# What does the EMC-SRC Correlation tell us about isospin dependence (and origin) of the EMC Effect?

John Arrington
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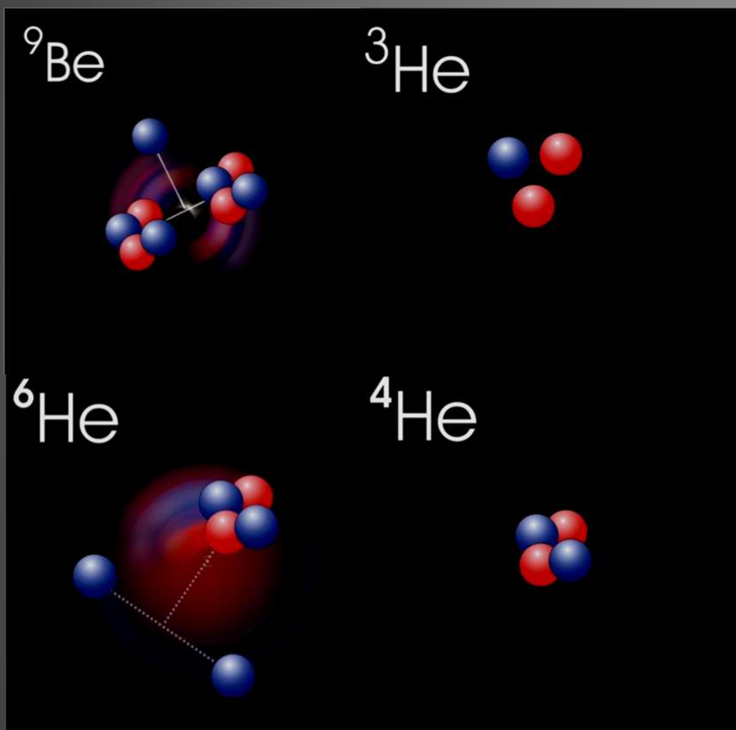
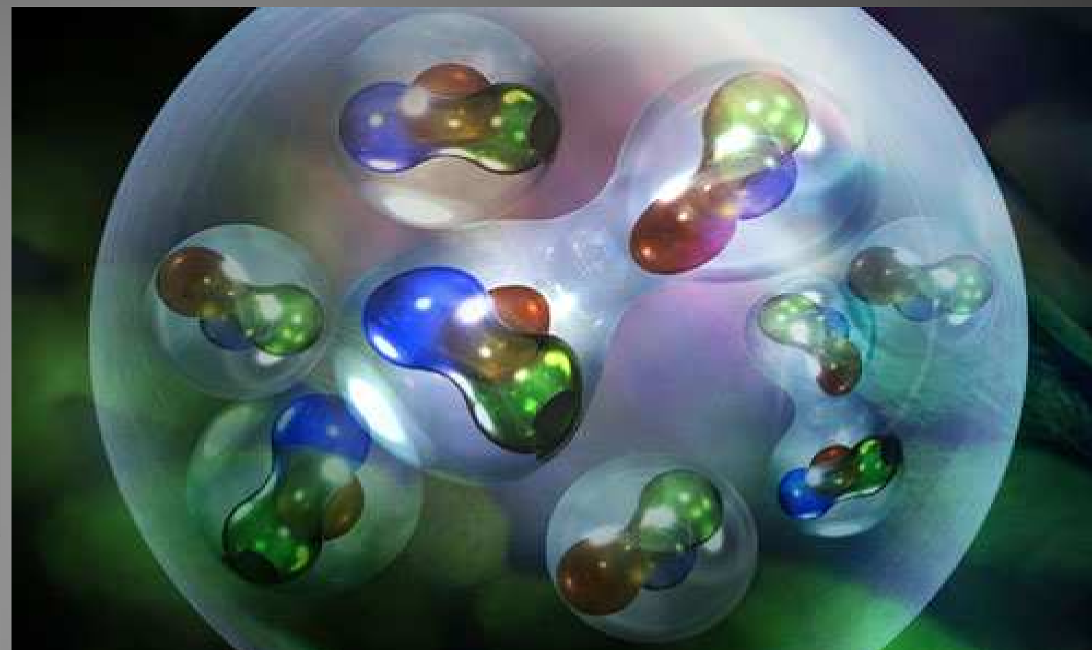
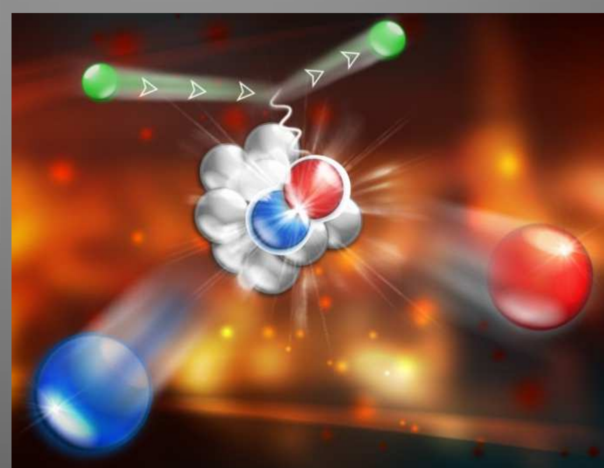
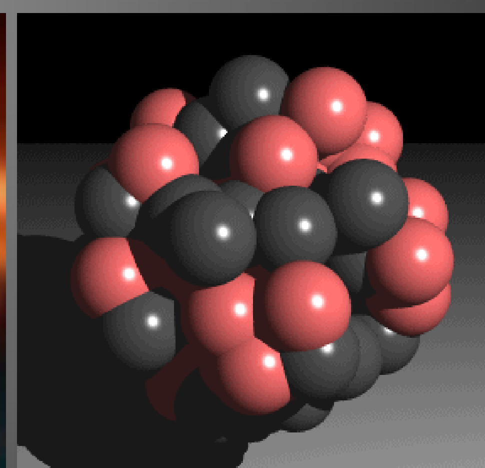






*Exploring QCD with light nuclei at EIC*

*January 21-24, 2020*

# Isospin dependence of the EMC effect?

- **Always assumed that EMC effect is <u>identical for proton and neutron</u>**
- **Becoming hard to believe, at least for non-isoscalar nuclei**
  - **Calculations show difference for u-, d-quark, as result of scalar and vector mean-field potentials in asymmetric nuclear matter**
    [I. Cloet, et al, PRL 109, 182301 (2012); PRL 102, 252301 (2009)]
  - **$^{48}$Ca, $^{208}$Pb expected to have significant neutron skin: neutrons preferentially sit near the surface, in low density regions**
  - **EMC-SRC correlation + n-p dominance of SRCs suggests enhanced EMC effect in minority nucleons**
    - In $^3$H, np-dominance suggests single proton generates same high-momentum component as two neutrons –> larger EMC effect in 'high-virtuality' picture

***All of these imply increased EMC effect in minority nucleons***

# Key 6 GeV inclusive measurements

JLab E02-019: JA, D. Day, B. Filippone, A. Lung

- Scatter from light nuclei at x>1
  - *Probe high-momentum nucleons in nuclei*
  - ***Study short-distance (high-density) structures** in nuclei*

JLab E03-103: JA and D. Gaskell, spokespersons

- DIS from light nuclei in high-x region
  - *EMC effect: **Nuclear dependence of quark distributions***

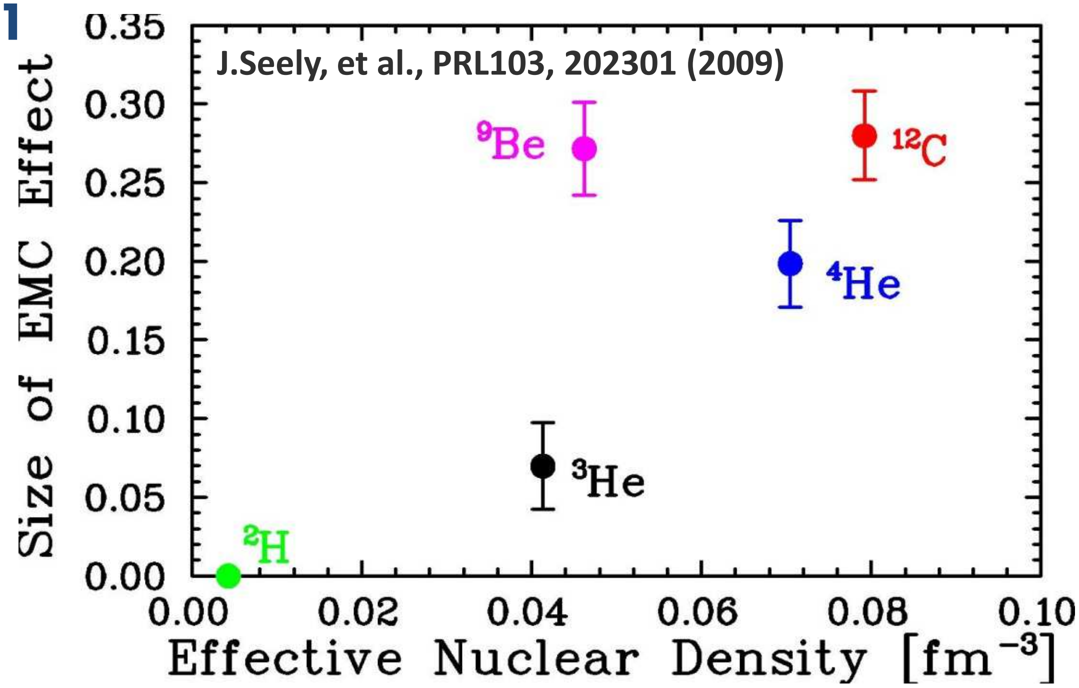
# EMC, SRCs in light nuclei

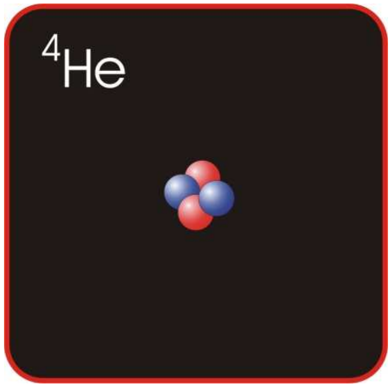
Density determined from
*ab initio* few-body calculation

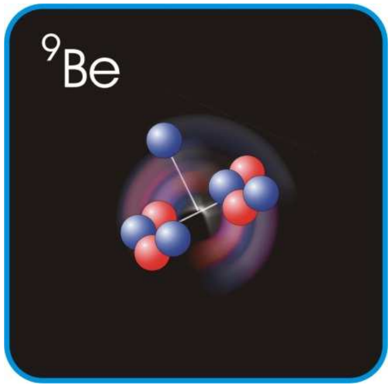
***S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)***

