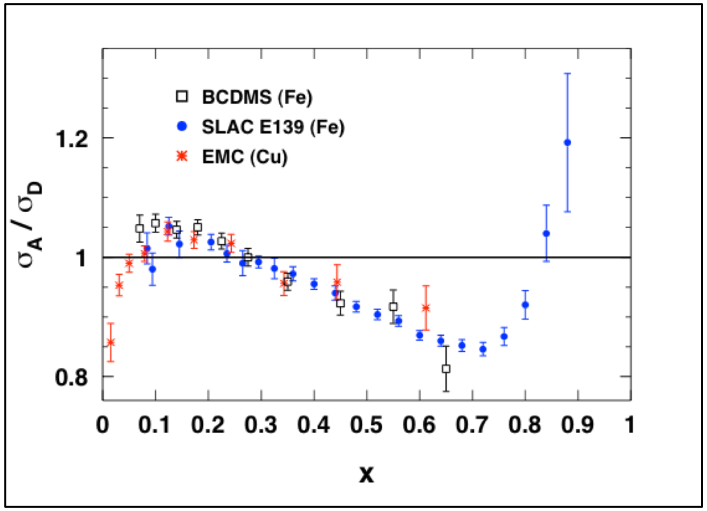
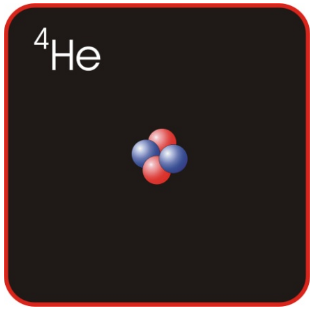
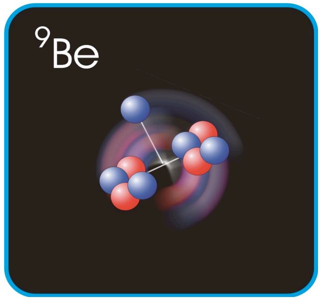
The EMC Effect - New Insights and Future Studies





Dave Gaskell
Jefferson Lab



CIPANP

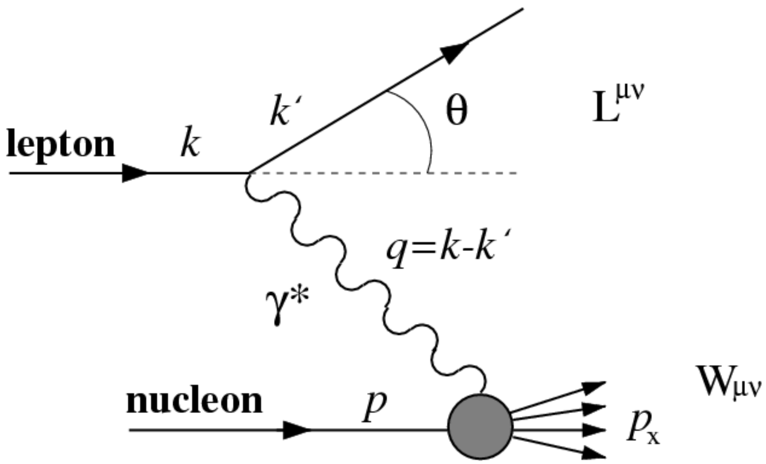
May 29-June 3, 2018

Jefferson Lab

Outline

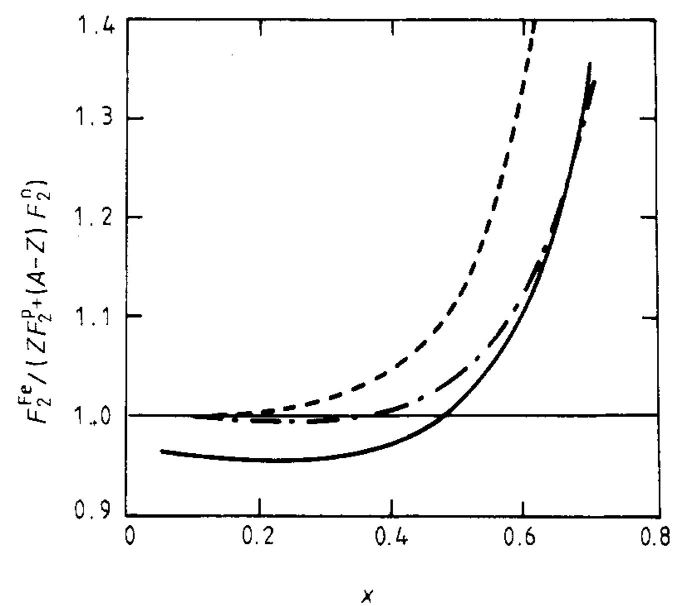
- Quarks in the Nucleus
- Overview of the EMC Effect
  - Discovery and dedicated measurements
  - Known properties of EMC effect
- Recent experimental results
  - Local density dependence
  - Link to Short Range Correlations?
- New Observables and Avenues for Exploration
- Future measurements

DIS: Structure Functions and Quarks in the Nucleus



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

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

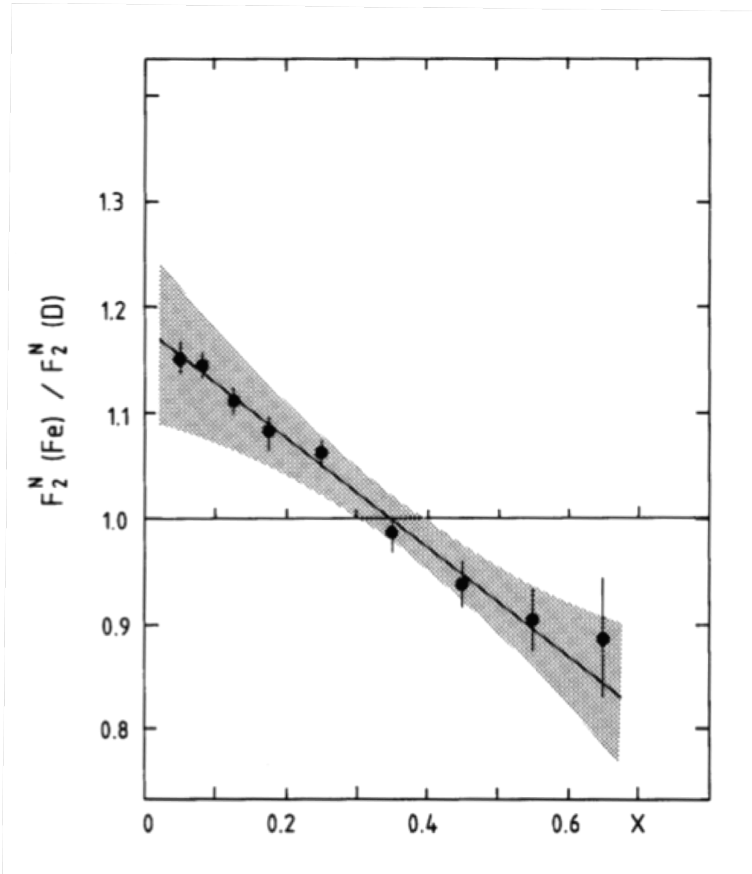


Nuclear binding energies (~MeV) small compared to typical DIS energies (~GeV) → (Naïve) expectation was that nuclear effects in DIS would be small

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

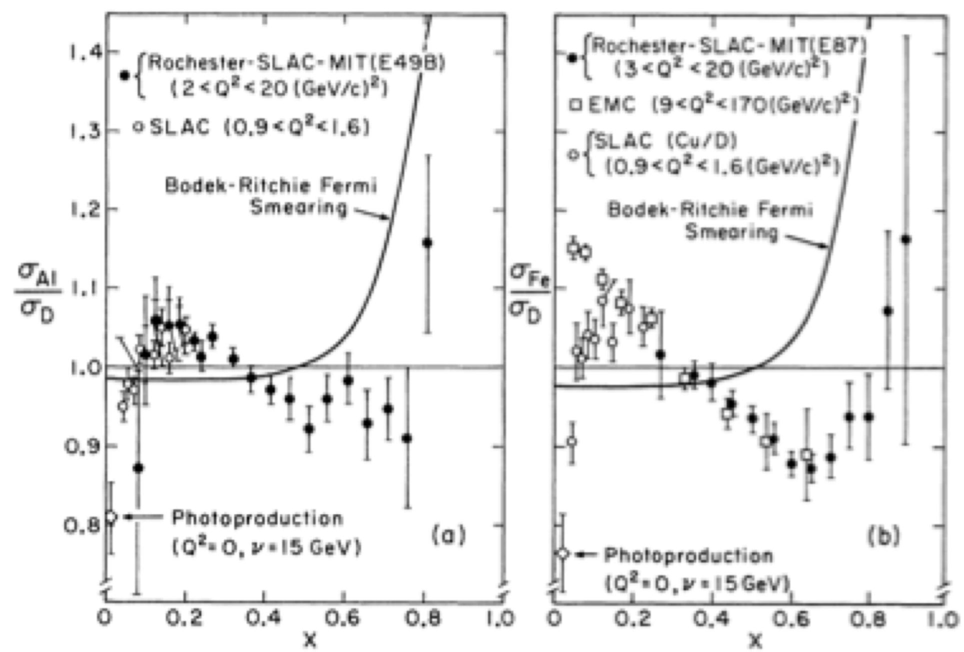
Figure from Bickerstaff and Thomas, J. Phys. G 15, 1523 (1989)
Calculation: Bodek and Ritchie PRD 23, 1070 (1981)

EMC Effect: Discovery and Confirmation



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

Discovery of the modification of $\boldsymbol{F_2(x)}$ demonstrated that quark distributions are modified in the nucleus
→ This suggests some new, unexplained dynamics at play in nuclear environment



