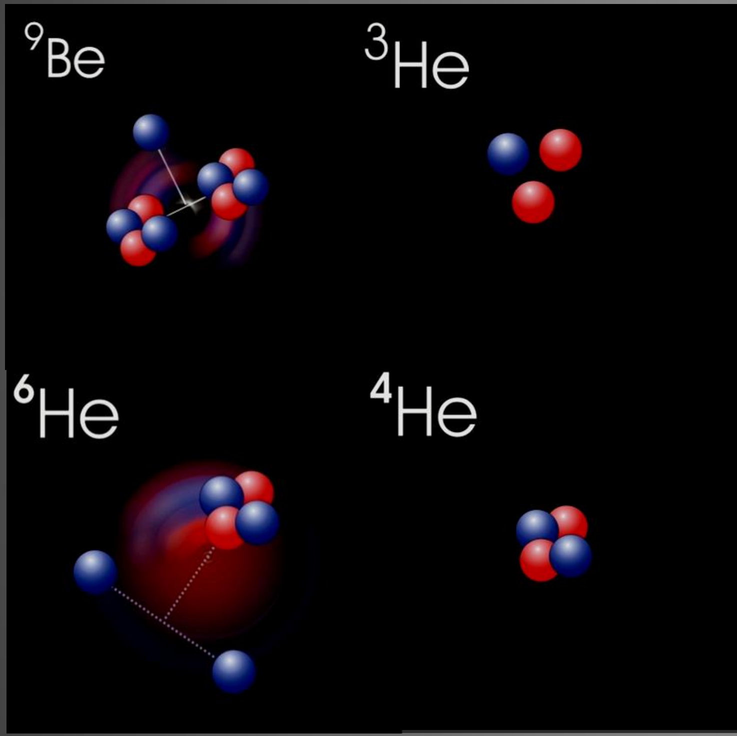
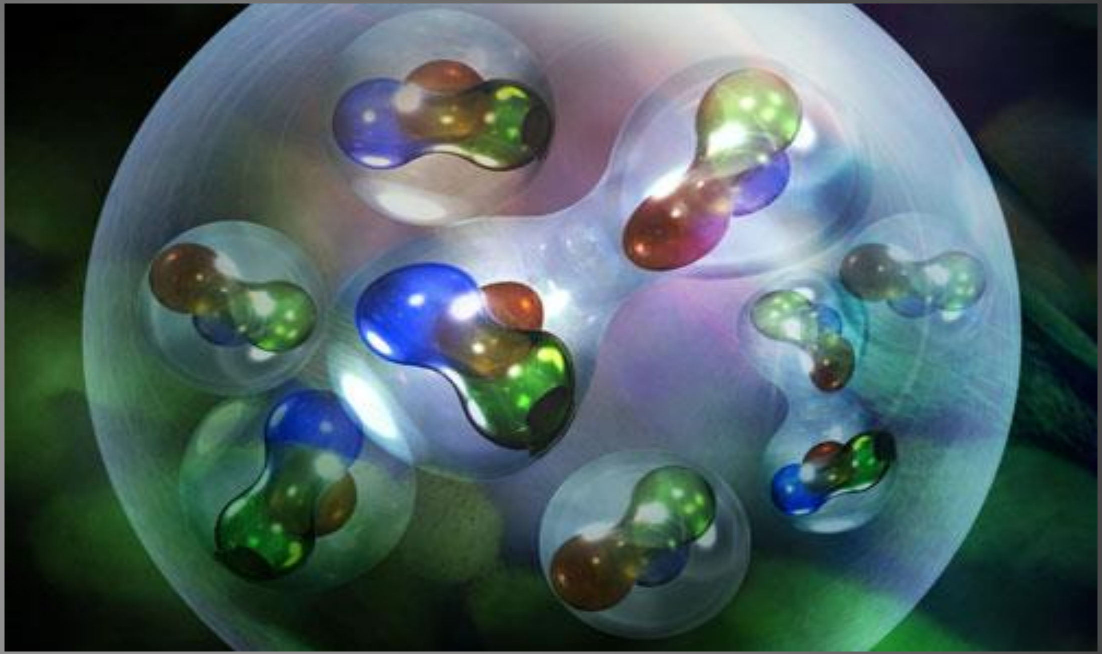
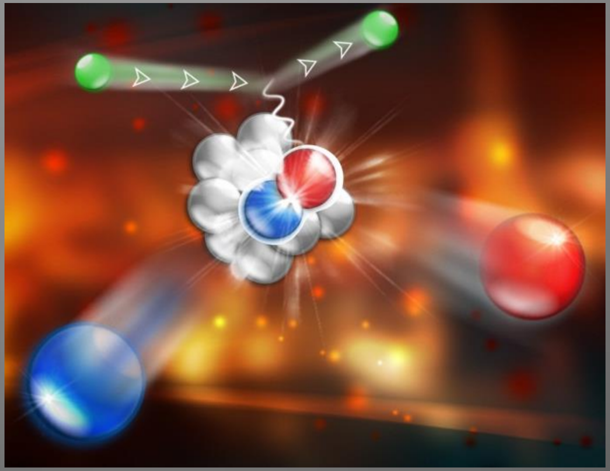
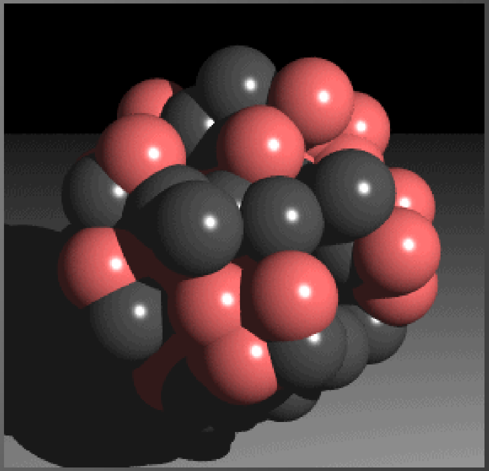
The EMC effect - JLab experimental findings and plans

John Arrington
Argonne National Lab





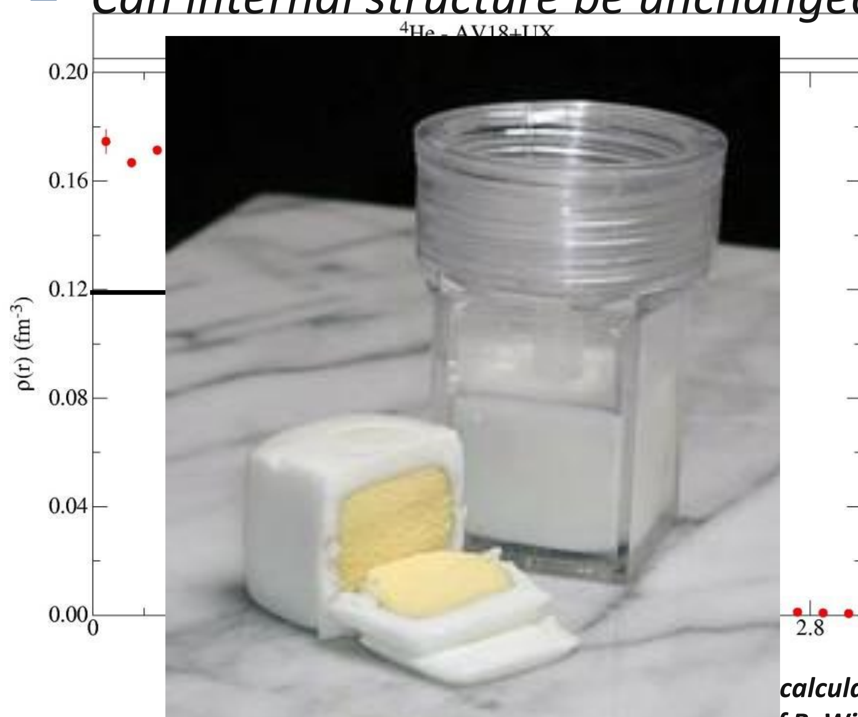




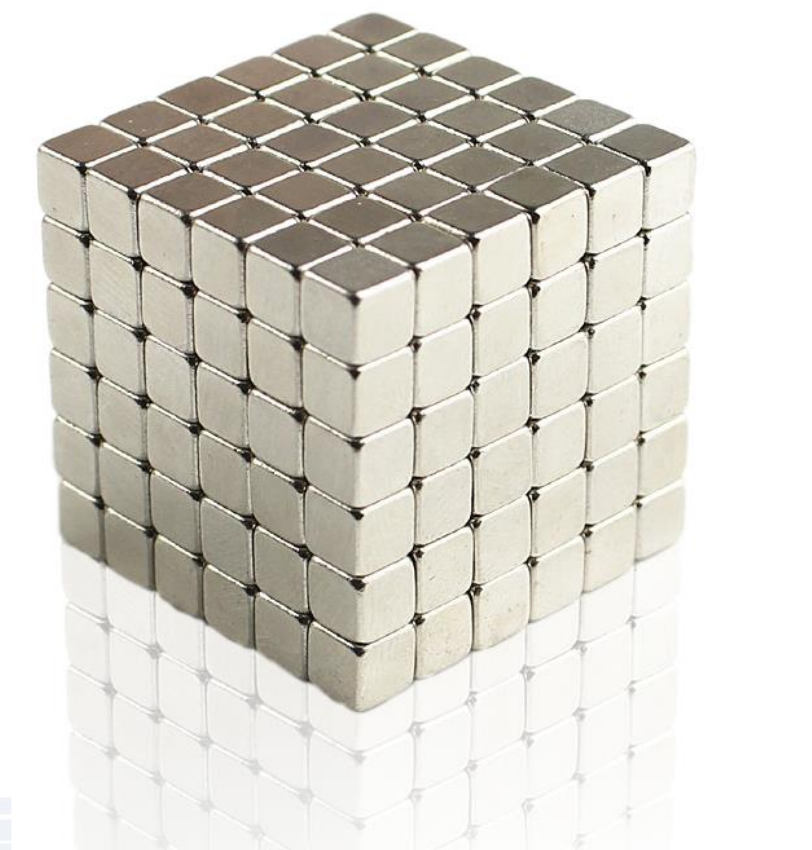
2nd International Conference on the Initial Stages of High-Energy Nuclear Collisions
Dec 6, 2014

How dense are nuclei?

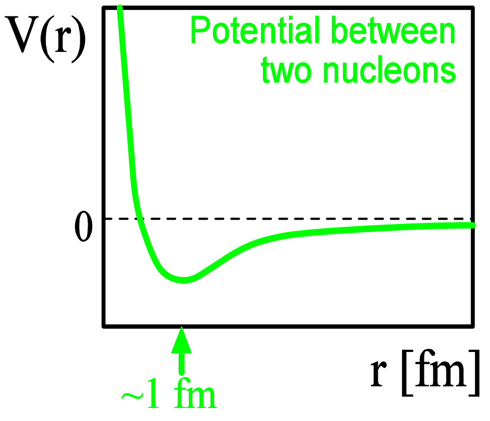
- **Proton RMS charge radius: $R_p \approx 0.85$ fm**
- **Corresponds to uniform sphere, R = 1.15 fm, density = 0.16 fm^{-3}**
- **Ideal packing of hard sphere: $\rho_{max} = 0.12$ fm^{-3}**
  - *Well below peak densities in nuclei*
  - *Need 100% packing fraction for dense nuclei*
  - *Can internal structure be unchanged??*



calculation,
of B. Wiringa

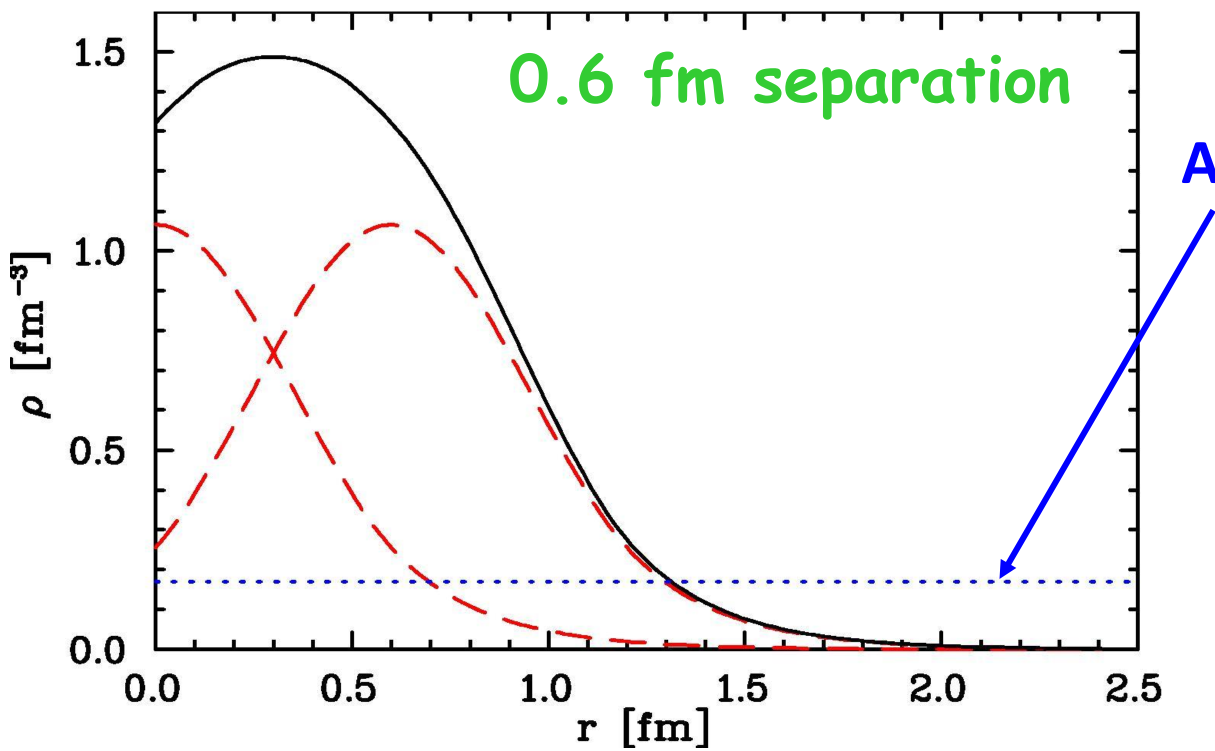


Nuclear densities and quark structure?



