

# Nuclear Structure Studies at Jefferson Lab

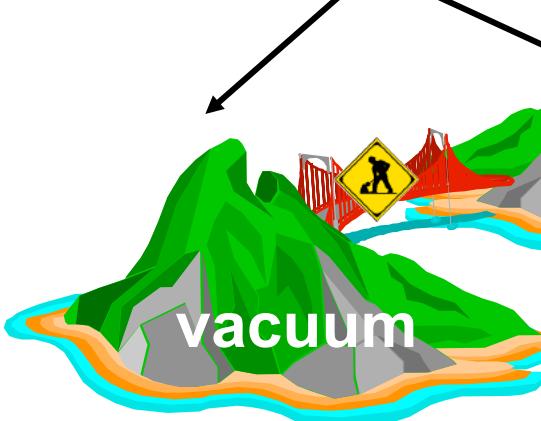
**John Arrington  
Physics Division  
Argonne National Laboratory**

**Nuclear Structure/Nuclear Astrophysics  
Town Meeting, Aug 21, 2014**

# Nuclear Structure Studies at Jefferson Lab

## Quark-Gluon Structure Of Nucleons and Nuclei

Nature of Confinement



Precise  
few-body data:  
Charge radii  
Form factors  
Mom. distributions

Exotic mesons  
and baryons



Correlations  
Neutron skin  
Hypernuclei  
Hadrons in-medium  
Effective NN (+ΛN) force

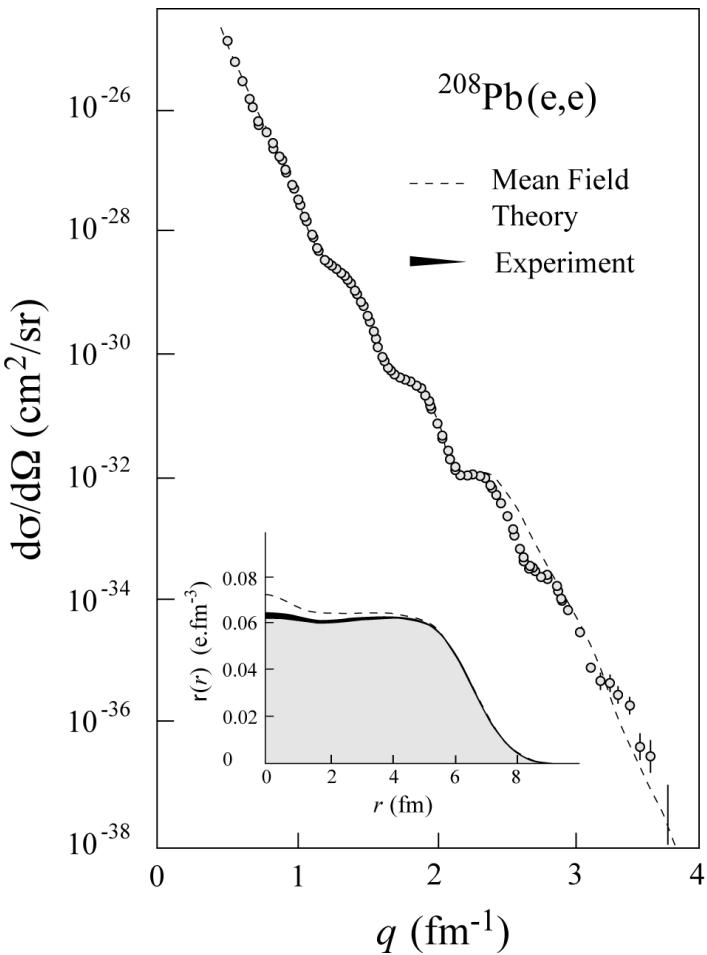
...n-stars

# Nuclear Structure Studies at Jefferson Lab

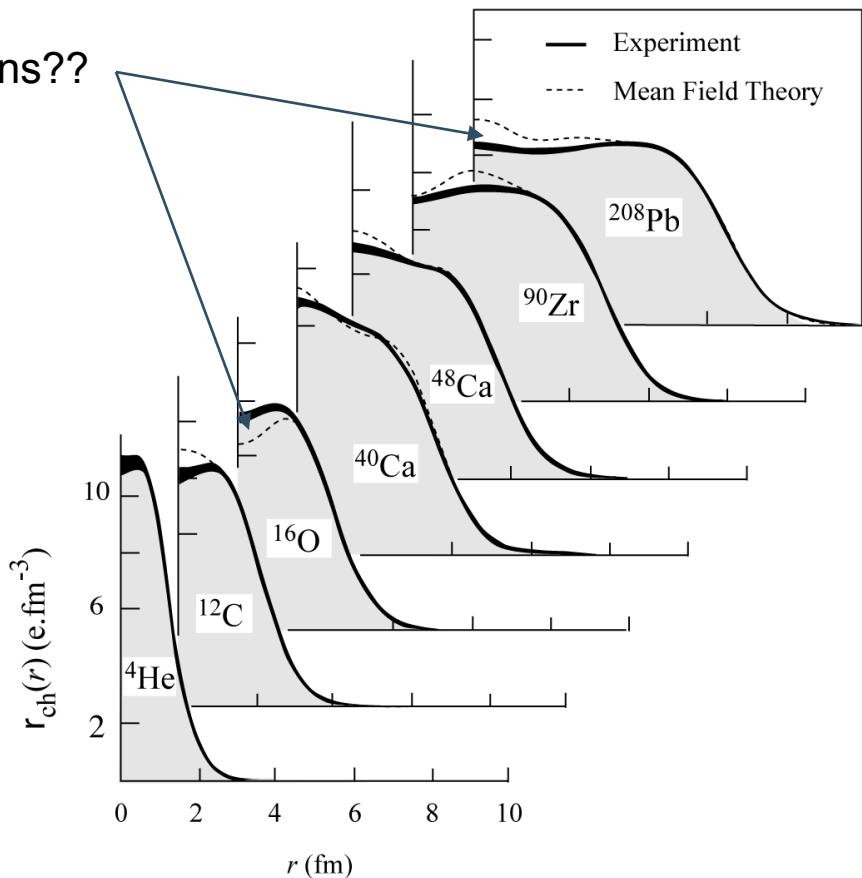
- **Spatial structure of nuclei**
  - Few-body form factors
  - Charge radii of light nuclei
  - Neutron skin of  $^{208}\text{Pb}$ ,  $^{48}\text{Ca}$
- **Nucleon momentum distributions in nuclei**
  - Spectral functions (nucleon energy-momentum distributions) at low and high-momentum
    - Tests of ab initio structure calculations
    - Input for neutrino scattering measurements
    - Long-range correlations
  - N-N short-range correlations (SRCs): high-momentum, high density components of nuclei
    - Input for neutrino scattering, neutron stars,
  - Connections between cluster structure, NN correlations, and the EMC effect
- **Beyond nucleonic degrees of freedom:**
  - Is the nucleon in the nucleus the same as a free nucleon?
  - Hypernuclei
  - Hadronization and Color Transparency



# Elastic e-A scattering: Nuclear Charge Distributions



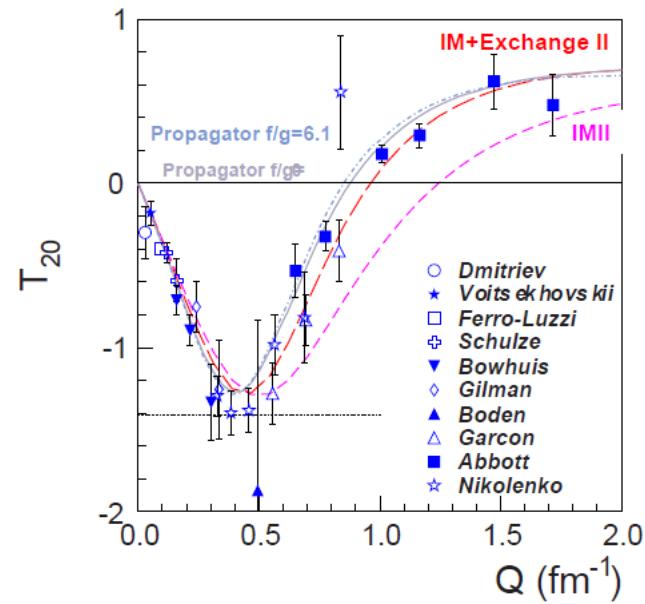
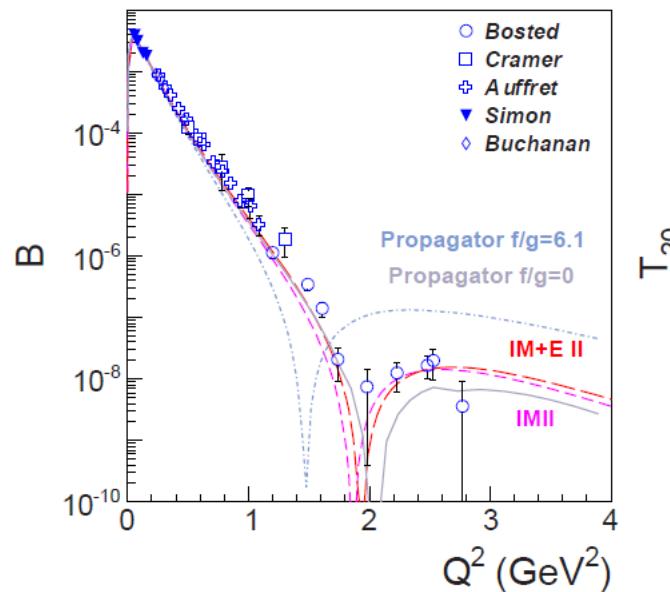
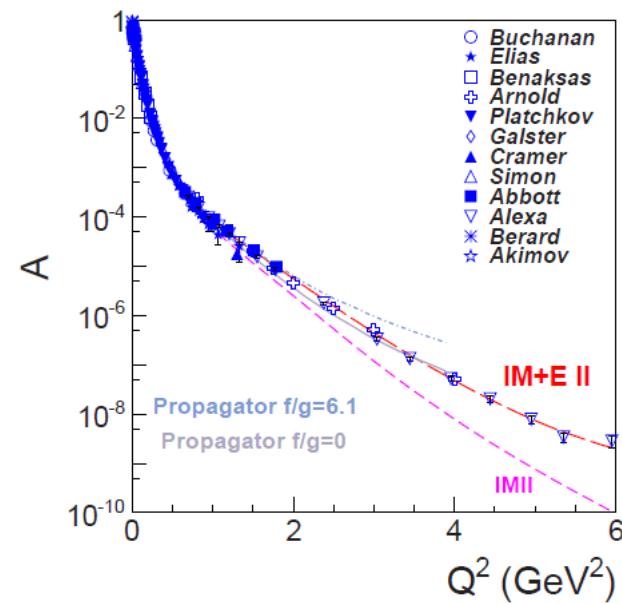
Correlations??



In '70s a large data set was acquired on elastic electron scattering (mainly at Saclay) over large  $Q^2$ -range and for variety of nuclei

"Model-independent" analysis of these data provided accurate results on charge distribution for comparison with the best available theory: Mean-Field Density-Dependent Hartree-Fock

# Elastic Electron-Deuteron Scattering - Polarization



$$\frac{d\sigma}{d\Omega} = \sigma_M \left[ A + B \tan^2 \frac{\theta}{2} \right]$$

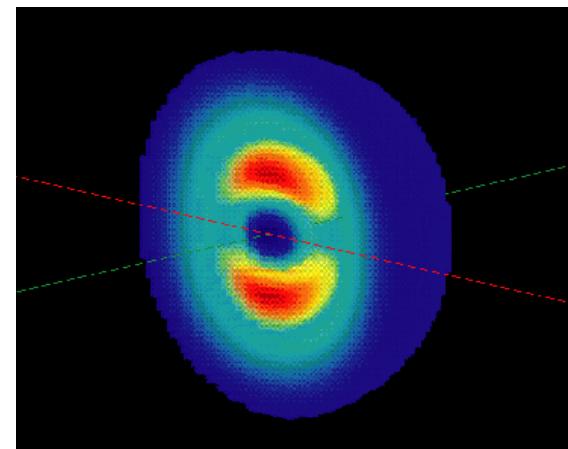
$$A(Q^2) = G_C^2 + \frac{8}{9}\tau^2 G_Q^2 + \frac{2}{3}\tau G_M^2$$

$$B(Q^2) = \frac{4}{3}\tau(1+\tau)G_M^2$$

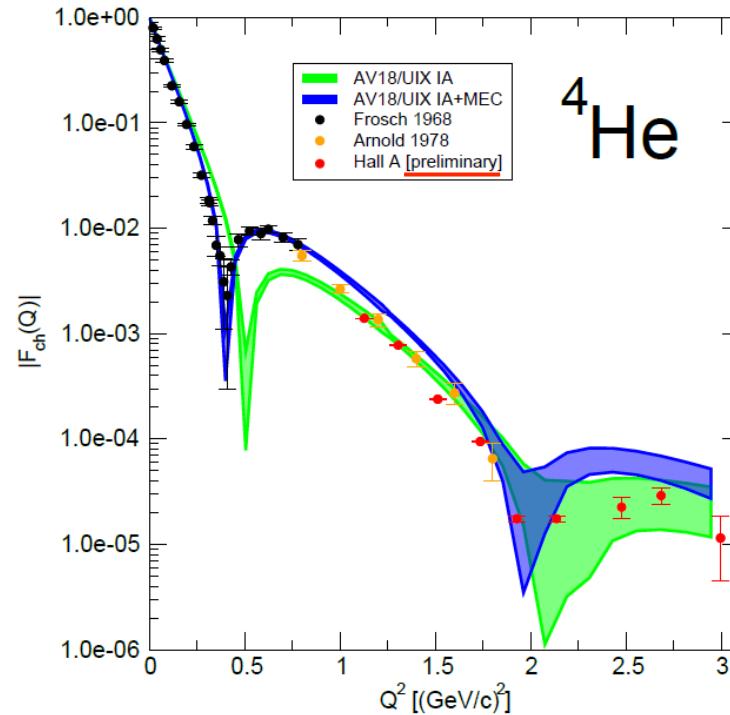
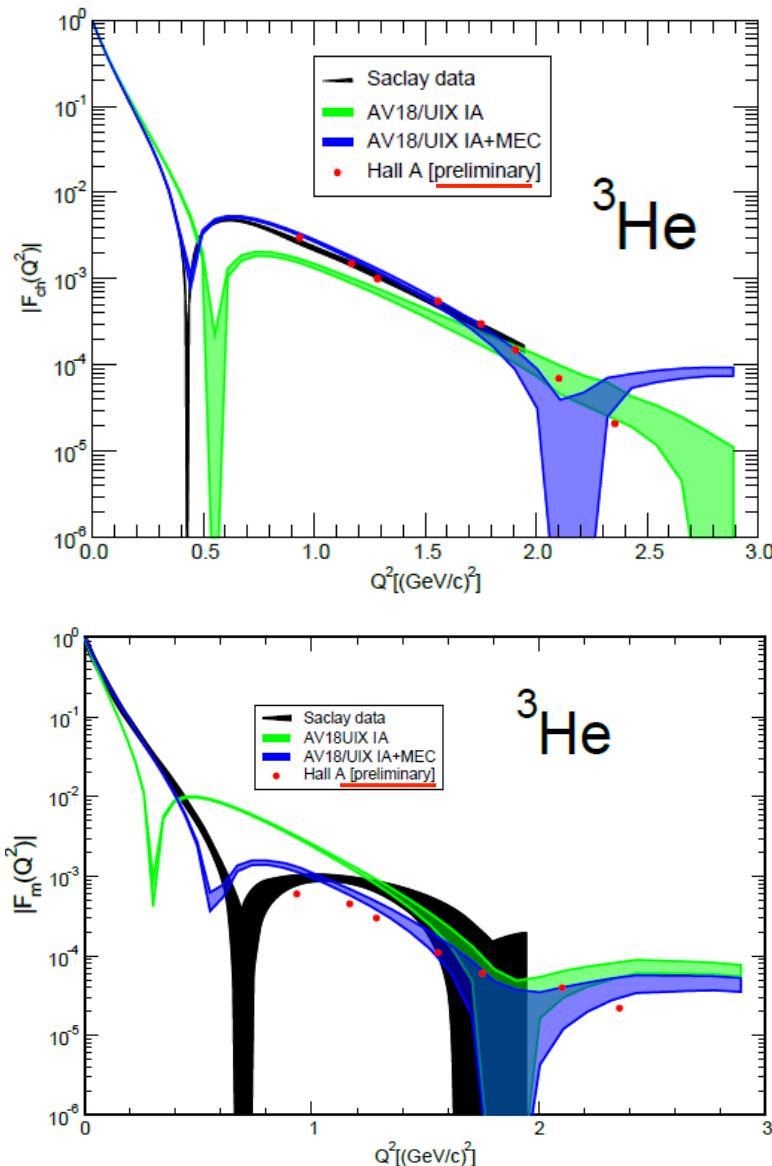
- 3rd observable needed to separate  $G_C$  and  $G_Q$
- › tensor polarization  $t_{20}$

**JLab6:** Combined data ⇒ Deuteron's Intrinsic Shape

**JLab12:** Tensor polarized quasielastic measurements: cleaner probe of D-wave contributions



# $^{3,4}\text{He}$ charge and magnetic form factors



Calculations w/MEC give a good description charge up to  $2 (\text{GeV}/c)^2$  (distance scales of 0.5 fm), but fail sooner for the  $^{3}\text{He}$  magnetic form factor

**Importance of understanding effects of exchange currents, relativity, 3-body forces, .....**?

# Low $Q^2$ Form Factors: Charge radii

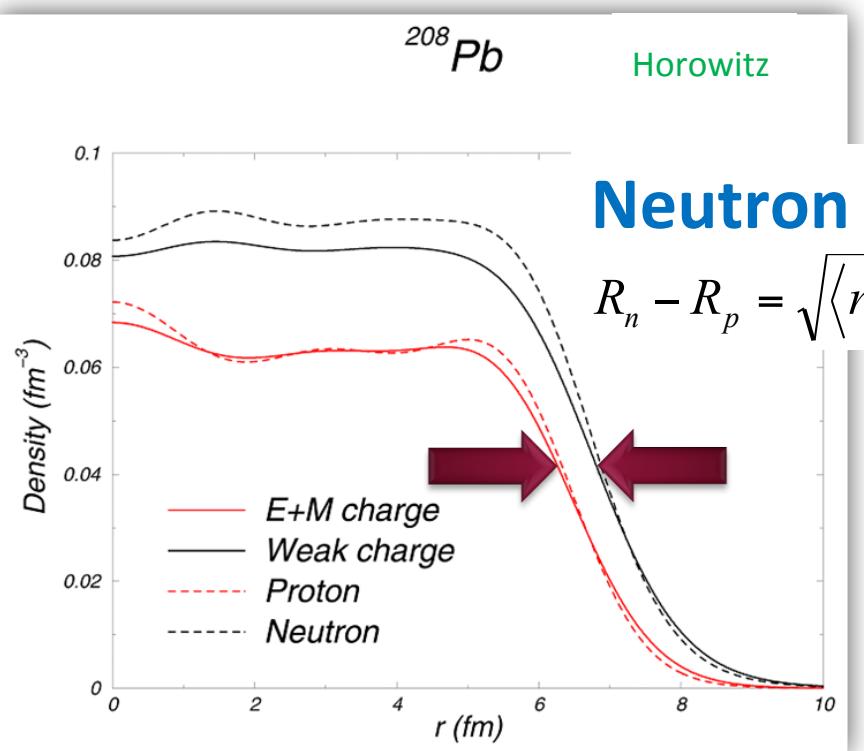
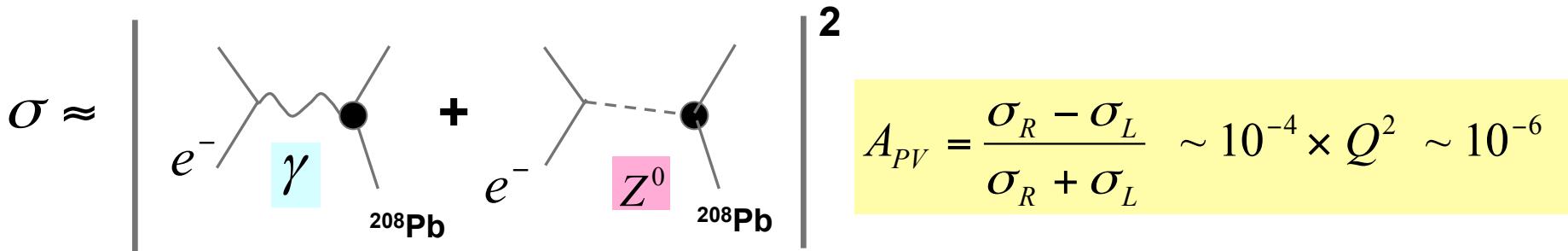
## *Recent data from 6 GeV era*