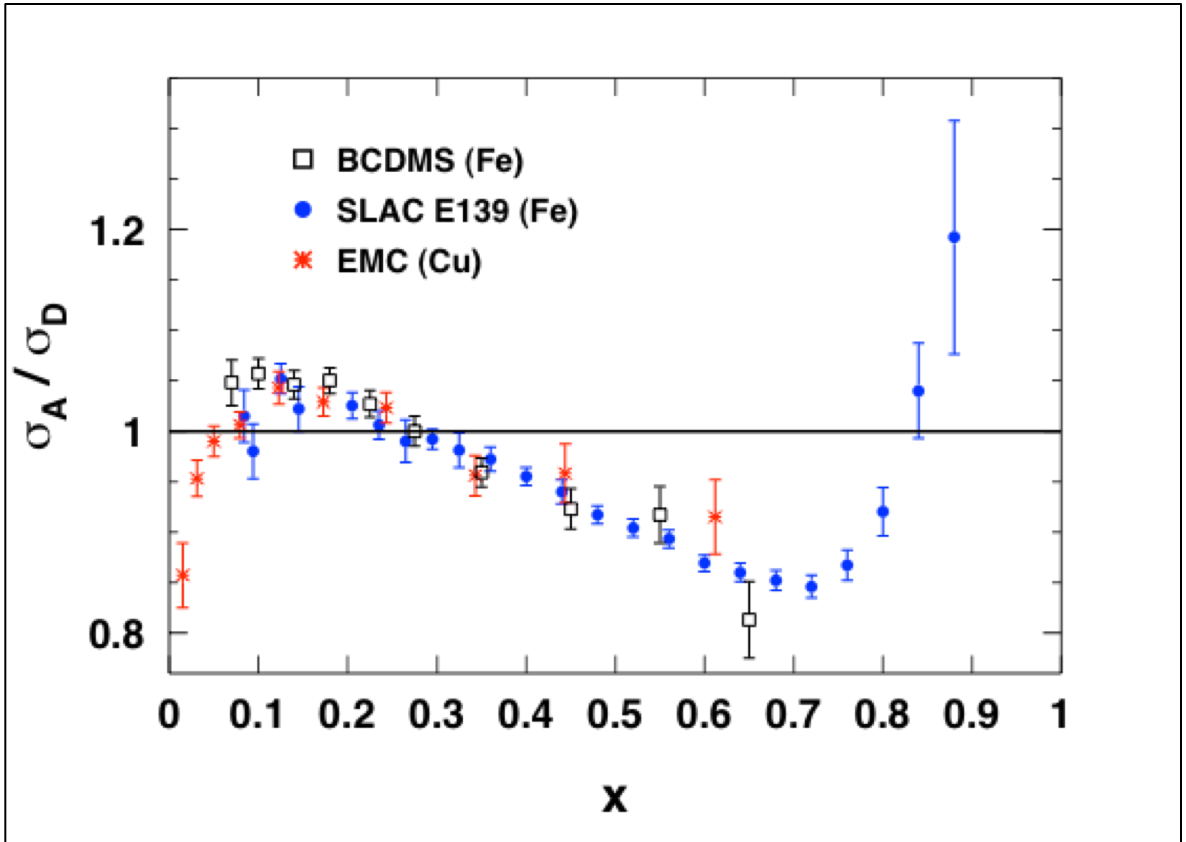
Bodek et al, PRL 50, 1431 (1983) and PRL 51, 534 (1983)

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

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*

Explaining the EMC Effect

- Plethora of models attempting to explain the EMC Effect
- "Conventional" nuclear physics not sufficient
  - Fermi motion dominates at large x, but minimal impact elsewhere
  - Binding effects small, nuclear pions ruled out by other measurements (Drell-Yan)
- Other models require more "exotic" effects
  - Dynamical rescaling $F_2^A(x,Q^2) = F_2^N(x,\xi_A(Q^2)\cdot Q^2)$
  - Multiquark clusters → 6, 9, 12 .. quark configurations
- More recently, models related to SRCs under investigation

35 Years of the EMC Effect

- No clear consensus on origin of EMC Effect
  - Conventional nuclear physics contributions can be handled with more precision, but still cannot explain whole effect
  - Testing models challenging – only a few observables (Inclusive DIS and Drell-Yan)
- Settling the question of the origin of the EMC effect will require new information
  - Explore effect for wider range of nuclei (different A, n/p ratios..)
  - New experimental avenues beyond inclusive DIS cross sections required

Nuclear Dependence of EMC Effect

SLAC E139 explored detailed ***nuclear dependence*** to gain new insight to EMC Effect

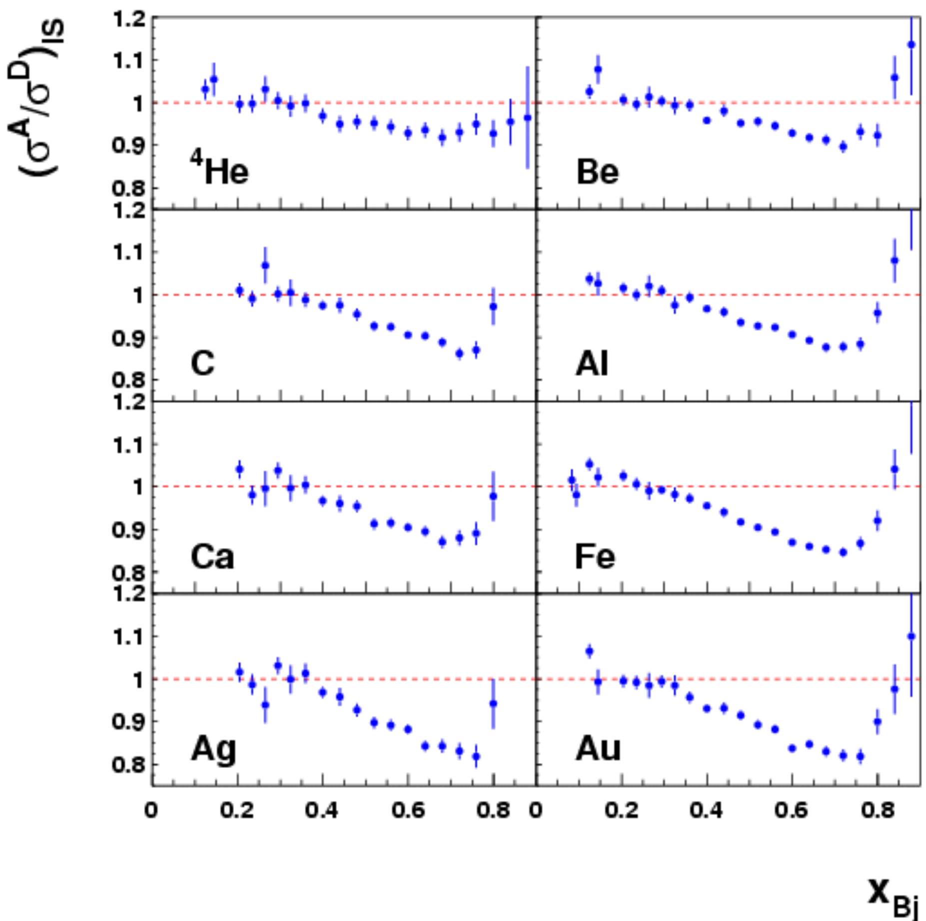
Provided the most extensive and precise data set for *x>0.2*

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

→ Verified that the *x* dependence was roughly constant

SLAC E139



J. Gomez, et al, Phys.Rev. D49 (1994) 4348-4372

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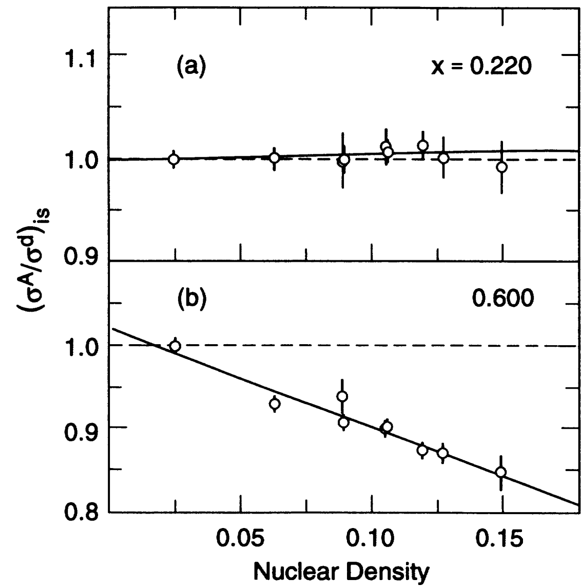
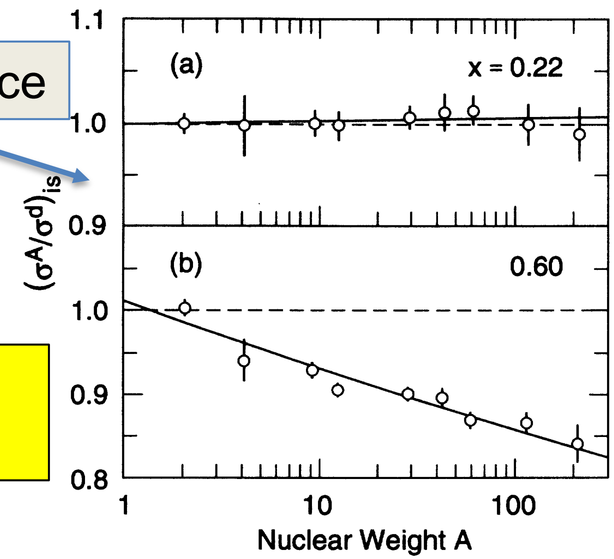


Density-dependence

A-dependence



E139 results consistent with both *A* and density dependent pictures

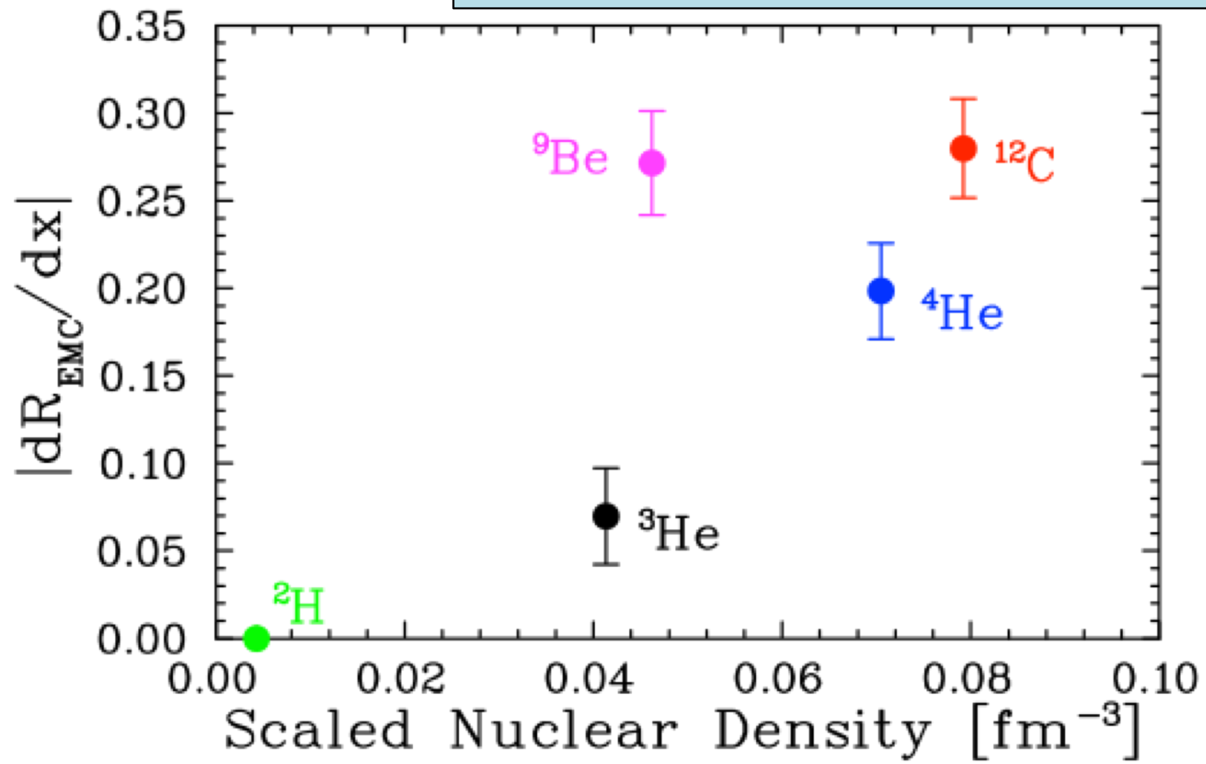
JLab E03103

JLab E03103 goal:
More information on nuclear dependence → emphasis on light nuclei: ^{3}He, ^{4}He, *Be, C*

→ New definition of size of EMC effect:
|dR/dx| for *0.35<x<0.7*

→ ^{3}He, ^{4}He, C, EMC effect scales well with density – Be does not!