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?

Quark distributions in nuclei: EMC effect

Deeply-inelastic scattering (DIS) measures structure function $F_2(x)$

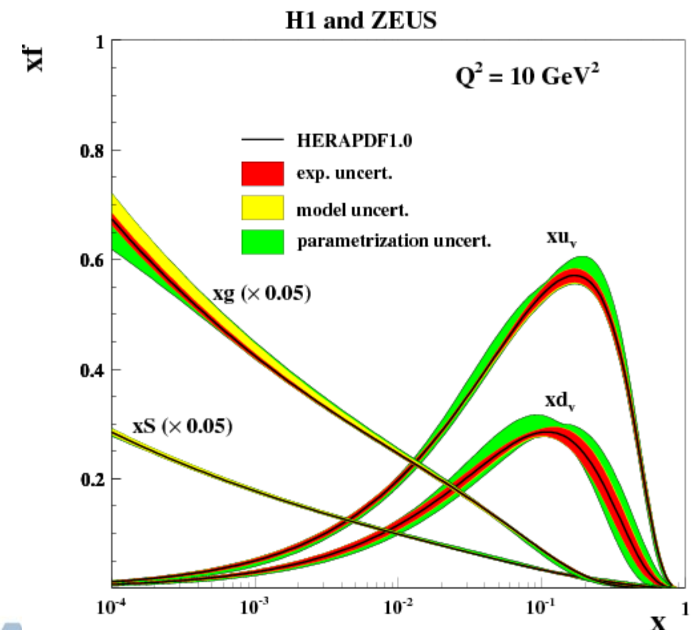
- x = quark longitudinal momentum fraction
- $F_2(x)$ related to parton momentum distributions (pdfs)

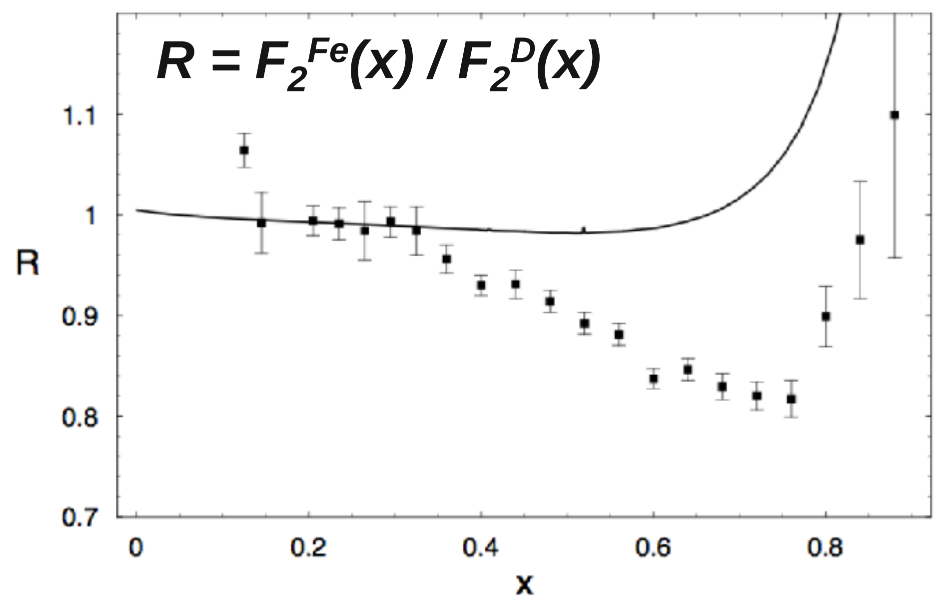
$$F_2(x) \sim \sum e_i^2 q_i(x) \qquad i=\text{up, down, strange}$$

Nuclear binding << energy scales of probe, proton/neutron excitations

Expected $F_2^A(x) \approx Z F_2^p(x) + N F_2^n(x)$

i.e. insensitive to details of nuclear structure beyond Fermi motion





J. J. Aubert, et al., PLB 123, 275 (1983)

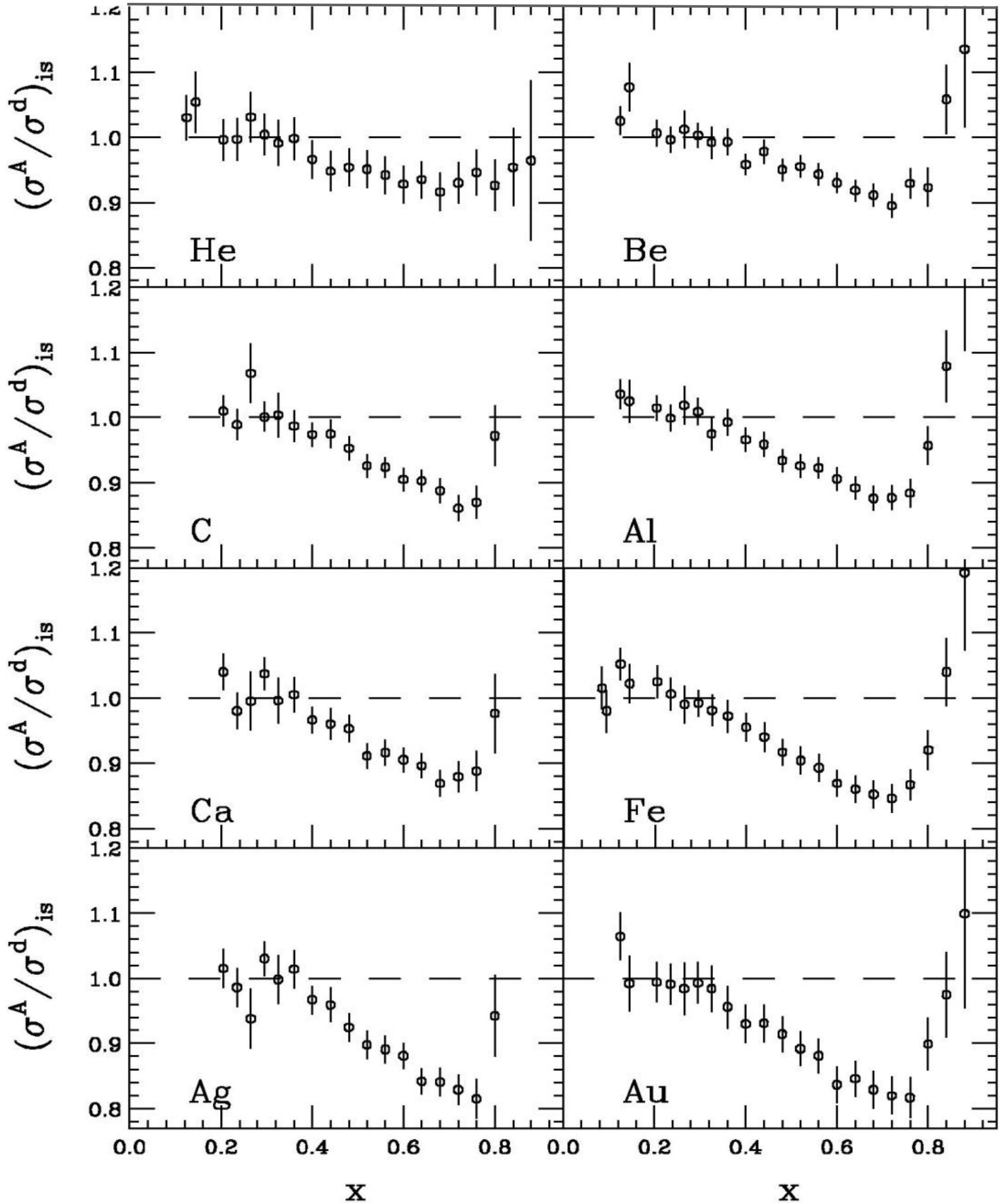
EMC effect: A-dependence

SLAC E139

- Most precise large-x data
- Nuclei from A=4 to 197

Conclusions

- Universal x-dependence
- Magnitude varies slowly



J. Gomez, et al., PRD49, 4349 (1994)

Importance of light nuclei

<u>**JLab E03-103:**</u> **EMC effect in light nuclei**

JA and D. Gaskell, spokespersons

J. Seely, A. Daniel, PhD students

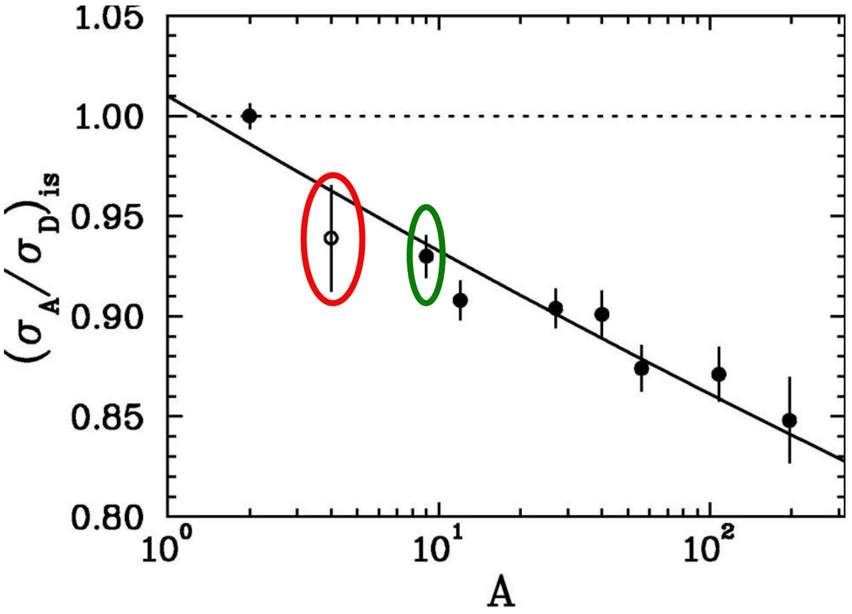
1) *Mass vs. density dependence*

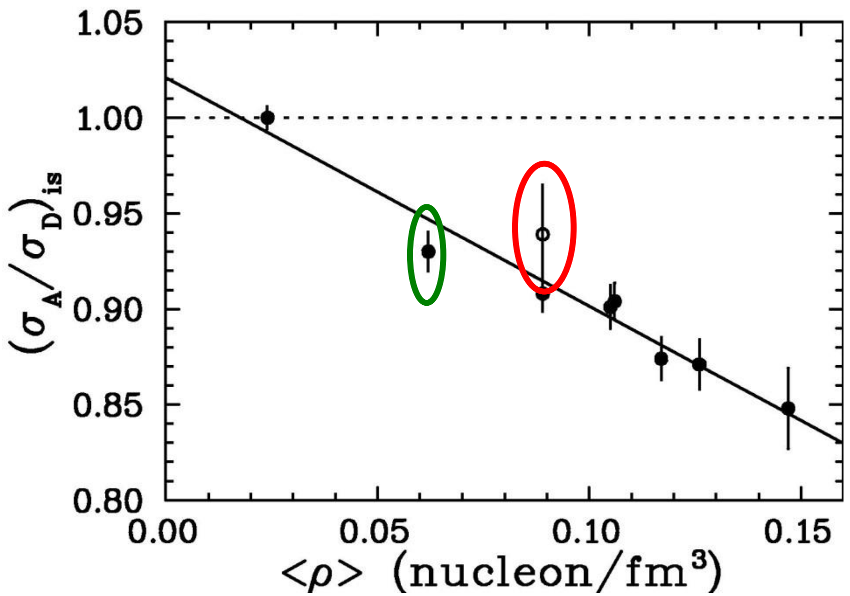
^{4}He is low mass, higher density

^{9}Be is higher mass, low density

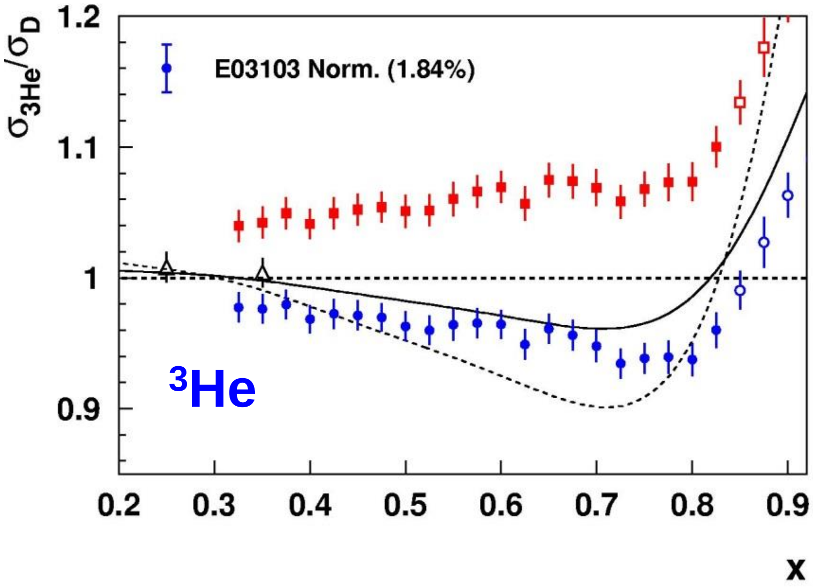
^{3}He is low mass, low density (no data)

