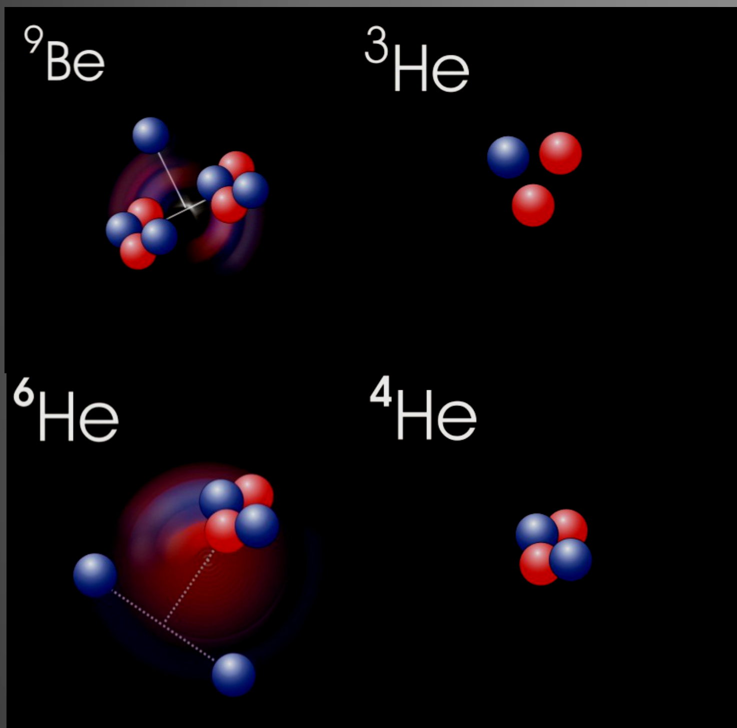
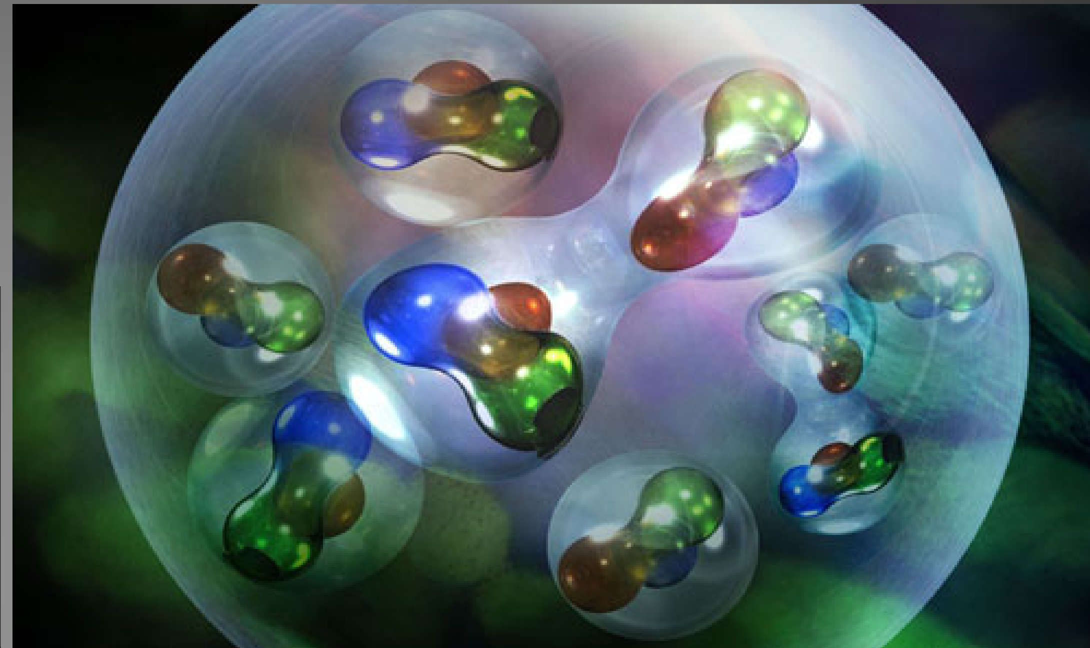
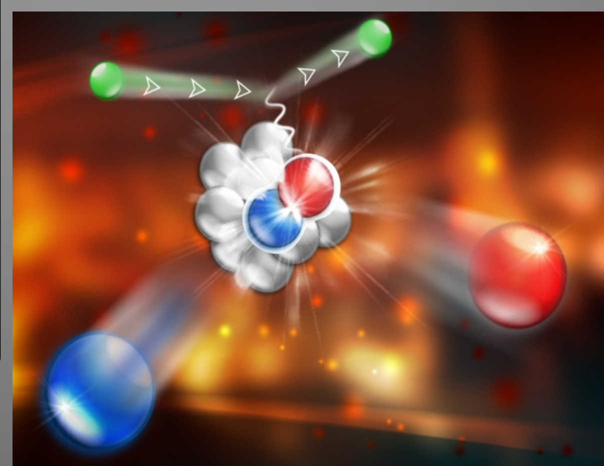
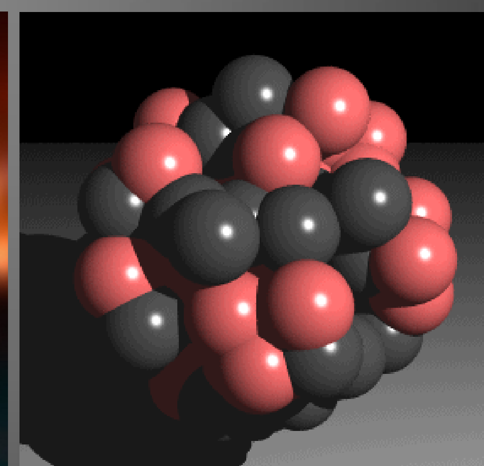
Clusters, Correlations and Quarks: a High-Energy Perspective on Nuclei

John Arrington
Argonne National Lab



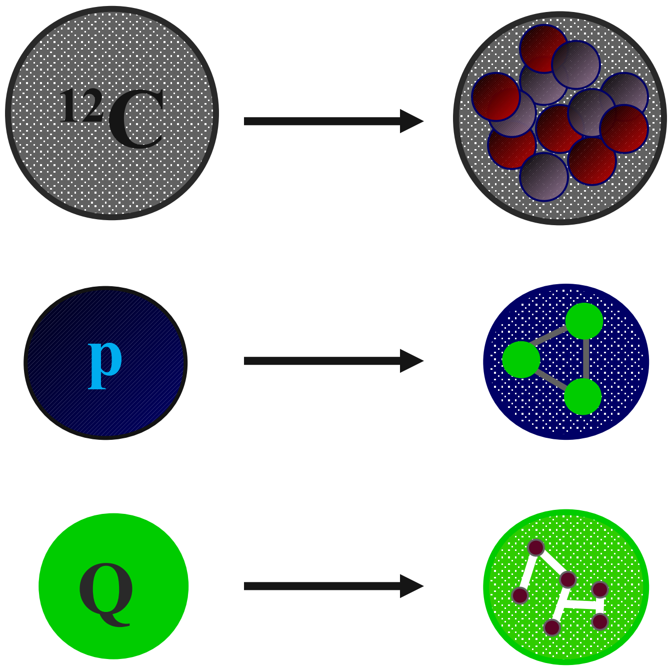






Nuclear and Quark Matter Seminar
GSI, February 4, 2015

A nucleus is different things to different people



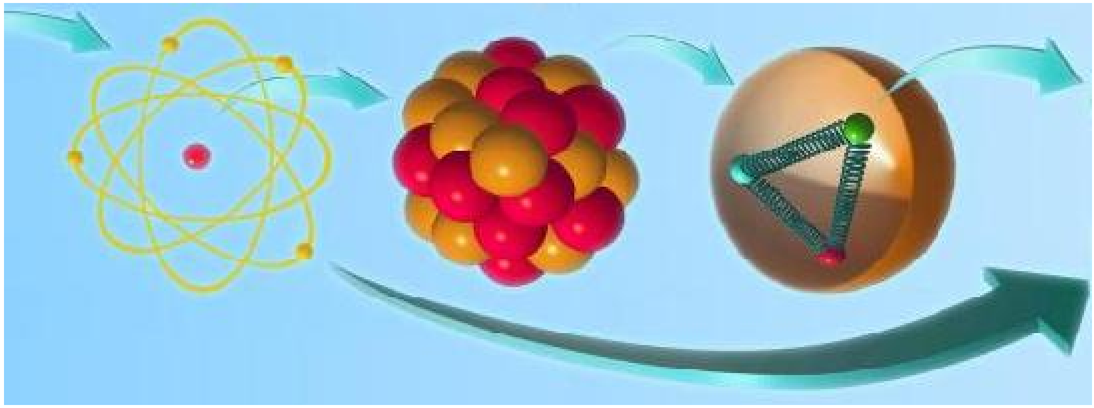
Nucleus = protons + neutrons + strong interaction of hadrons

proton = Constituent Quarks + strong interaction of Quarks

Constituent Quark = quarks + gluons + strong interaction of QCD

At each scale, the simplest description involves different constituents and interactions

A nucleus is different things to different people



Field	Picture of Nucleus
Chemistry/Atomic Physics	Small, heavy, static (uninteresting)
Low Energy Nuclear Physics	Protons + neutrons, complicated shell structure, angular momentum,….
Medium Energy Nuclear Physics (and most neutrino scattering)	Protons + neutrons (typically non-interacting)
High Energy Physics (& RHIC)	Bag of quasi-free quarks

Under certain conditions, there can be 'cross-talk' between these very different energy/distance scales

Nuclear structure impacting measurements at atomic scales (neV)

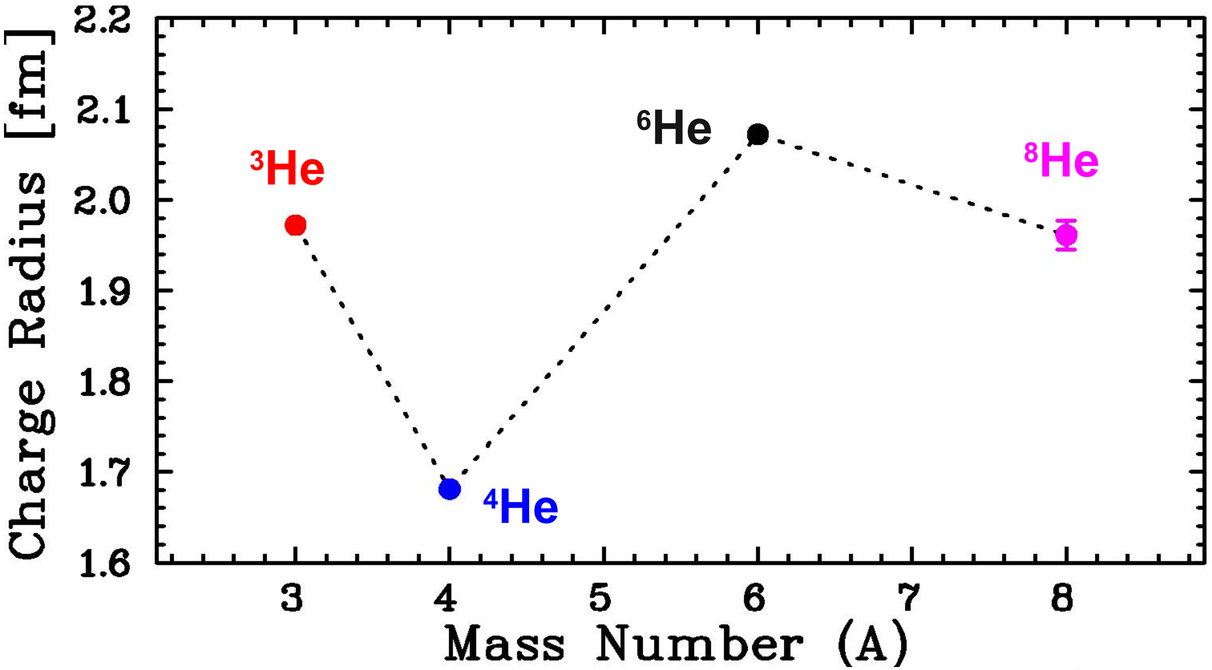
- **Extreme sensitivity to short distances**
  - *Muonic hydrogen: proton radius measurement*
- **Extremely high precision measurements**
  - *Isotope shifts, e.g. ^{6}He, ^{8}He charge radii*

Charge radii and nuclear structure

ATTA (Atom Trap Trace Analysis)

–*Trap rare ^{6}He, ^{8}He isotopes* (produced at ATLAS(ANL) or GANIL)

–*Measure isotopic shift in S → P transition*



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]

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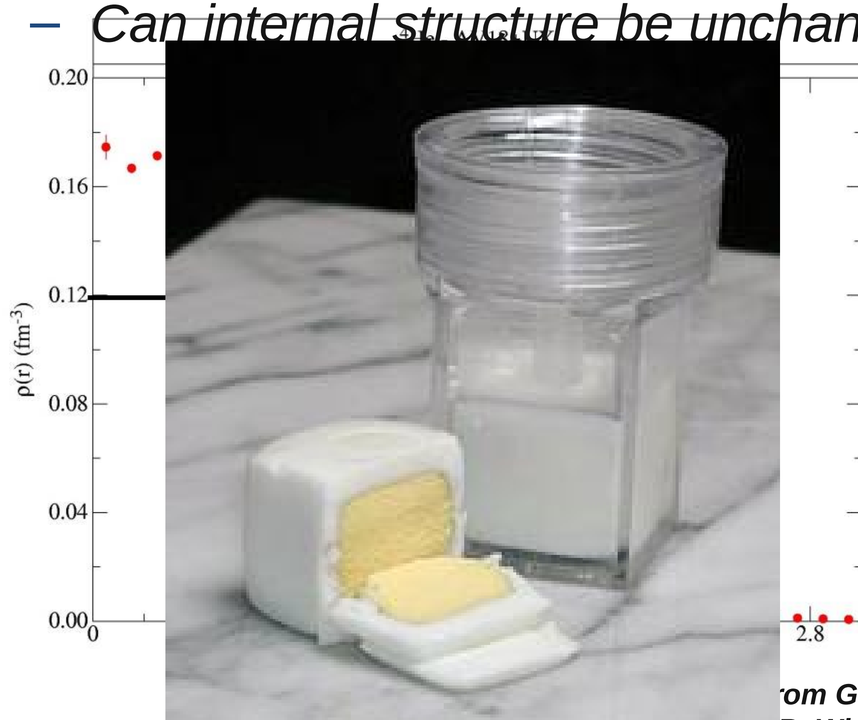
Does nuclear structure impact hadronic (quark-level) substructure ?

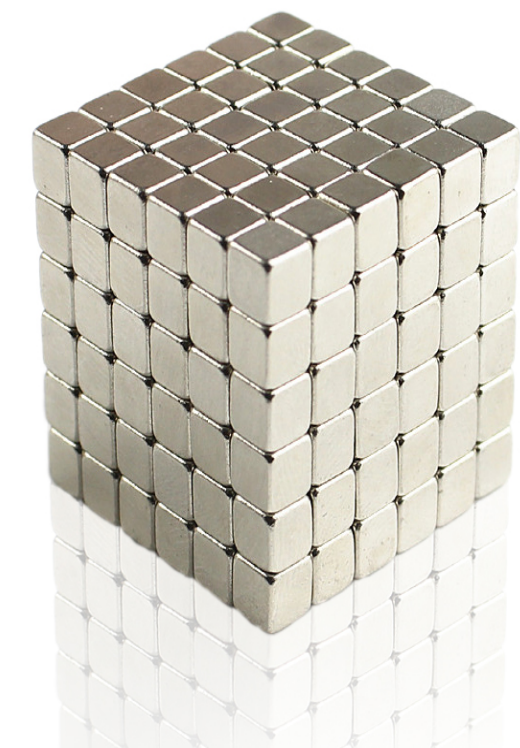
- **Extremely high energy scales in nuclei**
  - *Energy density [RHIC, LHC]*
    - *Introducing large* ***external*** *energy scale*
    - *Quark-Gluon Plasma = Nucleus ??*
  - *Matter density [Heavy nuclei, neutron star?]*

How dense are nuclei?

- **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: $_{max}$ = 0.12 fm^{-3}**
  - *Well below peak densities in nuclei*
  - *Need 100% packing fraction for dense nuclei*
  - *Can internal structure be unchanged*

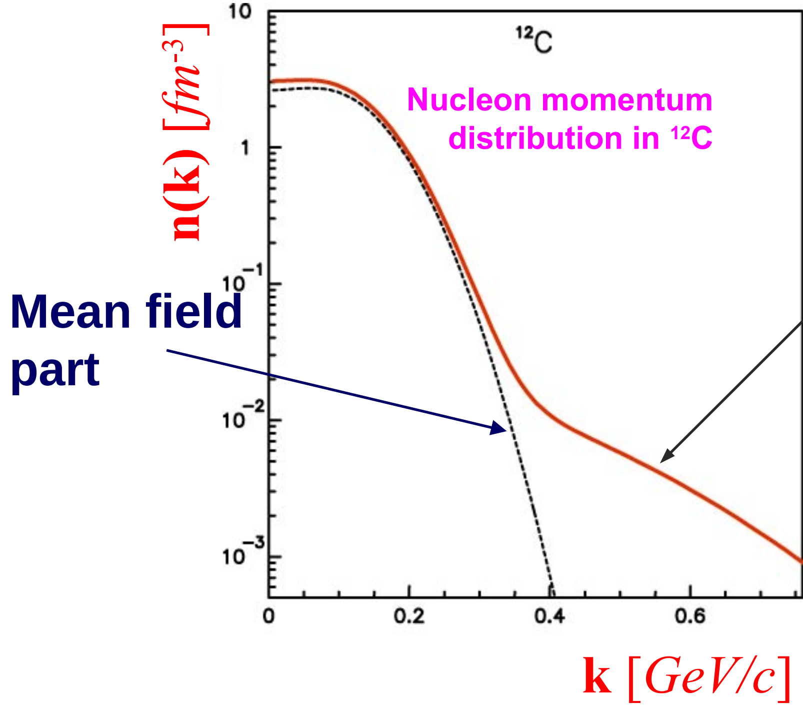


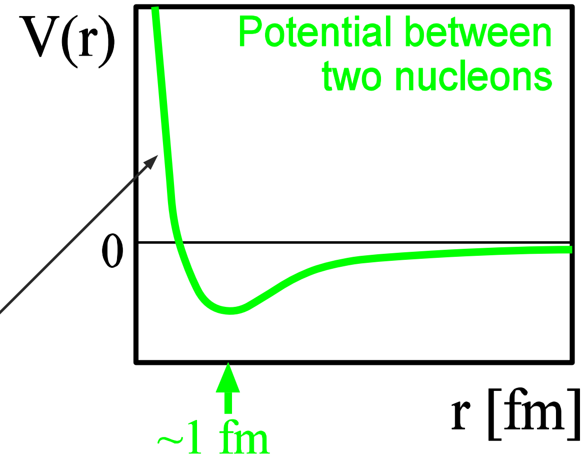
rom GFMC
B. Wiringa

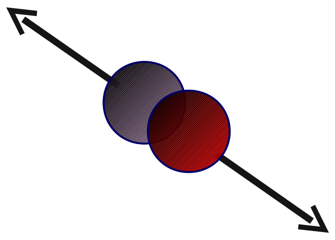


High-momentum nucleons (Short-Range Correlations)

N-N interaction ⟹ Hard interaction at short range
⟹ Pairs of high-momentum nucleons (up to 1 GeV/c)







Even in ^2H, 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**

Two key experiments

JLab E03-103 JA and D. Gaskell, spokespersons

- **Scatter from HIGH-MOMENTUM QUARKS in nucl**
  - *EMC effect -* ***Density dependence of quark pdf***

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

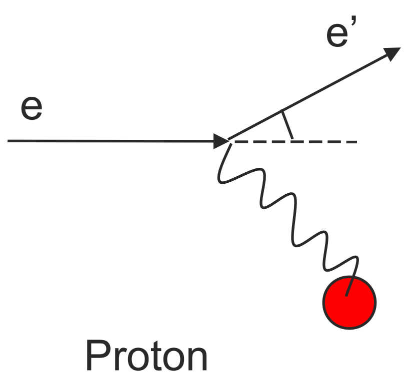
- **Scatter from HIGH-MOMENTUM NUCLEONS in nuclei**
  - *Probe* ***high-momentum nucleons*** *in nuclei*

Isolating high-momentum, high-density components

THESE EXPERIMENTS ARE REMARKABLY STRAIGHTFORWARD

ELASTIC ELECTRON-PROTON SCATTERING

- Scattering from stationary proton is simple billiard-ball scattering: x=1



Energy transfer $\nu = E - E'$

Momentum transfer $\vec{q} = \vec{k} - \vec{k}'$

4-momentum transfer $Q^2 = q^2 - \nu^2$

Bjorken-x $x_{Bj} = \frac{Q^2}{2M\nu}$

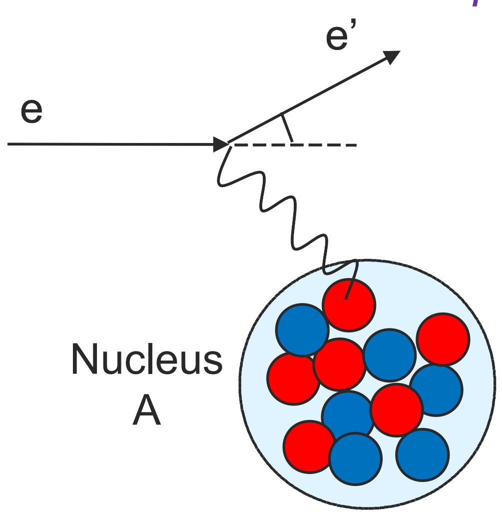
Isolating high-momentum, high-density components

THESE EXPERIMENTS ARE REMARKABLY STRAIGHTFORWARD

ELASTIC AND “QUASI-ELASTIC” ELECTRON SCATTERING

- Scattering from stationary proton is simple billiard-ball scattering: x=1
- Deviation from stationary-proton yields *proton initial momentum*
- Relatively high-energy probe to reach large initial momentum scales
- *Very high Q^2 → DIS: probe **quark distributions** in the same way*

  x = quark’s “longitudinal momentum fraction”



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Bjorken-x $x_{Bj} = \dfrac{Q^2}{2M\nu}$

Quark distributions in nuclei: EMC effect

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

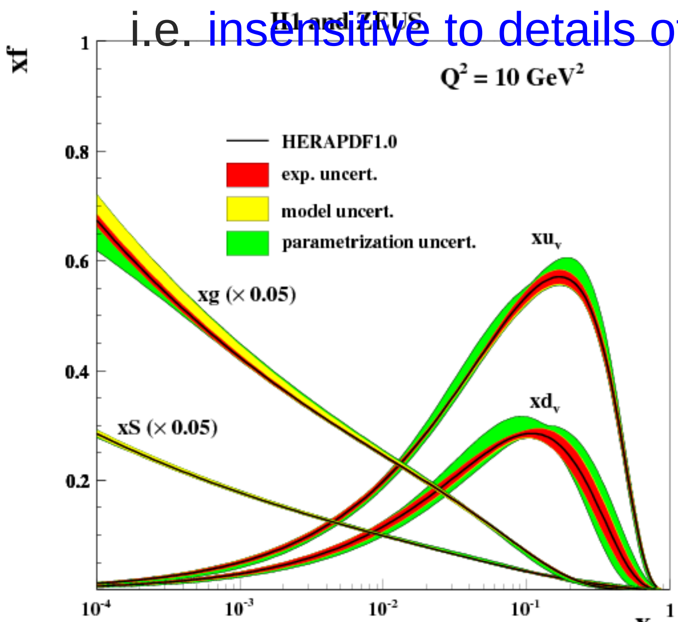
- x = quark longitudinal momentum fraction
- $F_2(x)$ related to parton momentum distributions (pdfs)

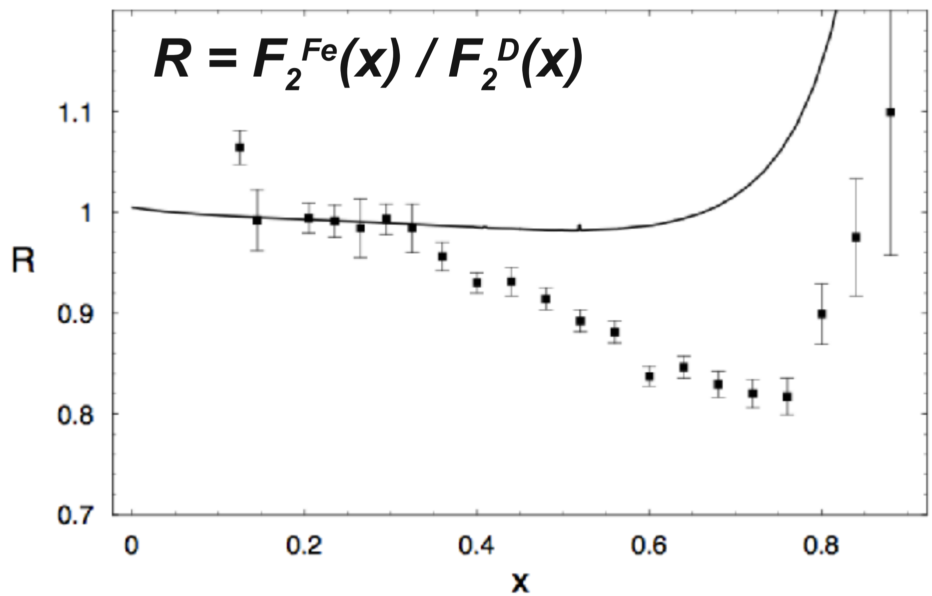
$F_2(x)$ $e_i^2\, q_i(x)$ *i=up, down, strange*

