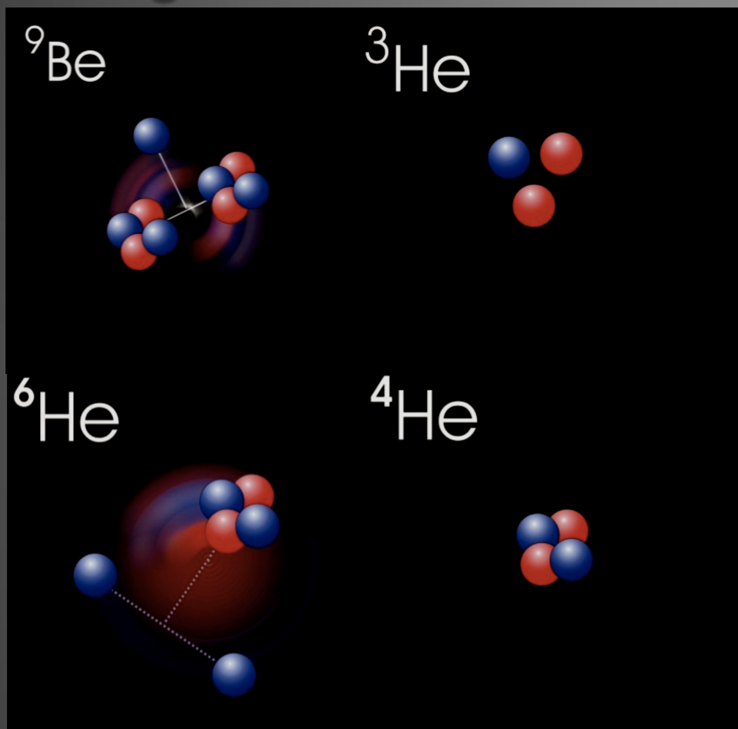
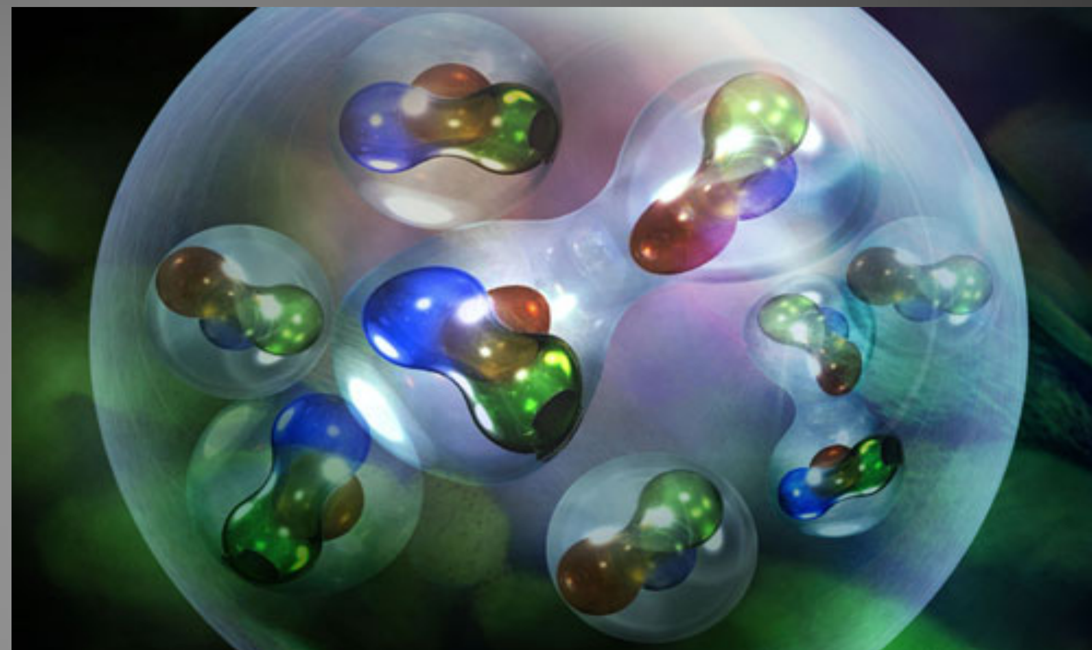
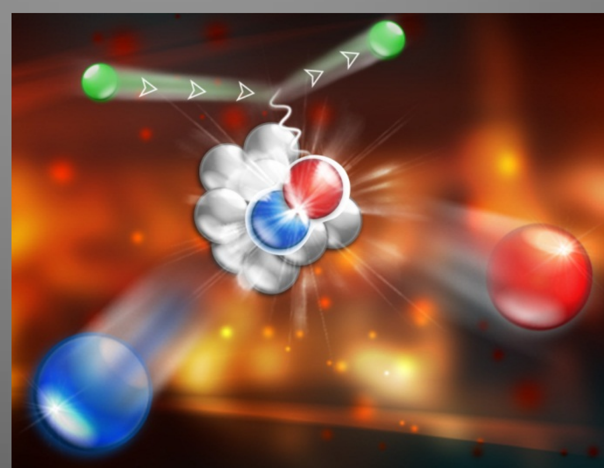
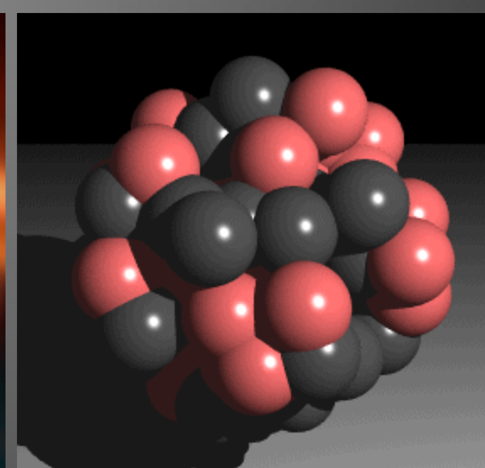
Isospin dependence of the EMC effect / Overview of JLab nuclear modification studies

John Arrington
Argonne National Lab









Next-generation nuclear physics with JLab12&EIC

Florida International University

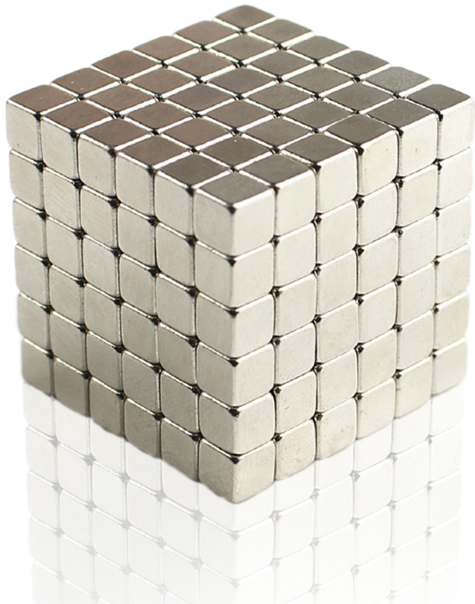
February 9, 2016

“Spherical cow” picture of nuclei

- **Proton as a hard sphere:** R=1.15 fm (RMS=0.85 fm) → **density=0.16 fm^{-3}**
- **Cubic packing of hard spheres → 50% packing fraction – 0.08 fm^{-3}**
- **Ideal packing of hard sphere → 75% packing fraction – 0.12 fm^{-3}**
  - *Interior nuclear densities require 100% packing fraction*
    - *Requires significant deformation, or significant (~30%) overlap of nucleon distributions*
  - *Can internal structure be unchanged??*

These are average densities; significantly more overlap in short-range components

Nucleons moving through each other at 10^7-10^8 m/s

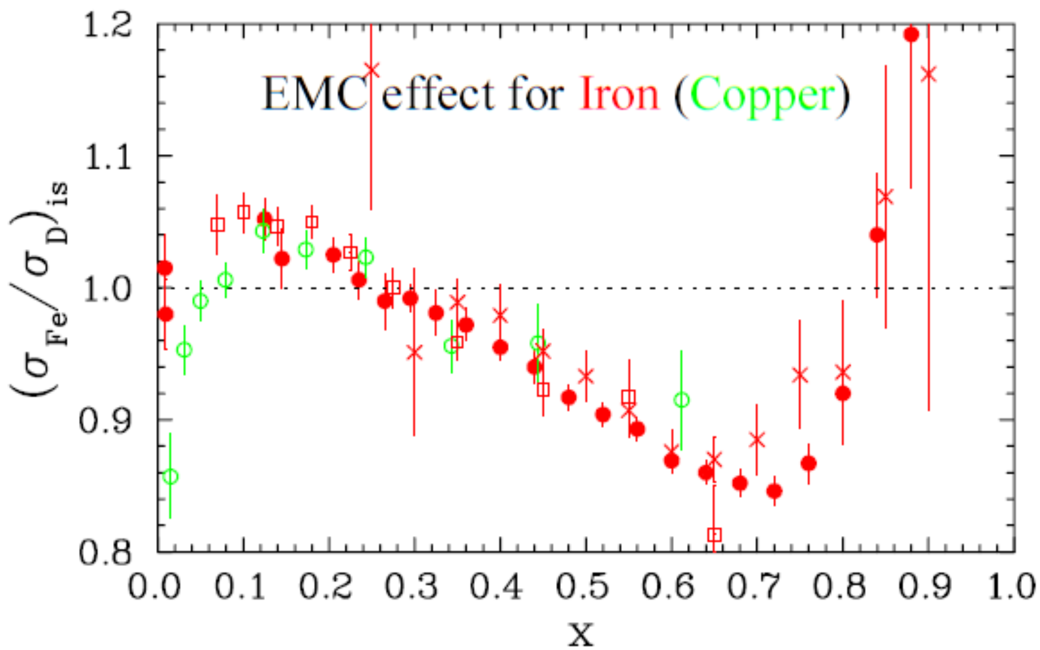


Medium modifications to nucleon structure?