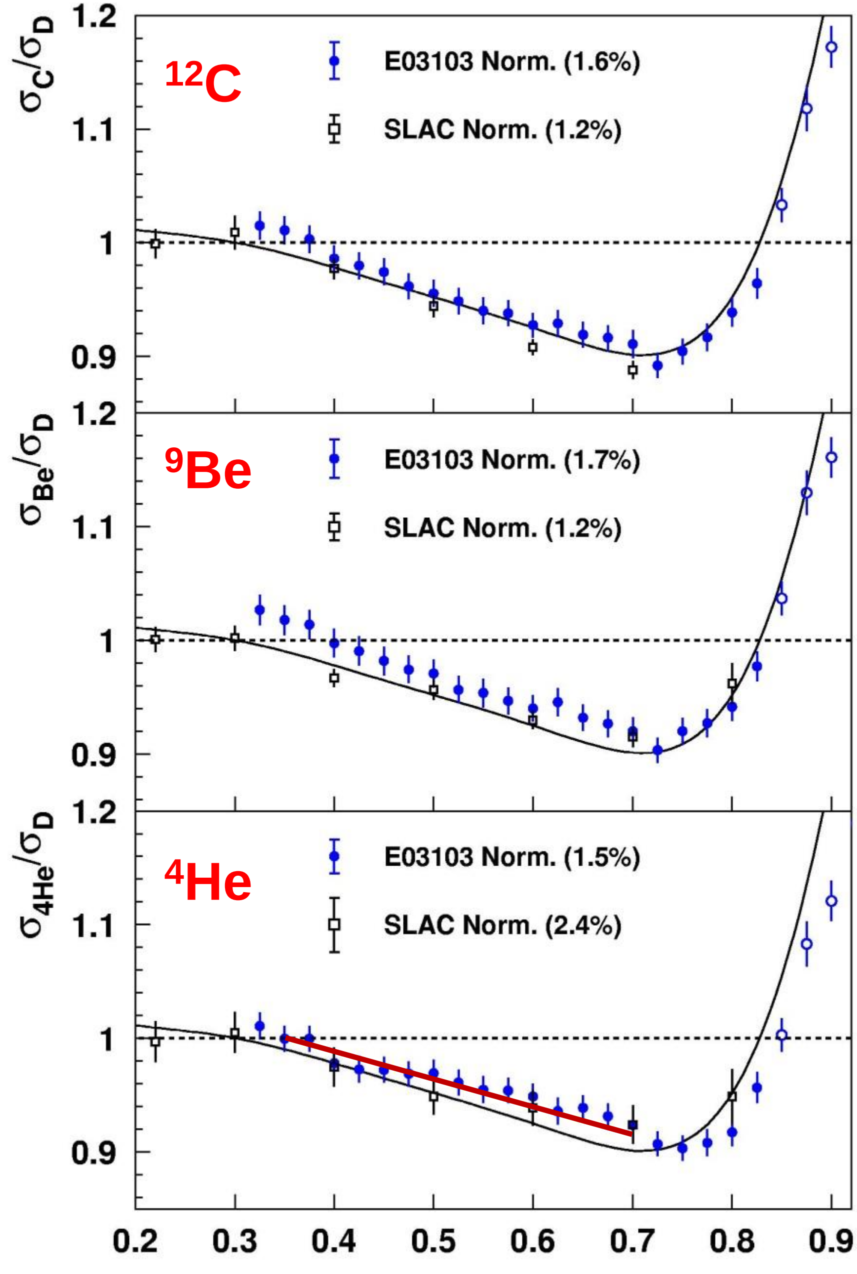
Calculations almost exclusively use nuclear matter, extrapolate to finite nuclei by scaling with density, A,…





JLab E03-103 Results





Consistent shape for all nuclei
(curves show shape from SLAC fit)

If shape (x-dependence) is the same for all nuclei, the slope ($0.35<x<0.7$) can be used to study A dependence

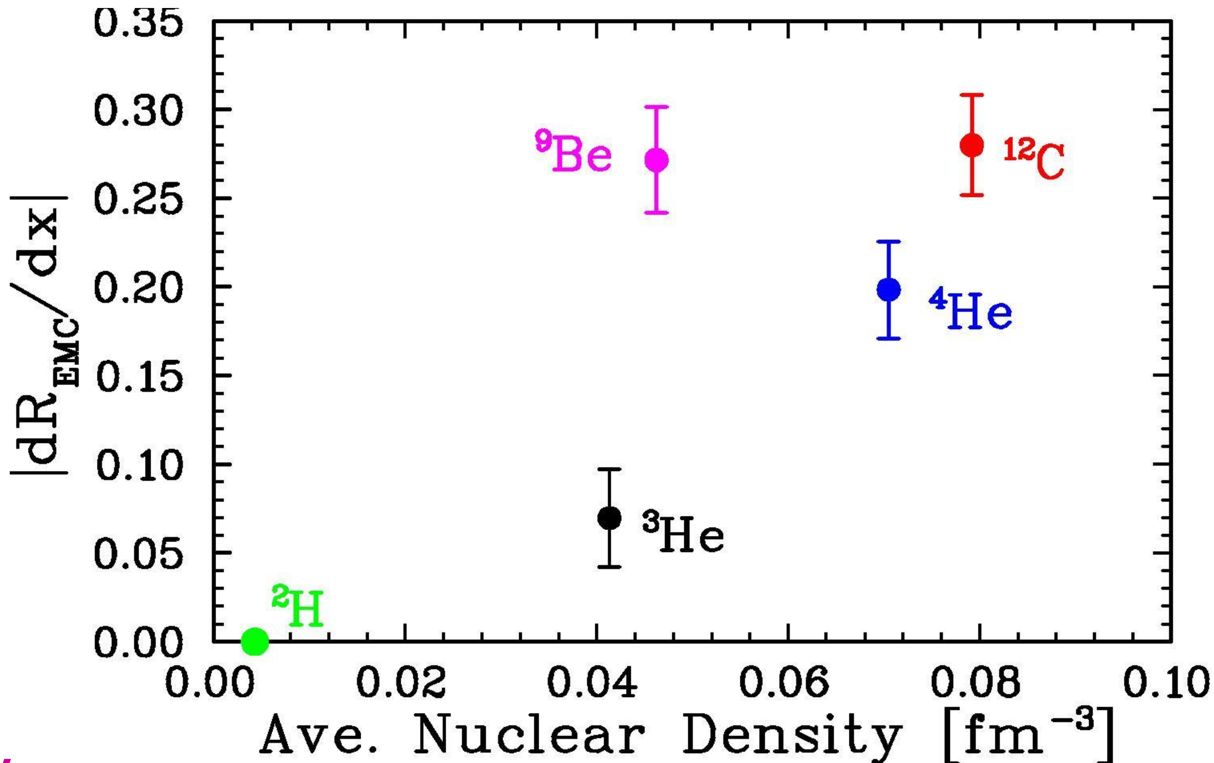
J.Seely, et al., PRL103, 202301 (2009)

A-dependence of EMC effect

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

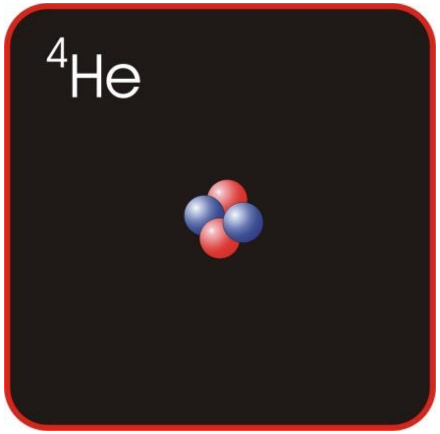
Density determined from *ab initio* few-body calculation

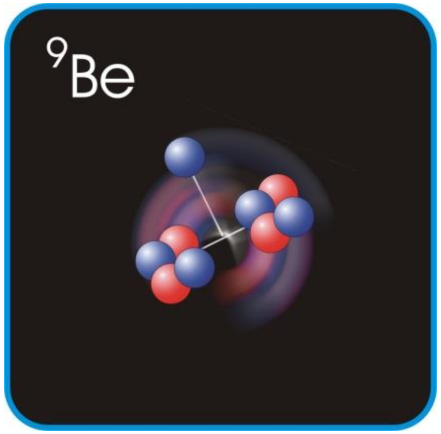
S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)



Data show smooth behavior as density increases, as generally expected… except for ^{9}Be

^{9}Be has **low average density**, but large component of structure is 2α+n





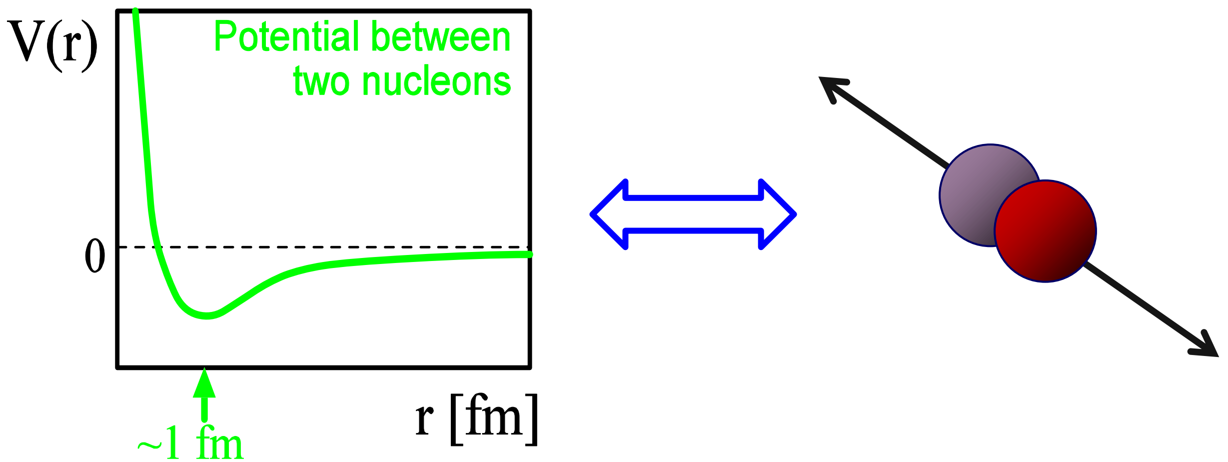
Most nucleons in tight, α-like configurations

K. Arai, et al., PRC54, 132 (1996)

Nuclear structure ←→ Quark effects?