- Proton magnetic radius from polarization measurements of  $G_M$
- $^{7\text{Li}}, ^{10\text{B}}$  charge radii
- Neutron skin of  $^{208}\text{Pb}$ :  $R_n - R_p = 0.33 \pm 0.17$  fm [Parity violating e-A]

## *Future approved experiments*

- Proton charge radius [novel zero-degree calorimeter, windowless target]
- Neutron skin of  $^{208}\text{Pb}$  and  $^{48}\text{Ca}$
- $^3\text{H}-^3\text{He}$  charge radius difference [neutron skin of  $^3\text{H}$ ]
  - Calculations give  $\Delta R = 0.2$  fm
  - Aim for 10% measurement of the difference [currently 50%]

# PREX [ $^{208}\text{Pb}$ ] and CREX [ $^{48}\text{Ca}$ ]



$$A \approx \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[ 1 - 4\sin^2\theta_W - \frac{F_N(Q^2)}{F_P(Q^2)} \right]$$

Electroweak Asymmetry:  
Measure of neutron distribution  
relative to proton distribution

**$\Delta R$  correlated with  
neutron matter EOS**

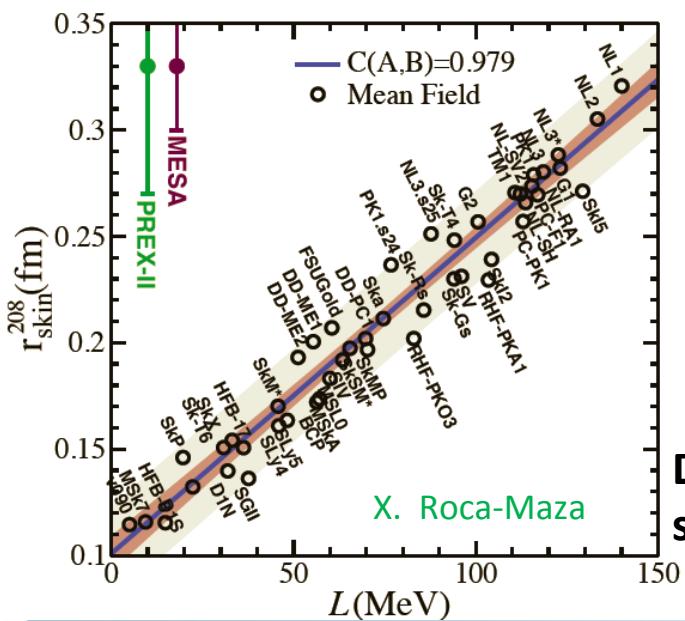
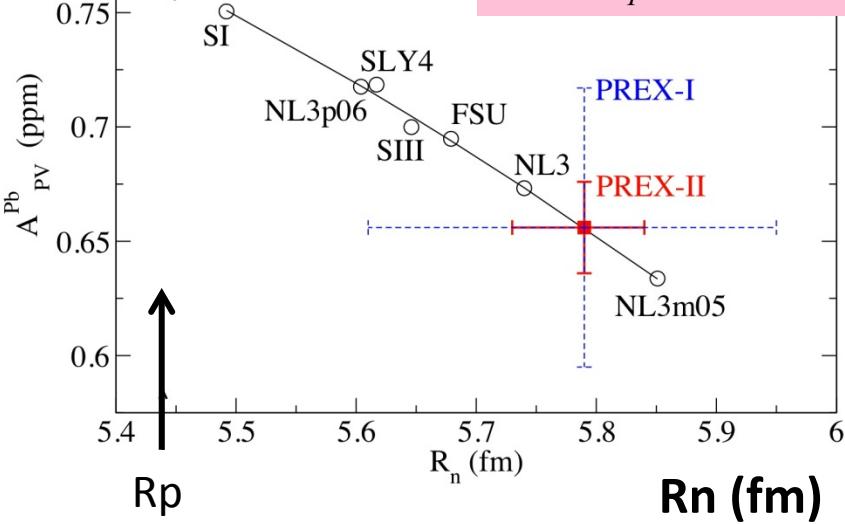


# PREX-I

PRL 108 (2012) 112502

$$A_{PV} = 0.656 \text{ ppm} \pm 0.060(\text{stat}) \pm 0.013(\text{syst})$$

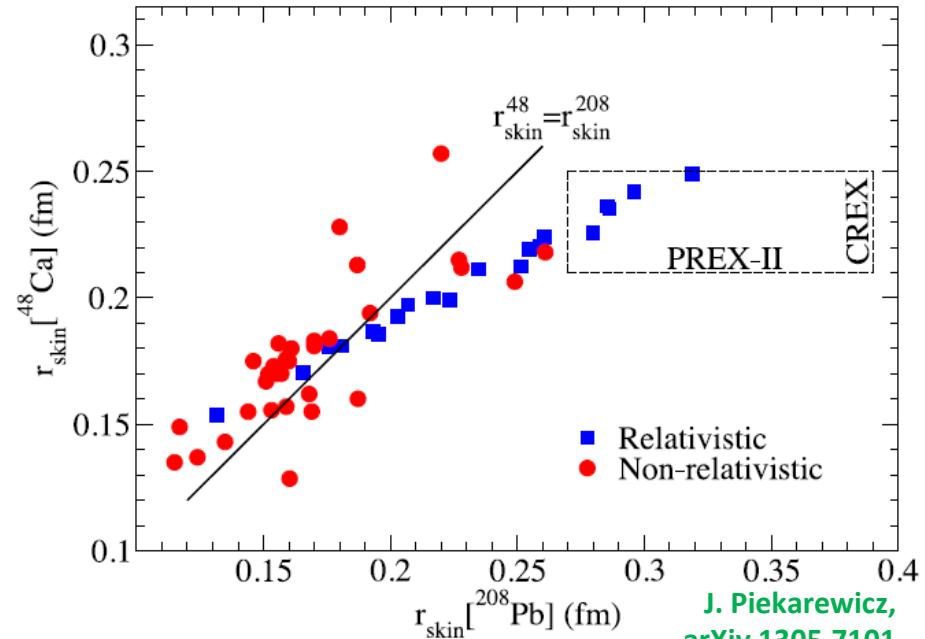
$$R_n - R_p = 0.33^{+16}_{-18} \text{ fm}$$



Density dependence of symmetry energy,  $L$

# PREX-II / CREX

$\Delta R$  to 0.06fm [Pb] / 0.02fm [ $^{48}\text{Ca}$ ]



J. Piekarewicz,  
arXiv 1305.7101

Neutron skin is highly correlated  
with neutron star properties

B. Michaels, Dense  
Nuclear Matter WG  
  
S. Riordan, Nuclear  
Structure WG

# Nuclear Structure Studies at Jefferson Lab

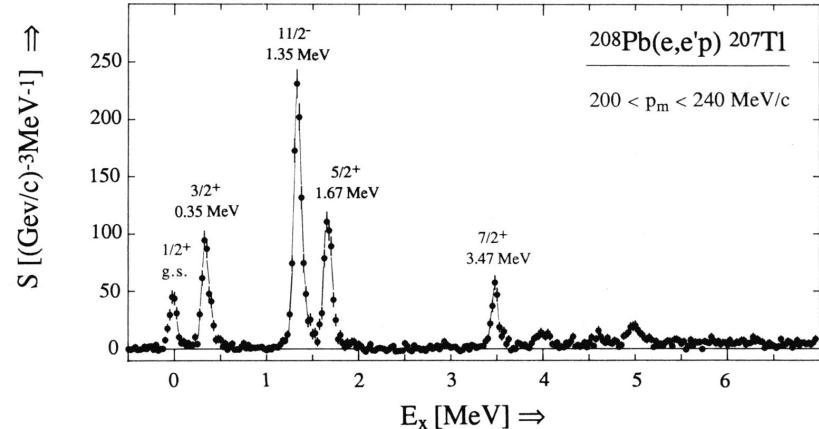
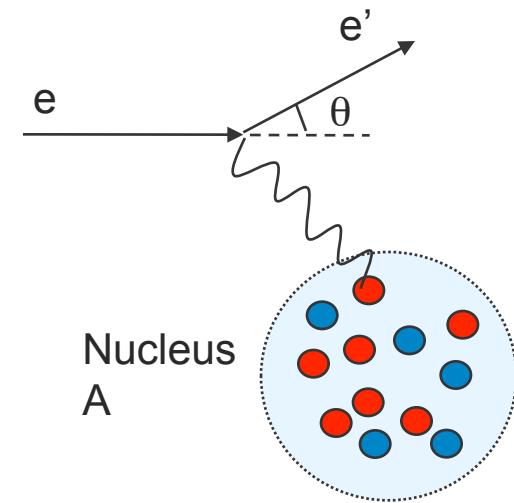
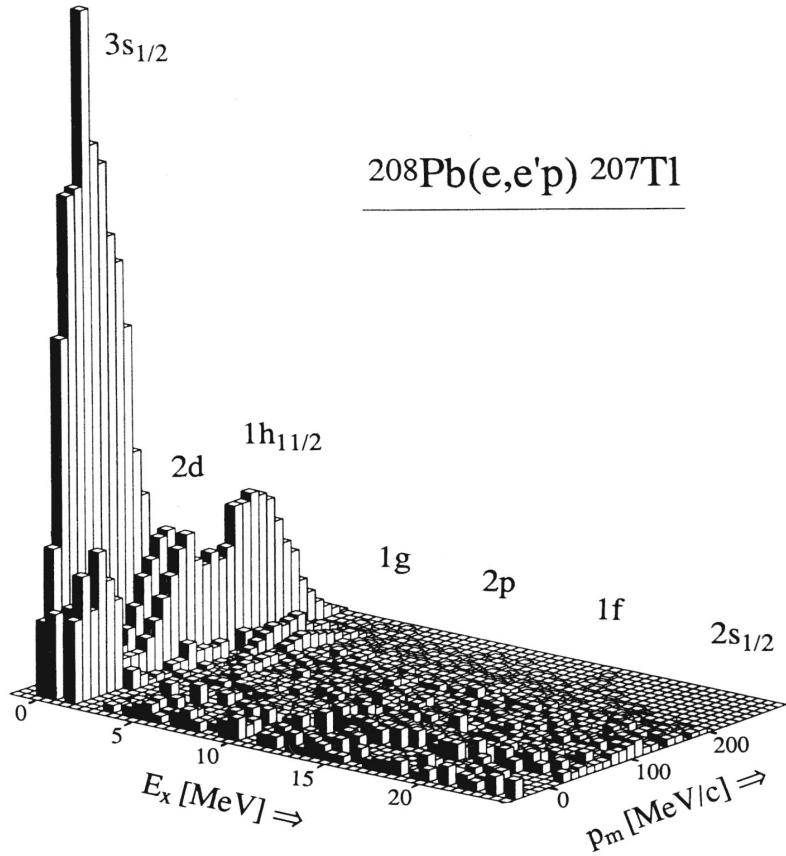
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# Quasielastic A( $e, e' p$ ) scattering

## PWIA approximation for proton knockout

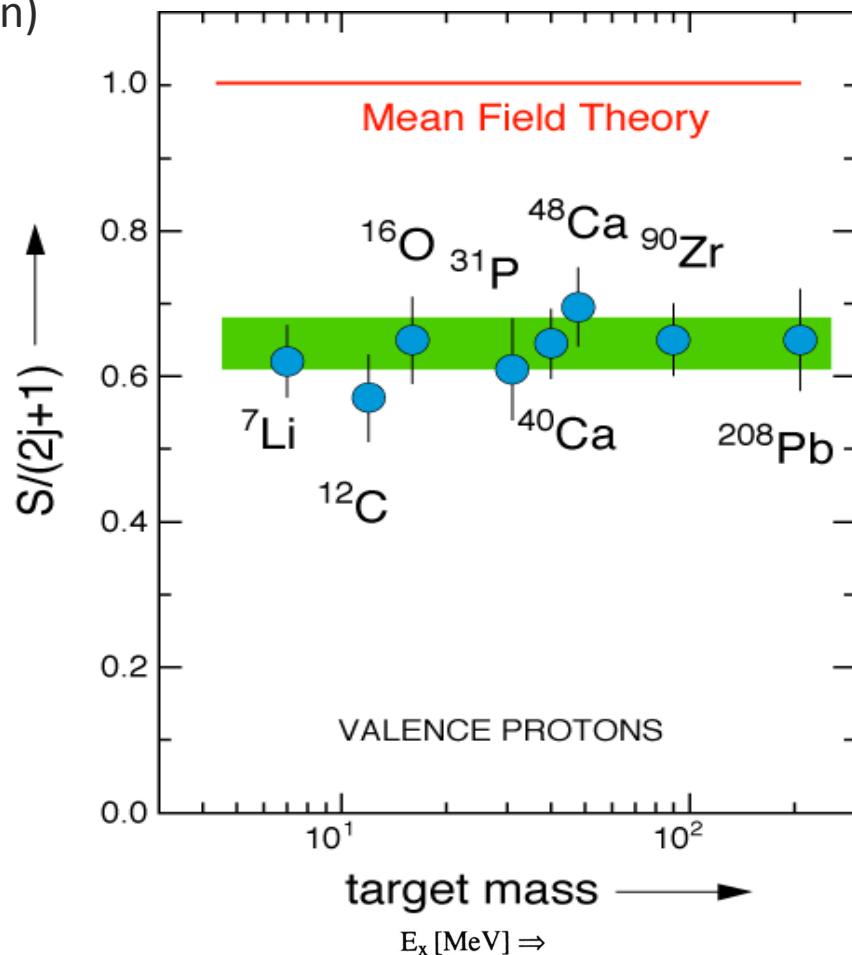
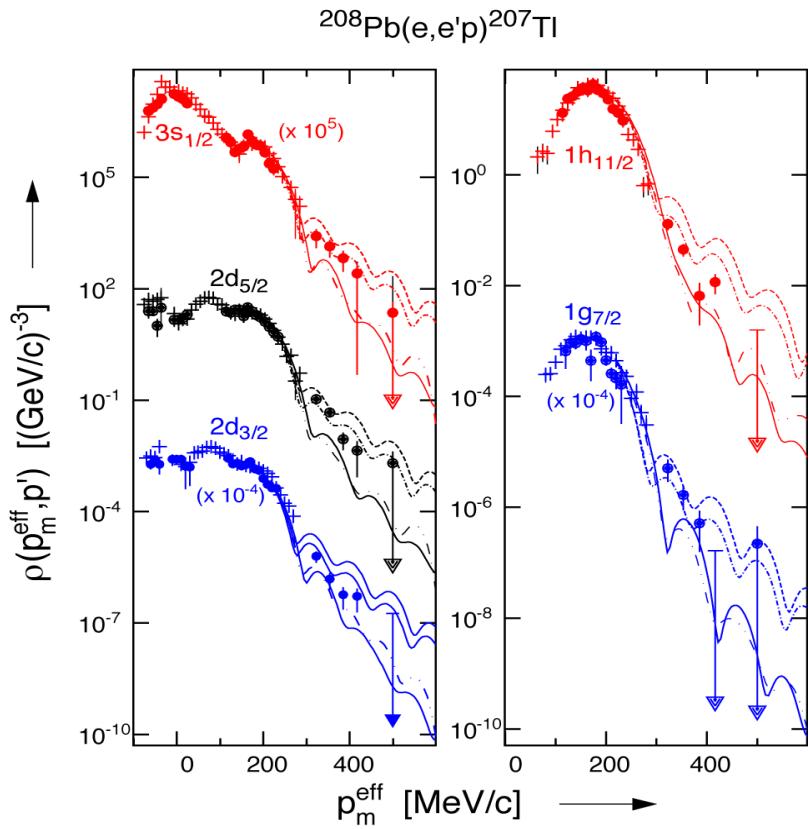
- Reconstruct initial proton binding energy ( $E_m$ ), momentum ( $p_m$ )



# 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)



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

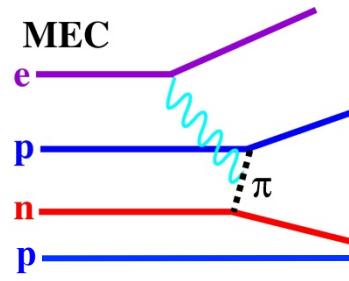
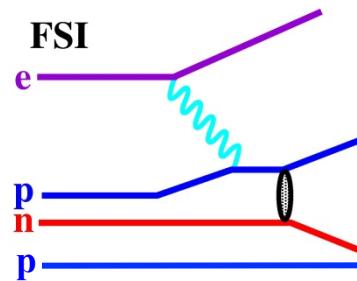
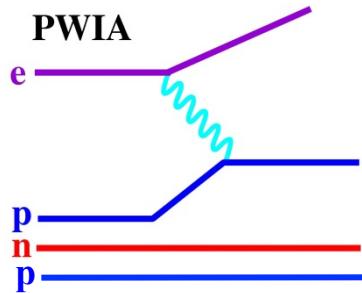
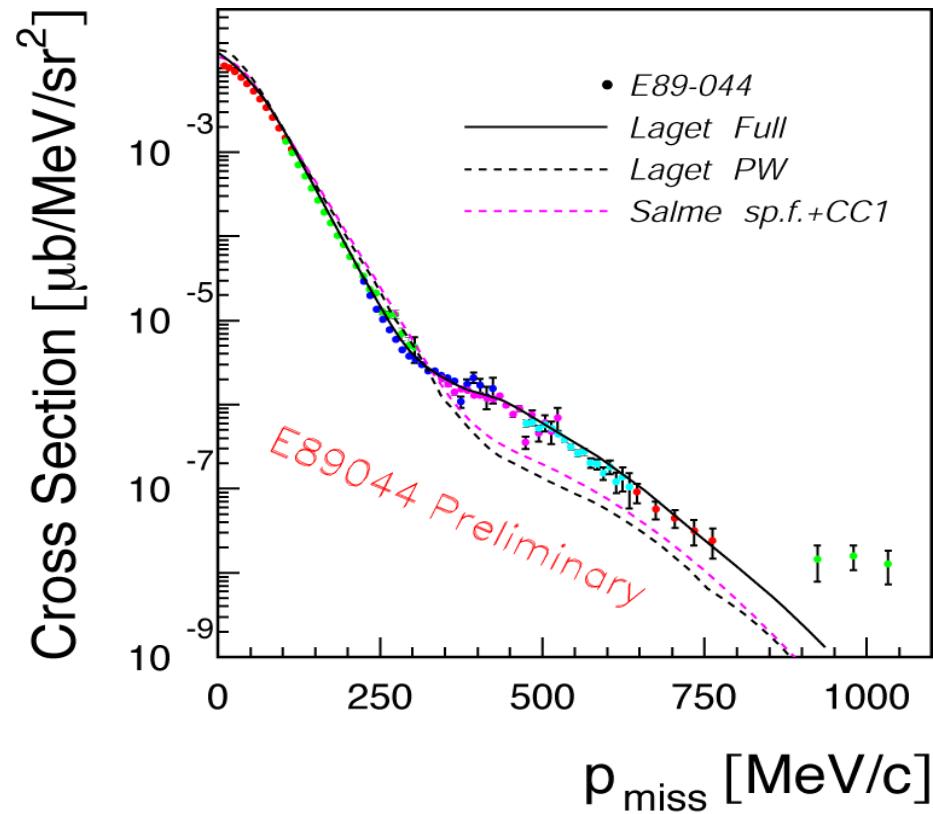
JLab E89-004:  ${}^3\text{He}(e,e'p)d$