Depletion of the structure function for 0.3<x<0.8

The magnitude of the effect increases with size/density

The x-dependence is identical for all nuclei



It has been clear for some time that binding, Fermi motion play important roles. Do we need something more than conventional nuclear physics?

Circa 2004

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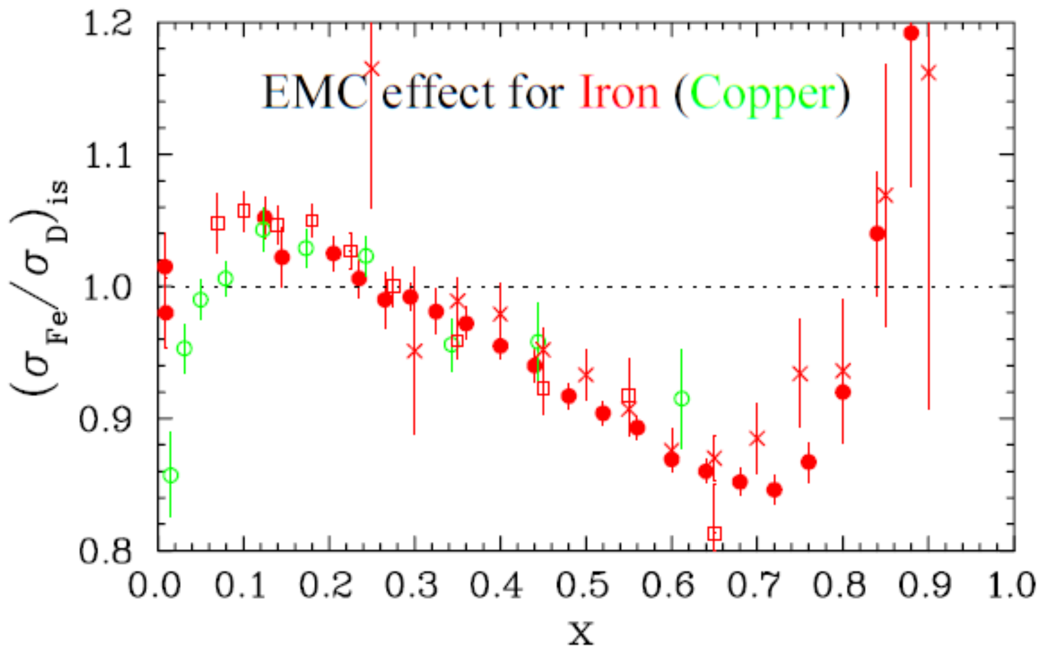

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Recently shown that...

The EMC effect cannot be explained by conventional nuclear physics...

most recently - J. Smith and G. A. Miller, PRC 65:015211 (2002)

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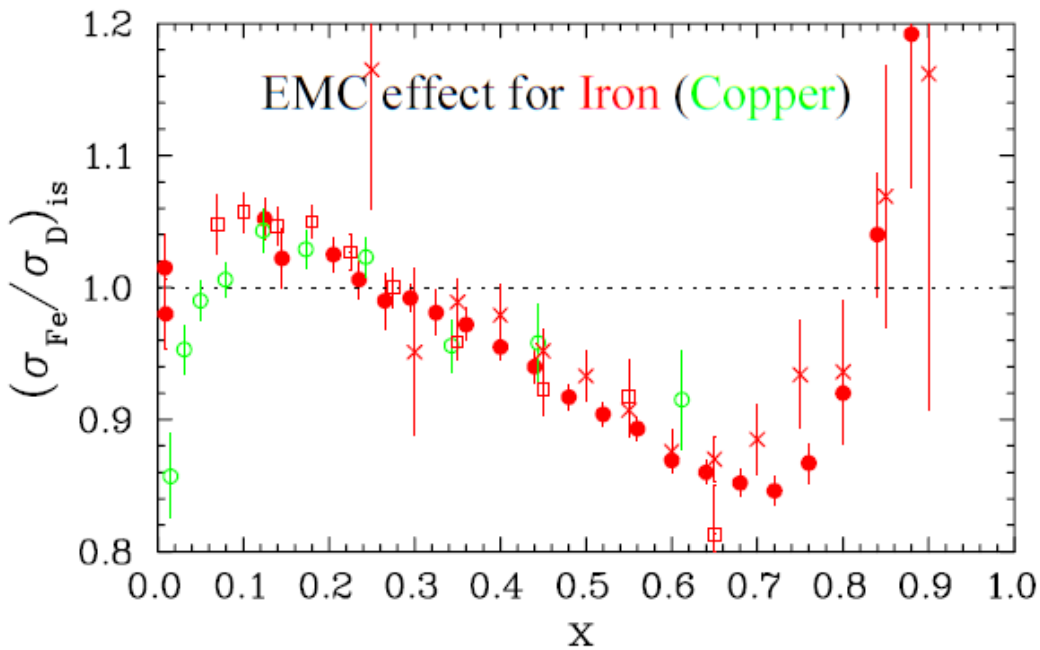

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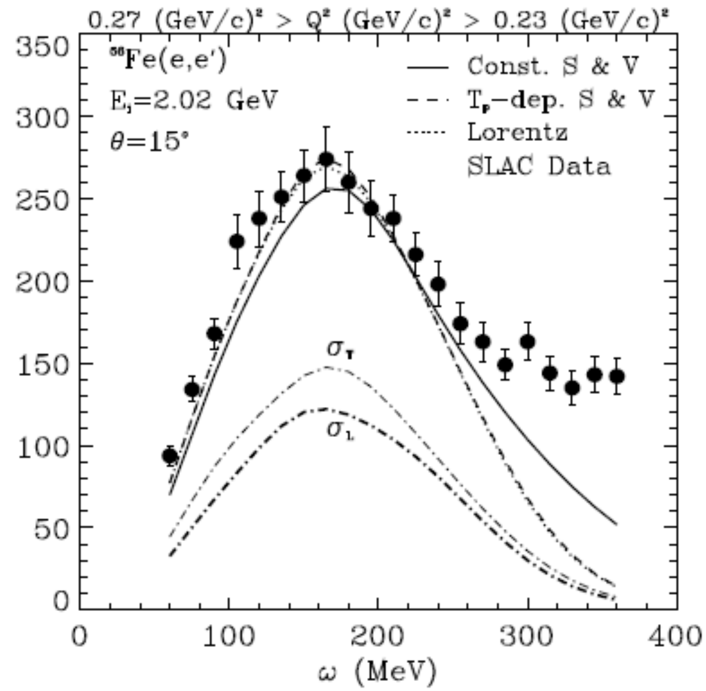
The Coulomb Sum Rule is fulfilled...

J. Jourdan, NPA 603, 117 (1996)

J. Carlson et al., PLB 553, 191 (2003)

Quasielastic response is (basically) nothing more than nucleon elastic scattering + nucleon distribution in nucleus



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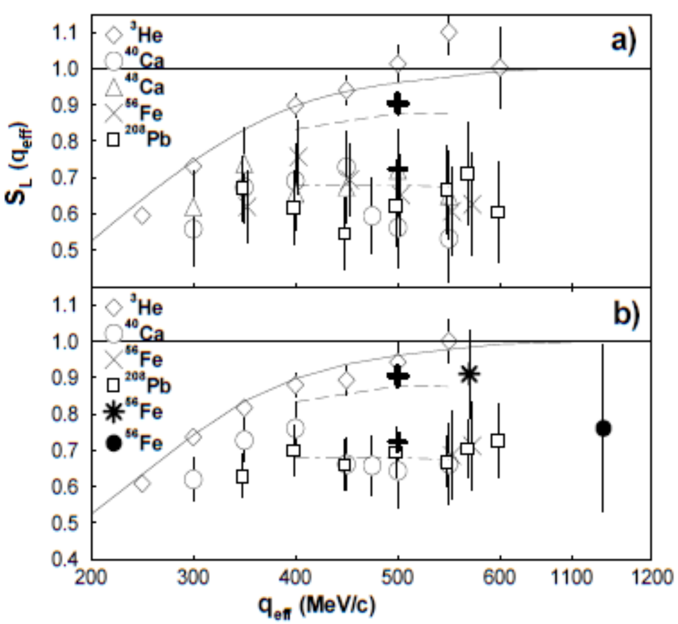
Except that maybe it isn't.