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



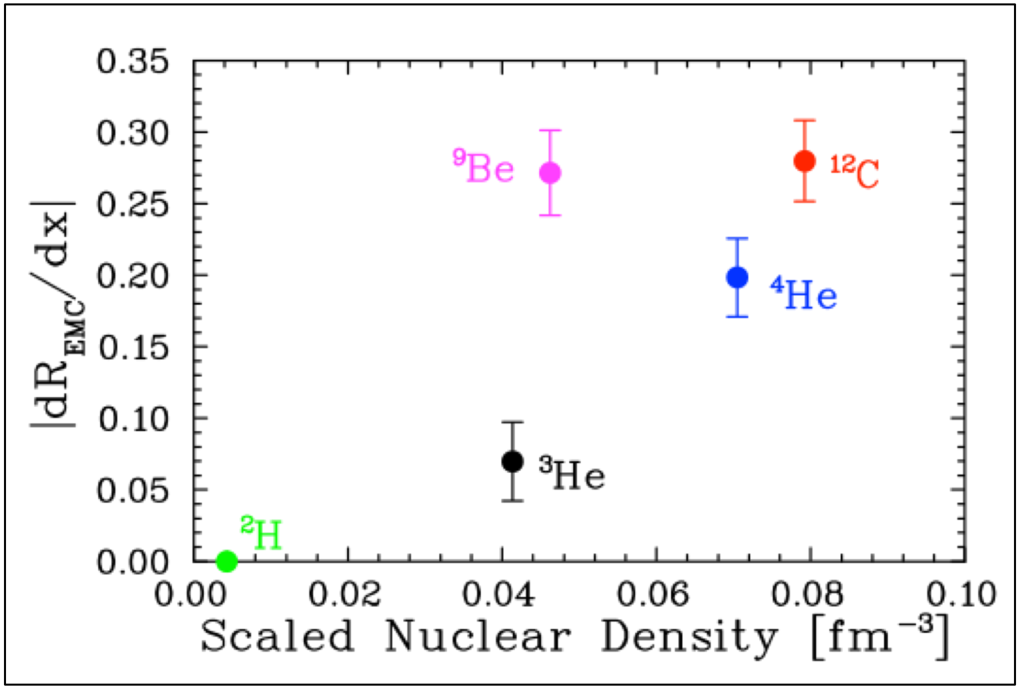
Scaled nuclear density = *(A-1)/A <ρ>*
→ remove contribution from struck nucleon

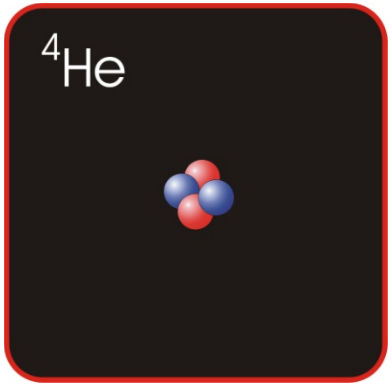
<ρ> from ab initio few-body calculations
→ ***[S.C. Pieper and R.B. Wiringa**, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)]*

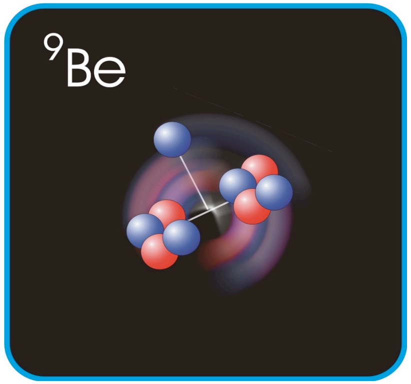
EMC Effect and Local Nuclear Density

^{9}Be has low average density
→ Large component of structure is ***2α+n***
→ Most nucleons in tight, *α*-like configurations

EMC effect driven by ***local*** rather than *average* nuclear density

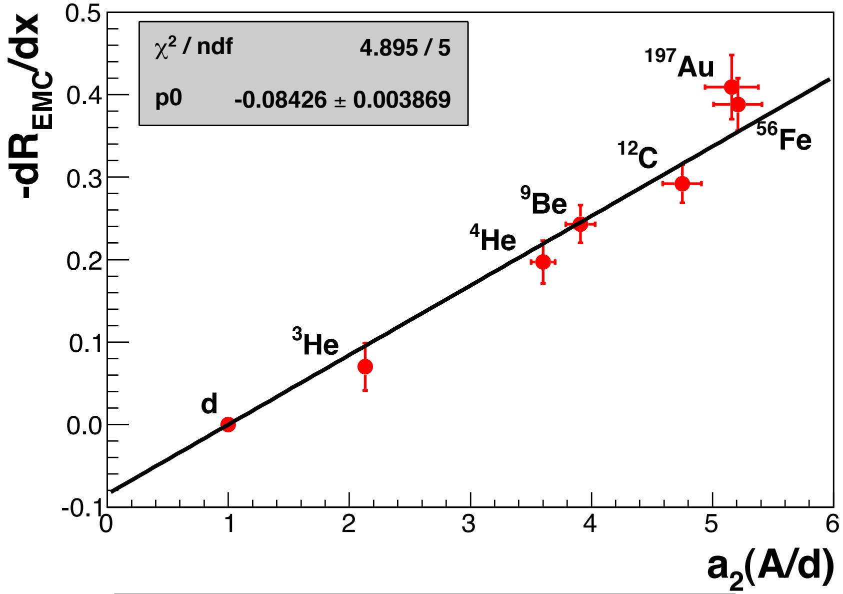






Can this "local density" picture be tied to other observables?

EMC Effect and Short Range Correlations



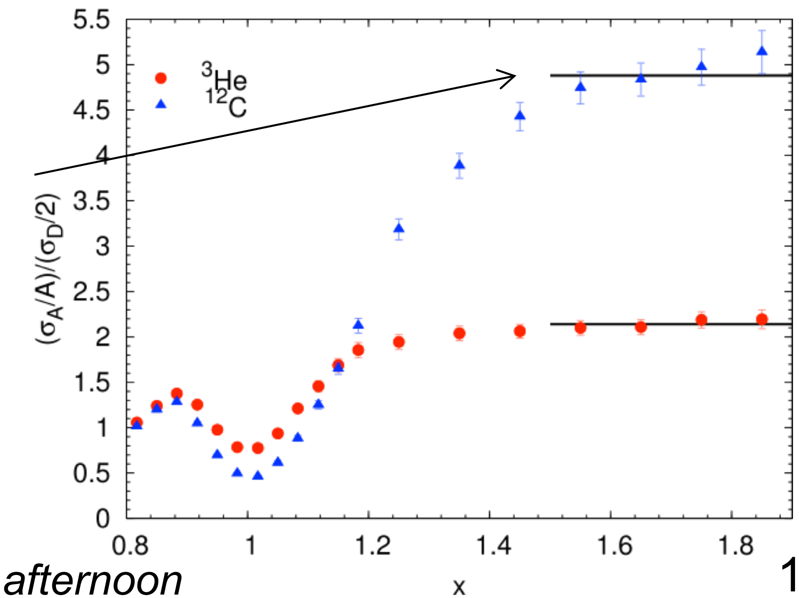
O. Hen et al, Phys.Rev. C85 (2012) 047301

Weinstein *et al,* Hen *et al* showed there is a linear correlation between size of EMC effect and Short Range Correlation "plateau"

→Nucleons in SRC pairs have high momentum – imply EMC Effect from "high virtuality" nucleons?

→ Or are SRCs a proxy for high local density?

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



Further Studies of the EMC Effect

EMC effect has been studied extensively – 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
- → Tagged measurements – Explore the EMC effect for different parts of nuclear wave function
- → Flavor dependence – Is EMC effect different for up and down quarks?
- → Polarized EMC Effect

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

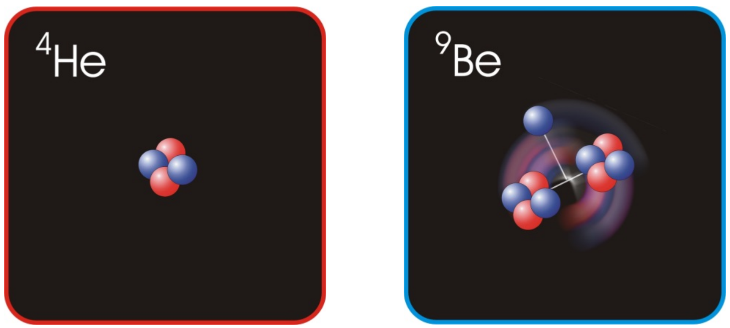
Spokespersons: J. Arrington, A. Daniel, N. Fomin, D. Gaskell

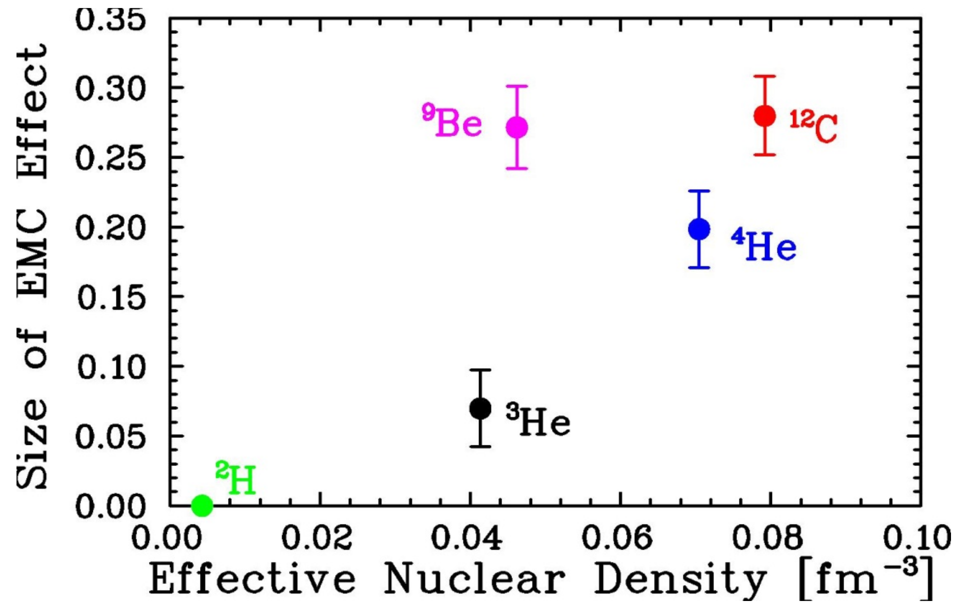
E03-103: EMC at 6 GeV

→ 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

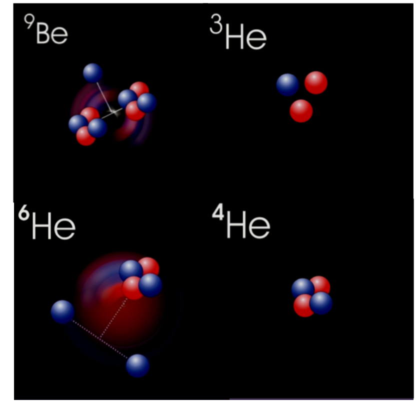
See talk by Eric Pooser (Wednesday)