Measured far into high momentum tail:  
Cross section is  $\sim 5\text{-}10\times$  expectation

High momentum pair can be from initial state short-range correlations (SRC)

OR

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

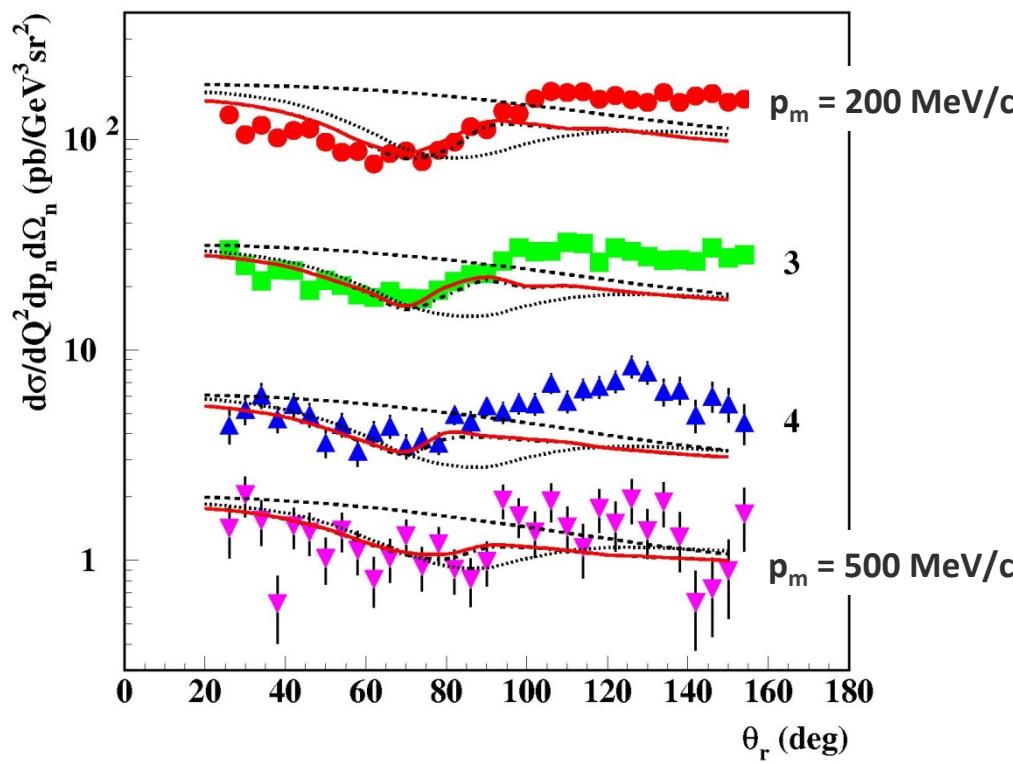


# Key progress: Understanding and Minimizing FSIs

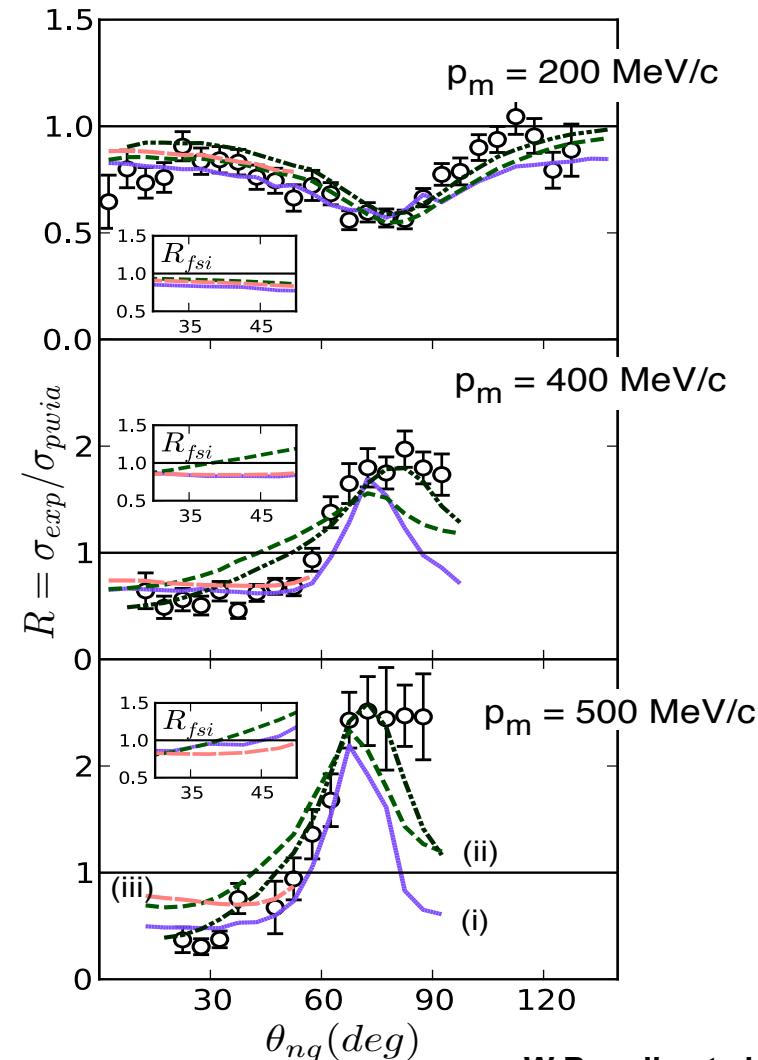
Hall B: D(e,e'p)n measurements over wide kinematic range

Rescattering well described for  $\theta_R$  below  $\sim 90$  degrees

FSI smaller at low  $\theta_R$



Hall C: push up to  $Q^2 = 3.5$  (GeV/c)<sup>2</sup>  
 $R = \sigma_{\text{EXP}} / \sigma_{\text{PWIA}}$  isolates FSI



# Future program: momentum distributions, spectral functions

$^{208}\text{Pb}$  under analysis

- Long-range correlations
- High  $p_m$  values

$^{40}\text{Ar}$  spectral function

- Input to  $\nu$  oscillation expts

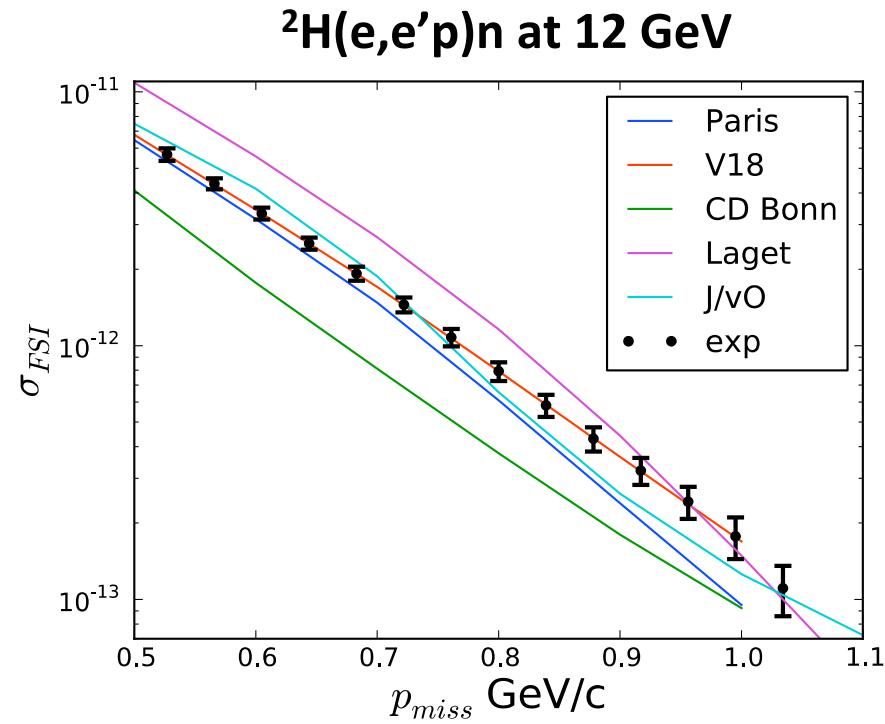
$^3\text{H}/^3\text{He}$  ratio of  $n(k)$

- Separate p, n
- Test few-body calcs

Deuteron  $n(k)$

- Further FSI tests
- Push to momenta where WF uncertainty dominates

More possible...

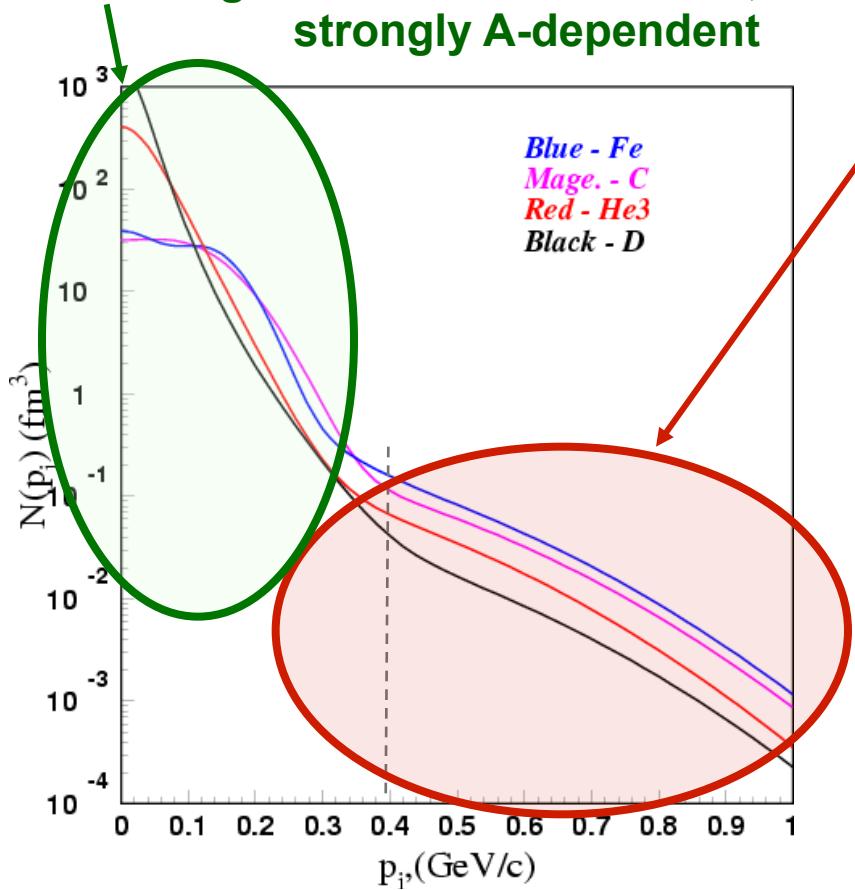


- ✓ Measure cross sections for  $p_m$  up to 1 GeV/c
- ✓  $Q^2 = 4.25 \text{ (GeV/c)}^2$
- ✓ Errors: dominated by statistics: 7% - 20%
- ✓ Estimated systematic error  $\approx 5\%$
- ✓ Very good theoretical support available

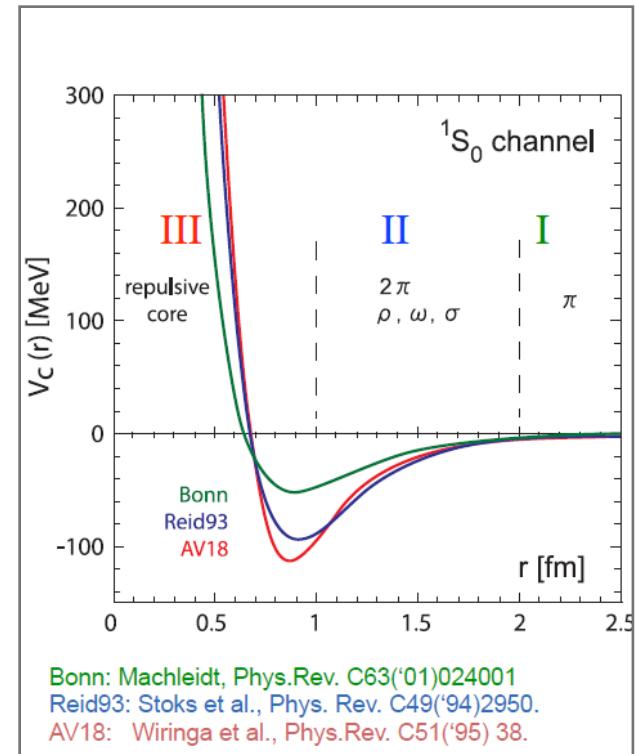
# Short-range correlations: high-p components

Short-Range Correlation: N-N pair  
with large *relative* momentum,  
small *total* momentum

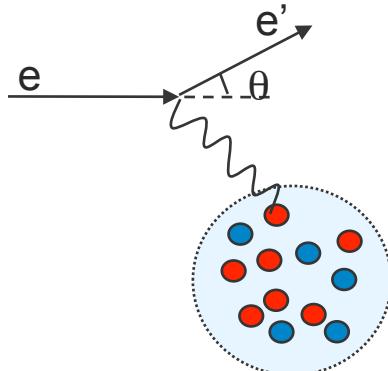
Mean-field region: collective behavior,  
strongly A-dependent



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

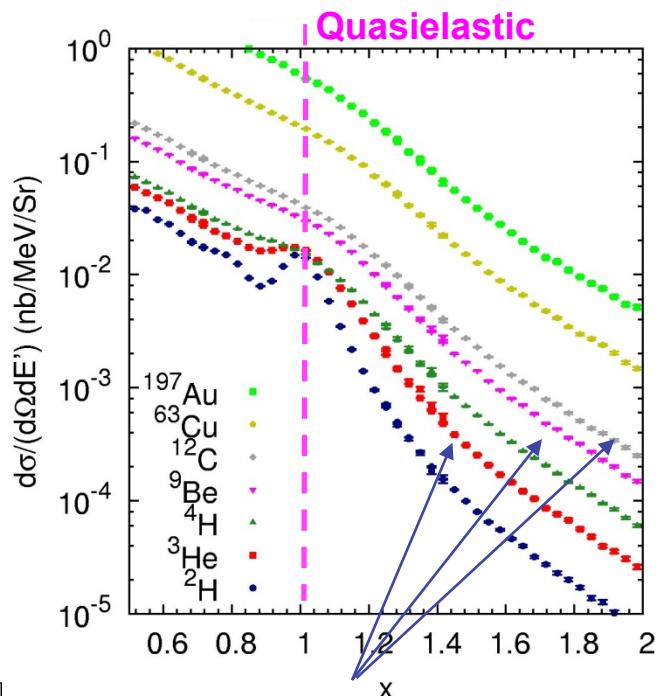
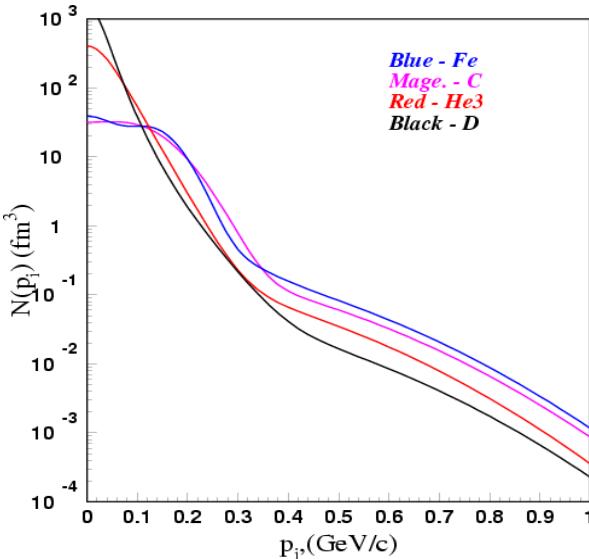


