]

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

Nuclear Dependence of F_L





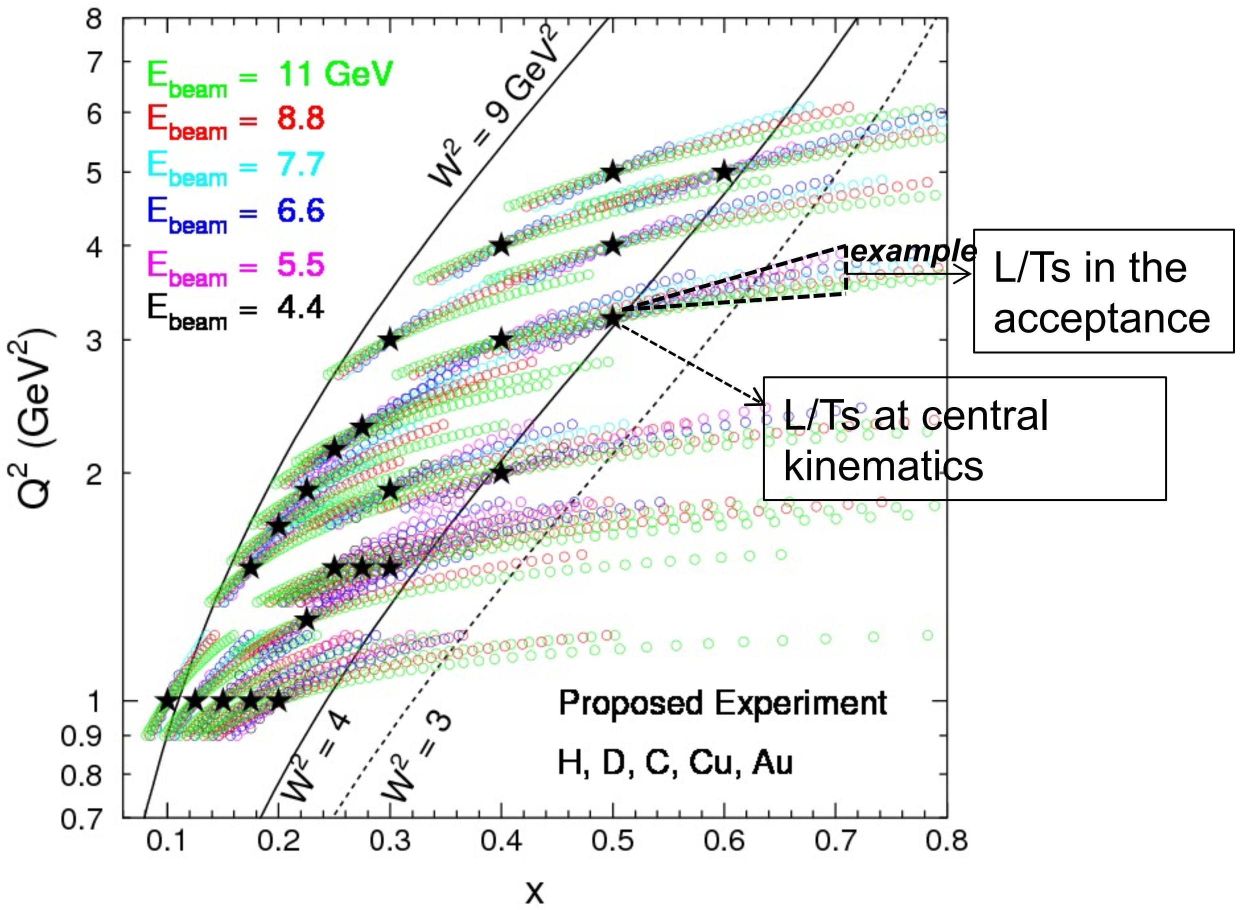
$$F_L(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \left[\frac{8}{3}F_2(z,Q^2) + \frac{40}{9}\left(1-\frac{x}{z}\right)zG(z,Q^2)\right]\frac{dz}{z^3}$$

Longitudinal cross section also has contributions from gluons→ measurements of R could provide constraints on gluon distributions

Jefferson Lab E12-14-002

- Precision Measurements and Studies of a Possible Nuclear Dependence of $R=\sigma_L/\sigma_T$ *[S. Alsalmi, M.E. Christy, D. Gaskell, W. Henry, S. Malace, D. Nguyen, T.J. Hague, P. Solvignon]*

