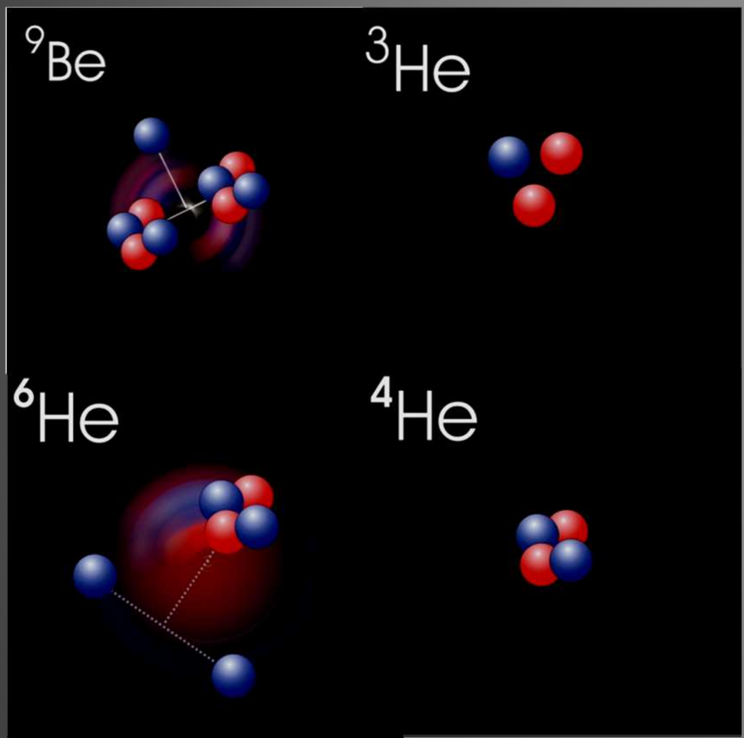
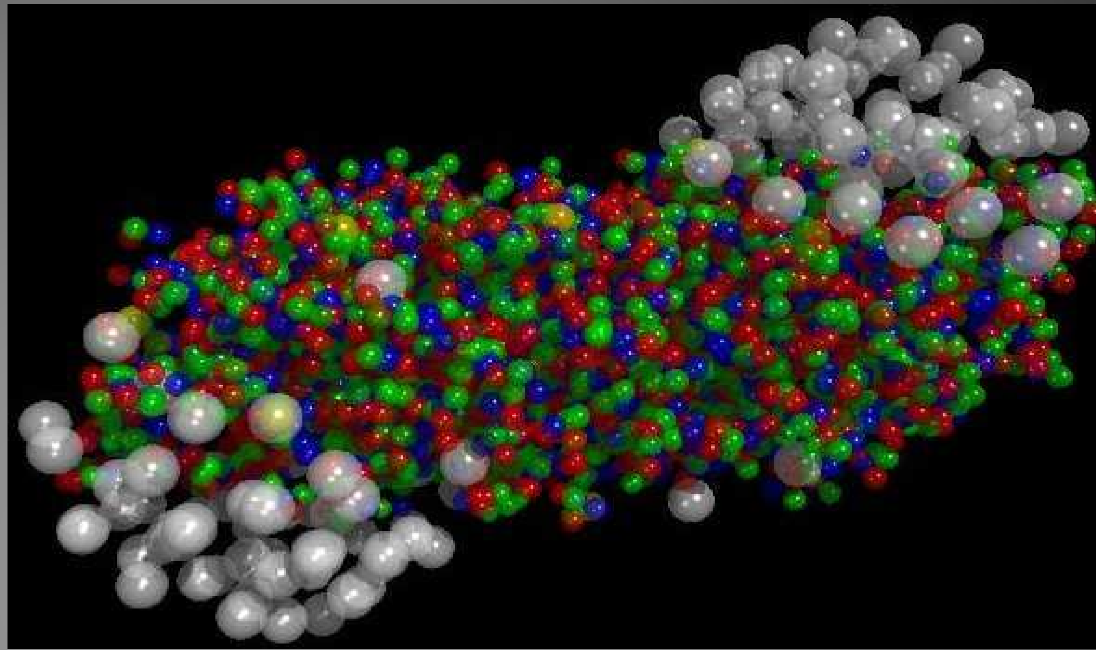
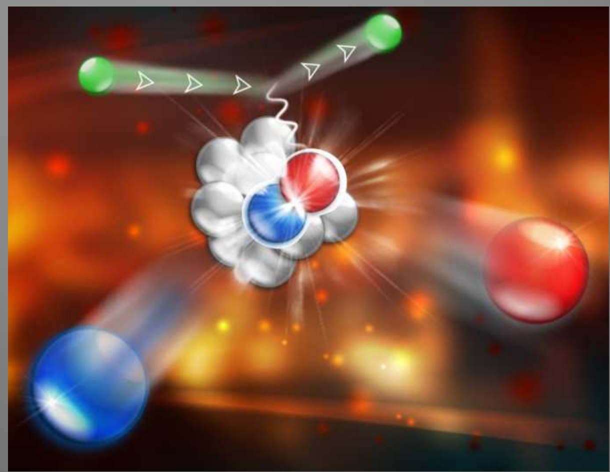
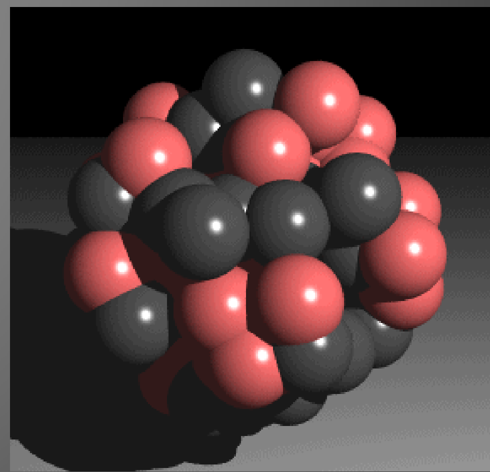
Clusters, Correlations and Quarks: a High-Energy Perspective on Nuclei

John Arrington
Argonne National Lab



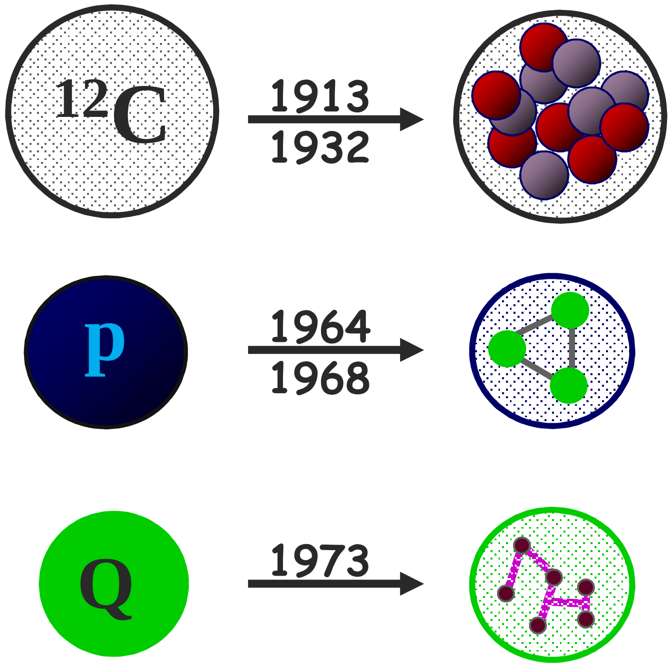






Physics Colloquium
University of Virginia
December 7, 2012

Why do we need a "high-energy perspective"



Nucleus = protons + neutrons

+ strong interaction of hadrons

proton = Constituent Quarks

+ strong interaction of Quarks

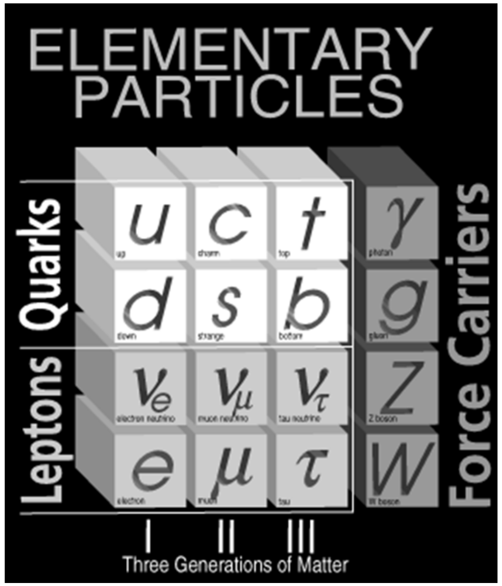
Constituent Quark =

quarks + gluons

+ strong interaction of QCD

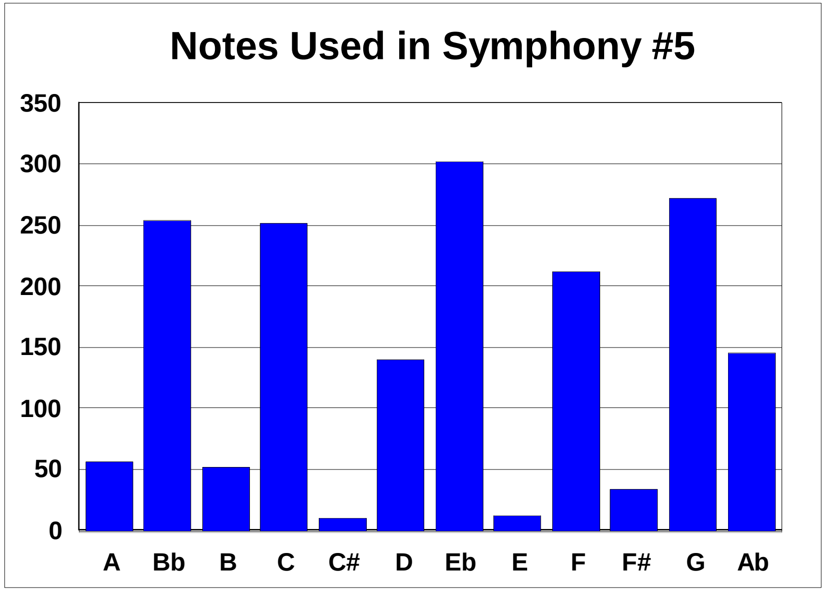
1) Different energy scales means different constituents of interest

Constituents are not enough

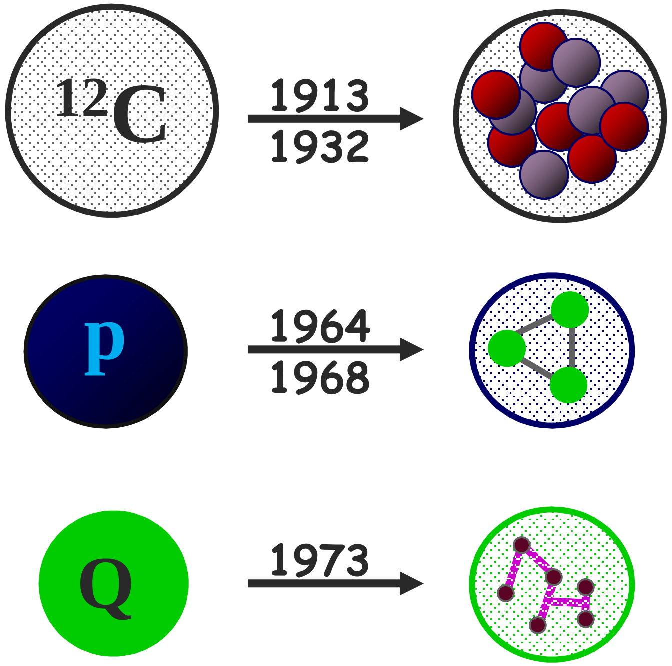


The fundamental constituents of matter (or at least most of them)

The constituents of the first movement of Beethoven's 5th Symphony



Why do we need a "high-energy perspective"



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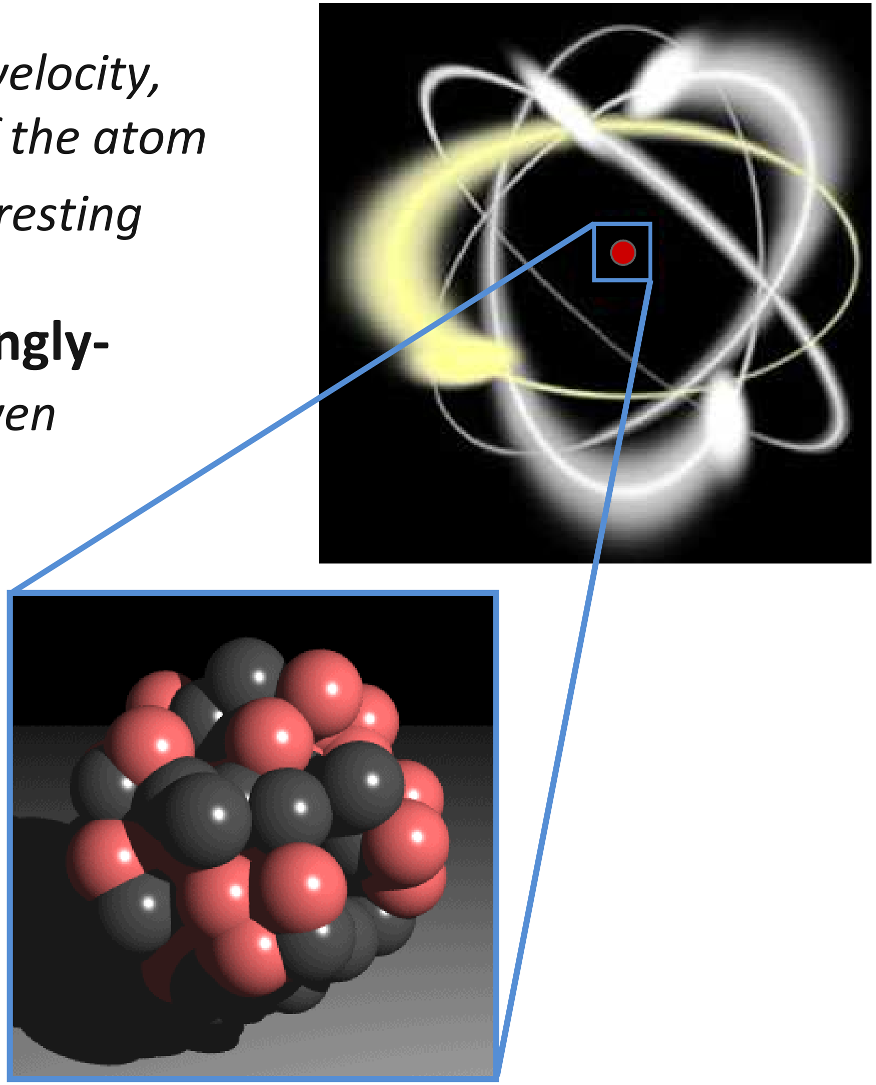
Constituent Quark =
quarks + gluons
+ strong interaction of QCD

2) Different energy scales → different dynamics

While we know the constituents at all scales, the dynamics start off complicated, and work their way towards hopeless as we approach QCD

- **Standard picture of the atom**
  - *Electrons zooming around at high velocity, drive the chemistry, interactions of the atom*
  - *Nuclei are small, static, and uninteresting*
- **In reality, nuclei are complex, strongly-interacting many-body systems** *(even ignoring complications of QCD)*
- **Separation of atomic, nuclear scales critical to the historical process of understanding matter one layer at a time**



Overlap of Scales

- Neglecting size, structure, and dynamics of the nucleus is a very useful starting point in atomic physics, but it's not perfect

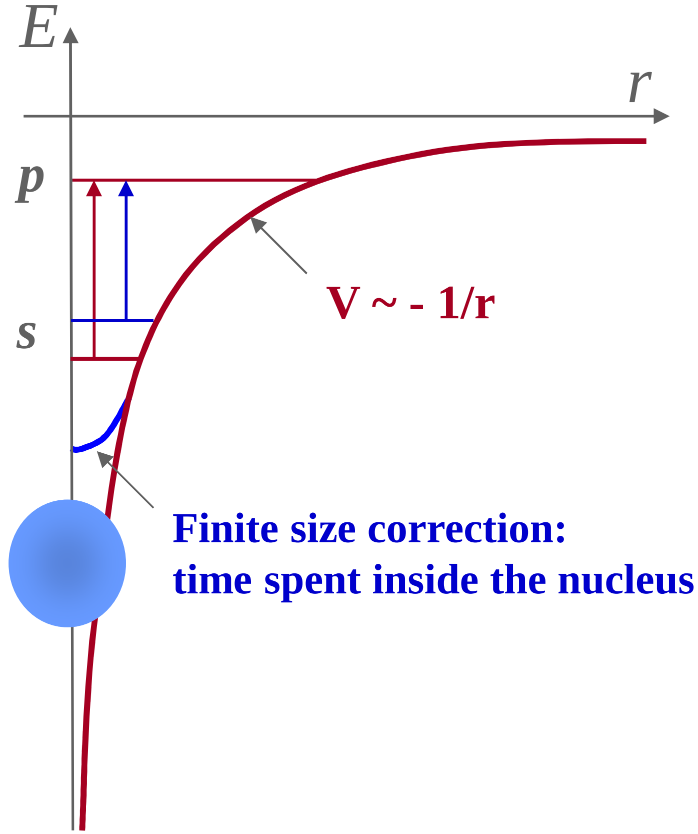
- Finite size of the nucleus has an impact on electron energy levels

- **Finite radius → level shifts**

  Measurement of levels/transitions → measure nuclear size (charge radius)

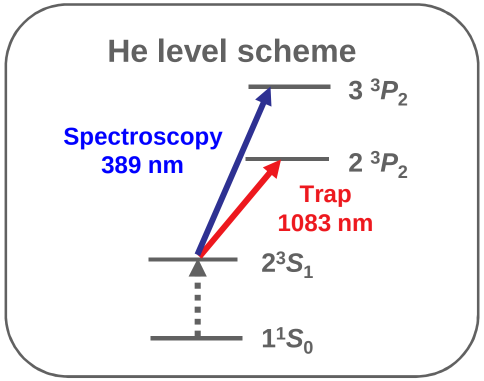
  Field (volume) shift between two isotopes:

