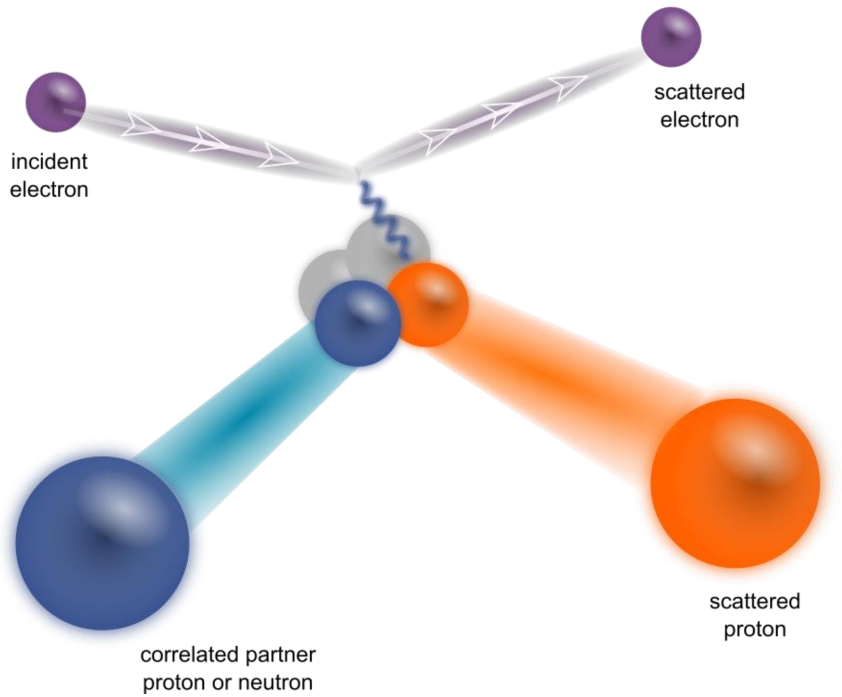
Nucleon Form Factors and the Nuclear Medium



Vincent Sulkosky

University of Virginia

HUGS 2014, Lecture 4

June 12th, 2014

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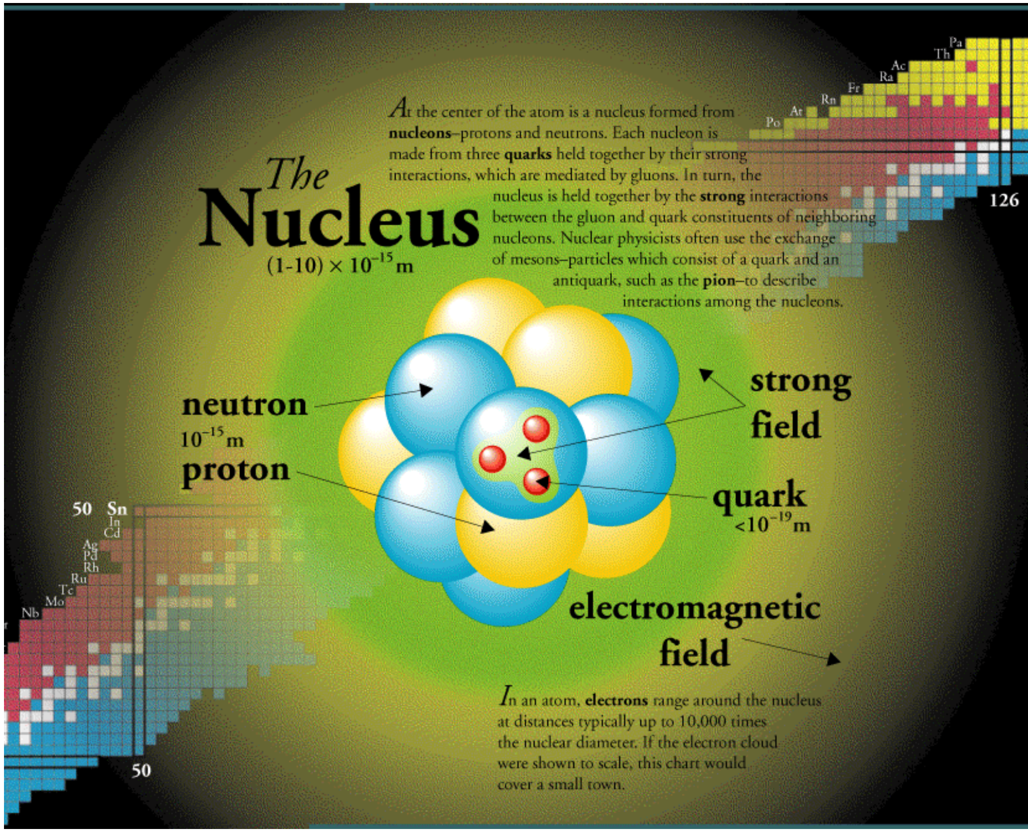
Questions to Ponder