EMC effect increases with density, as expected, except for $^{9}$Be

Detailed nuclear structure, beyond mass or average density, impact nuclear pdfs



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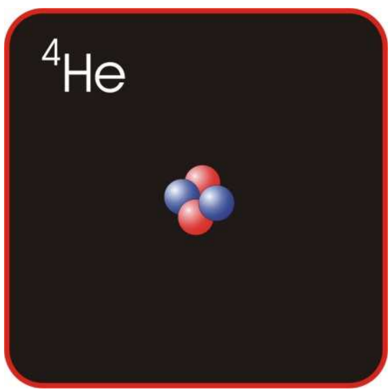
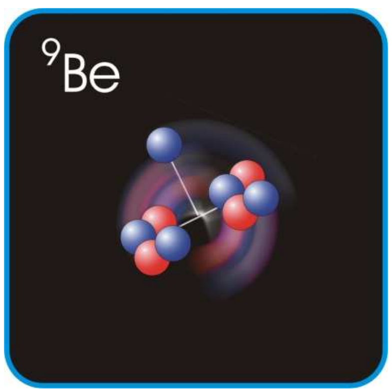
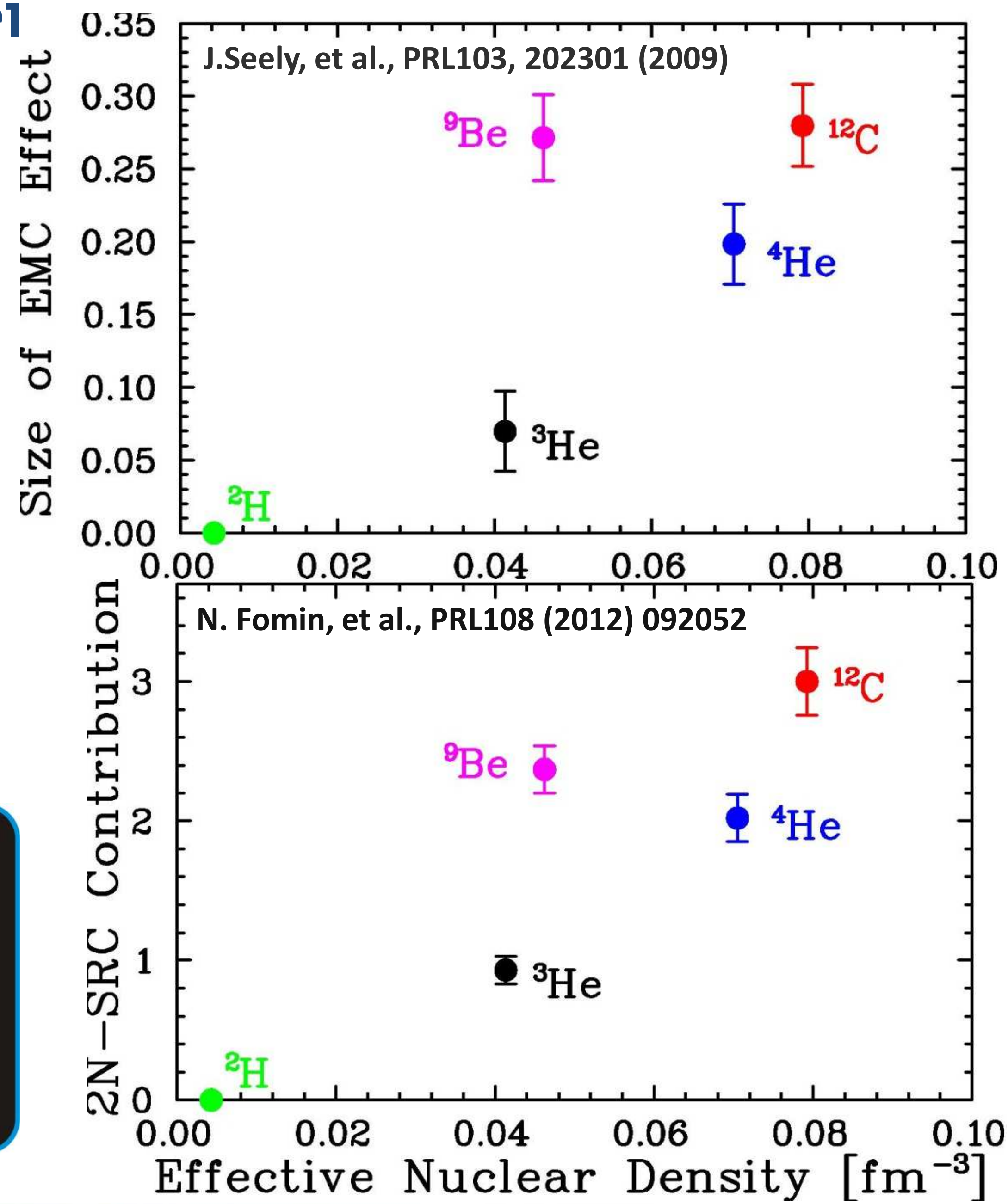
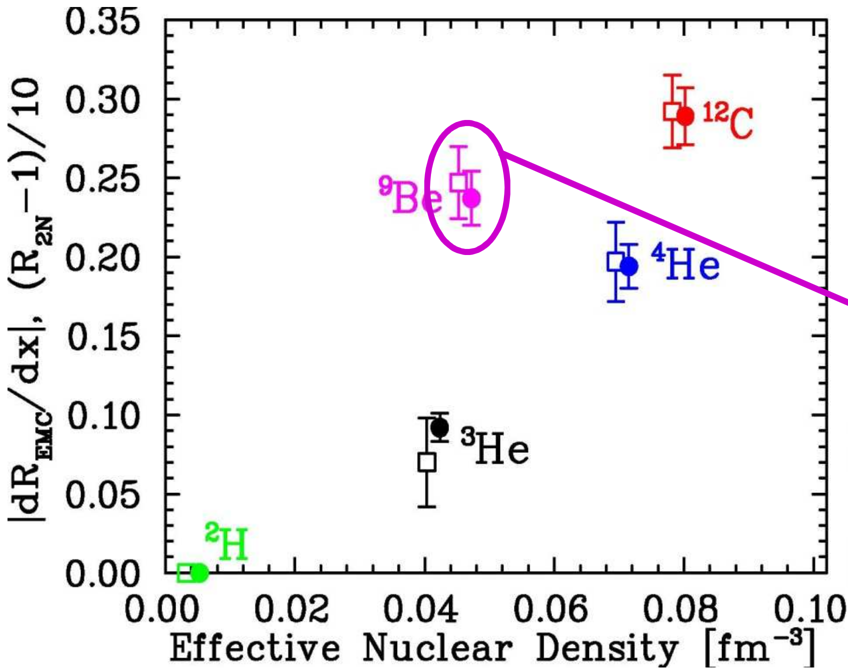


# EMC, SRCs in light nuclei

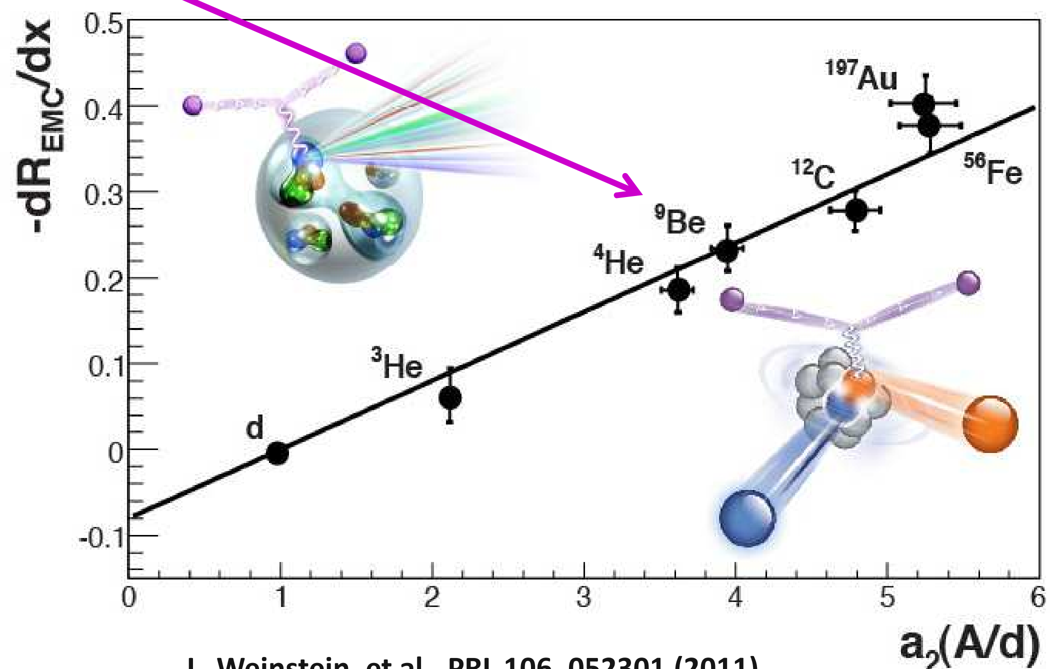


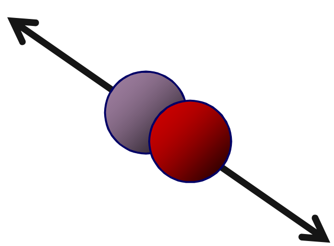

J. Seely, et al., PRL103, 202301 (2009)

N. Fomin, et al., PRL 108, 092052 (2012)

**SRCs are both short-distance and high-momentum components**

***Which matters for EMC effect??***
***(or neither, or some combination?)***



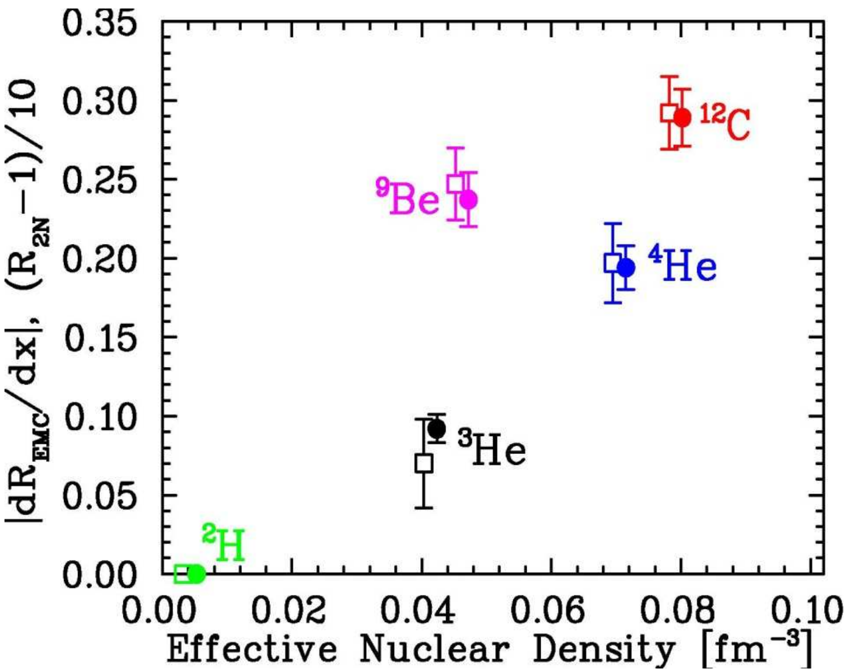



L. Weinstein, et al., PRL 106, 052301 (2011)
O. Hen, et al, PRC 85, 047301 (2012)
JA, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86, 065204 (2012)