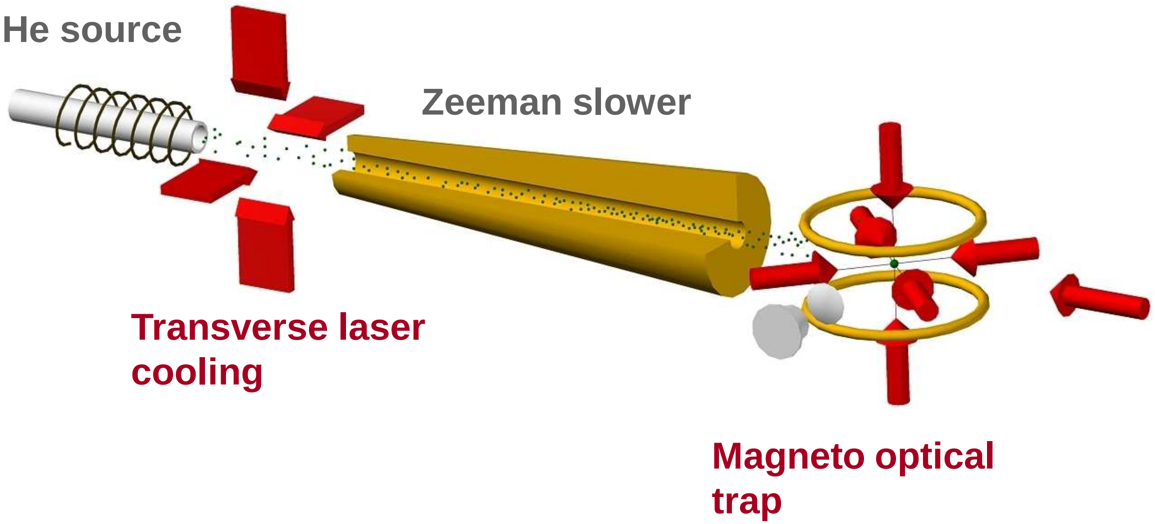
$$\delta\nu_{FS} = -\frac{2\pi}{3} Ze^2 \cdot \Delta|\Psi(0)|^2 \cdot \delta\langle r^2\rangle^{AA'}$$

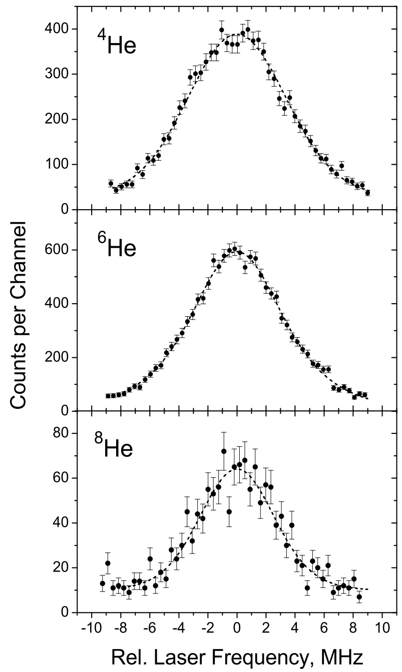


ATTA (Atom Trap Trace Analysis)

- *Trap rare (^{6}He, ^{8}He) Helium isotopes*
  (produced at ATLAS(ANL) or GANIL)
- *Measure isotopic shift in S → P transition*

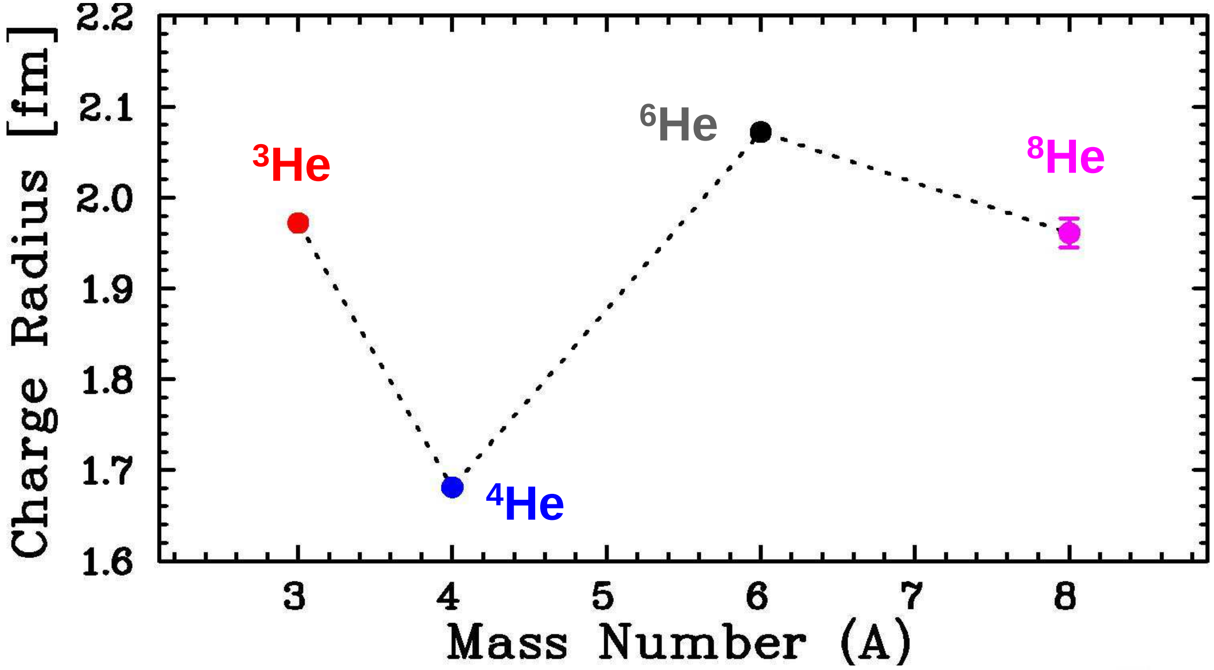






P. Mueller, et al., NIM ***B204****, 536 (2003)*

Charge radii and nuclear structure



Variation of the charge radius with isotope can be understood in terms of nuclear structure

L.B. Wang, et al., PRL93, 142501 (2004) [^{6}He]

P. Mueller, et al., PRL99, 252501 (2007) [^{8}He]

SUBTLE DETAILS OF NUCLEAR STRUCTURE (CLUSTERING/PAIRING) IMPACT ATOMIC PHYSICS, AT ENERGY AND DISTANCE SCALES THAT DIFFER BY ORDERS OF MAGNITUDE

- **`Cross-talk' between nuclear and atomic scales**
  - **HIGH PRECISION MEASUREMENTS**
    - *Isotope shifts*
  - **CASES OF PARTICULARLY HIGH SENSITIVITY TO SMALL DISTANCE**
    - *Muonic hydrogen*

- **Similar cases of overlap between nuclear and quark structure?**
  - **NEED EXTREMELY HIGH ENERGY SCALES IN NUCLEI**
    - *Energy density [RHIC, LHC]* *Quark-Gluon Plasma = Nucleus ?*
    - *Matter density [Neutron stars]* *Neutron star is almost Nucleus.*
    - *Kinetic energy [High-momentum nucleons]* *Perfect!*

Nuclei: energetic, dense, complex systems

- **Nuclei are incredibly dense**

  >99.9% of the mass of the atom

  <1 trillionth of the volume

  ~10^{14} times denser than normal matter

  (close to neutron star densities)

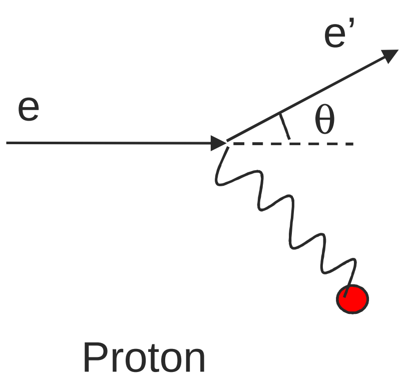
- **Nuclei are extremely energetic**
  - "Fast" nucleons moving at >50% the speed of light (electrons at 1-10%)
  - "Slow" nucleons moving at ~**10^9 cm/s**, in an object ~**10^{-12} cm** in size [ZHz]

The moon ($A_{moon} \approx 5\text{x}10^{49}$) at typical nuclear densities

Isolating high-momentum, high-density components

- **MOST OF THE EXPERIMENTS ARE REMARKABLY STRAIGHTFORWARD**

- **“QUASI-ELASTIC” ELECTRON SCATTERING**
  - Scattering from stationary proton is simple billiard-ball scattering
  - Deviation of final proton from expectation measured initial momentum
  - Relatively high-energy probe to reach high-momentum scales
  - A few `trick shots’ to go beyond this



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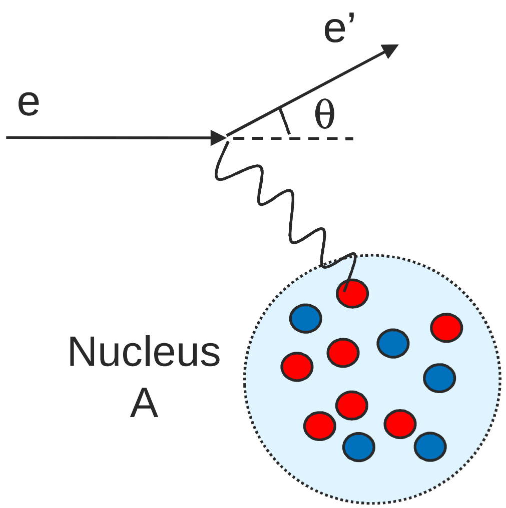
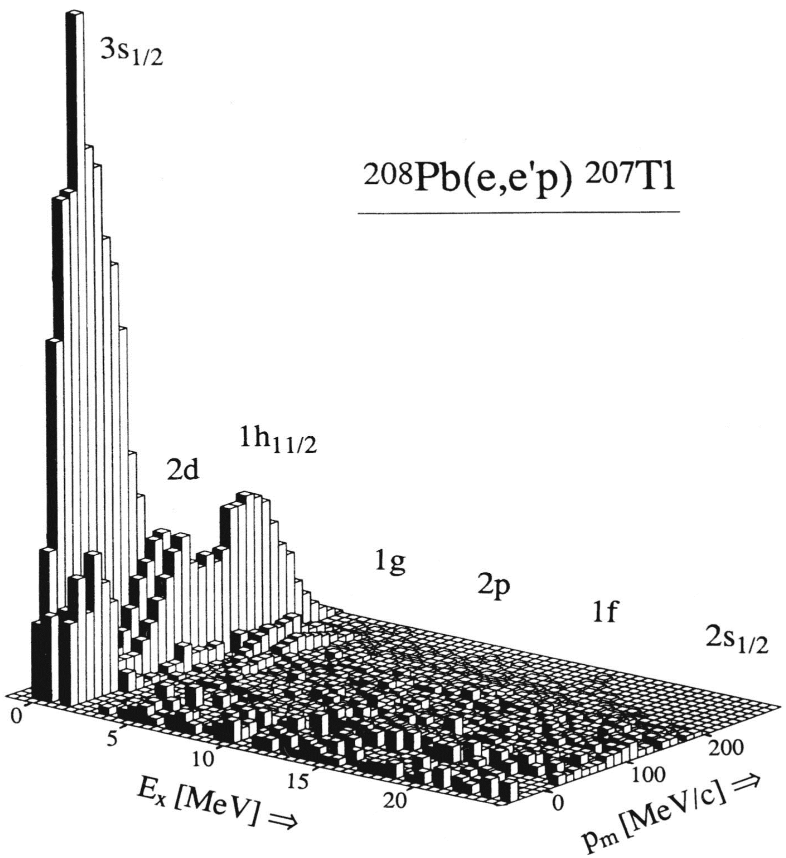
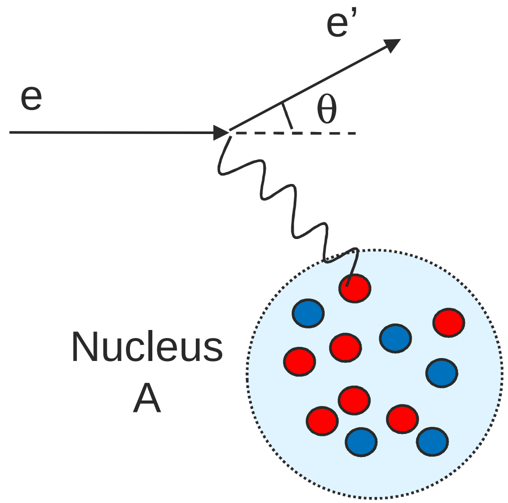
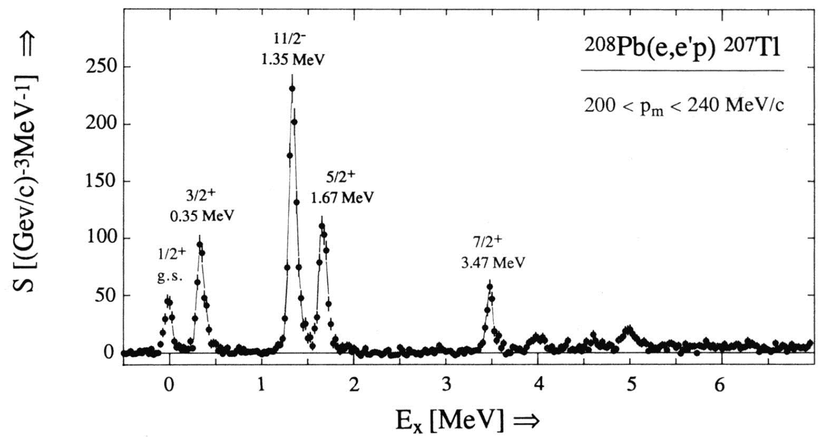


Quasielastic A(e,e'p) scattering

- **PWIA approximation for proton knockout**
  - Reconstruct initial proton binding energy (E_m), momentum (p_m)

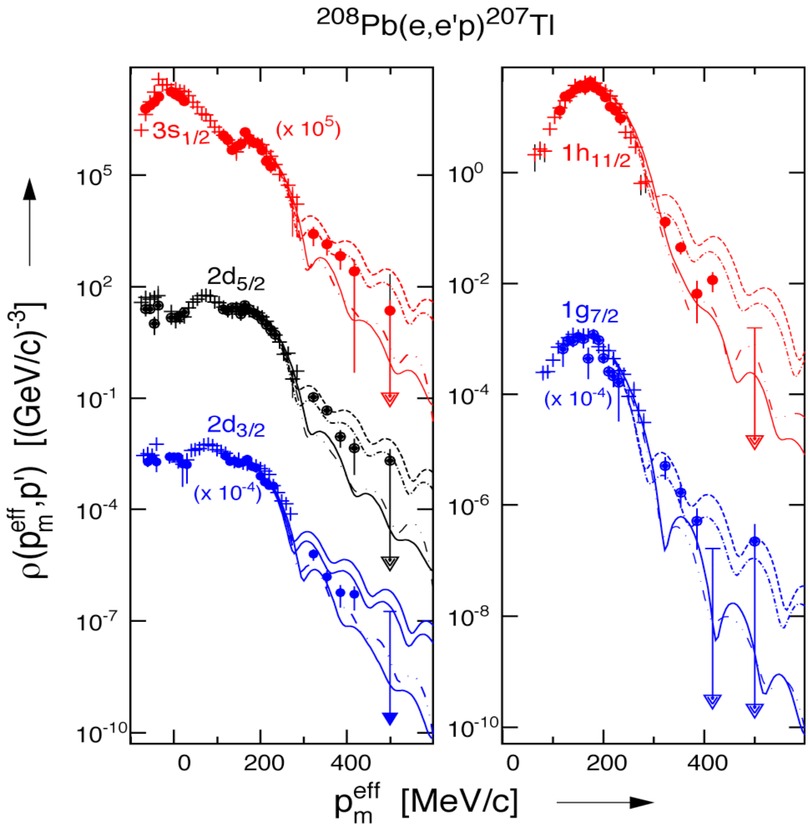


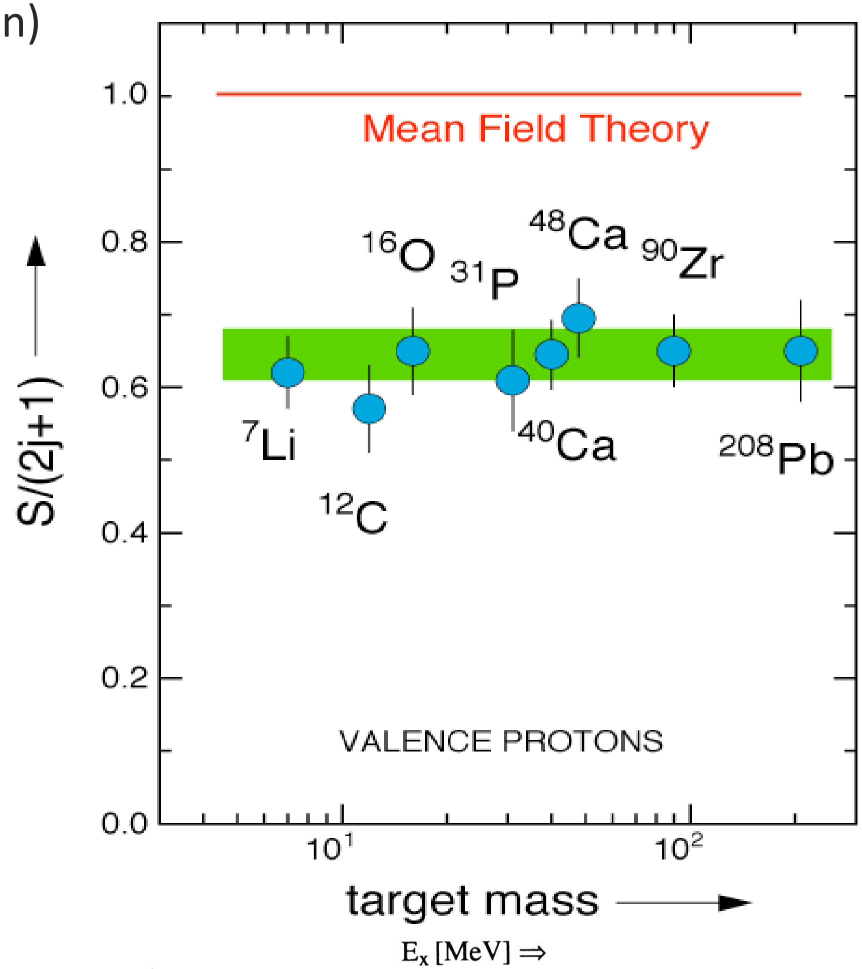




Quasielastic A(e,e'p) scattering

- **PWIA approximation for proton knockout**
  - Reconstruct initial proton binding energy (E_m), momentum (p_m)
  - Proton E_m,p_m distribution modeled as sum of independent shell contributions (arbitrary normalization)