# Short-Range Correlations: Inclusive measurements



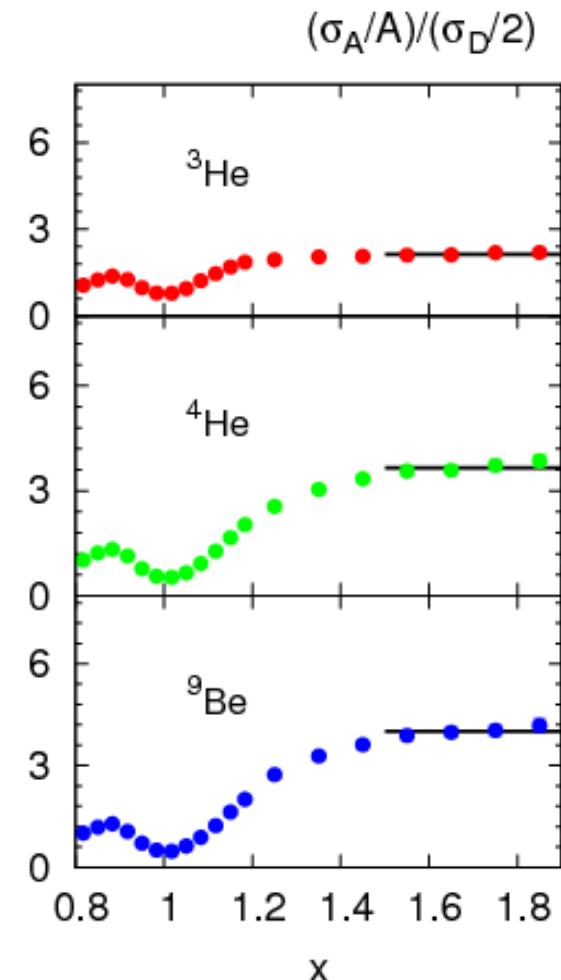
Quasielastic scattering  $x \approx 1$

Motion of nucleon in the nucleus broadens the peak



High momentum tails should yield constant ratio if SRC-dominated

Significantly reduced FSI – allows probe of relative SRC contributions in nuclei



# 2N, 3N correlations in inclusive ratios

$A/^2H$  ratios

$$\langle Q^2 \rangle = 2.72 \text{ GeV}^2$$

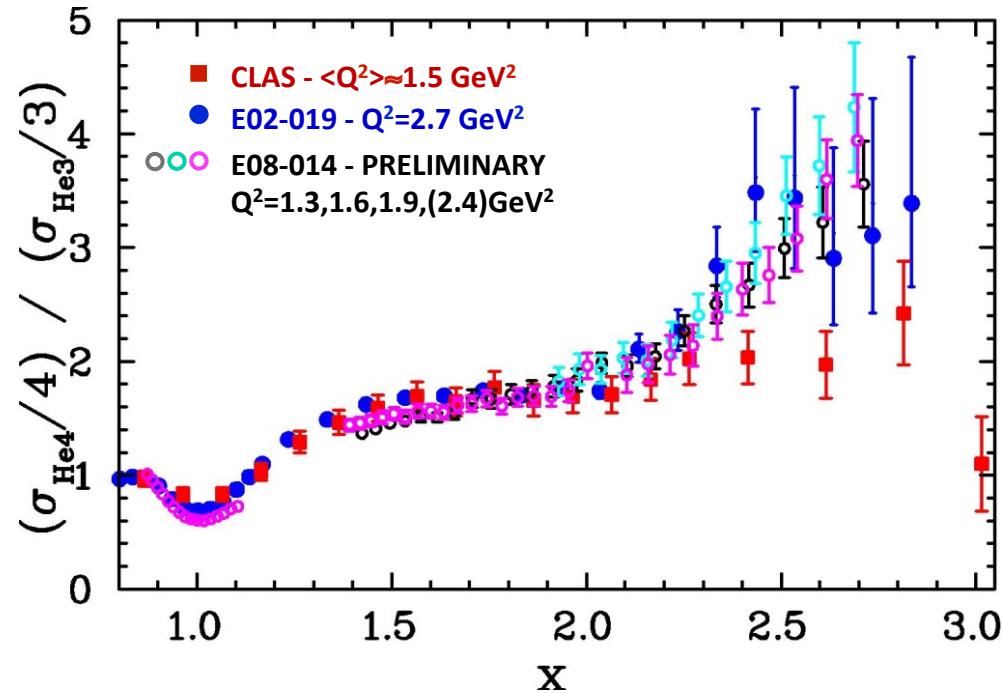
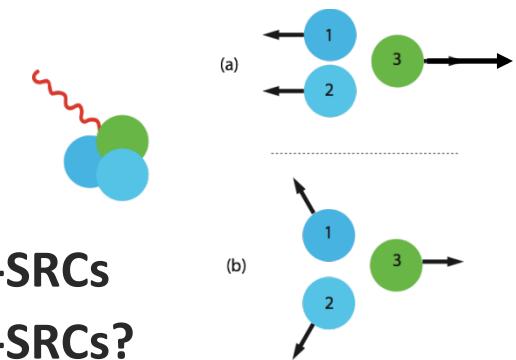
<i>SRC contribution (relative to <math>{}^2H</math>)</i>	
${}^3\text{He}$	$2.14 \pm 0.04$
${}^4\text{He}$	$3.66 \pm 0.07$
Be	$4.00 \pm 0.08$
C	$4.88 \pm 0.10$
Cu	$5.37 \pm 0.11$
Au	$5.34 \pm 0.11$

~20% of nucleons in  ${}^{12}\text{C}$  are part of SRC ( $k > 275 \text{ MeV}/c$ )

$A/{}^3\text{He}$  ratios:

$1.5 < x < 2$  sensitive to 2N-SRCs

$2.5 < x < 3$  sensitive to 3N-SRCs?



Determine if/where 3N-SRCs dominate  
Examine momentum structure  
Measure isospin dependence:  ${}^3\text{H}$  vs  ${}^3\text{He}$

# A-dependence of 2N-SRCs effect in light nuclei

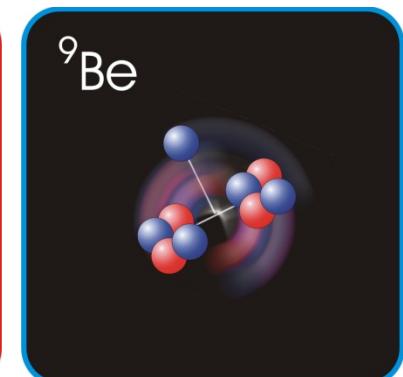
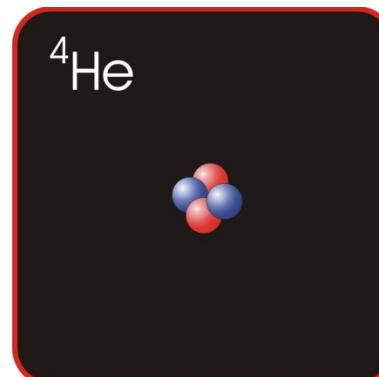
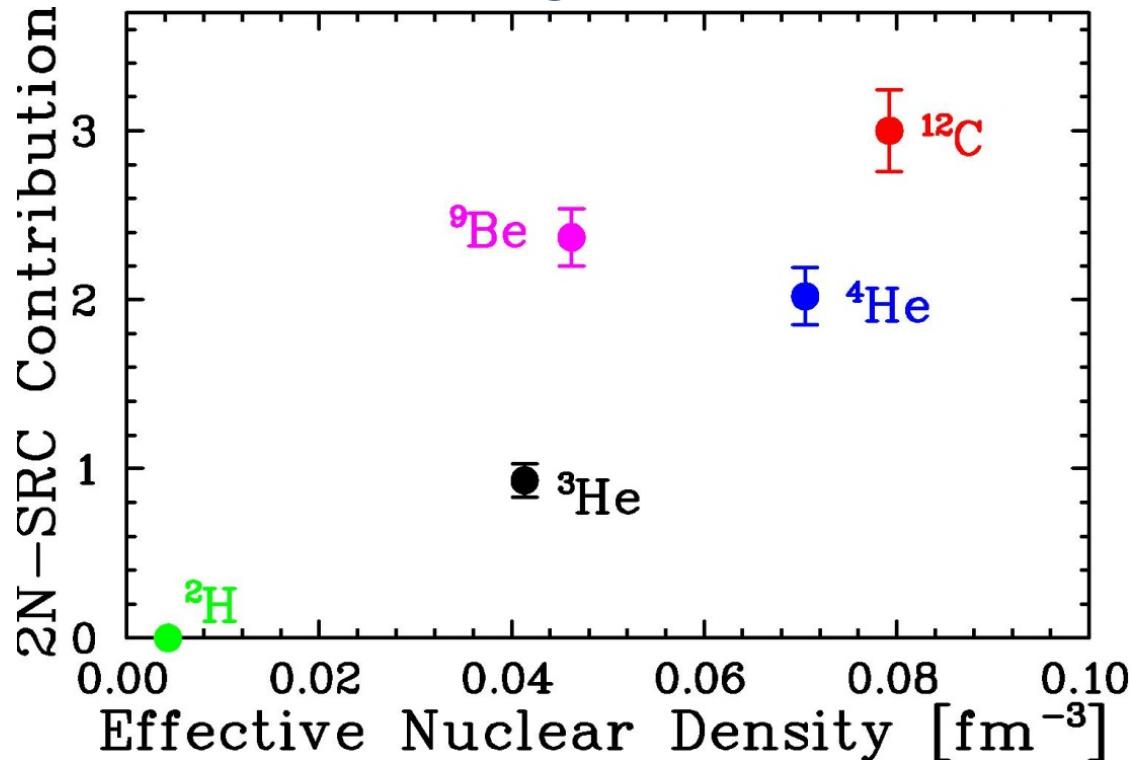
Density determined from  
*ab initio* calculation

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

Data show smooth behavior  
as density increases...  
except for  $^9\text{Be}$

$^9\text{Be}$  has low average density,  
but large component of  
structure is  $2\alpha + n$   
Most nucleons in tight,  $\alpha$ -like  
configurations

Cluster structure enhances  
the SRC contributions



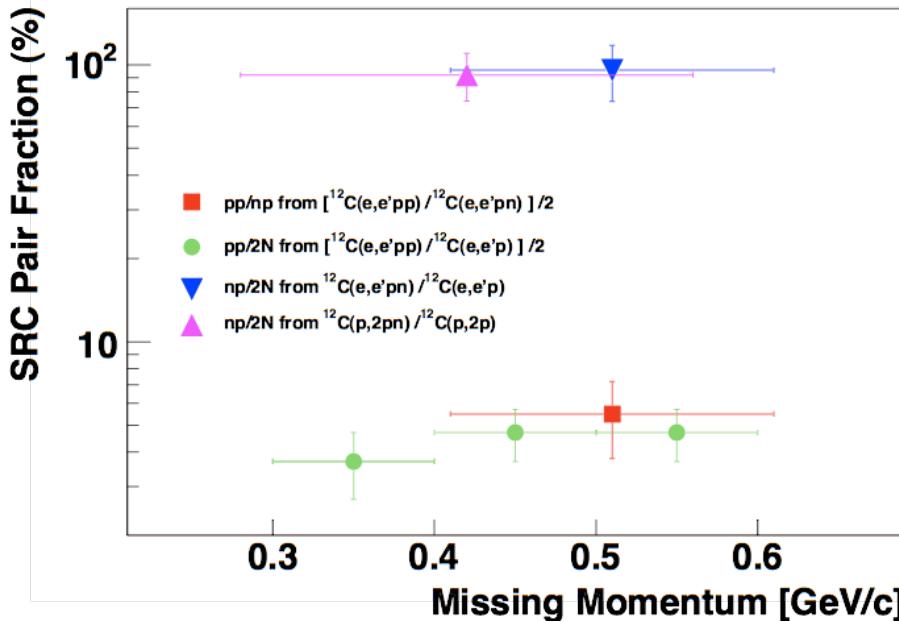
“SRC contribution” is (A/D) ratio minus one  
(so contribution is relative to deuteron)

# Isospin structure via ( $e, e' pN$ )

Measure  $A(e, e' p)$  at high- $P_m$

Look for correlated nucleon (p or n) with large momentum, opposite of  $P_m$

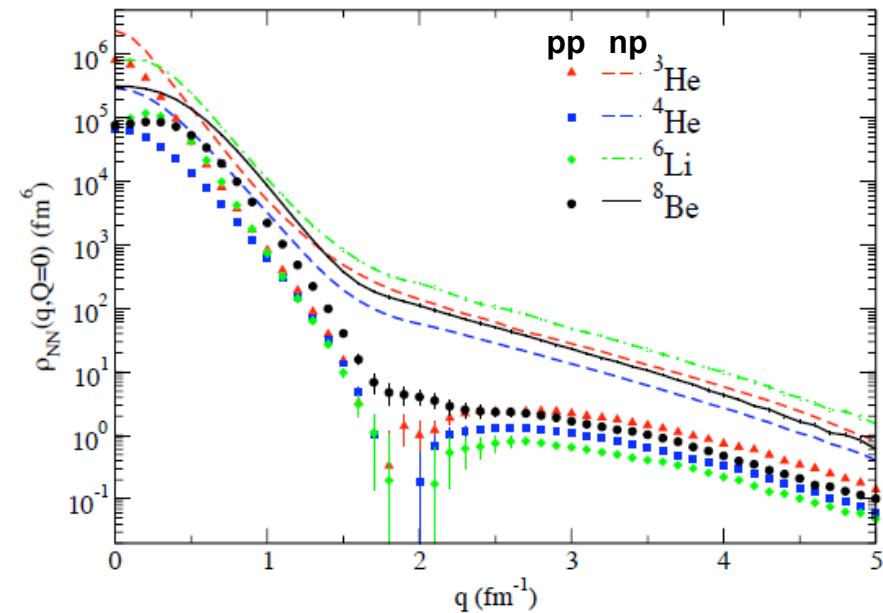
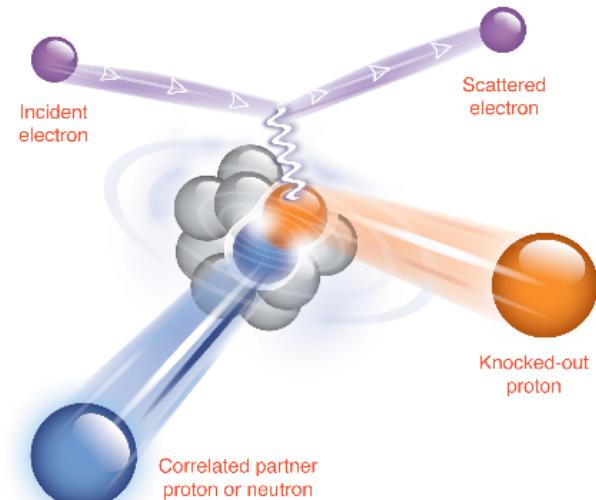
*R. Subedi et al, Science 320, 1476(2008)*



In  $^{12}\text{C}$ , 90% of observed pairs are pn; tensor force  $\rightarrow$  isosinglet dominance

$$R(pp/pn) = 0.056 \pm 0.018$$

$$R(T=0/T=1) = 20 \pm 8\%$$

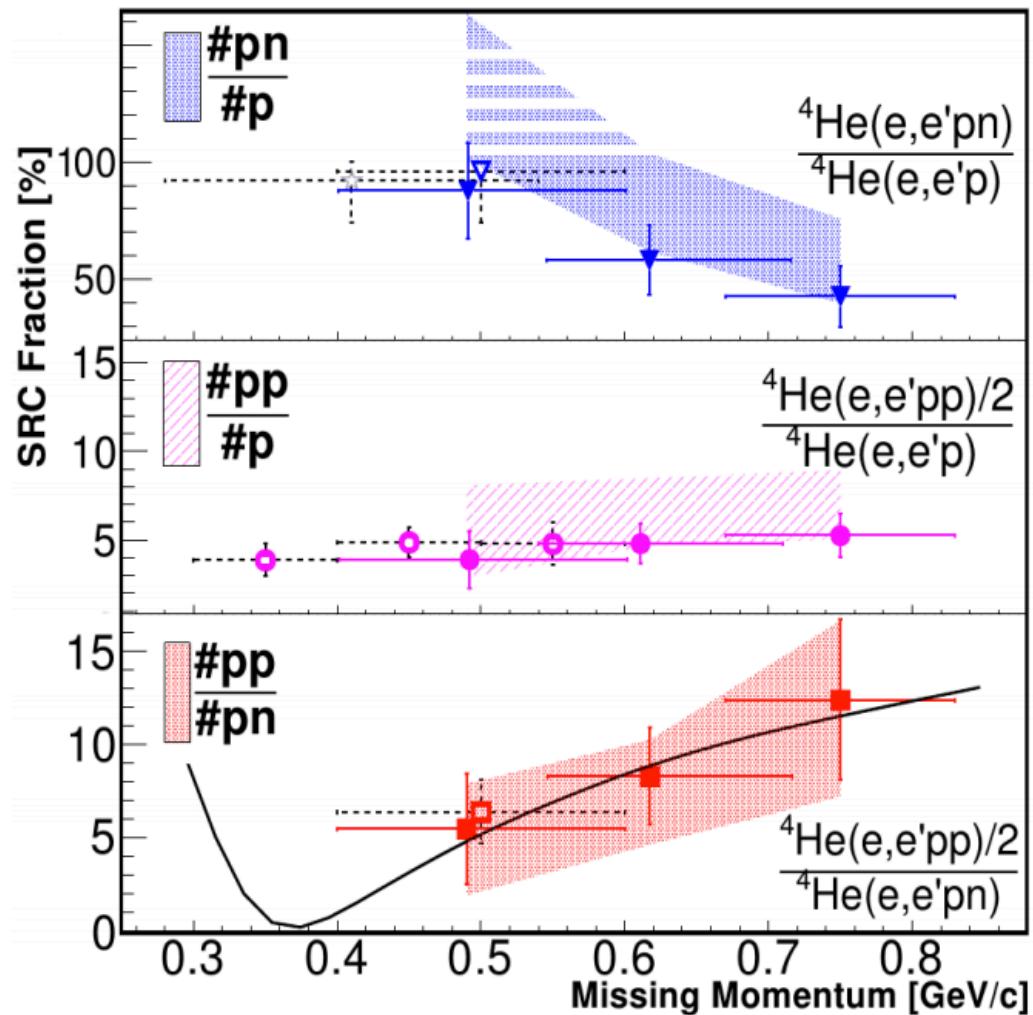


Schiavilla, Wiringa, Pieper, Carlson: PRL98, 132501 (2007)

# Isospin structure vs missing momentum

Examine breakup of  ${}^4\text{He}$  into high-momentum pair with low-momentum, low-excitation recoil 2N system

Observe transition from tensor interaction to central repulsive core through increase in the ratio of pp-SRC to np-SRC



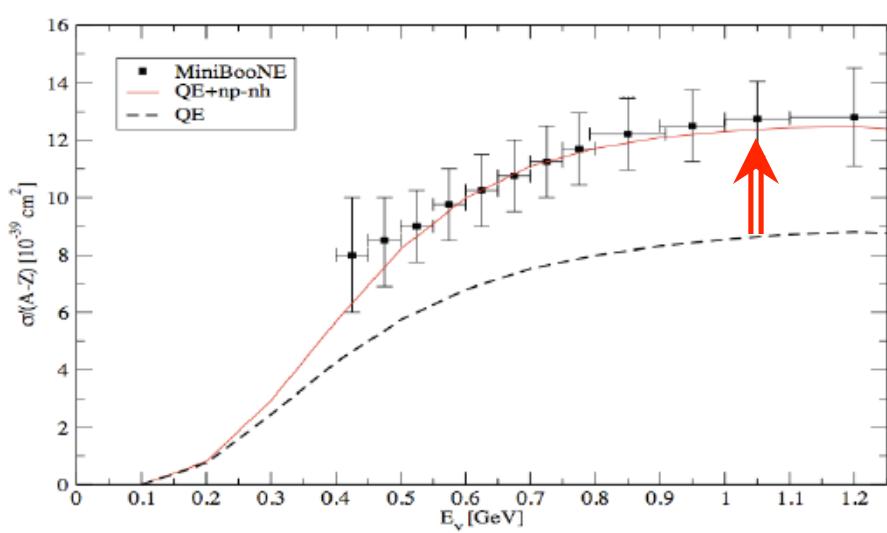
# SRC implications: $\nu$ -A scattering (e.g. MiniBooNE)



## Nuclear Effects to the Rescue?

14

- another possible explanation has recently emerged
- while traditional nuclear effects decrease the  $\sigma$ , there are processes that can increase the total yield ...



Martini et al., PRC 80, 065001 (2009)

- extra contributions coming from nucleon correlations in the nucleus  
(all prior calculations assume nucleons are independent particles)
- can predict MiniBooNE data without having to increase  $M_A$  (here,  $M_A=1.0$  GeV)

# SRC Implications: Symmetry Energy

Relates to the energy change when replacing n with p

- equation-of-state of neutron stars,
- heavy-ion collisions,
- r-process nucleosynthesis,
- core-collapse supernovae,
- more...