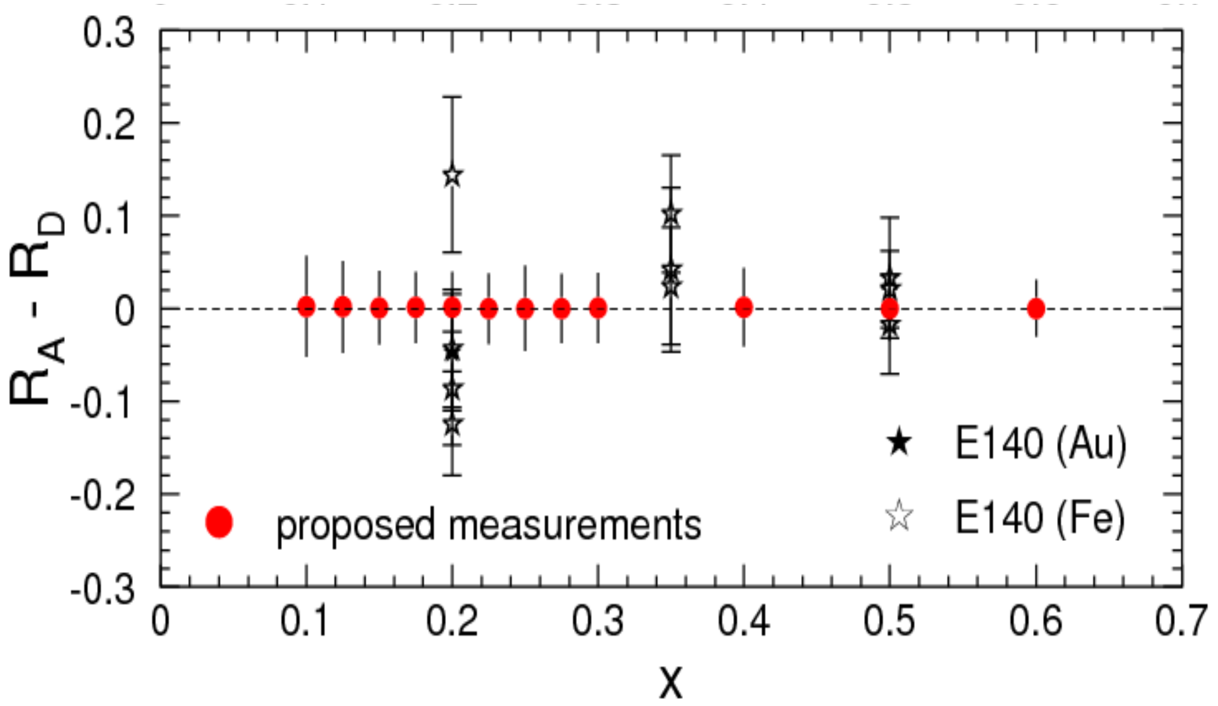
- Measurements of nuclear dependence of structure functions, R_A-R_D via direct L-T separations