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 nu





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

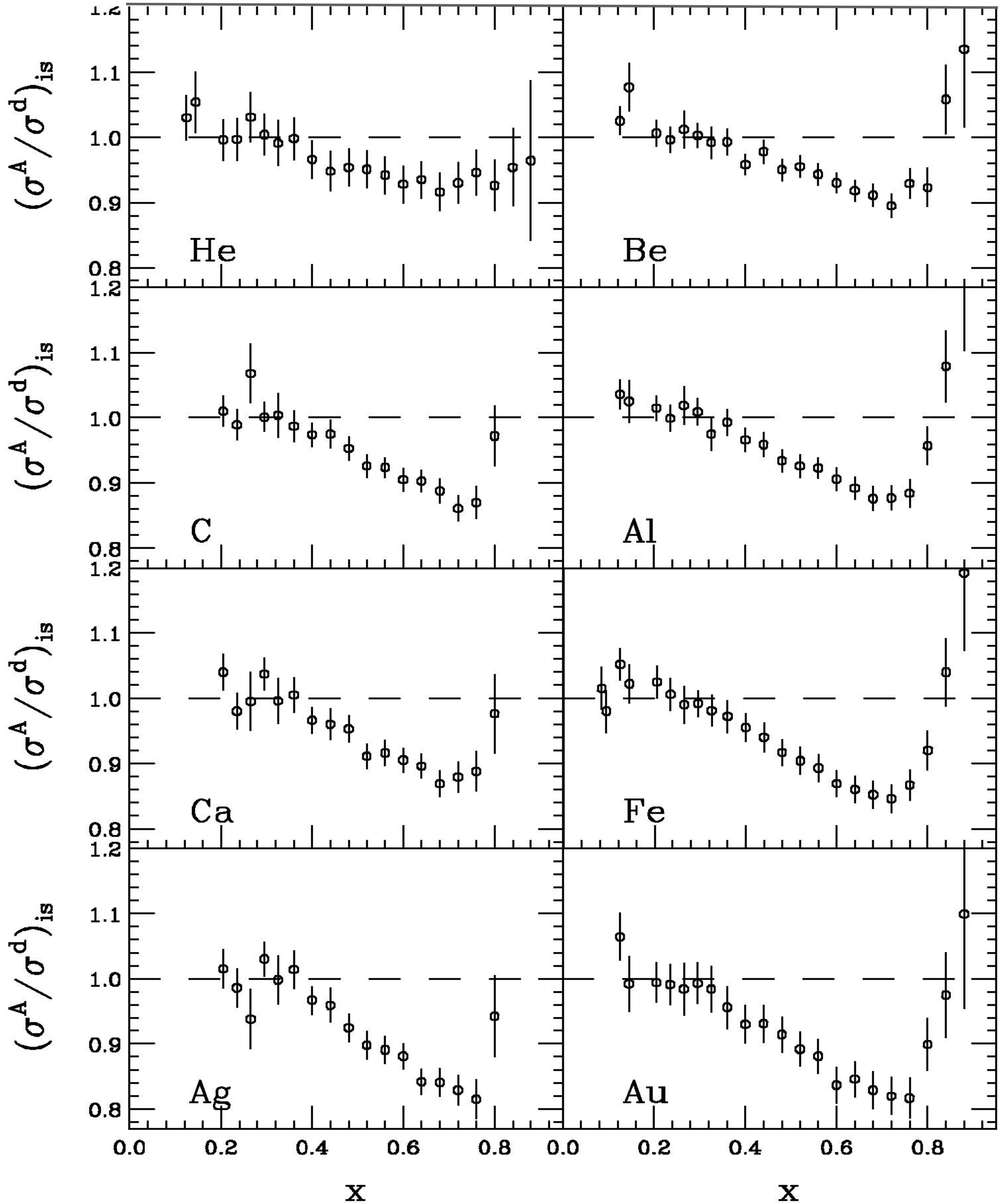
EMC effect: A-dependence

SLAC E139

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

Conclusions

- Universal x-dependence
- Magnitude varies
  - Scales with A (~$A^{-1/3}$)
  - Scales with density



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

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 nuclear/hadronic effects

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

Many ways to model the suppression of high-x quarks, but little to differentiate between these explanations

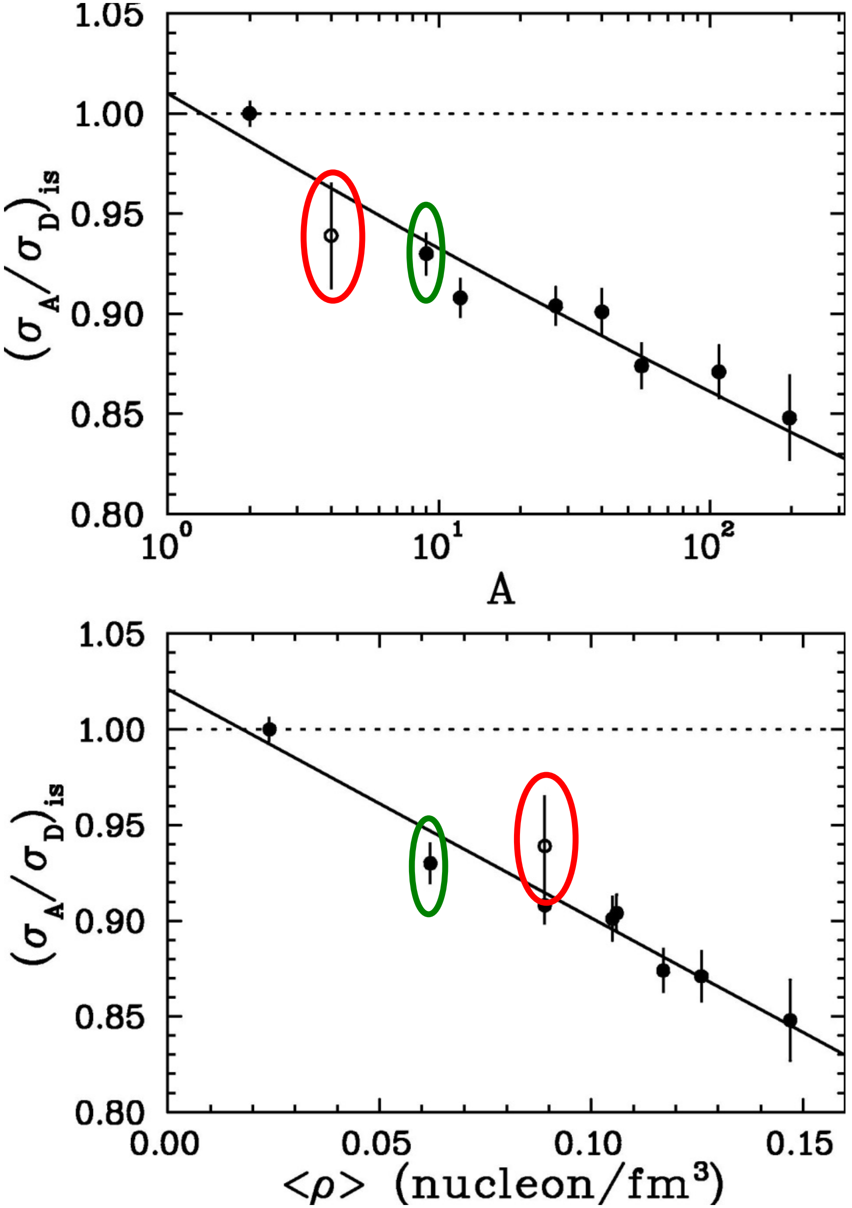
Importance of light nuclei

Test mass vs. density dependence

^{4}He is low mass, higher density

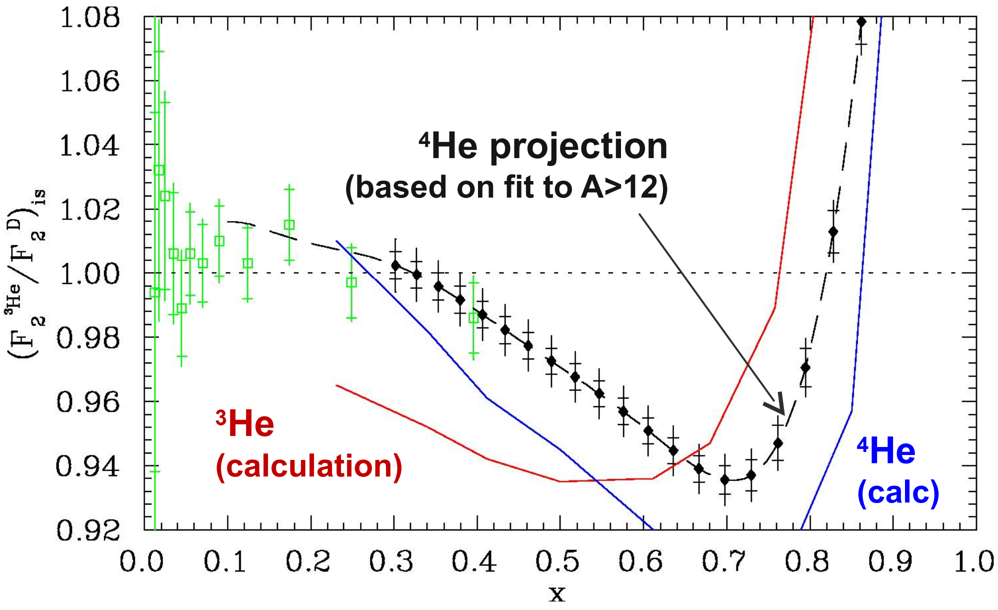
^{9}Be is higher mass, low density

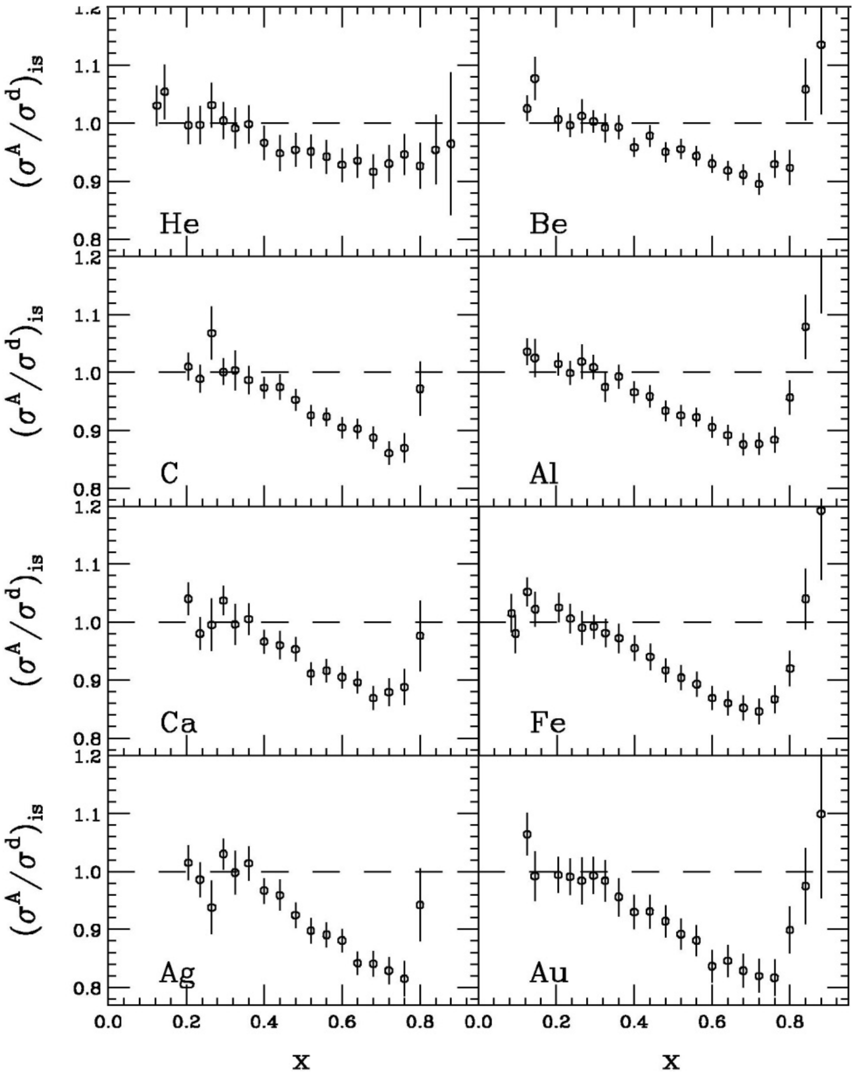
^{3}He is low mass, low density (no data)



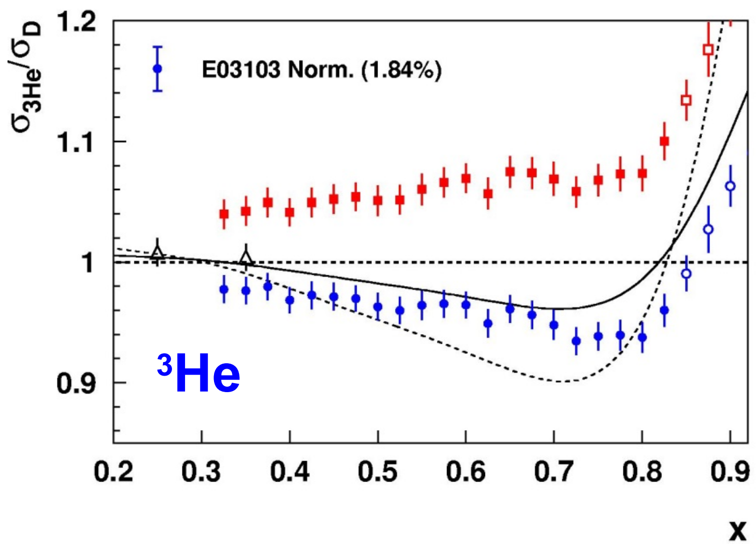
Importance of light nuclei

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



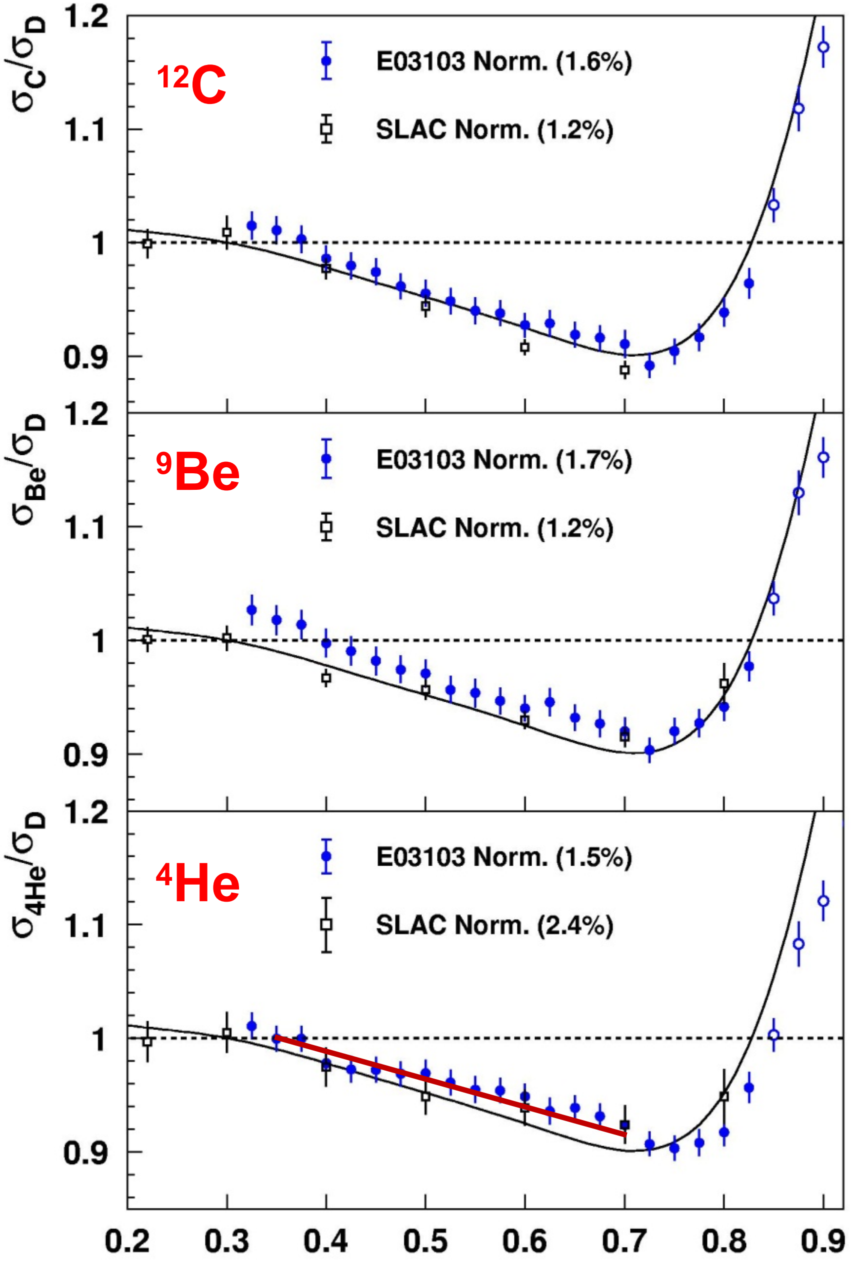


JLab E03-103 Results



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

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



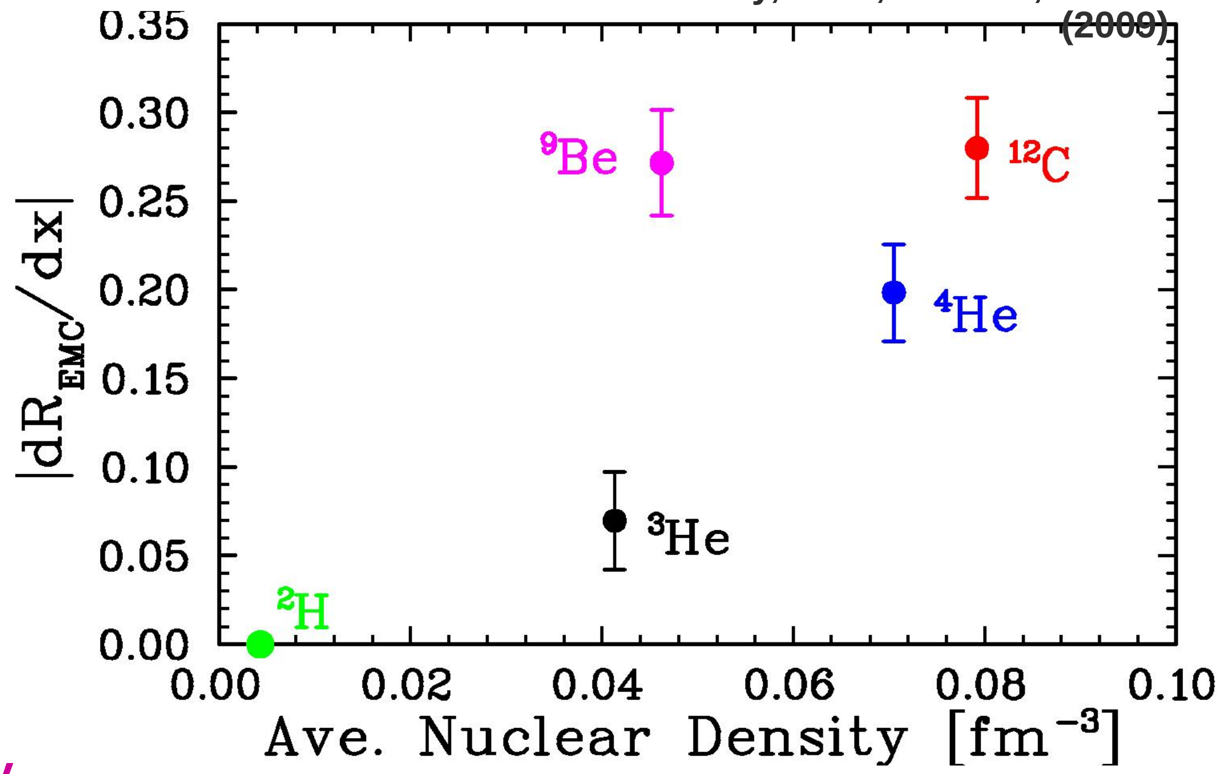
J.Seely, et al., PRL103, 202301 (2009)

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)

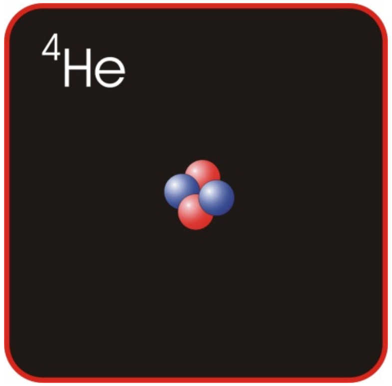


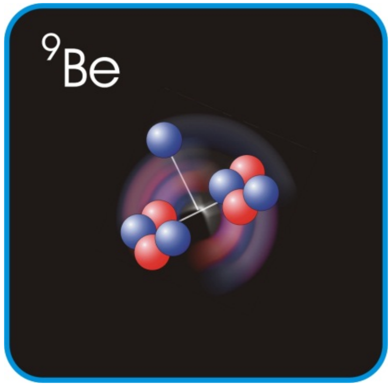
Data show smooth behavior as density increases, as generally expected…
except for ^{9}Be

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

Most nucleons in tight,   -like configurations

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

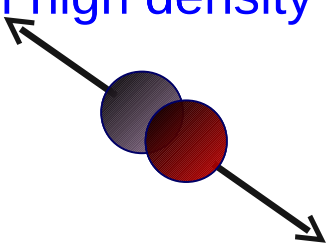


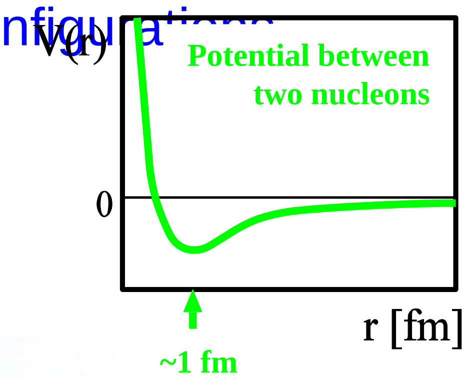


Nuclear structure ←→ Quark effects?