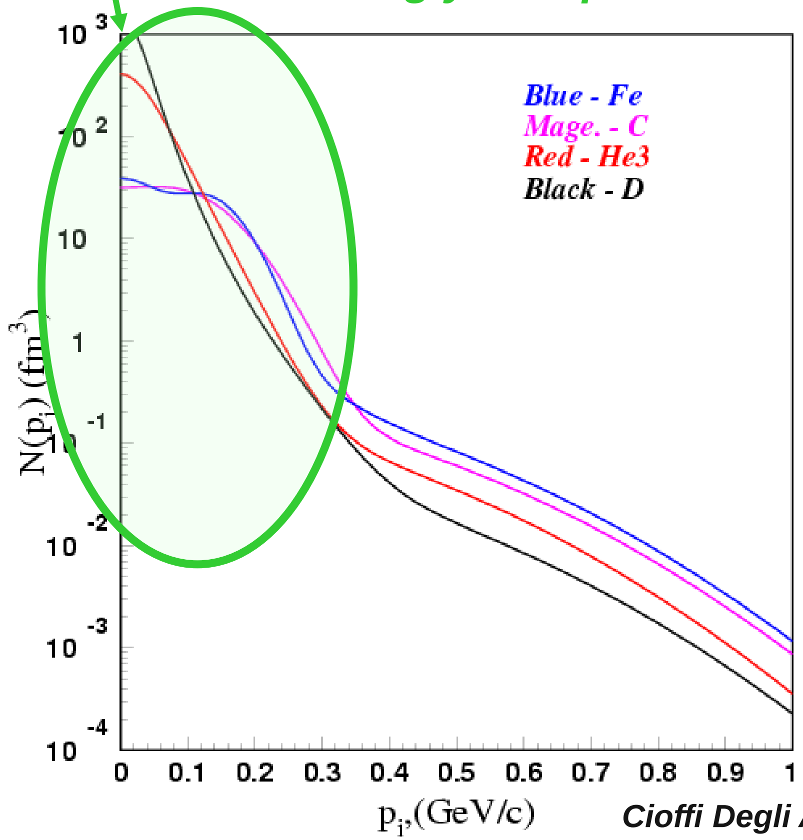
- **New EMC effect data suggest importance of 'local density'**
  - Suggests connection to detailed nuclear structure, clustering effects
  - New and intriguing behavior, but still no microscopic explanation

- **Can we study nucleons at high density (short distance) directly?**
  - "Short-range correlation" (SRC) measurements are meant to probe these high-density configurations
    - The experiments **measure** high momentum nucleons
    - Aim is to **study** contribution of high density configurations



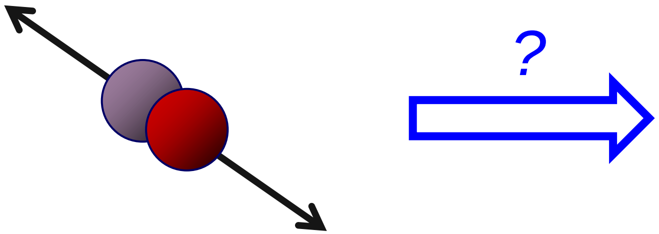
Collective behavior vs. two-body physics

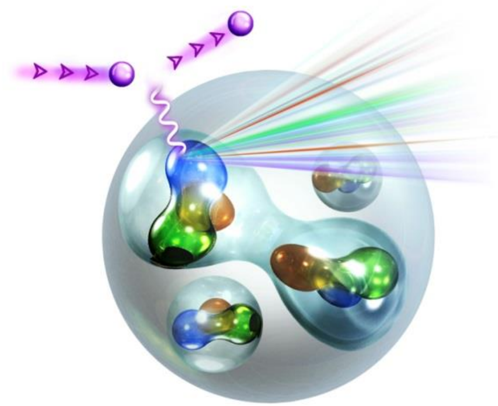
Mean-field region: collective behavior, strongly A-dependent

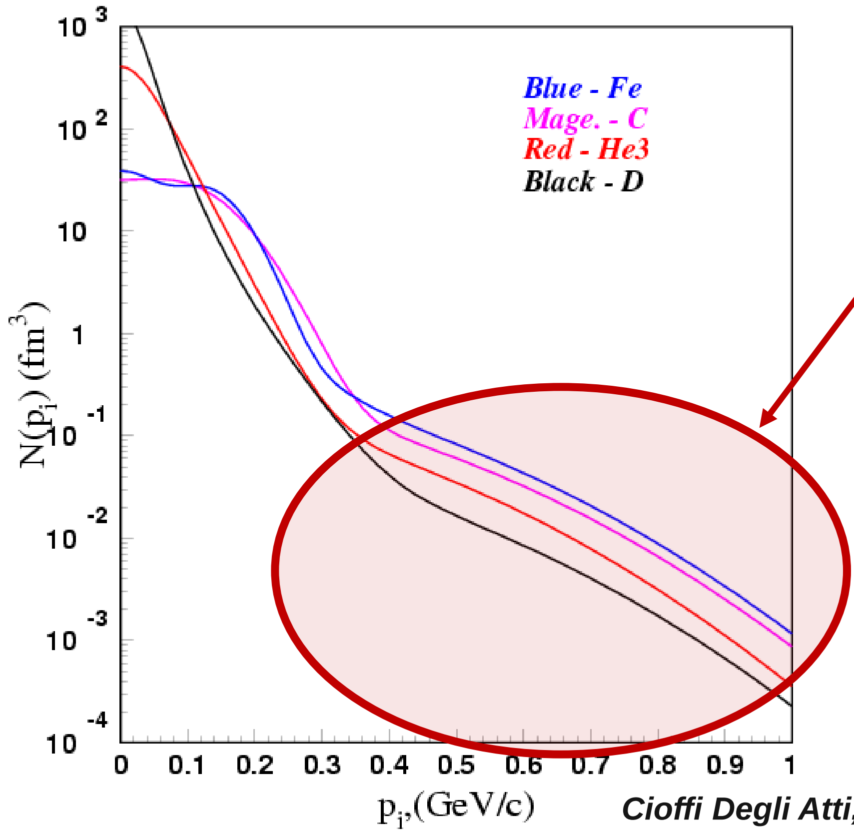


Cioffi Degli Atti, et al, PRC53, 1689 (1996)

Collective behavior vs. two-body physics







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

Could these Short-Range Correlations be dense enough to modify the quark structure of protons and neutrons?

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

SRC evidence: A/D ratios

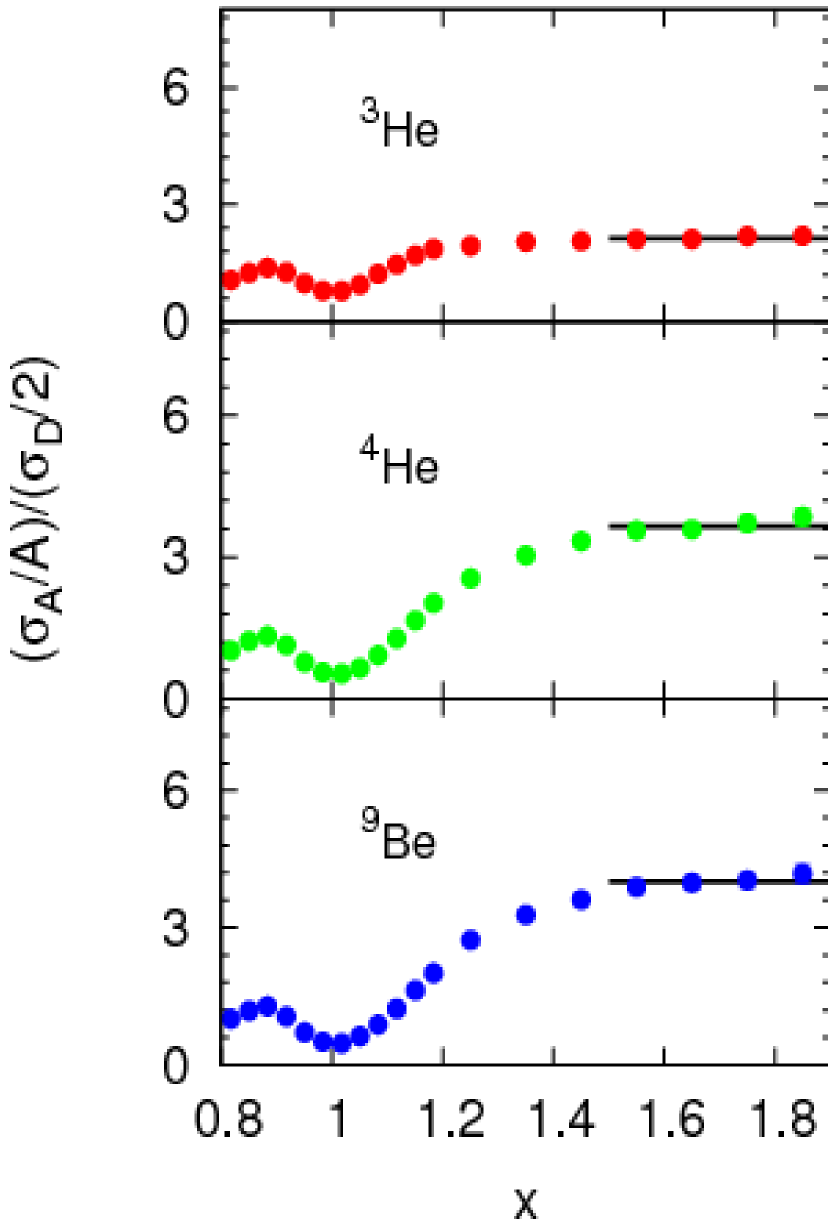
<u>**JLab E02-019:**</u> **Short-range correlations**

JA, D. Day, B. Filippone, A. Lung

N. Fomin – PhD student

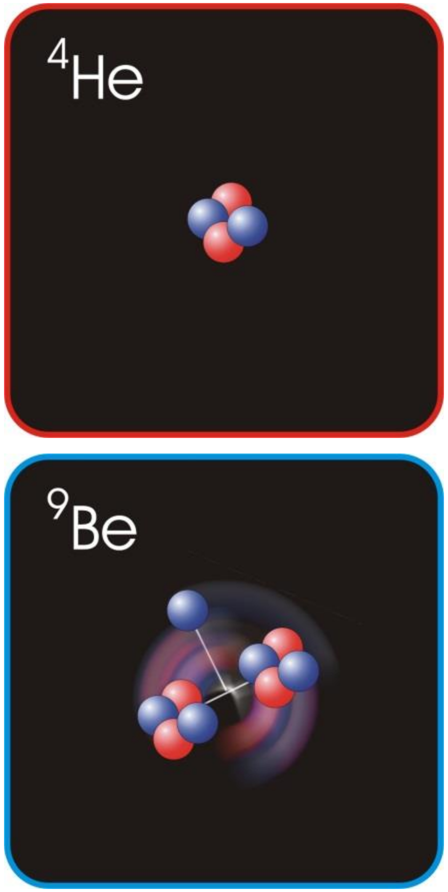
A/D Ratio	
^{3}He	2.14±0.04
^{4}He	3.66±0.07
Be	4.00±0.08
C	4.88±0.10
Cu	5.37±0.11
Au	5.34±0.11

Ratio of cross sections shows a (Q^2-independent) plateau above $x \approx 1.5$, as expected in SRC picture