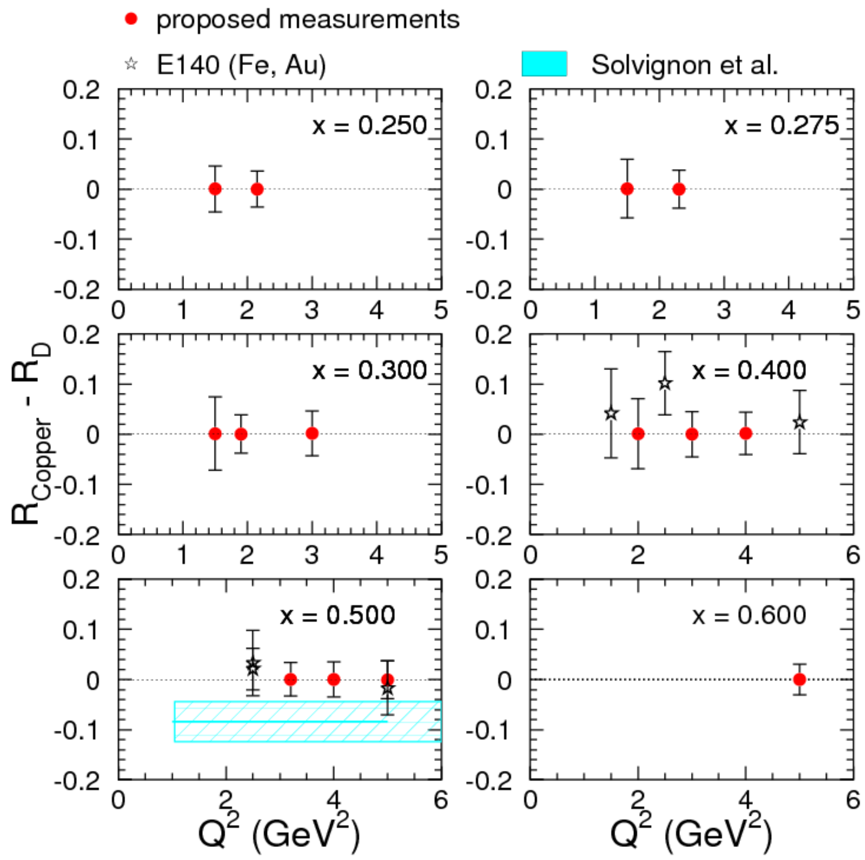


Detailed measurements of x and Q^2 dependence for Copper target
→ A dependence at select kinematics using C and Au

Jefferson Lab E12-14-002

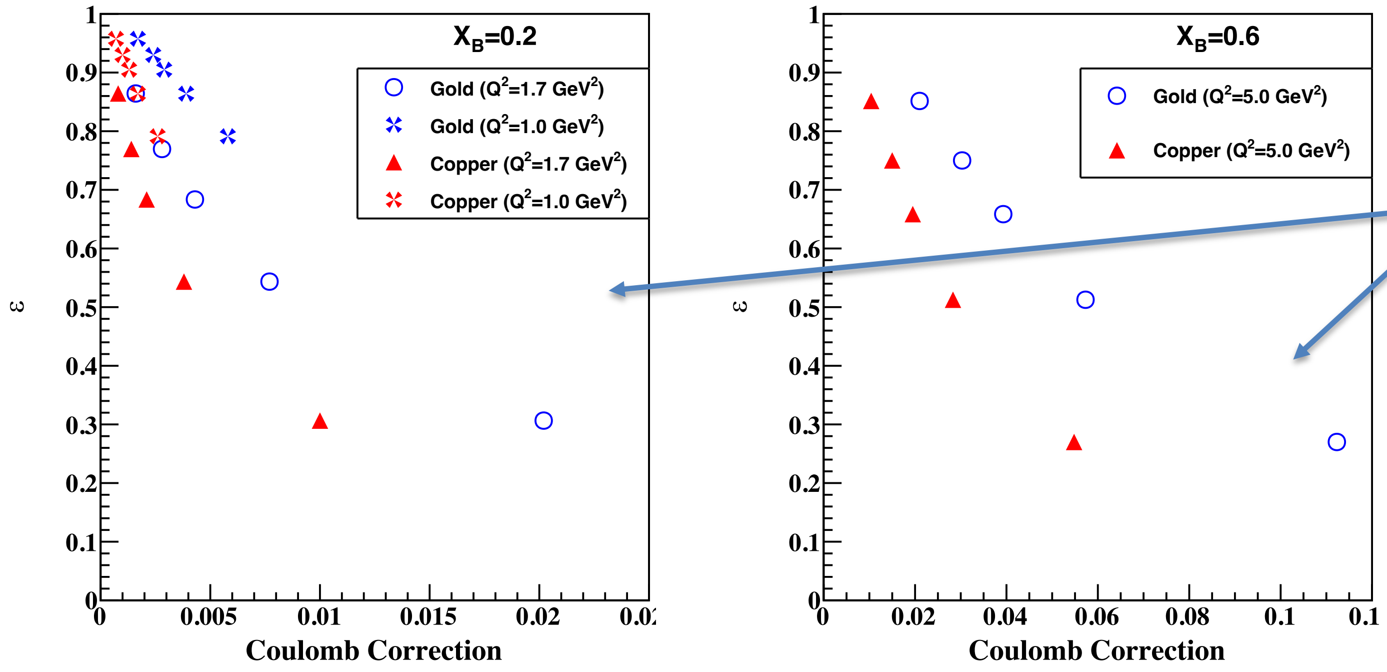
Projected uncertainties for R_A-R_D
→ will provide information on x-dependence and Q^2 dependence at fixed x