- **New EMC effect data suggest importance of 'local density'**
  - Suggests connection to detailed nuclear structure, clustering effects
  - Impact of clustering can be seen from neV shifts in electron energy level to GeV/TeV probes of nuclear quark distributions
  - New and intriguing information, but still no microscopic explanation

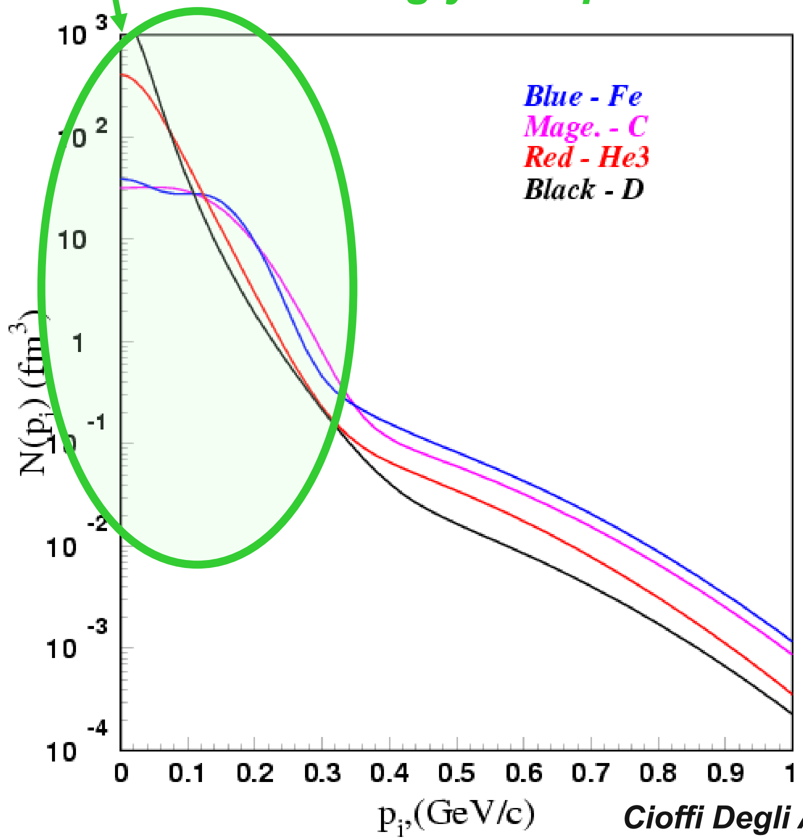
- **Can we study these high-density structures directly?**
  - Short-range correlation (SRC) measurements are meant to probe such high-density configurations
    - The experiments **measure** high momentum nucleons
    - Aim is to **study** contribution of high density configurations





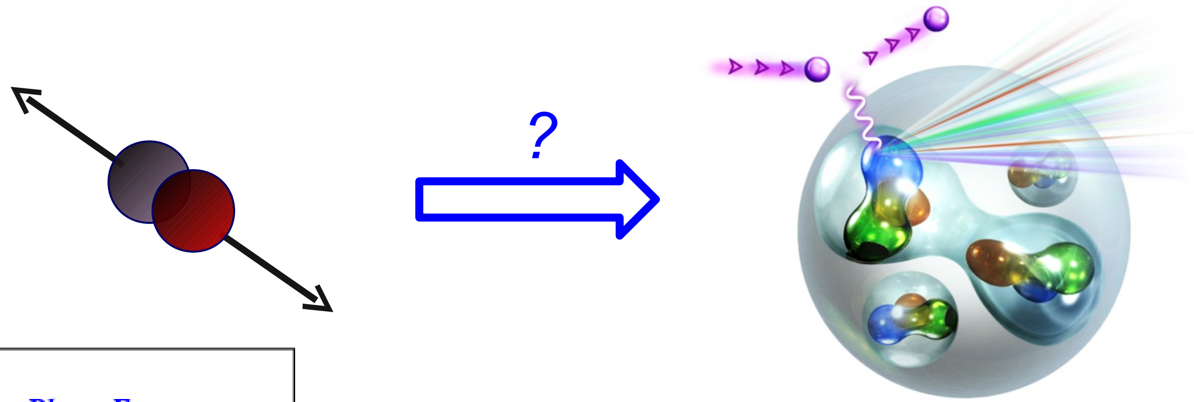
Collective behavior vs. two-body physics

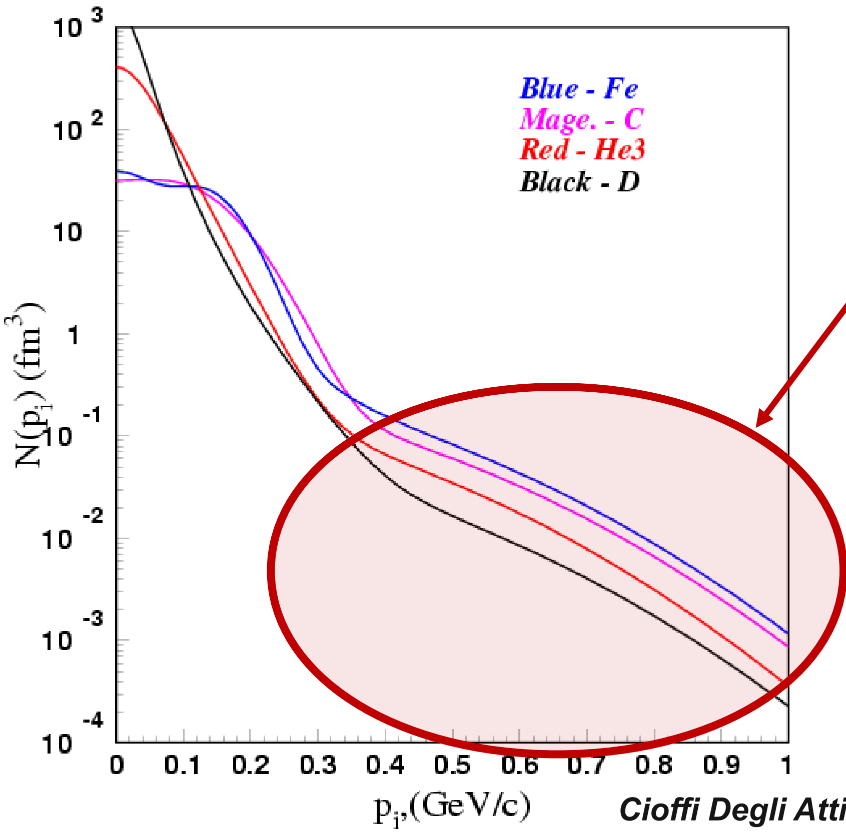
Mean-field region: collective behavior, strongly A-dependent



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

Collective behavior vs. two-body physics



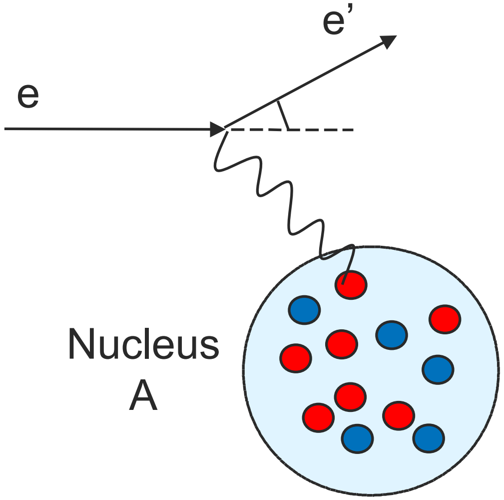


Cioffi Degli Atti, et al, PRC53, 1689 (1996)

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?

Inclusive scattering at large x

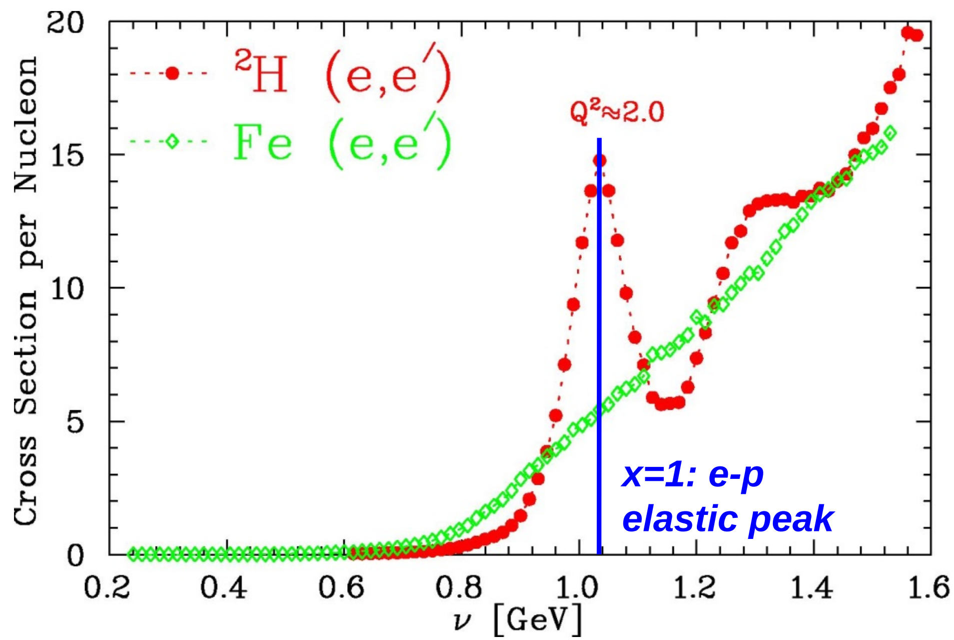


e-p elastic scattering: x = 1

Quasielastic scattering *x*   *1*

Motion of nucleon in the nucleus broadens the peak

Low energy transfer region (x>1) suppresses inelastic backgrounds



JA, et al., PRL 82 (2001) 2056

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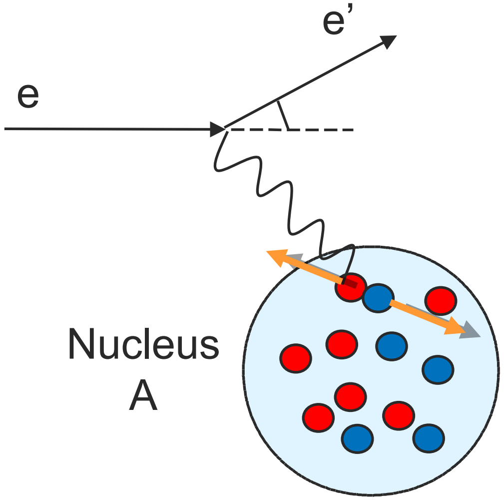

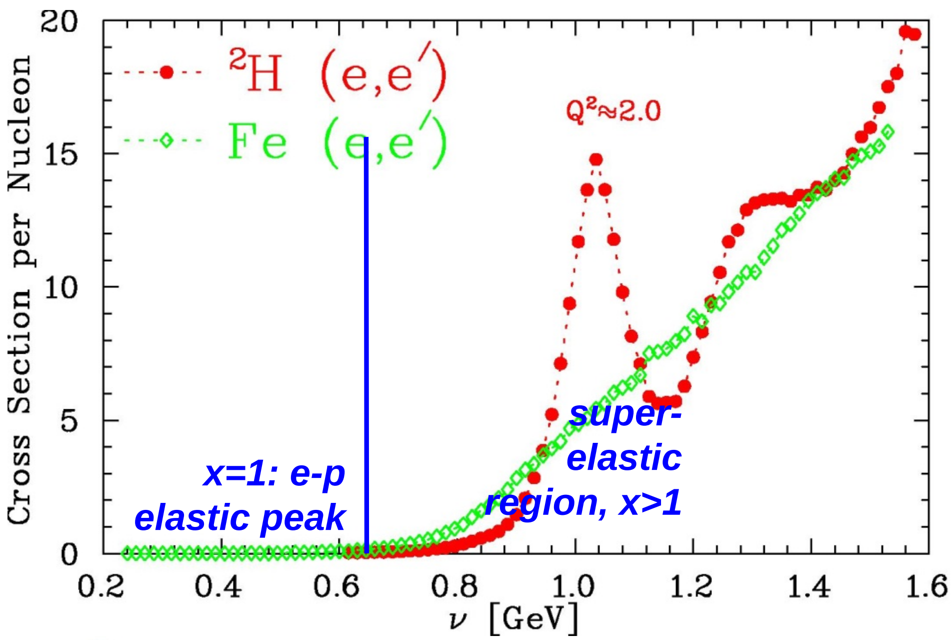

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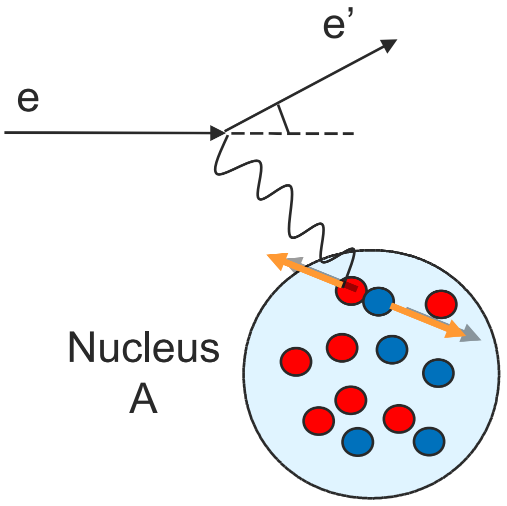
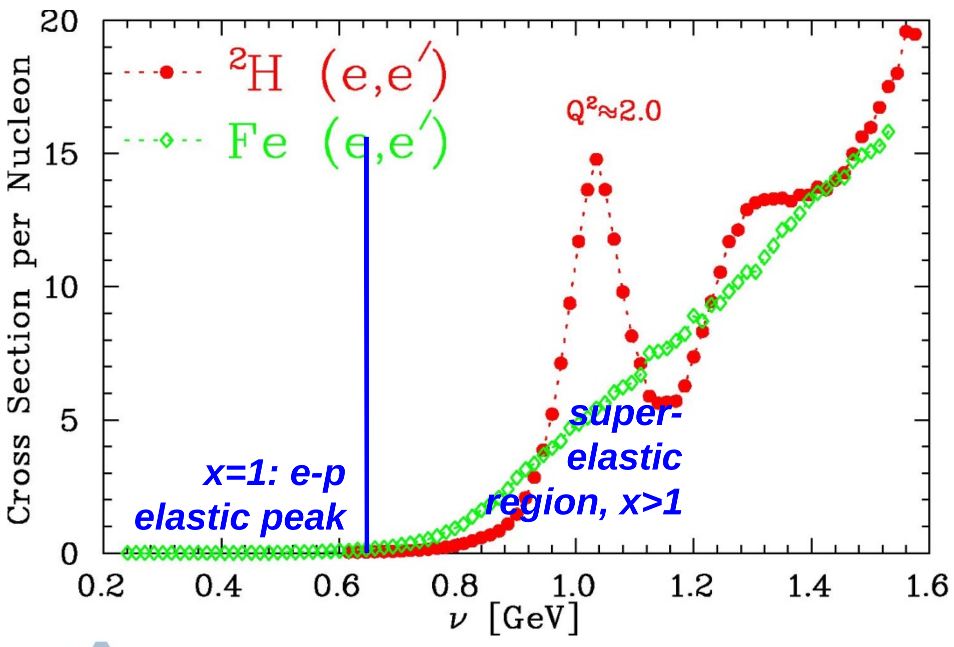
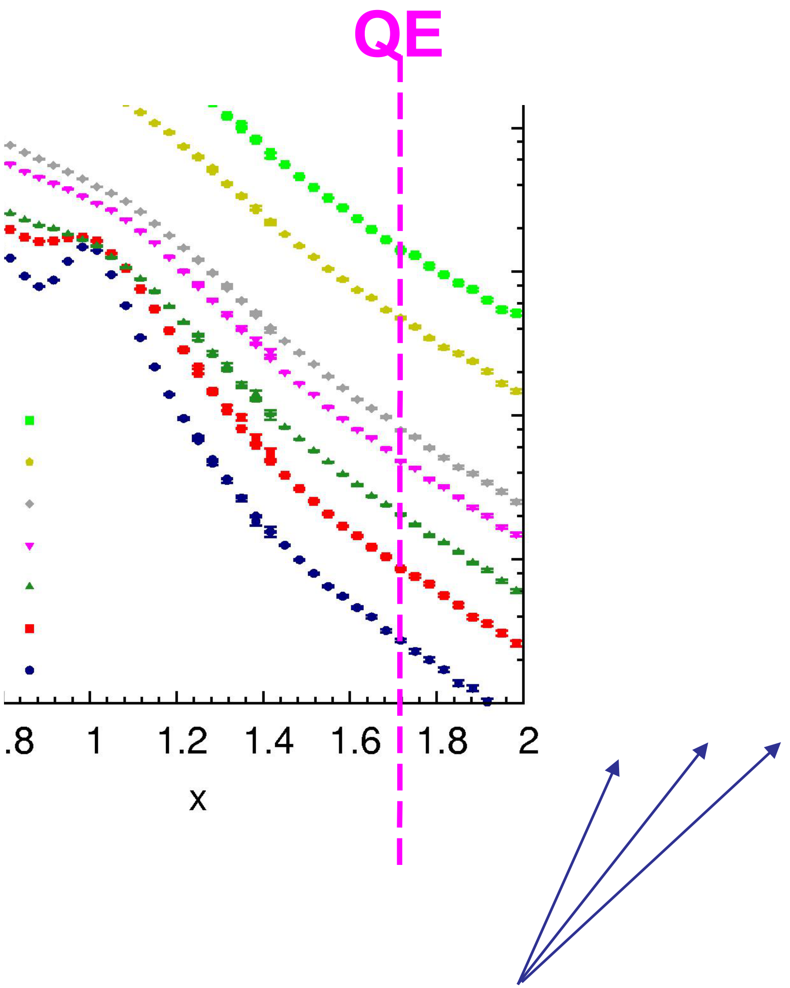


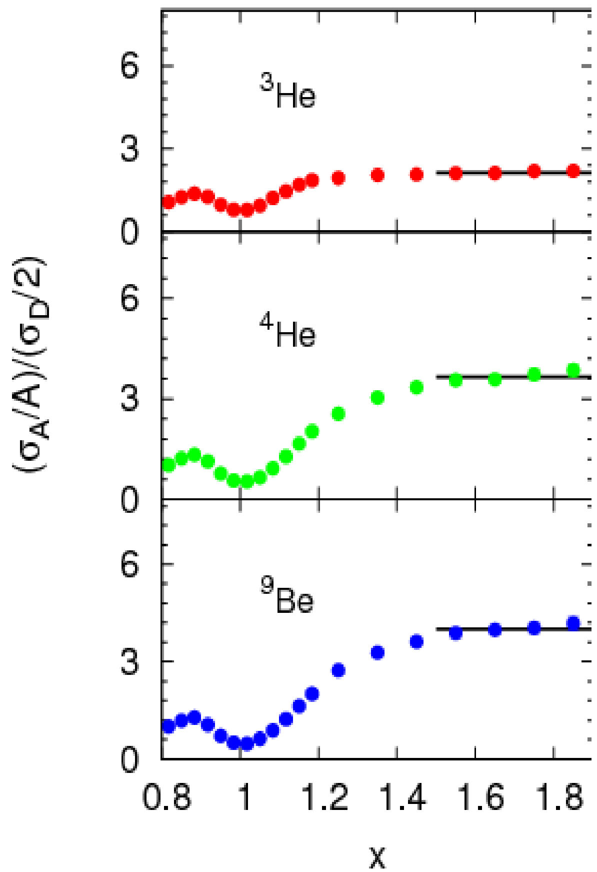


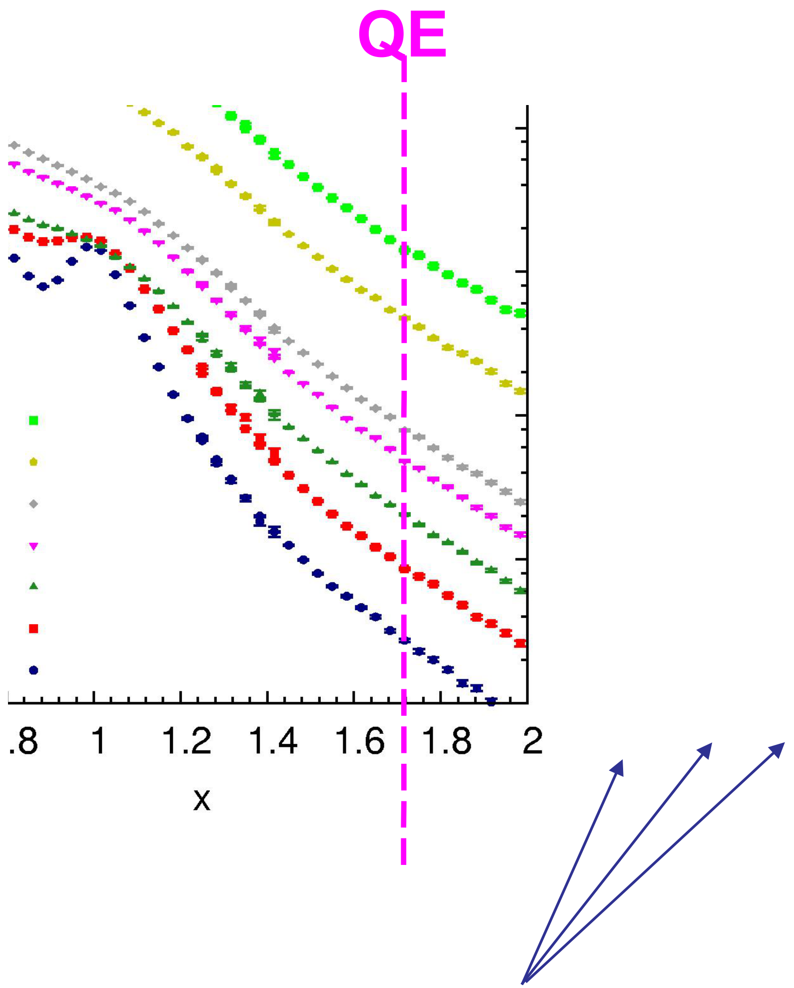


High momentum tails should yield constant ratio if SRC-dominated

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

SRC evidence: A/D ratios





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

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

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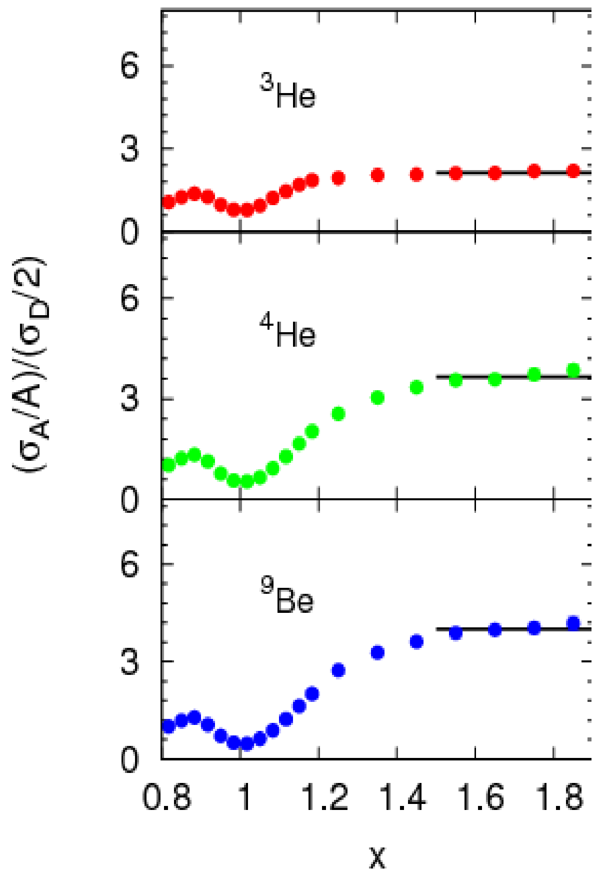


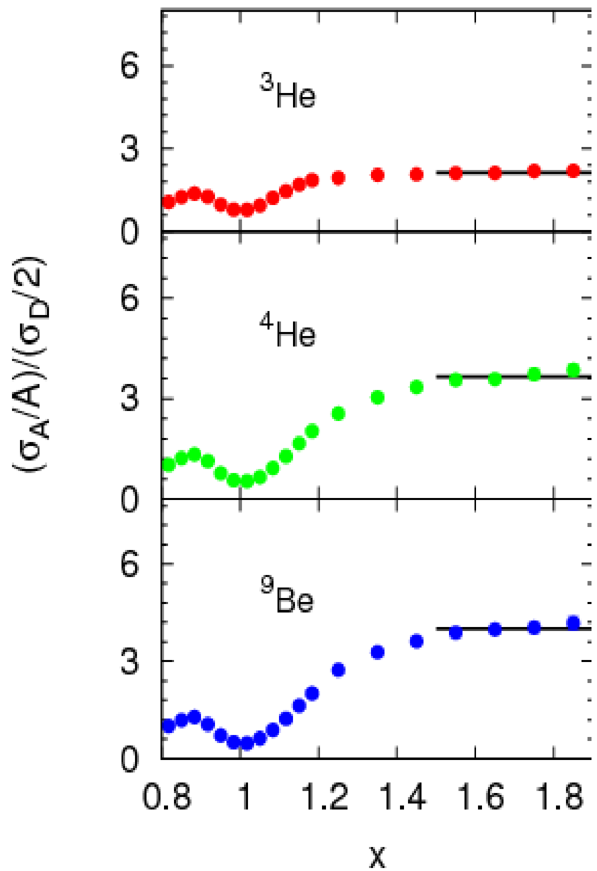
Ratio of cross sections shows a (Q^2-independent) plateau above x ≈ 1.5, as expected in SRC picture

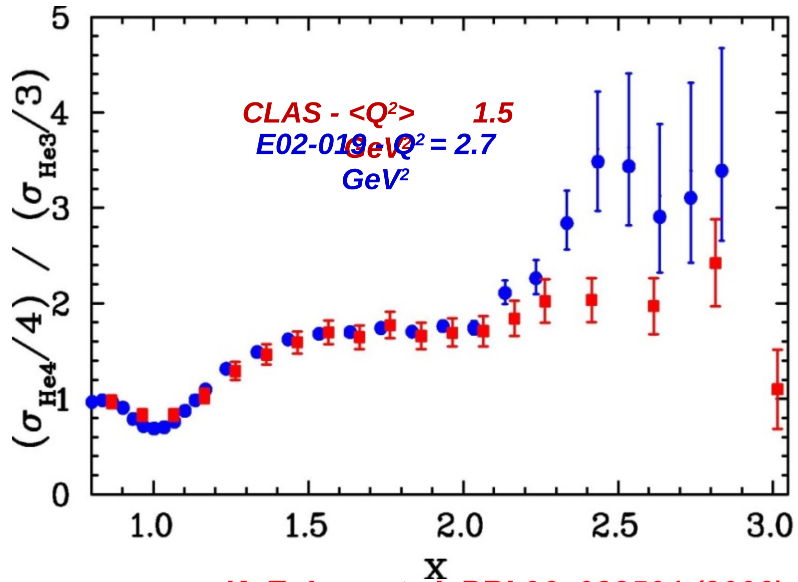
A/D Ratio	
^{3}He	2.14±0.04
^{4}He	3.66±0.07
Be	4.00±0.08
C	4.88±0.10
Cu	5.37±0.11
Au	5.34±0.11

Experimental observations:

- Clear evidence for 2N-SRC at $x>1.5$
- Map out strength vs A: 20-25% for A>12
- Suggestion of 3N-SRC plateau?