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

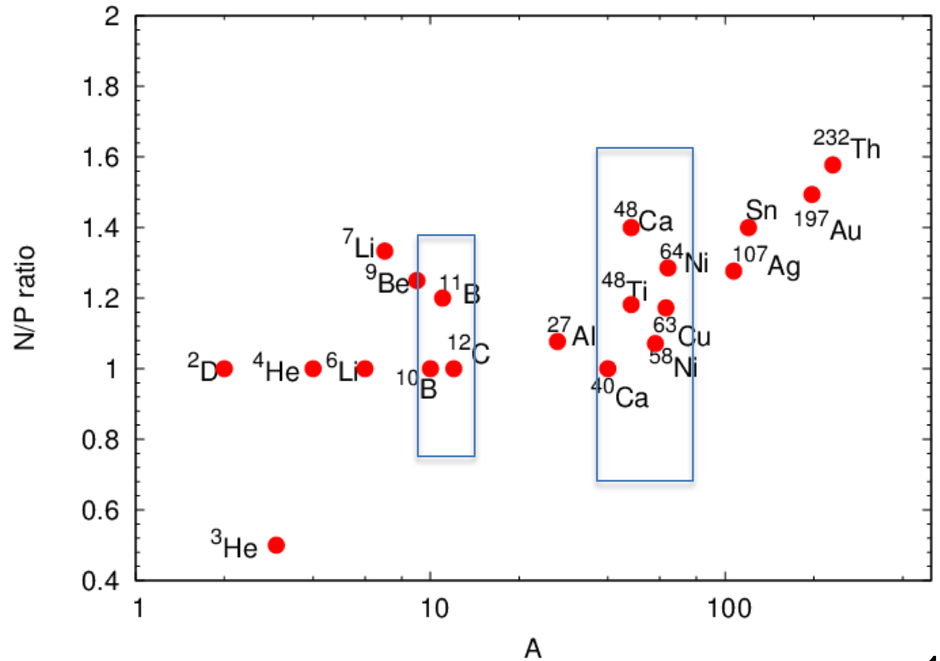
Light nuclei: Reliable calculations of nuclear structure (e.g. clustering)

^{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



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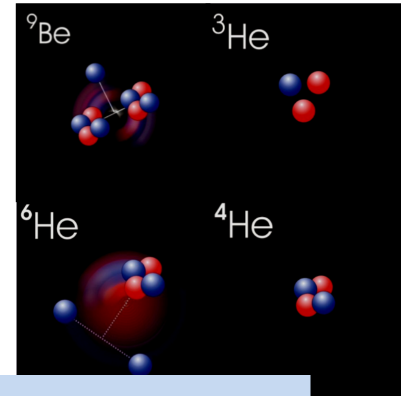
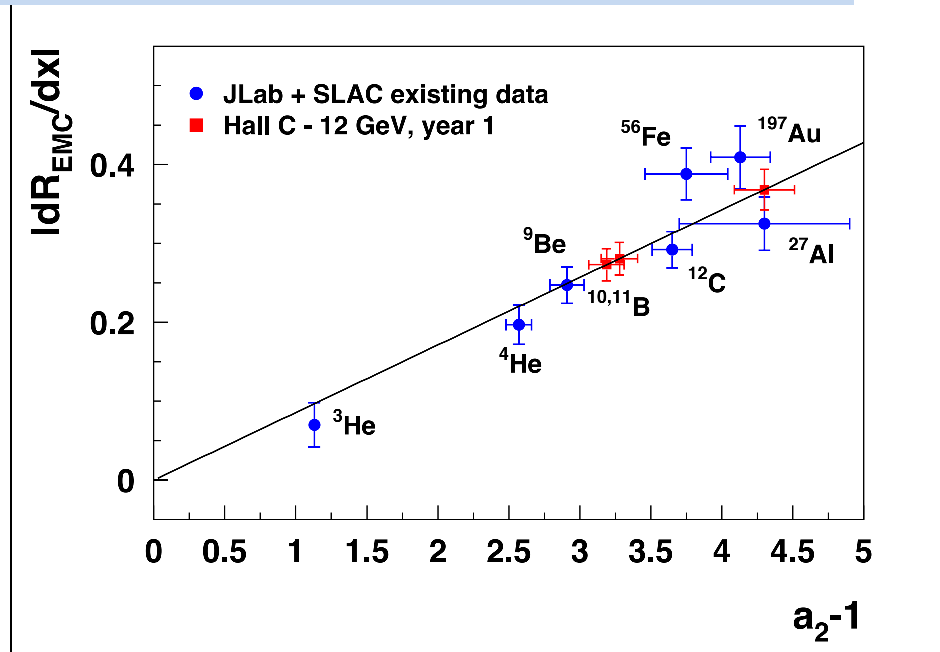


Data from ^{10}B, ^{11}B taken as part of commissioning experiments - Spring 2018



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^{48}Ti	^{119*}Sn
^{54}Fe	^{197*}Au
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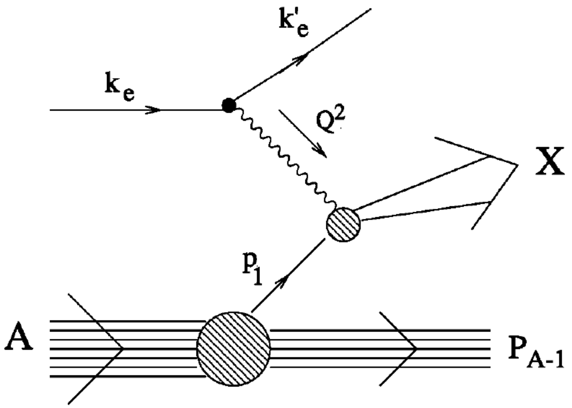
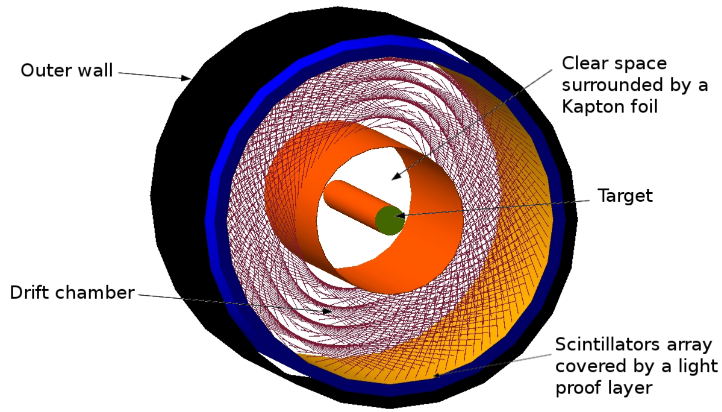
Spectator Tagging and the EMC Effect

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

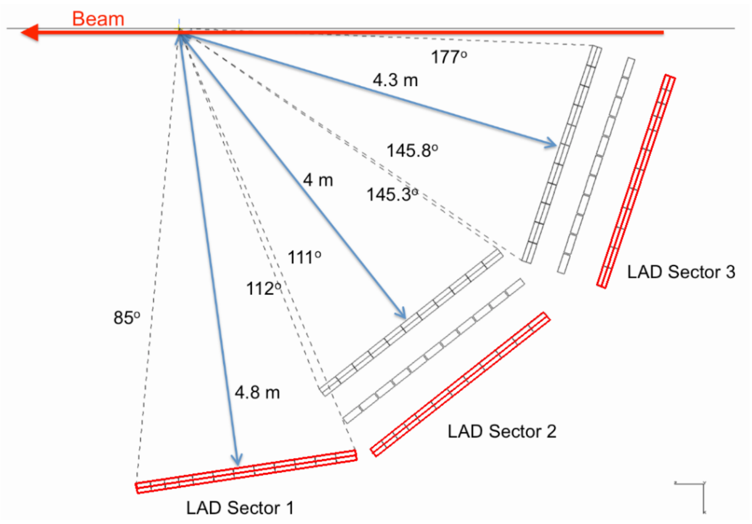


2 complementary programs of ”tagged EMC” measurements at JLab

Low energy recoil detector for reconstructing residual, recoiling nucleus

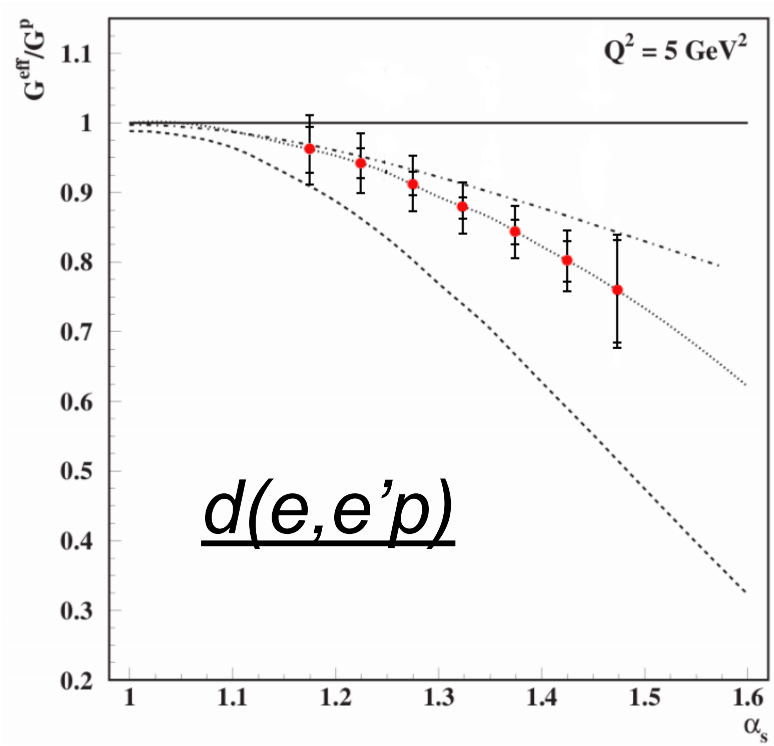


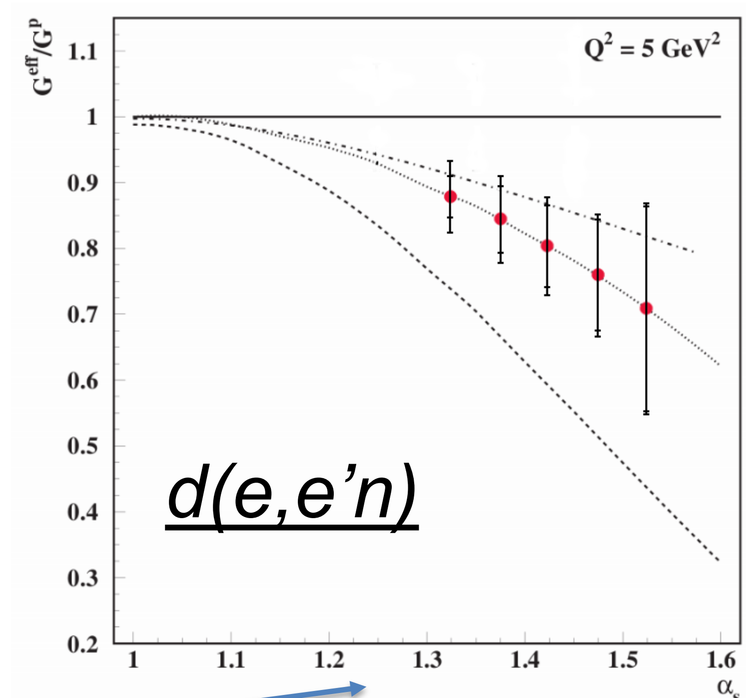
Backward angle proton/neutron detectors to sample high momentum (hundreds of MeV) nucleons