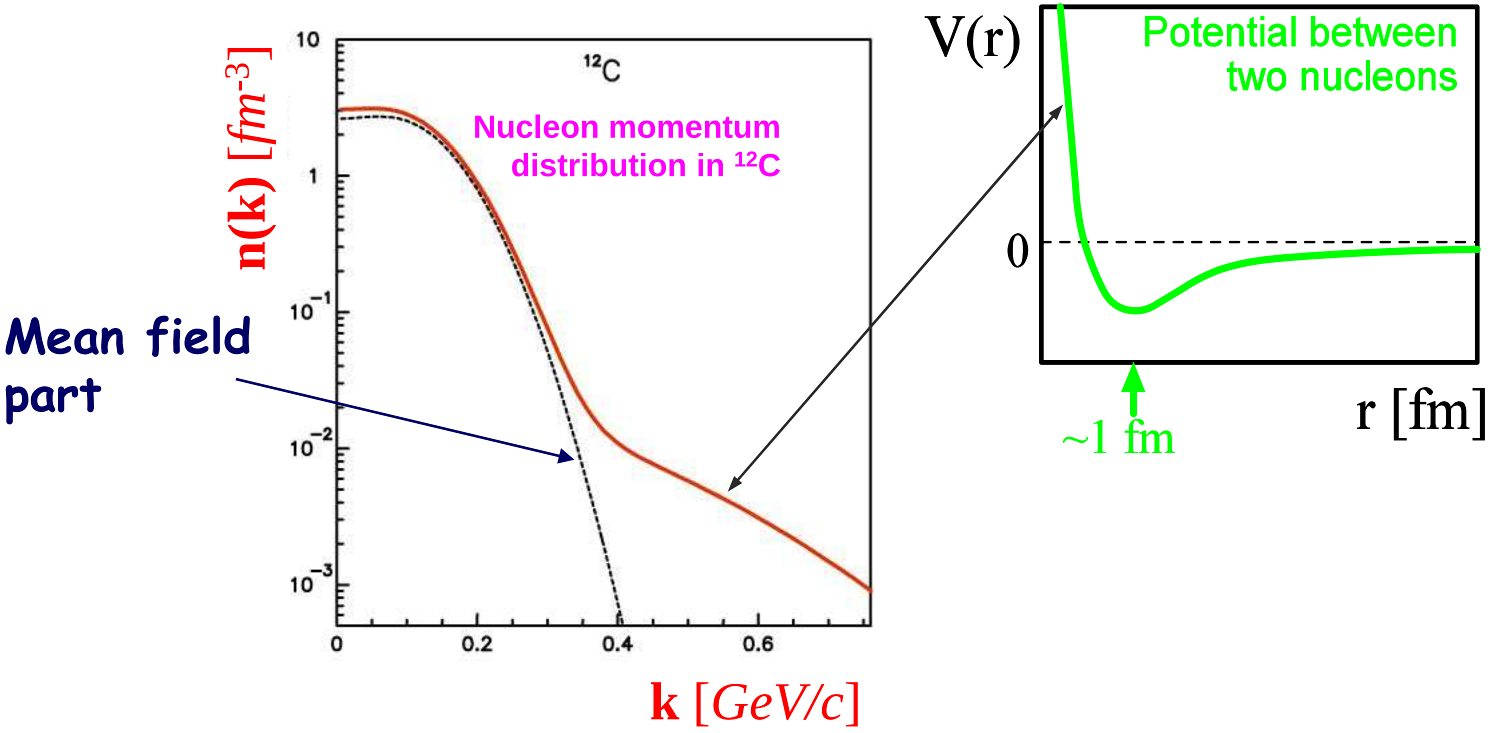




Missing Strength: Short Range Correlations

N-N interaction ⟹ Hard interaction at short range

Short range/distance ⟹ High relative momenta



High momentum tails in A(e,e'p)

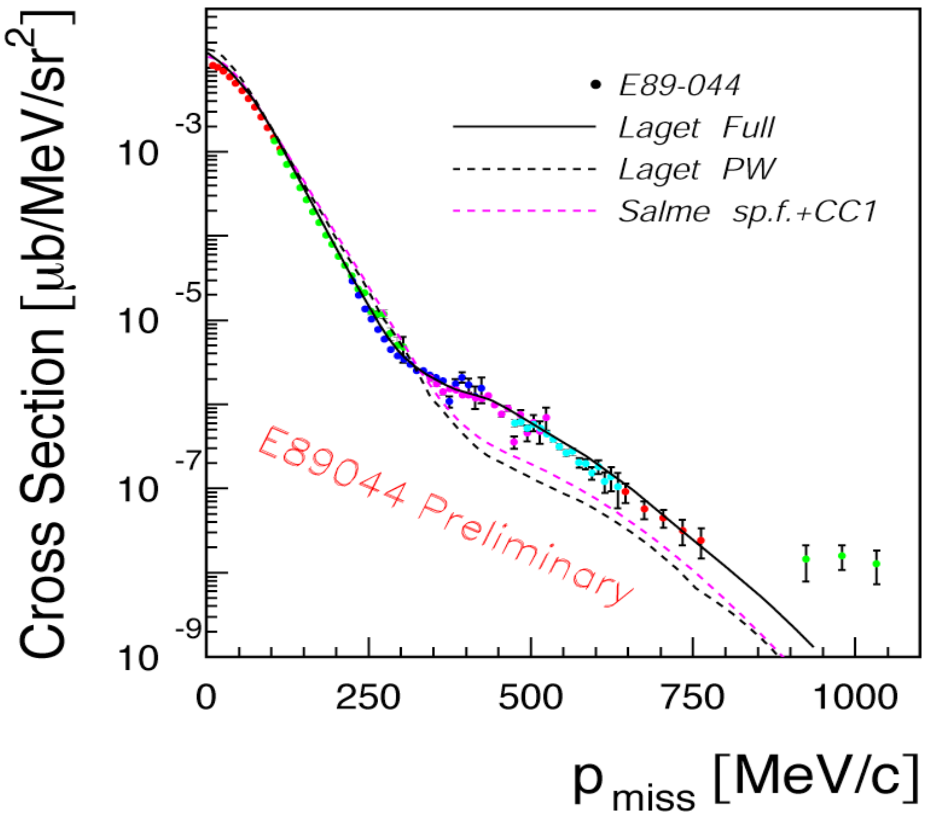
E89-004: Measure of ^{3}He(e,e'p)d

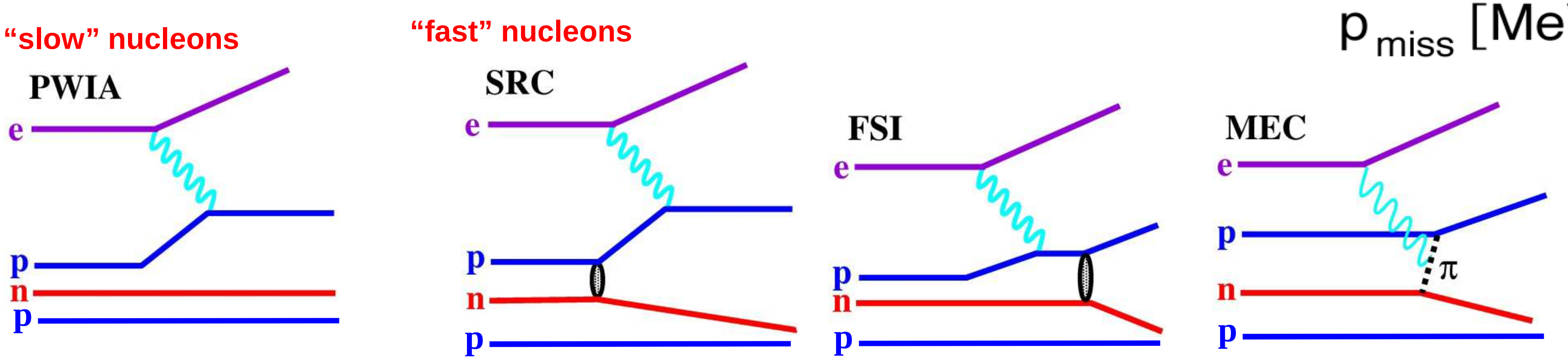
-Measured far into high momentum tail: Cross section is ~5-10x expectation

-High momentum pair can come from SRC (initial state)

OR

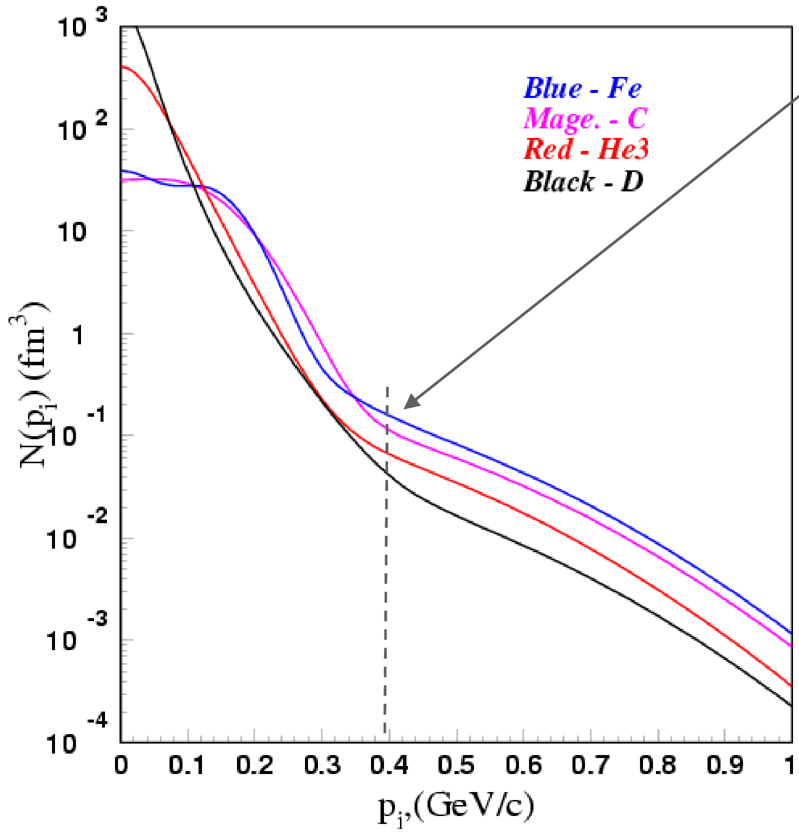
-Final State Interactions (FSI) and Meson Exchange Contributions (MEC)





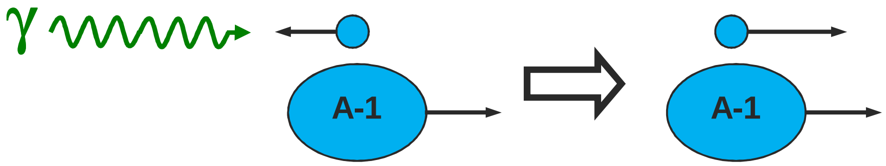
Inclusive measurements of SRCs

- **Inclusive scattering: A(e,e')**
  - Insensitive to proton interactions in the final state
  - Does not provide enough information to reconstruct E_m, p_m



Select kinematics where $p_{init}>k_{Fermi}$

- Two-body physics → ***Same structure for all A***
- ***Ratios** of A/D* → ***relative** high-momentum tails*



Large momentum transfer: q, Q^2

Small energy transfer: ν

→ $x = Q^2/2M\nu > 1$ [stationary proton: x=1]

→ *Large minimum nucleon momentum*

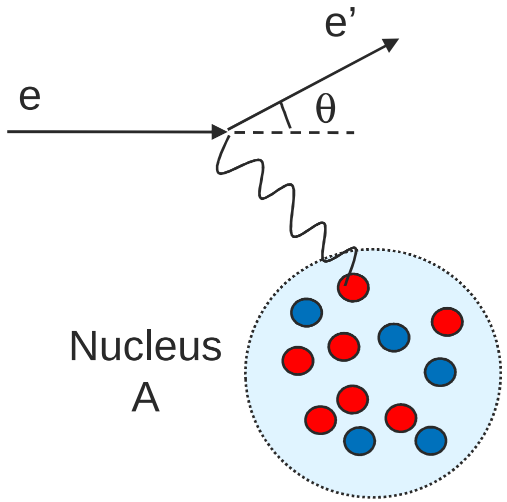
→ *Isolate quasielastic scattering (no energy to excite to higher state)*

Two key experiments

- **JLab E02-019** JA, D. Day, A. Lung, B. Filippone
  - **SCATTER FROM HIGH-MOMENTUM NUCLEONS IN NUCLEI**
    - *Probe high-momentum nucleons in nuclei*
    - *Study short-distance structures in nuclei*

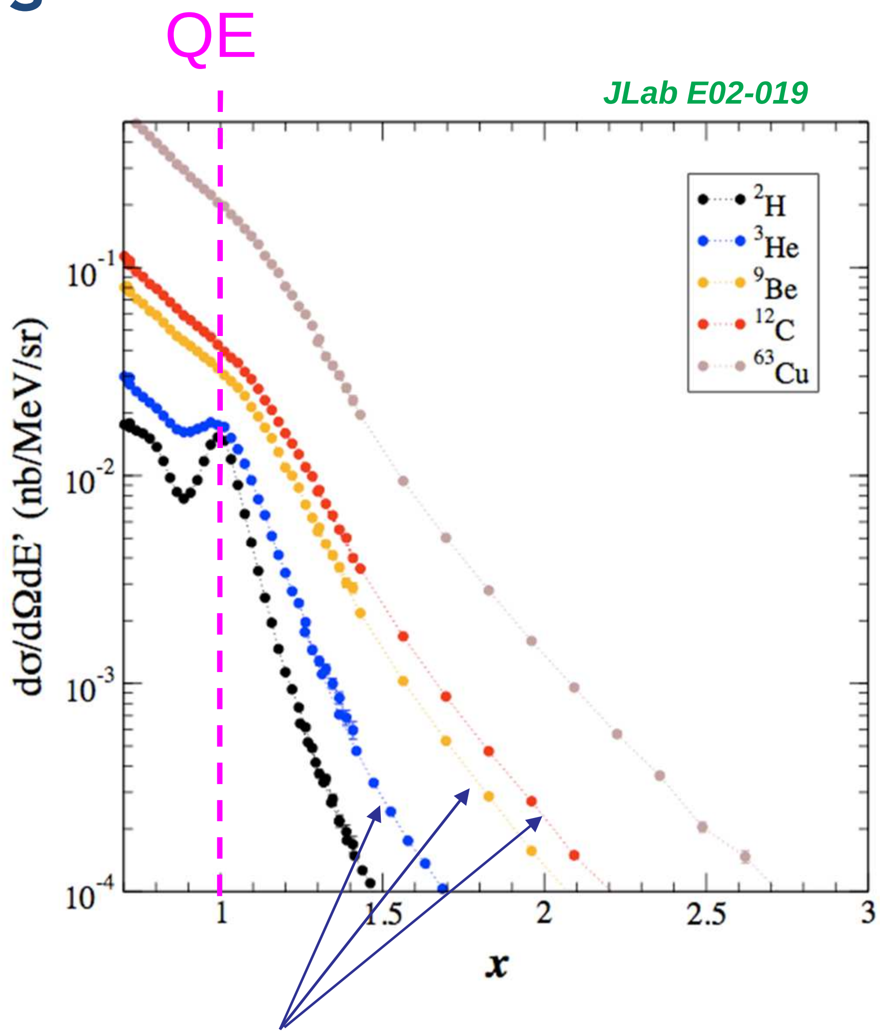
- **JLab E03-103** JA and D. Gaskell, spokespersons
  - **SCATTER FROM HIGH-MOMENTUM QUARKS IN NUCLEI**
    - *Look for nuclear-dependence to quark distributions*

Inclusive scattering at large x



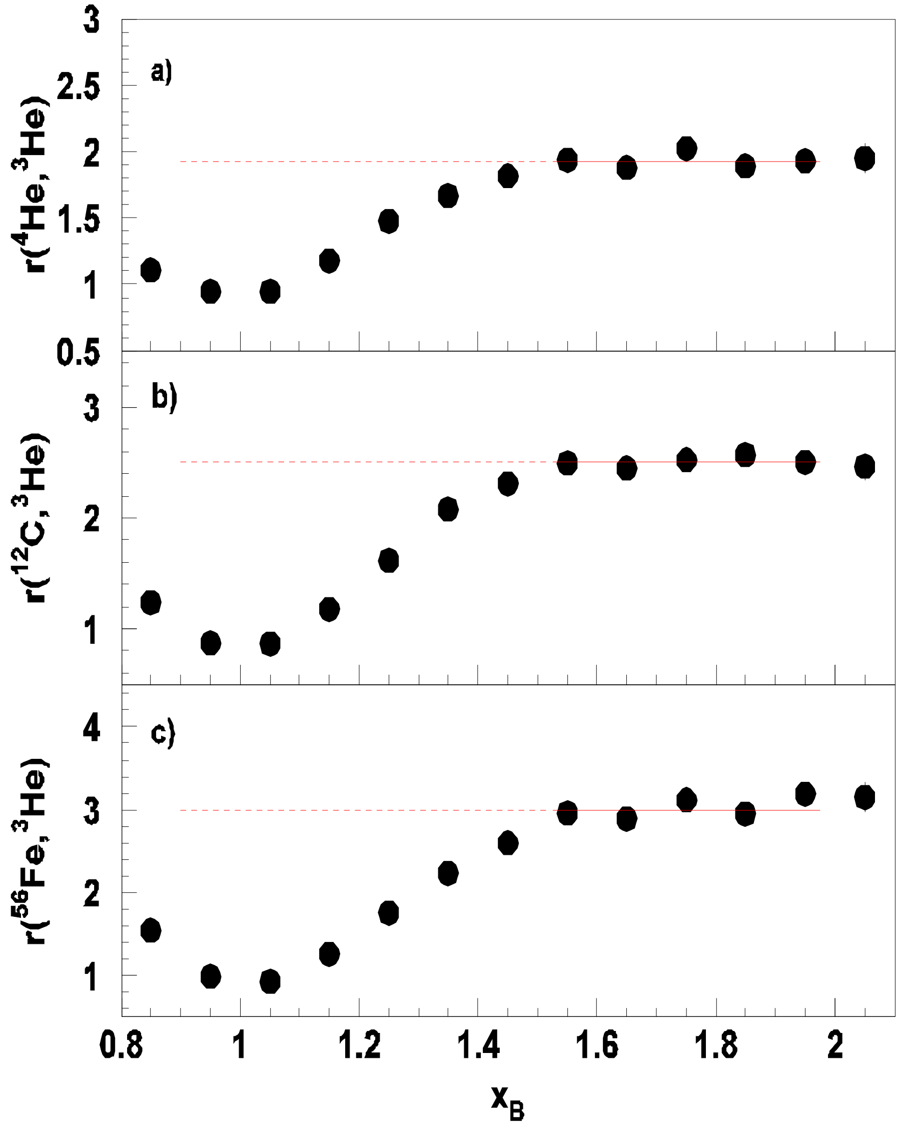
Quasi-Elastic Scattering
x ≈ 1

Motion of nucleon in the nucleus broadens the peak

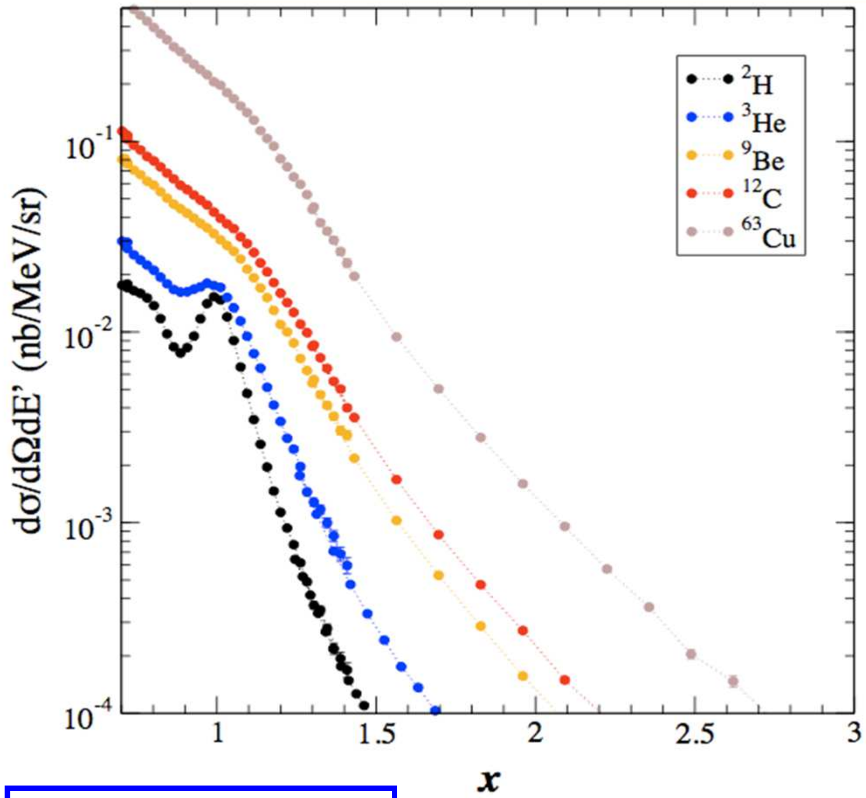


High momentum tails should yield constant ratio if seeing SRC

SRC evidence: A/D ratios



CLAS: K. Egiyan et al., PRC 68, 014313 (2003)