Depends critically on correct application of Coulomb Corrections

E12-14-002 and Coulomb Corrections



Size of Coulomb Correction correlated with ε

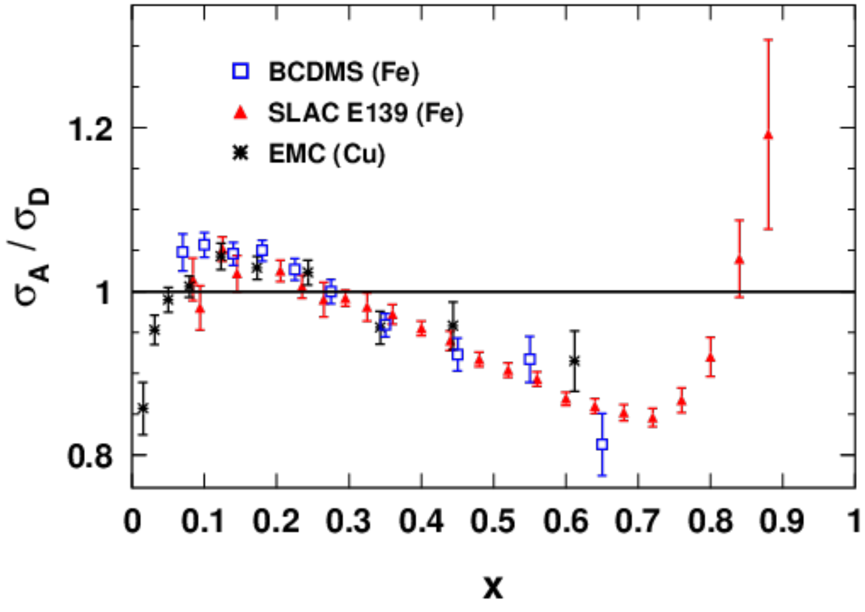
Coulomb corrections a key systematic issue for E12-14-002

→ L-T separations require varying epsilon. Smaller epsilon corresponds to smaller beam energies and scattered electron momenta → larger Coulomb corrections
→ Size of Coulomb correction highly correlated with the very effect we are trying to study
→ Need robust tests to verify CC magnitude and epsilon dependence

Testing Coulomb Corrections with Electrons

Coulomb corrections can be tested by measuring target ratios at fixed ***x*** and **ε**
→ Varying Q^2 allows us to change E and E' and hence size of CC

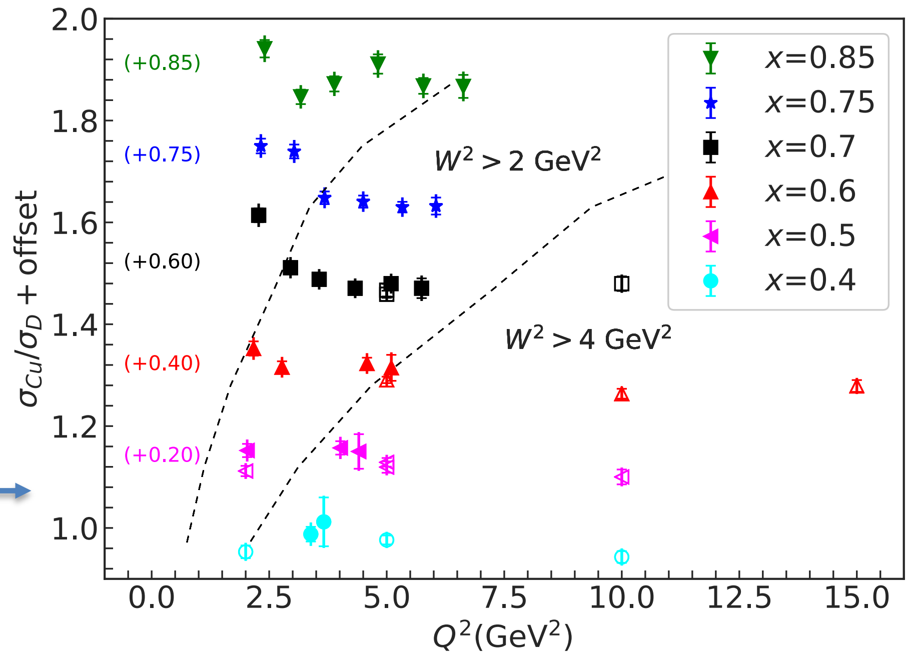
Fixed ***x*** required due to EMC effect



Fixed **ε** minimizes potential dependence on R_A-R_D

$$\boxed{\frac{\sigma_A}{\sigma_D} = \frac{F_2^A(1+\epsilon R_A)(1+R_D)}{F_2^D(1+R_A)(1+\epsilon R_D)}}$$