SRC evidence: A/D ratios





K. Egiyan et al, PRL96, 082501 (2006)
N. Fomin, et al., PRL 108 (2012) 092052
Z. Ye, et al., In Preparation

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

Experimental observations:

- Clear evidence for 2N-SRC at x>1.5
- Map out strength vs A: 20-25% for A>12
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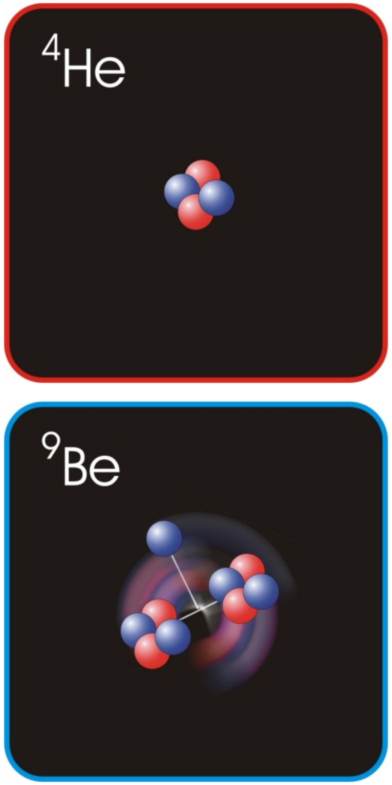
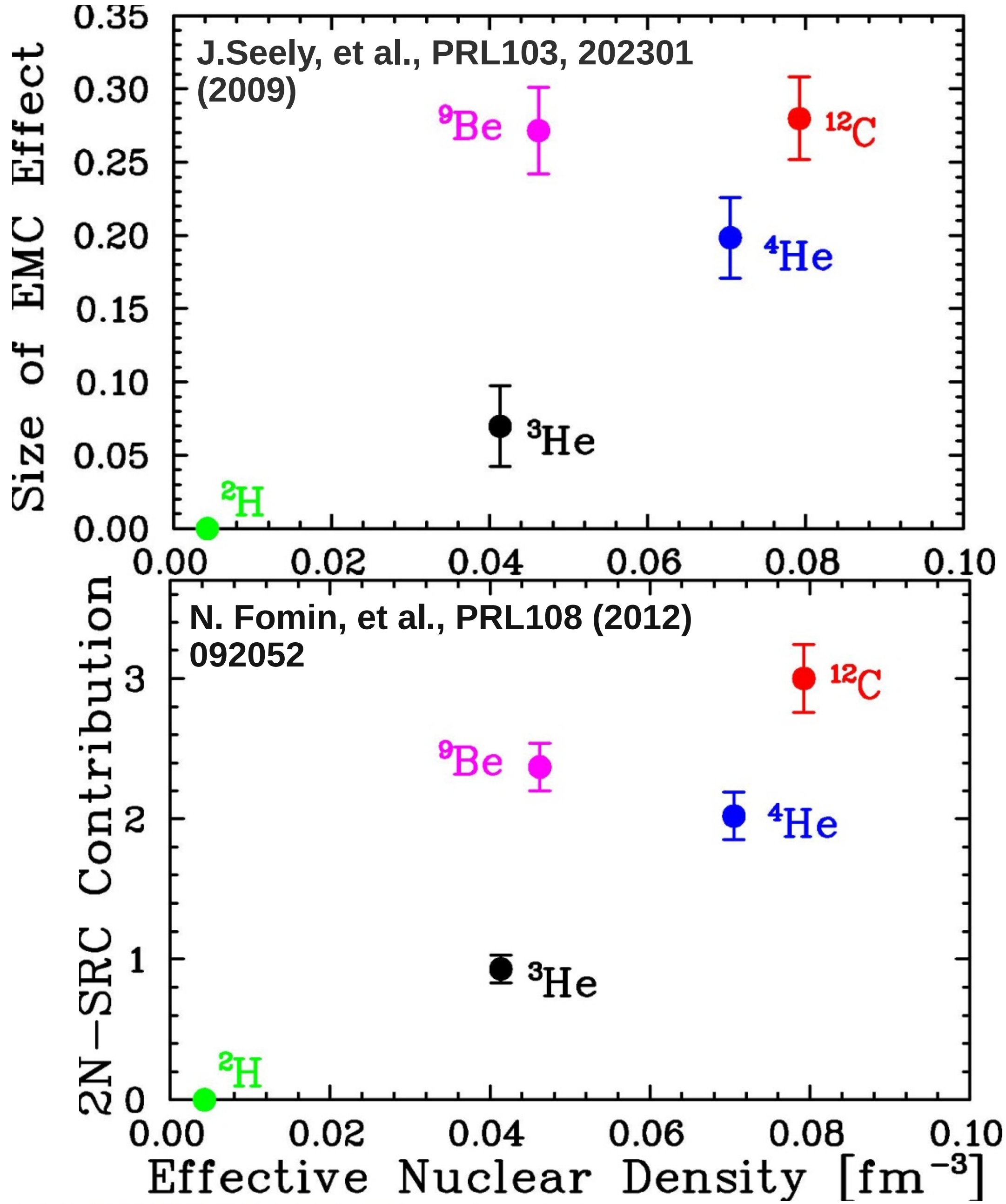
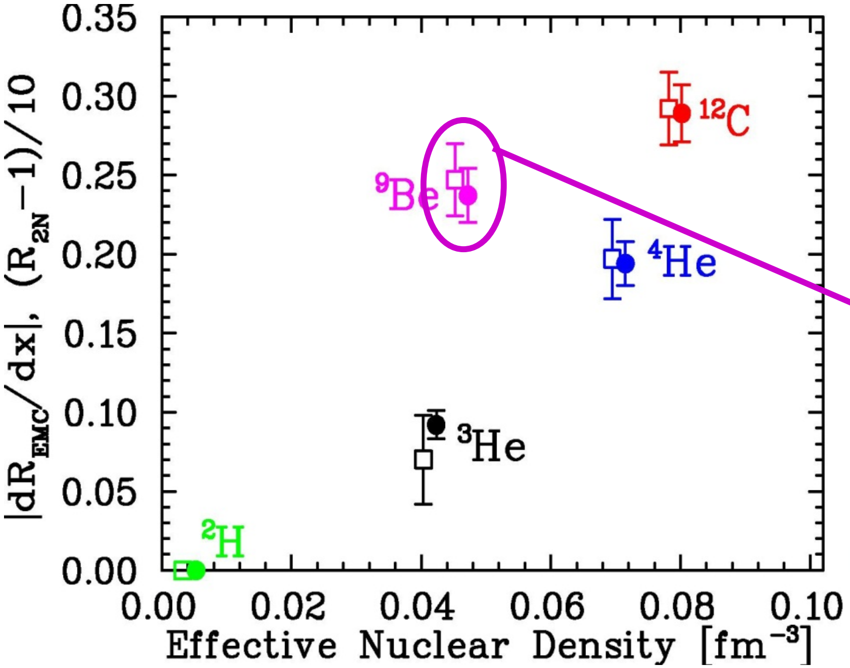
Connection to EMC effect?



Credit: P. Mueller



EMC effect: Importance of two-body effects?



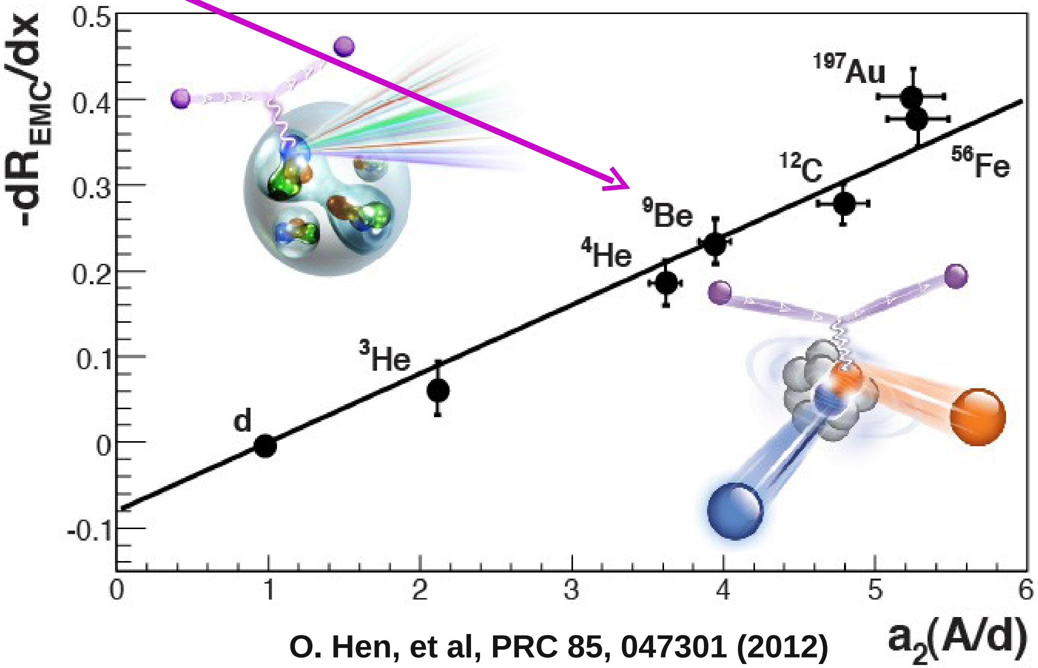
J. Seely, et al., PRL103, 202301 (2009)

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?

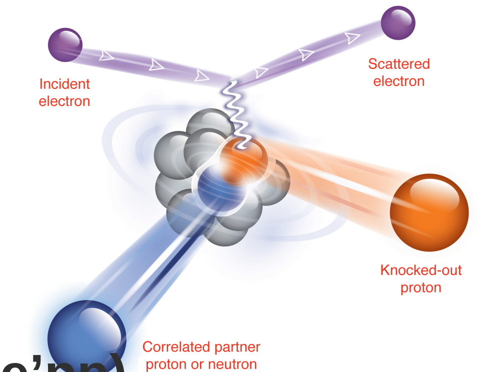
25-50% change in the 20% of nucleons at very high momenta?



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

Brief detour: Isospin dependence of SRCs

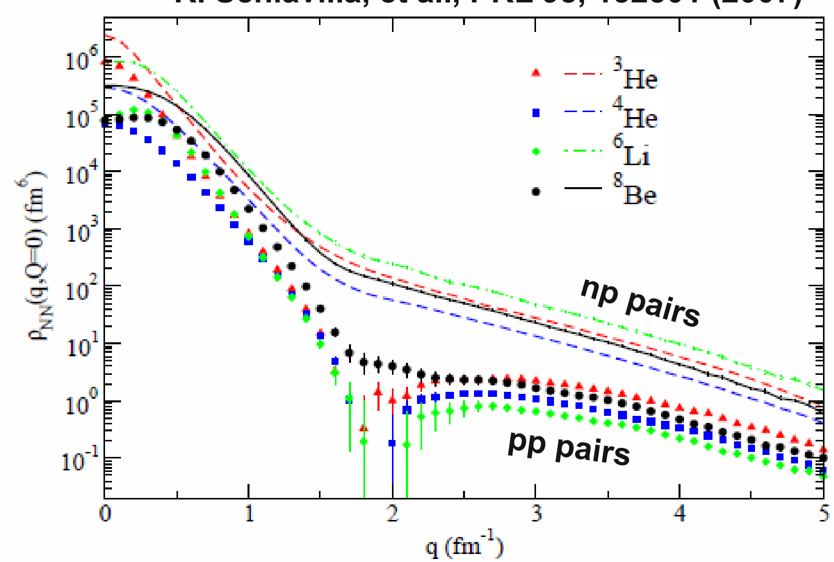
Inclusive ratios:
•Shows SRC-dominance for high momentum
•Determines relative SRC contributions
•Can't separate scattering from proton and neutron



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
•Fraction of pp pairs increases with initial nucleon momentum

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)



Brief detour: 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**
  - EMC/SRC connection + SRC n-p dominance suggests 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

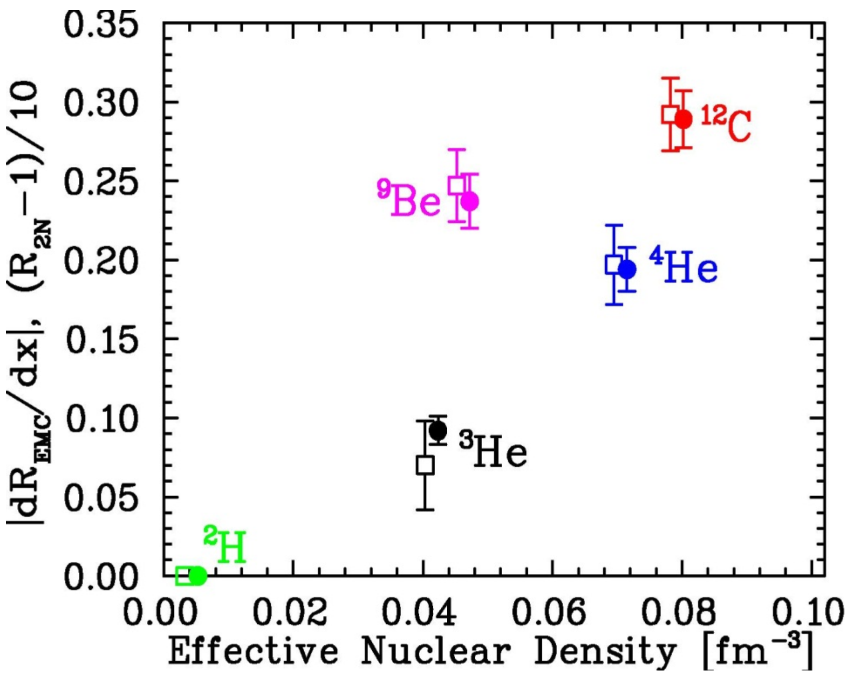
    [I. Cloet, et al, PRL 109, 182301 (2012); PRL 102, 252301 (2009)]

- **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 u(x)/d(x) at large x in the proton
  - ^{48}Ca: flavor dependence of 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]



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

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

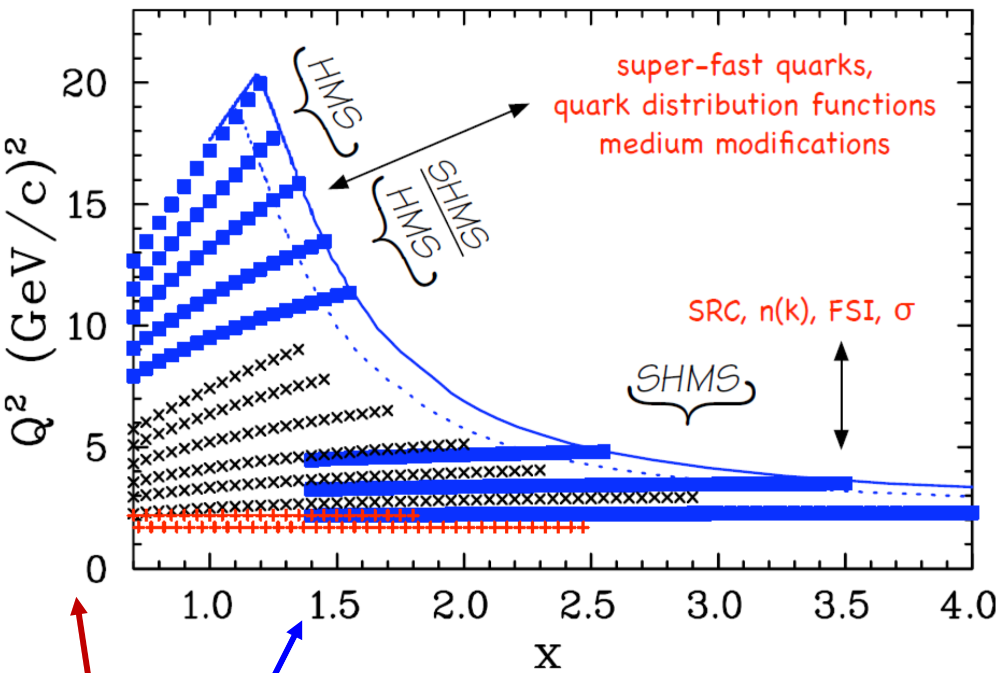
JA, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86 (2012) 065204

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

Where do we go from here?

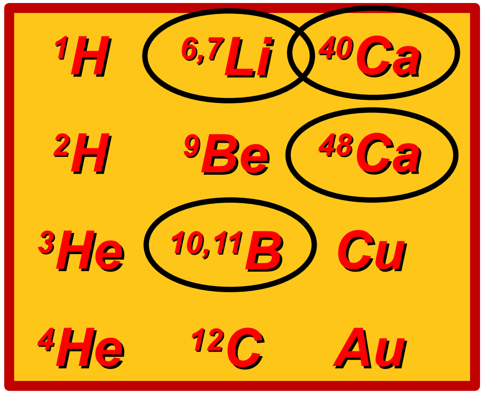
1) Additional nuclei to study cluster structure, EMC-SRC correlation

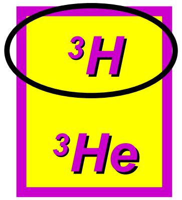
EMC and SRCs with JLab 12 GeV Upgrade

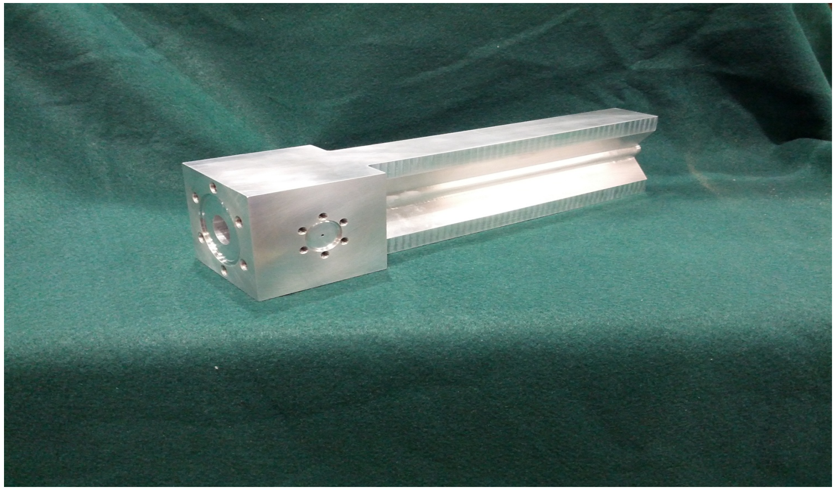


SRCs at x>1 at 12 GeV
[E06-105: JA, D. Day, N. Fomin, P. Solvignon]

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)

^{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

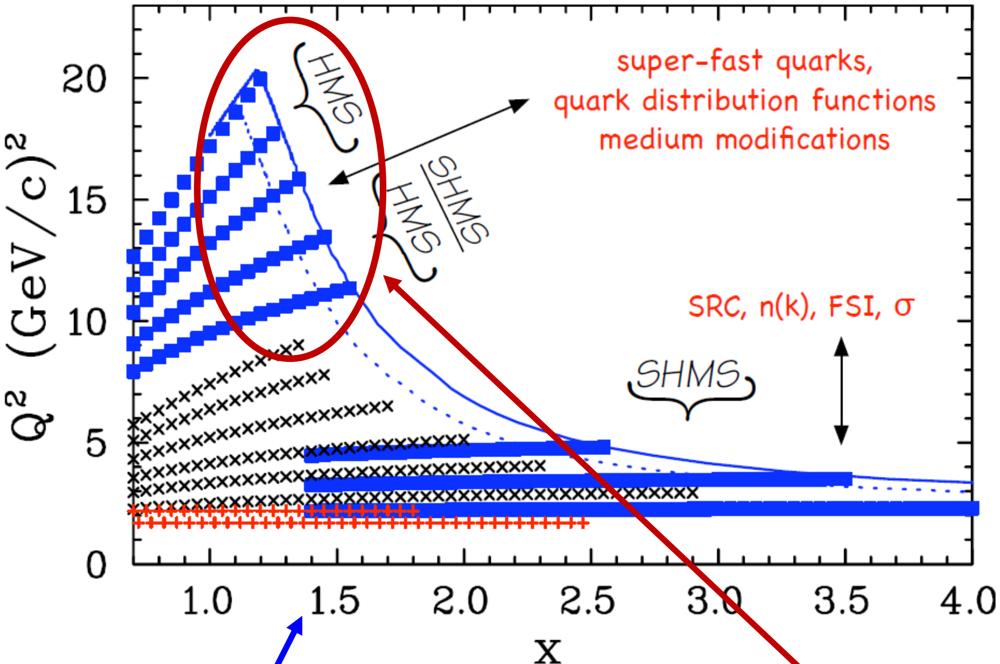
Where do we go from here?

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*

EMC and SRCs with JLab 12 GeV Upgrade



^{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

SRCs at x>1 at 12 GeV

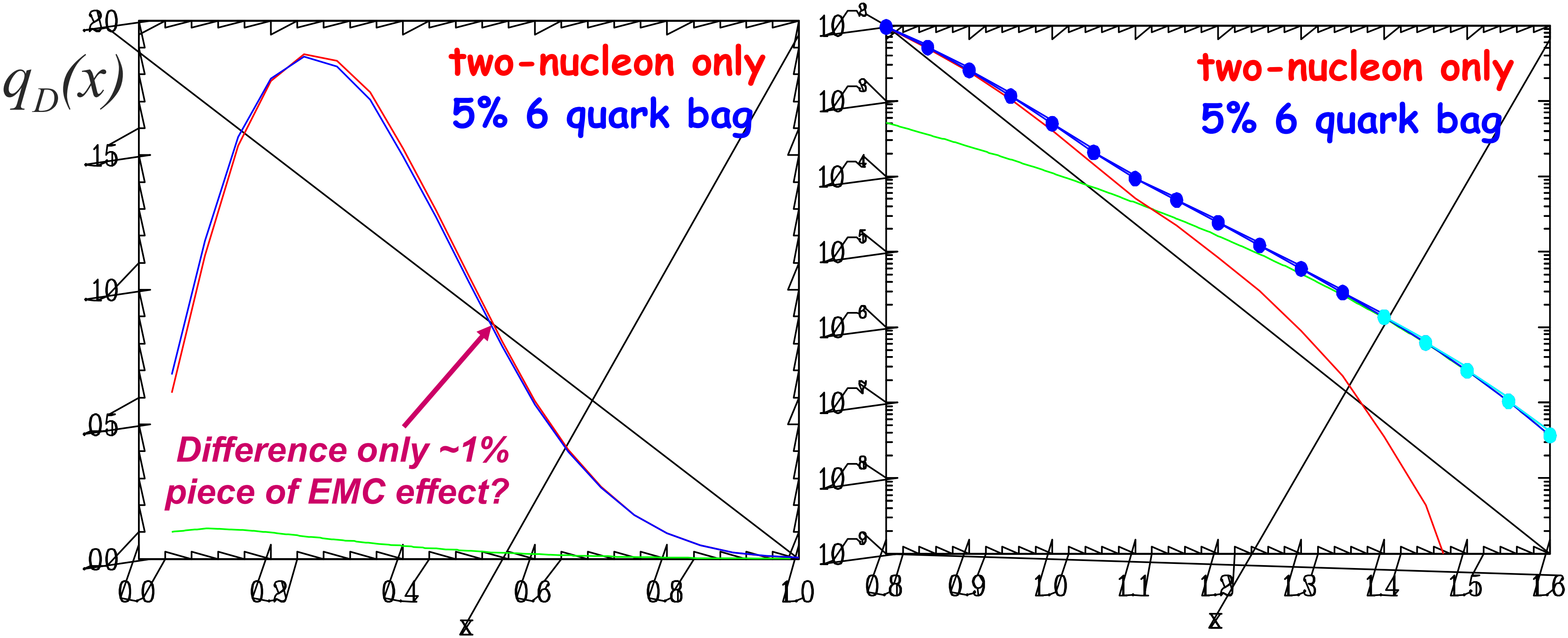
[E06-105: JA, D. Day, N. Fomin, P. Solvignon]

Focus on ^{2}H target at x>1 to isolate SRCs

Push to largest Q^2 to study 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

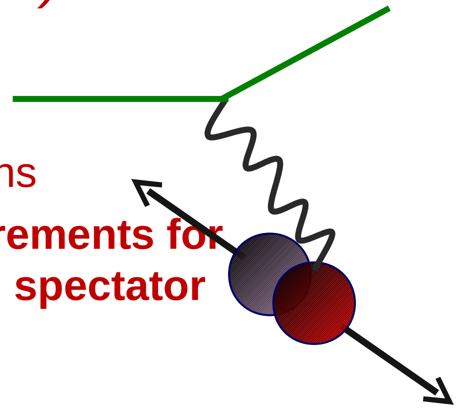
Where do we go from here?