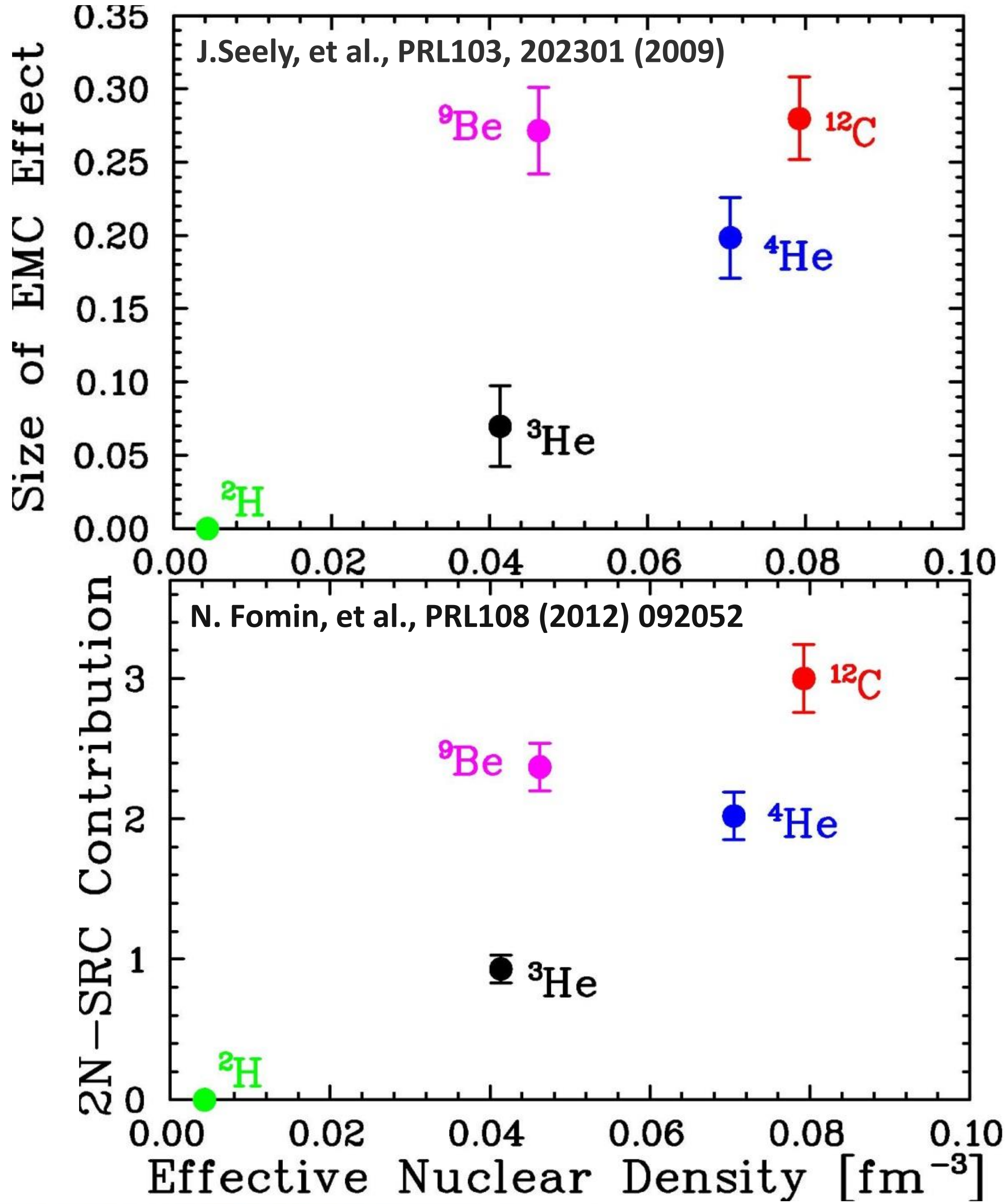


N. Fomin, et al., PRL108 (2012) 092052

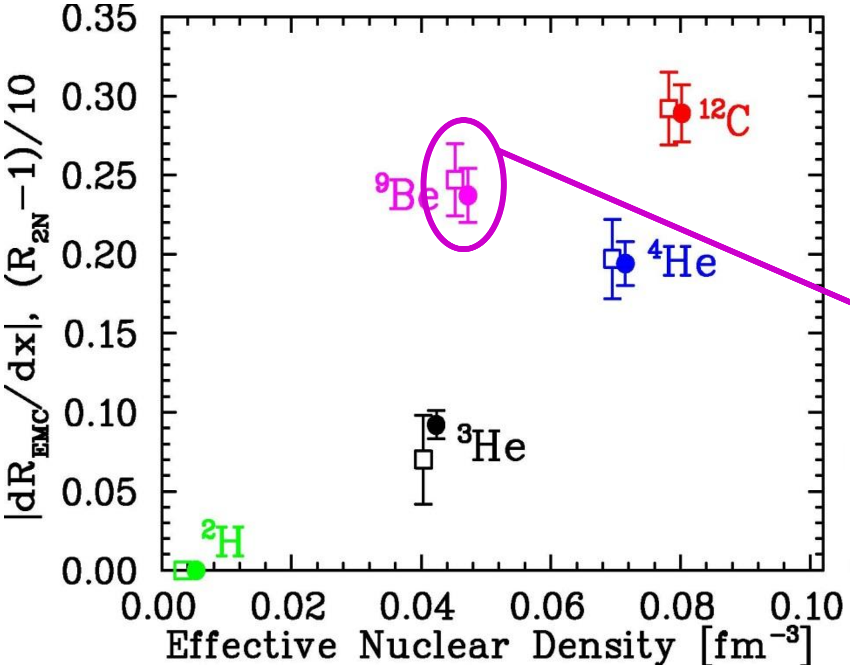
Connection to EMC effect?



Credit: P. Mueller



EMC effect: Importance of two-body effects?



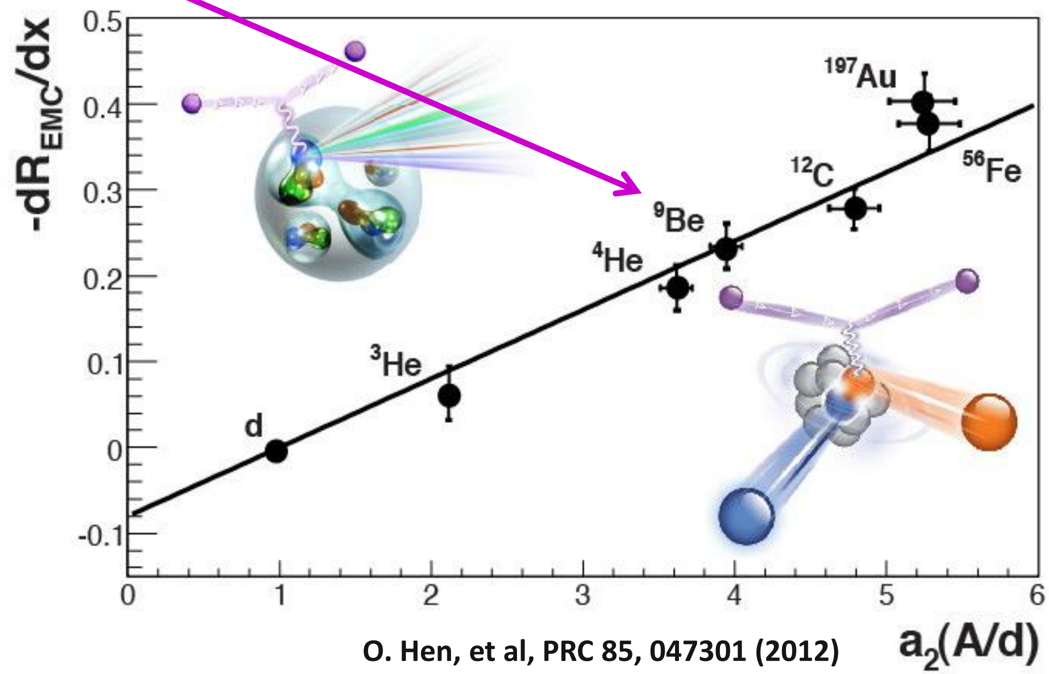
J. Seely, et al., PRL103, 202301 (2009)

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

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

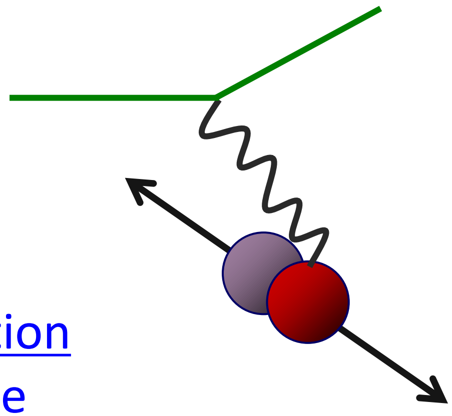
5-10% suppression in all nucleons?

25-50% change in the 20% of nucleons at very high momenta?



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

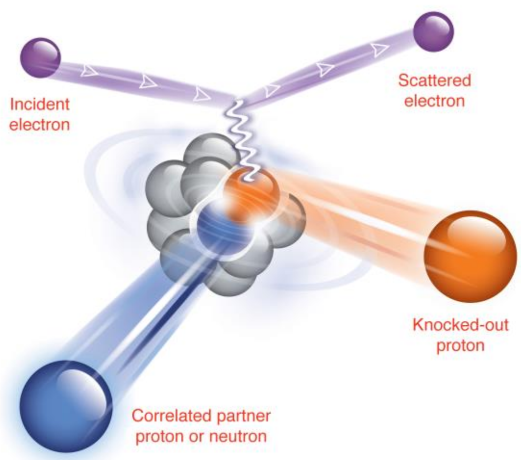
Isospin dependence of SRCs

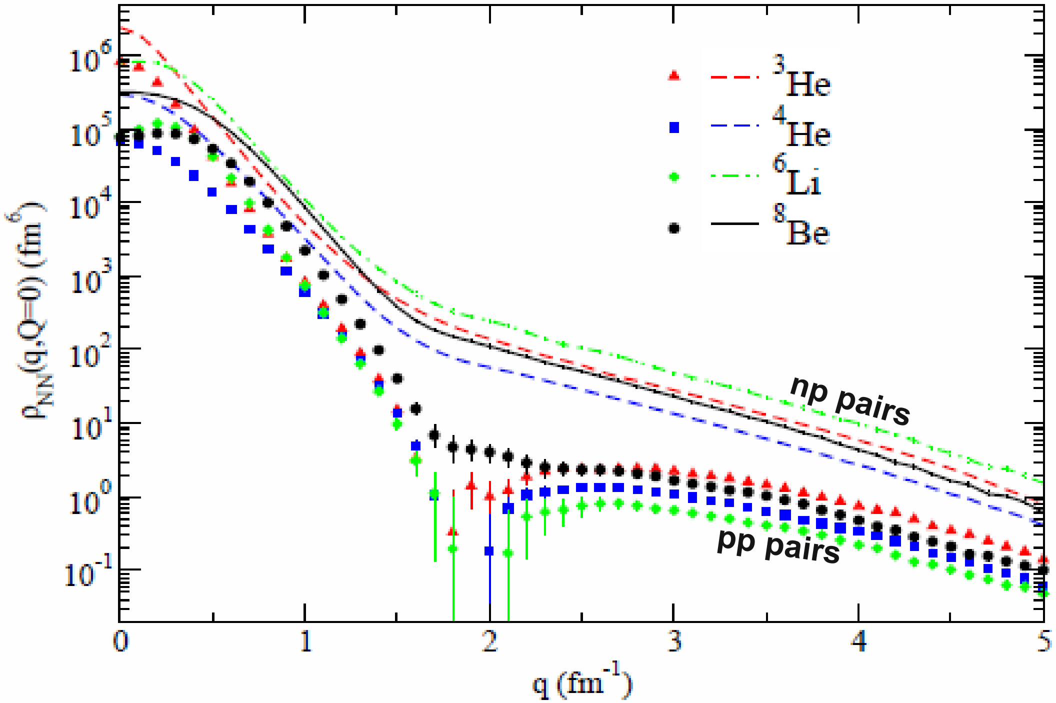


Two-nucleon knockout: ^{12}C(e,e'pN), ^{4}He(e,e'pN), A(e,e'pp)

- Reconstruct ***initial high momentum proton***
- Look for ***fast spectator nucleon*** from SRC in opposite direction
- Find spectator ~100% of the time, neutron >90% of the time

R. Subedi, et al., Science 320, 1476 (2008)
I. Korover, et al., PRL 113, 022501 (2014)
O. Hen, et al., Science 346, 6209 (2014)





R. Schiavilla, et al., PRL 98, 132501 (2007)

Isospin dependence of the EMC effect

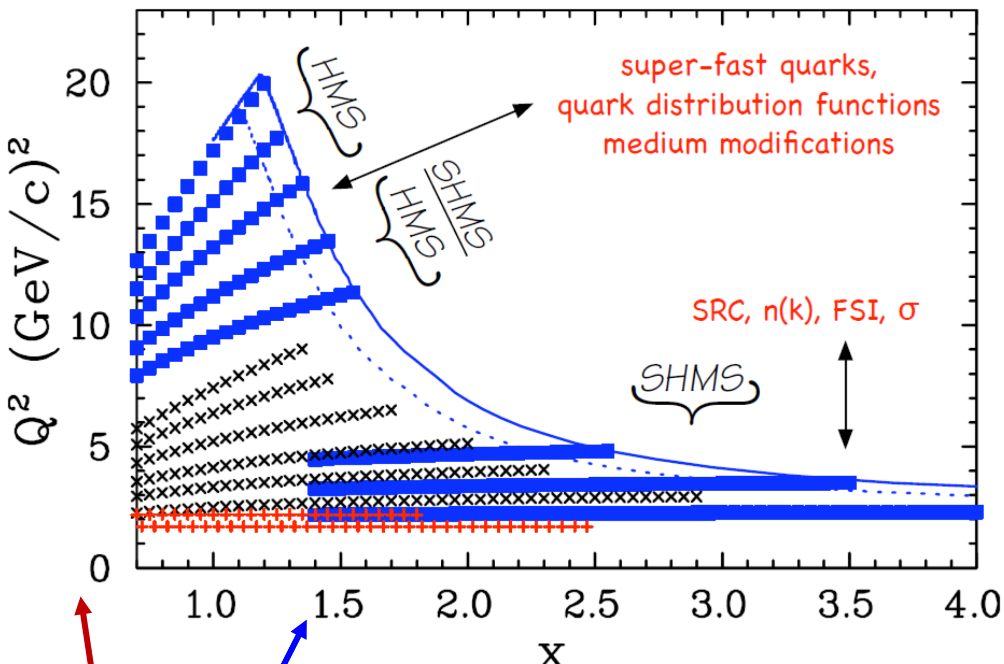
- **EMC effect nearly always assumed to be identical for d(x), u(x)**

- **Becoming hard to believe, at least for non-isoscalar nuclei (^{3}He, ^{208}Pb)**
  - EMC/SRC connection + SRC n-p dominance suggests enhanced high-momentum distribution and enhanced EMC effect in minority nucleons
  - ^{48}Ca, ^{208}Pb expected to have significant neutron skin: neutrons preferentially sit near the surface, in low density regions
  - 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)]

- **Impacts input pdfs for ν-A, p-A, A-A collisions: Important for hard, flavor-dependent processes (e.g. W+/W-)**

- **Key measurement: parity-violating DIS from ^{48}Ca (SoLID collab. at JLab)**
  - ^{2}H PVDIS: search for beyond standard model physics
  - ^{1}H PVDIS: clean separation of d(x)/u(x) at large x in the proton
  - Nuclei: flavor dependence of EMC effect, Charge-symmetry violation

EMC and SRCs with JLab 12 GeV Upgrade



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

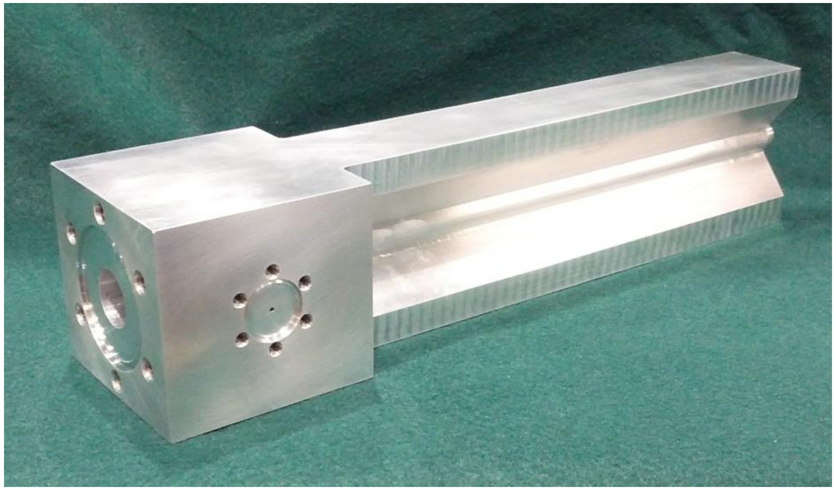
EMC effect at 12 GeV
[E10-008: JA, A. Daniel, D. Gaskell]