**np-SRC pairs increase the kinetic energy of SNM with almost no effect on PNM**

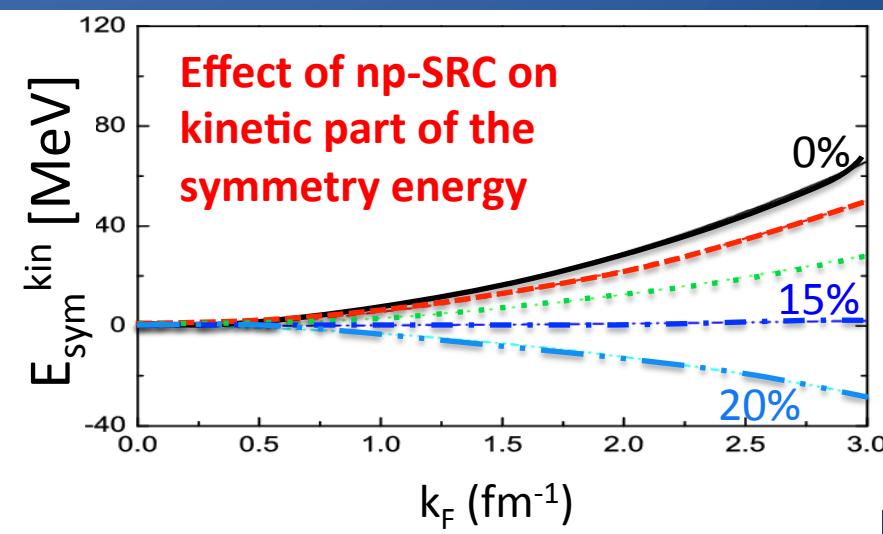
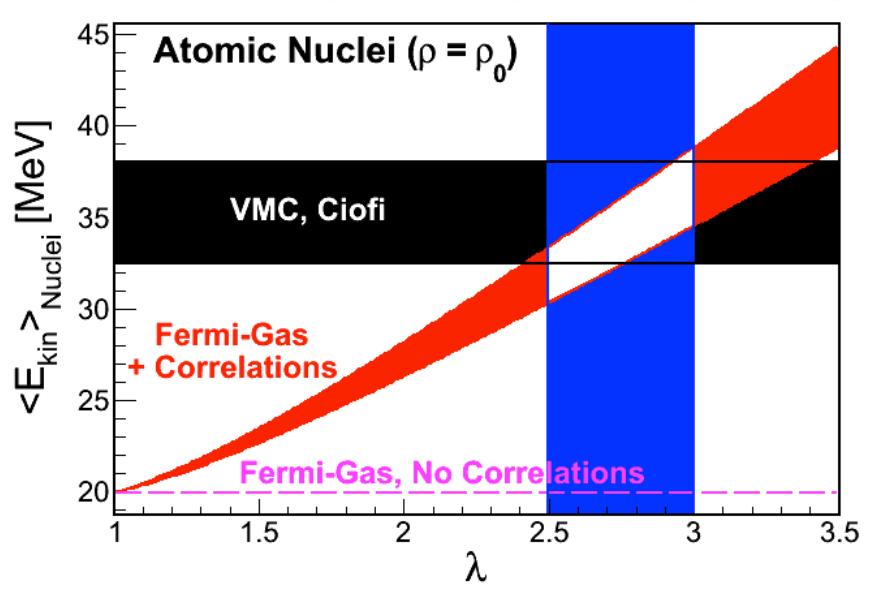
(symmetric,  
 $\#n=\#p$ )

(pure neutron)

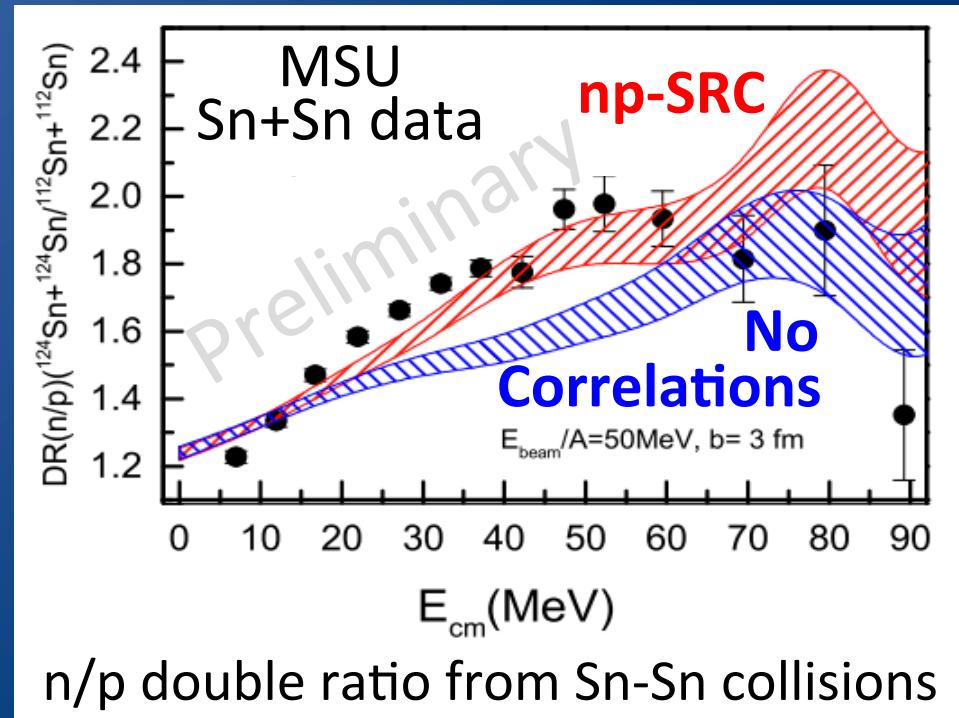
$\Rightarrow E_{\text{sym}} = E_{\text{PNM}} - E_{\text{SNM}}$  Reduced Dramatically

# Kinetic symmetry energy of correlated NM

Phenomenological model for np-SRC impact  
on kinetic part of symmetry energy:



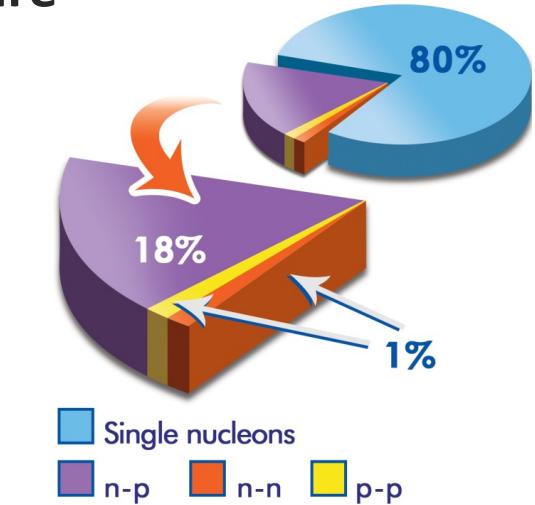
Impact of np-dominated SRC  
on analysis of heavy-ion data



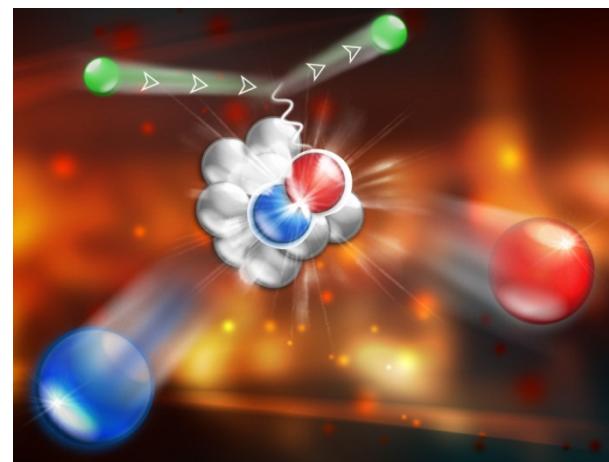
# Summary: Short-Range Correlations

SRCS are an important component to nuclear structure

- ~20% of nucleons in SRC, *mainly pn pairs*
  - Perhaps small 3N-SRCs contributions
  - Some room for more exotic configurations (6q bag)
- Impact on nuclear matter, neutron stars
- Important for realistic description of e-A,  $\nu$ -A scattering
- Modify some observables in nucleus-nucleus interactions



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



SRCS represent dense, energetic configurations:  
Natural to look for impact on proton structure,  
possible connection impact of dense matter on  
proton/neutron structure



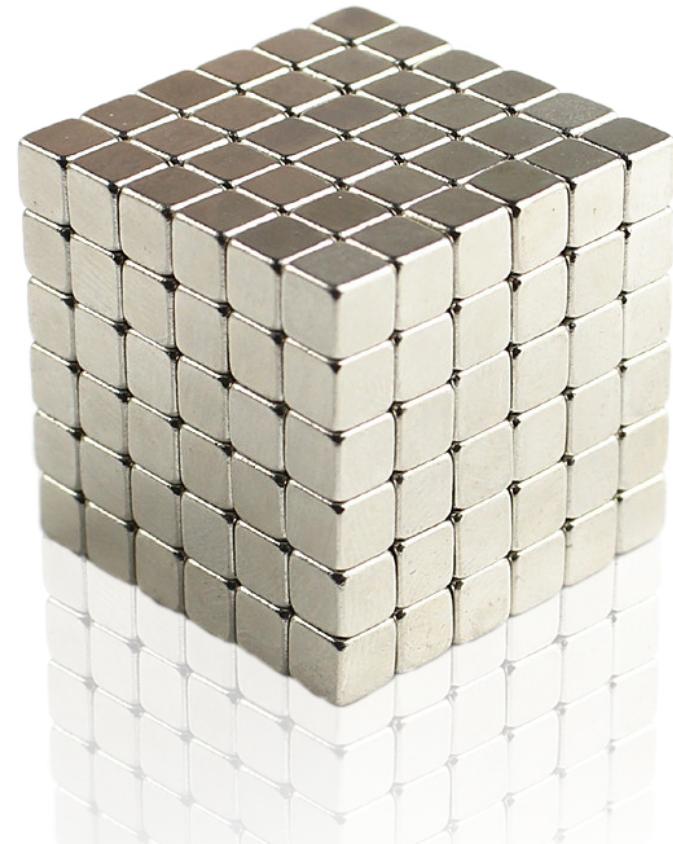
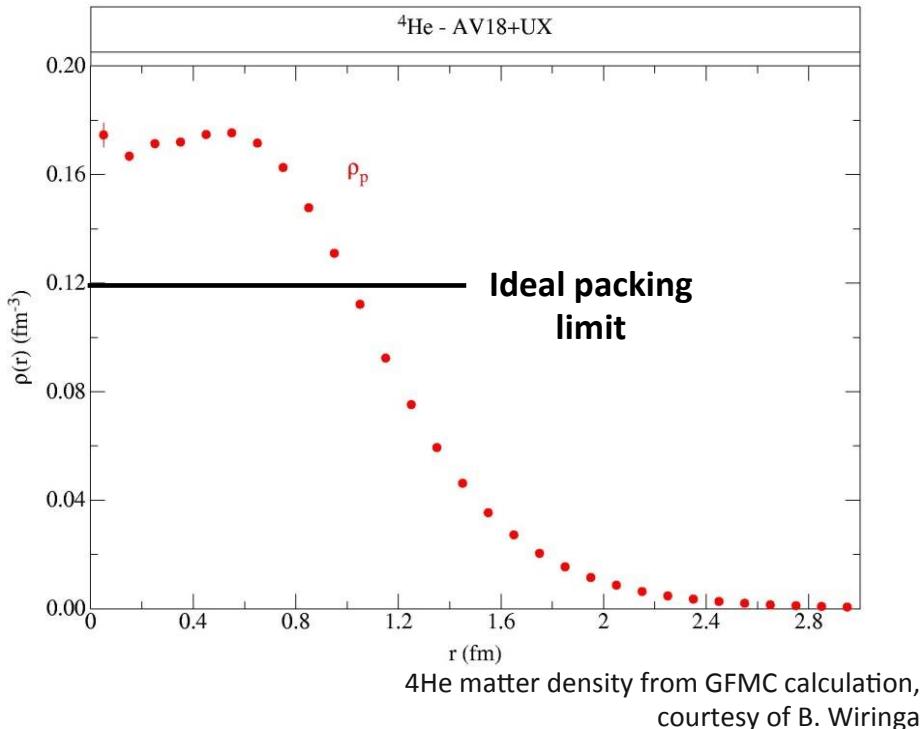
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# Proton vs. Nuclear Densities

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



# 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  
(approaching 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]

Very tightly packed and incredibly energetic!



The moon ( $A \approx 5 \times 10^{49}$ ) at typical nuclear densities



# Quark distributions in nuclei: EMC effect

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

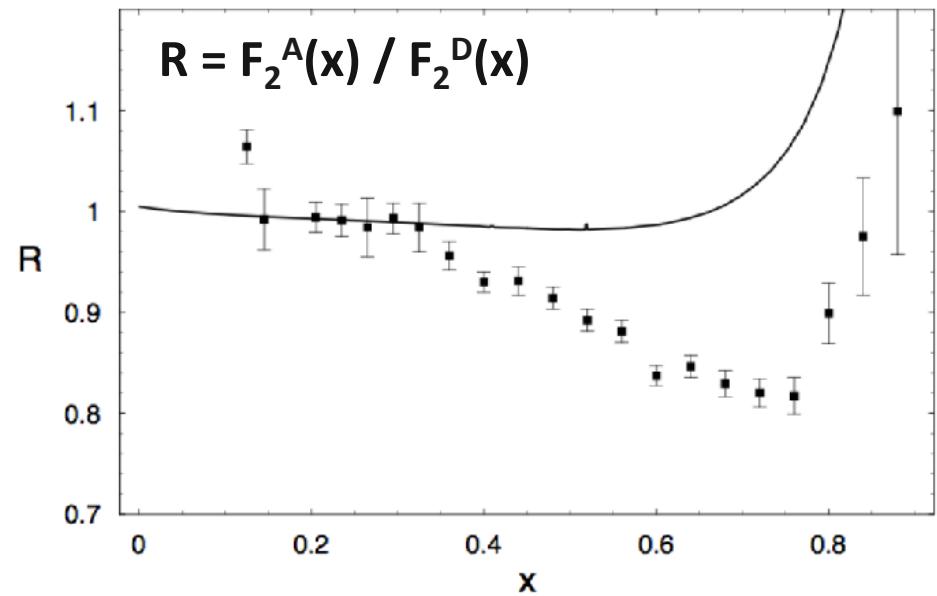
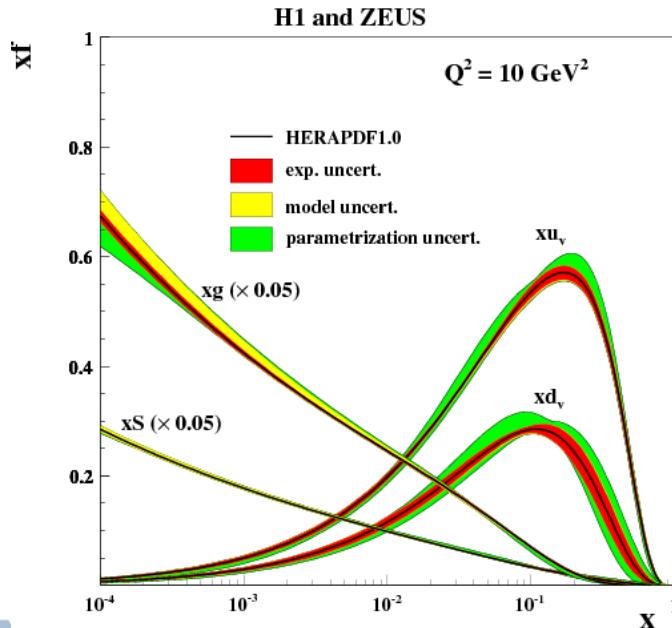
- $x$  = quark longitudinal momentum fraction
- $F_2(x)$  related to parton momentum distributions (pdfs)

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

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



# A-dependence of EMC effect in light nuclei

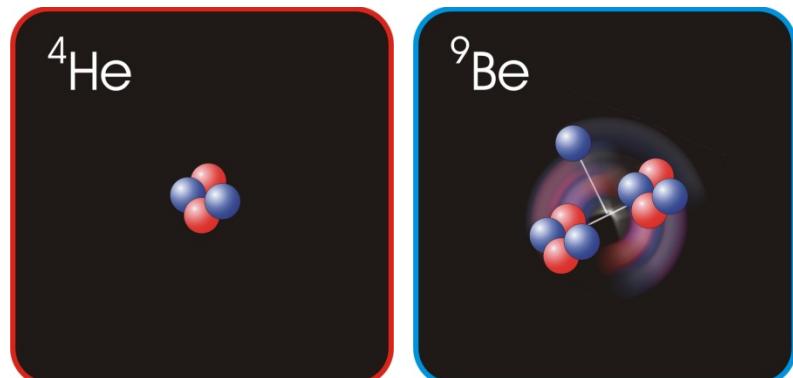
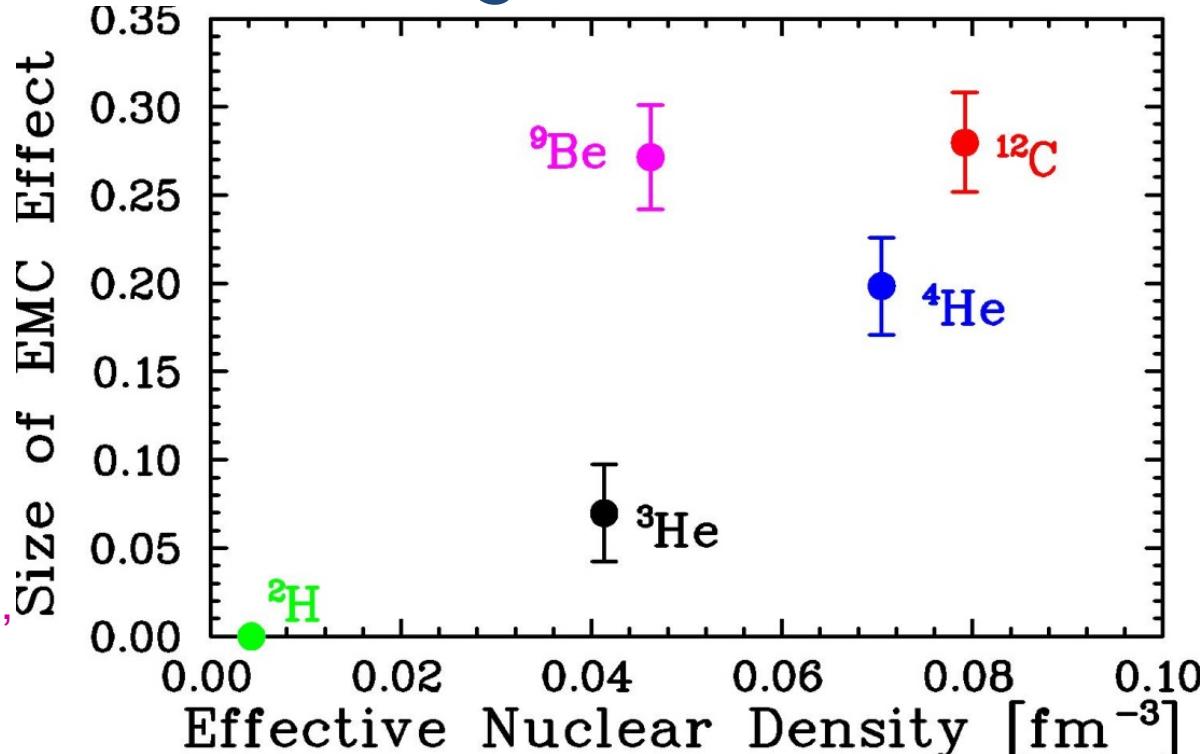
Density determined from  
*ab initio* calculation