J. Morgenstern, Z.-E. Meziani, PLB 515, 269 (2001)

Integrated quasielastic response
suppressed by ~30-40%

Fig. 6



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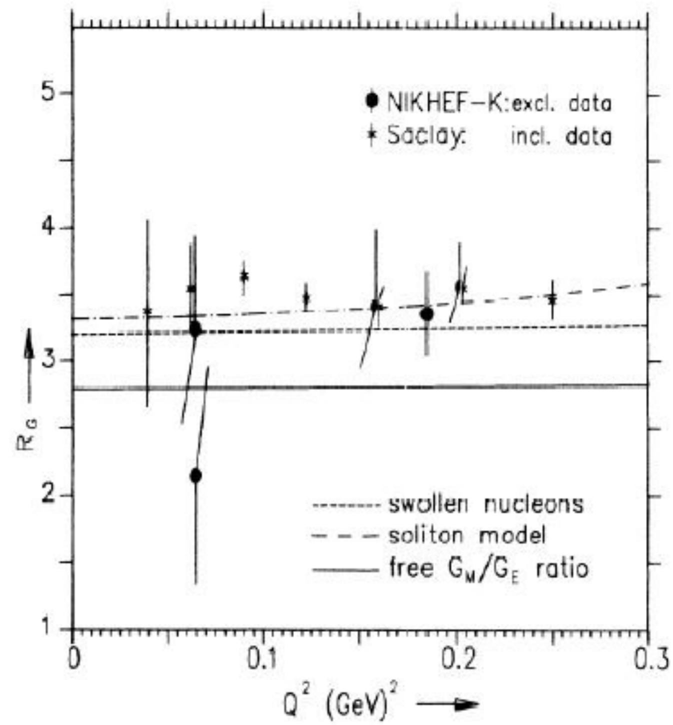
Nucleon form factors are modified in nuclei...

G. Van der Steenhoven, et al., PRL 57, 182 (1986)
[form factor ratio in nuclei]

G_E/G_M modified for nucleons in a nucleus



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Unless they aren't.

T. D. Cohen, J.W. Van Orden, A. Picklesimer,
PRL 59, 1267 (1987) [form factor ratio in nuclei]
I. Sick, NPA 434, 677 (1985)
R.W. McKeown, PRL 56, 1452 (1986)
[y-scaling limits]

What do we ***really know*** about medium modifications?

The EMC effect cannot be explained by conventional nuclear physics...

most recently - J. Smith and G. A. Miller, PRC 65:015211 (2002)

Unless it can be explained by conventional nuclear physics

most recently - J. Rozynek and G. Wilk, NPA 721, 388 (2003)

The effects are small

The Coulomb Sum Rule

J. Jourdan, NPA 603, 117 (1996)
J. Carlson et al., PLB 553, 191 (2003)

Except that maybe it isn't.

J. Morgenstern, Z.-E. Meziani, PLB 515, 269 (2001)

The experiments are hard

Nucleon form factor

G. Van der Steenhoven, et al., PRL 57, 182 (1986)
[form factor ratio in nuclei]

Unless they aren't.

T. D. Cohen, J.W. Van Orden, A. Picklesimer
PRL 59, 12
I. Sick, NPA
R.W. McKeown, PRL 56, 1452 (1986)
[y-scaling limits]

The theory is very complicated

Jefferson Lab needs to do more than just improve a few measurements...

What did JLab do at 6 GeV?

- **New techniques/observables:**
  - Polarization transfer measurements of 'In-medium form factors'
  - Tagged measurements in the deuteron
    - Low-momentum spectators: free neutron – BoNUS
    - High-momentum spectators: off-shell effect – D(e,e' p_s)
- **New focus: EMC in light nuclei**
  - A dependence for A≤12 clearly demonstrate role of nuclear structure
  - Connection to SRCs
- **New direction: SRC studies**
  - A dependence
  - Isospin structure

A-dependence of EMC effect

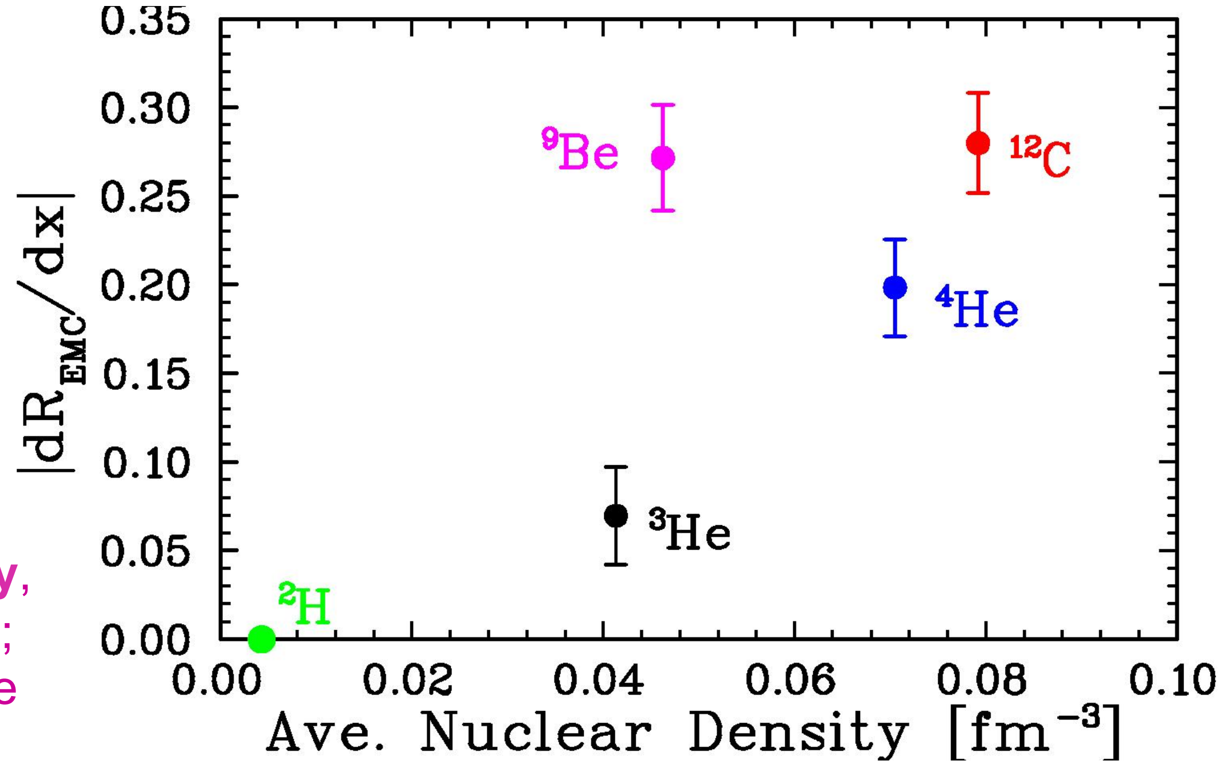
J.Seely, et al., PRL103, 202301 (2009)

Density determined from *ab initio* few-body calculation

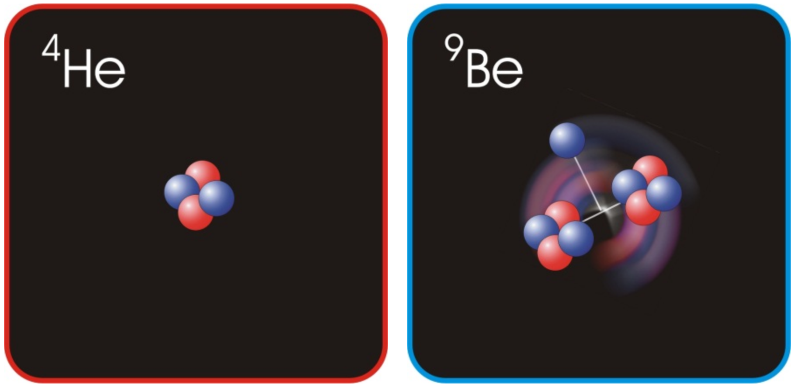
S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)

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

^{9}Be has **low average density**, but significant 2α+n structure; most nucleons in dense α-like configurations