Full ^{3}H, ^{3}He program (4 expts) in 2016 (Hall A)

Initial set of light/medium nuclei in 2017 (Hall C)

^{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 DIS: EMC effect and d(x)/u(x)
SRC Isospin dependence: ^{3}H vs ^{3}He
Charge radius difference: ^{3}He - ^{3}H

Future Plans

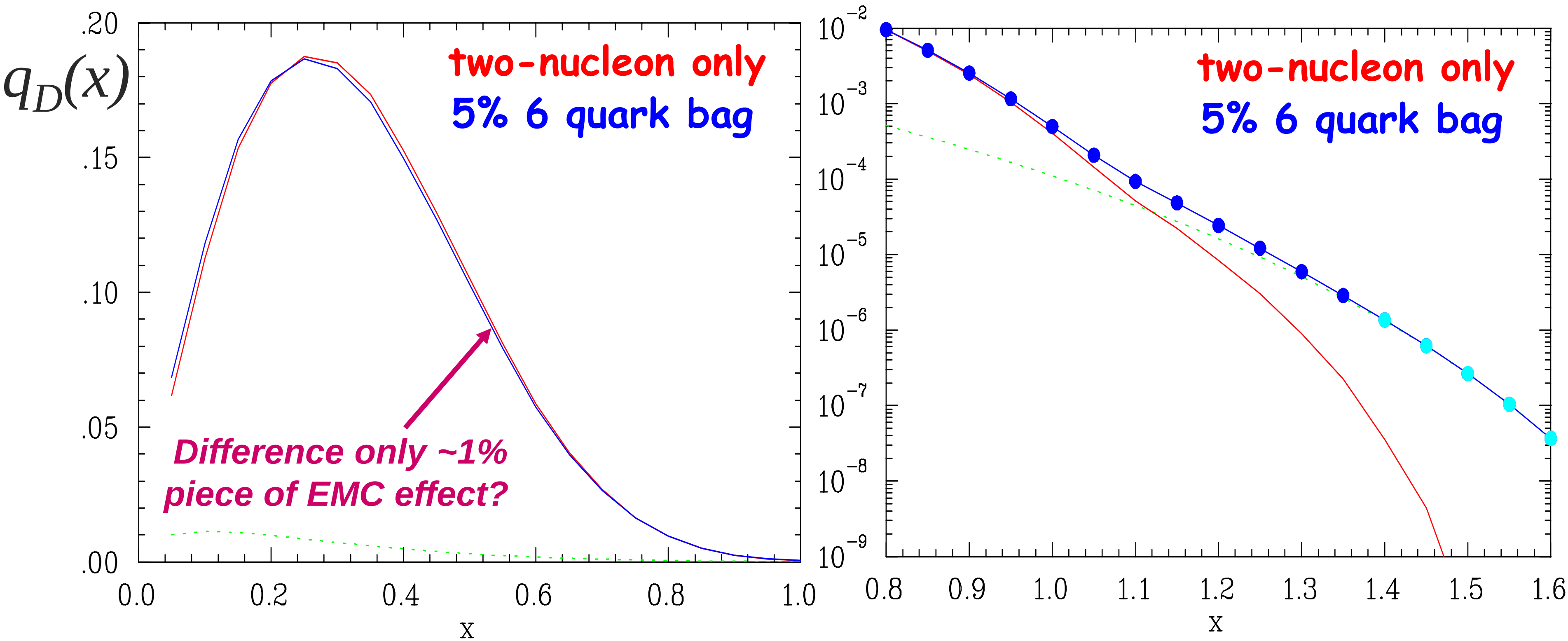
1) Additional nuclei to study cluster structure, EMC-SRC correlation

2) Two-body physics driving SRCs makes deuteron the most 'natural' place to study impact of extremely high density configurations

- *Isolate SRCs and probe their quark distributions*

Quark distributions of SRC: "Super-fast" quarks

Inclusive scattering at x>1 isolates SRCs
High energy scattering probes quark distributions



6q bag is 'shorthand' for any model where overlapping nucleons allows free sharing of quark momentum

First Look from 6 GeV: N. Fomin, et al., PRL 105 (2010) 212502
Suggests quark distributions can be extracted for x>1

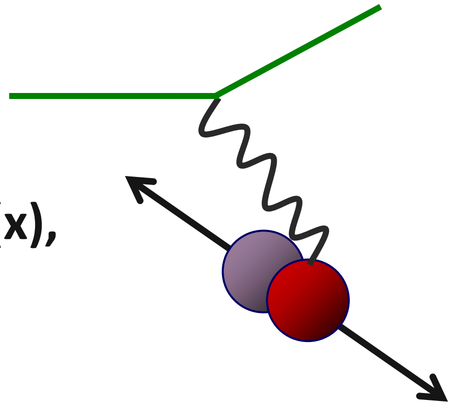
Future Plans

1) Additional nuclei to study cluster structure, EMC-SRC correlation

2) Two-body physics driving SRCs makes deuteron the most 'natural' place to study impact of extremely high density configurations

- *Isolate SRCs and probe their quark distributions*
  - *Kinematically isolate SRCs, probe at very high scales [DIS on SRCs]*
- *"Tag" scattering from slow (on-shell) or fast (off-shell) nucleon in ^2H*
  - JLab: Measure **form factors** of slow and fast protons
  - JLab: Measure **quark distributions** of slow and fast protons
  - **EIC with forward tagging will provide complete measurements for nucleon in deuteron with low- or high-momentum spectator**

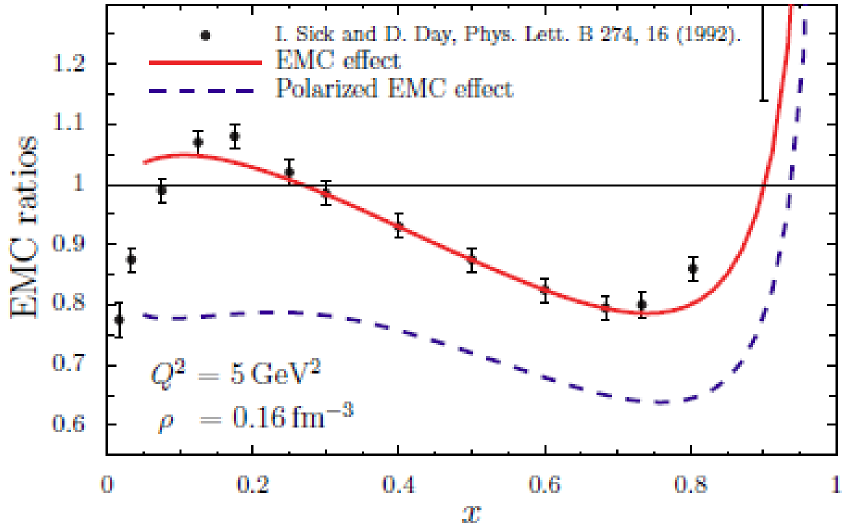
3) Spin-dependent EMC effect: polarized proton in 7Li

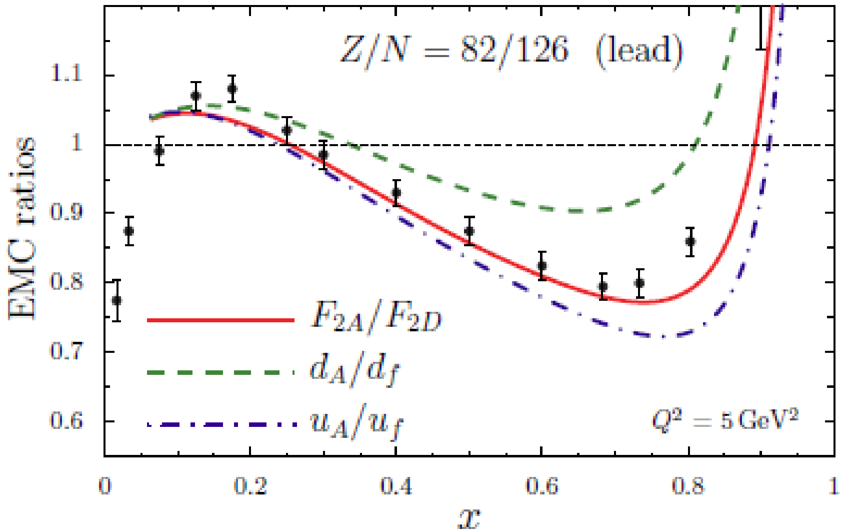


4) PVDIS, Drell-Yan, ν-A can provide information on u(x) vs d(x), quark vs. antiquark (valence vs sea)

Understanding the EMC effect

- *The puzzle posed by the EMC effect will only be solved by conducting new experiments that expose novel aspects of the EMC effect*
- Measurements must help distinguish between explanations of EMC effect; e.g. whether *all nucleons* are modified by the medium or only those in SRCs
- Important examples are measurements of the *EMC effect in polarized structure functions* & the *flavour dependence of EMC effect*
- A JLab experiment has been approved to measure the spin structure of ^{7}Li
- Flavour dependence will be accessed via JLab DIS experiments on ^{40}Ca & ^{48}Ca; also parity violating DIS stands to play a pivotal role

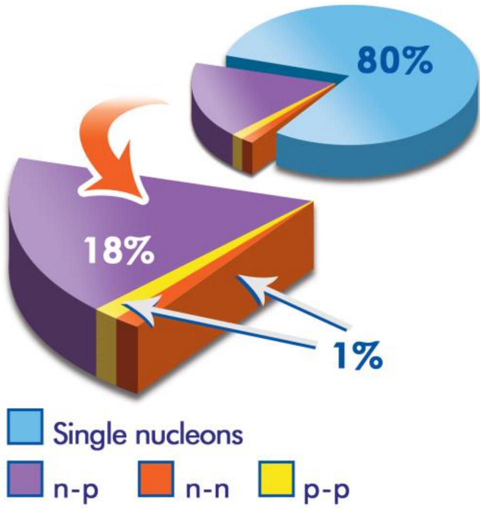




Summary

SRCs are an important component to nuclear structure

- ~20% of nucleons in SRC, mainly np pairs
  - Room for small additional contributions (3N-SRCs, 6q bags)
- **Impact ν-A scattering, neutron stars, symmetry energy**



R. Subedi et al., Science 320, 1476 (2008)

These dense, energetic configurations appear to drive the EMC effect, modifying proton's internal structure

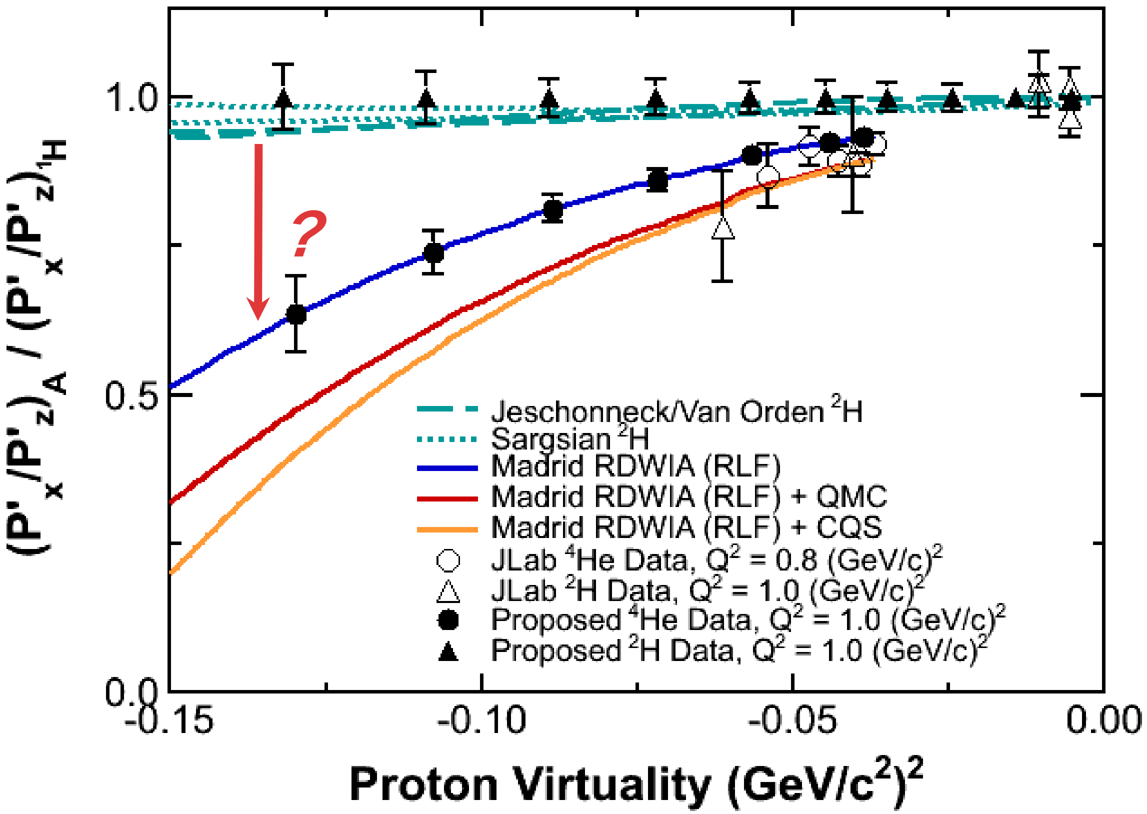
JLab 12 GeV and EIC can use tagging to probe structure of nucleons inside these high-density configurations