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

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





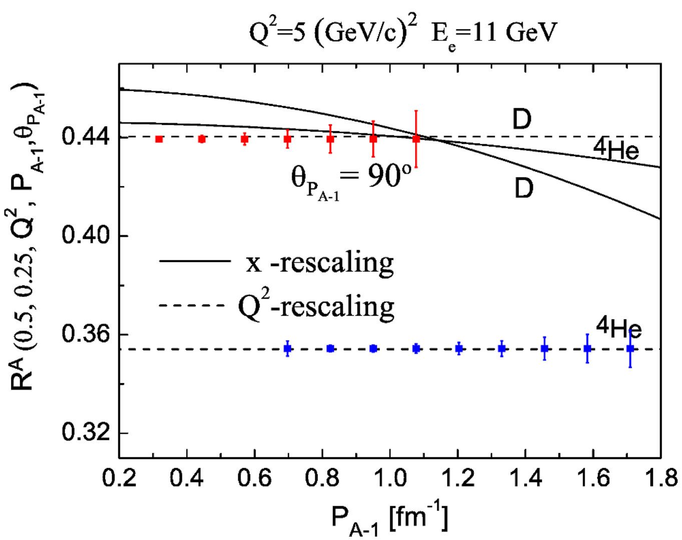
Nucleon virtuality: $\alpha_s = (E_s - p_s^z)/m_s$

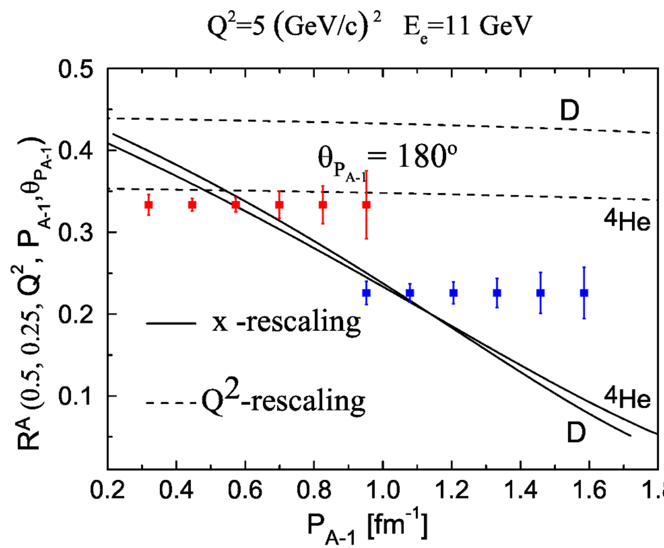
Measure structure function of high momentum nucleon in **deuterium** by tagging the spectator

→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

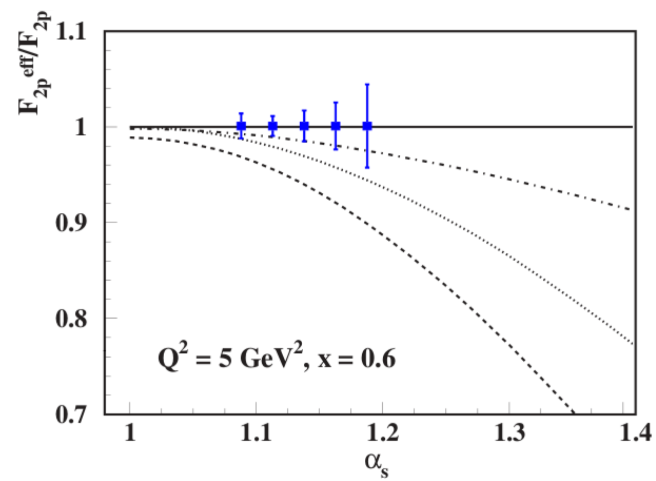
ALERT Program in Hall B





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

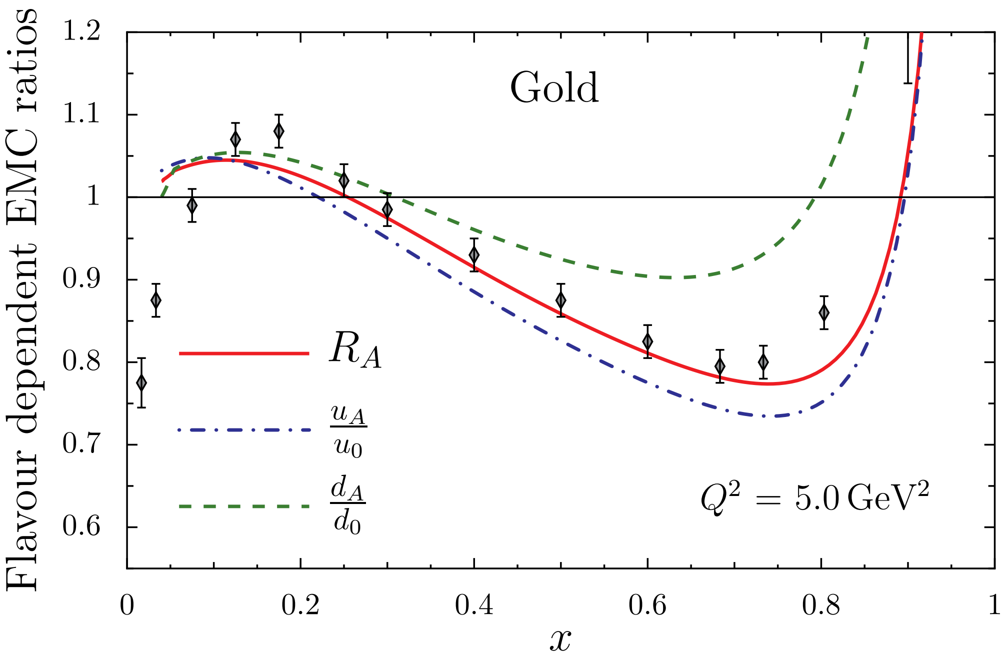
Deuterium



Low energy recoil detector gives high precision at low, moderate virtuality
→ Significant difference between "*x*-rescaling" (binding) and Q^2 rescaling models

Flavor Dependence of the EMC Effect

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



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

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

In principle, models that predict the EMC Effect generated by "high momentum" nucleons may also result in some flavor dependence

Experimentally, this flavor dependence has not been observed directly

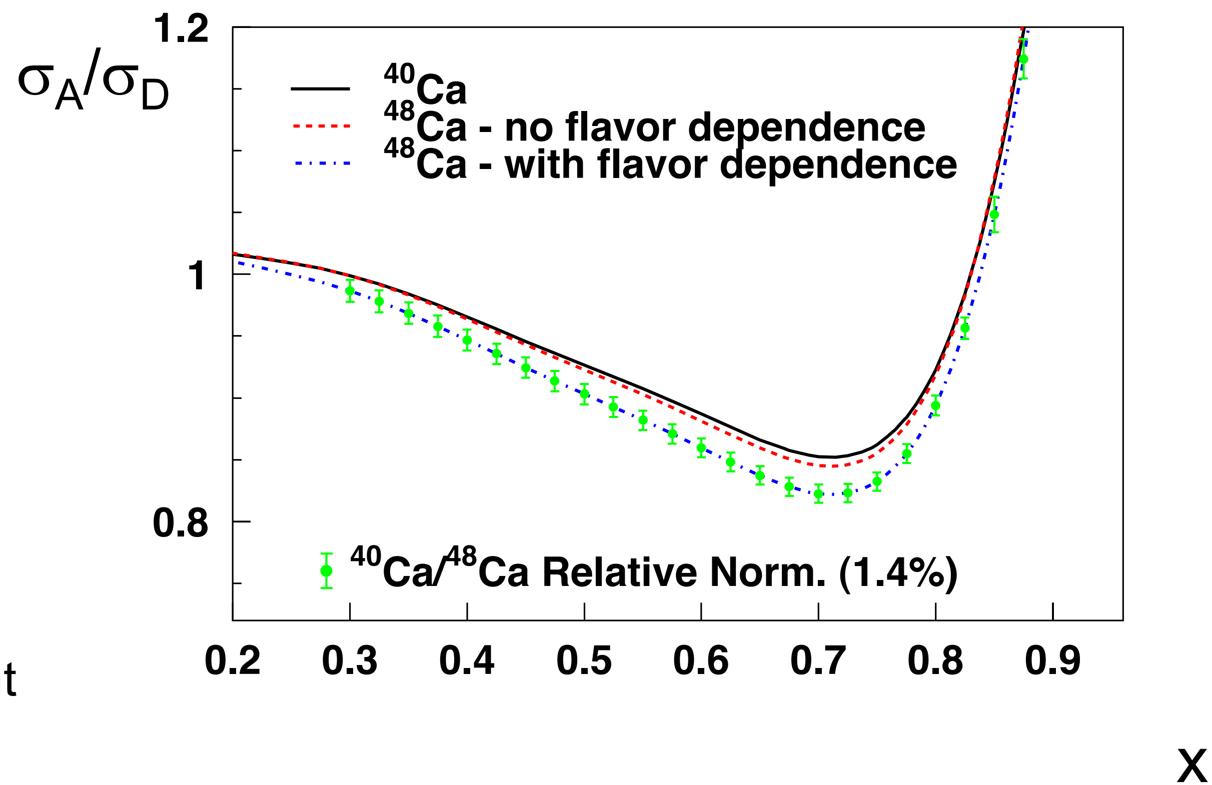
Flavor dependence could be measured using PVDIS, pion Drell-Yan, SIDIS, unpolarized EMC Effect…

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)



Measurement of unpolarized EMC effect in ^{40}Ca and ^{48}Ca provides ***some*** sensitivity to possible flavor dependent effect → E12-10-008 (Hall C)