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

Data show smooth behavior  
as density increases...  
except for  $^9\text{Be}$

$^9\text{Be}$  has **low average density**,  
but large component of  
structure is  $2\alpha + \text{n}$   
Most nucleons in tight,  $\alpha$ -like  
configurations

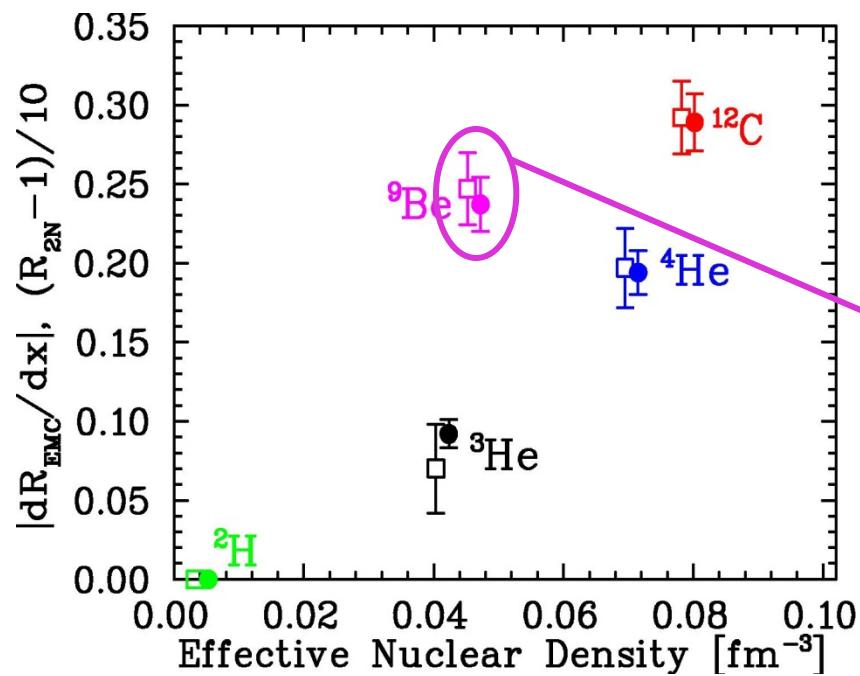
Same cluster structure that  
enhances NN correlations  
appears to drive EMC effect



"Size of EMC effect" is slope of ( $A/D$ ) ratio vs  $x$  for  $0.3 < x < 0.7$

# Correlation between SRCs and EMC effect

## Importance of two-body effects?



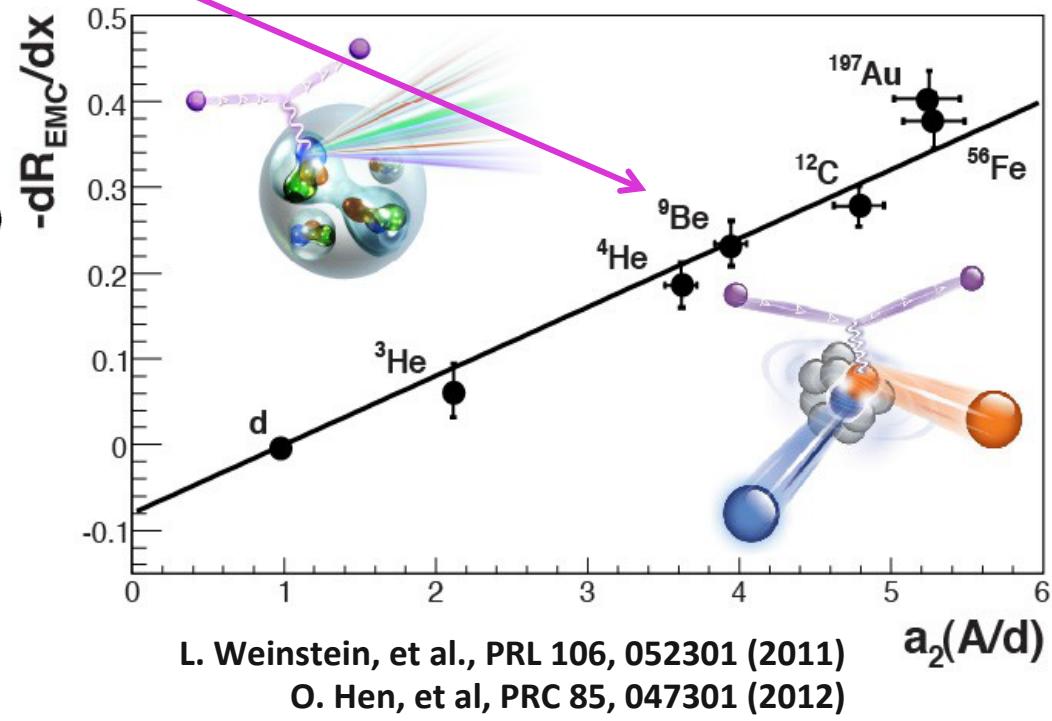
J. Seely, et al., PRL103, 202301 (2009)

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

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

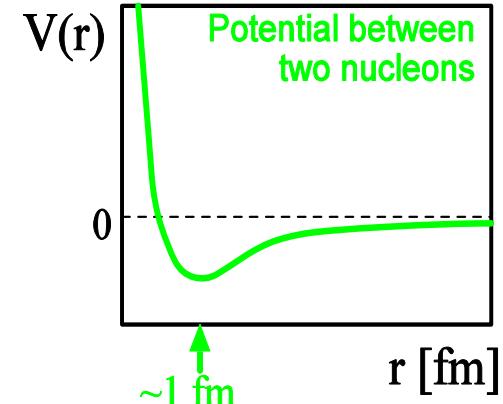
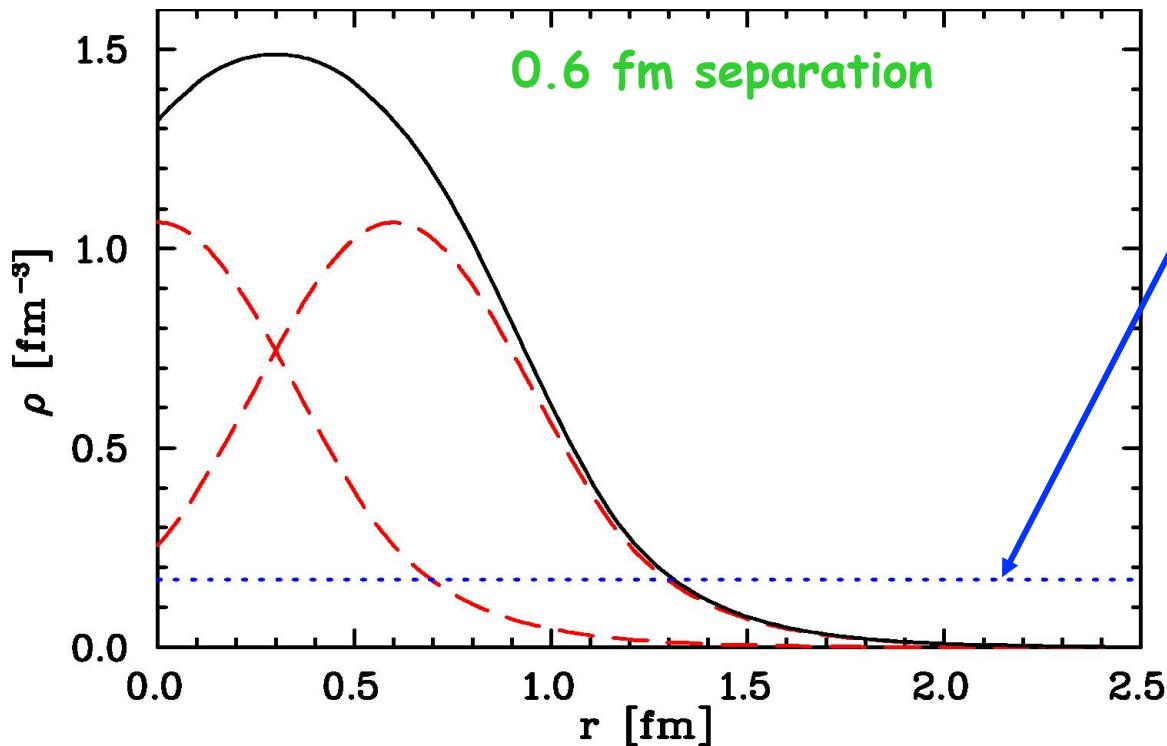
5-10% suppression in all nucleons?

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



# Nucleon overlap in nuclei?

Nucleons are composite objects  
charge radius  $\sim 0.86$  fm  
separation in heavy nuclei  $\sim 1.7$  fm



Average nuclear density

Are nucleons unaffected by this overlap?

Do they deform as they are squeezed together?

Do the quarks exchange or interact?

# Future measurements: SRCs, EMC effect

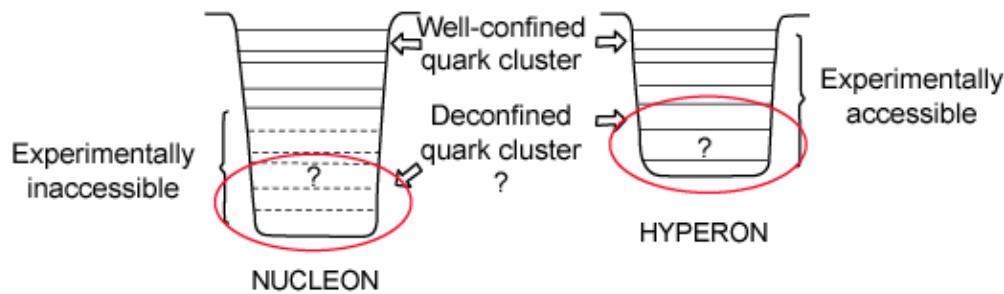
- Apparent connection between cluster structure, short-range (high-momentum) pairs, and suppression of high-x quark distributions
- So far, mainly observed in correlation between observables, non-trivial A dependence
- JLab @ 12 GeV:
  - Additional light nuclei:  $^3\text{H}$ ,  $^3\text{He}$ ,  $^{6,7}\text{Li}$ ,  $^{10,11}\text{B}$ ,  $^{40,48}\text{Ca}$ 
    - Cluster structure, isospin dependence
  - Detailed deuteron studies, attempting to isolate SRCs (high-density configuration)
    - Inclusive DIS: quark distributions at  $x > 1$ , where SRCs dominate
    - $^2\text{H}(\text{e},\text{e}'\text{p})$  at large missing momentum: modification of proton form factor?
    - Spectator tagging (backward going nucleon): modification of proton pdfs?
  - EIC allows for significant additional measurements with spectator tagging

J. Arrington, Dense  
Nuclear Matter WG

C. Weiss, Nuclear  
Structure WG

# Hypernuclei: unique window on nuclear structure

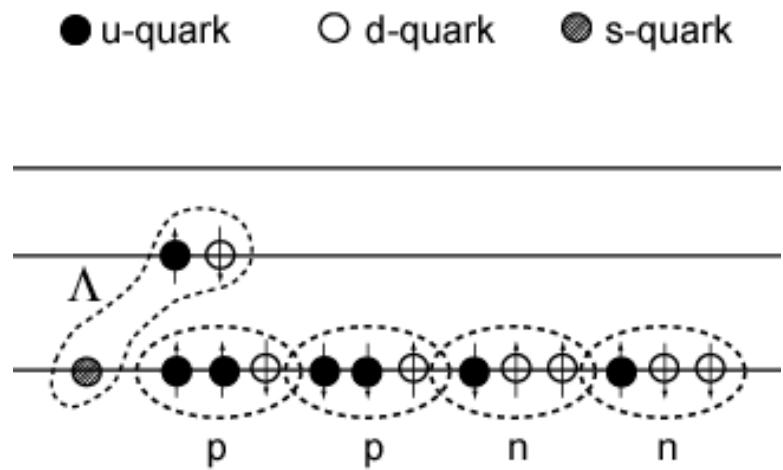
The distinguishability of the hyperon permits us to probe deeply-bound shells in nuclei



Possible single-particle orbitals for nucleons and for a hyperon. The nucleon orbitals are occupied up to the Fermi surface, while the hyperon orbitals are unoccupied.

T. Yamazaki

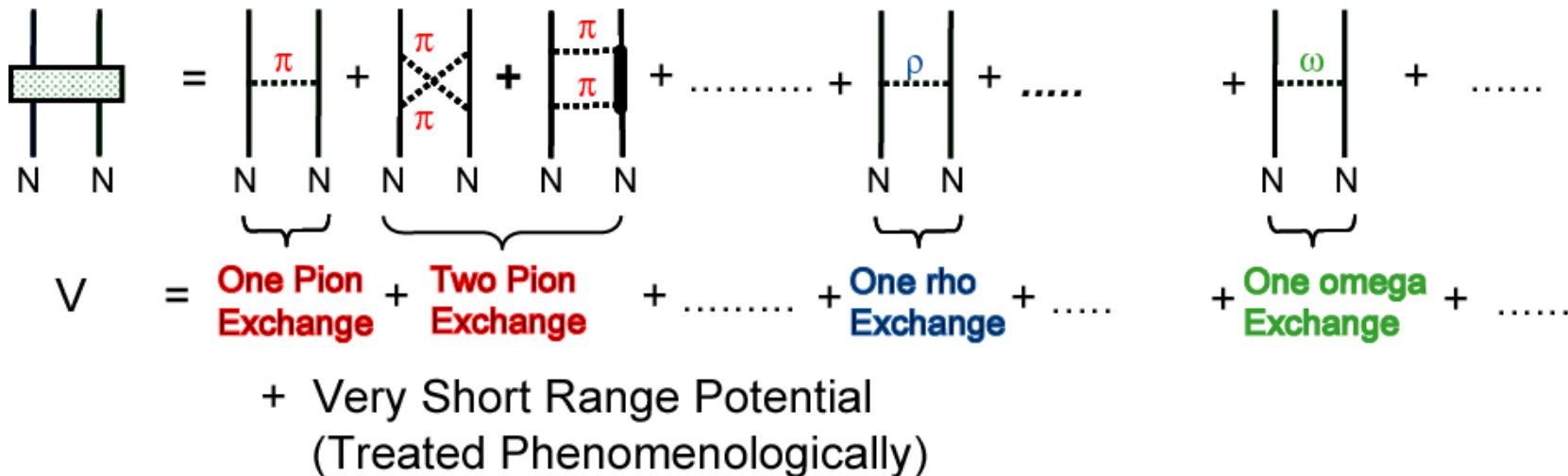
Access deeply bound nuclear states in a potential given by the  $\Lambda$ -N interaction rather than the N-N interaction...



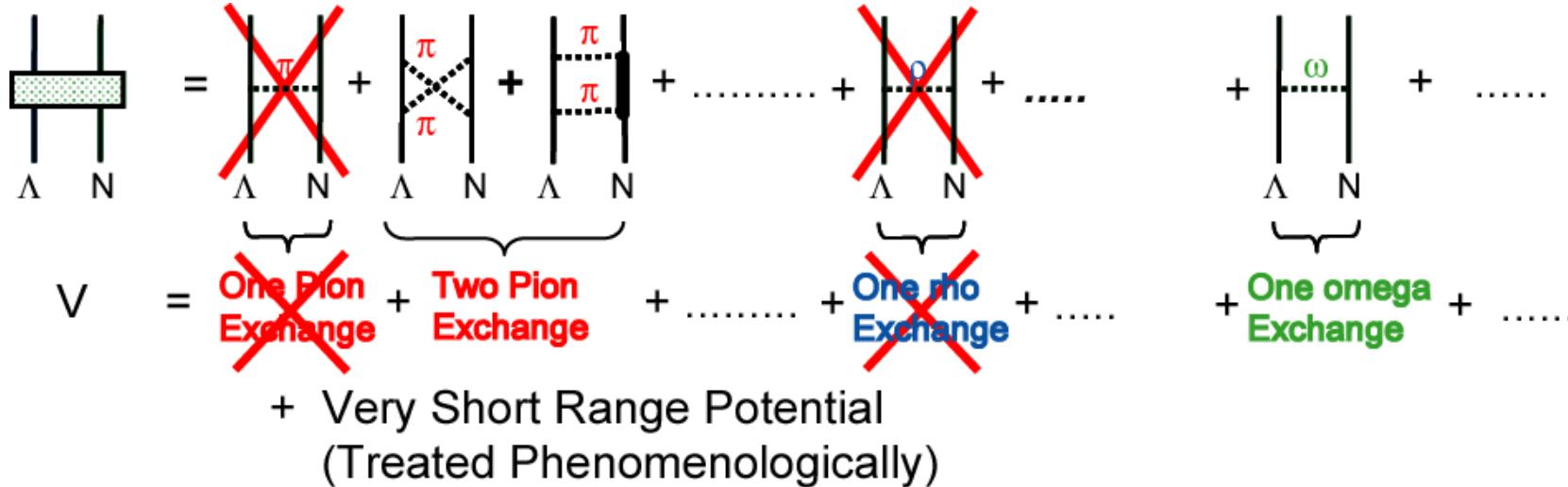
and provide the opportunity to probe the quark structure of nuclear systems in new and different ways.