# Short-distance behavior and the EMC effect

~~1. EMC effect driven by **average density** of the nucleus~~

~~[J. Gomez, et al., PRD 94, 4348 (1994), Frankfurt and Strikman, Phys. Rept. 160 (1988) 235]~~




If EMC effect and SRC contributions both scaled with density, it would explain the EMC-SRC correlation

**It would not explain the anomalous result for 9Be**

*Note: in some cases, e.g. Frankfurt and Strikman review, average density was used to represent probability of nucleon overlap – conceptually consistent with idea of large 9Be EMC effect*

# Short-distance behavior and the EMC effect

~~1. EMC effect driven by **average density** of the nucleus~~

~~[J. Gomez, et al., PRD 94, 4348 (1994), Frankfurt and Strikman, Phys. Rept. 160 (1988) 235]~~

2. EMC effect is driven by **Local Density (LD)** – overlap of nucleons

[J. Seely et al., PRL 103, 202301, 2009]

**SRCs generated by interactions in short-distance (high-density) np pairs**

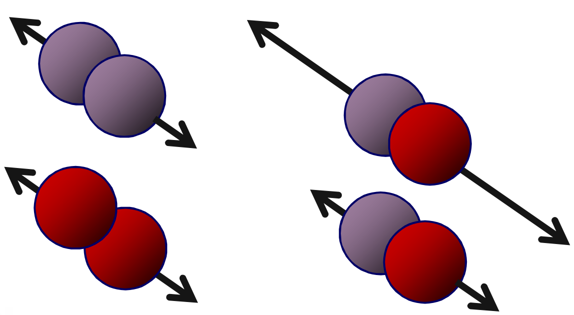
**EMC effect driven by high-density nucleon configurations (pairs, clusters)**

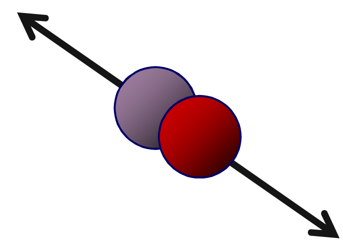
3. EMC effect driven by **High Virtuality (HV)** of the nucleons

[L. Weinstein et al, PRL 106, 052301,2011]

**SRC measurements directly probe high-momentum nucleons**

**EMC effect driven by off-shell effects in high-momentum nucleons**



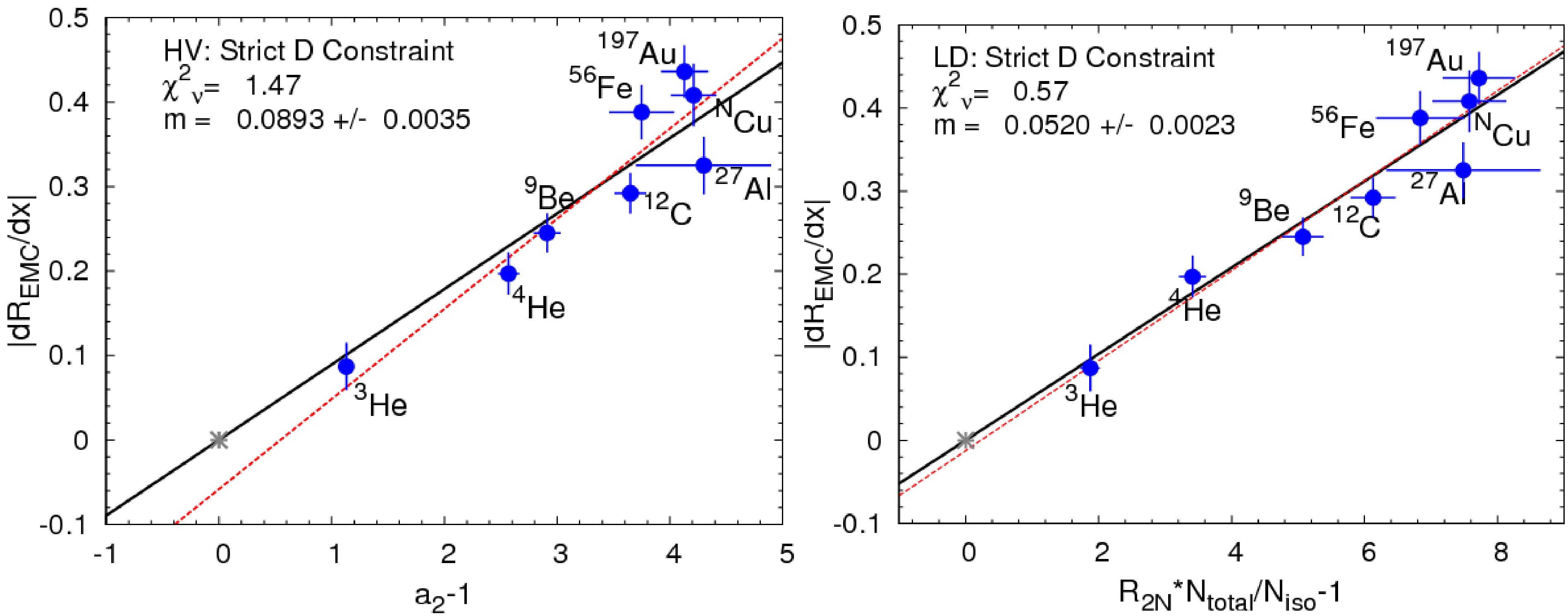


**First comparison of HV/LD explanations of EMC-SRC correlation:**
**JA, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86 (2012) 065204**

# Two Hypotheses for EMC-SRC correlation

| Hypothesis | Fit type | $\chi^2_\nu$ | EMC(D) |
|---|---|---|---|
| High Virtuality | 2-param<br>No constraints | 1.26 | -0.058±0.036 |
| High Virtuality | 1-param | 1.47 | – |
| Local Density | 2-param<br>No constraints | (0.64) 0.84 | -0.012±0.033 |
| Local Density | 1-param | (0.57) 0.74 | – |

JA, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86 (2012) 065204



# New, closely related, approach

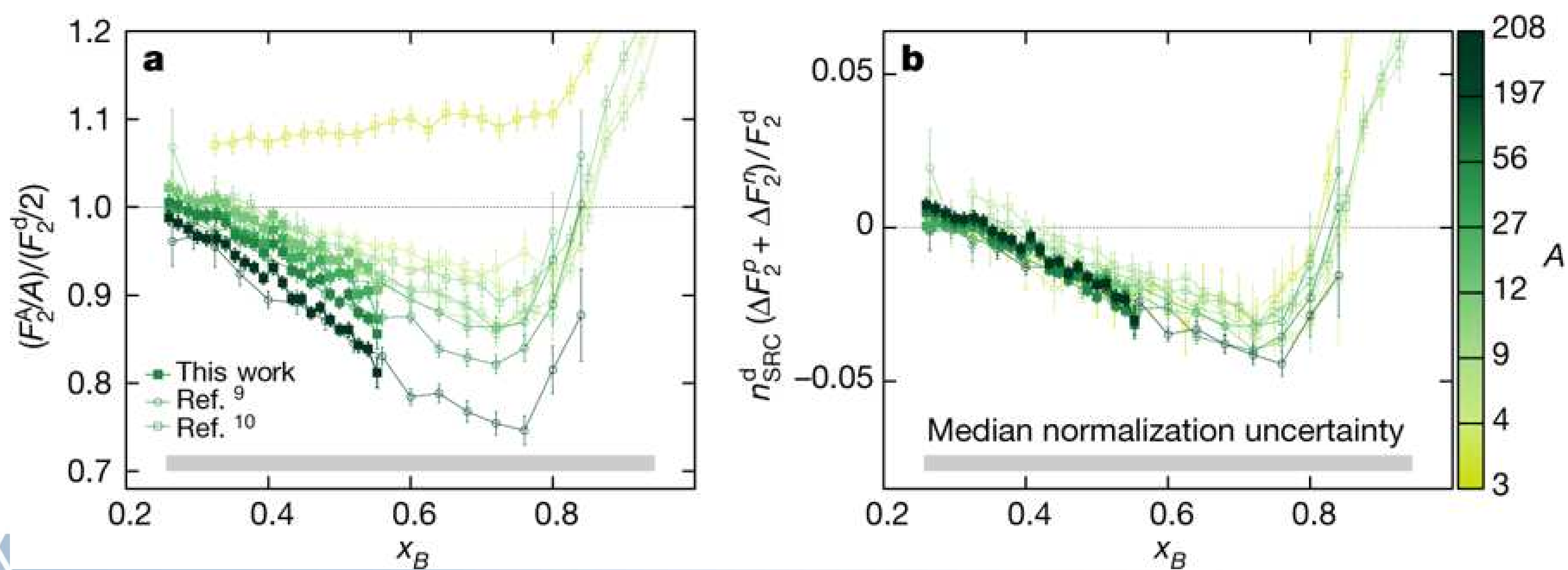
If EMC effect due to high-momenta (our HV hypothesis), can extract universal modification of (F2p+F2n)/F2d in a deuteron

*B. Schmookler, et al., Nature 566 (2019) 345*

$$F_{univ}^{HV} = \frac{(\sigma_A/\sigma_D) - (Z-N)\frac{F_2^p}{F_2^d} - N}{(A/2)a_2 - N}$$

For isoscalar nuclei, simplifies to $(R_{EMC}-1)/(a_2-1)$

More detailed way of looking at EMC-SRC correlation (**and** isospin structure of EMC effect)



If EMC effect due to high-momenta (“HV” hypothesis), can extract universal modification of (F2p+F2n)/F2d in a deuteron

$$F_{univ}^{HV} = \frac{(\sigma_A/\sigma_D) - (Z-N)\frac{F_2^p}{F_2^d} - N}{(A/2)a_2 - N}$$

*B. Schmookler, et al., Nature 566 (2019) 345*

Observation of universal function shows data are consistent with the HV picture. How much better (worse) is this than an isospin-independent picture?