EMC effect measurements have shown little or no dependence on Q^2 →



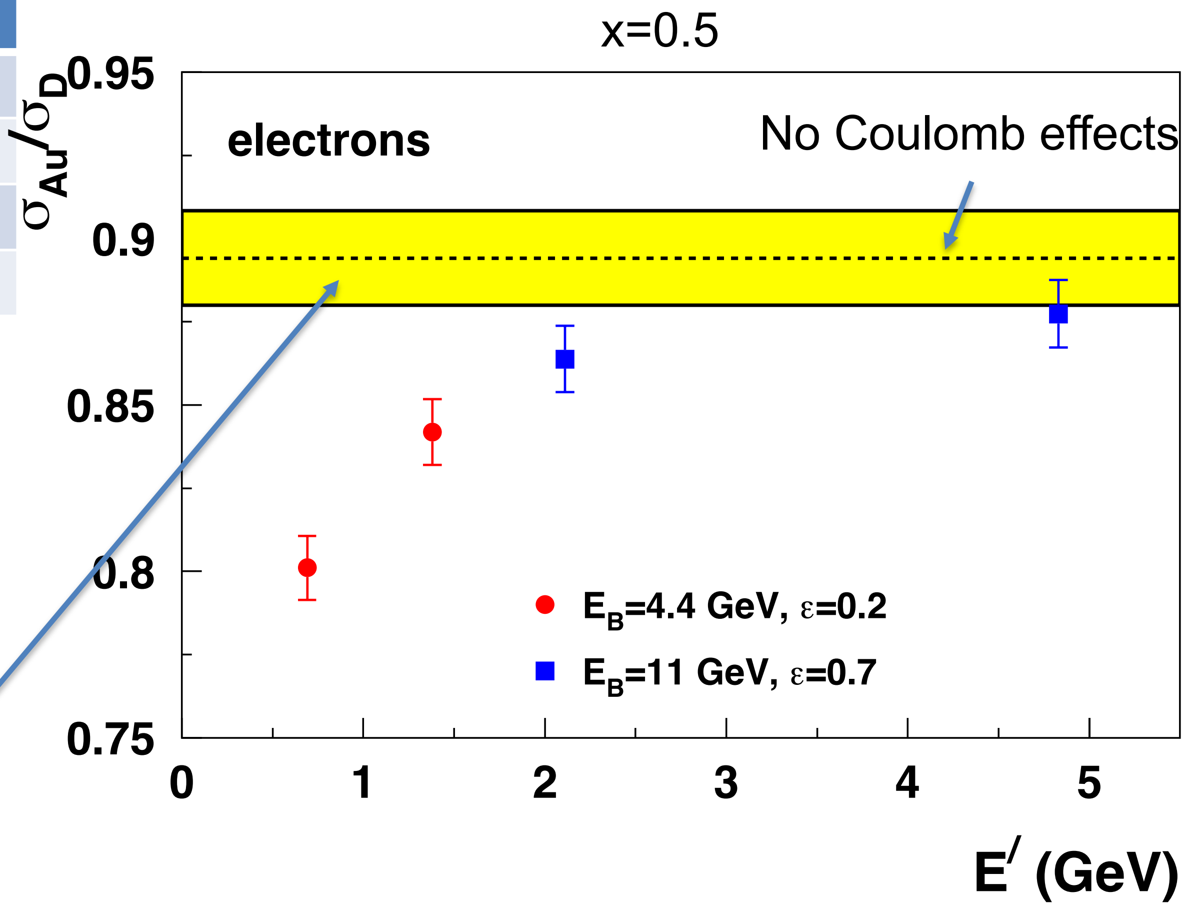
E12-14-002 Coulomb Corrections Test

CC test will measure precise Au/D ratios in HMS
→ 2 shifts (16 hours) at 60 μA

ε	Q^2 (GeV^2)	E (GeV)	E' (GeV)	θ (deg.)	$C_{Coulomb}$
0.2	3.48	4.4	0.69	64.6	11.6%
0.2	9.03	11.0	1.38	45.5	6.2%
0.7	2.15	4.4	2.11	27.9	3.5%
0.7	5.79	11.0	4.83	19.0	1.9%