# Hypernuclei allow tests of $\Lambda$ -N ( $\Sigma$ -N) interaction

For the N-N System:



For  $\Lambda$ -N System: long-range terms suppressed (by Isospin)

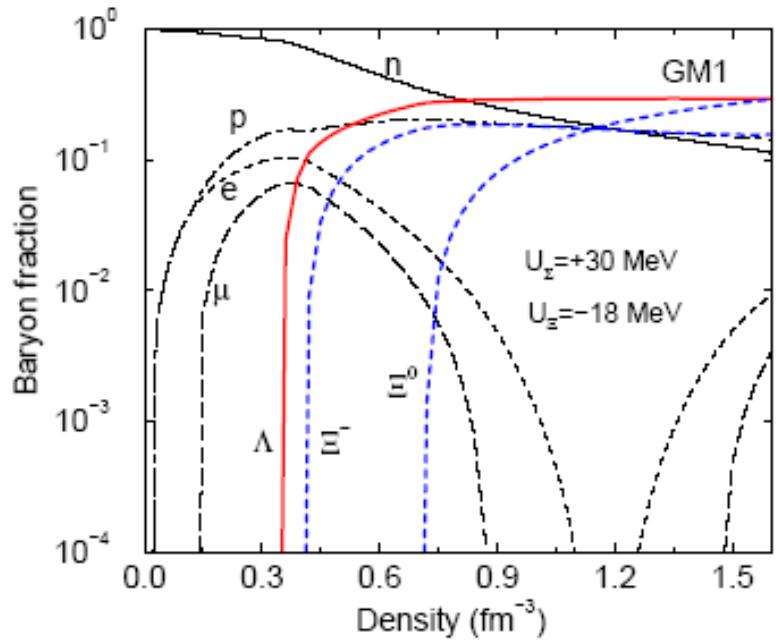
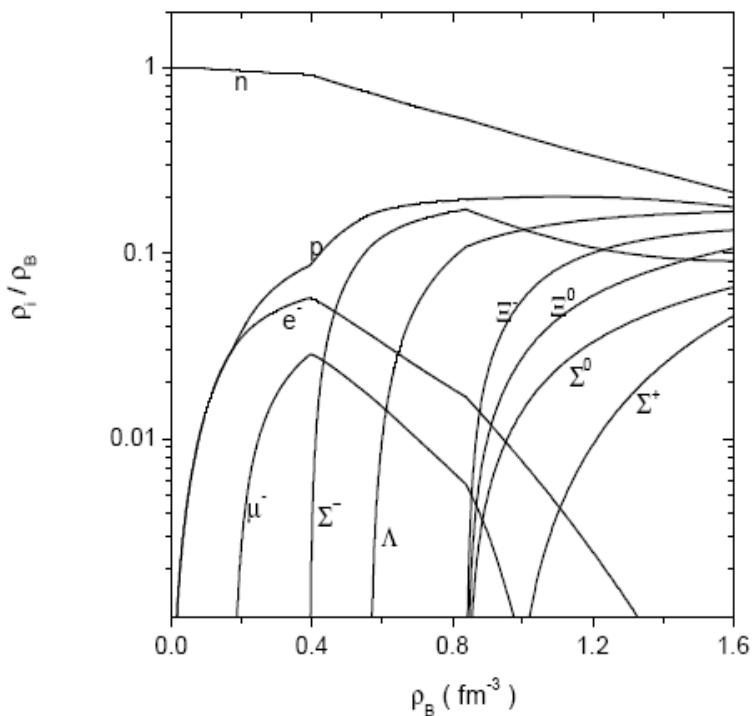
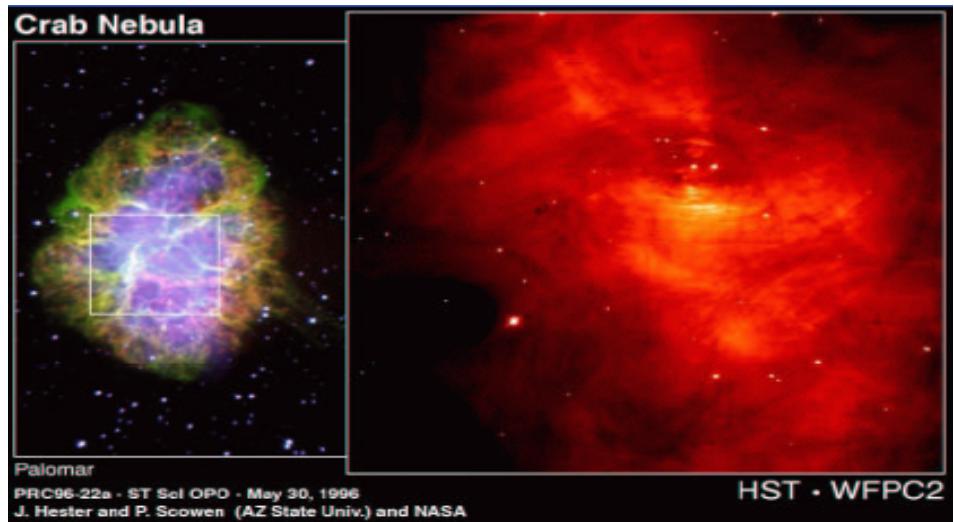


# Hyperons impact Neutron Star Composition

Hyperons enter at just  $2-3 \rho_0$

Need effective  $\Sigma$ -N and  $\Lambda$ -N forces in this density region!

$\Xi$  - Hypernuclear data is important input: we have none!



# Why Study Hypernuclei?

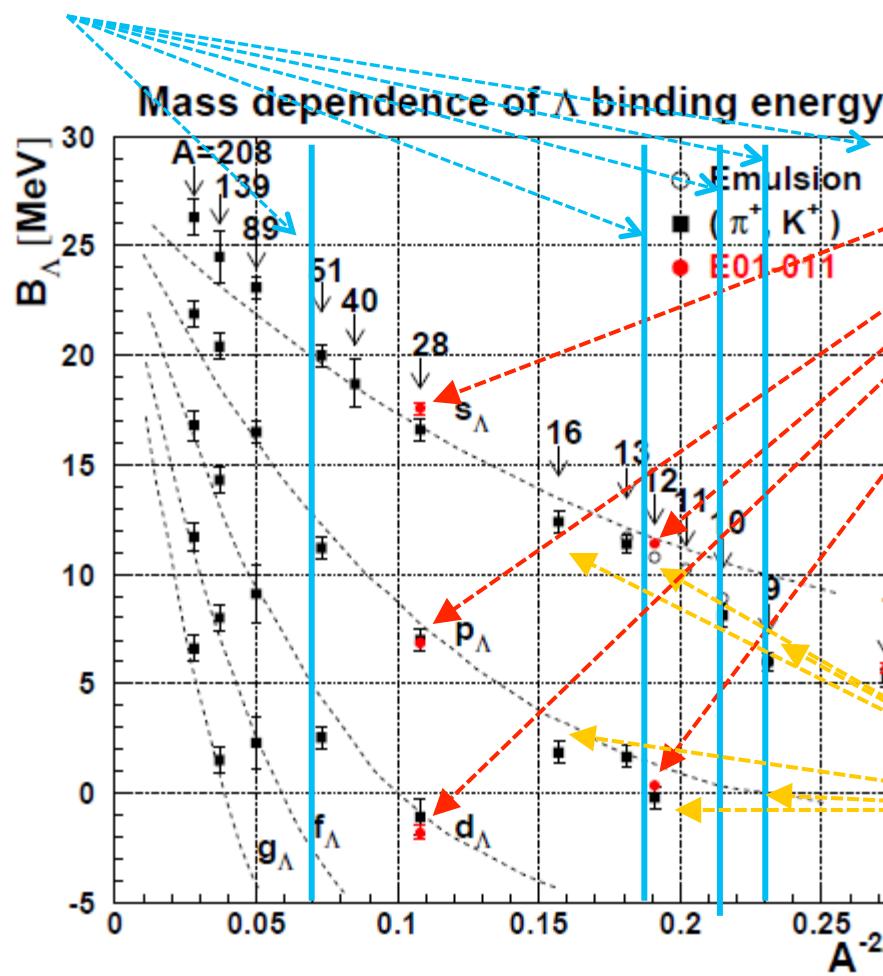
- Contain a strongly interacting particle ( $\Lambda$ ) that is not a proton/neutron
  - Spectroscopy provides information on the **strong interaction of the  $\Lambda$**
  - Non-identical particle avoids Pauli blocking, providing access to **deeply bound (s & p wave) states**
  - Unique opportunities for studying baryon structure in the nuclear medium
- Physics Issues Addressed:
  - $\Lambda$ -N force vs N-N force will provide clues to the **QCD description of the N-N Force** (one- $\pi$  and one- $\rho$  exchange are suppressed)
  - **Equation of state for neutron stars**
  - Elementary  $\Lambda$ -electroproduction cross section
  - Weak interaction in the nuclear medium, w/ non-mesonic decay
- Hypernuclear Program at JLab:
  - Proven the feasibility and technique of electro-production
  - Achieved the highest possible precision in mass spectroscopy  
( $\delta E \sim 500$  keV FWHM and  $\delta B_\Lambda < \pm 100$  keV) – Unique
  - Studied the spectroscopy of a sequence of  $\Lambda$ -hypernuclei:  
 ${}^7_{\Lambda}\text{He}$ ,  ${}^9_{\Lambda}\text{Li}$ ,  ${}^{10}_{\Lambda}\text{Be}$ ,  ${}^{12}_{\Lambda}\text{B}$ ,  ${}^{16}_{\Lambda}\text{N}$ ,  ${}^{28}_{\Lambda}\text{Al}$ , and  ${}^{52}_{\Lambda}\text{V}$  –only new results of past decade

# JLab's Hypernuclear Program To Date

Nucleus	What Have We Learned?
$^{12}\text{C}(\text{e},\text{e}'\text{K}^+)^{12}_{\Lambda}\text{B}$	A reference nucleus. Demonstrates improved resolution relative to $\pi$ -production (0.6 vs 2 MeV). S-shell portion of spectrum well-reproduced by theory, p-shell portion is not.
$\text{H}(\text{e},\text{e}'\text{K})\Lambda$ and $\text{H}(\text{e},\text{e}'\text{K})\Sigma^0$	Measurement of the elementary interactions – $\text{H}(\text{e},\text{e}'\text{K})\Lambda$ and $\text{H}(\text{e},\text{e}'\text{K})\Sigma^0$ – permits absolute energy calibration and normalization of production cross sections. Hypernuclear program has pushed data on the elementary process to very forward angles, revealing substantial discrepancies with current theoretical models of the elementary process
$^{16}\text{O}(\text{e},\text{e}'\text{K}^+)^{16}_{\Lambda}\text{N}$	Within errors, binding energy and excited levels of mirror hypernuclei ( $^{16}_{\Lambda}\text{O}$ from pion production experiments and $^{16}_{\Lambda}\text{N}$ from $(\text{e},\text{e}'\text{K})$ ) are in agreement
$^9\text{Be}(\text{e},\text{e}'\text{K}^+)^9_{\Lambda}\text{Li}$	Theory doesn't reproduce observed energies and strengths. Possible explanations include current calculations of the underlying core nucleus $^8_{\Lambda}\text{Li}$ structure and spectroscopic factors.
$^{28}\text{Si}(\text{e},\text{e}'\text{K}^+)^{28}_{\Lambda}\text{Al}$	First sd shell hypernuclear spectroscopy w/ isotopically pure target. Preliminary determination of mass suggests that it disagrees by ~1 MeV with shell model prediction (potential major impact).
$^7\text{Li}(\text{e},\text{e}'\text{K}^+)^7_{\Lambda}\text{He}$	First reliable observation of $^7_{\Lambda}\text{He}$ w/ good statistics – comparison between $^7_{\Lambda}\text{He}$ , and data on $^7_{\Lambda}\text{Li}^*$ and $^7_{\Lambda}\text{Be}$ from gamma decay experiments provides data on CSB in hypernuclei. The experimental results are NOT reproduced by theory, bringing potential into question.
$^{52}\text{Cr}(\text{e},\text{e}'\text{K}^+)^{52}_{\Lambda}\text{V}$	New data under analysis. Demonstrated the feasibility of measurements of heavy hypernuclei, w/ deeply bound $\Lambda$ , which are not accessible using the gamma ray decay measurement technique.
$^{10}\text{B}(\text{e},\text{e}'\text{K}^+)^{10}_{\Lambda}\text{Be}$	New data under analysis. Will be compared with related data on as a cross check on modifications to CSB calculations likely to be done to explain the $^7_{\Lambda}\text{He} / ^7_{\Lambda}\text{Li}^* / ^7_{\Lambda}\text{Be}$ result.

# $\Lambda$ single particle energies

E05-115 (HKS-HES)



E01-011(HKS)

Per John Millener:  
“a textbook example of  
single particle structure”

E94-107  
(Hall A HY)

Calculation by Millener, Dover and Gal (PRC 38, 2700 (1988), using a Woods-Saxon potential with a depth of 28 MeV and a radius parameter of  $1.128 + 0.439A^{-2/3}$ )

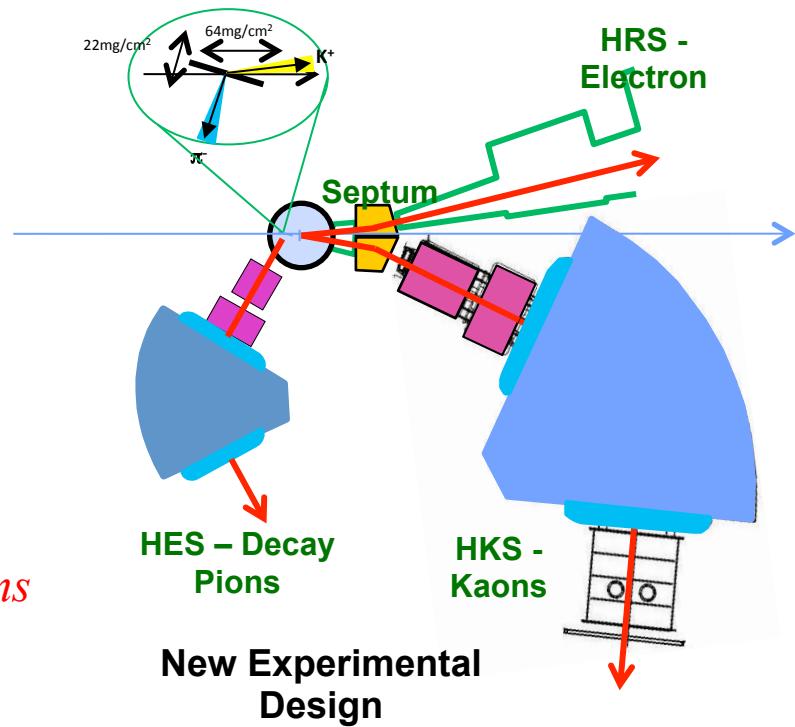
# Future: Program on Hypernuclear Spectroscopy

## Technical Features:

- High precision and high yield  
( $\delta E \sim 600$  keV FWHM and  $\delta B_\Lambda \sim \pm 50$  keV)
- “Free” of accidental background
- All major equipment already exist

## Physics:

- Few body  
*Charge Symmetry Breaking (CSB) in  $\Lambda N$  interactions*
- Medium heavy hypernuclei  
*LS force; shell model on baryonic many-body system;  
structure or deformation of the core nuclei probed by  $\Lambda$*
- Heavy hypernuclei ( $A \sim 200$ ) – precise  $B_\Lambda$  and level spacing  
*Importance of 3B/4B forces; many body vs QCD descriptions*
- Decay pion spectroscopy (Ground state of light hypernuclei;  $\delta E \sim 130$  keV,  $\delta B_\Lambda \sim \pm 20$  keV)  
 *$\Lambda N$  interactions; CSB;  $\Lambda$ - $\Sigma$  coupling; drip line hypernuclei ( ${}^6 {}_\Lambda H$ )*

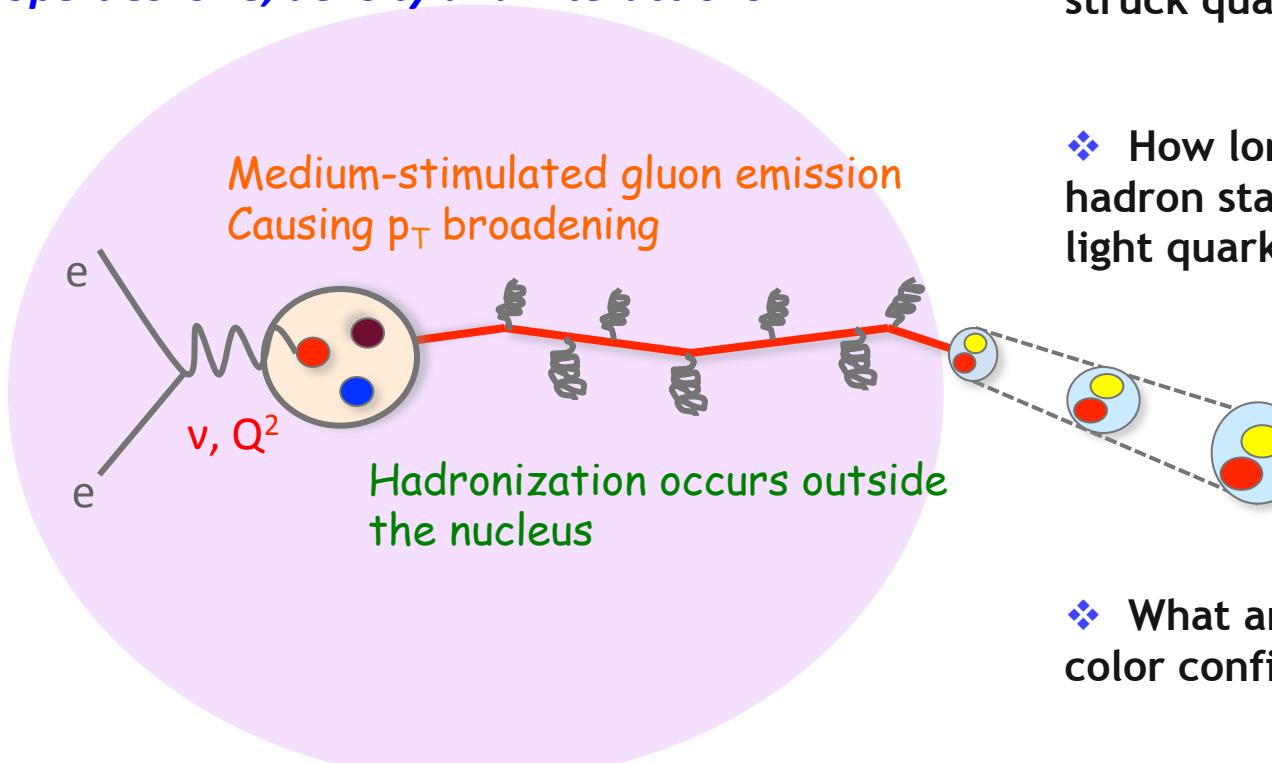


L. Tang, Nuclear  
Structure WG

# Hadronization in cold nuclear matter

## Quark propagation and hadron formation

*Use nuclei as spatial filters with known properties: size, density and interactions*

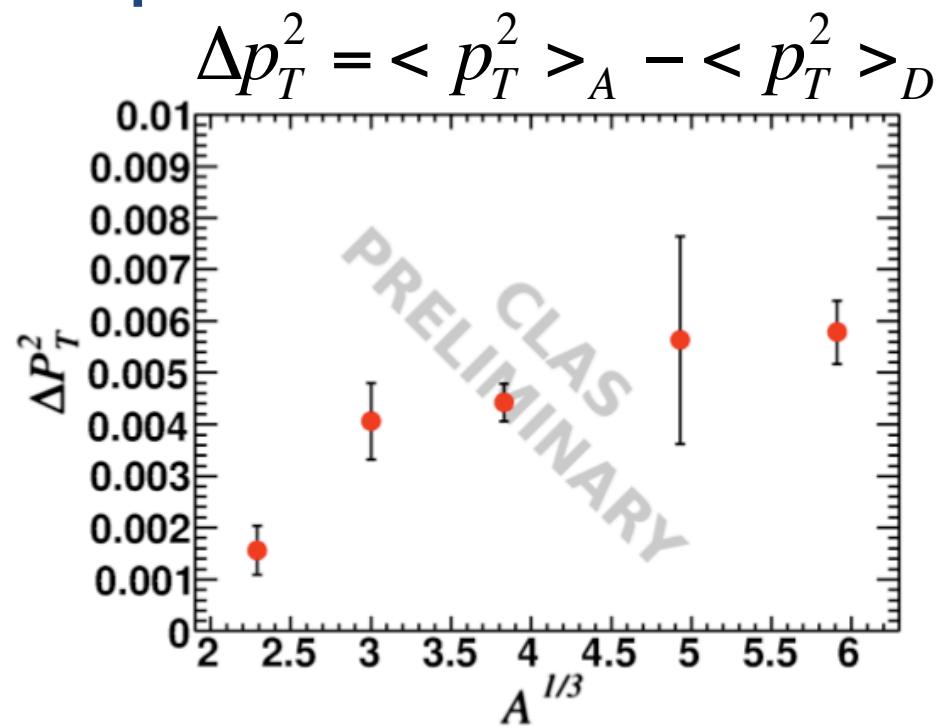
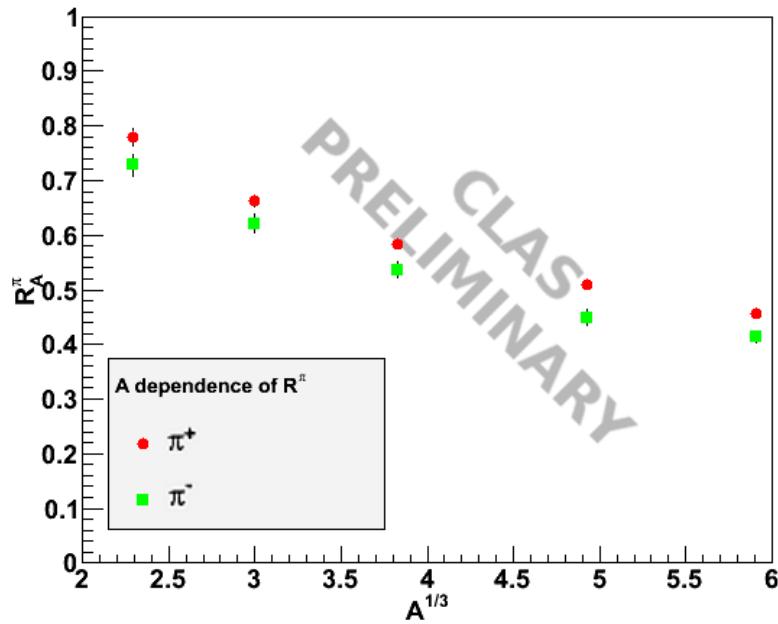


- ❖ What is the interaction of the struck quark before it hadronizes?
- ❖ How long does it take to form a hadron starting from an energetic light quark?
- ❖ What are the dynamics leading to color confinement?