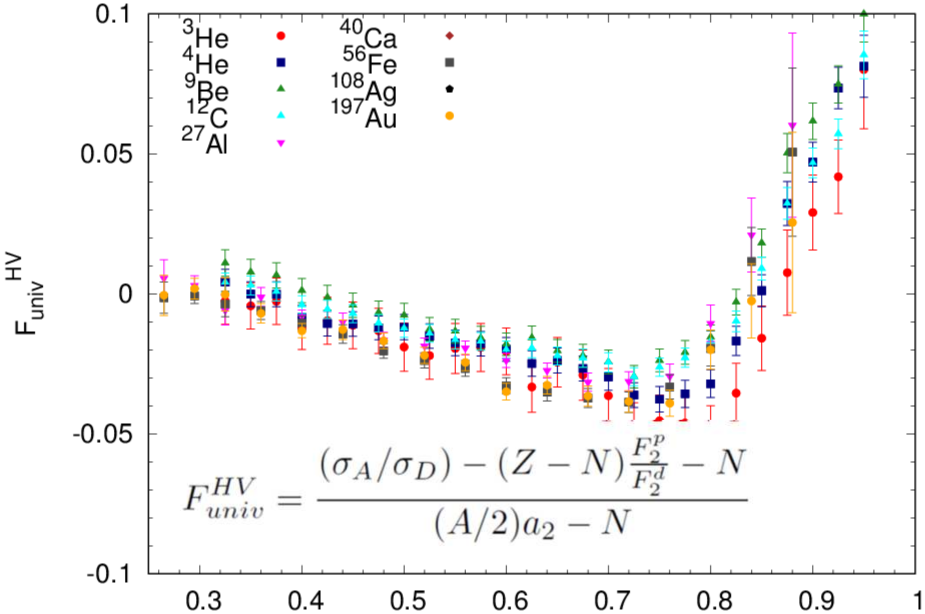
Define similar function under assumption that all NN pairs contribute with no isospin dependence:

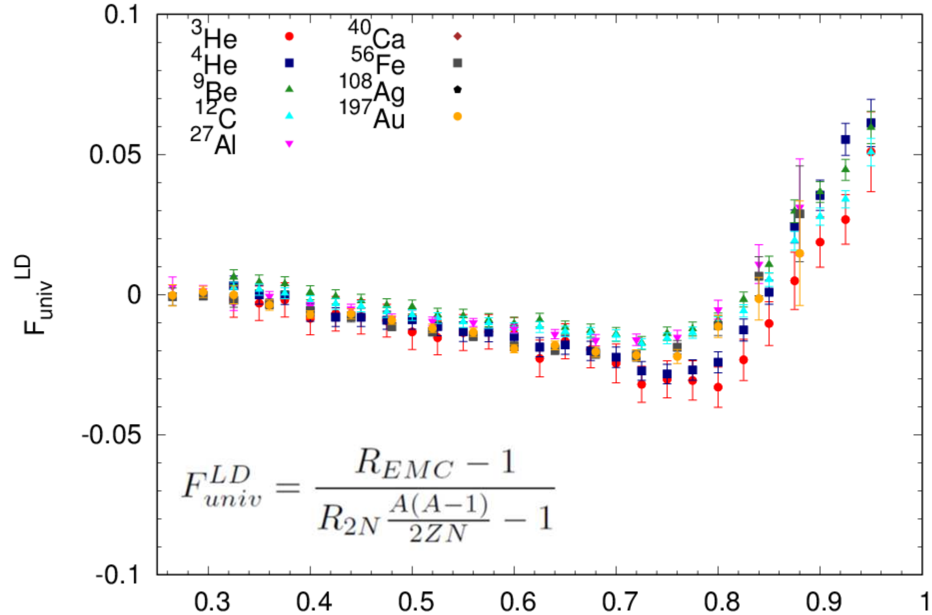
$$F_{univ}^{LD} = \frac{R_{EMC} - 1}{R_{2N}\frac{A(A-1)}{2ZN} - 1}$$

*JA, N. Fomin, PRL 123 (2019) 042501*

*In both versions, isoscalar corrections from the data sets unified correction applied [different F2n/F2p in our analysis, but correction nearly identical for x<0.7]*

*We used SLAC + JLab(Hall C) EMC data; have not included new CLAS results.*



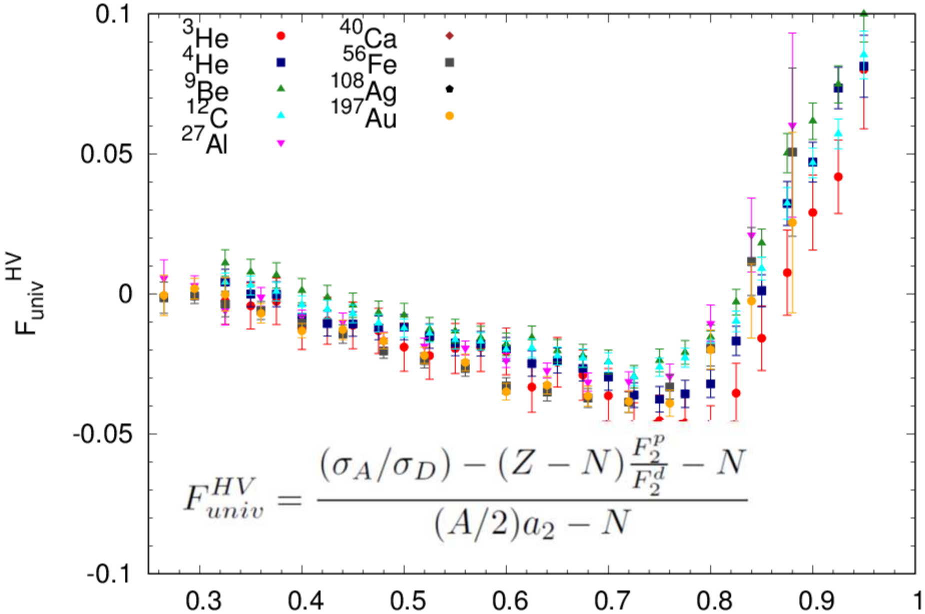



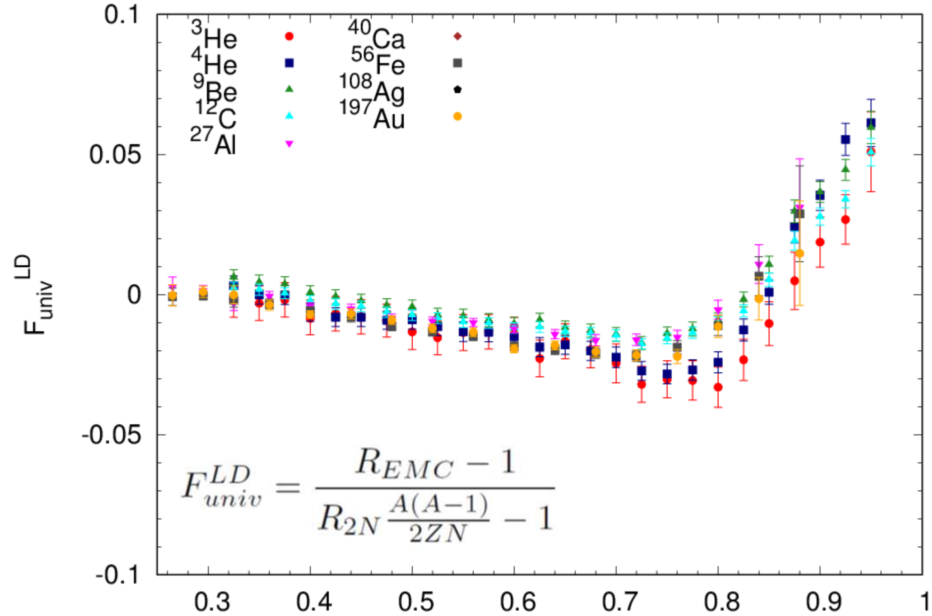

*HV picture: np-dominance generates predicable isospin dependence of EMC effect*

*LD picture: EMC effect from short-distance pairs, assumed to be isospin independent*

*Both give a good description in terms of a universal modification*

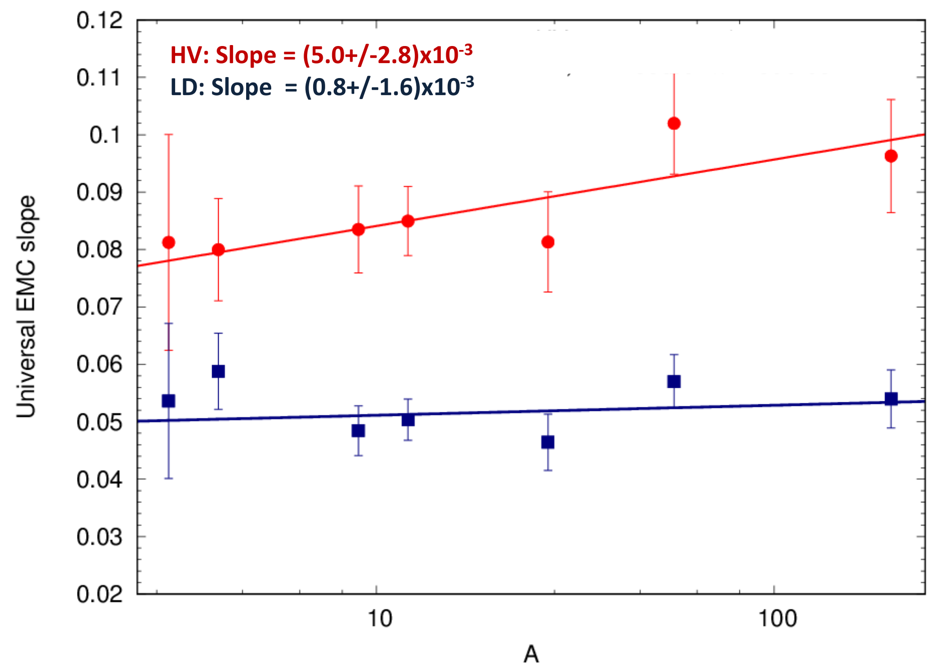
*As in 2012 EMC-SRC analysis, somewhat better description in isospin-independent LD picture*