Gold and Deuterium targets at fixed x=0.5

Normalization uncertainty → dominated by gold and LD2 target thicknesses



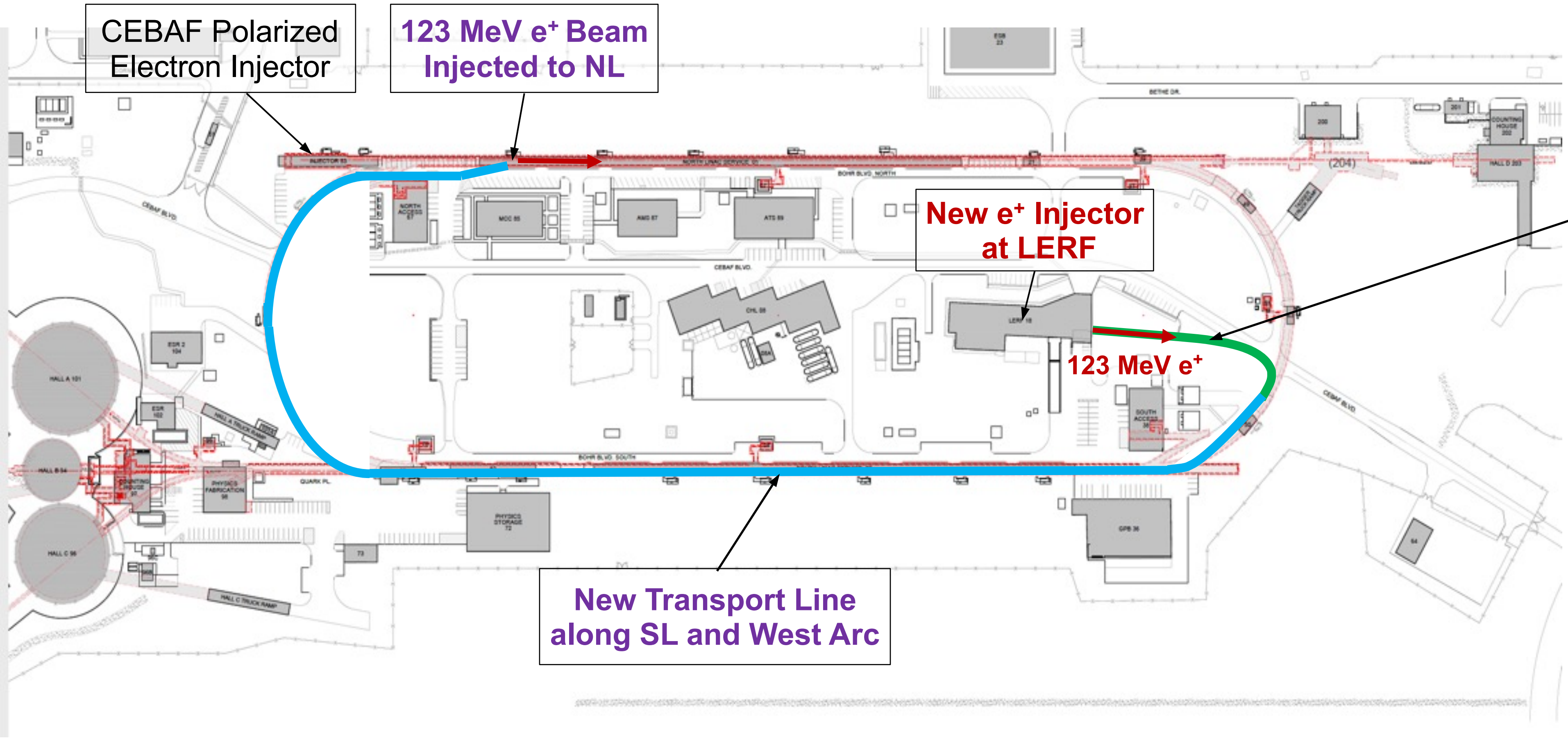
Testing Coulomb Corrections with Positrons

Positron beam at JLab an excellent opportunity for studying Coulomb Corrections in DIS

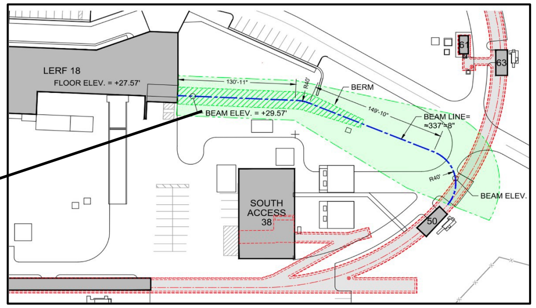
<u>Key questions:</u>

1. Are Coulomb Corrections relevant for DIS?
   - For QE scattering effects have been clearly observed experimentally – consensus that CC are required
   - “Makes sense” that they should be needed for DIS, but proof is needed
2. Is the Improved Effective Momentum Approximation (EMA) adequate/appropriate for DIS?
   - EMA has been checked/optimized in QE scattering via comparisons to DWBA calculations
   - Equivalent calculations for DIS appear to be more challenging and perhaps model dependent

Future 12 GeV Ce$^+$BAF Accelerator Complex



New Beamline to CEBAF Tunnel



Slide courtesy Joe Grames, Positron Working Group Meeting, March 2025

JLab Positron Program (so far..)