- ❑ Complementary way of studying confinement (compared to traditional spectroscopy)
- ❑ Test theoretical tools used to determine the properties of strongly coupled Quark-Gluon Plasma
- ❑ Reduce systematic uncertainties in neutrino experiments using nuclear targets



# CLAS Preliminary Results : A Dependence



- $p_T$  broadening sensitive to quark energy loss mechanism
- Multiplicity ratio (absorption in nucleus) probes formation time
- Nuclear effect saturates at high  $A$  – Does not follow  $A^{1/3}$  or  $A^{2/3}$ 
  - Could be understood if multiple scattering occurs in parton stage vs hadron phase → small production time
- Multiplicity ratio and  $P_t$  broadening show same trend – same cause?
- 6 GeV only slightly overlaps kinematics of interest: need range in  $v$  (energy transfer),  $Q^2$ , and  $A$ .

# 12 GeV Anticipated Data

## Examples of Experimental Data and Theoretical Predictions

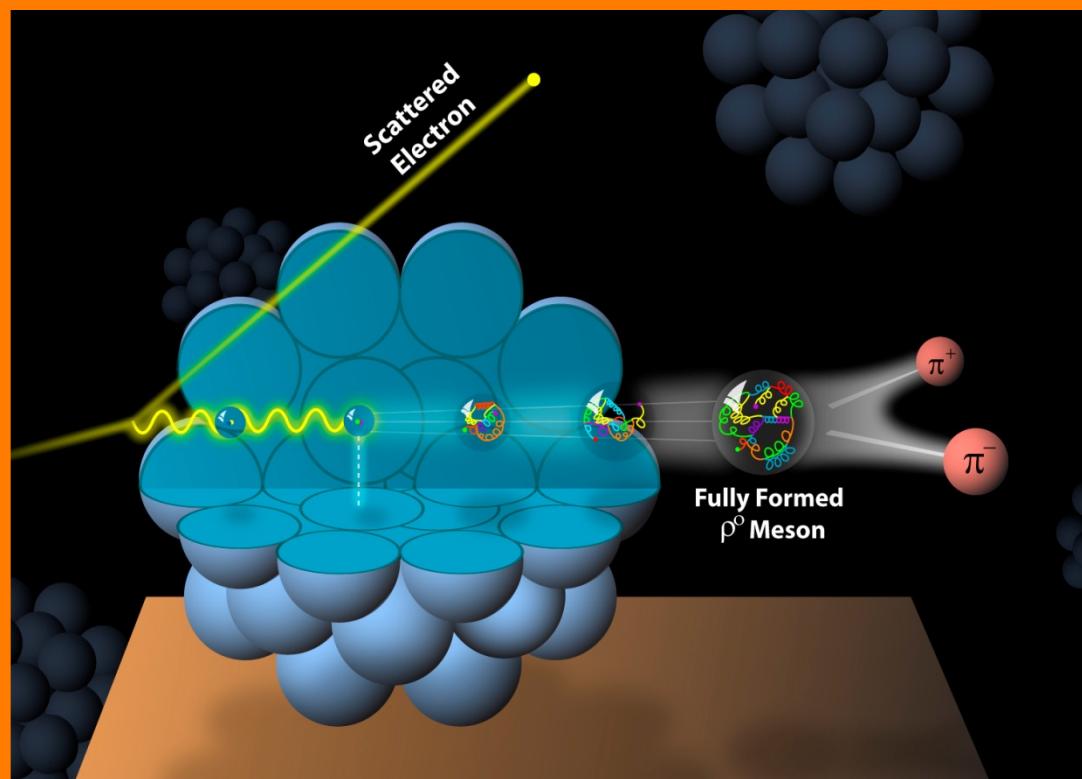


# Color Transparency “CT”

## The creation and propagation of Point-Like Configuration

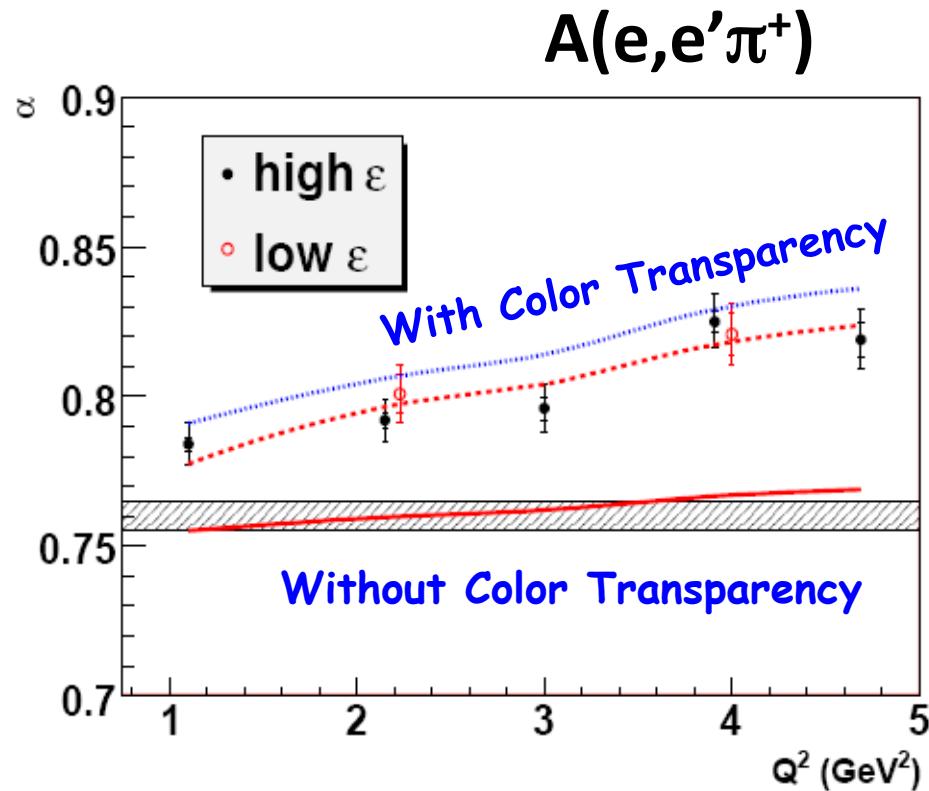
- ❖ Create color-singlet small size object (**PLC**)
- ❖ **PLC** has **reduced interaction** with the medium
- ❖ **PLC** does not expand immediately

Provides unique probe of the **space-time evolution** of from PLC of valence quarks to fully dressed hadron wave function

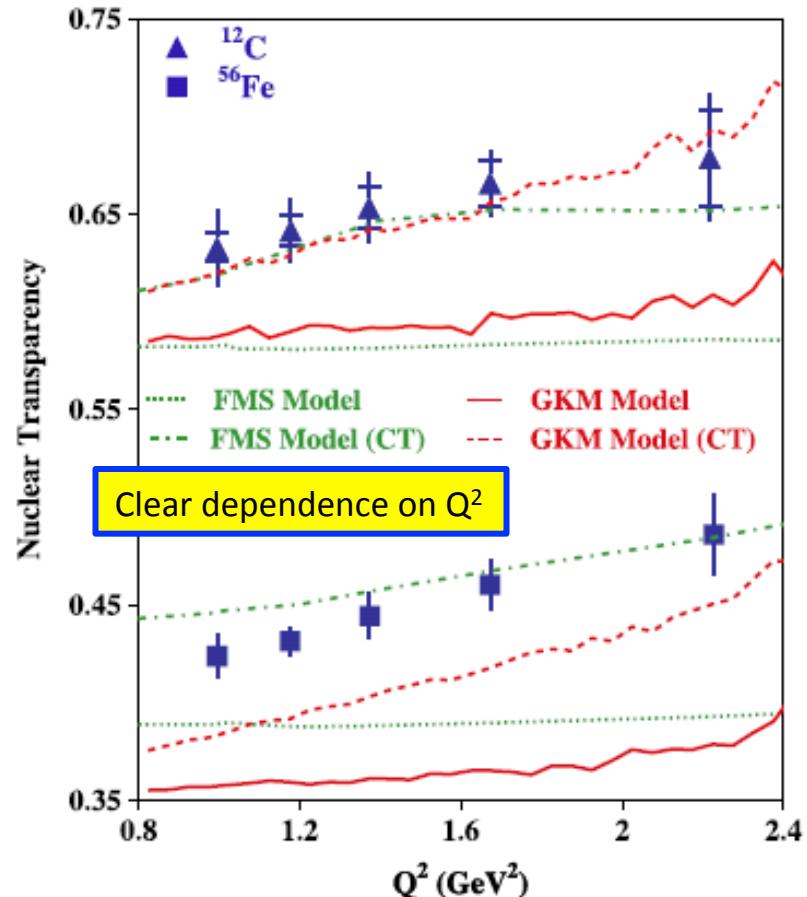
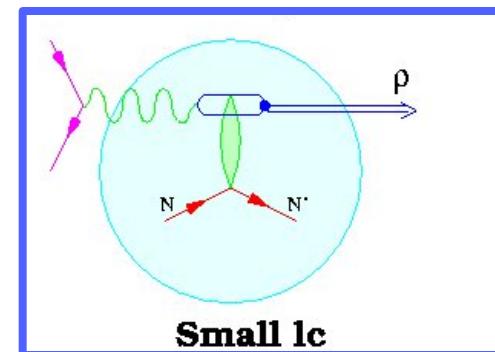


- ❑ Studies in proton knockout and pion,  $\rho^0$  production off nuclei
- ❑ Increasing  $Q^2$  drives formation of PLC, leads to longer lifetime of the small sized “pre-hadron”
- ❑ Variation of nuclear size and  $Q^2$  probes formation of PLC, timescale of evolution, and interaction of PLC with nuclear medium

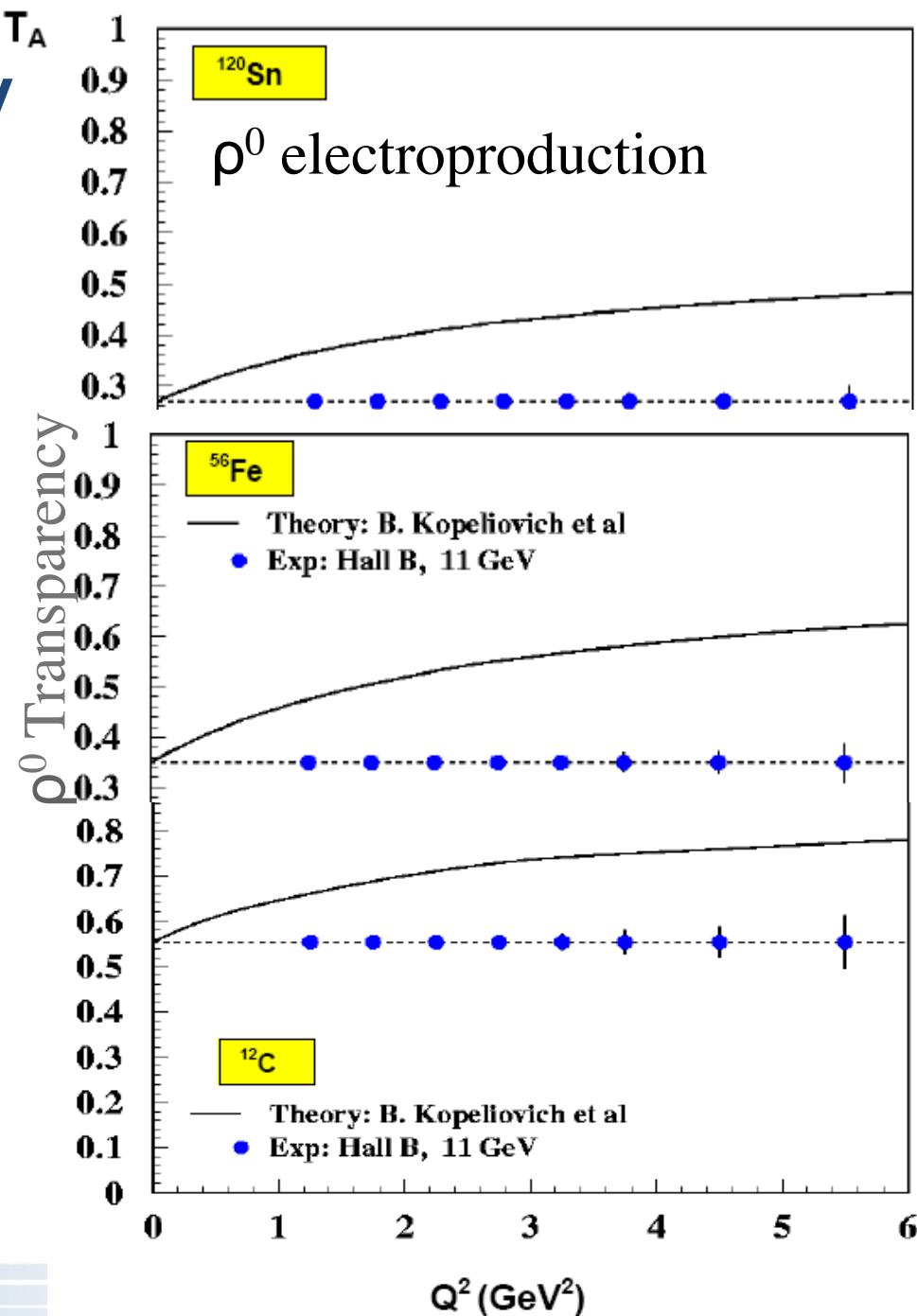
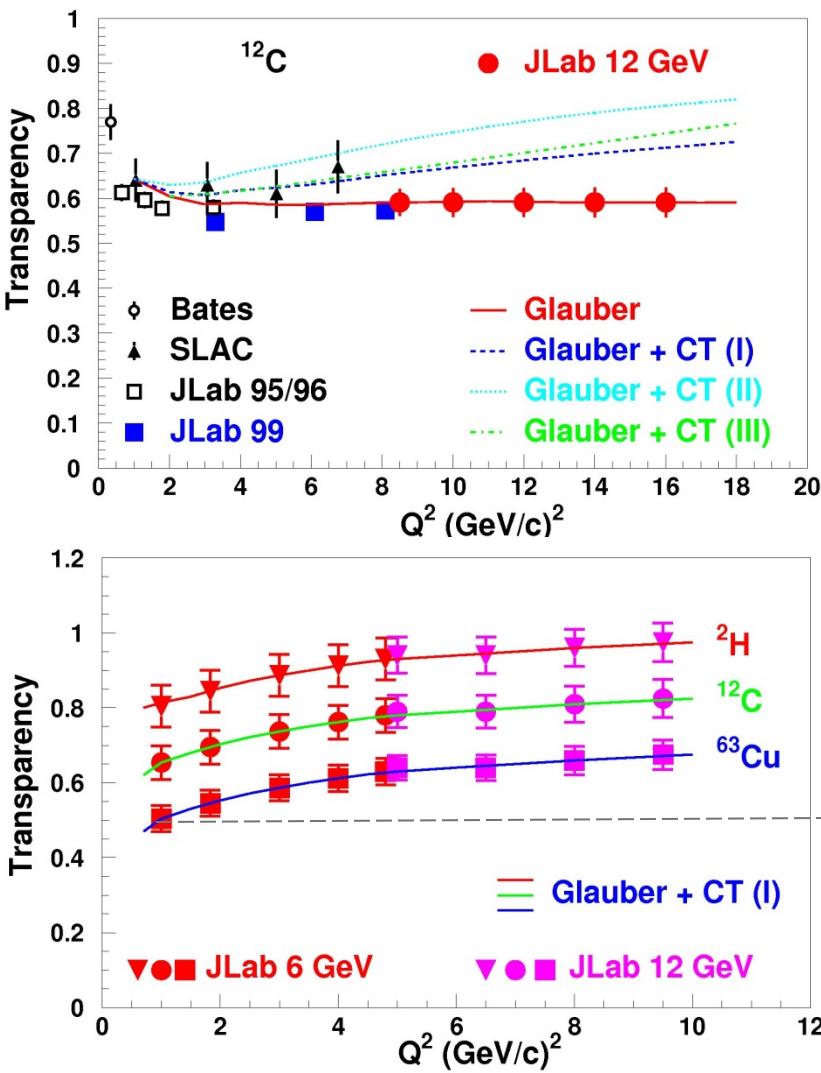
# Evidence for the onset of CT



$$T_A = \frac{N_A^\rho}{N_D^\rho}$$



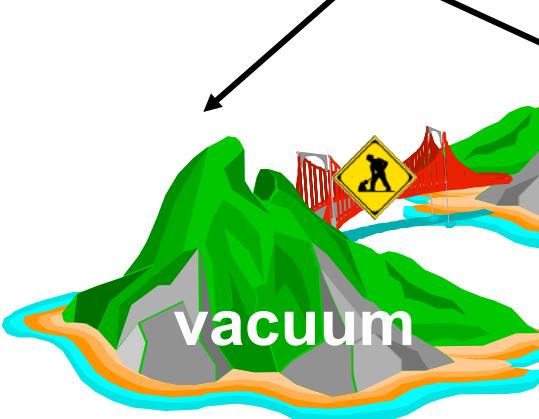
# CT predictions at 12 GeV



# Nuclear Structure Studies at Jefferson Lab

## Quark-Gluon Structure Of Nucleons and Nuclei

Nature of Confinement



Precise  
few-body data:  
Charge radii  
Form factors  
Mom. distributions

Exotic mesons  
and baryons



Correlations  
Neutron skin  
Hypernuclei  
Hadrons in-medium  
Effective NN (+ΛN) force

...n-stars