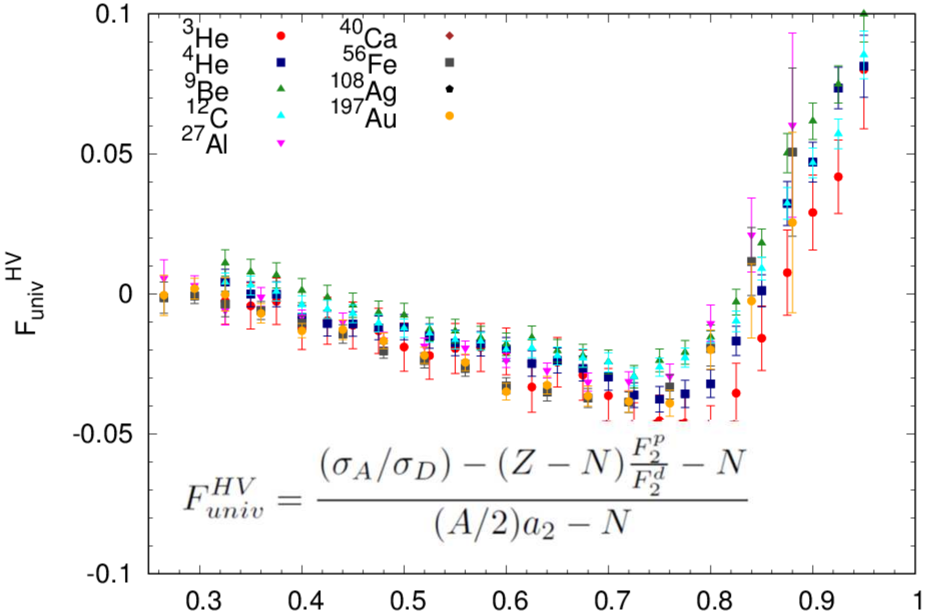


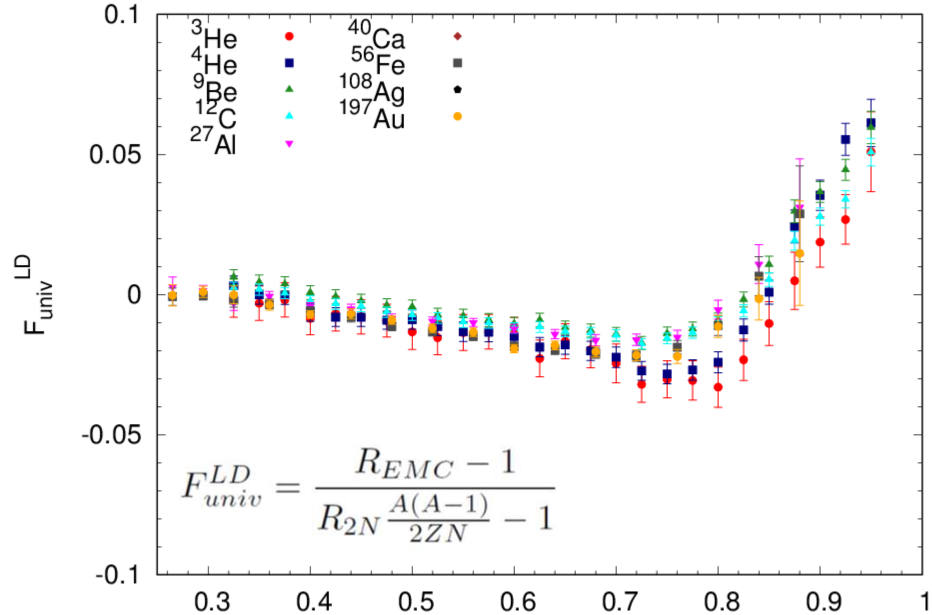




*HV picture: EMC effect from np-SRC, generates known isospin dependence*

*LD picture: Driven by short-distance pairs, assumed to be isospin independent*



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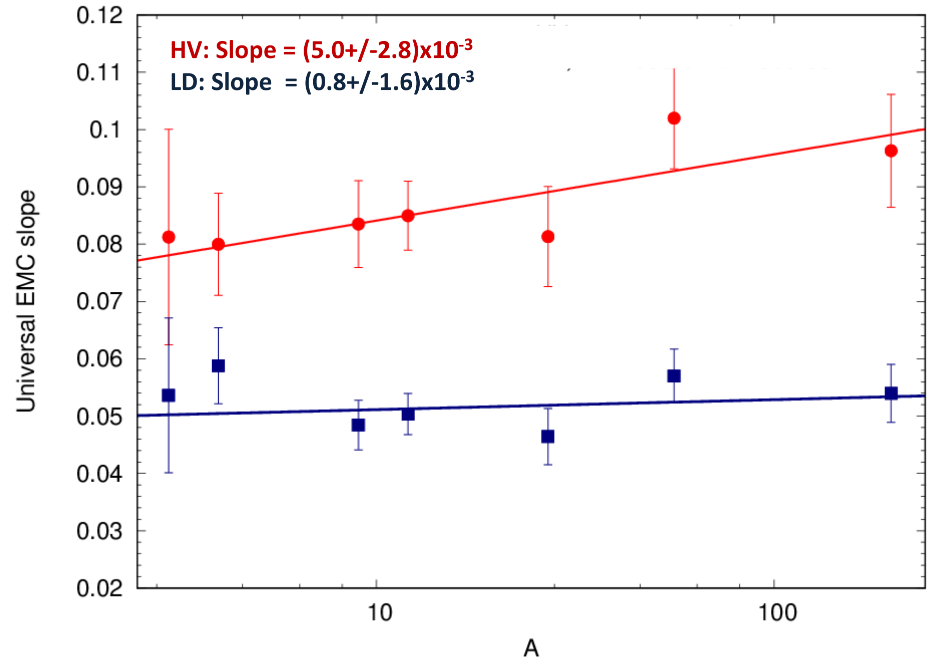



*Differences in formulae/analyses:*

*CLAS EMC data not included in JA/Fomin*

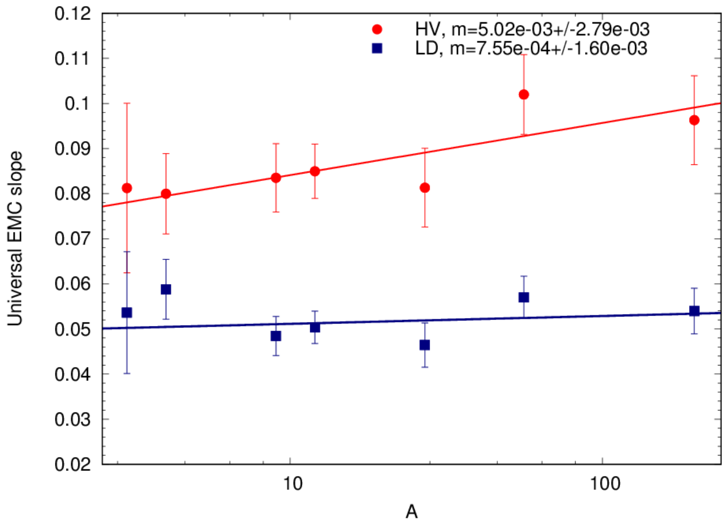
*$a_2$ vs $R_{2N}$*

*np pairs vs. all NN pairs*

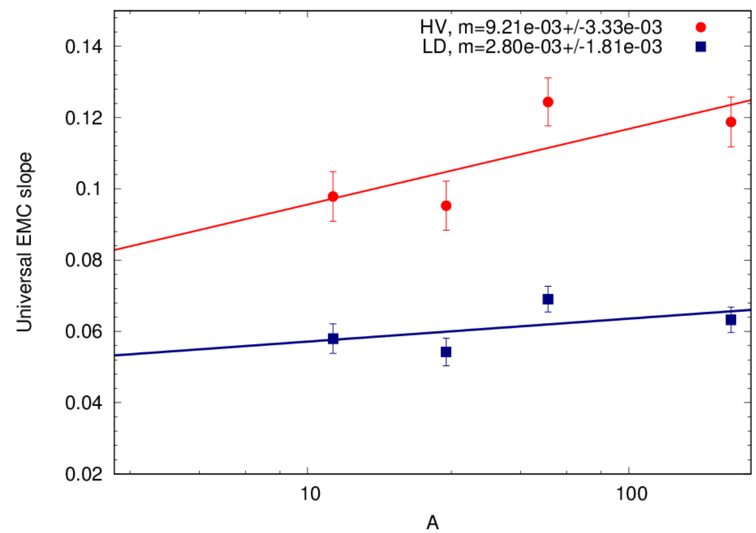
*Flavor indep vs. flavor dependent EMC*

# Impact of new CLAS EMC data

SLAC + Hall C



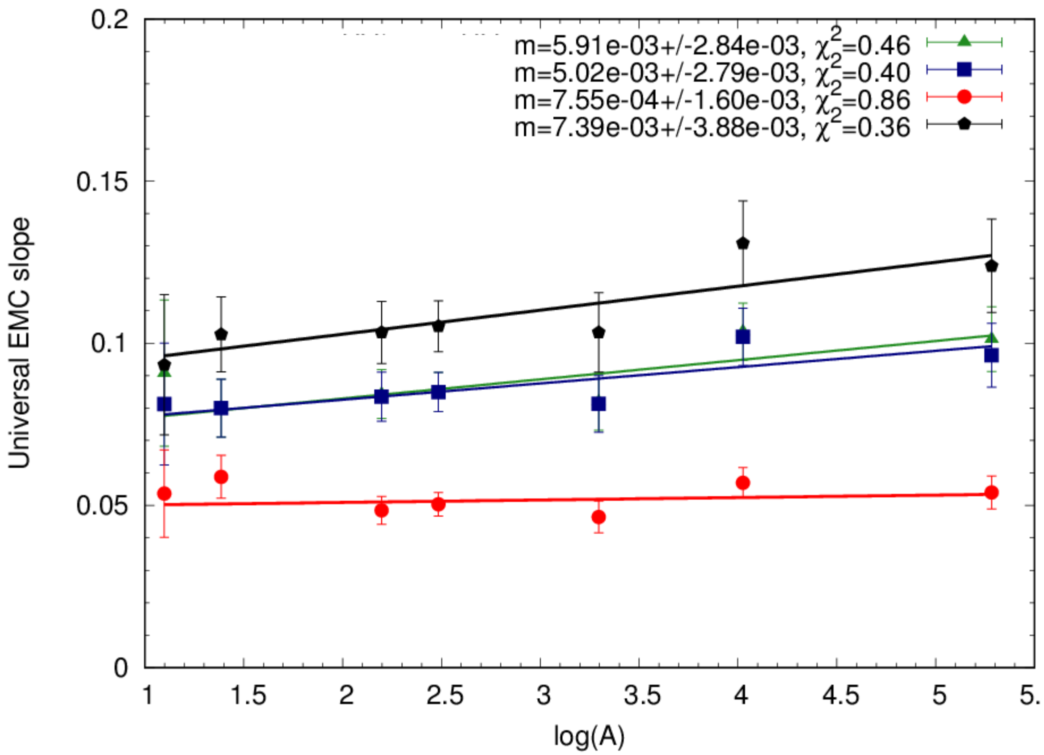

CLAS EMC data




Combined slope still favors HV picture:

HV: slope = (6.75 +/- 2.06) x $10^{-3}$
LD: slope = (1.65 +/- 1.01) x $10^{-3}$

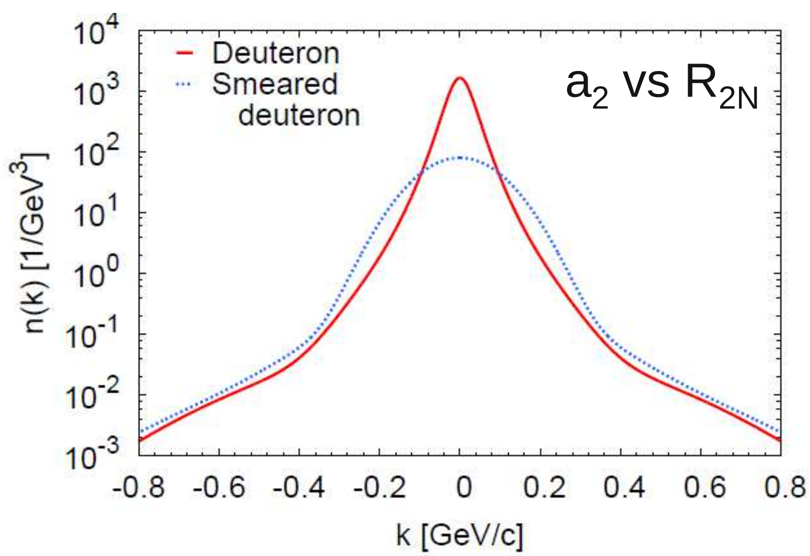
# What drives the difference?