$a_2(^3He)=1.7(3)$

$a_2(^4He)=3.3(5)$

$a_2(^{12}C)=5.0(5)$

$a_2(^{27}Al)=5.3(6)$

$a_2(^{56}Fe)=5.2(9)$

$a_2(^{197}Au)=4.8(7)$

Ratio in plateau, proportional to # of 2N SRCs

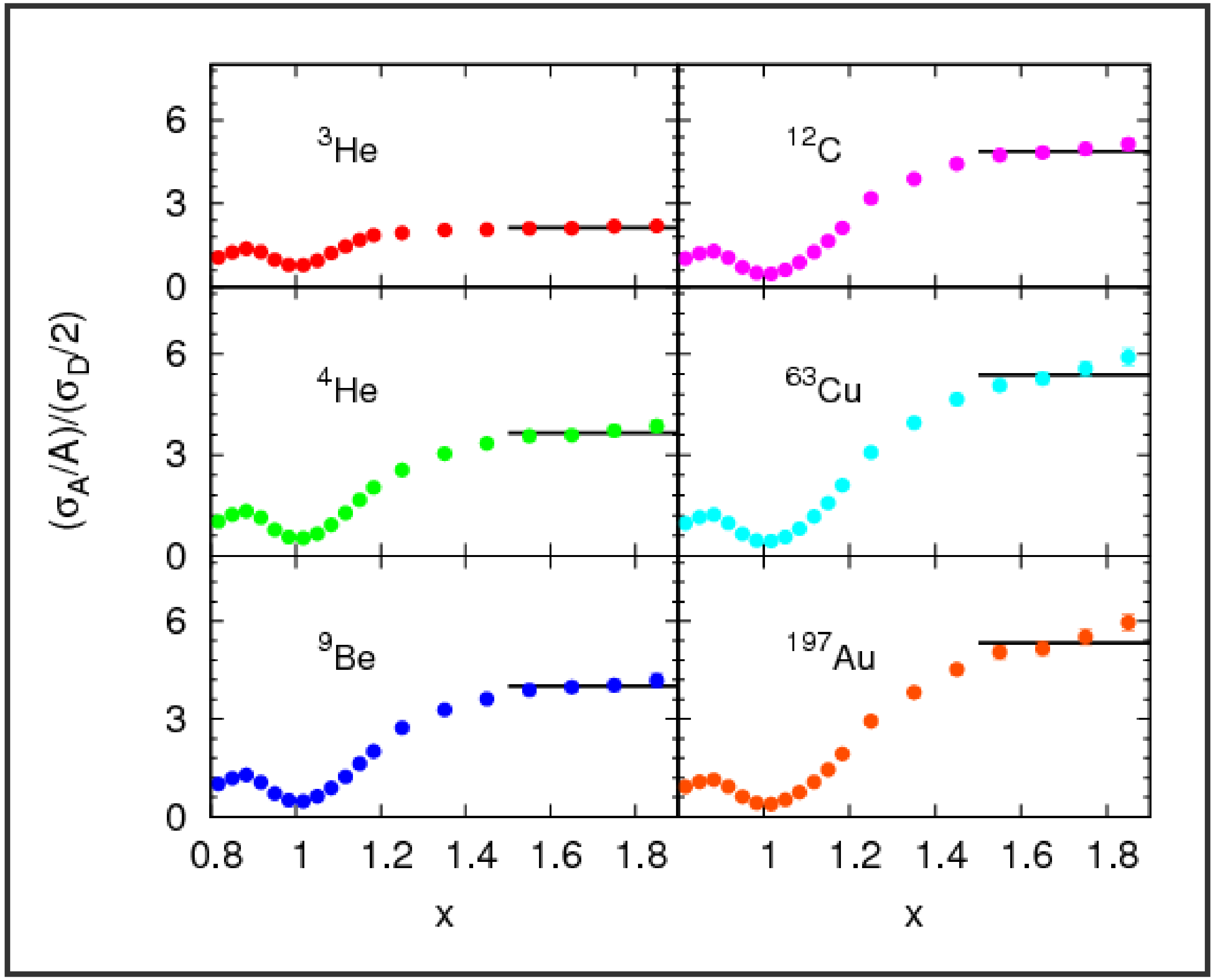
SLAC: D.B. Day et al., PRL 59, 427 (1987)

JLab E02-019: 2N correlations (SRCs) in A/D ratios

$\langle Q^2 \rangle = 2.72 GeV^2$

Focus on light nuclei

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



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

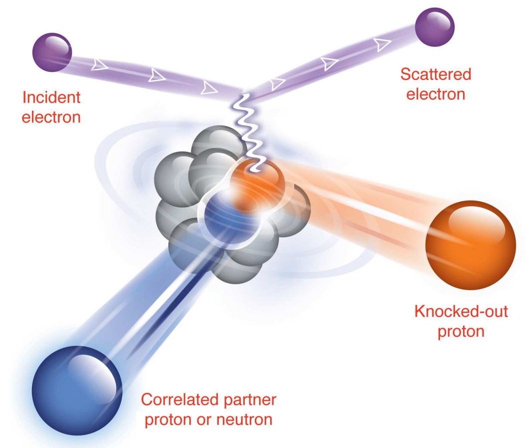
Detour: More detailed SRC studies

Inclusive ratios

– Shows SRC-dominance for high momentum

– Determines relative SRC contributions

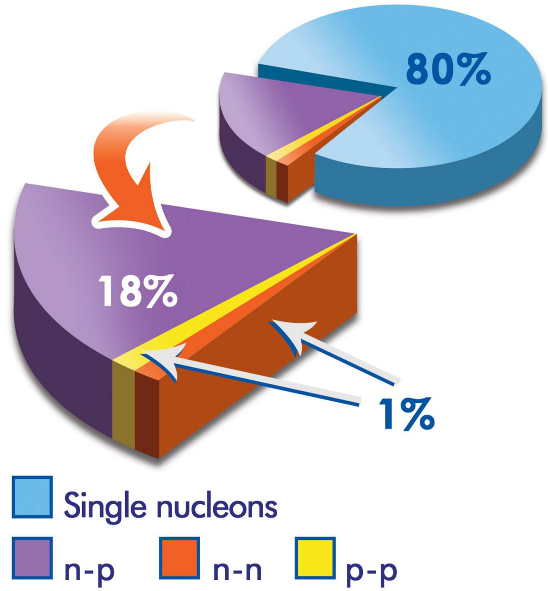
– Can't separate scattering from proton and neutron



JLab E01-015, E07-006: $^{12}C(e,e'pN)$, $^{4}He(e,e'pN)$

– Reconstruct initial *high momentum proton*

– Look for fast proton or neutron in opposite direction



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

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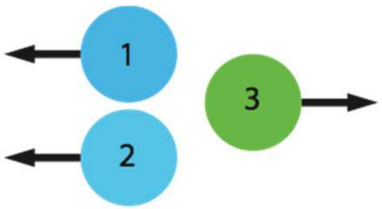

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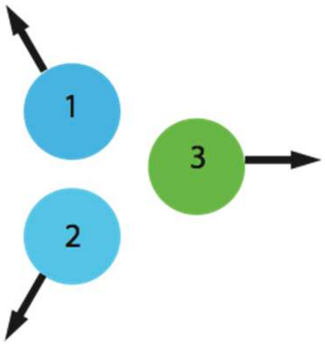


E08-014: Inclusive ratios: x>2

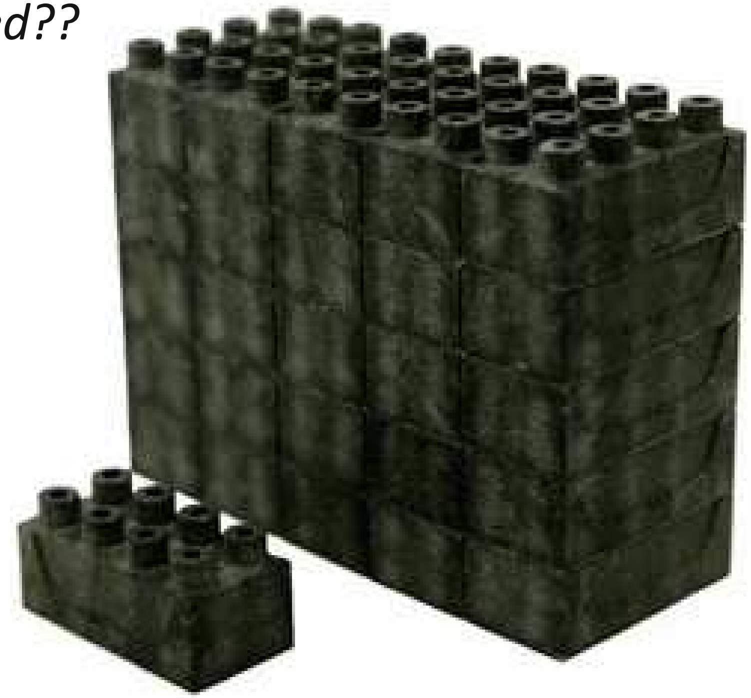
– x>2 requires 3+ nucleons involved in scattering

– Study three-nucleon clusters with significant momentum sharing

[JA, D. Day, D. Higinbotham, P. Solvignon
PhD: Zhihong Ye]

Nuclear densities and quark structure?

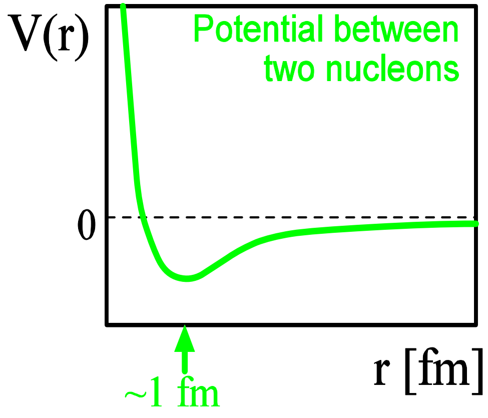
- **NOTES ON DENSITY** (_average_ nuclear density)
  - Proton RMS charge radius: R_p = 0.85 fm
  - Corresponds to uniform sphere, R = 1.15 fm, density = 0.16 fm^{-3}
  - Ideal packing of hard sphere: ρ_{max}=0.12 fm^3
    - *Well below peak densities in nuclei*
    - *Need 100% packing fraction for nuclear matter*
    - *Can internal structure be unchanged??*

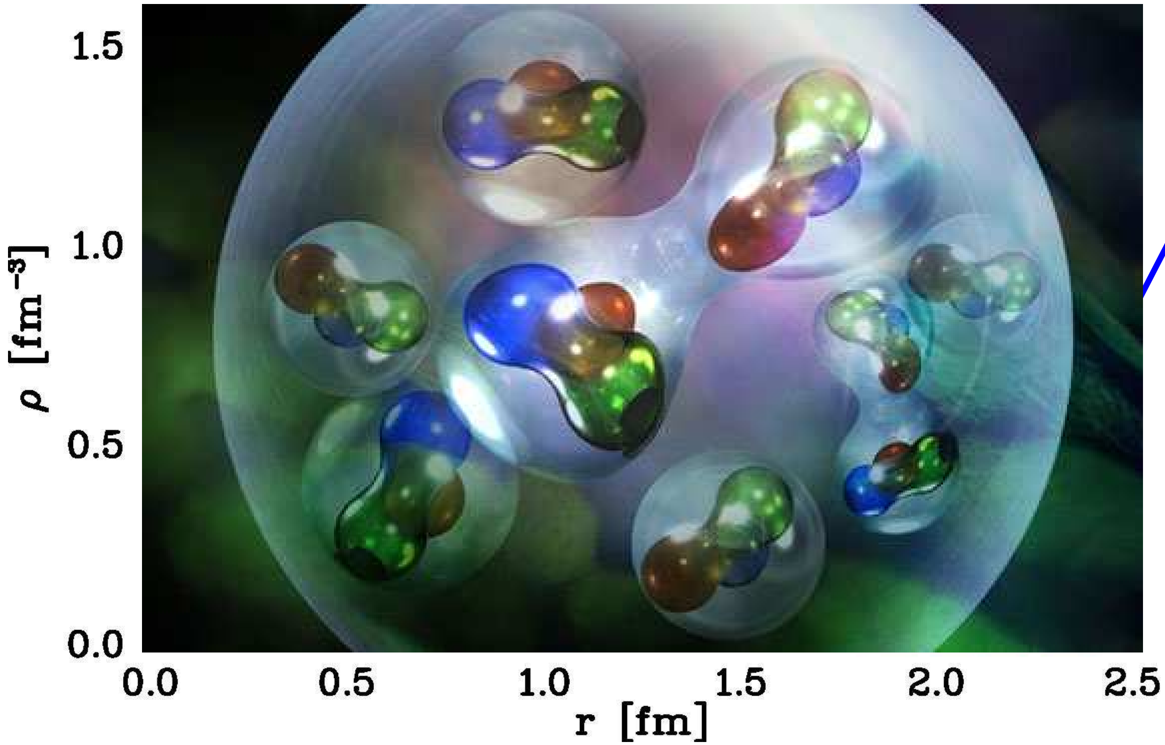


Nuclear densities and quark structure?

Nucleons are composite objects

charge radius ~0.86 fm
separation in heavy nuclei ~1.7 fm





Average Nuclear density

Are nucleons unaffected by this overlap?

Do they deform as they are squeezed together?

Do the quarks exchange or interact?