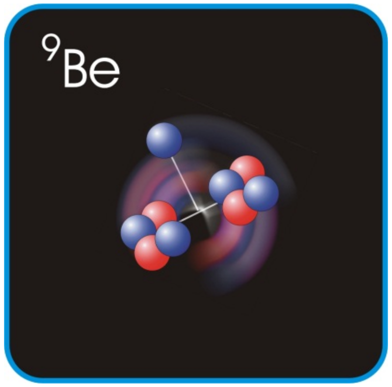


Detailed nuclear structure matters! Clusters, SRCs



Credit: P. Mueller

EMC effect and SRCs in light nuclei

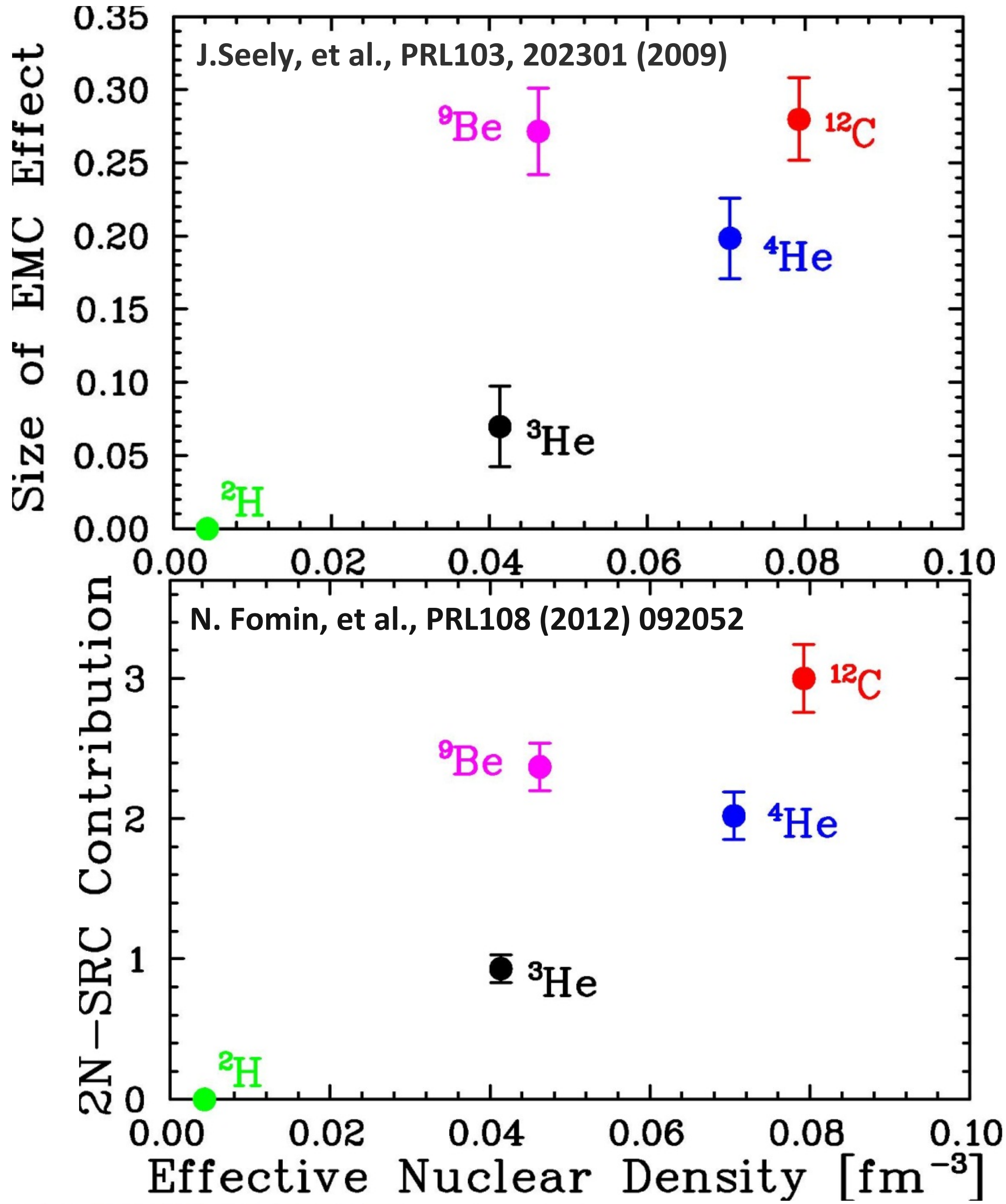


JLab E03-103

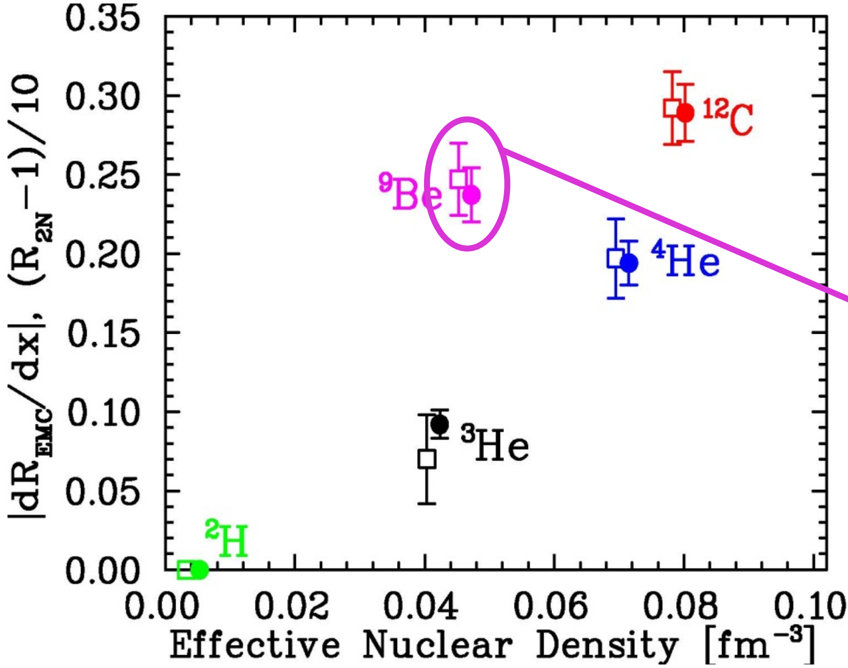
- JA and D. Gaskell, spokespersons
- *EMC effect in light nuclei*

JLab E02-019

- JA, D. Day, B. Filippone, A. Lung
- *Probe* ***high-momentum nucleons***
- *Study* ***short-distance (high-density) structures*** *in nuclei*



EMC-SRC correlation



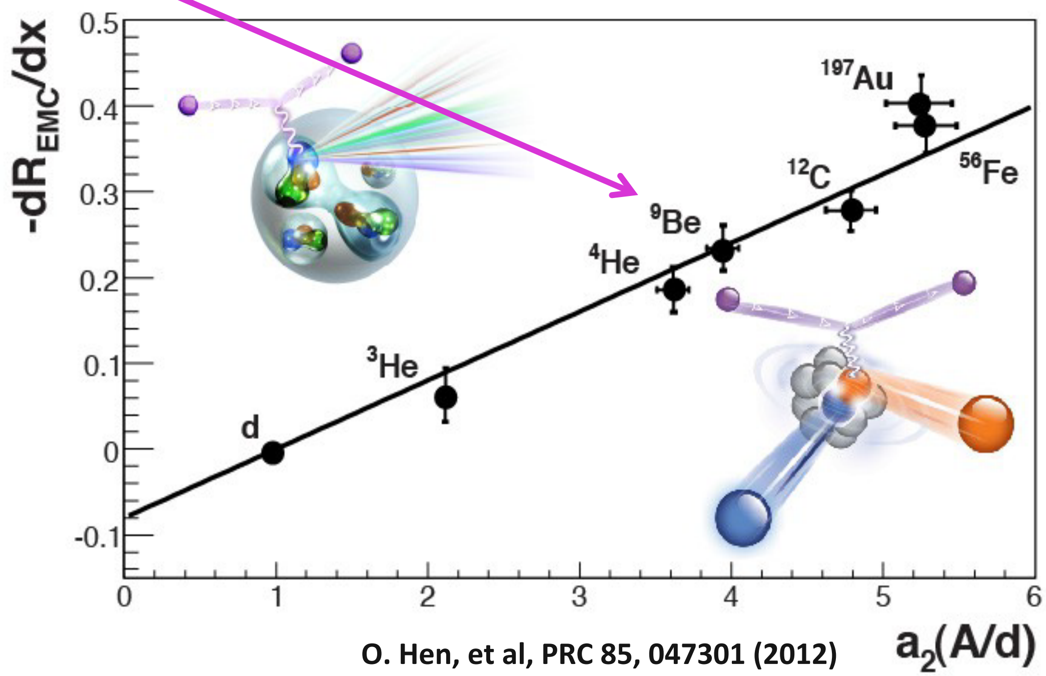
J. Seely, et al., PRL103, 202301 (2009)

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

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

SRCs are both short-distance and high-momentum components

Which matters for EMC effect??



O. Hen, et al, PRC 85, 047301 (2012)
L. Weinstein, et al., PRL 106, 052301 (2011)

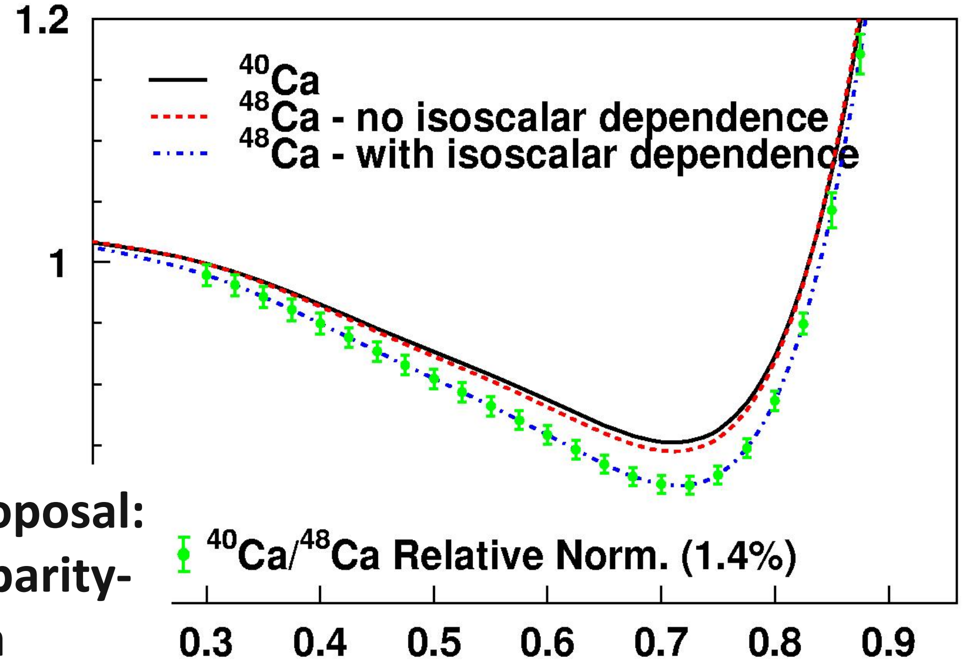
New directions for JLab@12 GeV

- **Deuteron as a variable-density nucleus**
  - Nucleon pdfs as function of initial momentum in deuteron [S. Kuhn, D. Higinbotham]
    - Measure spectator proton to tag initial neutron momentum or vice-versa ["Deeps", "BoNUS"]
  - Nucleon form factors as function of initial momentum in deuteron
    - Reconstruct initial momentum in d(e,e' p)
  - Inclusive: quark structure of SRCs [D. Day, A. Freese]
    - Kinematics (x>1) isolates SRC, high-Q^2 probes pdfs
- **Spin dependence of EMC** [I. Cloet]
- **Further EMC, SRC studies** [E. Piasetzky, E. Cohen, N. Fomin, D. Higinbotham,…]
  - Additional light nuclei, 3H and 3He, etc…
- **Flavor/isospin dependence of EMC effect**