SLAC + Hall C only (PRL)
Blue = HV (full flavor dependent version)
Red = LD

Black = HV with $R_{2N}$ instead of $a_2$
Changes scale, not overall behavior
Green = 'naïve' EMC-SRC correlation
Slope = EMC slope / $a_2$

HV → $(R_{EMC}-1)/(a_2-1)$ for isoscalar nuclei.
Differs from naïve approach due to explicit isospin dependence for non-isoscalar nuclei, but impact is small (blue vs green points)



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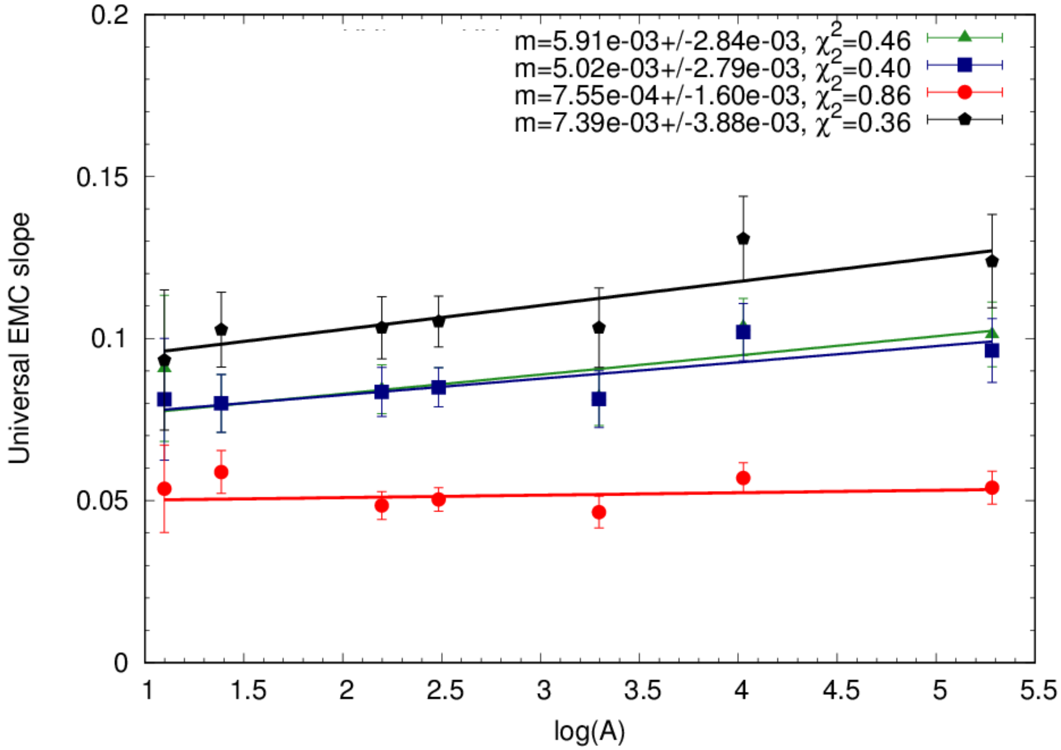


SLAC + Hall C only (PRL)
Blue = HV (full flavor dependent version)
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Changes scale, not overall behavior
Green = 'naïve' EMC-SRC correlation
Slope = EMC slope / $a_2$

Difference comes from pair counting: N*Z np pairs vs. A(A-1)/2 NN pairs
[SRCs measure np pairs; we translate to total pairs]

| A | #np | #pp | np/pp | #NN | NN/np |
|---|---|---|---|---|---|
| 4 | 4 | 1 | 4 | 6 | 1.5 |
| 12 | 36 | 15 | 2.4 | 66 | 1.83 |
| 40 | 400 | 190 | 2.11 | 780 | 1.95 |

*Simple modeling of flavor dependence*

*Future experimental directions*

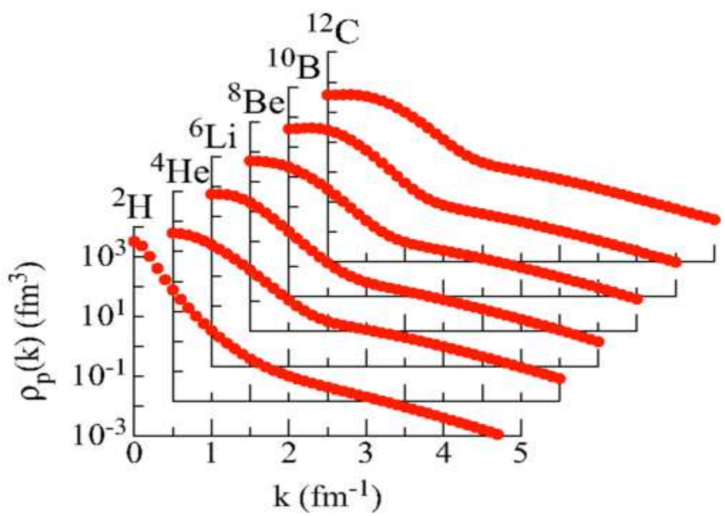
# Quantum Monte Carlo EMC estimates for light nuclei

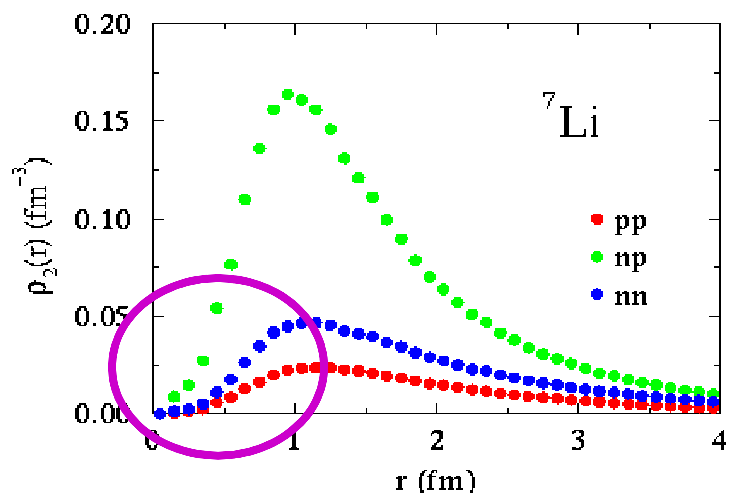
- Provides *ab initio* calculations of several important quantities up to A=12
  - n(k): Fraction of **high-momentum nucleons**, ave. **kinetic energy** of nucleons
  - Density distributions: Average **density** of nucleus
  - Two-body densities: Average **'overlap' (local density)** of nn, pn, pp pairs

- **Predict A-dependence of unpolarized EMC effect [JLab E12-10-008]**
  - **Cross section weighted average of proton and neutrons**

*R. Wiringa, R. Schiavilla, S. Pieper, and J. Carlson, Phys. Rev. C89 (2014) 024305*

- **Can calculate each of these for protons and neutron separately**
  - **Isospin/flavor dependence as function of fractional neutron excess: (N-Z)/A**



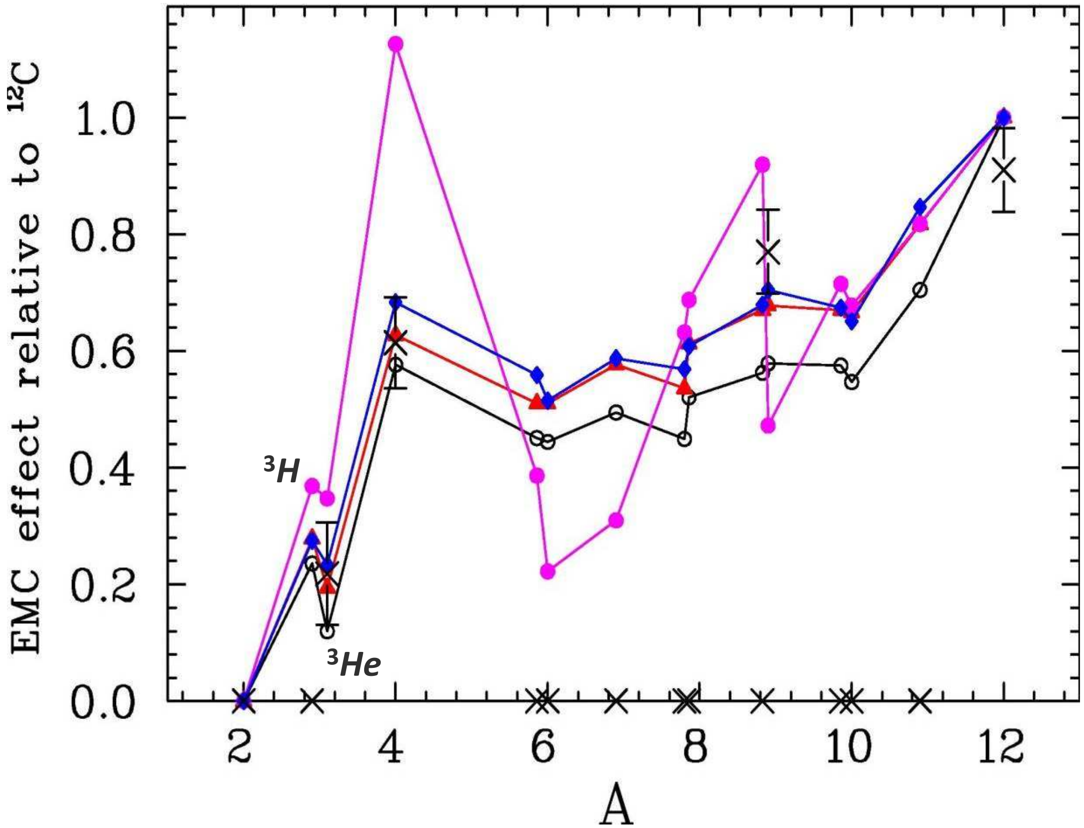



# A-dependence of unpolarized EMC effect

4 simple models of EMC scaling:

***Fraction of n(k) above 300 MeV***
***Average Kinetic Energy***
~~***Average Density***~~
***Nucleon Overlap ($r_{12}$ < 1 fm)***

Fixed normalizations for $^2$H for $^{12}$C




A-dependence of light nuclei already excludes **average density**

**High-momentum tail** has small, systematic difference for most nuclei

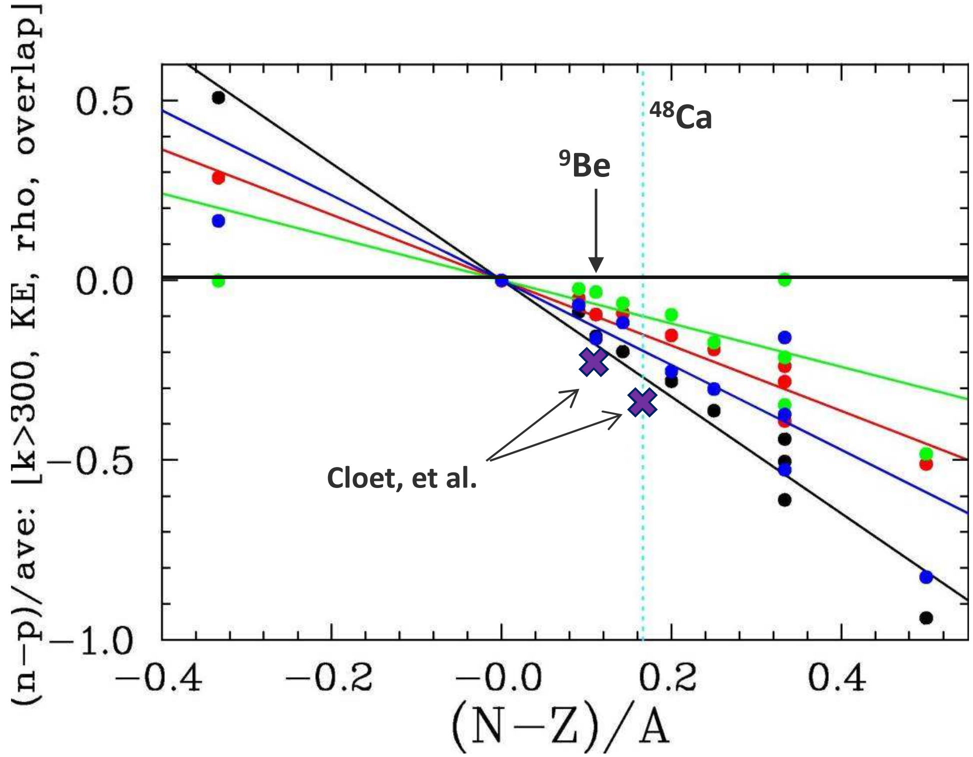
# Isospin dependence vs fractional neutron excess

4 simple models of EMC scaling:

***Fraction of n(k) above 300 MeV***
***Average Kinetic Energy***
~~***Average Density***~~
***Nucleon Overlap ($r_{12}$ < 1 fm)***

EMC effect isospin asymmetry:
(neutron-proton)/average

**Cloet estimates ($^9$Be, $^{48}$Ca): scaled from nuclear matter**



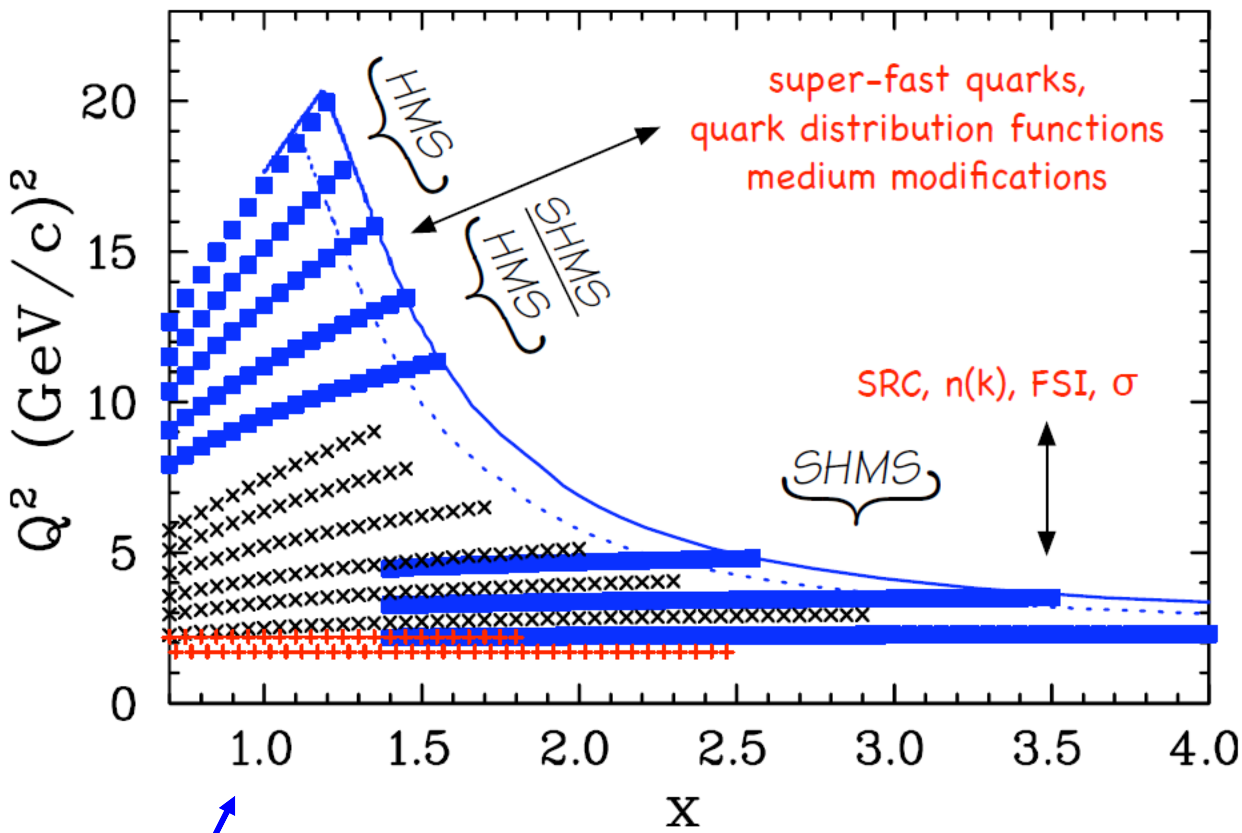

**Can be probed directly in parity-violating electron scattering**

*$^{48}$Ca measurements proposed at JLab*

*- Need detailed structure calculations for $^{48}$Ca*

*Light nuclei (e.g. $^9$Be) may also have good sensitivity; help disentangle effects*