- Probe internal structure of SRCs
- Isolate nearly free nucleons (e.g. effective free neutron target)
- Isolate extremely high-momentum, highly-off shell nucleons

Drell-Yan and ν-A scattering (FNAL), PVDIS, and EIC can examine flavor dependence and isolate nuclear effects for sea, valence, and glue

In-Medium Nucleon Form Factors

[E11-002: E. Brash, G. M. Huber, R. Ransom, S. Strauch]



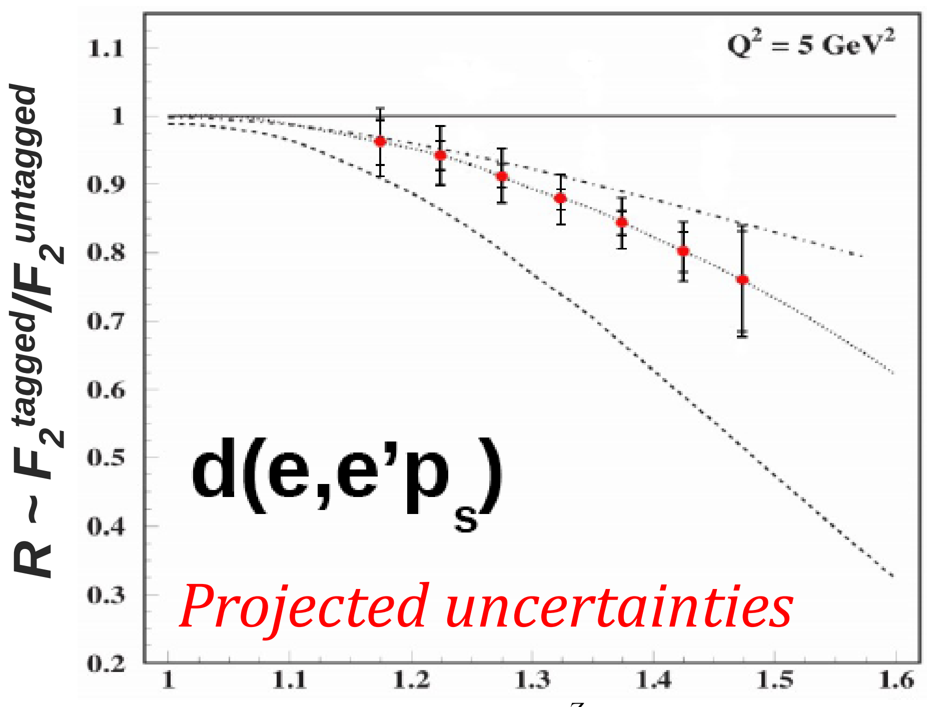
- Compare proton knock-out from dense and thin nuclei: ^{4}He(e,e'p)^{3}H and ^{2}H(e,e'p)n
- Modern, rigorous ^{2}H(e,e'p)n calculations show reaction-dynamics effects and FSI will change the ratio at most 8%
- QMC model predicts 30% deviation from free nucleon at large virtuality

S. Jeschonnek and J.W. Van Orden, Phys. Rev. C 81, 014008 (2010) and Phys. Rev. C 78, 014007 (2008); M.M. Sargsian, Phys. Rev. C82, 014612 (2010)

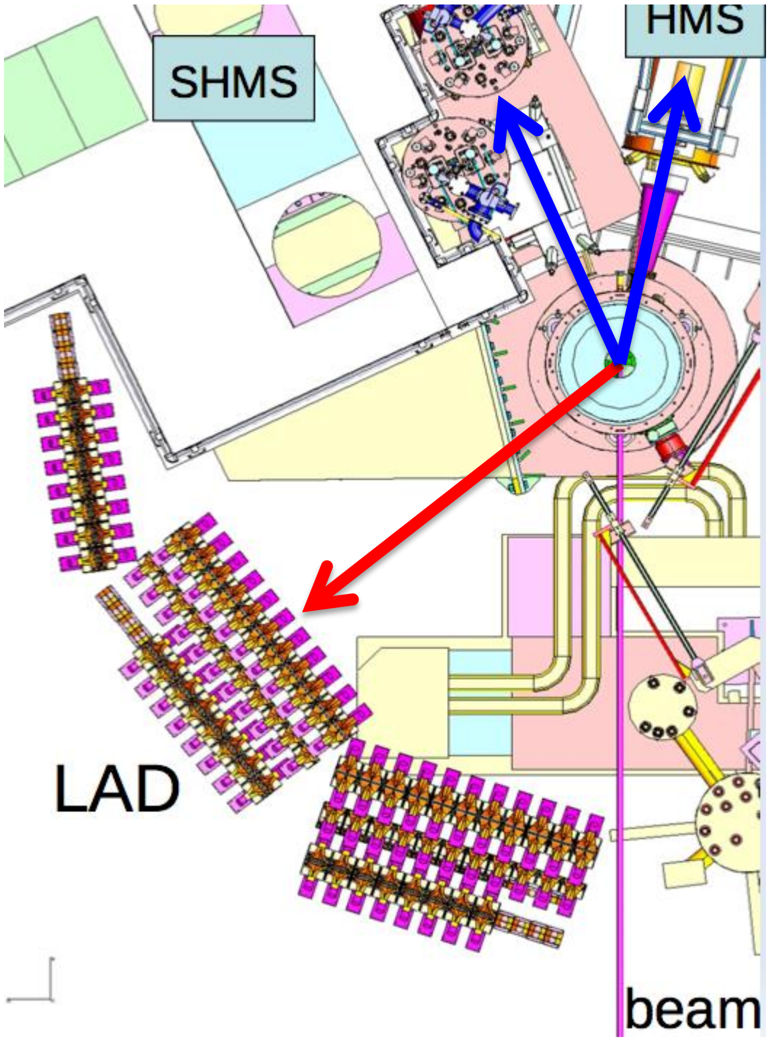
In-Medium Nucleon Structure Functions

[E11-107: O. Hen, L.B. Weinstein, S. Gilad, S.A. Wood]

- *DIS scattering from nucleon in deuterium*
- *Tag high-momentum struck nucleons by detecting backward "spectator" nucleon in Large-Angle Detector*
- *α_s related to initial nucleon momentum*



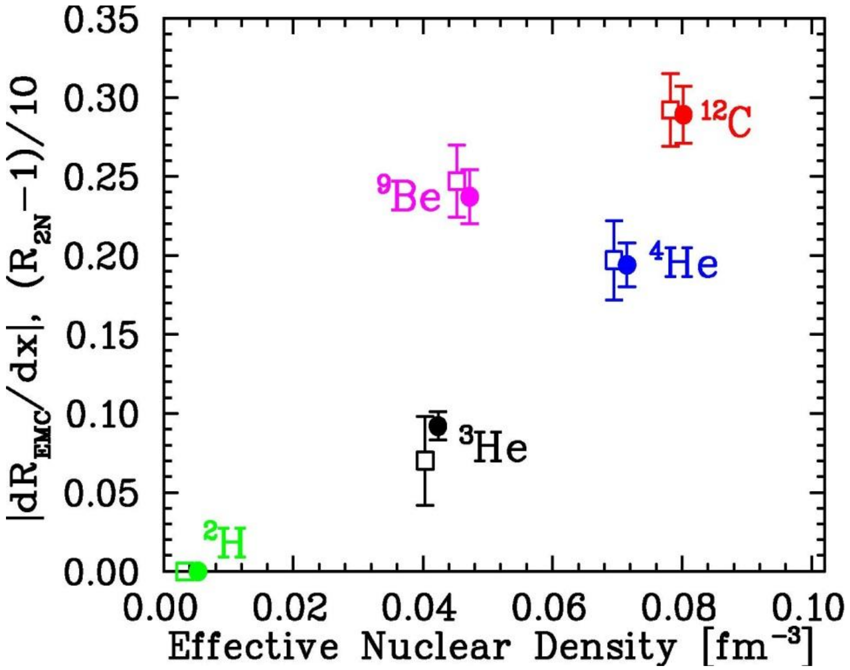
$a_S = (E_S - p_S^Z)/m_S$



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]



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)**

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

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

SRCs believe to be generated by short-distance (high-density) np pairs

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

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

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

SRC measurements directly probe high-momentum nucleons

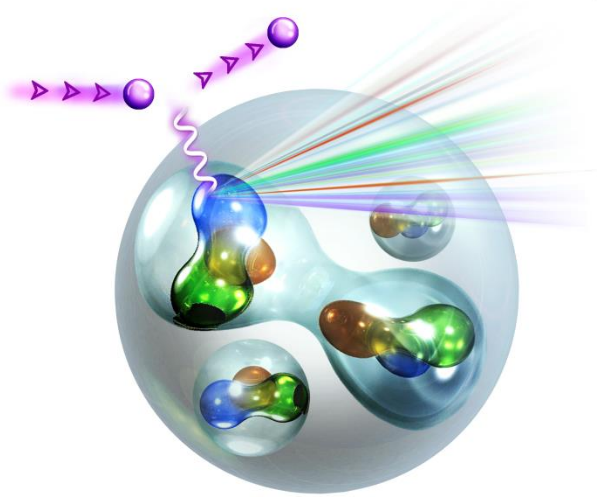
Isospin dependence of SRCs implies slightly different correlation:
Small, dense configurations for all NN pairs, high momentum only for np pairs

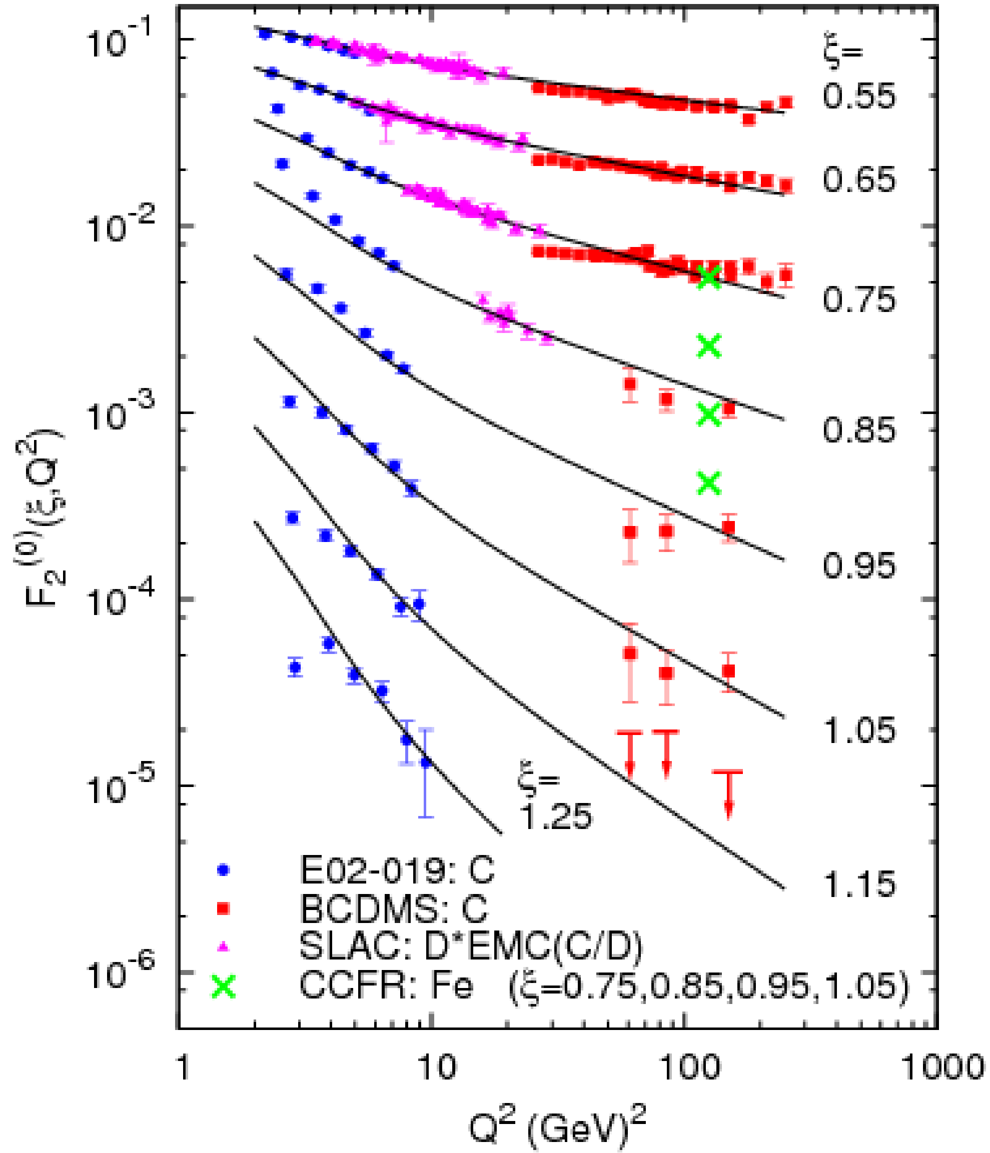
JA, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86 (2012) 065204