Flavor Dependence from PVDIS

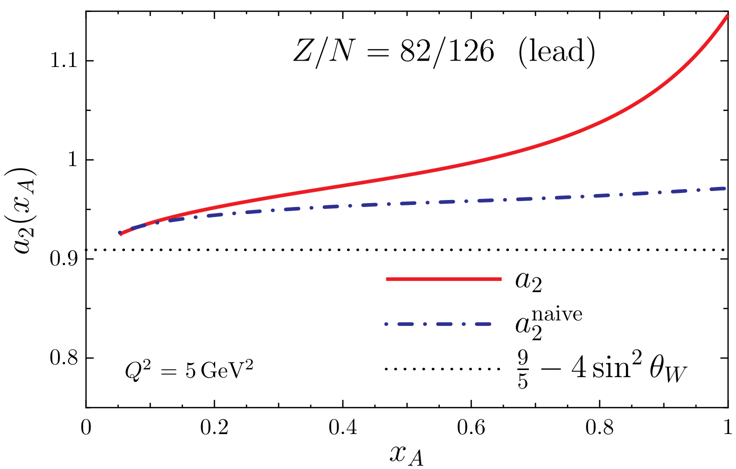
$$A_{PV} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2} a_3(x)\right]$$

← Suppressed by small values of C_2, y-factor

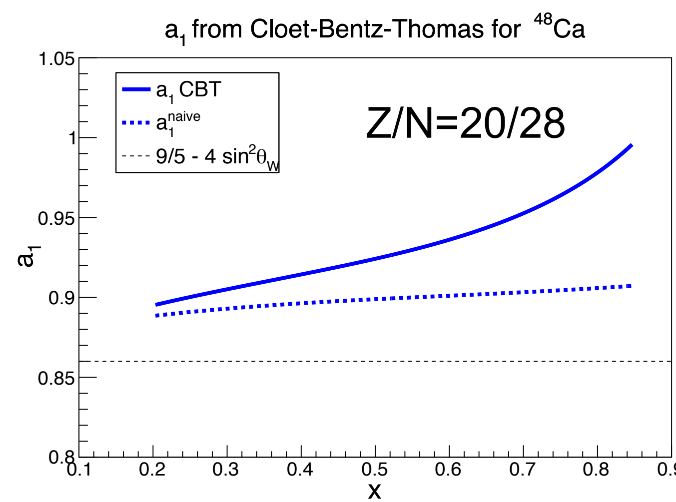
$$a_1(x) = 2\frac{\sum C_{1q} e_q (q+\bar{q})}{\sum e_q^2 (q+\bar{q})}$$

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

Lead



Calcium-48



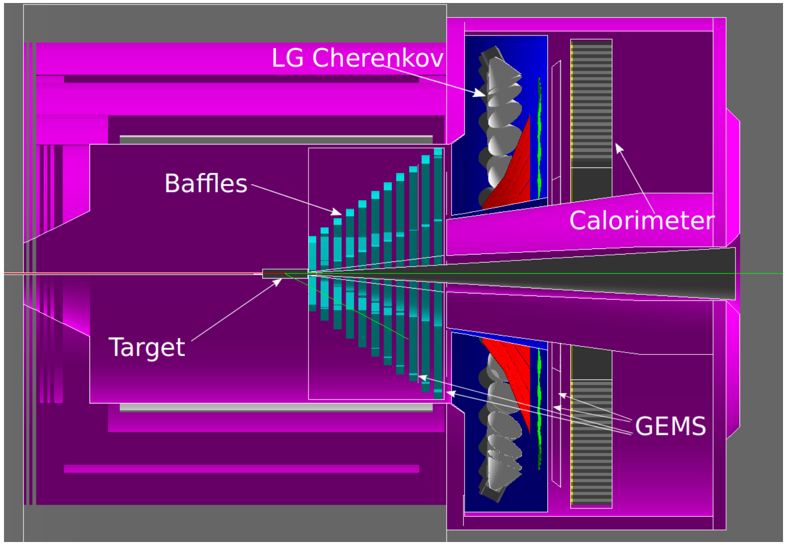
Cloët, Bentz, and Thomas, PRL 109, 182301 (2012)

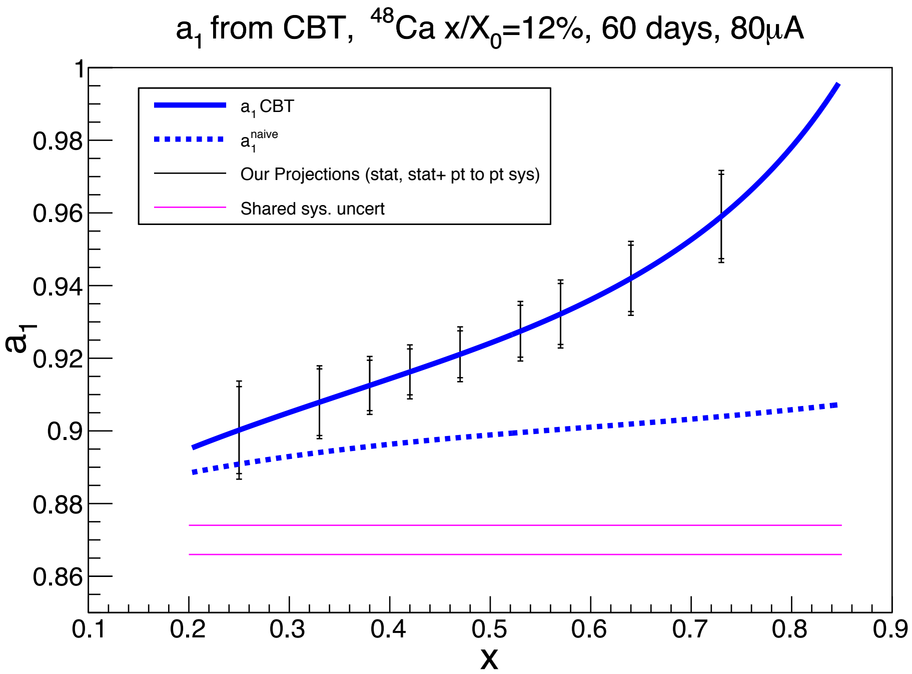
Jefferson Lab

Flavor Dependence from PVDIS

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

Precise measurement of PV asymmetry from ^{48}Ca could be made with large acceptance device (SOLID spectrometer) in Hall A (proposed, not yet approved)



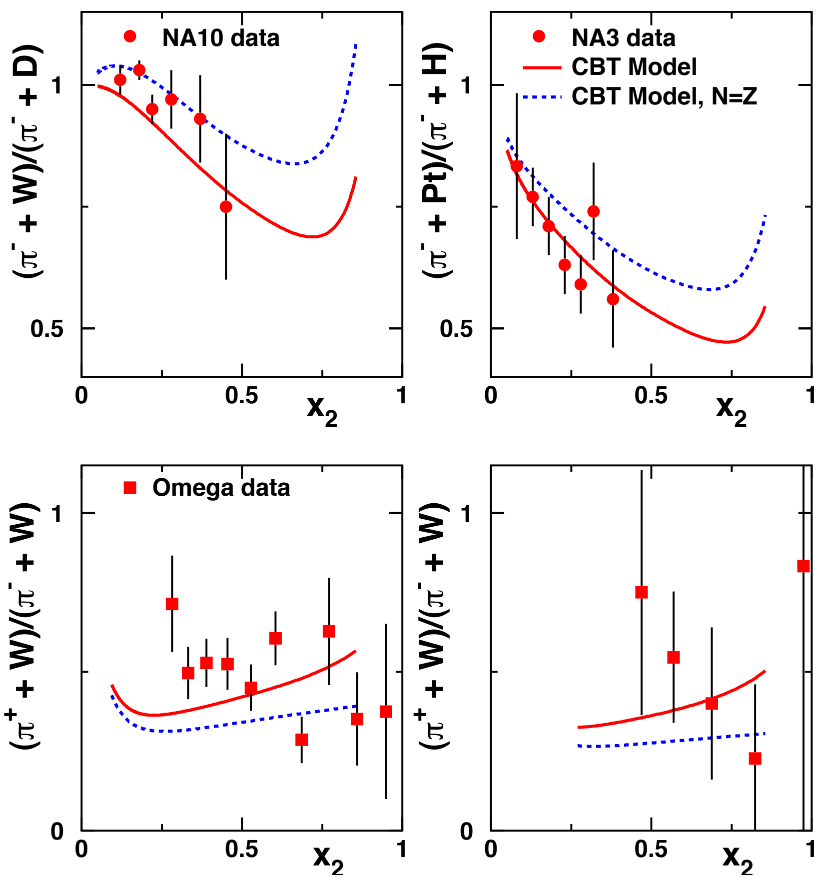


Projections, figure S. Riordan

Cloët, Bentz, and Thomas calc.

EMC Flavor Dependence: Pion Drell-Yan

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



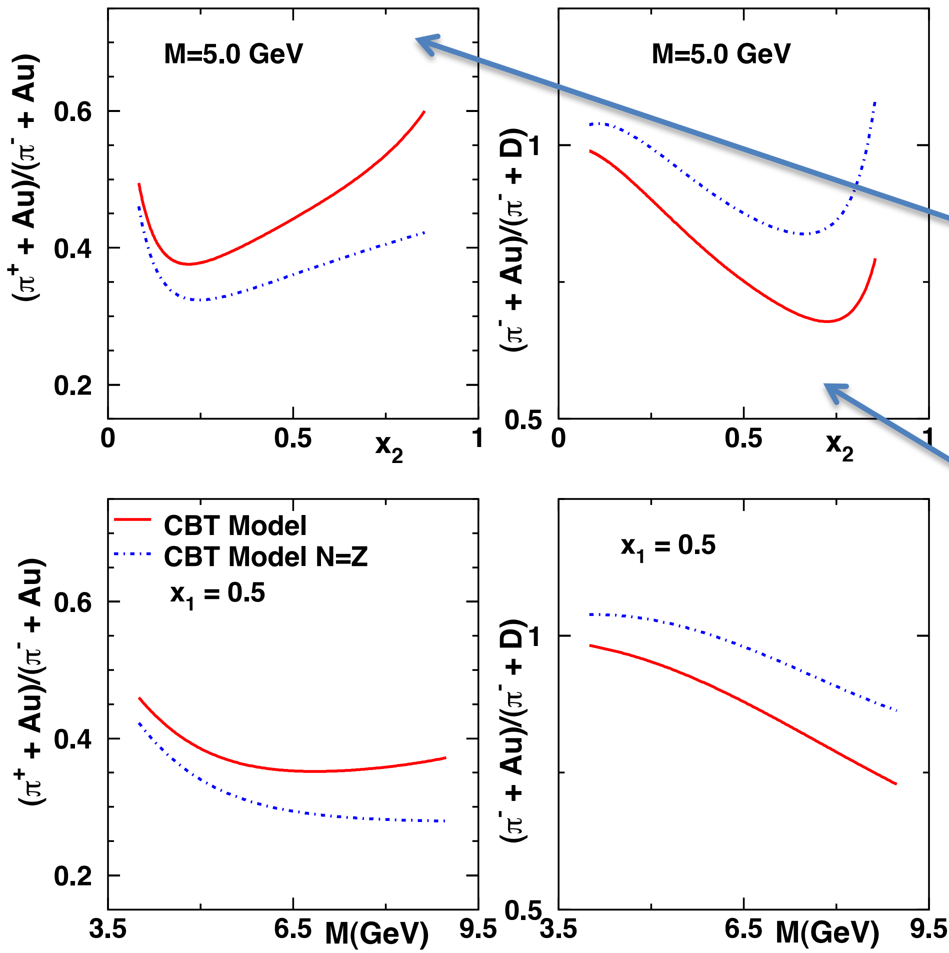
Experiment	Flavor Ind.	Flavor dep.
NA3	1.3	0.5
NA10	0.60	2.5
Omega (low Q^2)	6.2	3.2
Omega (high Q^2)	1.4	0.96