# Unpolarized EMC measurements: JLab@12 GeV

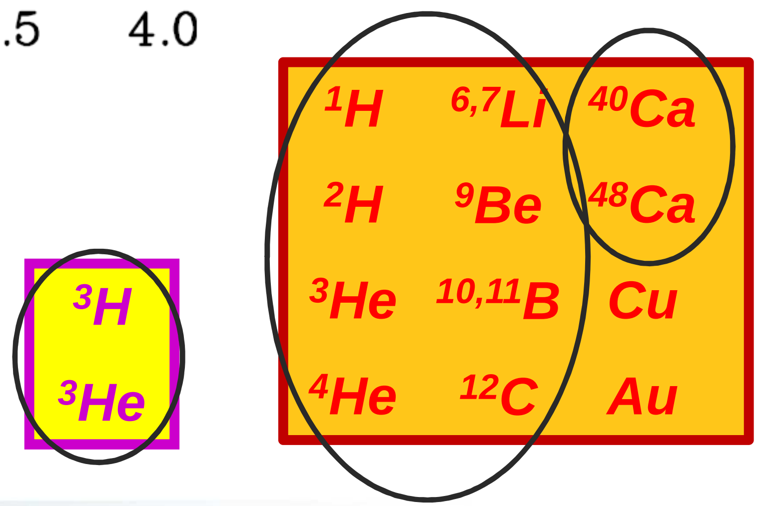



***SRCs at x>1 at 12 GeV***

*[E06-105: JA, D. Day, N. Fomin, P. Solvignon]*

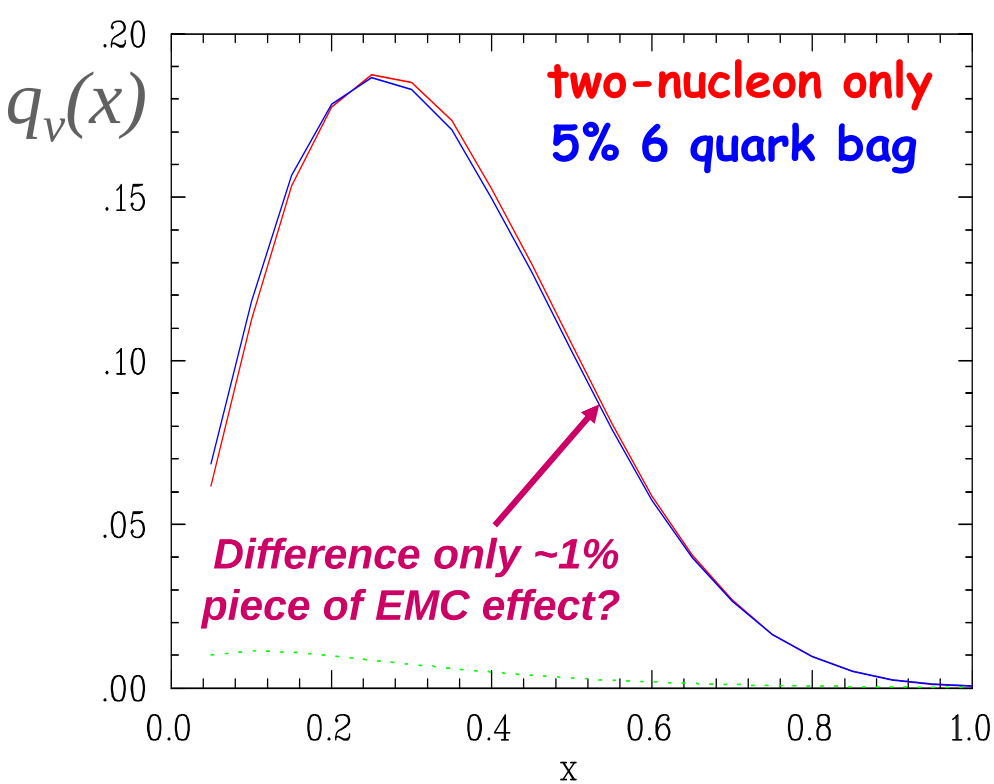
***EMC effect at 12 GeV***

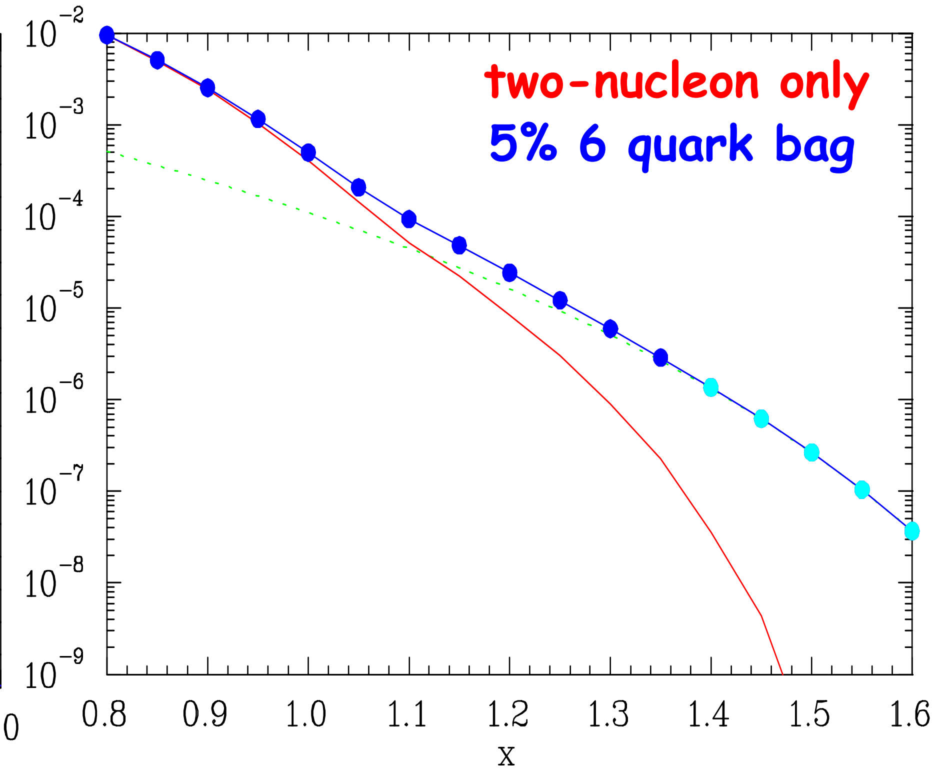
*[E10-008: JA, A. Daniel, D. Gaskell]*



# Quark distributions of SRC: "Super-fast" quarks

## D(e,e') at very high $Q^2$ and x>1 (SRC-dominated region) could provide a clear signature of exotic states in nuclei




**Experiment approved to map out superfast quark distributions at JLab**

**Dramatic increase in $Q^2$ range with an EIC**

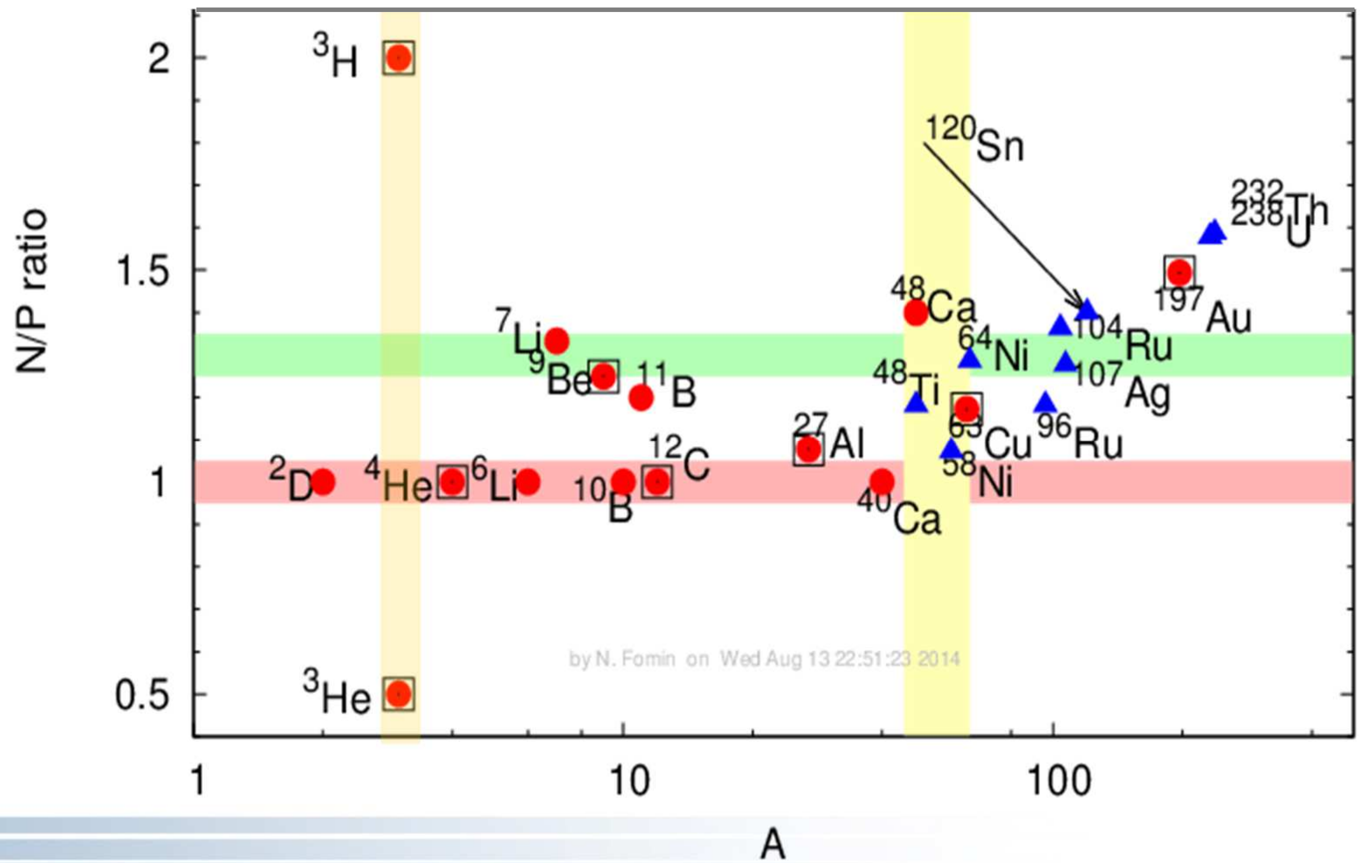
# Disentangling A dependence and isospin effects

<u>**Additional nuclei added since original proposal**</u>

- **Vary N/Z for approximately fixed mass**
- **Vary mass for approximately fixed N/Z**

**Sensitivity to N/Z small in comparing EMC-SRC correlation → systematic study**

$^{112}$Sn, $^{124}$Sn also possible
[Lee Sobotka, WUSTL]



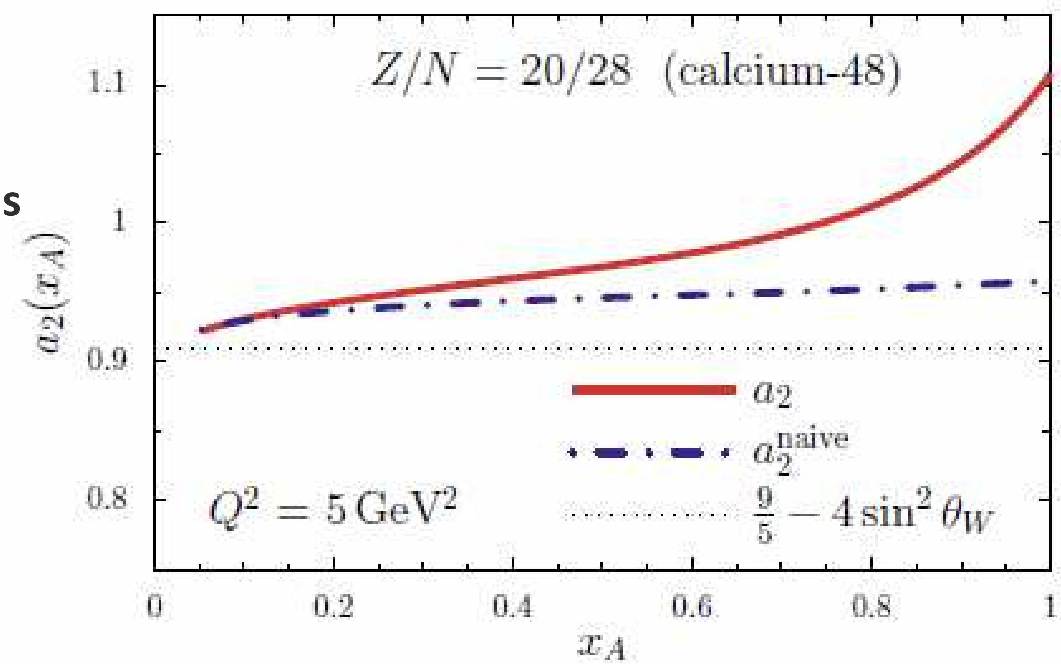
# EMC effect in Parity-Violating electron scattering

**Knowing d(x)/u(x) for the proton and assuming flavor-independent EMC effect, can calculate e-A PV-DIS response**

**PV asymmetry is independent of overall size of EMC effect; only sensitive to difference in EMC effect for u and d quarks**

**Cloet, et al. calculations predicts 5% deviation at large x – comparable to larger predictions from simple models**

**SoLID spectrometer planned for Hall A at Jefferson Lab can make ~1% measurements of PVDIS on non-isoscalar nuclei**




**Best (only?) option for a clean, quantitative measurement of flavor dependence**

# Summary

**Measurements of the EMC effect in light nuclei show importance of detailed nuclear structure, connection with short-range correlations**

**This, along with recent calculations, suggest that there must be a flavor dependence to the EMC effect in neutron rich nuclei**

- Important to separate A dependence from isospin dependence
- Provides information on underlying causes

**Very limited information from unpolarized EMC effect vs N/Z**

- No indication of flavor dependence
- 12 GeV provides broader, systematic study; still limited
- SIDIS (flavor-tagging with $\pi^{\pm}$ – questions about clean interpretation)

**Direct Parity-violating scattering measurements possible using SoLID**

- $^{48}$Ca: flavor dependence of EMC effect
- Light nucleus ($^{9}$Be) may also be important to disentangle effects