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
  - tons
  - **surements for**
    um spectator

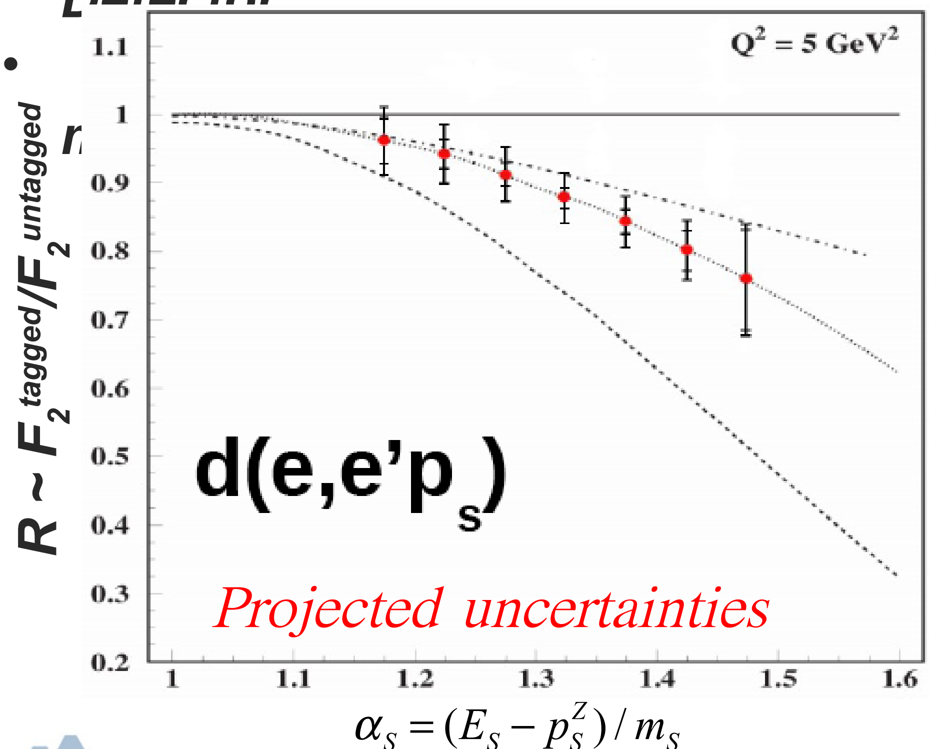
I won't discuss tagged measurements – instead, want to try and reconcile these observations with what we know about protons and neutrons

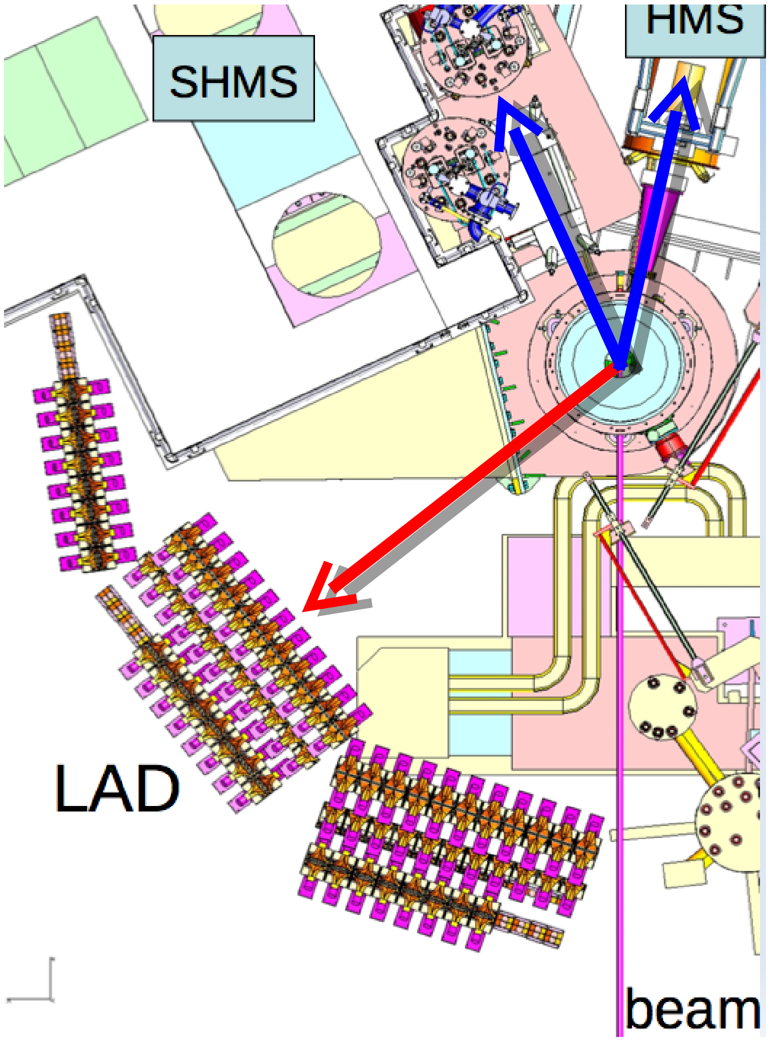


In-Medium Nucleon Structure Functions

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

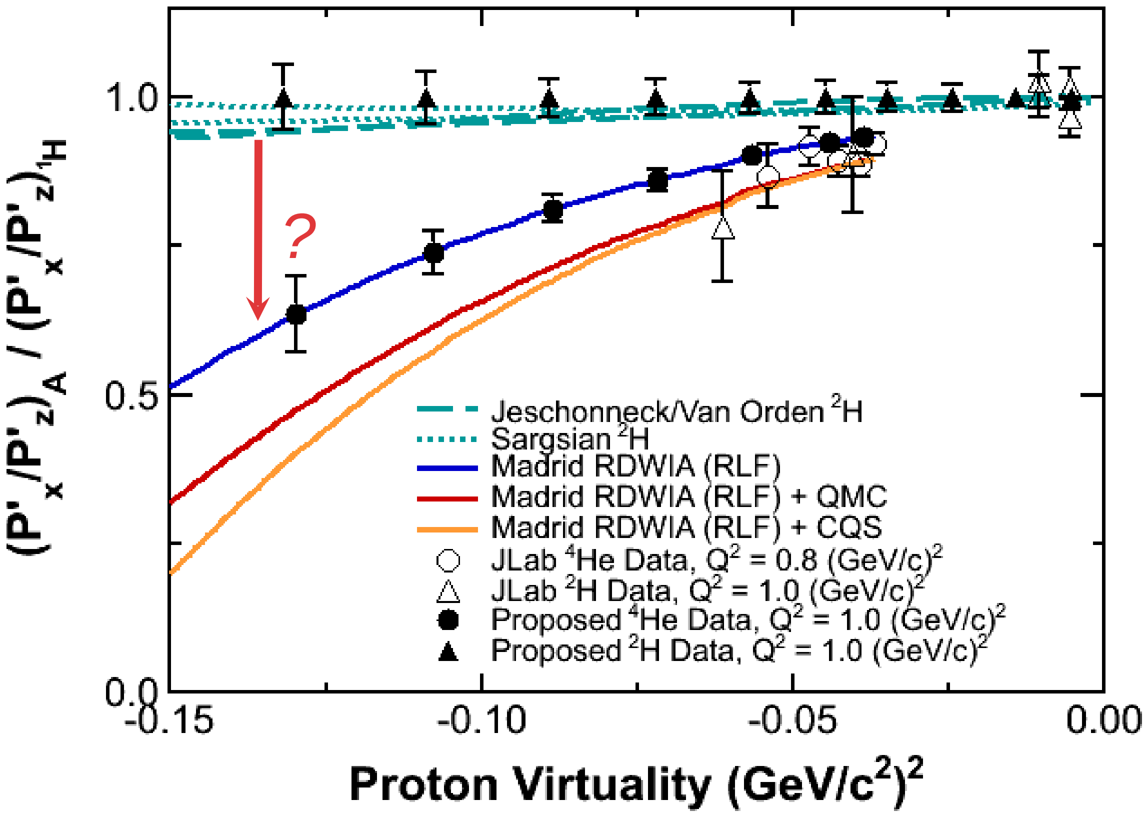
- ***DIS scattering from nucleon in deuterium***
- ***Tag high-momentum struck nucleons by detecting backward "spectator" nucleon in Large-Angle Detector***





In-Medium Nucleon Form Factors

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

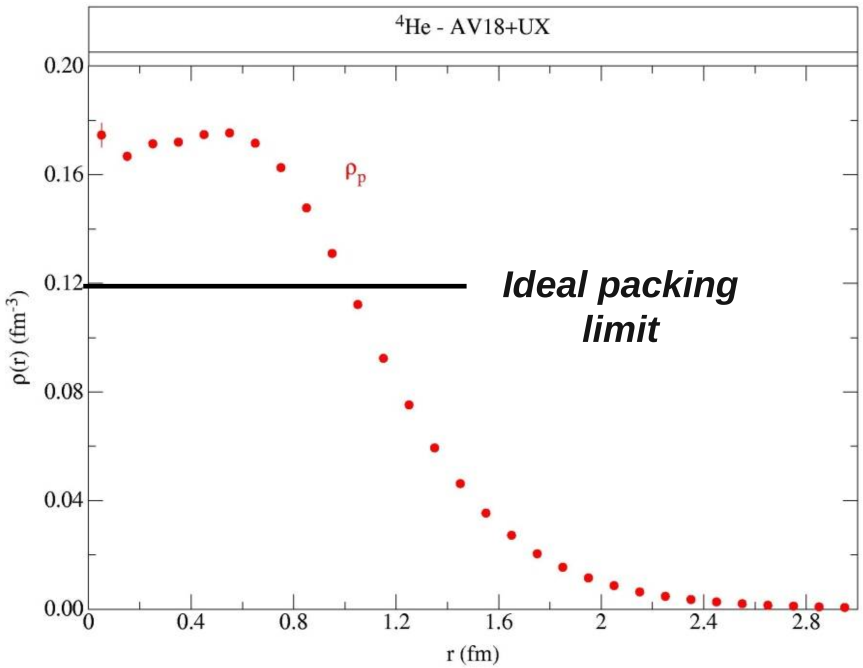


- **Compare proton knock-out from dense and thin nuclei:** **$^4He(e,e'p)^3H$ and $^2H(e,e'p)n$**
- **Modern, rigorous $^2H(e,e'p)n$ calculations show reaction-dynamics effects and FSI will change the ratio at most 8%**
- **QMC model predicts 30% deviation from free nucleon at large virtuality**

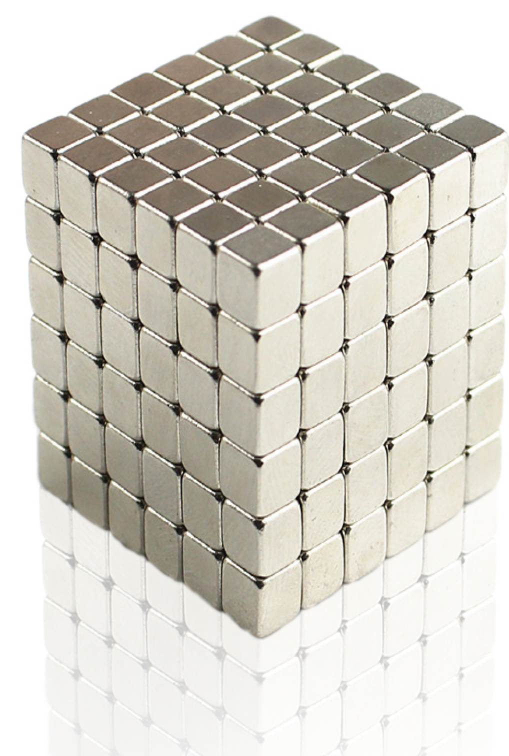
S. Jeschonnek and J.W. Van Orden, Phys. Rev. C 81, 014008 (2010) and Phys. Rev. C 78, 014007 (2008); M.M. Sargsian, Phys. Rev. C82, 014612 (2010)

How dense are nuclei?

- **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: $_{max}$ = 0.12 fm^{-3}**
  - *Well below peak densities in nuclei*
  - *Need 100% packing fraction for dense nuclei*
  - *Can internal structure be unchanged*

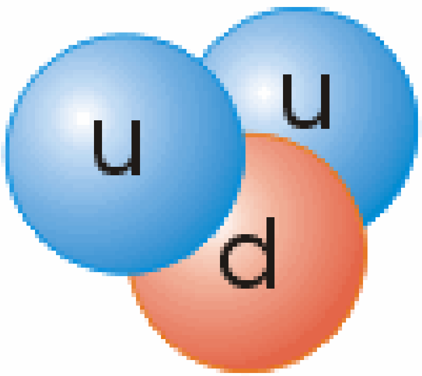


4He matter density from GFMC calculation, courtesy of B. Wiringa

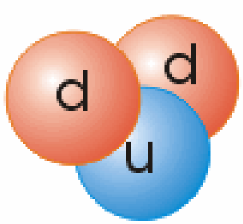


A Simple, Popular, View of the Proton

The Proton



The Neutron

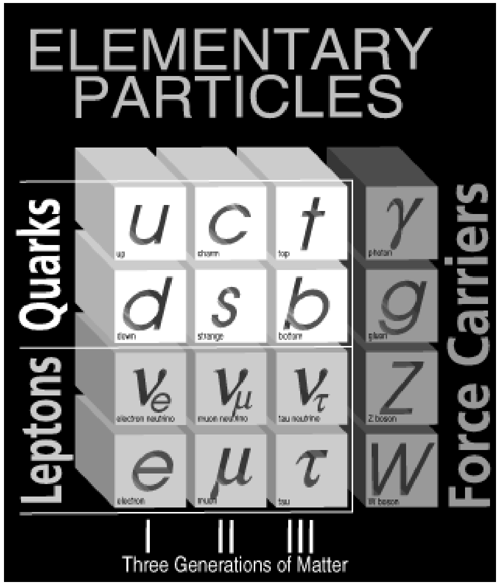


- **The proton consists of two up (or *u*) quarks and one down (or *d*) quark.**
  - **A u-quark has charge +2/3**
  - **A d-quark has charge –1/3**
- **The neutron consists of two down, one up**
  - **Hence it has charge 0**
- **The u and d quarks mass is ≈1/3 the proton's**
  - **Explains why m(n) = m(p) to ~0.1%**
- **But, very hard to explain zoo of hadrons**
  - **M   ≈ 140, 490, 550, 780 MeV**
  - **M   ≈ 1120, 1190, 1230 MeV**

with 300 MeV quarks

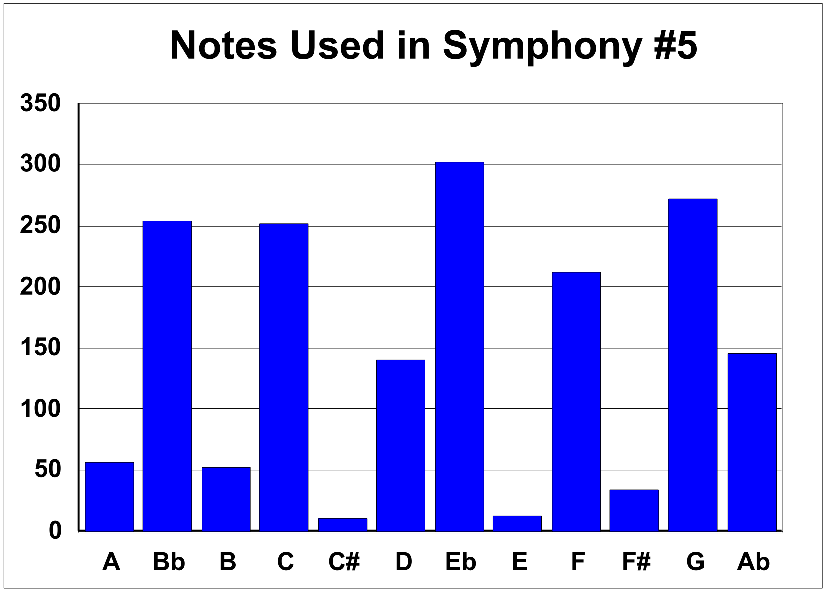
Slides adapted from Tom LeCompte

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



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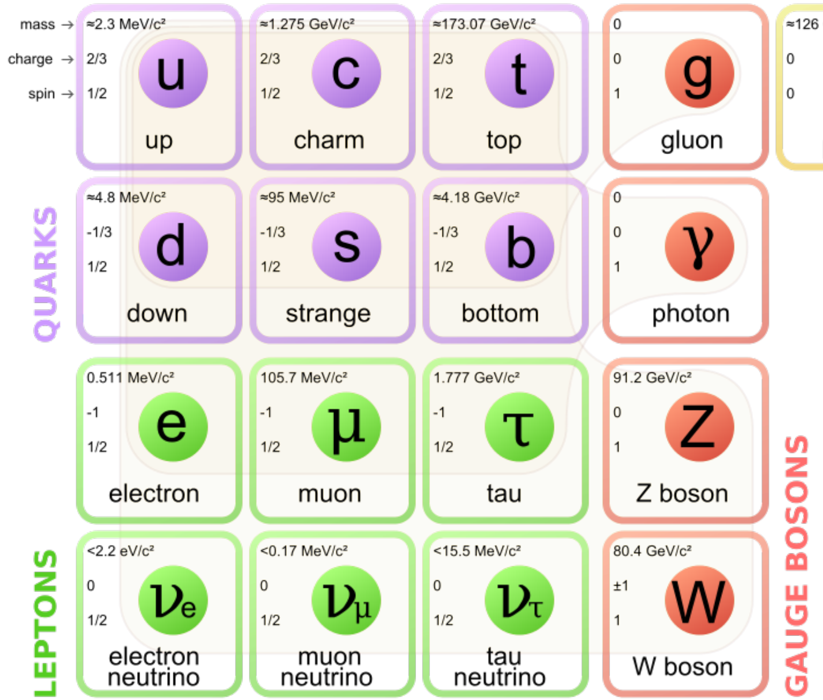
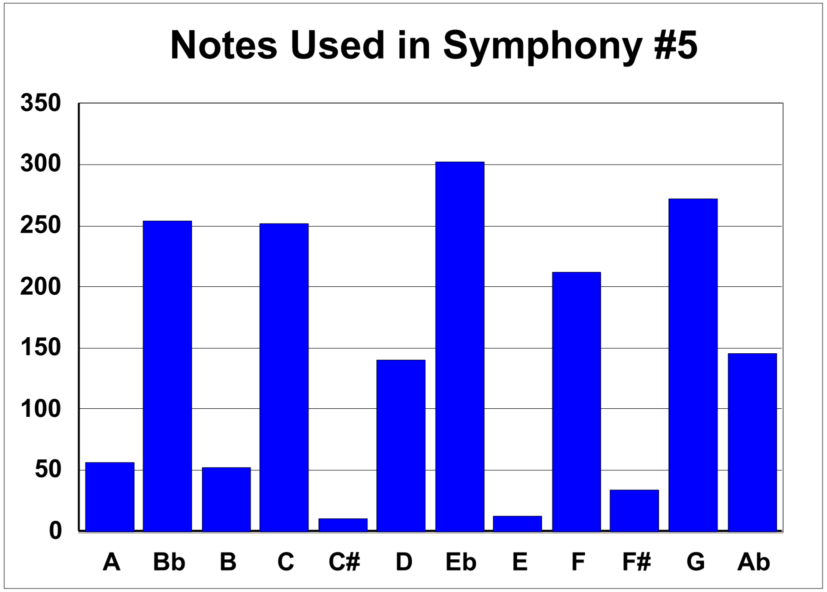


Fundamental constituents of matter

The constituents (and frequency of appearance) of the first movement of Beethoven's 5th Symphony



Energy is Stored in Fields

- We know energy is stored in electric & magnetic fields
  - Energy density ~ $E^2 + B^2$
- Energy is also stored in the 'gluon field' in a proton
  - There is an analogous $E^2 + B^2$ that one can write down
  - Nothing unusual about the idea of energy stored there
    - What's unusual is the amount:

	Energy stored in the field
Molecule	$\sim 10^{-10}$ (4 eV / 60 a.m.u.) [NaCl, O_2]
Atom	$\sim 10^{-8}$ (13.6 eV / 938 MeV)
(Relative to $M_{electron}$)	$\sim 10^{-5}$ (13.6 eV / 511keV)
Nucleus	~1% (10 MeV / nucleon)

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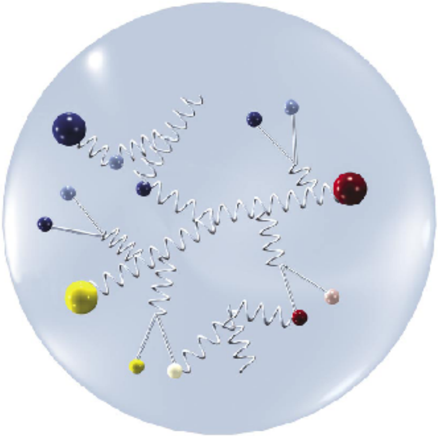
(Relative to $M_{electron}$)	~10^{-5} (13.6 eV / 511keV)
Nucleus	~1% (10 MeV / nucleon)
Proton (hadron)	??? ~10 MeV (u+u+d), 938 MeV total 99% is in the field; **increases mass!**

A Better, More Complicated Picture of the Proton



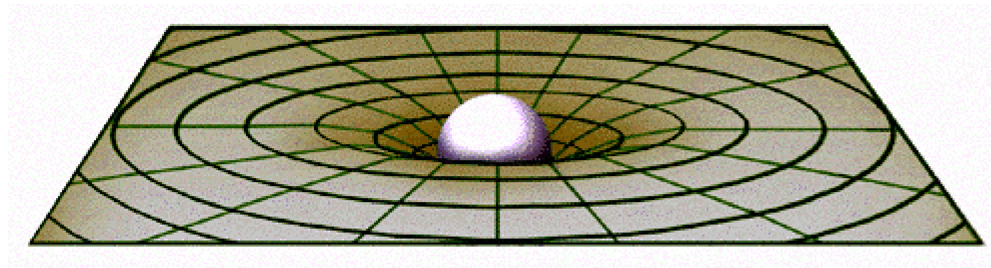
The Proton

- **99% of the proton's mass/energy is due to this self-generating 'gluon field'**
- **The two u-quarks and single d-quark**
  - **Provide the 'identity'** of the hadron through electromagnetic properties(*quantum numbers*)
  - Act as *boundary conditions* on the field (more than generators of the field)
- **Similarity of the proton and neutron masses is because the gluon dynamics are the same**
  - Has almost nothing to do with the quarks

Hadron as a dynamic, self-interacting gluon field localized around quarks whose quantum numbers identify the hadron

Analogy to gravity

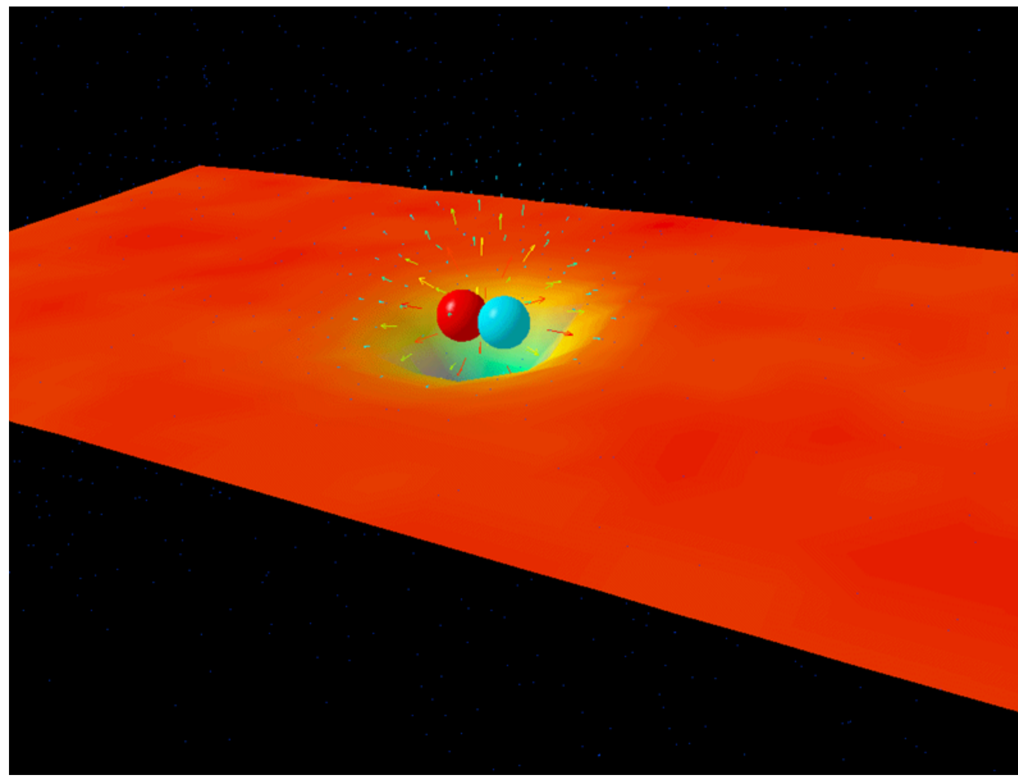
Just as gravity can be viewed as mass distorting spacetime, one can picture a hadron as quarks distorting the quantum vacuum



DSE and Lattice QCD show localized generation of a chiral condensate in hadrons. Lowest Fock state is 3q core with R_{core} 0.6 fm vs. R_{proton} 0.9 fm

More natural scale for NN potential

<u>Identity</u> of proton localized in central 1/3 of it's volume; the large overlap in nuclei is mainly limited to this surrounding universal gluon field



Localized condensate helps

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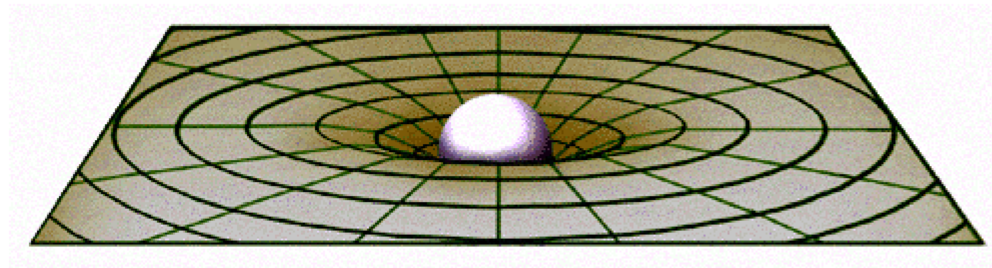