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 – Measurements at COMPASS



160 GeV pions on gold

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

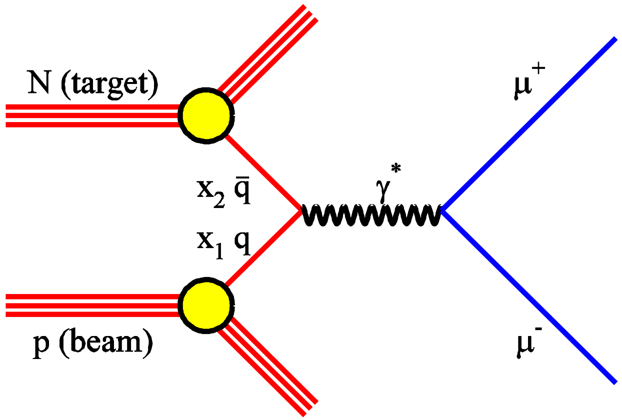
$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$

Dutta et al, PRC 83, 042201 (2011)

Some data on nuclear targets from COMPASS-II, more proposed (COMPASS++ LOI)

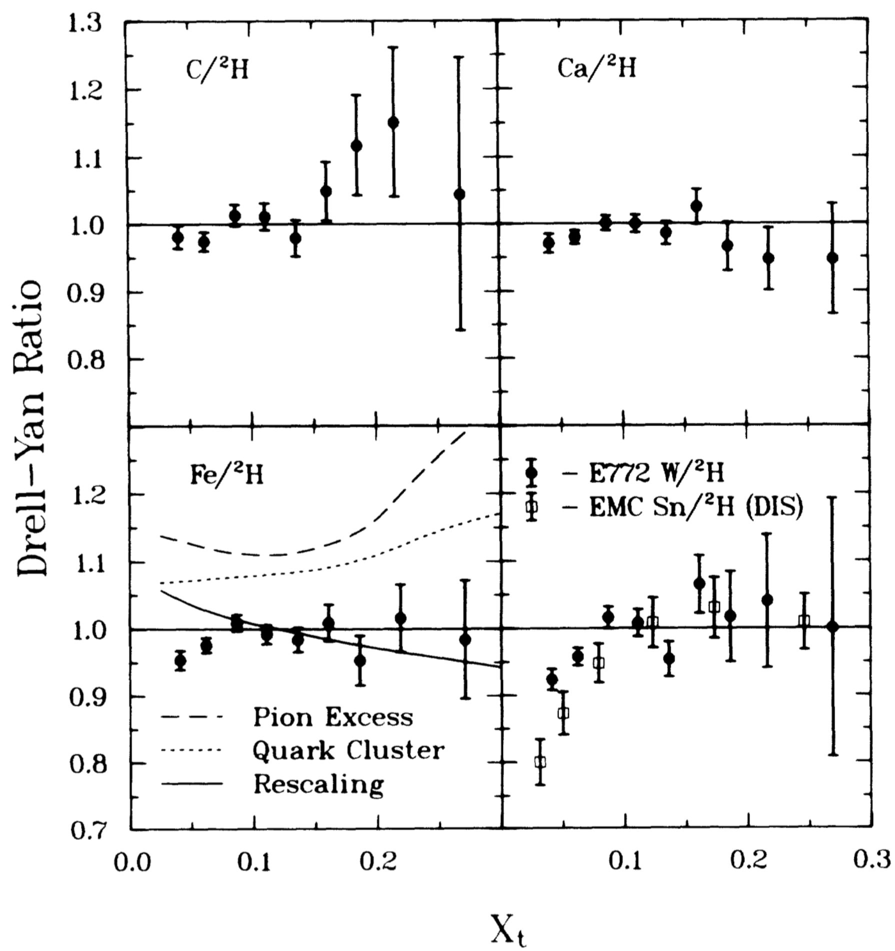
$$\frac{d\sigma_{\pi^\pm A}}{dx_\pi dx_2} = \frac{4\pi\alpha^2}{9sx_\pi x_2}\sum_q e_q^2[q_{\pi^\pm}(x_\pi)\bar{q}_A(x_2) + \bar{q}_{\pi^\pm}(x_\pi)q_A(x_2)]$$

A Dependence of Anti-quark Distributions



→ Proton Drell-Yan process sensitive to anti-quark distributions in the target

→ E772 at Fermilab measured no *A* dependence over limited *x* range, with limited precision



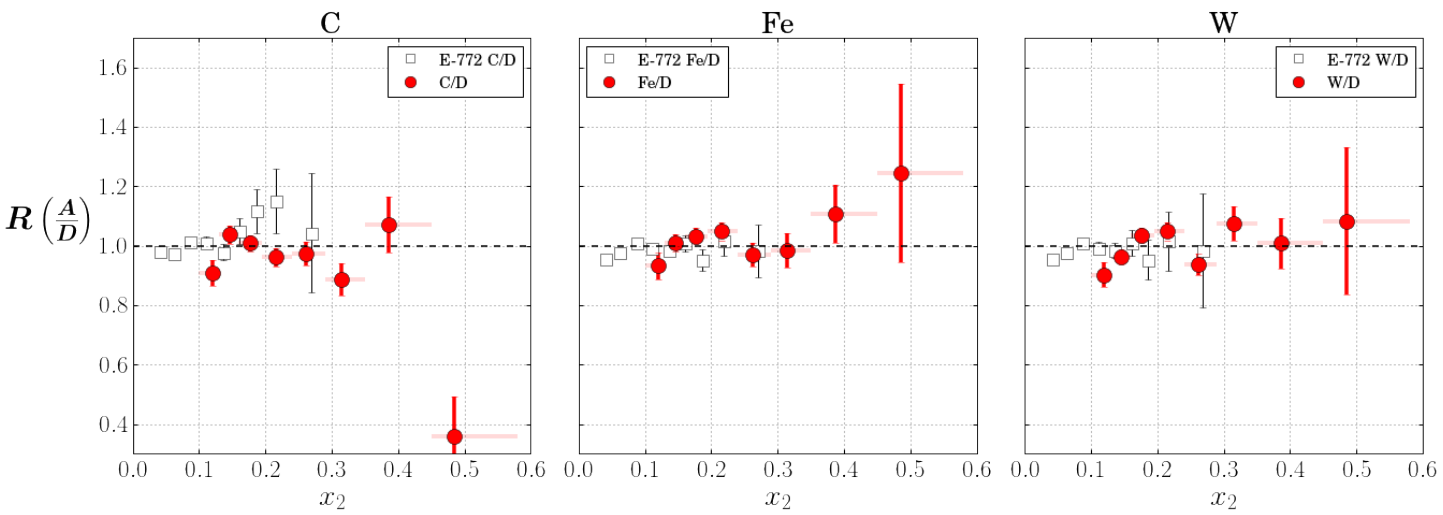
Ruled out significant contributions from nuclear pions

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

E906 and Nuclear Anti-quarks

E906 (SeaQuest) at Fermilab
→ Primary goal measurement of sea-quark asymmetry in proton
→ Finished data taking in 2017
→ Also measured Drell-Yan from nuclear targets (C, Fe, and W)

Extends to higher x than E772
→ x up 0.5 – regime where "EMC Effect" should be significant



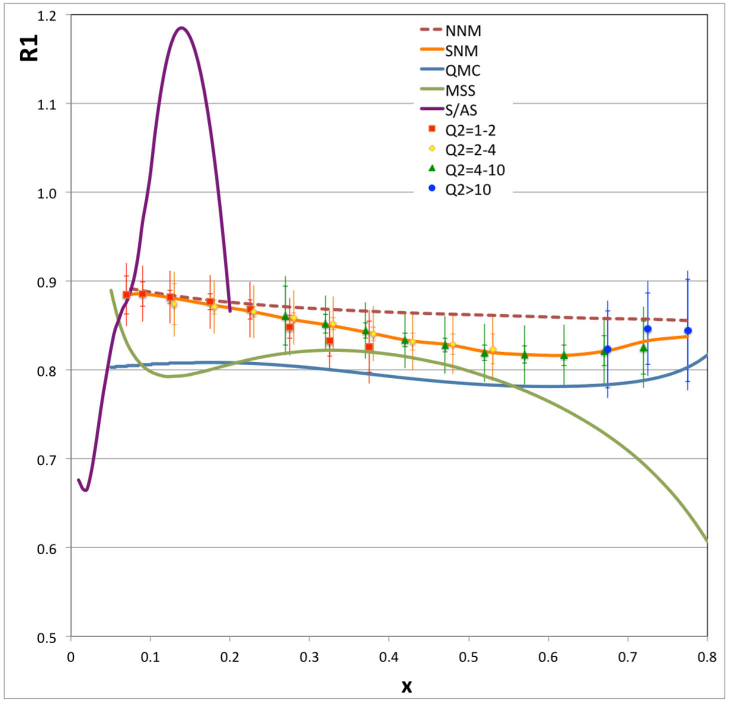
B. Dannowitz, PhD Thesis, UIUC – not official E906 results