From SRCs as important part of nucleus to SRCs as unusual state of matter

- High-density clusters, potentially interesting
- 1st slide, with overlapping nucleons [just how dense is nucleus? Just how much denser are SRCs?]
- Would like to isolate, look at quark structure

- 2nd slide: exact same experiment, different SCALE
- QE → DIS
- QE: assume billiard-ball scattering from single nucleon
  - High energy probe → transverse motion negligible; probe longitudinal momentum of the nucleon
  - Problem: one direction → less energy transfer (QE), other direction → greater energy transfer for fixed q → inelastic; no longer billiard ball

  - Extremely high energy; scattering entirely dominated by scatting from single quark bound in nucleon (nucleus)
  - High energy → transverse motion negligible; probe longitudinal momenutm

Higher energy scattering: quark distributions

- **At very high energies, hadrons break up and scattering probes elastic electron-quark scattering**
  - Deep-Inelastic Scattering (DIS) limit

- **DIS scattering measures structure function $F_2(x)$**
  - x = quark momentum fraction
  - $F_2(x)$ related to parton momentum distributions (pdfs)

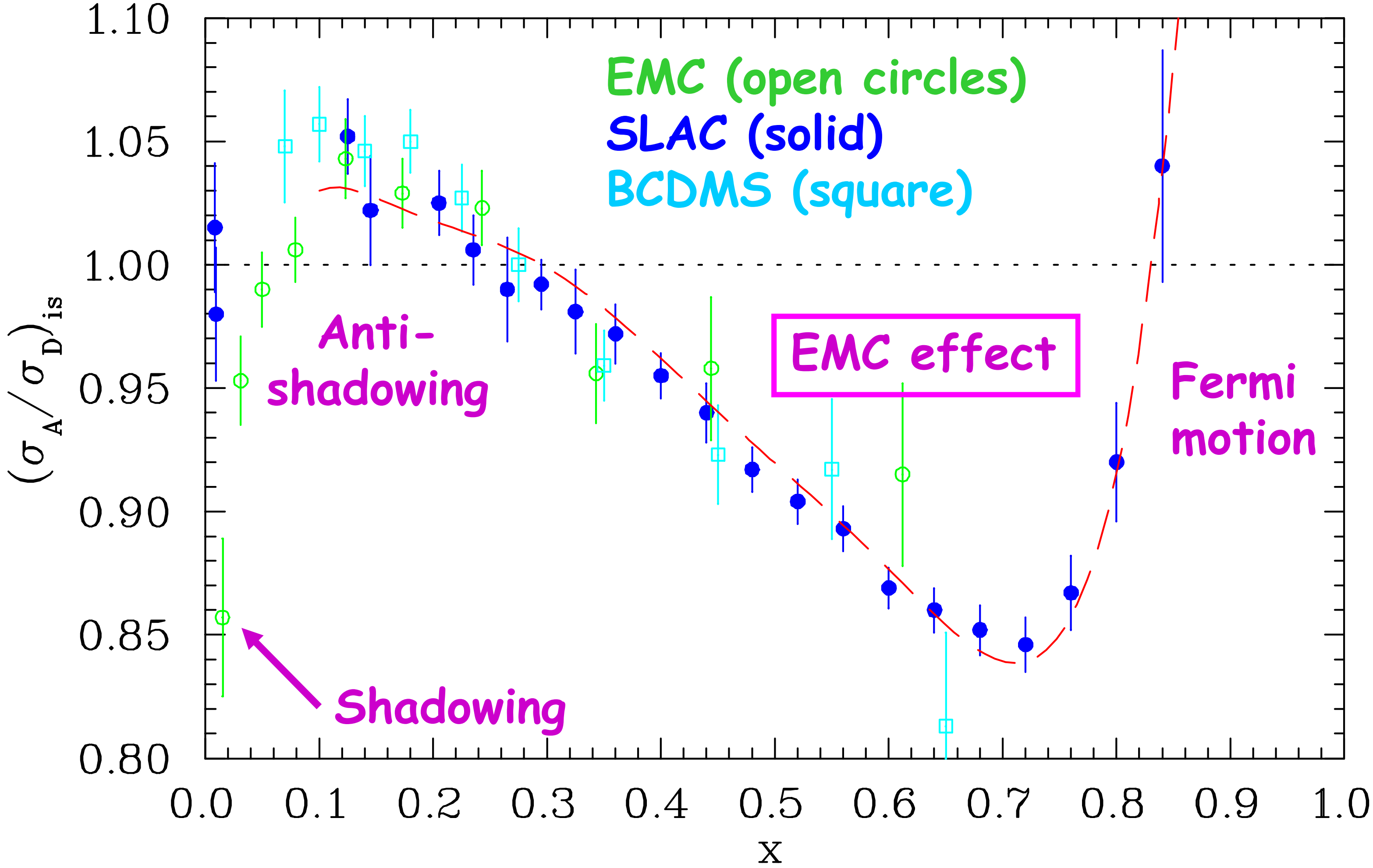
$$F_2(x) \sim \sum e_i^2 \, q_i(x) \qquad i = up,\ down,\ strange$$

- **Nuclear binding energies << energy scales of probe**

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

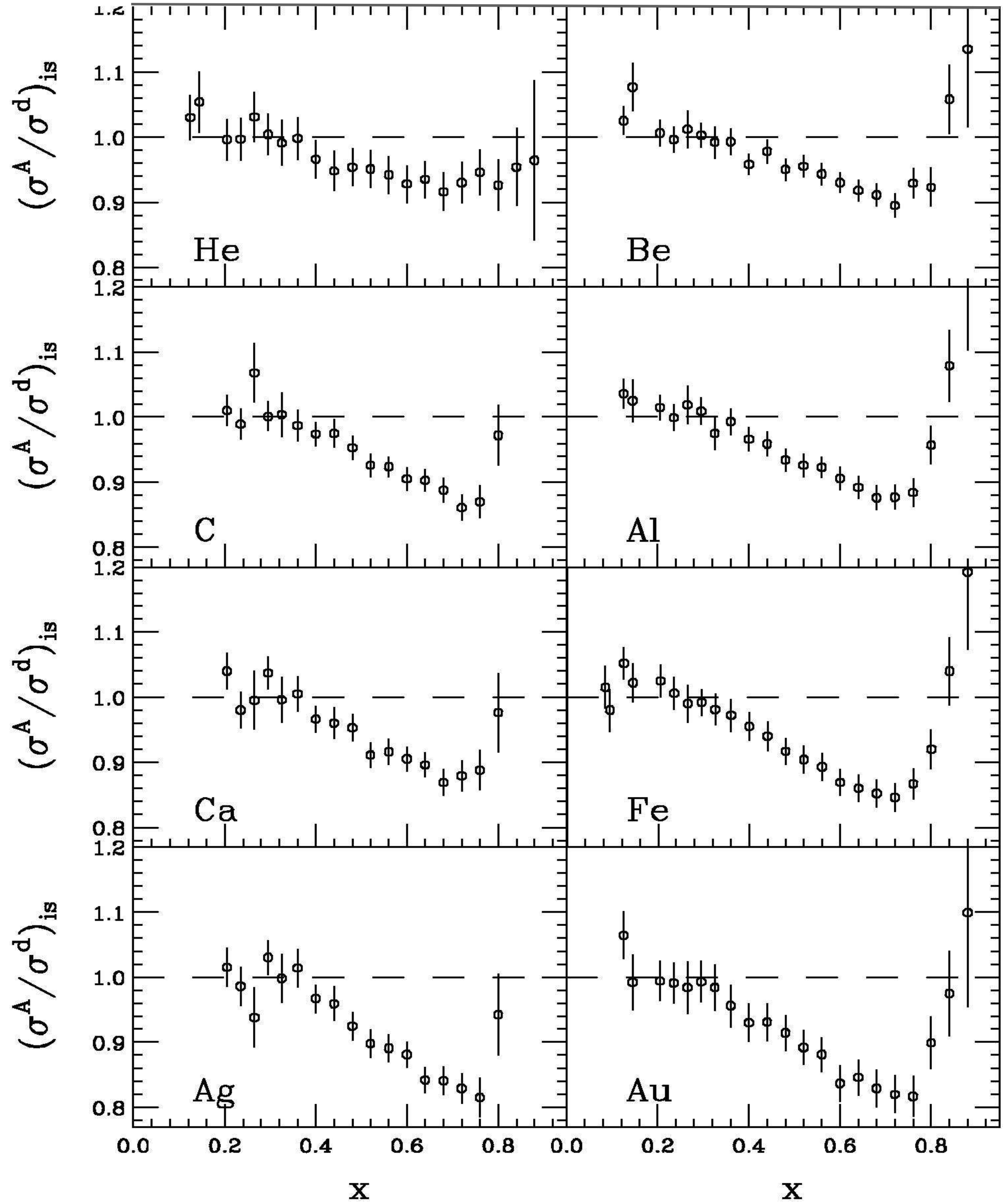
Nuclear quark distributions: The EMC effect



First measurement (EMC collaboration - 1983) found a small excess of low-x quarks, large deficit of high-x quarks in heavy nuclei

EMC effect:
A-dependence

- **SLAC E139**
  - Most precise large-x data
  - Nuclei from A=4 to 197
- **Conclusions**
  - **Universal x-dependence**
  - **Magnitude varies with A**
    - Scales with A (~$A^{-1/3}$)
    - Scales with average density



E03-103: Light nuclei

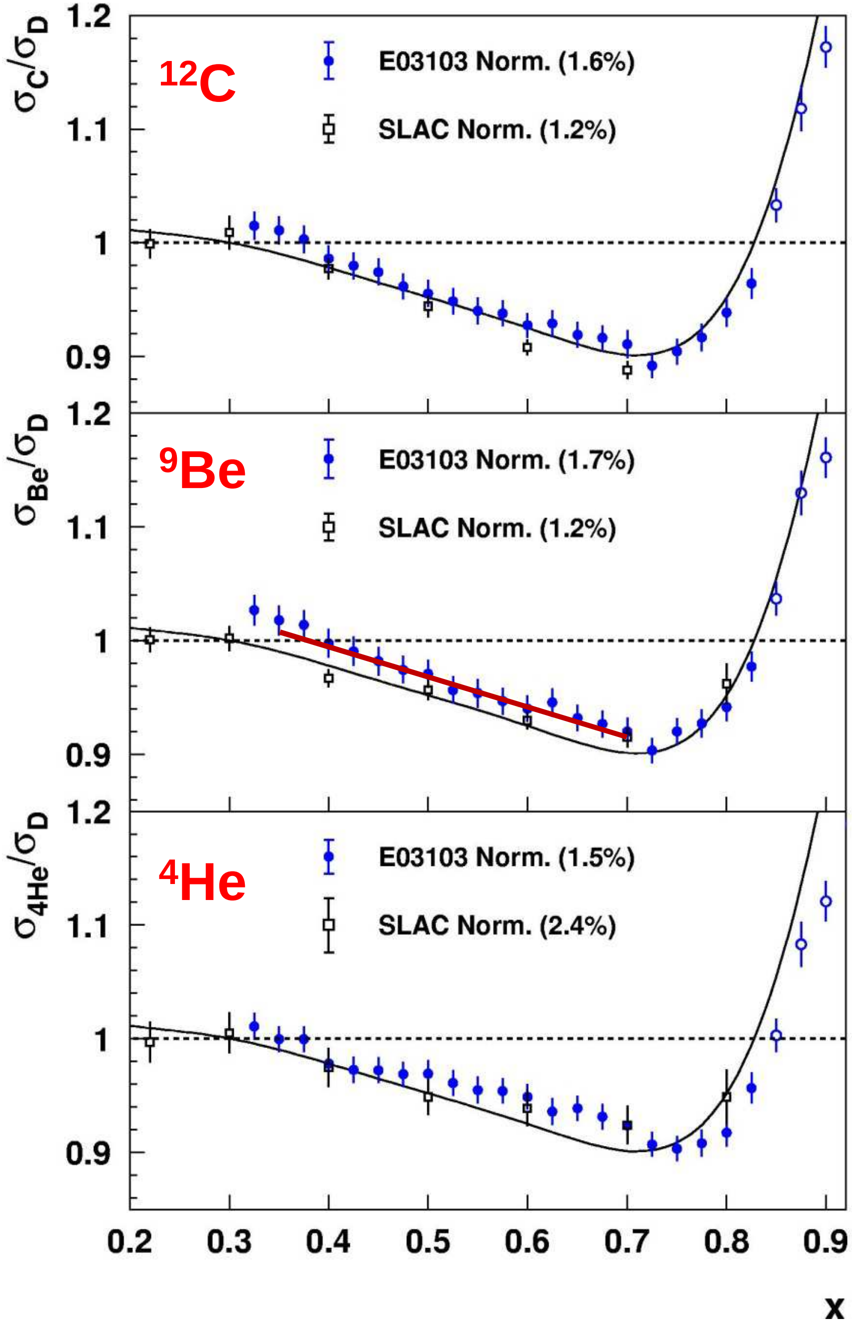
EMC Effect similar in C, Be and ^{4}He (curve is SLAC fit to C)

No clear difference in shape

^{4}He (low mass) and ^{9}Be (low density) both similar to ^{12}C

Normalization uncertainty limits extraction of A-dependence

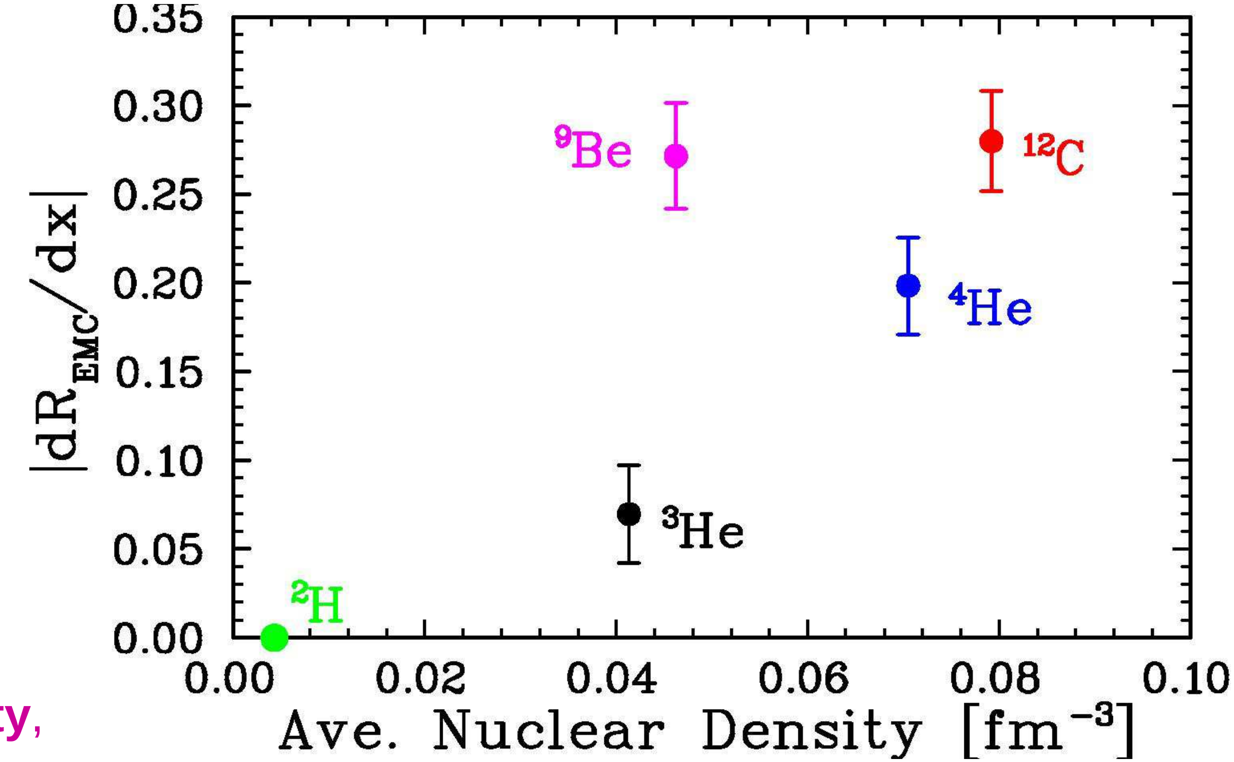
If shape (x-dependence) is same for all nuclei, the slope (0.35<x<0.7) can be used to study dependence on A



A-dependence of EMC effect

Density determined from *ab initio* few-body calculation

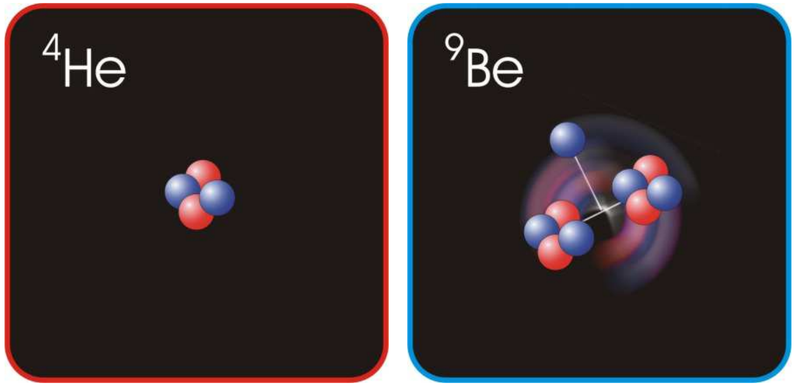
S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)



Data show smooth behavior as density increases…
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)



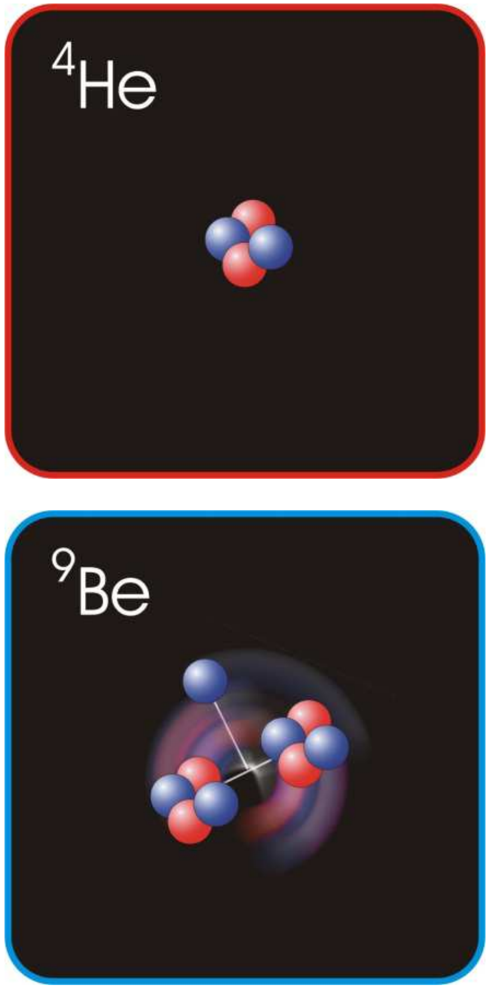
Nuclear structure ←→ Quark effects

- **New EMC effect data suggest importance of 'local density'**
  - Impact of clustering, correlations can be seen from eV scales (electron energy levels) and GeV scales (quark distributions)

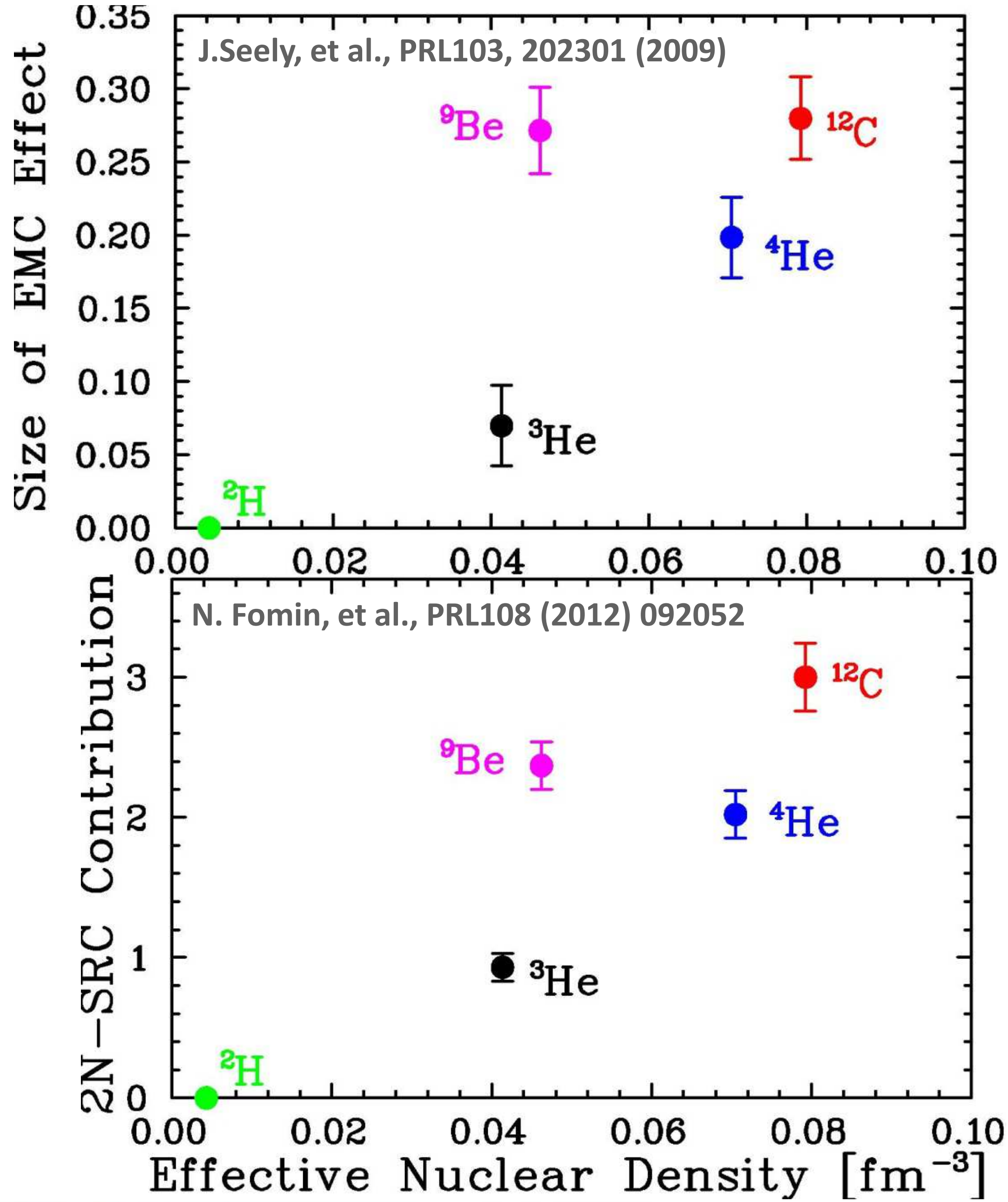
- **Short-range correlations are meant to probe 'local density'**
  - The experiments **measure** high momenta
  - Aim is **study** short distance, high density