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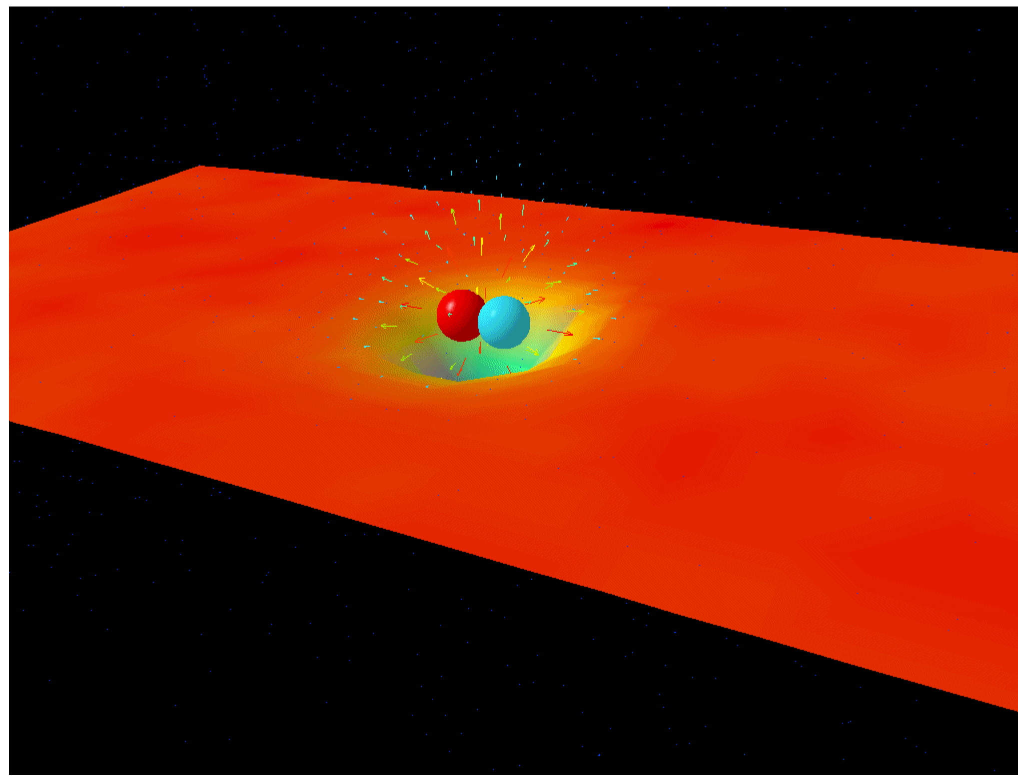

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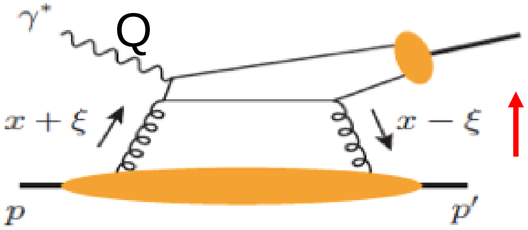
Localized condensate helps

GPDs: Imaging gluons at an EIC

Exclusive vector meson production:



$J/\Psi, \Phi, \cdots$

t-dep

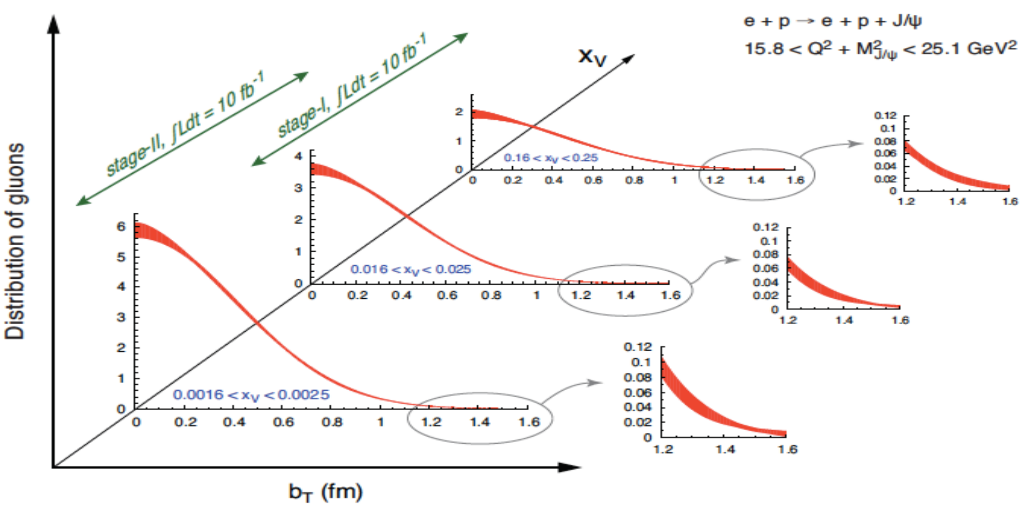
$$\frac{d\sigma}{dx_B dQ^2 dt}$$

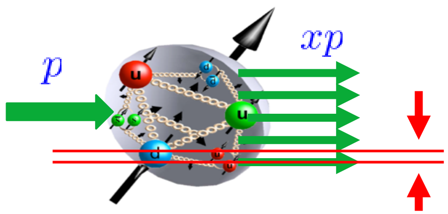
Fourier transform of the t-dependence

→ *Spatial imaging of glue density*

Resolution ~ 1/Q or 1/M_Q

Gluon imaging from simulation:



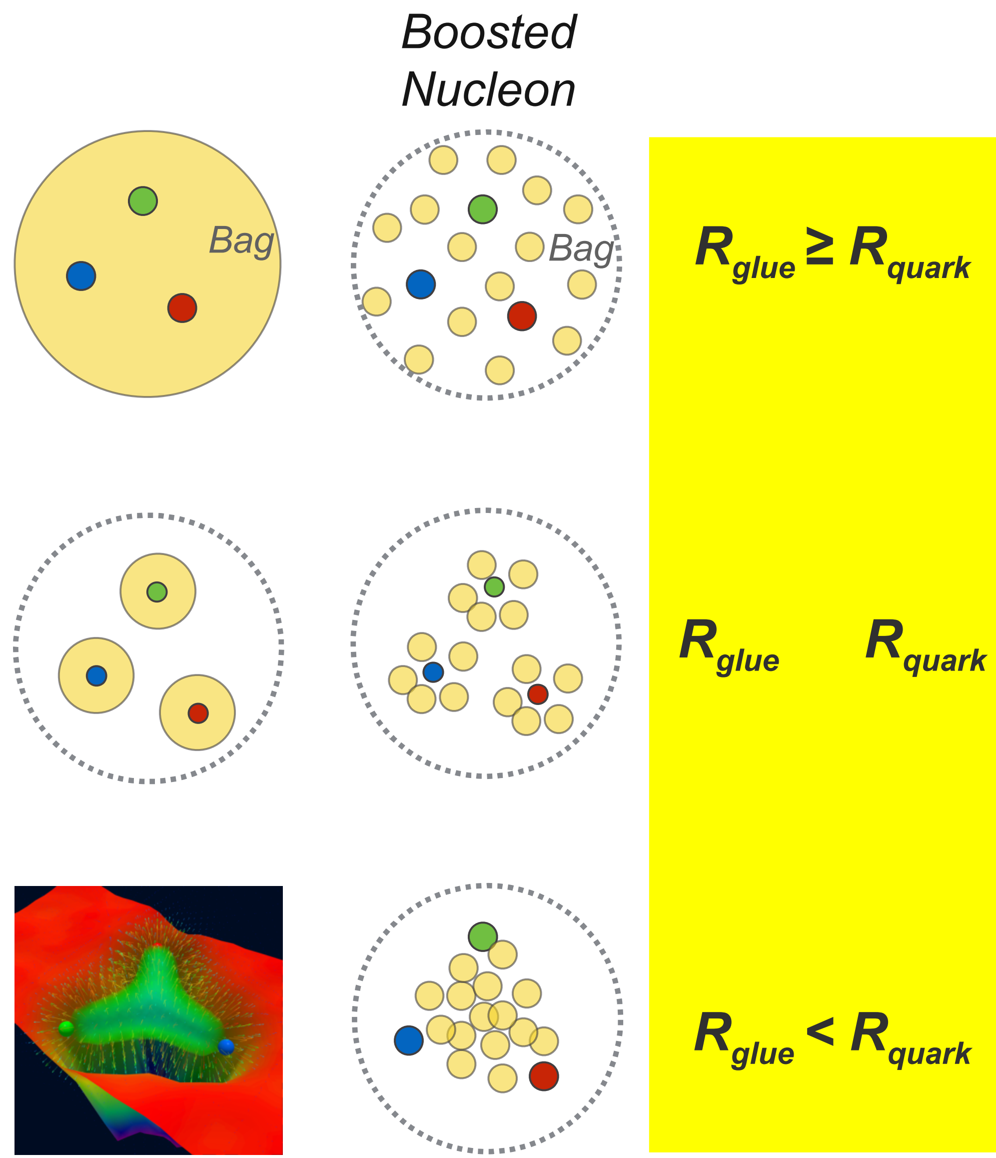


Images of transverse gluon distributions from exclusive J/ production

Only possible at the EIC: From the valence quark region deep into the gluon / sea quark region

Where are the gluons?

- Bag model:
  - Bag radius provides as single size scale for both quarks and gluons/sea
- Constituent quark model:
  - Gluons and sea quarks "bound" inside massive quarks
  - Sea parton distribution similar to valence quark distribution
- Flux tube picture:
  - Shown in quenched LQCD
  - gluons localized in center



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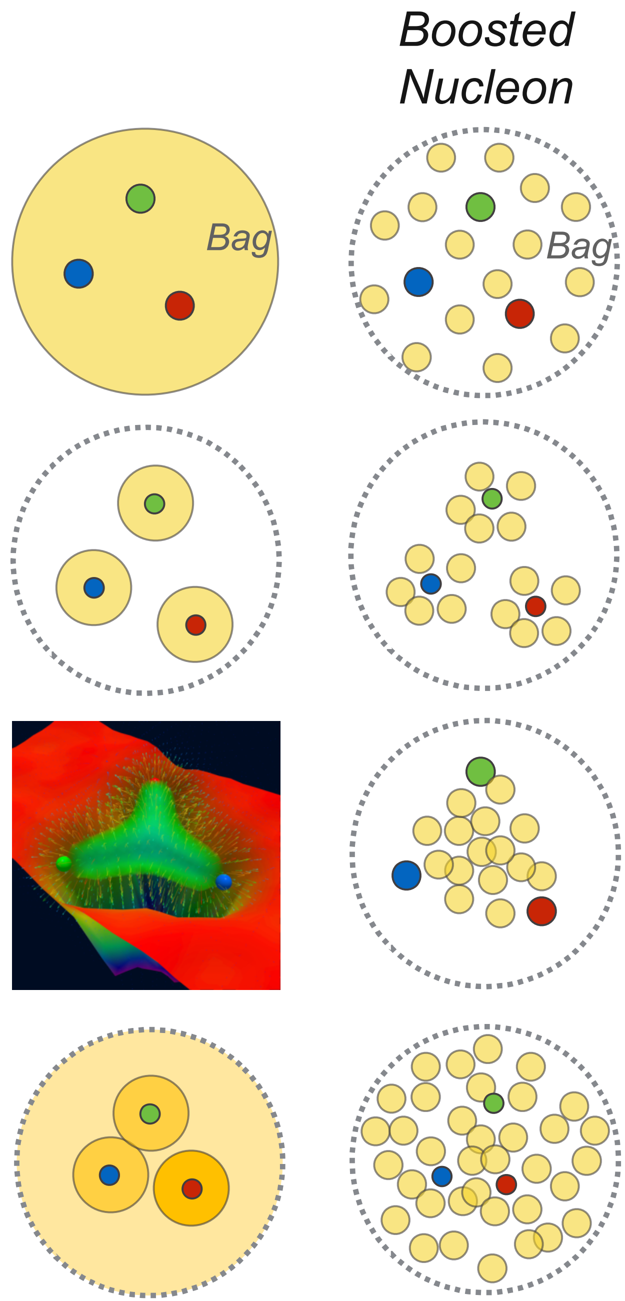
- Flux tube picture:
  - Shown in quenched LQCD
  - Gluons localized in center
- 3q core (0.6 fm), gluon field (0.9fm)
  - Quark core is ~1/3 of volume
  - Overlap in nuclei is mainly



$R_{glue} \geq R_{quark}$

R_{glue} R_{quark}

$R_{glue} < R_{quark}$

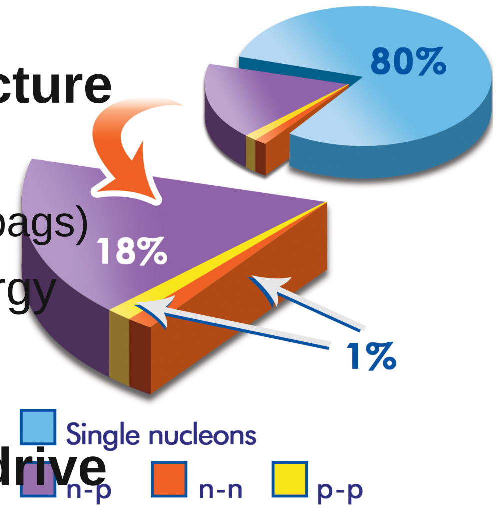
$R_{glue} > R_{quark}$

by ~50%

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   -A scattering, neutron stars, symmetry energy



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

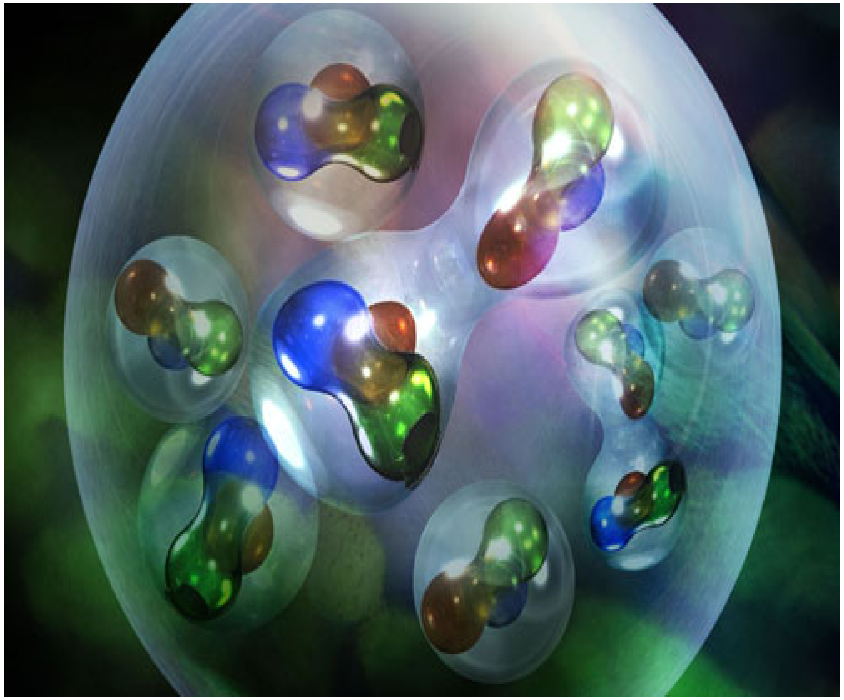
These dense, energetic configurations appear to drive the EMC effect, modifying proton's internal structure

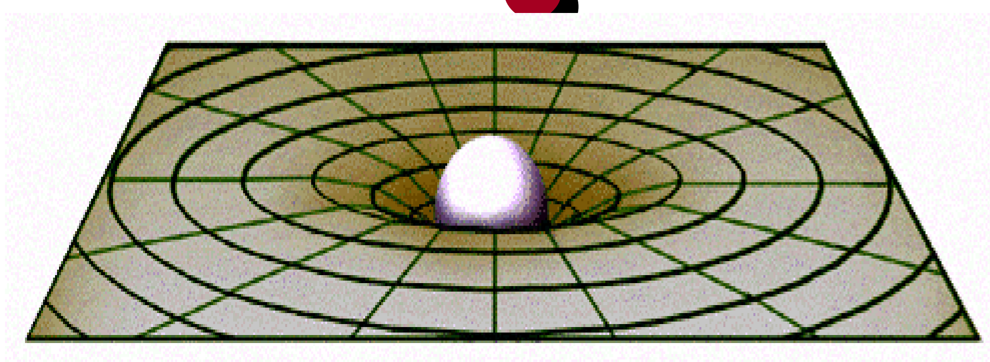
JLab 12 GeV and EIC can use tagging to probe structure of nucleons inside these high-density configurations

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

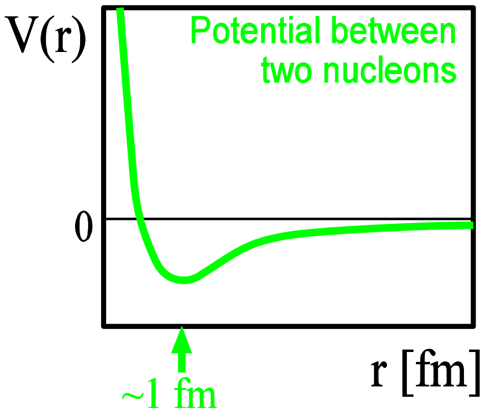
Drell-Yan and   -A scattering (FNAL), PVDIS, and EIC can examine flavor dependence and isolate nuclear effects for sea, valence, and glue

Fin....





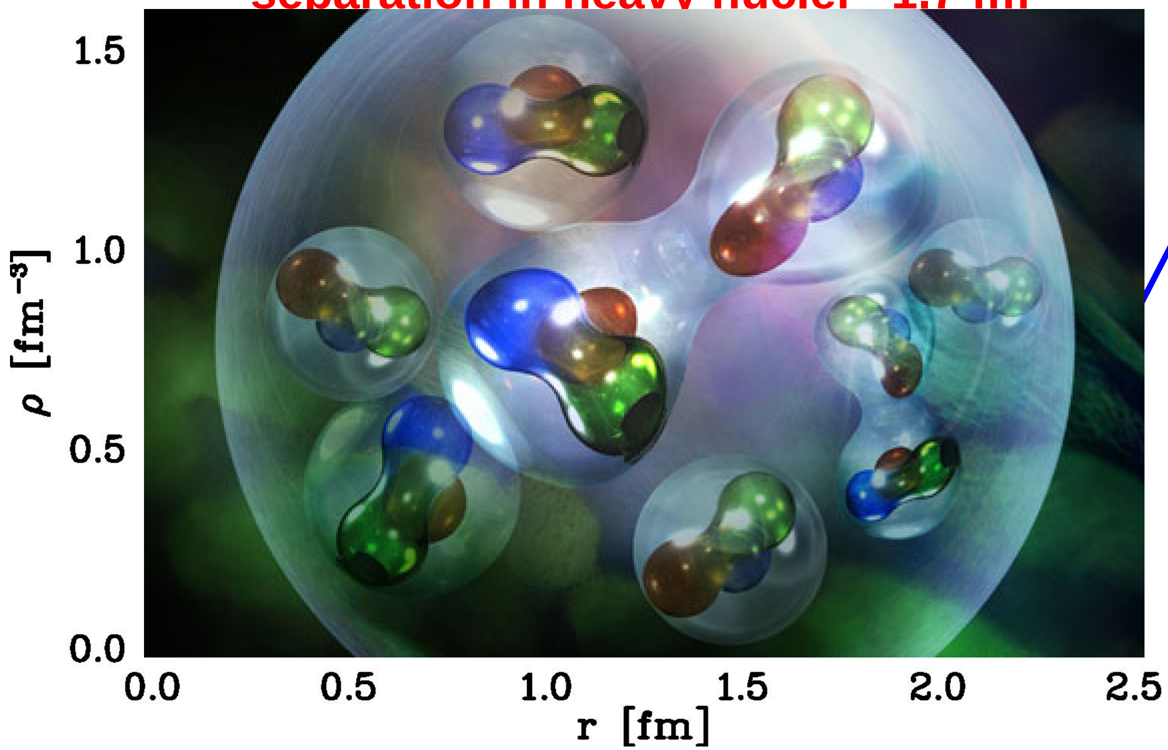
Nuclear densities and quark structure?



Nucleons are composite objects

charge radius ~0.86 fm

separation in heavy nuclei ~1.7 fm



Average nuclear density

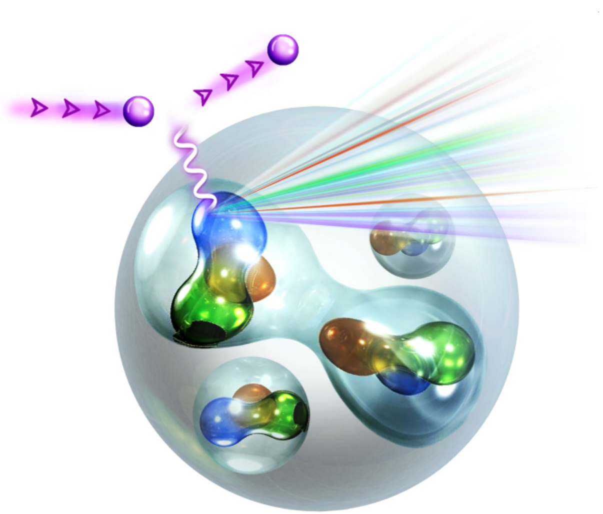
Are nucleons unaffected by this overlap?

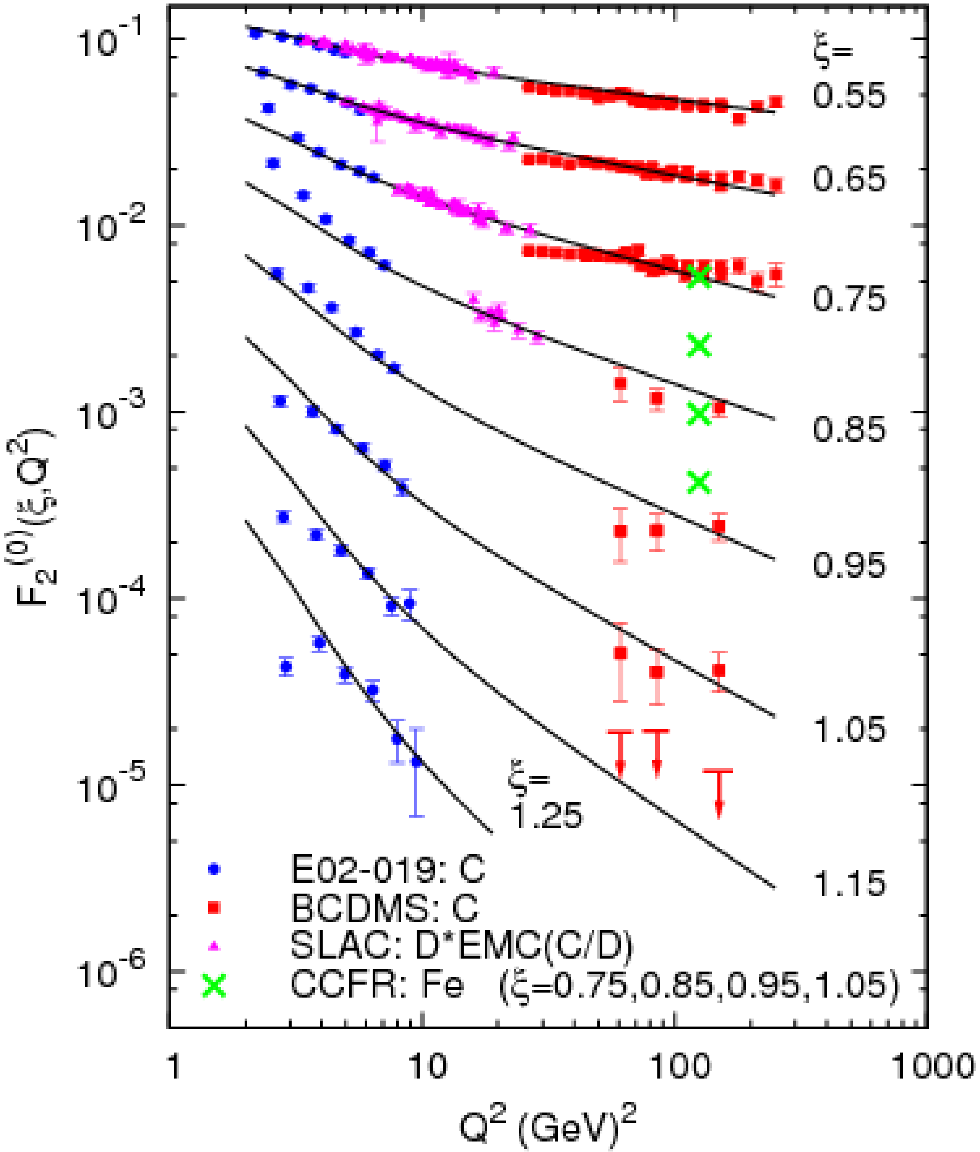
Do they deform as they are squeezed together?

Do the quarks exchange or interact?