- **EIC….**
  - Further measurements with tagging [K. Park]
  - Push Q^2 for high-x studies [A. Freese]
  - Nuclear effects in glue (the dominant low-x, large-distance component)

Flavor/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**
  - **Recent 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)]
- **12 GeV experiment: ^{40}Ca and ^{48}Ca**
  [JA, A.Daniels, D.Gaskell]
  - Same at small x
  - 4% lower for ^{48}Ca at x=0.75
  - 2-3σ flavor-dependent effect



- **Calculation Motivated "PVEMC" proposal: flavor-dependent EMC effect from parity-violating electron scattering in 48Ca**
  [S.Riordan, R. Beminiwattha]

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    [I. Cloet, et al, PRL 109, 182301 (2012); PRL 102, 252301 (2009)]

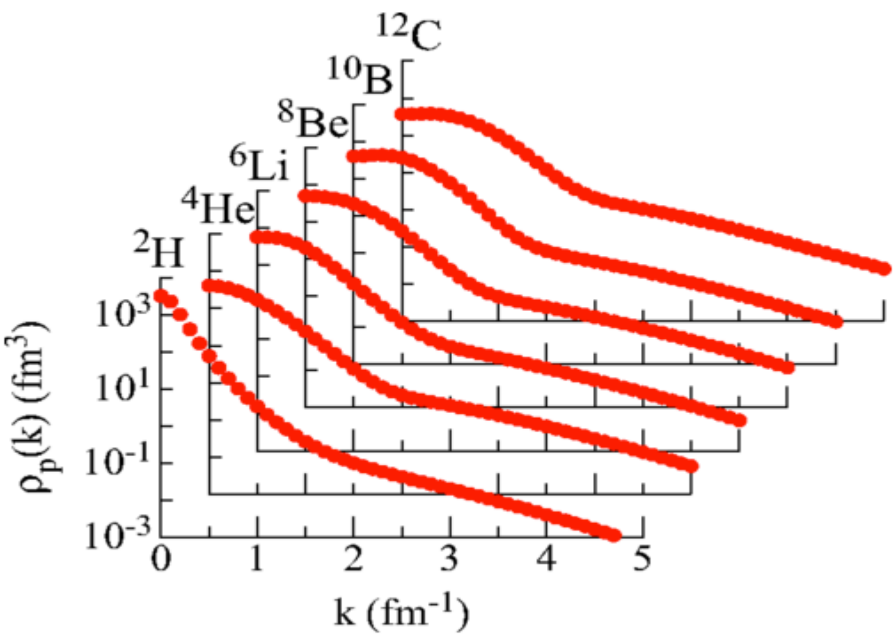
  - **EMC-SRC correlation + n-p dominance of SRCs suggests enhanced EMC effect in minority nucleons**
    - In ^{3}H, np-dominance suggests single proton generates same high-momentum component as two neutrons –> larger proton EMC effect in 'high-virtuality' picture

  - **^{48}Ca, ^{208}Pb expected to have significant neutron skin: neutrons preferentially sit near the surface, in low density regions**

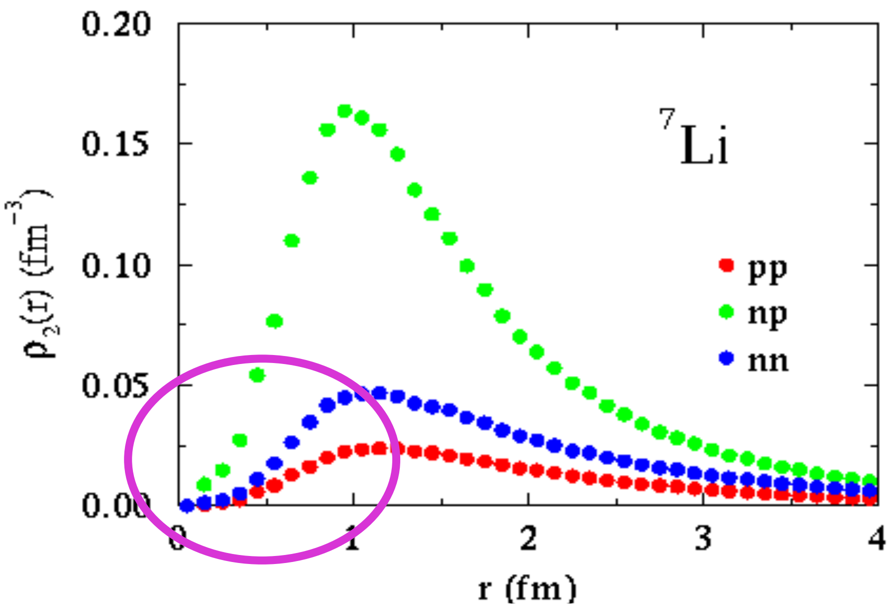
All of these imply increased EMC effect in minority nucleons

Estimates from Quantum Monte Carlo

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



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



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

- **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:

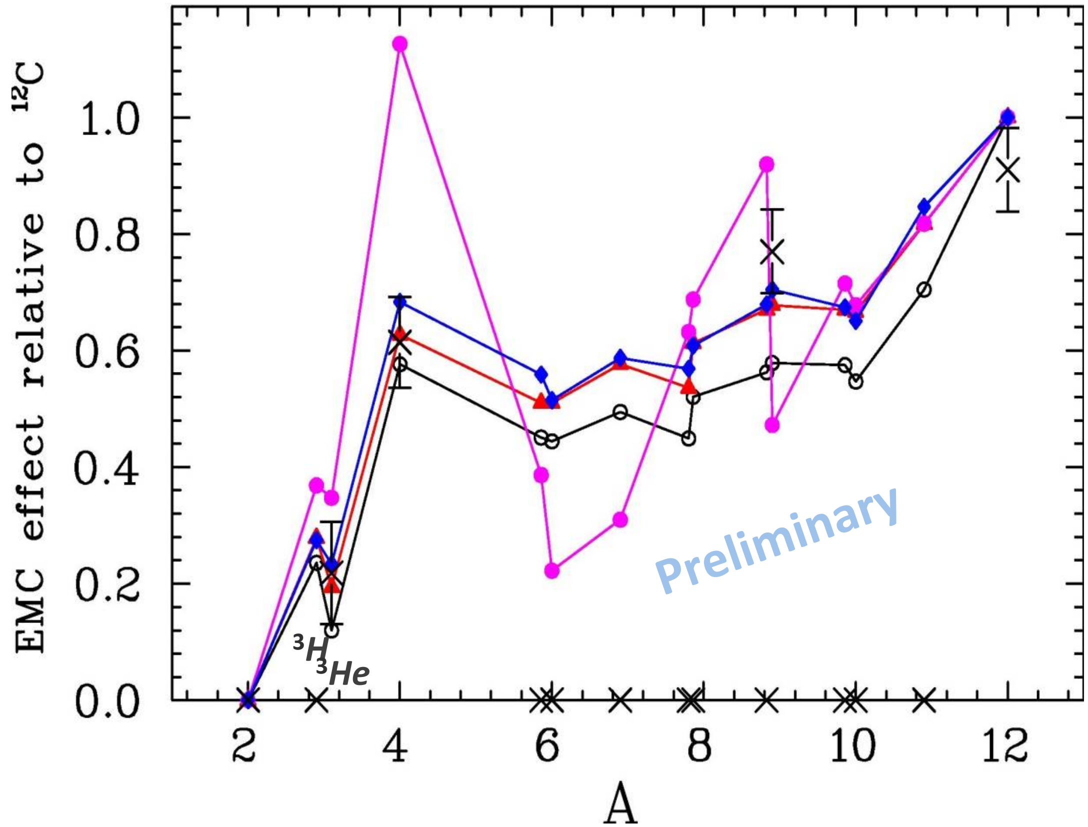
Fraction of n(k) above 300 MeV

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

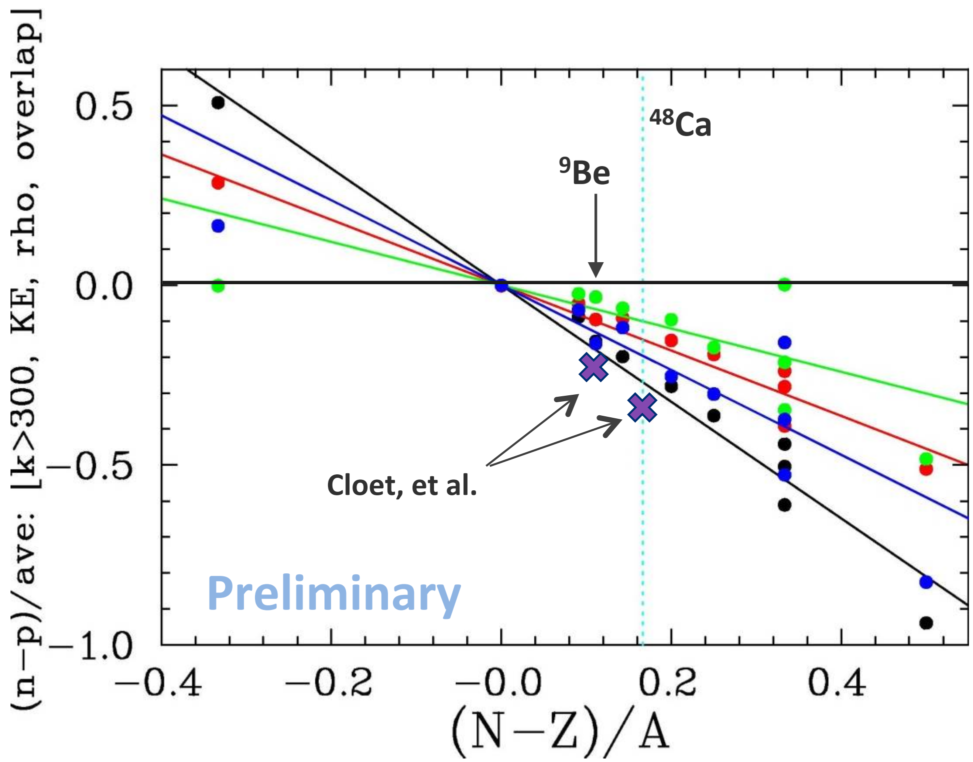
Isospin dependence vs fractional neutron excess