- **Possible connection between EMC effect, SRCs**

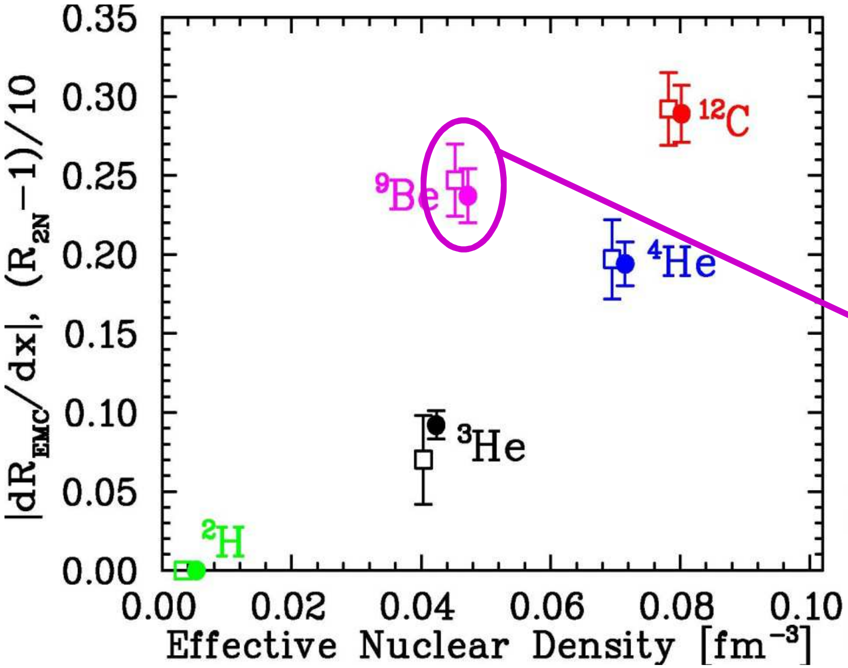
Density dependence?



Credit: P. Mueller



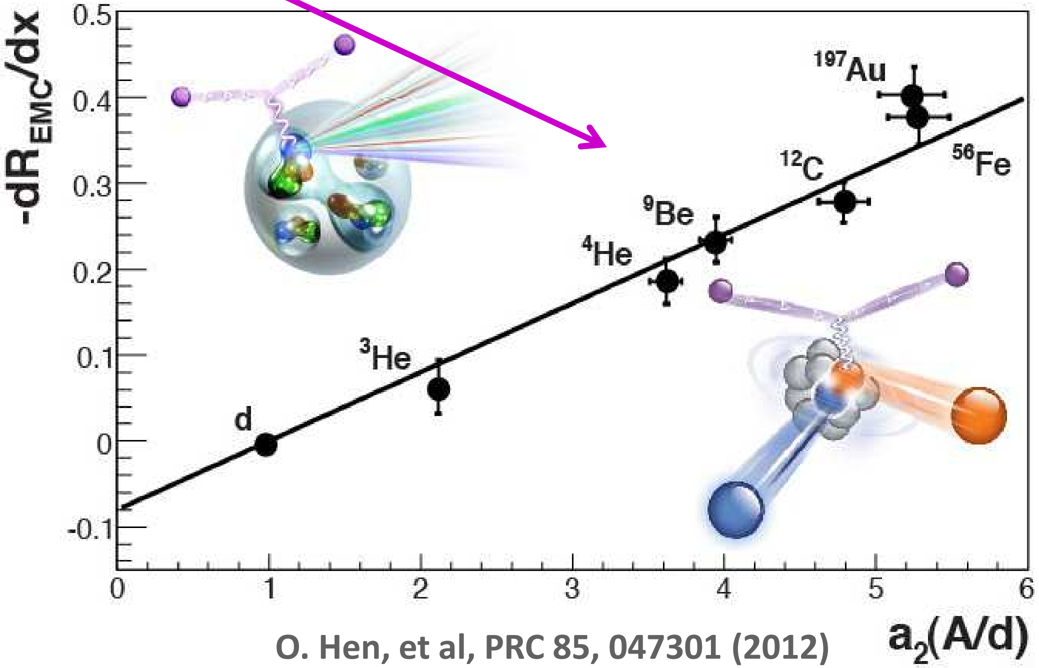
Correlation between SRCs and EMC effect



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 (in press, Phys. Rev. C)



O. Hen, et al, PRC 85, 047301 (2012)

L. Weinstein, et al., PRL 106, 052301 (2011)

Short-distance behavior and the EMC effect

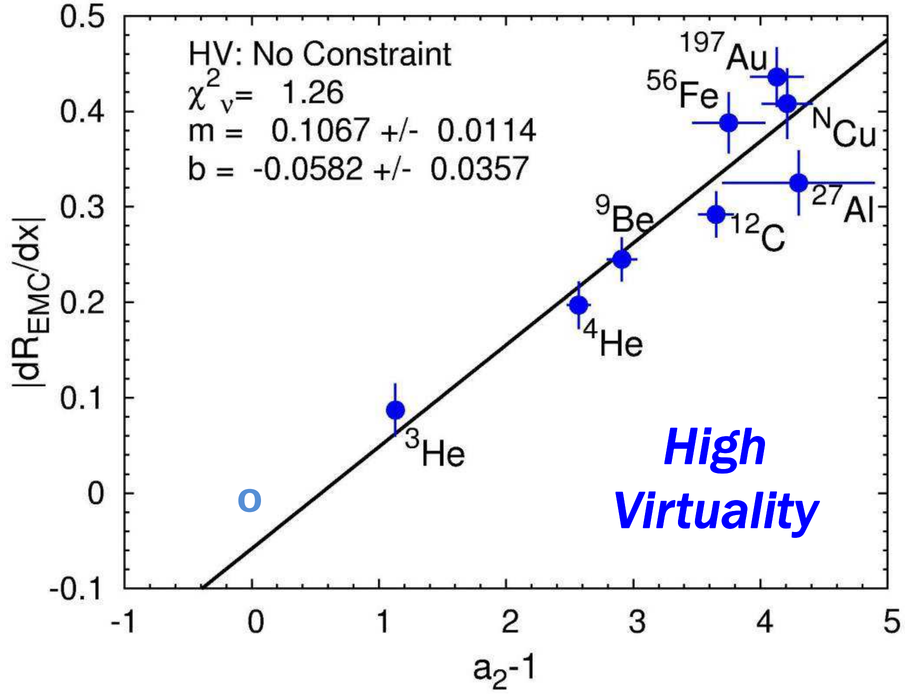
1. ~~EMC effect driven by **average density** of the nucleons~~
~~[J. Gomez, et al., PRD 94, 4348 (1994), Frankfurt and Strikman, Phys. Rept. 160 (1988) 235]~~

2. EMC effect driven by **High Virtuality (HV)** of the nucleons
[L. Weinstein et al, PRL 106, 052301,2011]
Test by comparing EMC effect to relative number of high-momentum nucleons in the nucleus, as measured in the SRC measurement

3. EMC effect is driven by **Local Density (LD)**
[J. Seely et al., PRL 103, 202301, 2009]
Compare EMC effect to number of high-density nucleon pairs
(small correction going from # of high-momentum nucleons to # of pairs)
ALL pairs (nn, np, pp) can contribute, while only np pairs have high-momenta

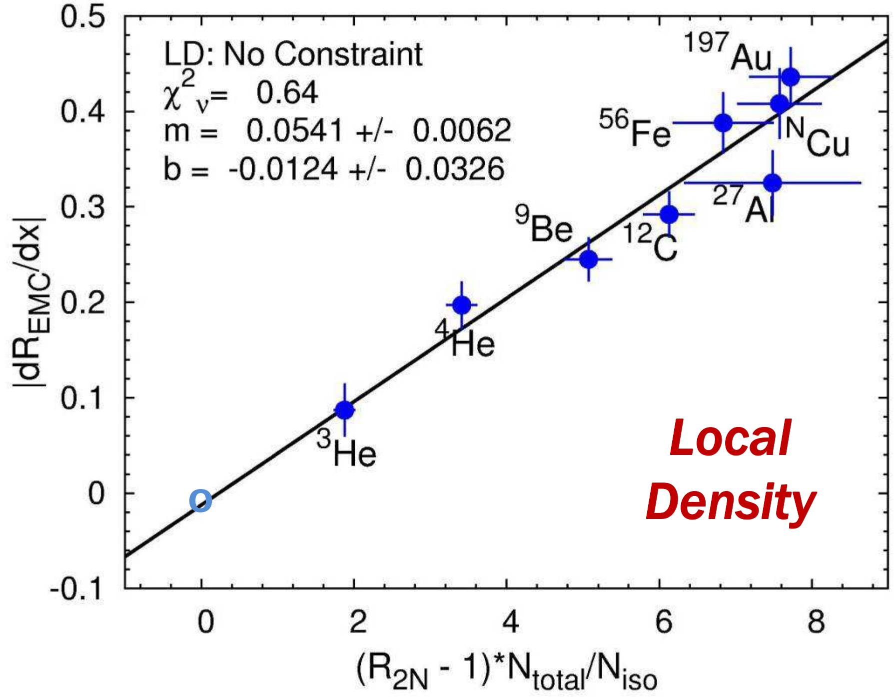
Imply slightly different correlation between EMC effect and contribution from SRCs

Two Hypotheses for EMC-SRC correlation



HV: OK linear correlation (χ_v^2=1.26)
Fair extrapolation to deuteron:
EMC(^{2}H) = -0.058 ± 0.036

# of nucleons at high momentum (relative to ^{2}H)



***LD:** Good linear correlation (χ_v^2=0.64)*
Good extrapolation to deuteron:
EMC(^{2}H) = -0.012 ± 0.033

# of nucleons in small-sized configurations

Two Hypotheses for EMC-SRC correlation

Hypothesis	Fit type	χ^2_ν	EMC(D)
High Virtuality	2-param No constraints	1.26	-0.058±0.036
High Virtuality	1-param	1.47	–
Local Density	2-param No constraints	(0.64) 0.84	-0.012±0.033
Local Density	1-param	(0.57) 0.74	–

Each hypothesis is tested with 2 types of fits:

1) 2-parameter fit, no deuteron constraint
2) 1-parameter fit, deuteron constraint

2nd value for χ^2_ν excludes uncertainty from calculated correction which artificially suppresses the extracted χ^2 value

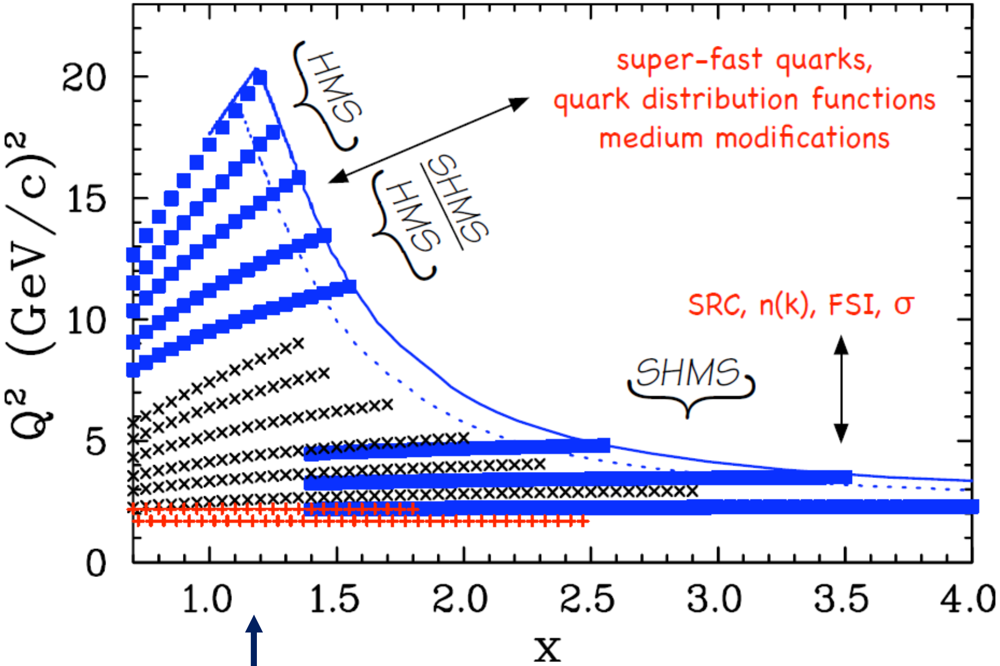
Comparison of correlations and EMC effect **favors** Local Density hypothesis, but the difference is too small to exclude either possibility

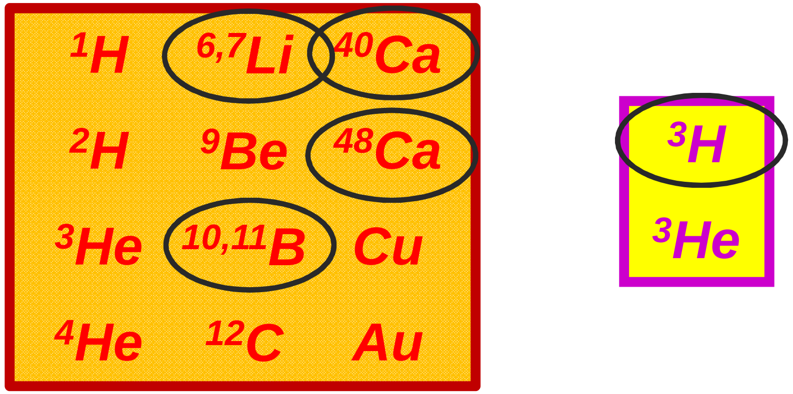
Where do we go from here?

- **New data on light nuclei**
  - *Show that neither effect simply scales with nuclear density*
  - *Suggest that short-range configurations may cause quark modification, or that both correlations and EMC effect driven by same physics*

- **Next step is to better understand connection**
  - *Better tests of relationship between correlations and quark distributions*
  - *Isolate SRCs and probe their quark distributions*
  - *"Tag" scattering from in high-virtuality nucleons*
    - *Measure quark distributions (DIS scattering)*
    - *Measure form factors (elastic scattering)*

EMC and SRCs at 12 GeV JLab

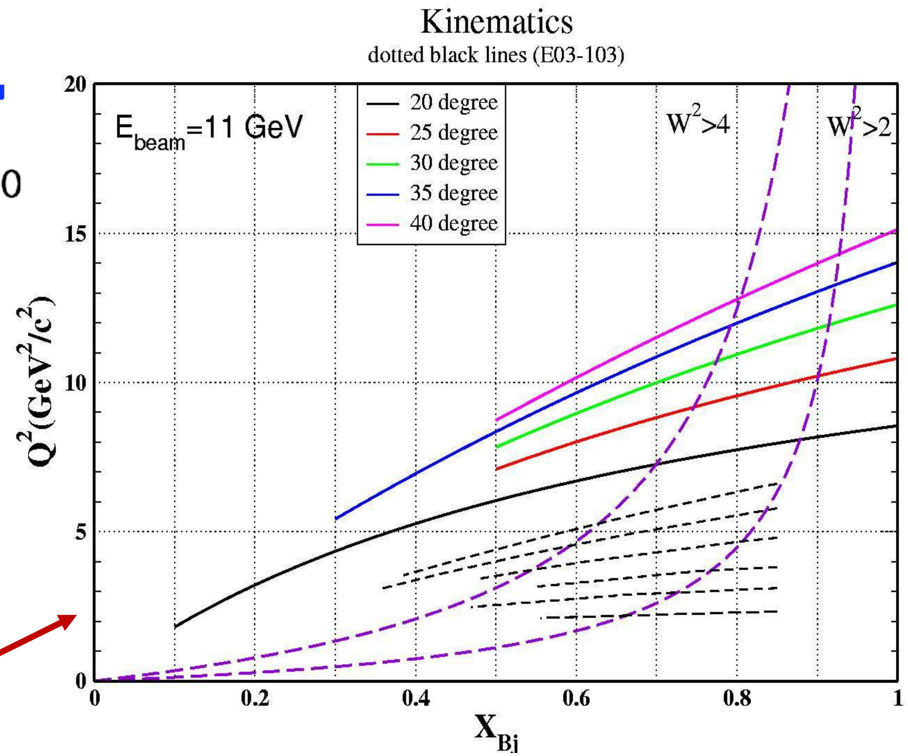




x>1 at 12 GeV

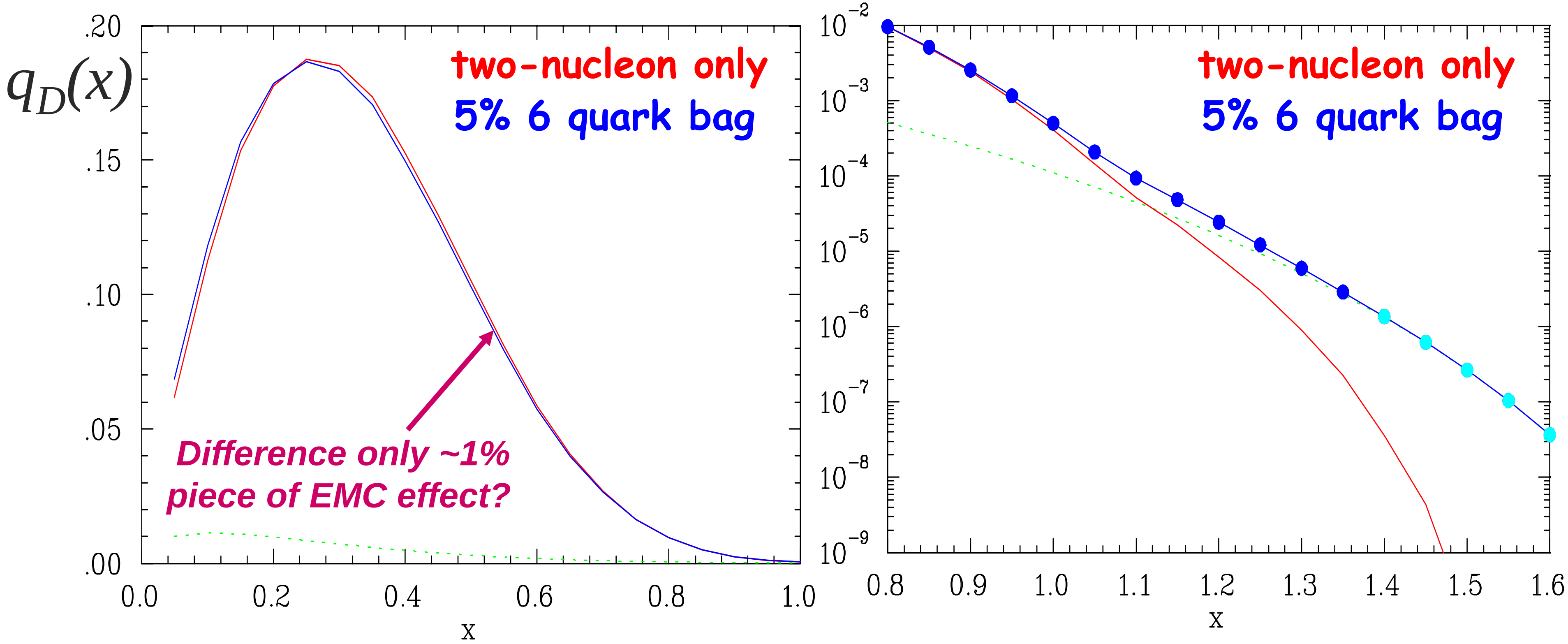
Follow-up experiments for EMC effect and x>1