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)

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

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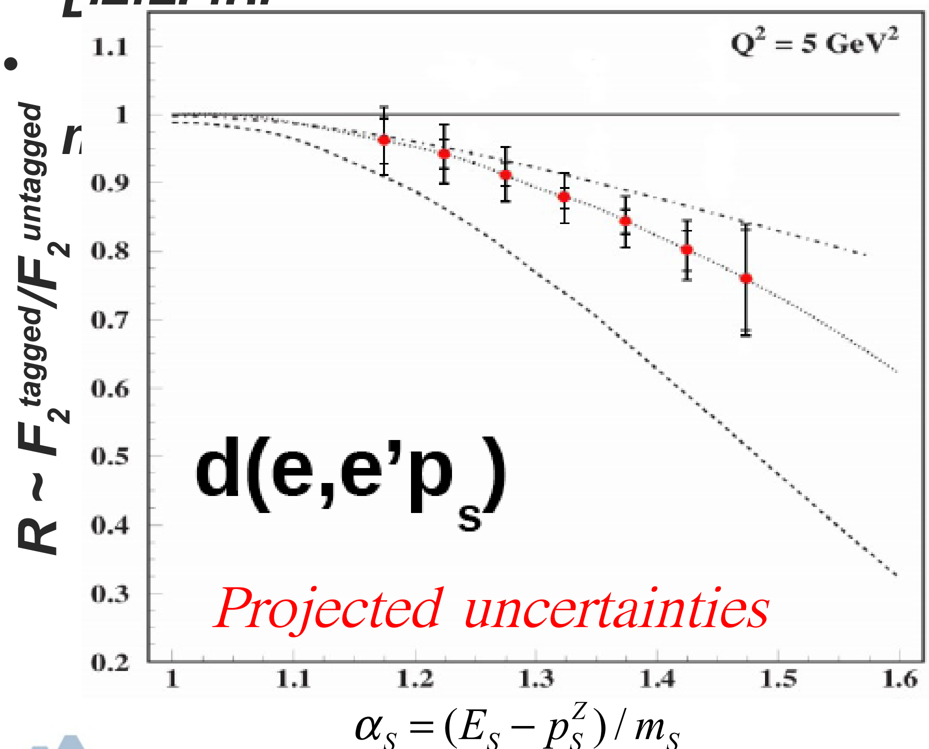
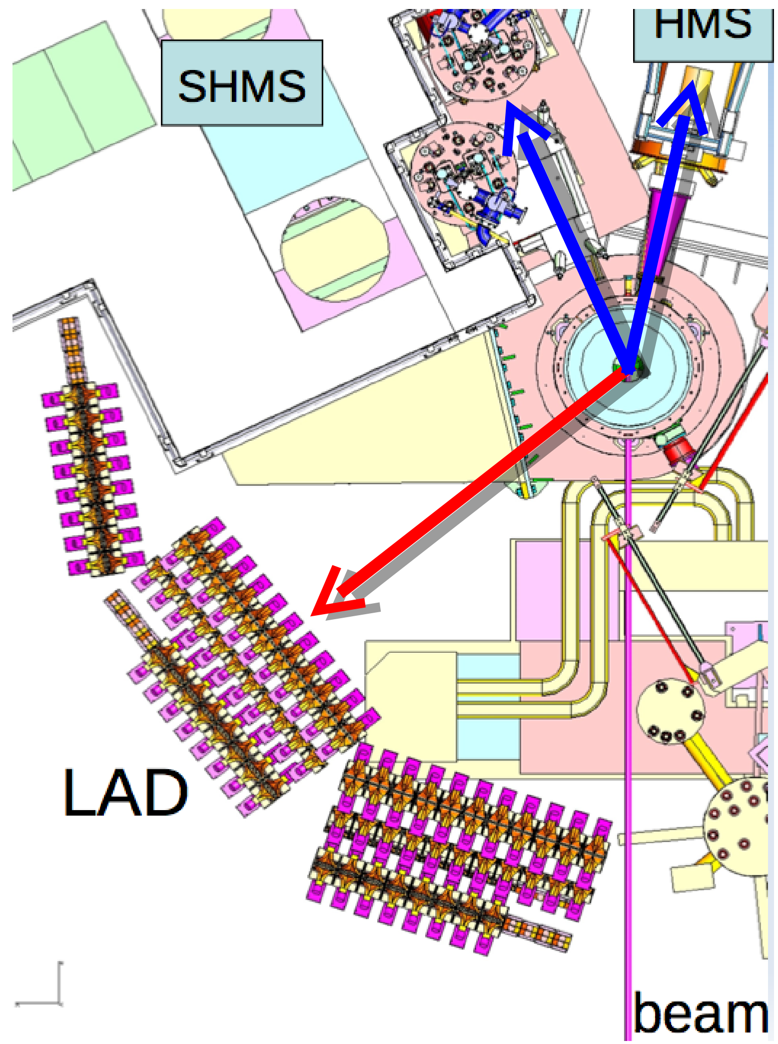
- *r*





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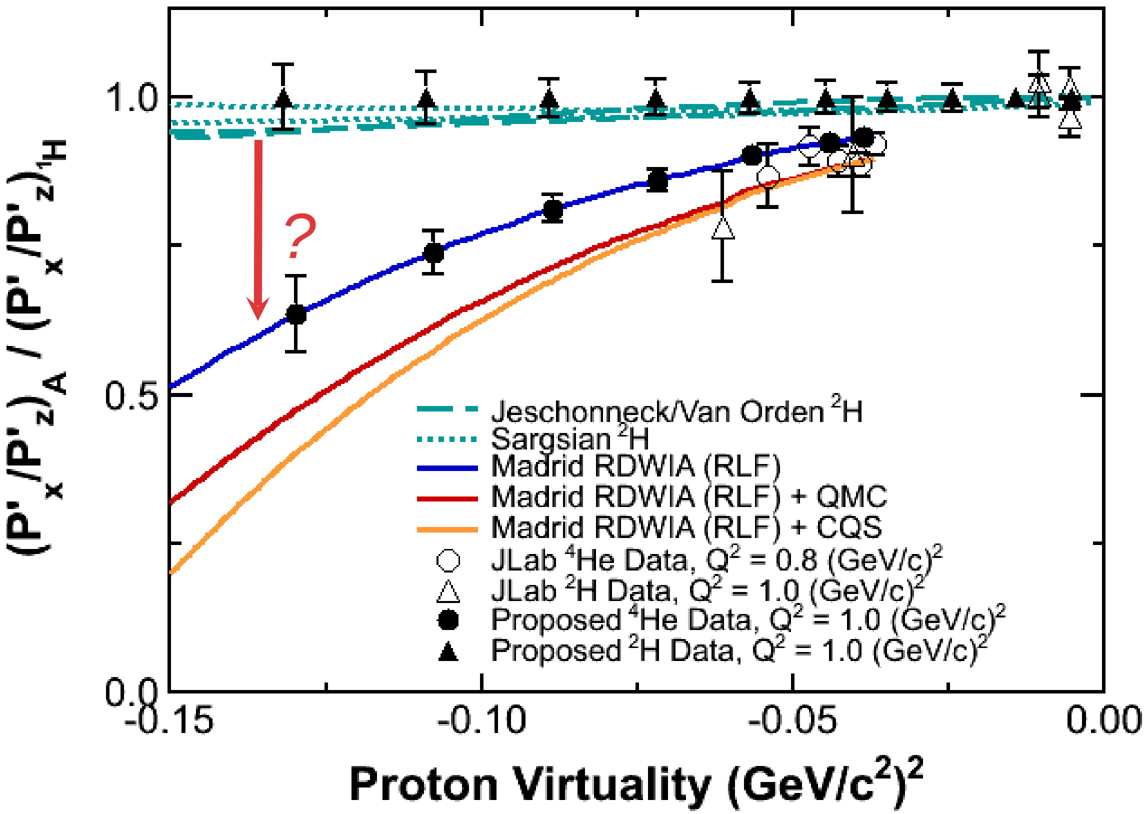

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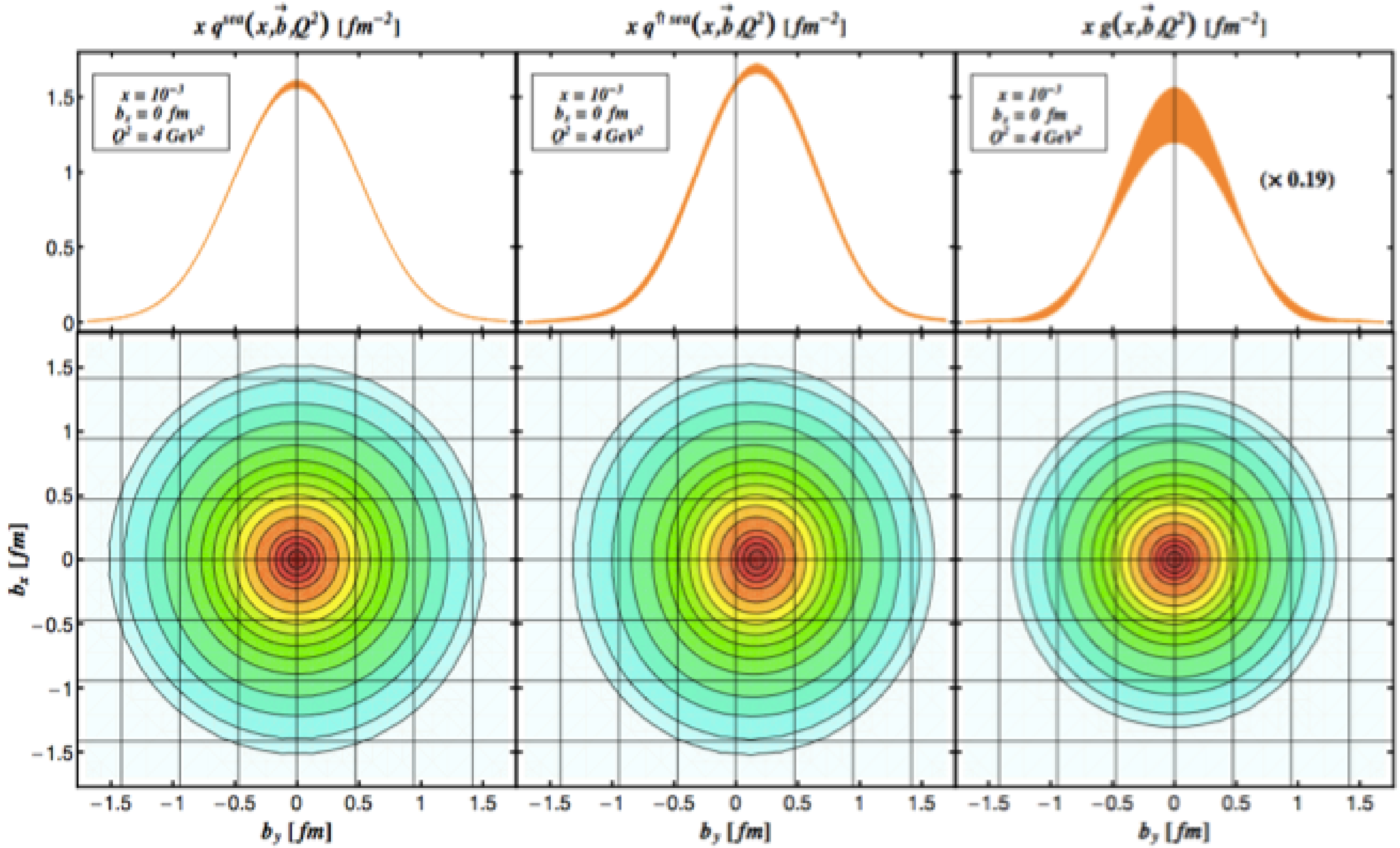
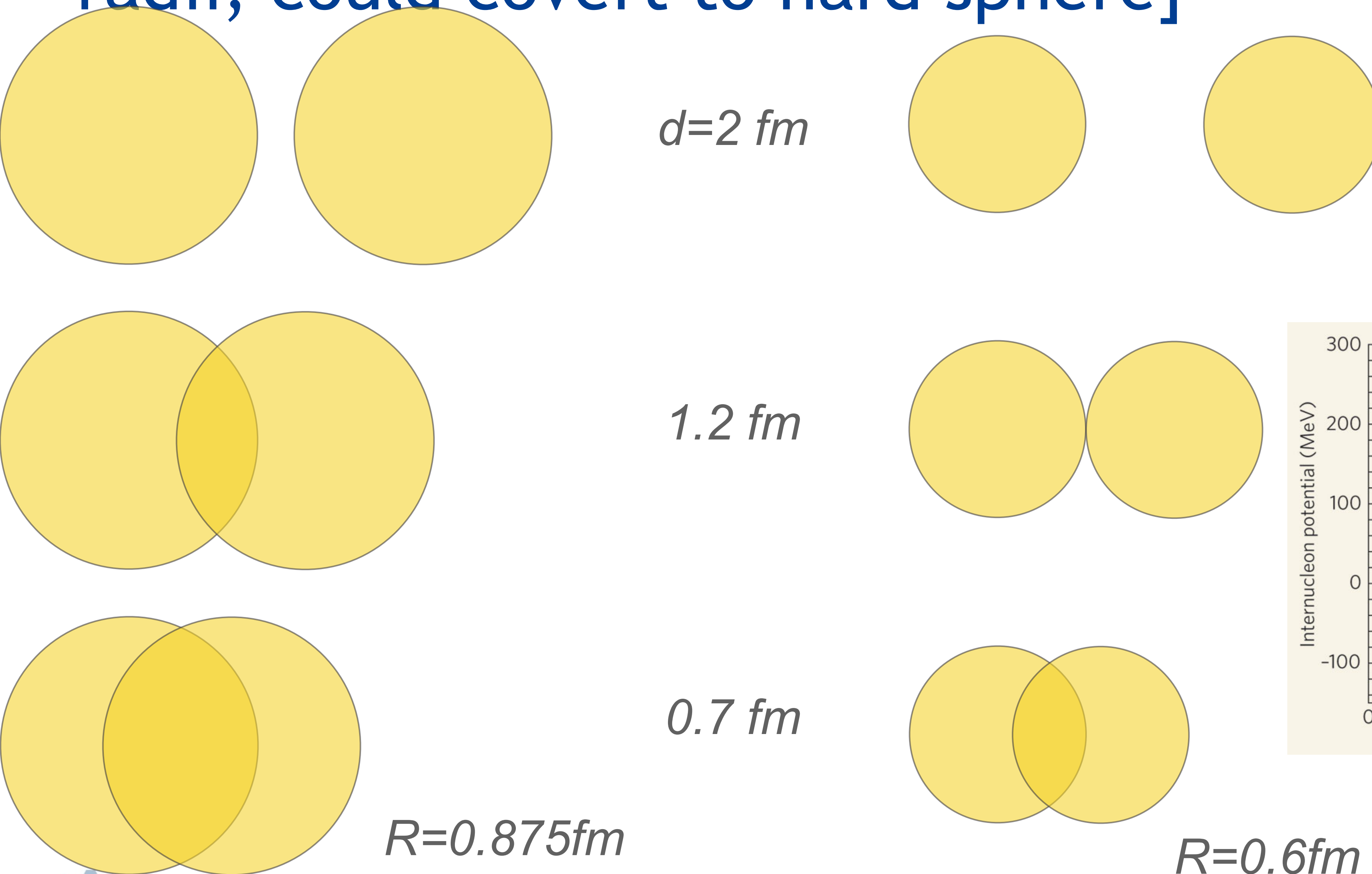
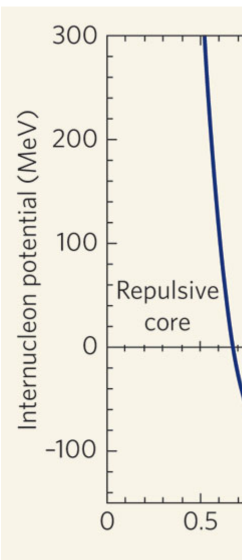
Imaging quarks and gluons

using Generalized Parton Distributions (GPD's):

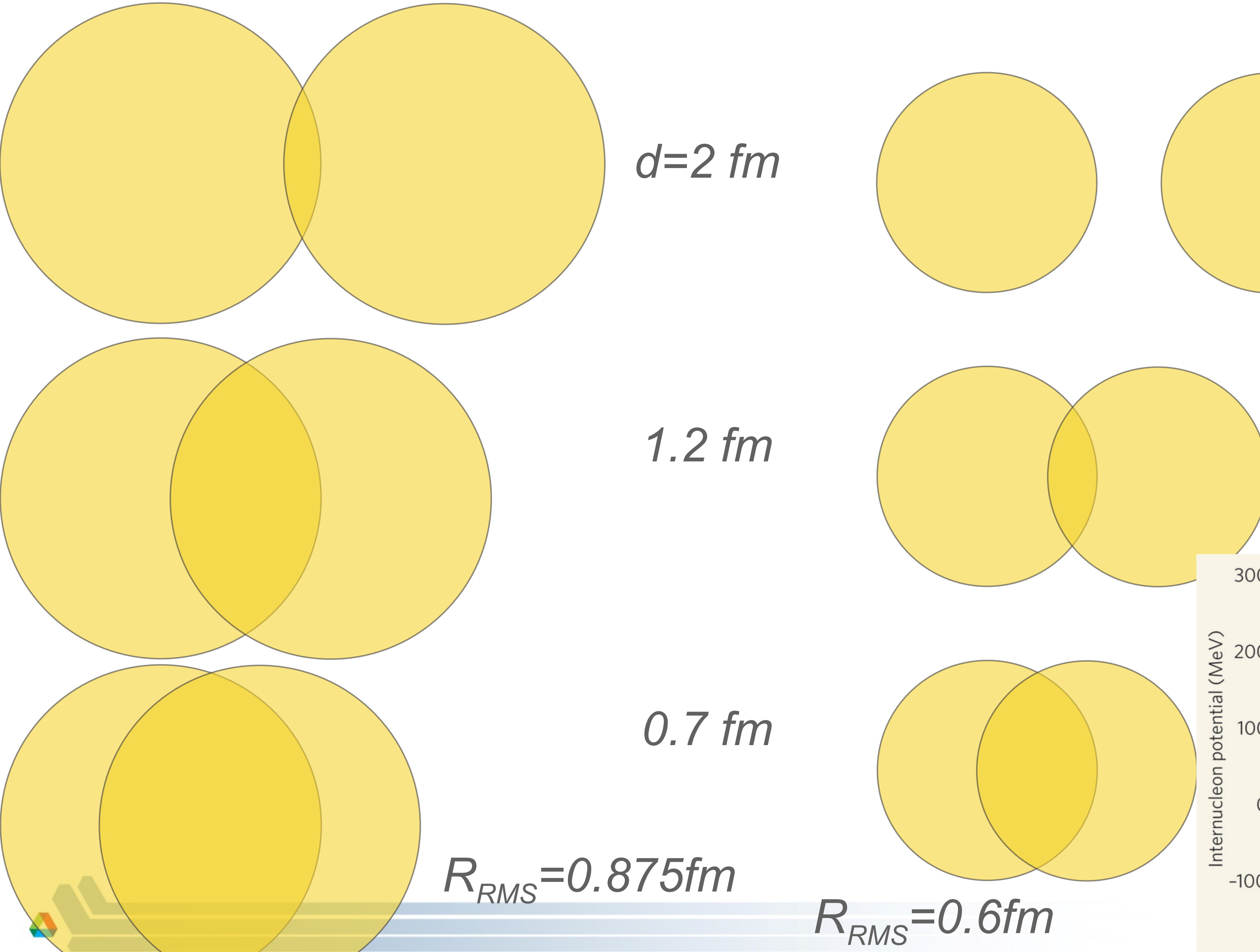


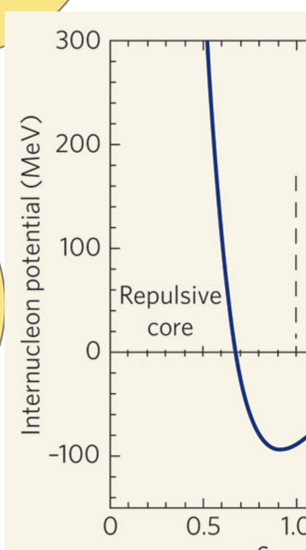
Where are the gluons? [showing RMS radii, could covert to hard sphere]



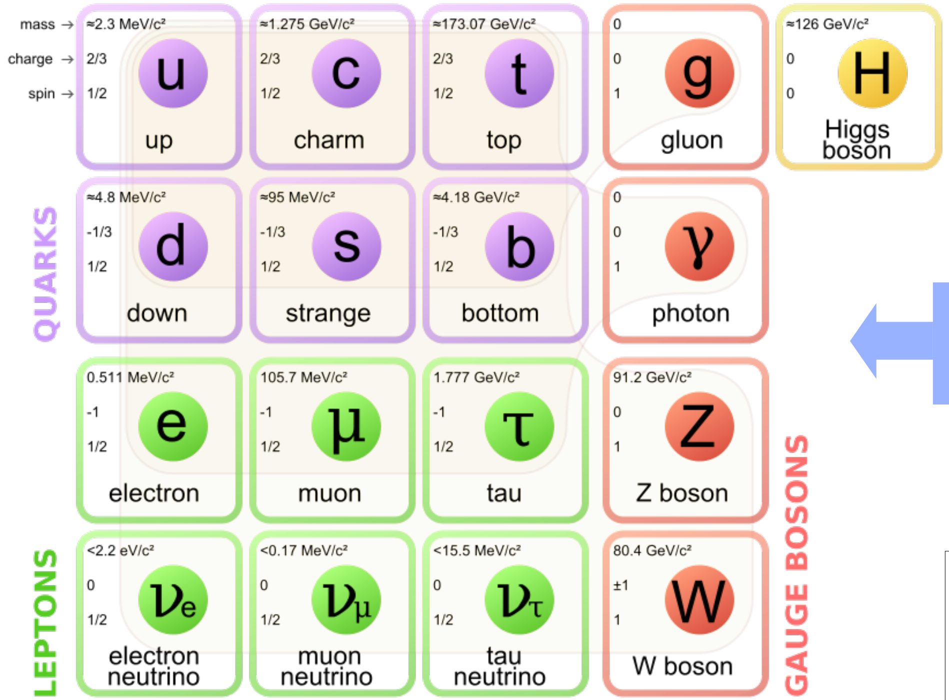


Where are the gluons? [uniform sphere]



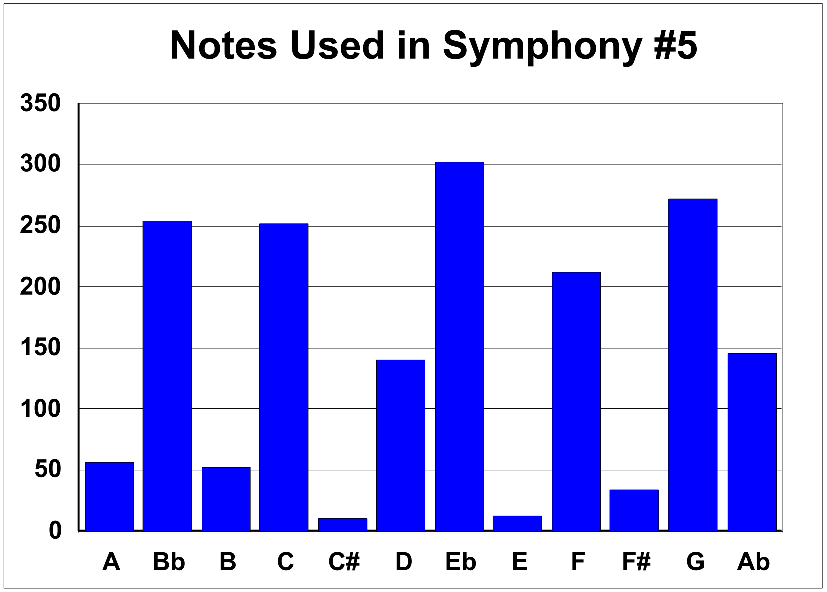


Constituents are not enough



Fundamental constituents of matter

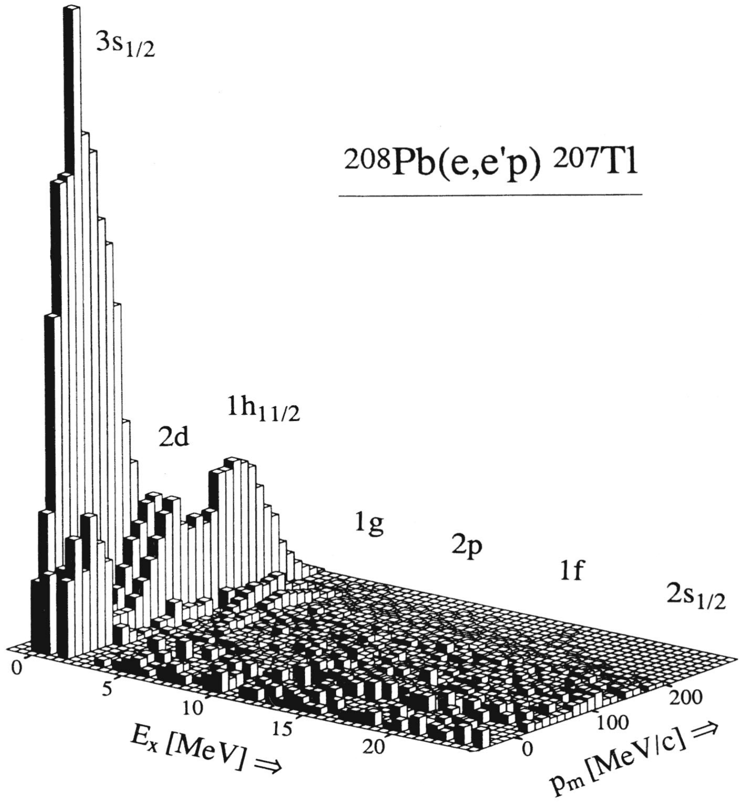
The constituents (and frequency of appearance) of the first movement of Beethoven's 5th Symphony