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: scaled from NM



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

Parity-Violating EMC effect (PVEMC)

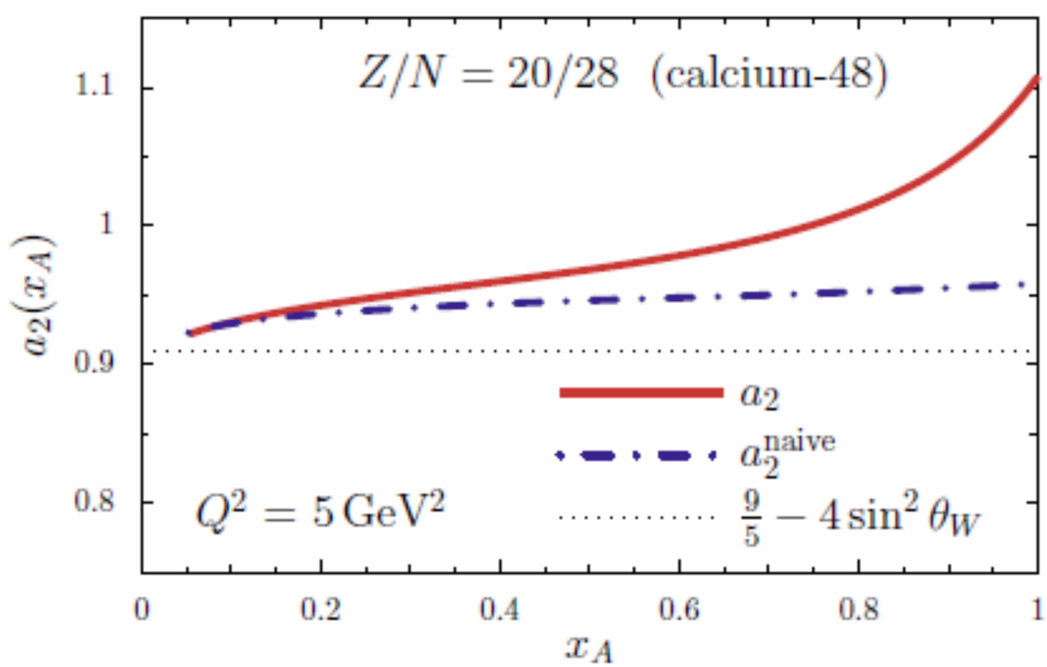
Knowing d(x)/u(x) for the proton and assuming flavor-independent EMC effect, can calculate e-A PV-DIS response

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

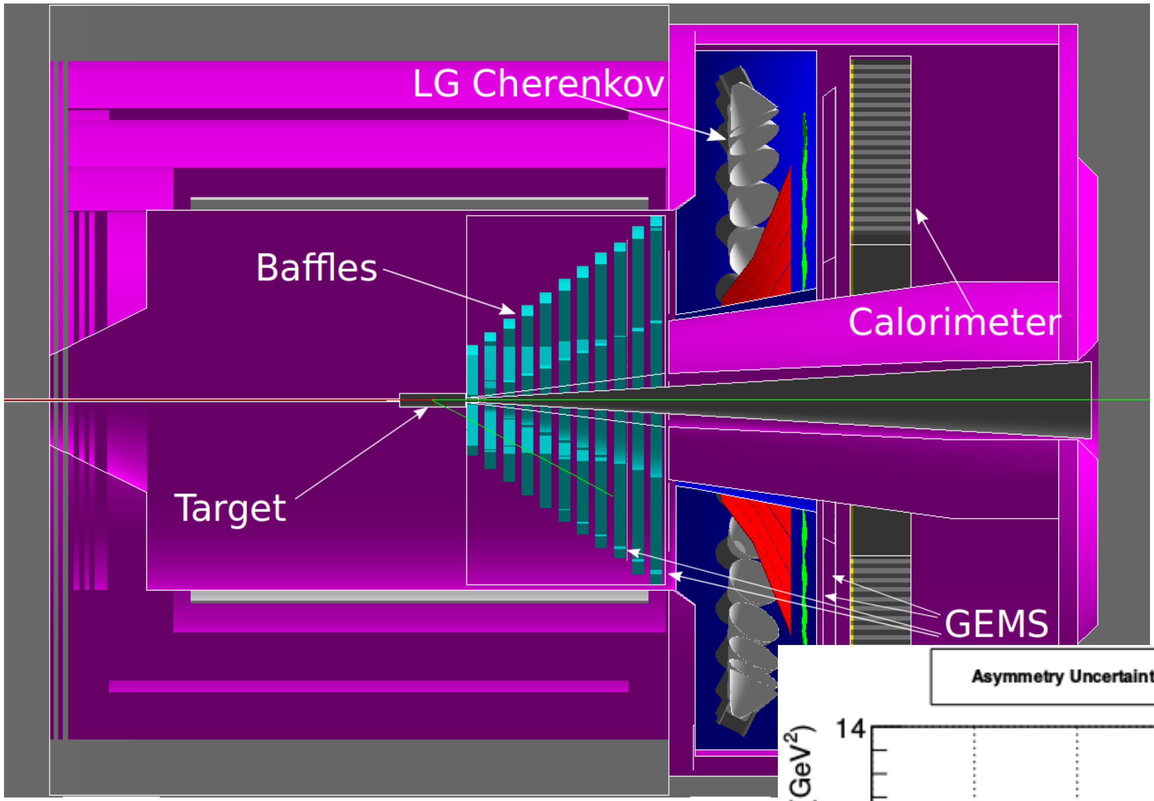
Cloet, et al: 5% deviation at large x

SoLID spectrometer can make ~1% measurements of PVDIS with normalization uncertainty <0.5%

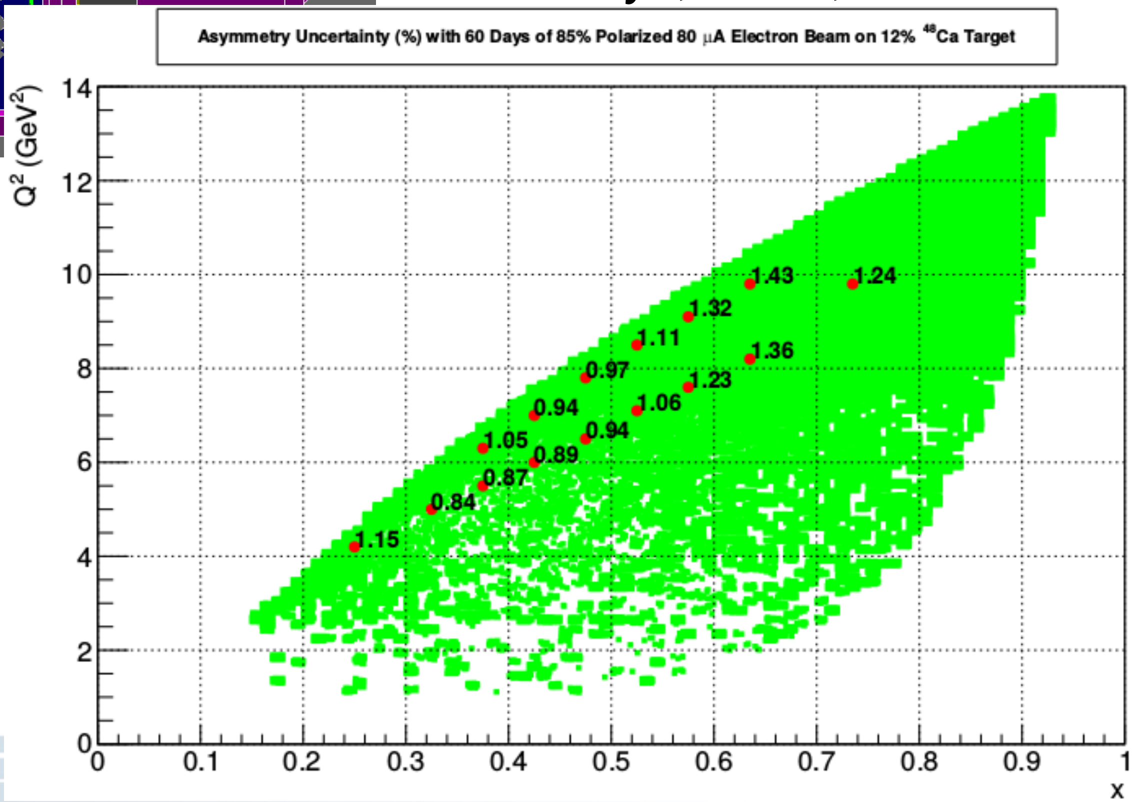
Doesn't require comparison to isoscalar nuclei; sensitive only to flavor dependence