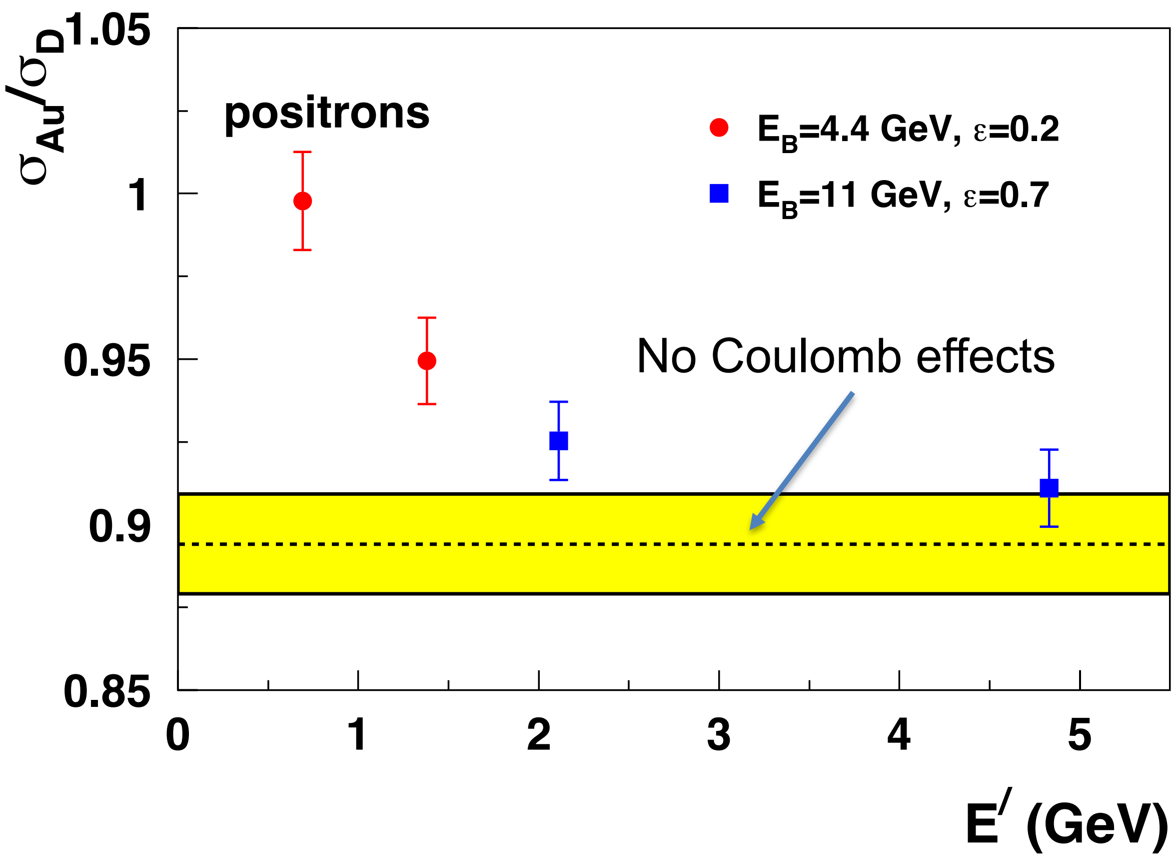
NUMBER	TITLE	PHYSICS THEME	CONTACT PERSON	HALL	DAYS AWARDED	SCIENTIFIC RATING	PAC DECISION
PR12+23-002	Beam Charge Asymmetries for Deeply Virtual Compton Scattering on the Proton at CLAS12	GPDs	Eric Voutier	B	100	**A-**	**C1**
PR12+23-003	Measurement of Deep Inelastic Scattering from Nuclei with Electron and Positron Beams to Constrain the Impact of Coulomb Corrections in DIS	TPE	Dave Gaskell	C	9.3	**A-**	**C1**
PR12+23-006	Deeply Virtual Compton Scattering using a positron beam in Hall C	GPDs	Carlos Muñoz Camacho	C	137	**A-**	**C1**
PR12+23-008	A Direct Measurement of Hard Two-Photon Exchange with Electrons and Positrons at CLAS12	TPE	Axel Schmidt	B	55	**A**	**C1**
PR12+23-012	A measurement of two-photon exchange in unpolarized elastic positron–proton and electron–proton scattering	TPE	Michael Nycz	C	56	**A-**	**C1**
PR12+24-005	A dark photon search with a JLab positron beam	BSM	Bogdan Wojtsekhowski	B	55	**A-**	**C1**

JLab E12+23-003

E12+23-003 *[D. Gaskell, N. Fomin, W. Henry]* will perform CC test w/positrons at same kinematics as E12-14-002

→ Conditionally approved in 2023
→ Will allow **direct** comparison of electrons and positrons
→ Target ratios (Au/D) minimize uncertainty in e+/e- comparison
→ Measurement requires only one of the Hall C spectrometers
→ Even with low maximum beam current (1 μA), short run time