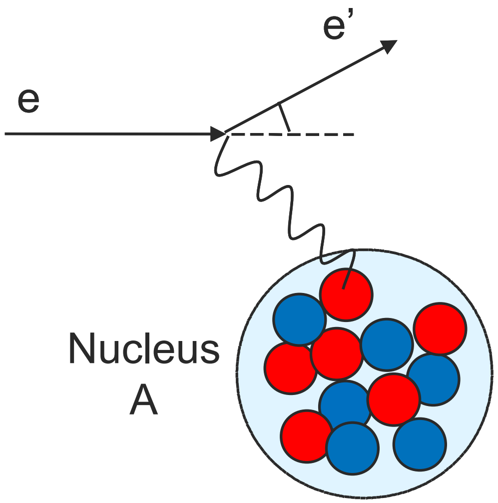


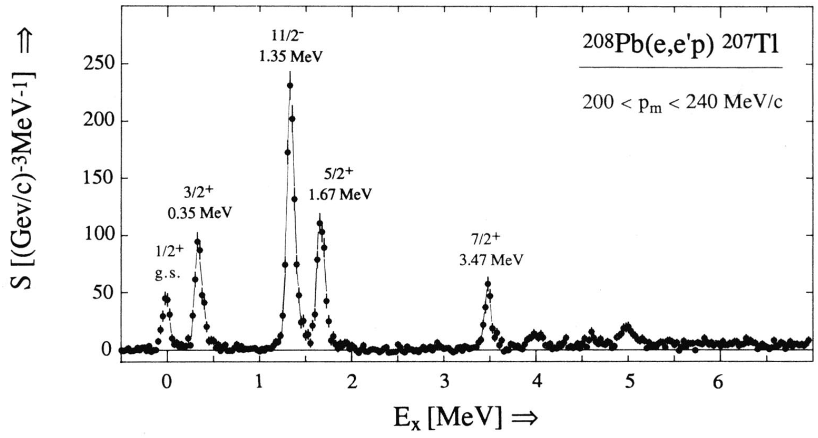
Quasielastic A(e,e'p) scattering

PWIA approximation for proton knockout

- Reconstruct initial proton binding energy (E_m), momentum (p_m)



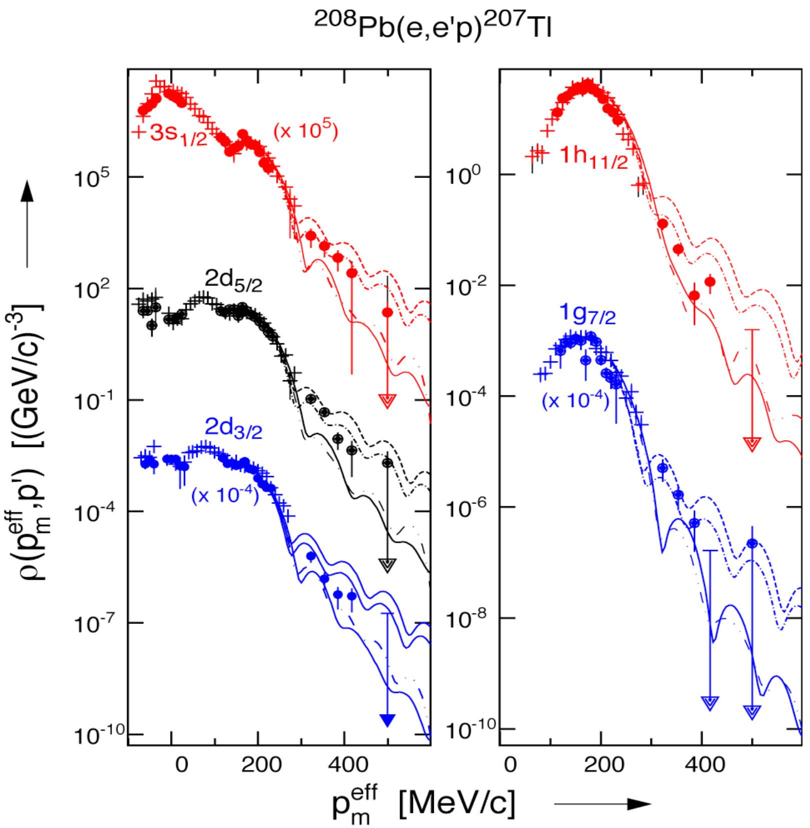


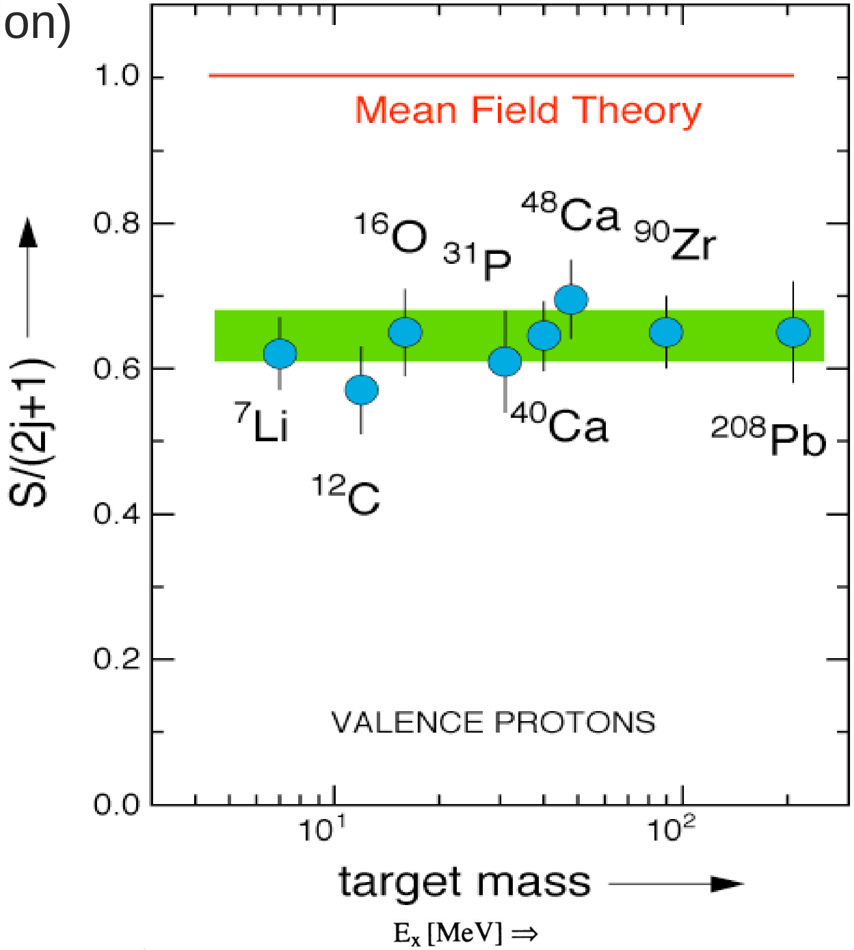


Quasielastic A(e,e'p) scattering

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)





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

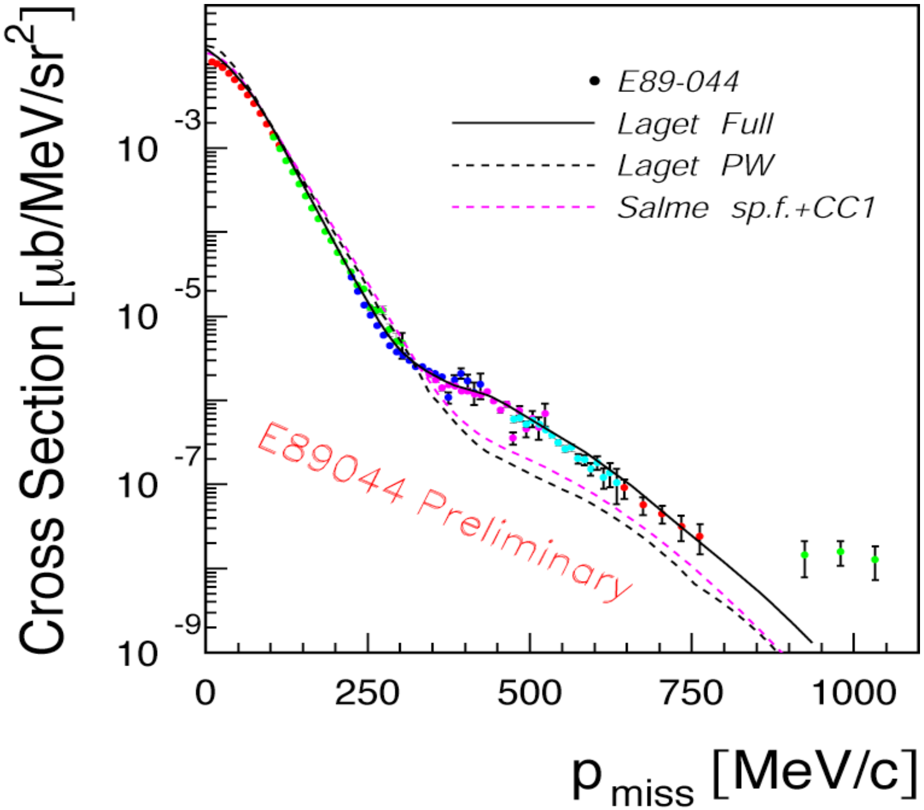
JLab E89-004: ^{3}He(e,e'p)d

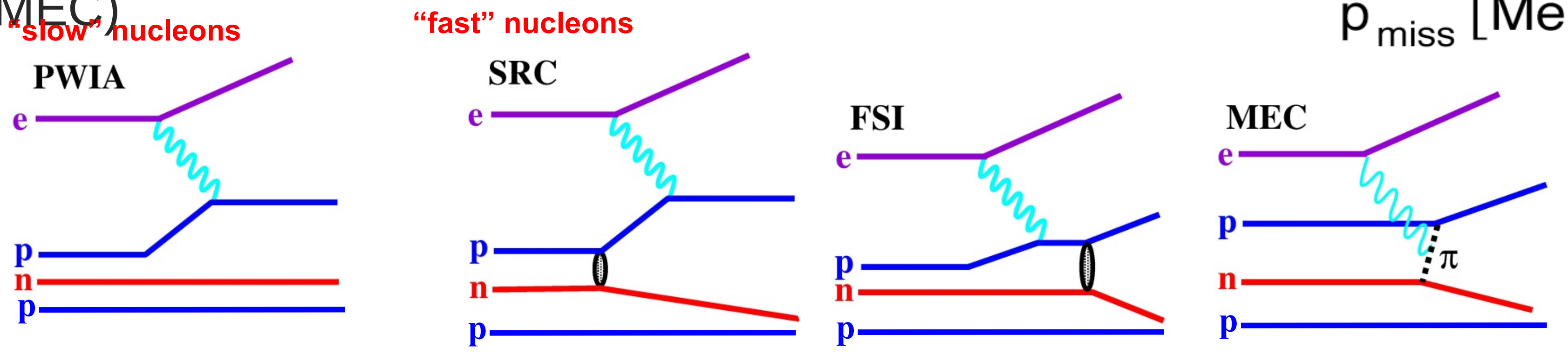
Measured far into high momentum tail: Cross section is ~5-10x expectation

High momentum pair can come from initial state short-range correlations

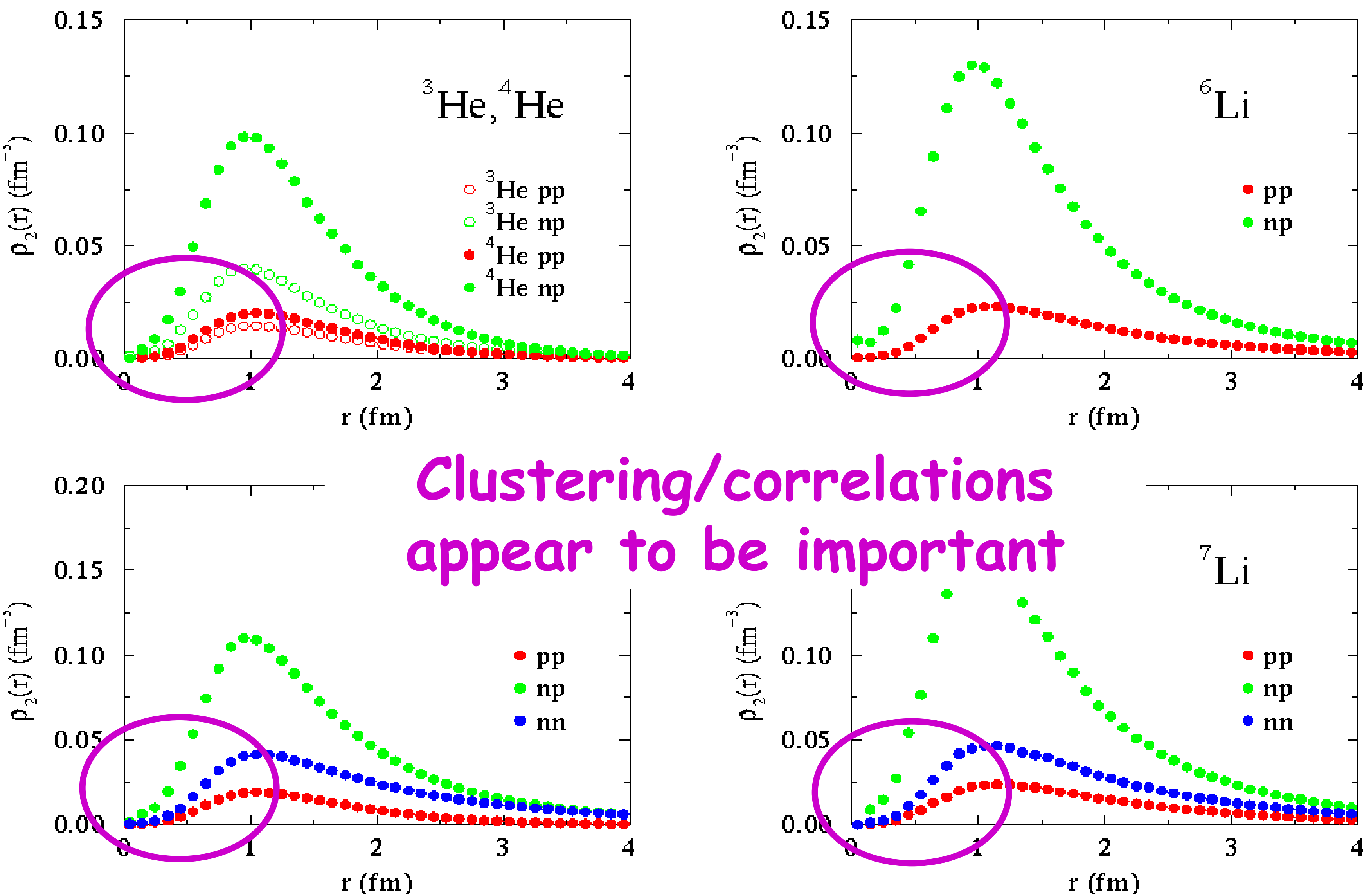
OR

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





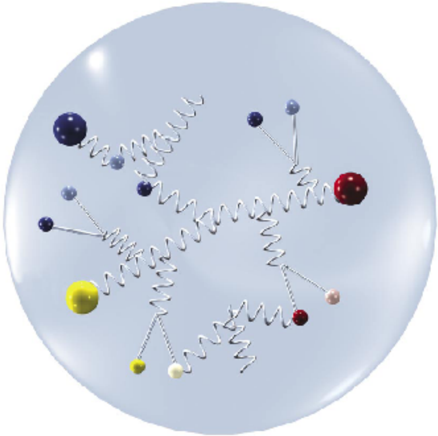
Average density, or average overlap?



Clustering/correlations appear to be important

Two-body densities: Pieper and

A Better, More Complicated Picture of the Proton



The Proton

The Plum Pudding Proton

- **99% of the proton's mass/energy is due to this self-generating 'gluon field'**

- **The two u-quarks and single d-quark**
  - **Provide the 'identity'** of the hadron through electromagnetic properties(*quantum numbers*)
  - Act as *boundary conditions* on the field (more than generators of the field)

- **Similarity of the proton and neutron masses is because the gluon dynamics are the same**
  - Has almost nothing to do with the quarks

Hadron as a dynamic, self-interacting gluon field localized around quarks whose quantum numbers identify the hadron

Importance of light nuclei

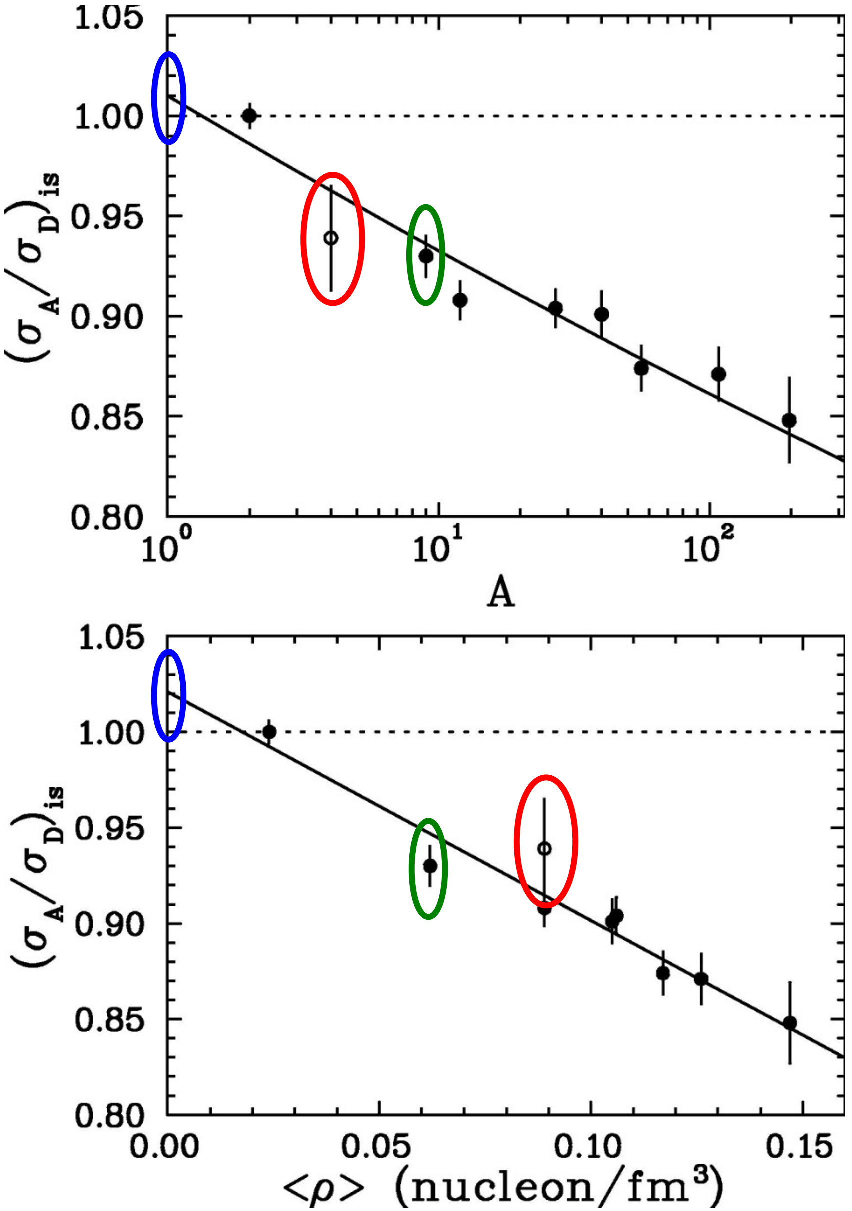
^{4}He is low mass, higher density

^{9}Be is higher mass, low density

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

Test mass vs. density dependence

Constrain ^{2}H – free nucleon difference



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

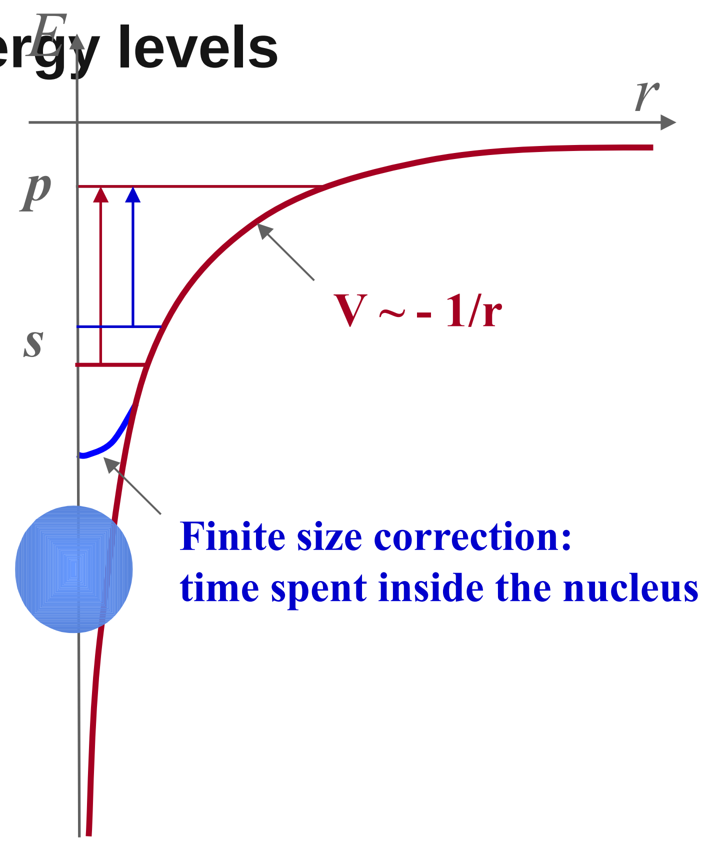
Finite nuclear size shifts electron energy levels

Finite radius → level shifts

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

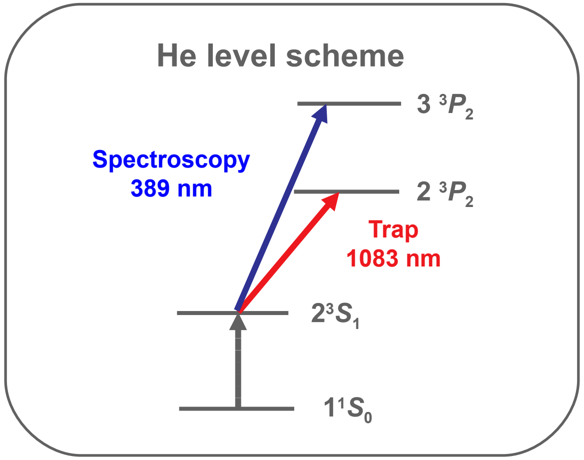
Field (volume) shift between two isotopes: $\Delta E_{FS} = \frac{2}{3}\pi Z e^2 |\psi(0)|^2 \delta\langle r^2\rangle^{AA'}$

Field shift in He isotopes: few neV

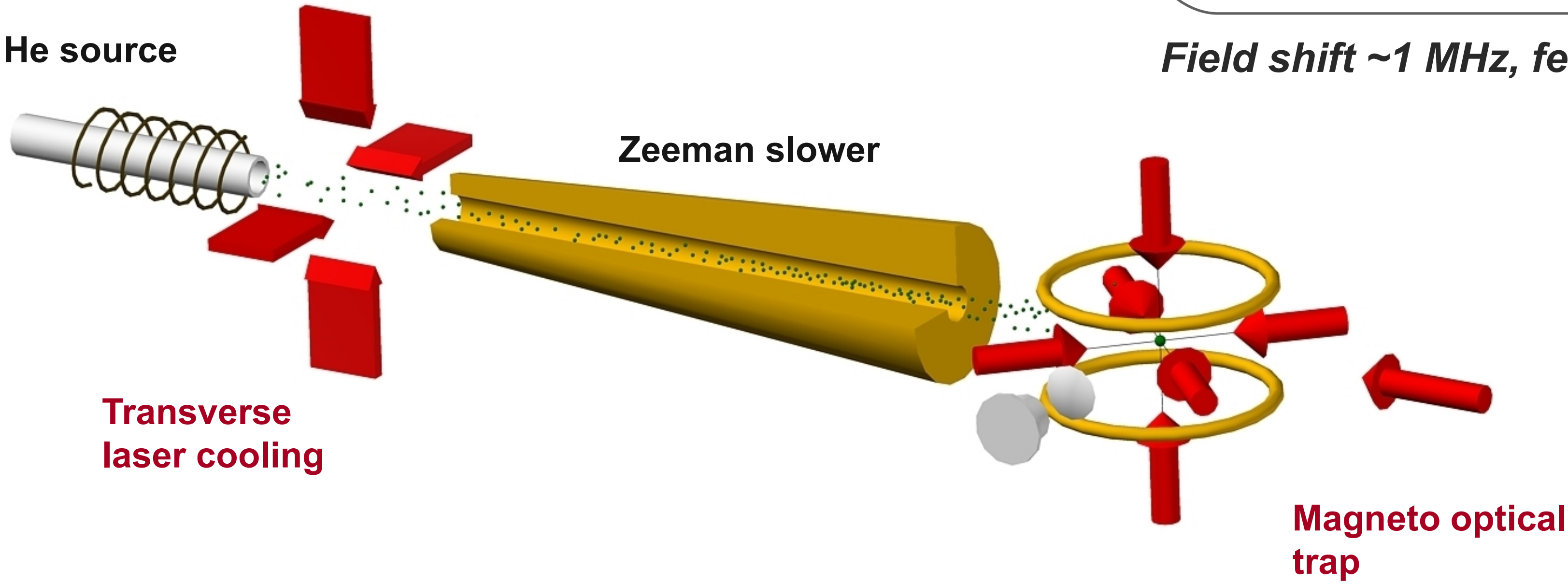


ATTA (Atom Trap Trace Analysis)

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



Field shift ~1 MHz, few neV



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