PVEMV with SoLID



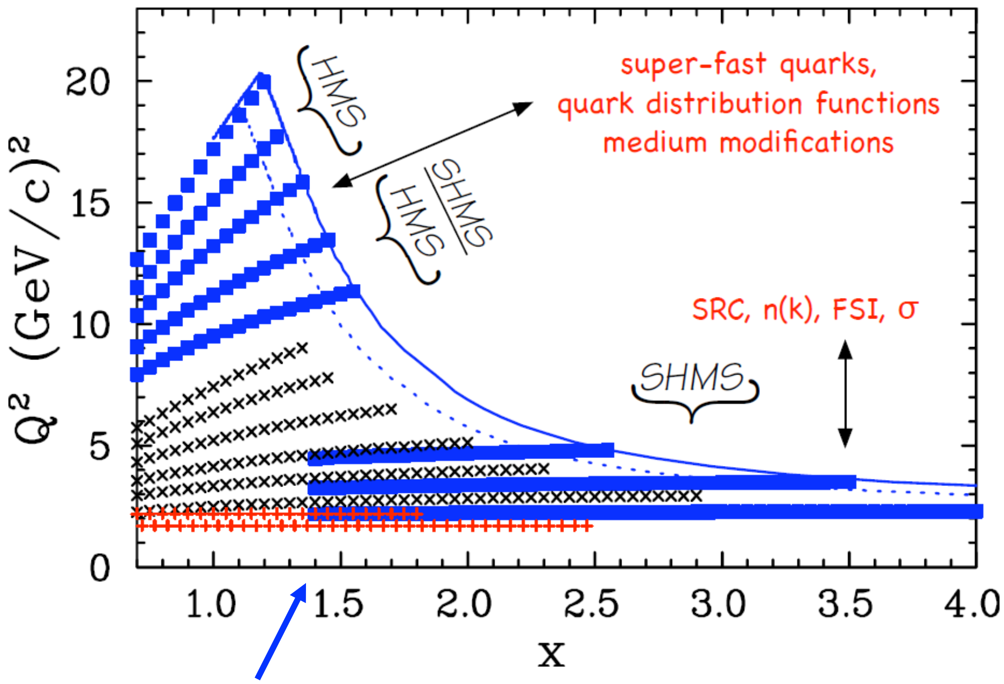
60 days, 80uA, 11 GeV



Cloet, et al., calculation yields >5σ signal for the projected statistics, systematics

Extra model dependence based on current uncertainty in proton d/u; should be greatly reduced by the time SoLID would run

Unpolarized EMC measurements: JLab@12 GeV

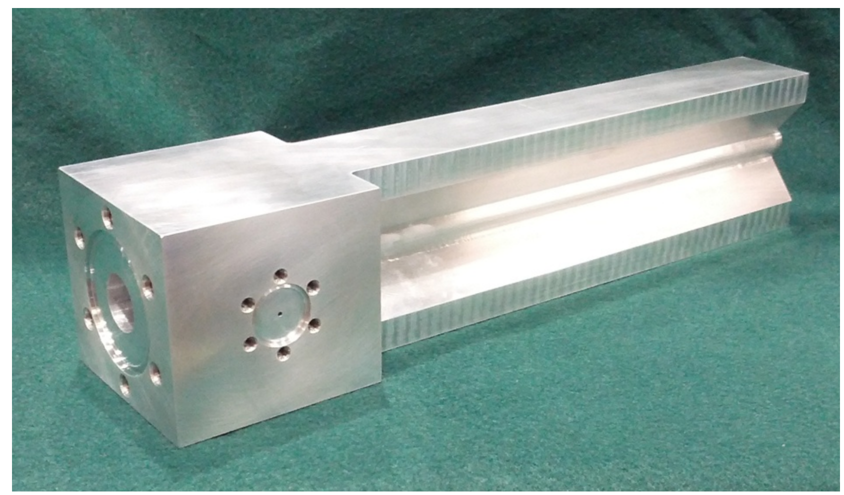


SRCs at x>1 at 12 GeV
[E06-105: JA, D. Day, N. Fomin, P. Solvignon]

EMC effect at 12 GeV
[E10-008: JA, A. Daniel, D. Gaskell]

^{1}H	$^{6,7}Li$	^{40}Ca
^{2}H	^{9}Be	^{48}Ca
^{3}He	$^{10,11}B$	Cu
^{4}He	^{12}C	Au

^{3}H
^{3}He



^{3}H, ^{3}He program (4 experiments in Hall A) starts in the next year

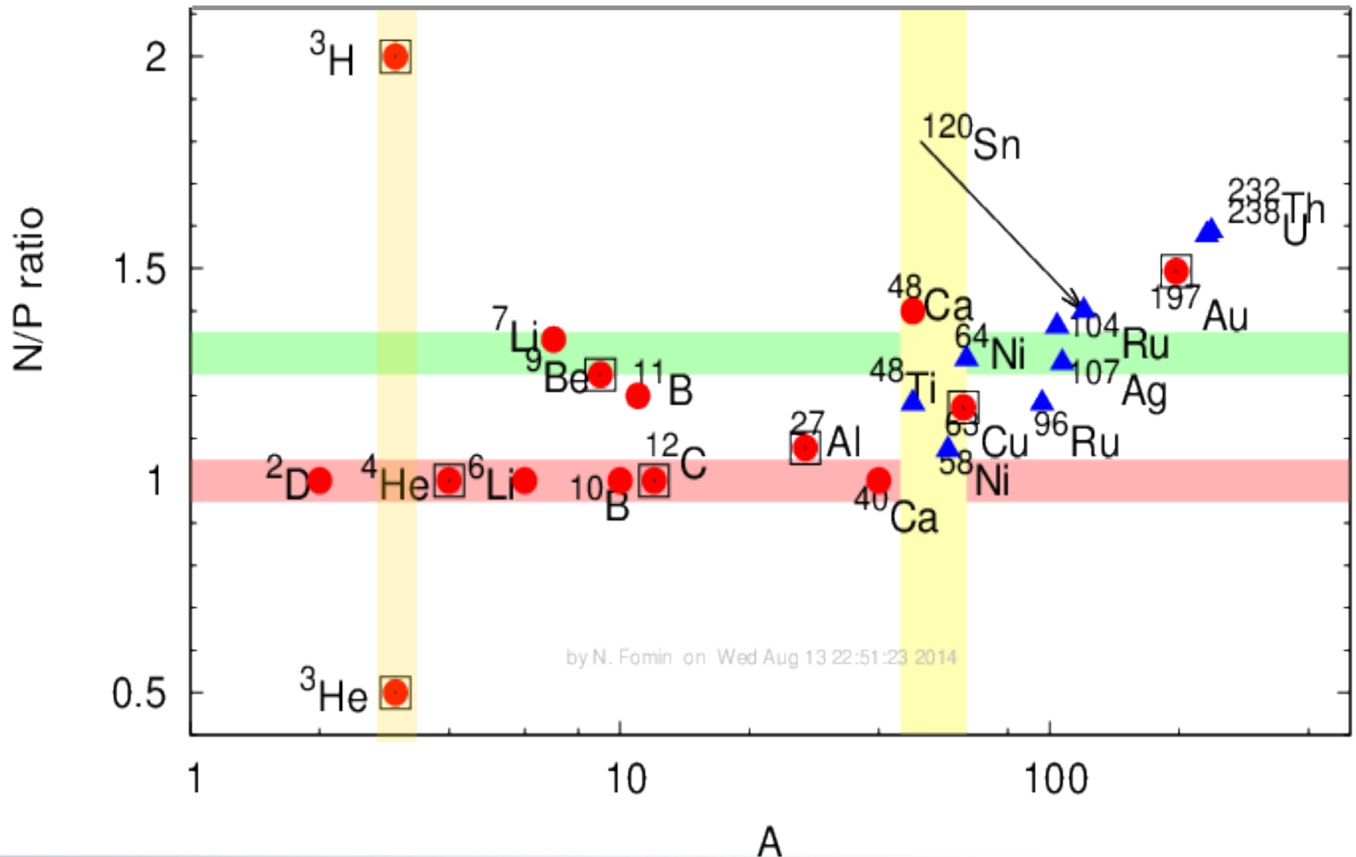
- ^{3}H, ^{3}He DIS: EMC effect and d(x)/u(x)
- SRC Isospin dependence: ^{3}H vs ^{3}He
- Proton/neutron n(k) from 3H/3He(e,e'p)
- Charge radius difference: ^{3}He - ^{3}H

Flavor dependence: going beyond ^{40}Ca - ^{48}Ca

<u>We are planning to add additional heavier nuclei</u>

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

Start trying to disentangle A dependence and N/Z dependence



Summary (flavor dependence)

The EMC-SRC connection as well as recent calculations, suggest that there must be a flavor dependence to the EMC effect in neutron rich nuclei

- Provides new sensitivity to the underlying physics
- Key ingredient of the EMC effect: we cannot say that we understand the EMC effect if we don't understand the isospin dependence

Some information will come from unpolarized EMC effect vs N/Z

- Only possible for 'similar' nuclei with different N/Z

Direct, precise measurements possible using PVES in SoLID

- **^{48}Ca: flavor dependence of EMC effect**
- **Light nuclei (^{9}Be) may provide additional sensitivity**

A major caveat…

These discussions generally assumes a single origin of the EMC effect

In the rest frame convolution formalism, the average removal energy, not just the overall binding energy, is relevant. This part of the EMC effect scales with average removal energy, which is dominated by the high-momentum contribution associated with SRCs.