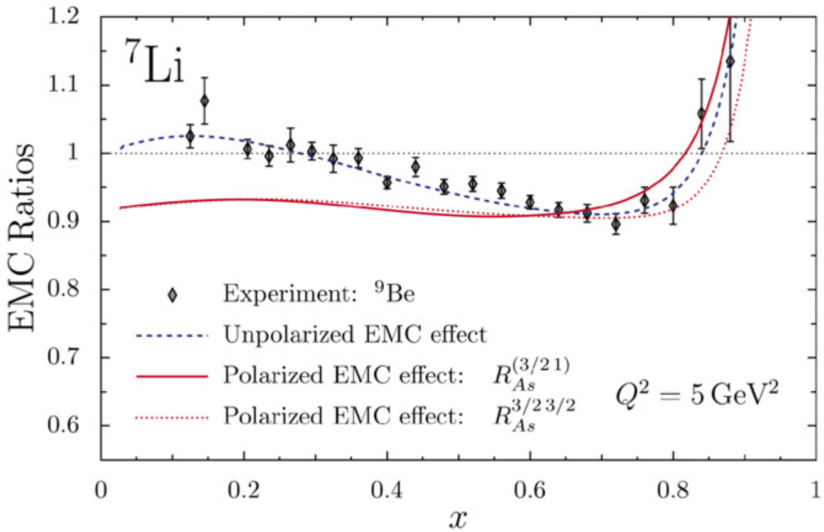
Polarized EMC Effect

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

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

$$R = \frac{g_{1A}}{P_p g_{1p} + P_n g_{1n}}$$





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

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

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

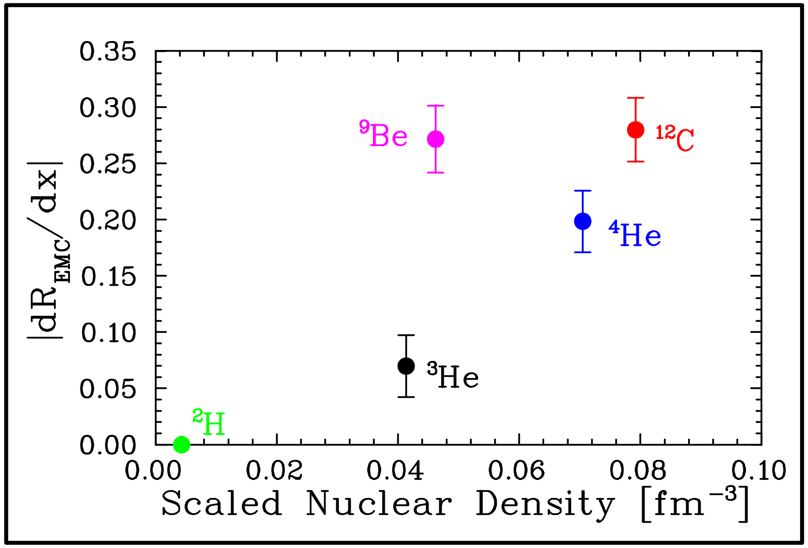
Jefferson Lab

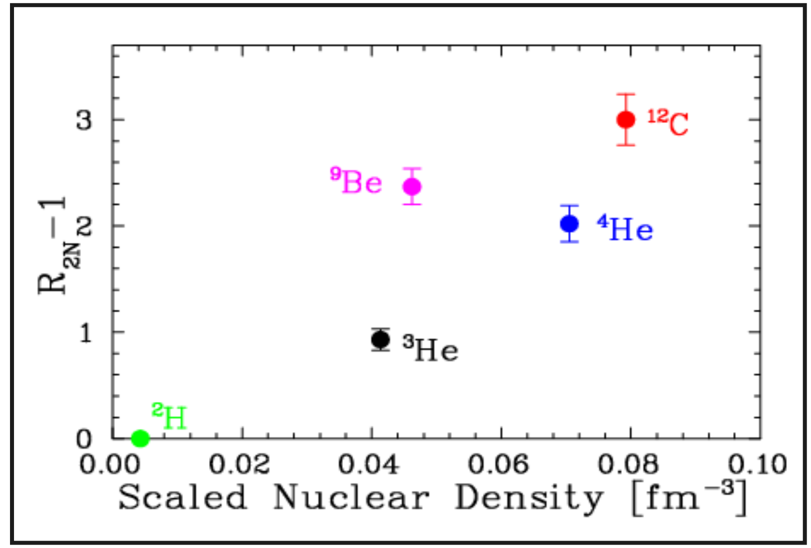
Summary

- 35 years of inclusive experiments have provided a lot of information about the properties of the EMC Effect
  - No consensus on origin
- New experimental and theoretical results have motivated several avenues of investigation
  - Connection with Short Range Correlations
  - Tagged measurements
  - Flavor dependence (valence)
  - EMC effect in polarized quark distributions
  - Sea-quarks
- Jefferson Lab 12 GeV program will cover much of the above
  - Drell-Yan program at Fermilab (sea quarks) and COMPASS (flavor dependence) will also provide important input

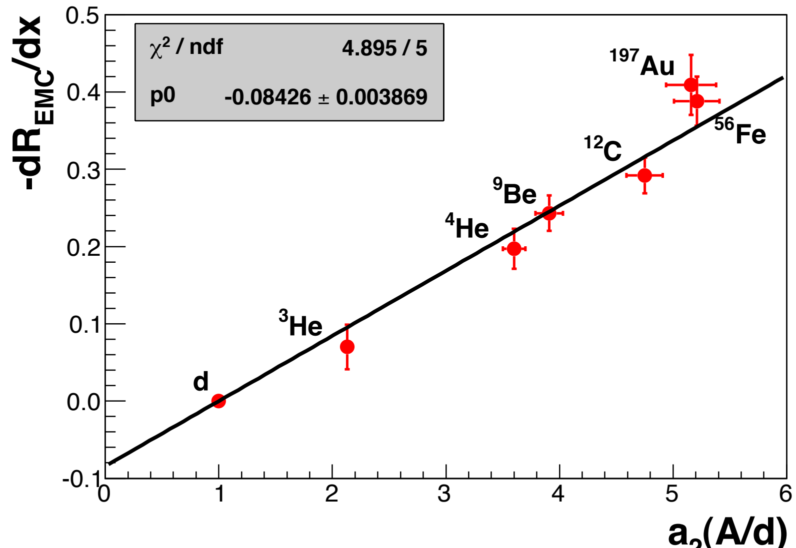
EXTRA

EMC Effect and SRC



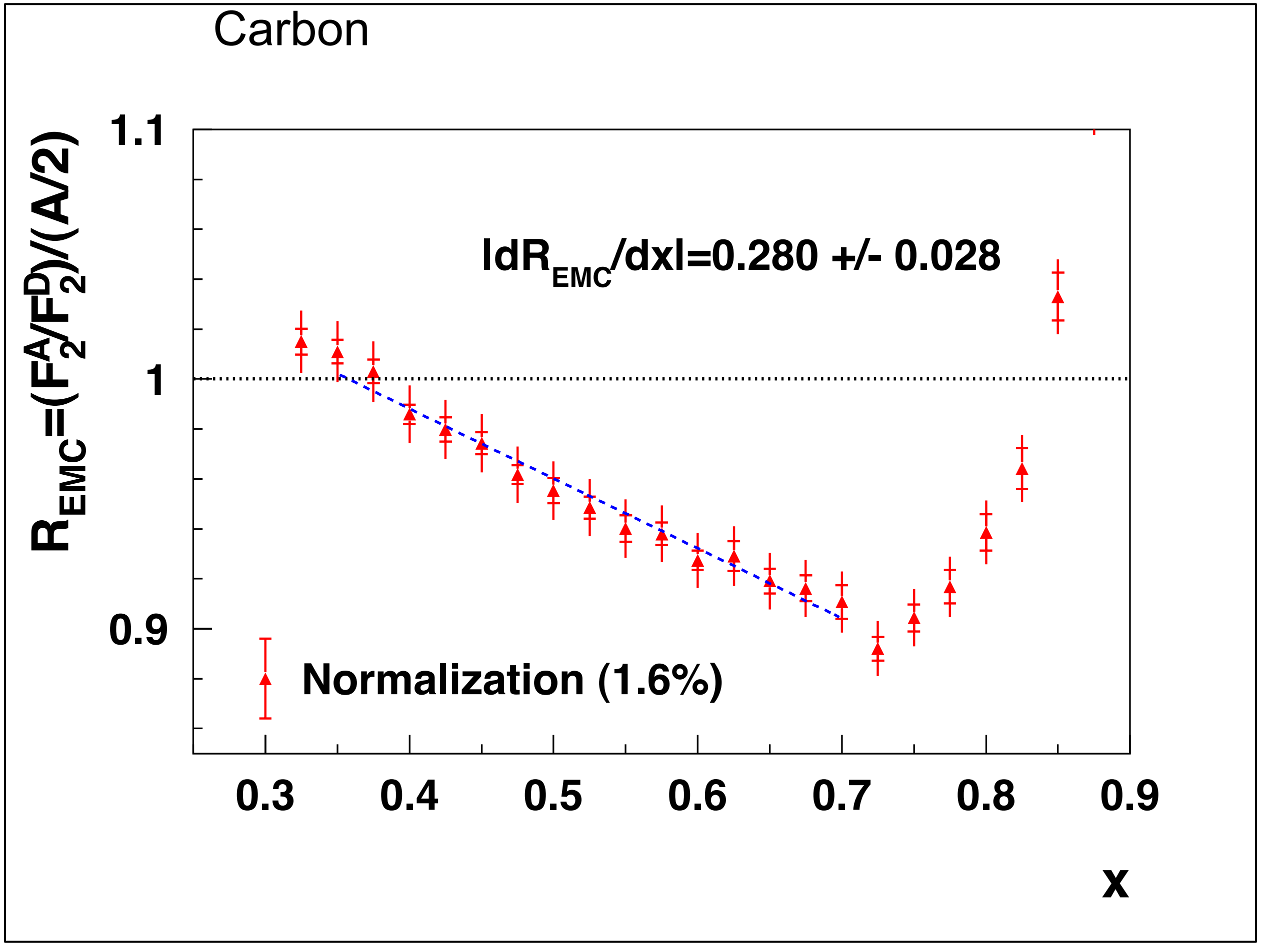


EMC-SRC connection became more intriguing with the addition of Be SRC data
→ Both EMC and SRC display similar dependence on nuclear density



O. Hen et al, Phys.Rev. C85 (2012) 047301

JLab E03103 and the Nuclear Dependence of the EMC Effect



New definition of "size" of the EMC effect

→Slope of line fit from x=0.35 to 0.7

Assumes shape is universal for all nuclei

→Normalization uncertainties a much smaller relative contribution

Flavor dependence and SRCs

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

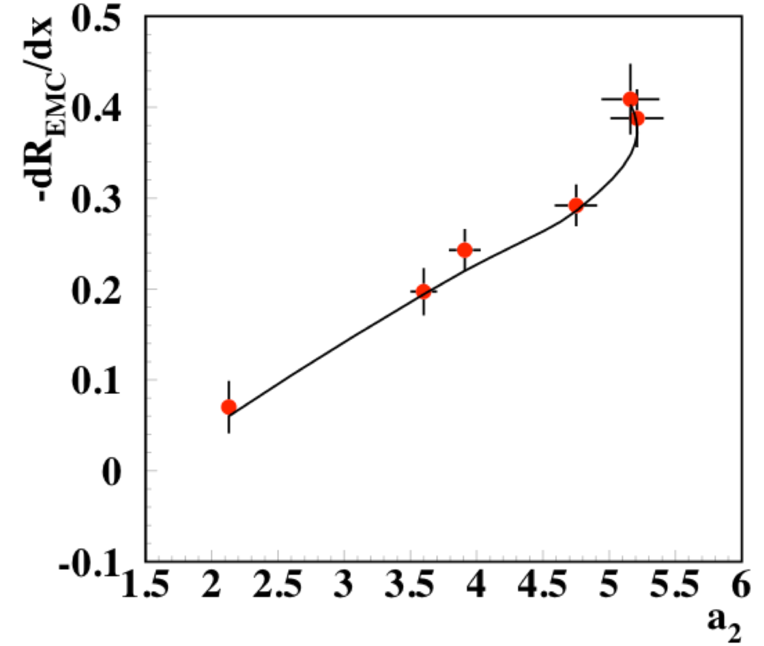
→The relative probability to find a high momentum proton is larger than for neutron for *N>Z* nuclei

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

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

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]