EMC effect at 12 GeV



Quark distributions of SRC: "Super-fast" quarks

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

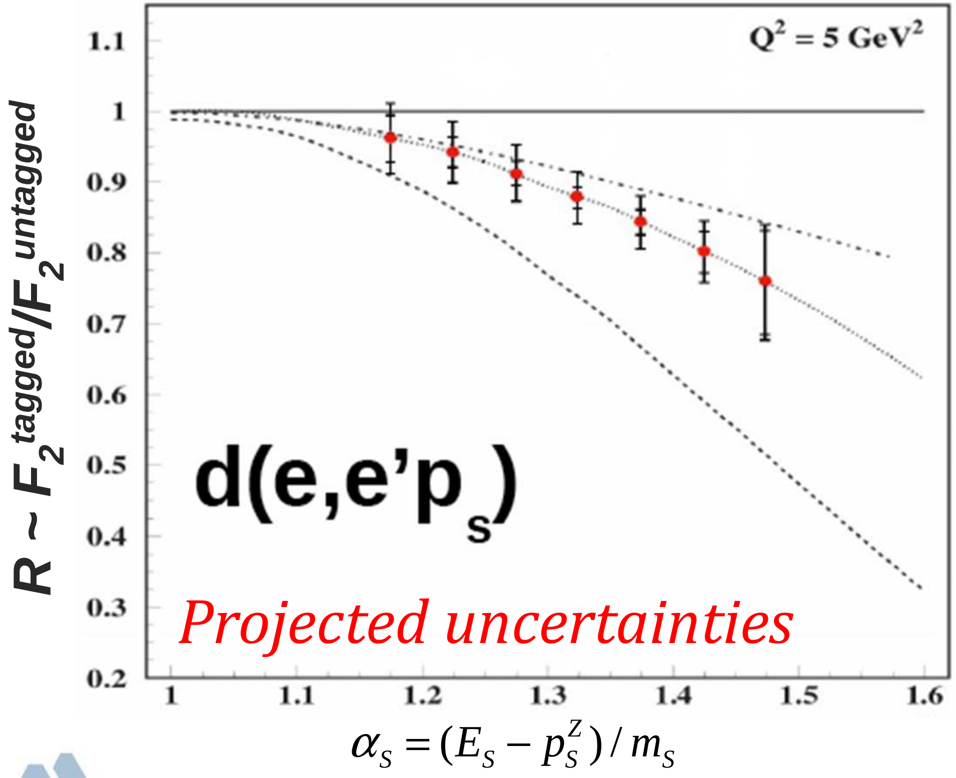


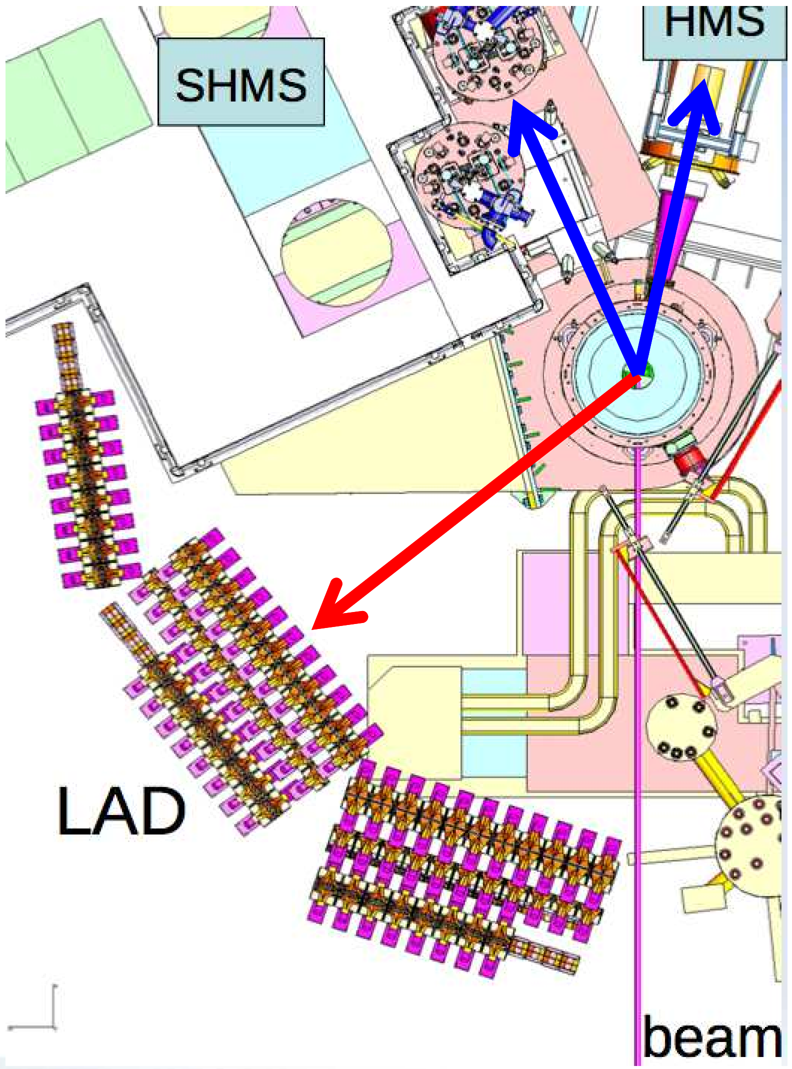
6q bag is 'shorthand' for any model where overlapping nucleons allows free sharing of quark momentum ("High Density" effect)
High Virtuality would tend to suppress strength at largest x

In-Medium Nucleon Structure Functions

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

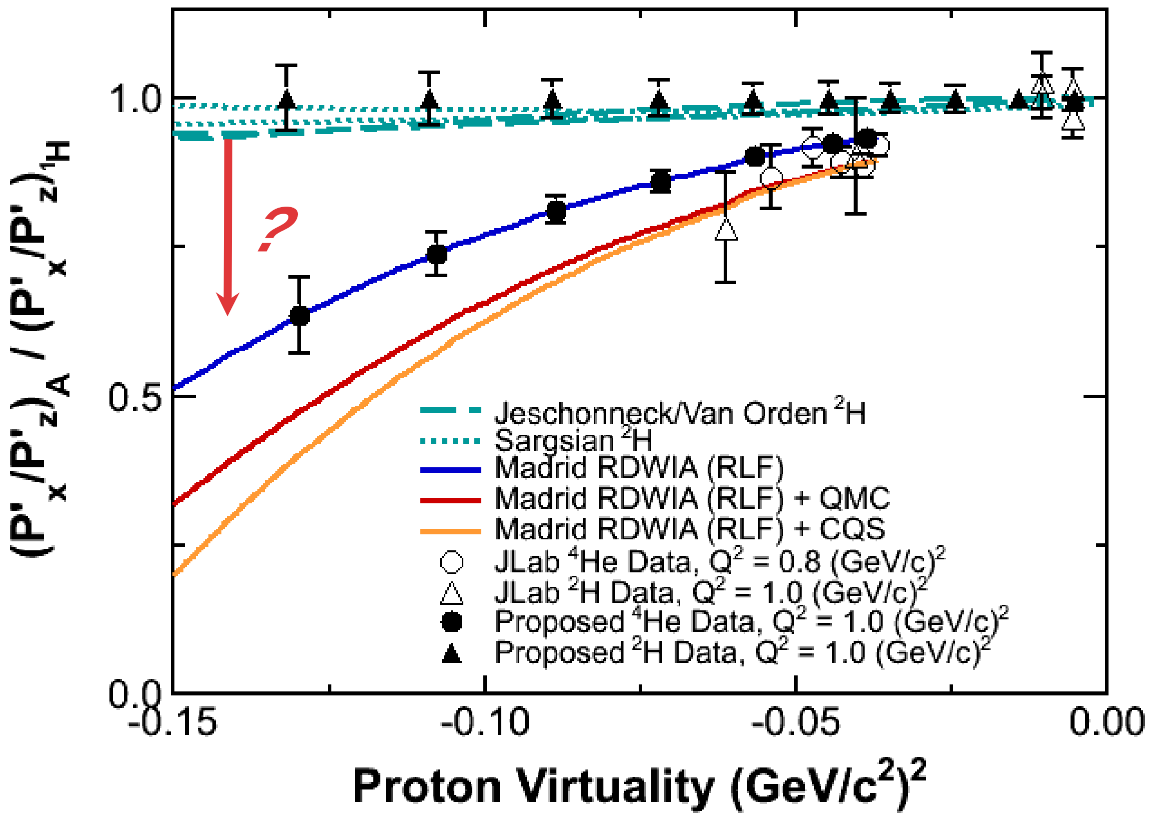
- *DIS scattering from nucleon in deuterium*
- *Tag high-momentum struck nucleons by detecting backward "spectator" nucleon in Large-Angle Detector*
- *α_s related to initial nucleon momentum*





In-Medium Nucleon Form Factors

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



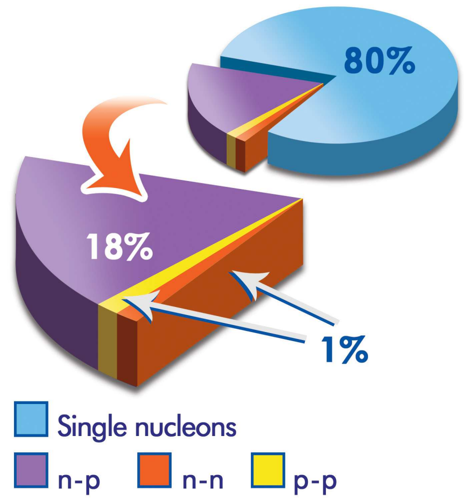
- **Compare proton knock-out from dense and thin nuclei: $^4He(e,e'p)^3H$ and $^2H(e,e'p)n$**
- **Modern, rigorous $^2H(e,e'p)n$ calculations show reaction-dynamics effects and FSI will change the ratio at most 8%**
- **QMC model predicts 30% deviation from free nucleon at large virtuality**

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)

Summary

- **SRCs are an important component to nuclear structure**
  - ~20% of nucleons in SRC, mainly pn pairs
  - Limited room for other things
    - Multi-nucleon correlations
    - More exotic configurations (6q bag)
  - Impact on ν-A scattering, neutron stars

    Frankfurt and Strikman arXiv:0806.0997

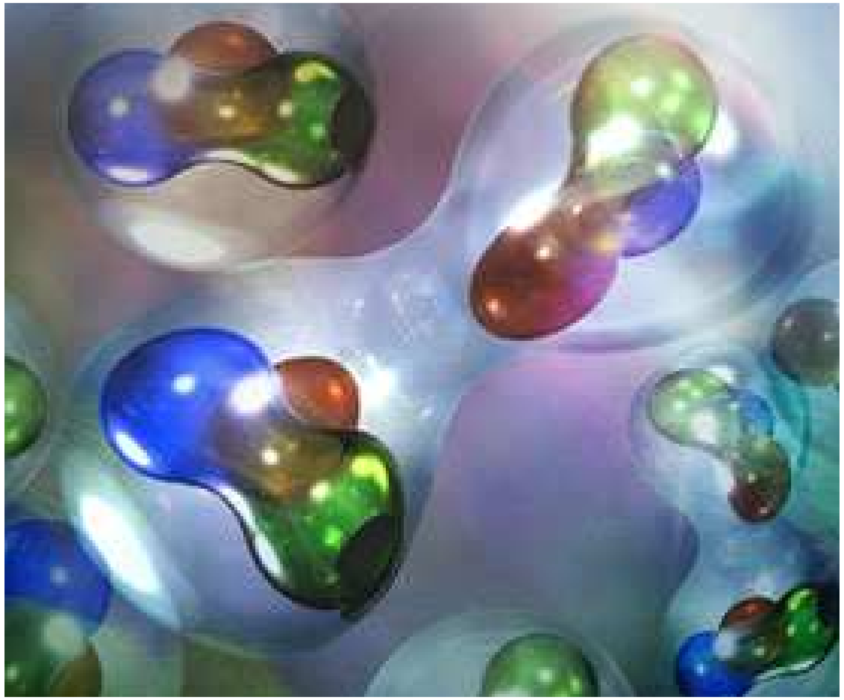


R. Subedi et al., Science 320, 1476 (2008)

- **New data strongly suggest connection between SRCs, quark structure of nucleons**

- **Plans to probe structure of nucleons inside these high-density configurations living in surprisingly dense ordinary nuclei**
  - Probe internal structure of SRCs
  - Isolate, study highly-virtual nucleons

Fin....

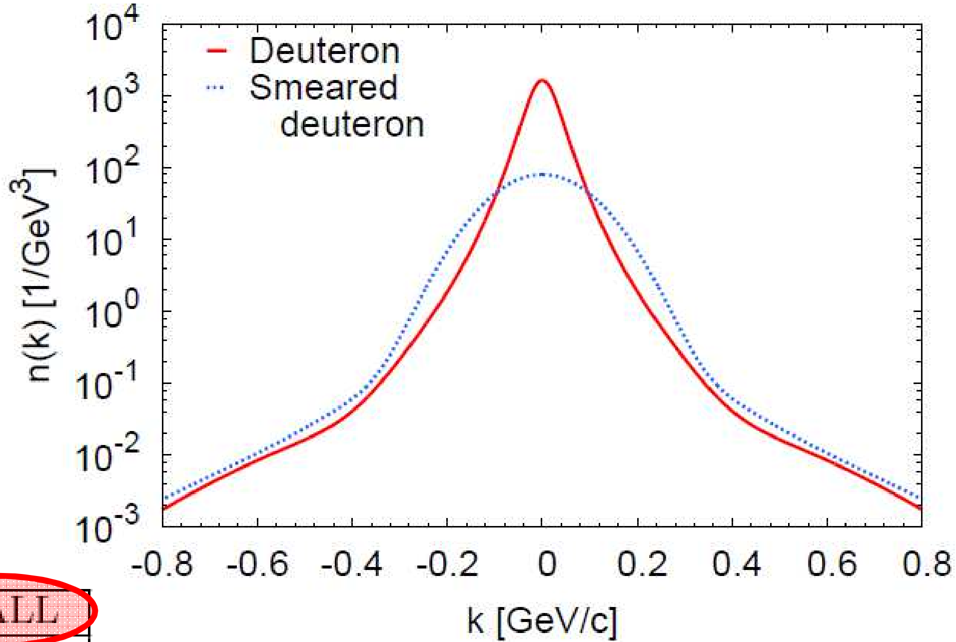


?