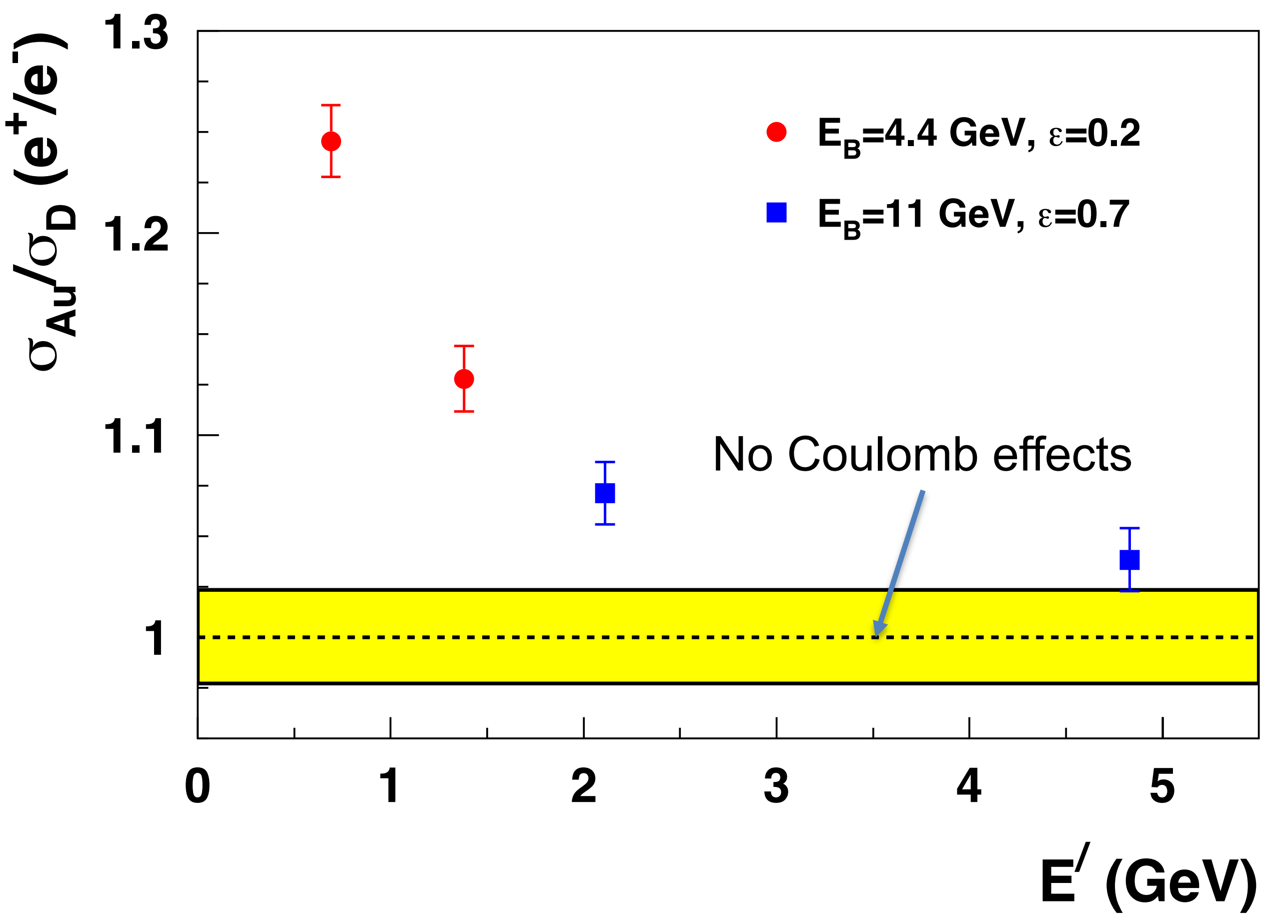
Measurement time with overhead <10 days



Coulomb Corrections Test: Electrons and Positrons

Cleanest measurement of CC from super-ratio for e+/e-:
→ Insensitive to assumptions in electron/positron-only CC test

$$R = \frac{\left(\frac{\sigma_{Au}}{\sigma_D}\right)^{e+}}{\left(\frac{\sigma_{Au}}{\sigma_D}\right)^{e-}}$$



Summary: Part 2

- In addition to studying the EMC Effect – important to constrain assumptions behind EMC Effect measurements
- Measuring the nuclear dependence of R experimentally challenging, but ideally suited for JLab and Hall C
  - Coulomb corrections a crucial question
  - Can be quantified with a possible positron beam