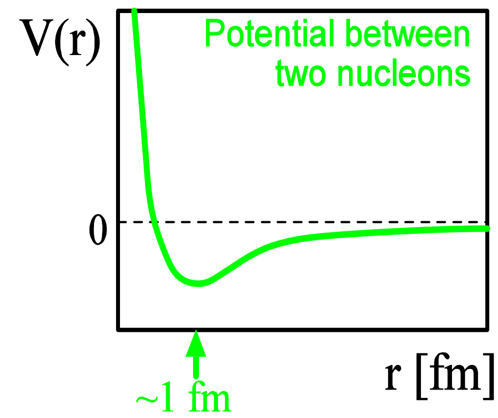
JA, et al, PRC 86 (2012) 065204
O. Benhar and I Sick, arXiv:1207.4595,

So it's not purely an exotic density- or virtuality-driven effect, but appears to be mix of binding corrections and something more exotic

The binding calculations of Kulagin & Petti explain half of the EMC effect, and the effect is correlated with the presence of SRCs. This suggests that the remaining half is also correlated with SRCs, although the evaluation of the removal energy is model dependent and uncertain

S. Kulagin and R. Petti, Nucl. Phys. A765 (2006) 126

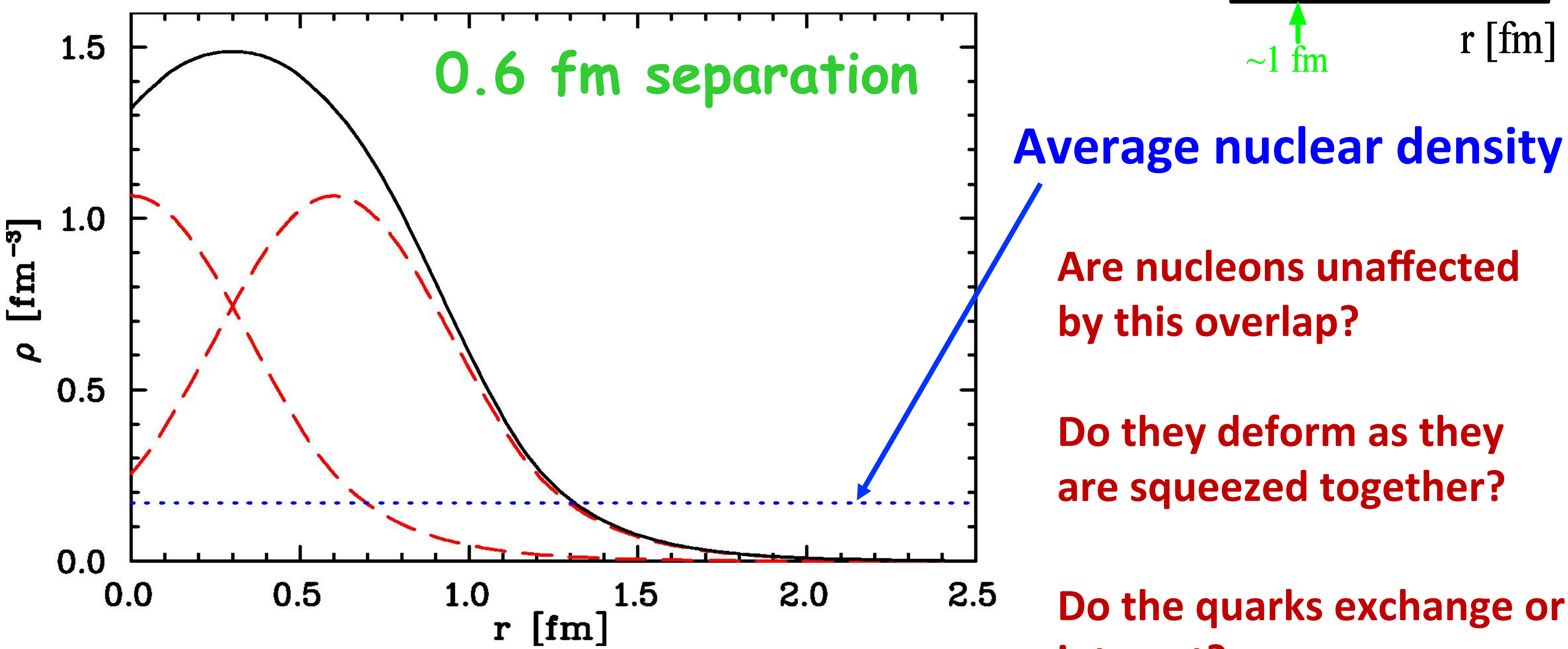
Nuclear densities and quark structure?



Nucleons are composite objects

Nucleon (RMS) diameter ~ 1.7 fm

separation in heavy nuclei ~ 1.7 fm



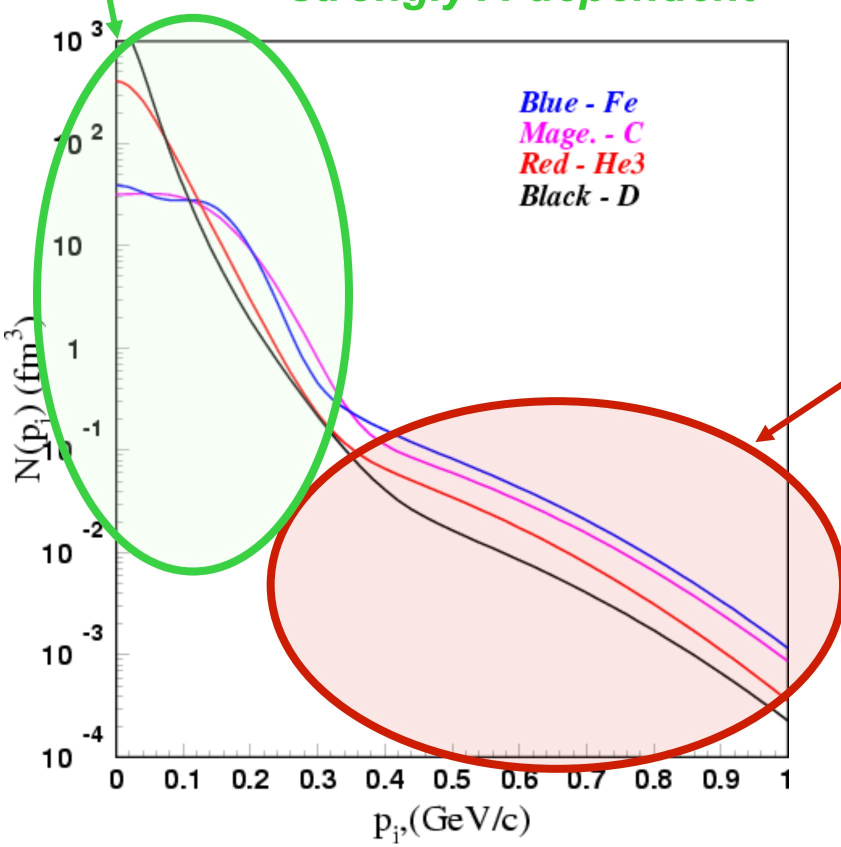
Are nucleons unaffected by this overlap?

Do they deform as they are squeezed together?

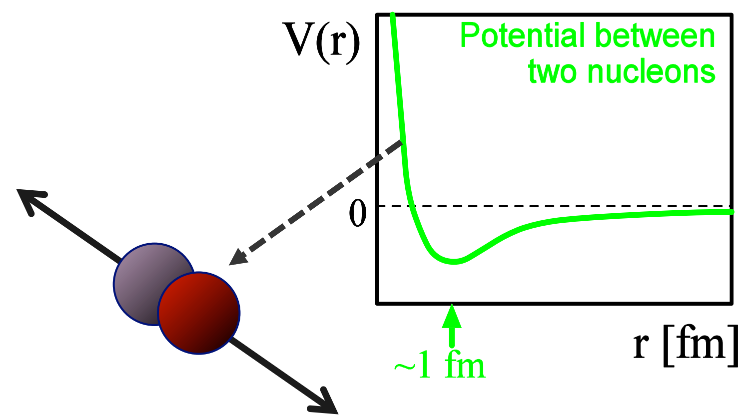
Do the quarks exchange or interact?

Short-range correlations

Mean-field region: collective behavior, strongly A-dependent



Cioffi Degli Atti, et al, PRC53, 1689 (1996)



High-momentum region: short-range interactions, mainly 2-body physics, largely A-independent

Small N-N separation

Large momenta (SRCs) ⇔ **High-density Configurations (EMC effect?)**

Short-distance behavior and the EMC effect

~~1. EMC effect, SRCs 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)**
[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

Dominance of np pairs in SRCs implies slightly different correlation:
Small, dense configurations for all NN pairs, high momentum only for np pairs
JA, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86 (2012) 065204

EMC-SRC correlation favors local density, but very much an open question…