From cross section ratios to SRC ratios

- Motion of the deuteron-like pair smears out peak, enhances tail of the momentum distribution
- Enhances high-momentum tail by about 20% in heavy nuclei

Ciofi degli Atti, Simula, PRC 53, 1689 (1996)



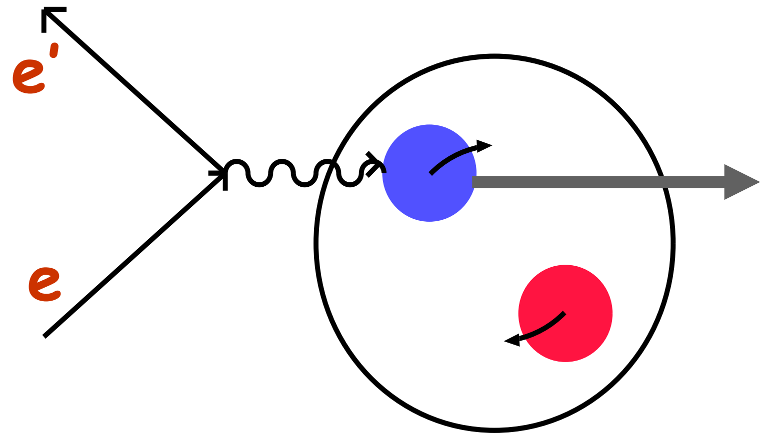
	E02-019	SLAC	CLAS	R_{2N}-ALL	a_2-ALL
^{3}He	1.93±0.10	1.8±0.3	–	1.92±0.09	2.13±0.04
^{4}He	3.02±0.17	2.8±0.4	2.80±0.28	2.94±0.14	3.57±0.09
Be	3.37±0.17	–	–	3.37±0.17	3.91±0.12
C	4.00±0.24	4.2±0.5	3.50±0.35	3.89±0.18	4.65±0.14
Al	–	4.4±0.6	–	4.40±0.60	5.30±0.60
Fe	–	4.3±0.8	3.90±0.37	3.97±0.34	4.75±0.29
Cu	4.33±0.28	–	–	4.33±0.28	5.21±0.20
Au	4.26±0.29	4.0±0.6	–	4.21±0.26	5.13±0.21

$a_2 = \sigma_A/\sigma_D$ → Number of nucleons in high-momentum tail (relative to ^2H)

R_{2n} → Number of nucleons in short-range configurations (relative to ^2H)

A scheme for "tuning" SRC density

e + d → e′ + N + X



Detect backward (spectator) proton

Slow backward proton (small P_s) tags free neutron

Fast backward proton (large P_s) tags high density configuration (SRC)

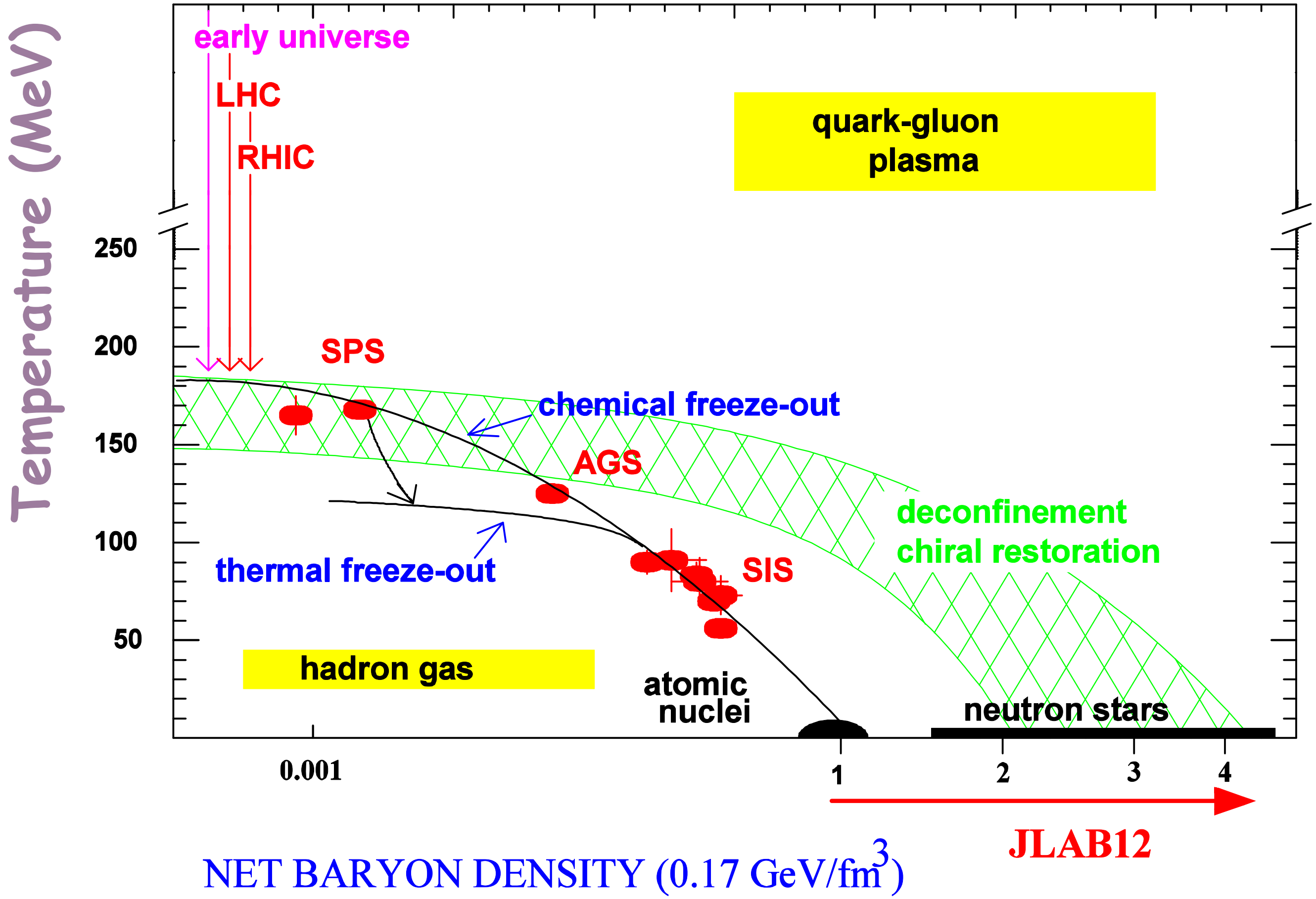
Already being used as "free" neutron target [BoNuS experiment], and preliminary use as tightly bound (Deeply off-shell) target

Phases of Nuclear Matter

High energy
- Cosmic rays
- SLAC, DESY, LHC

High temperature
- Early universe
- RHIC?

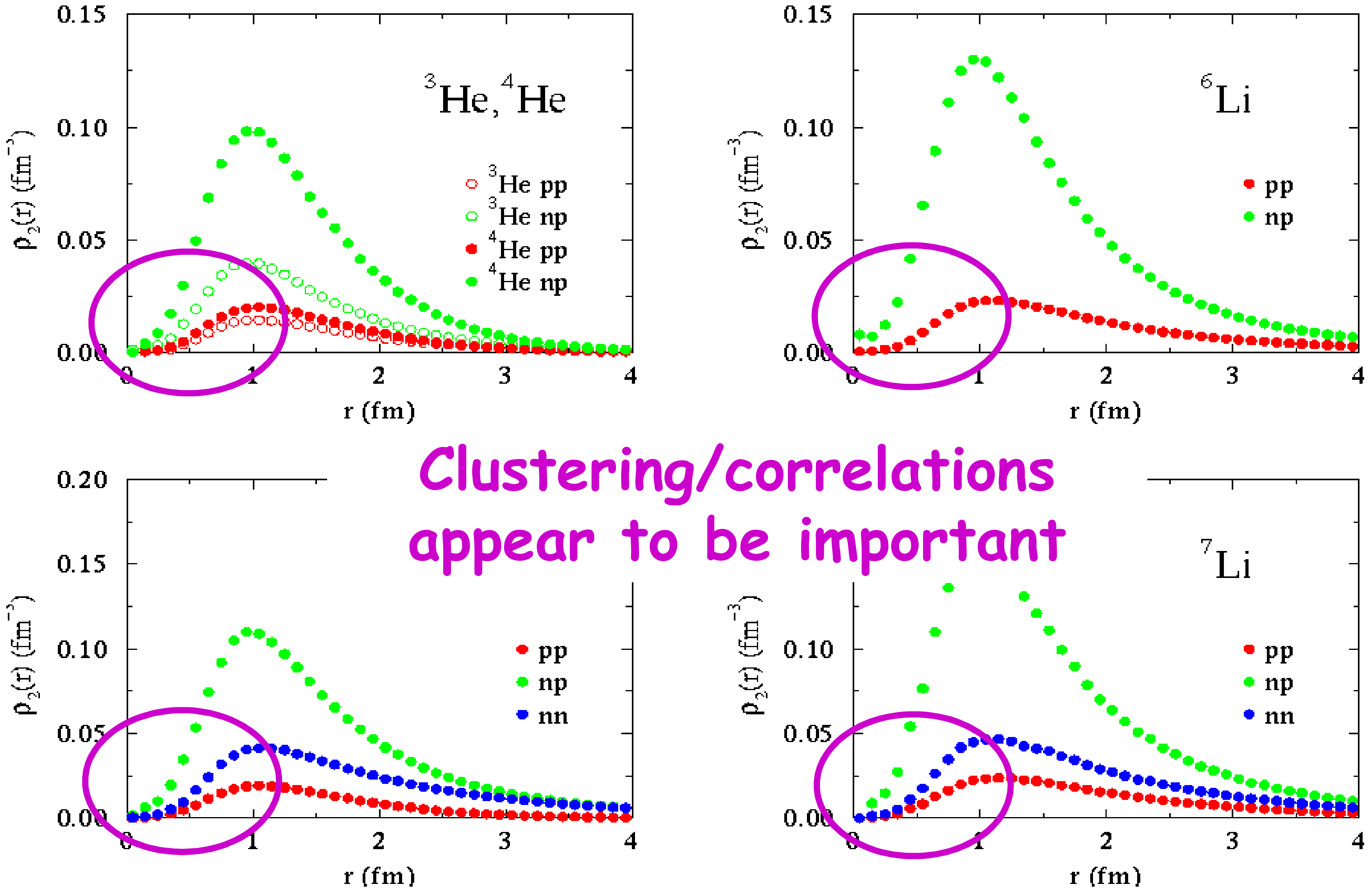
High densities
- Neutron stars
- Nuclei??
- JLab????



We *do* see density-dependent effect in nuclear structure (EMC)

Do these effects have anything to do with quarks?

Average density, or average overlap?



Clustering/correlations appear to be important

Models of the EMC effect

Nuclear Medium modifies internal nucleon structure

- Dynamical rescaling
- Nucleon 'swelling'
- Multiquark clusters (6q, 9q 'bags')

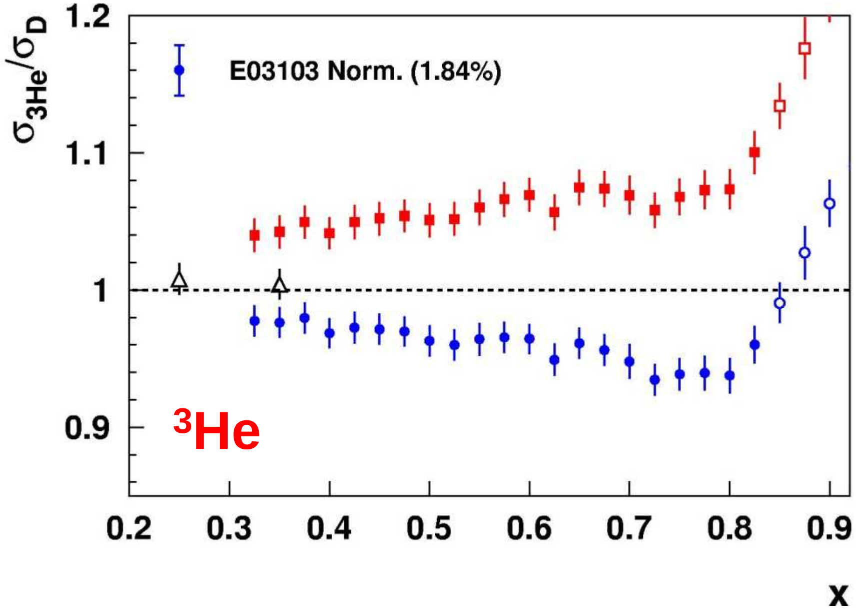
or

Nuclear structure is modified due to hadronic effects

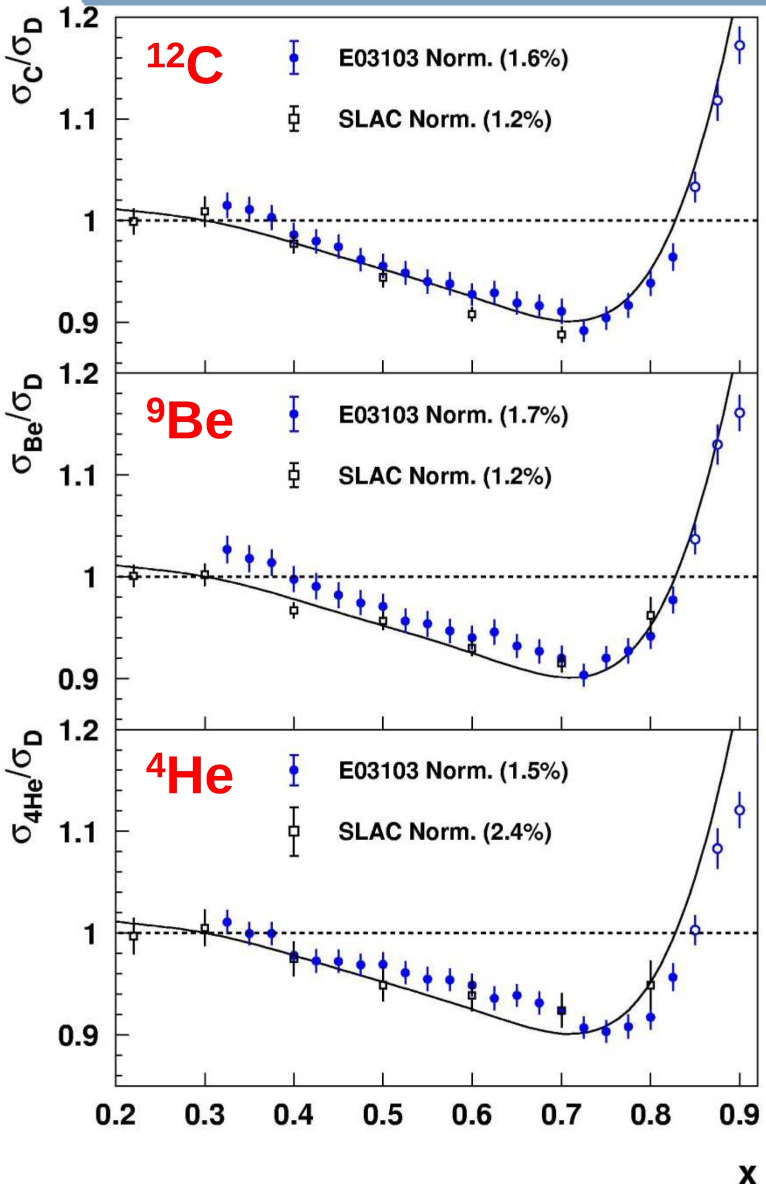
- More detailed binding calculations
  - Fermi motion + binding
  - N-N correlations
- Nuclear pions

Many models, but no complete, consistent picture

EMC effect in light nuclei



³He requires large isoscalar correction (correct for proton excess in ³He relative to ²H)

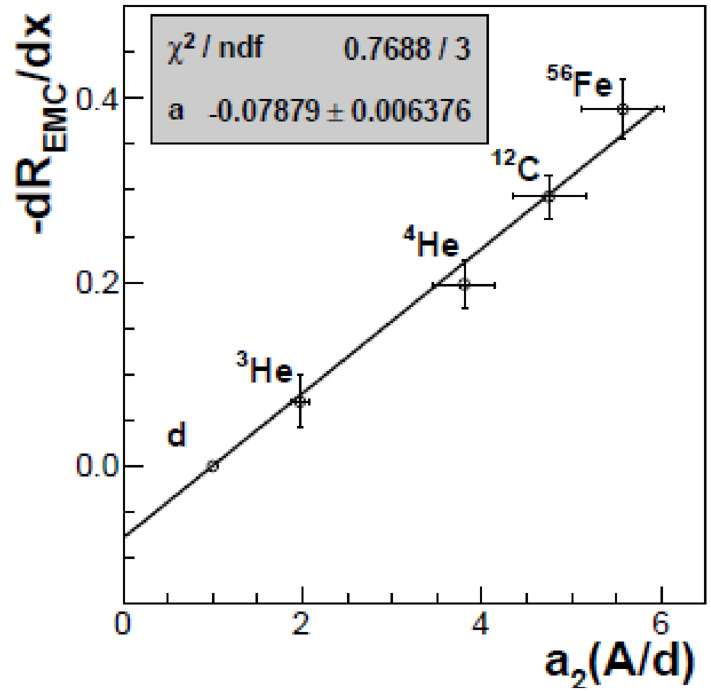


Normalization uncertainty limits extraction of A-dependence

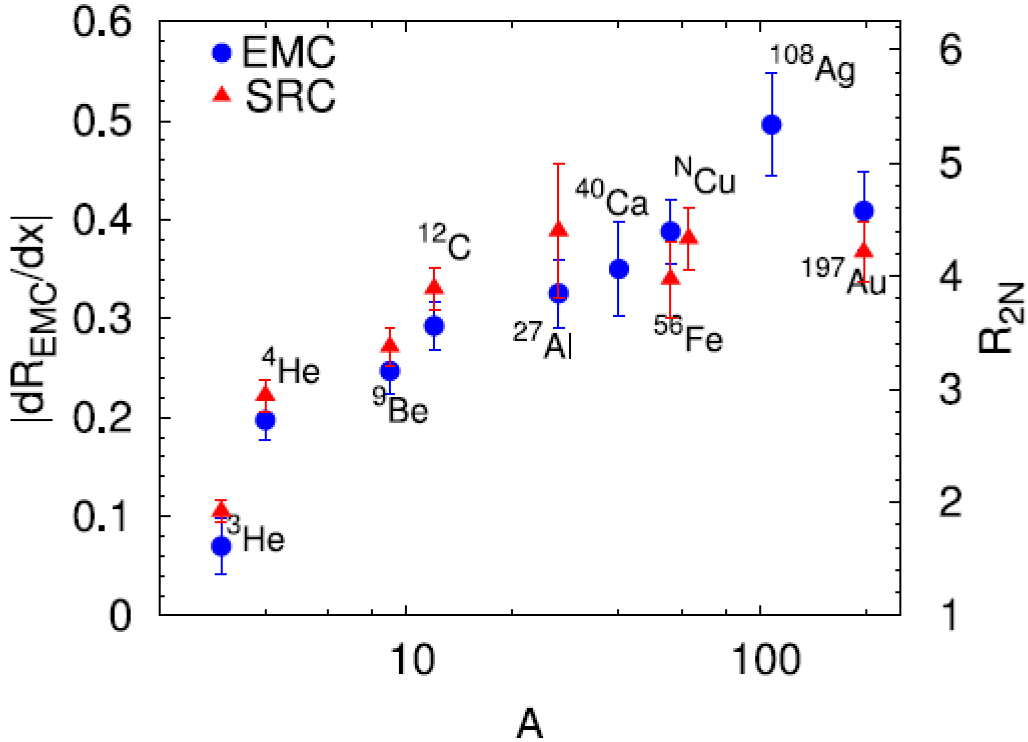
If shape (x-dependence) is same for all nuclei, the slope (0.35<x<0.7) can be used to study dependence on A

Connection between EMC effect and SRCs

Linear relationship between EMC effect and SRC



L. Weinstein, et al., PRL 106, 052301, (2011)



JA, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, arXiv:1206.6343

Suggests the same physics may drive both phenomena

*SRC data **measure** high momenta, aim to **study** short distance, high density*