Data favors local density interpretation, but very much an open question…

Super-fast quarks

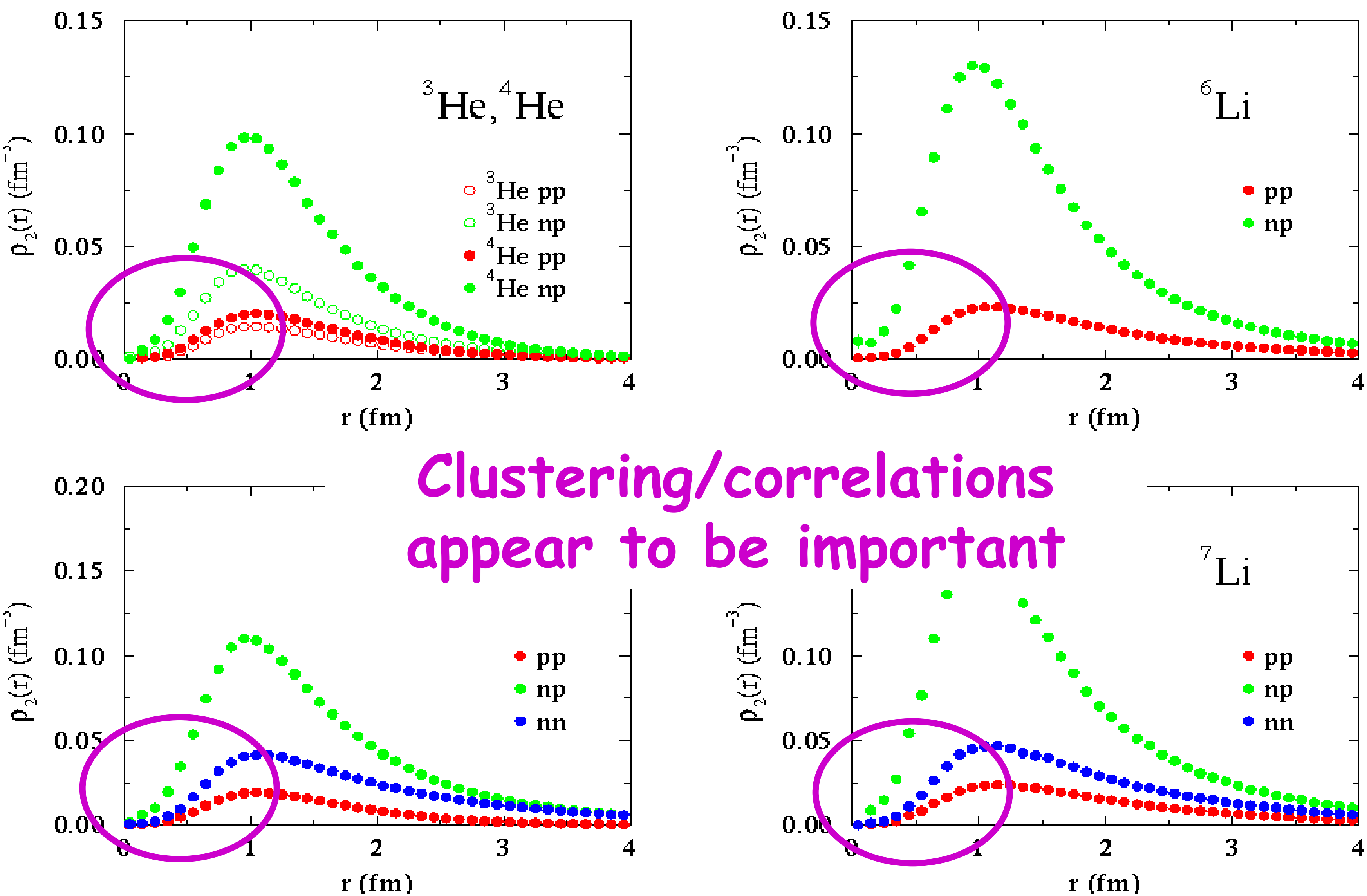
Current data at highest Q^2 (JLab E02-019) already show partonic-like scaling behavior at x>1





N. Fomin et al, PRL 105, 212502 (2010)

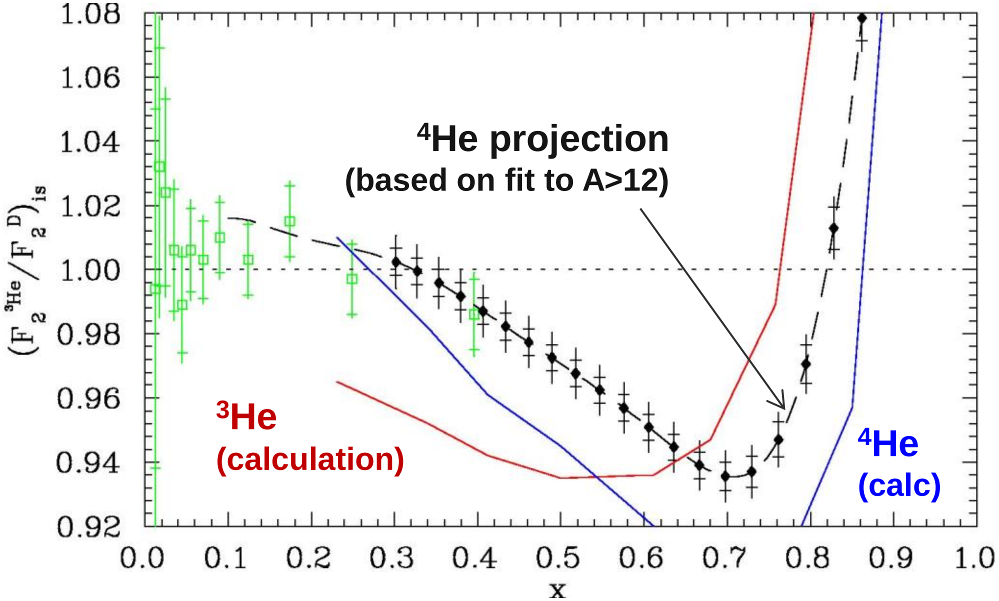
Average density, or average overlap?

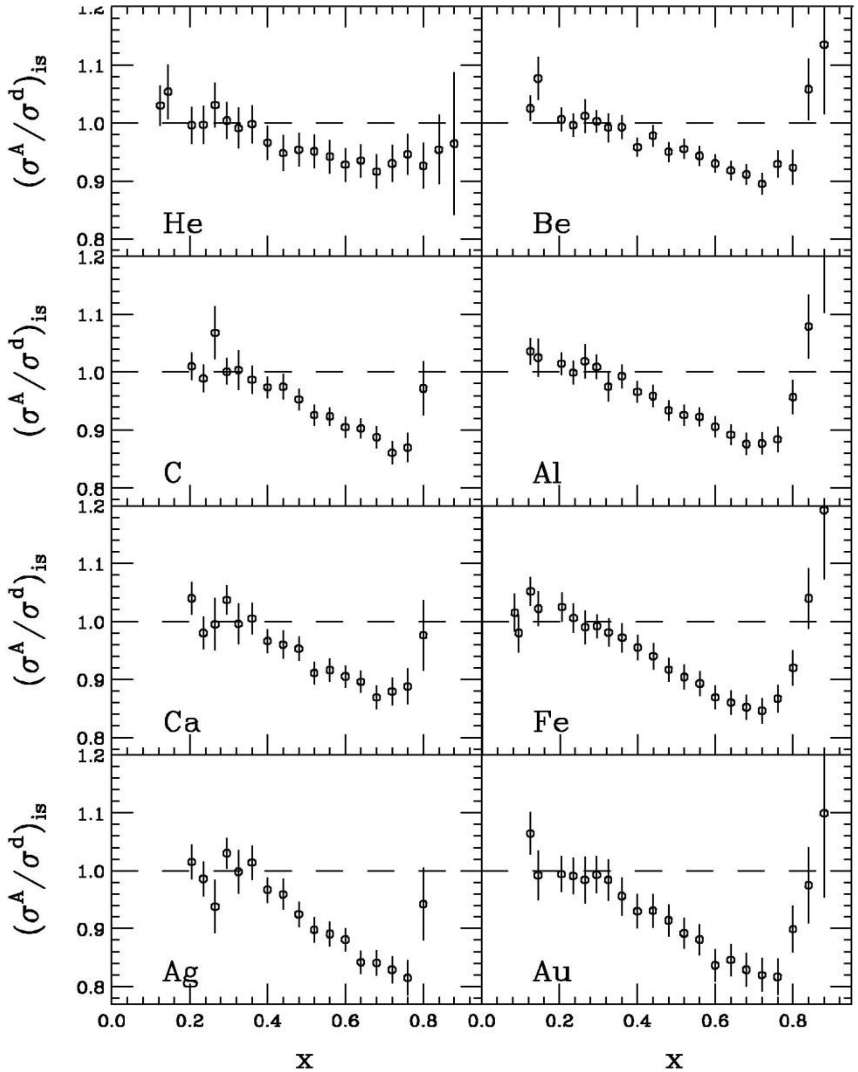


Two-body densities: Pieper and Wiringa

Importance of light nuclei

If two-body effects important, few-body nuclei may differ from 'saturated' effect in heavy nuclei





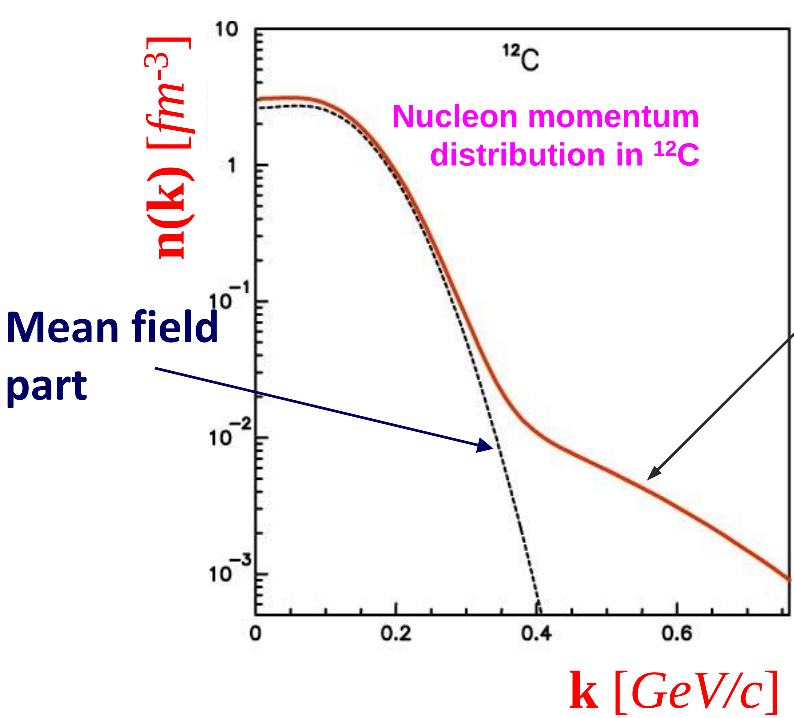
<u>JLab E03-103:</u> EMC effect in light nuclei

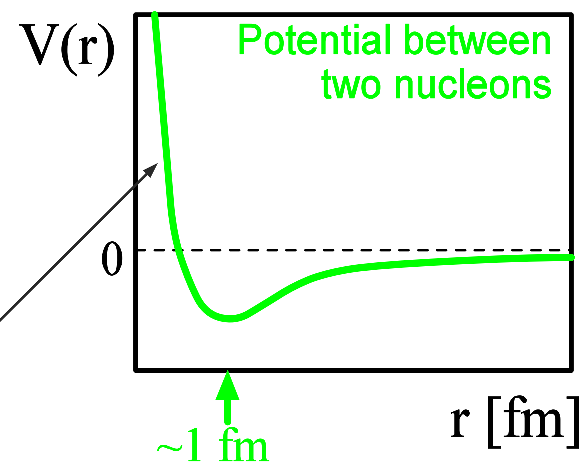
JA and D. Gaskell; J. Seely, A. Daniel, PhD students

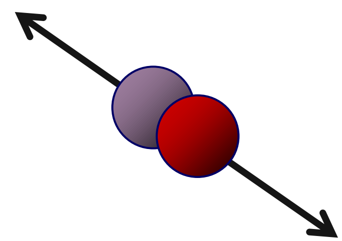
High-momentum nucleons (Short-Range Correlations)

N-N interaction ⟹ Hard interaction at short range

⟹ Pairs of high-momentum nucleons (up to 1 GeV/c)







Even in ^{2}H, nearly half of the K.E. comes from the ~5% of nucleons above k=250 MeV/c

Small N-N separation ⇔ **Large momenta** ⇔ **High-density configurations**