1) Have we reached the repulsive core of the NN potential?
2) What implications do SRC pairs have in terms of the broader field of nuclear physics?
3) Is there evidence for 3N-SRC?
4) What is the EMC effect?
5) Is there a connection between SRC and the EMC effect?



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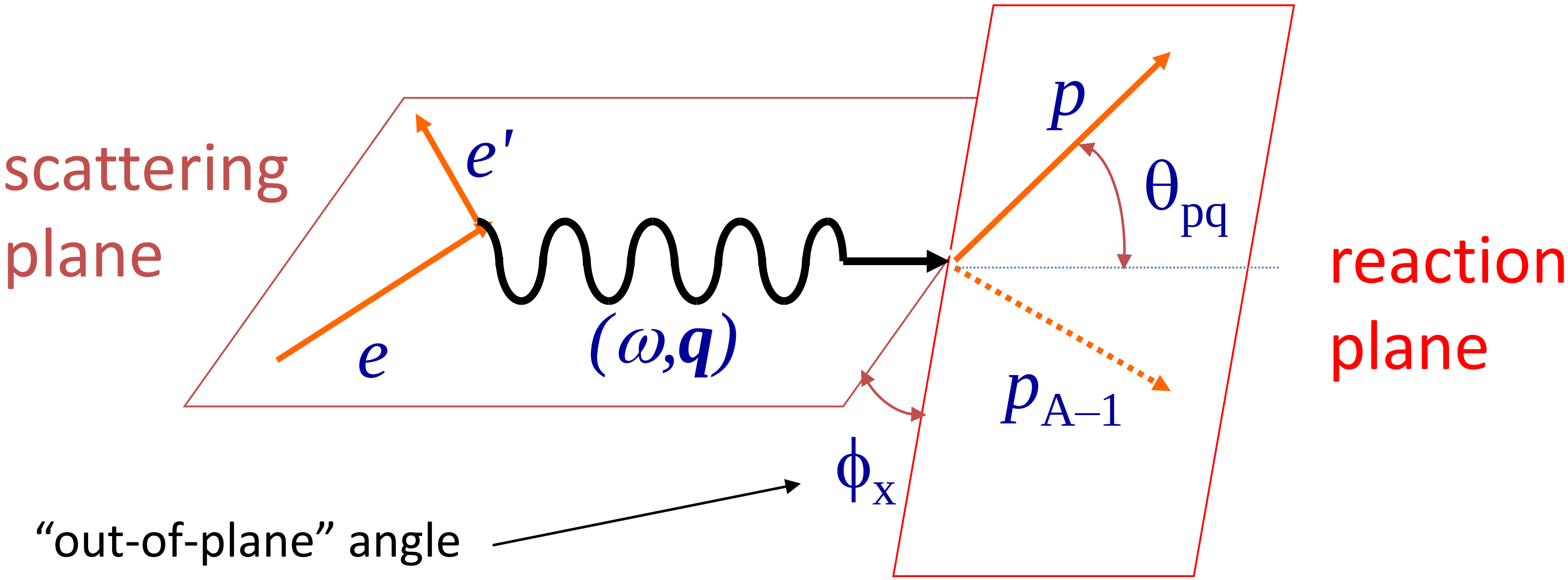
A(e,e'p)A-1 Kinematics



Four-momentum transfer squared: $Q^2 \equiv -q_\mu q^\mu = \boldsymbol{q}^2 - \omega^2$

Missing momentum: $\boldsymbol{p}_{\mathrm{m}} = \boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{A-1}$

Difference between transferred and detected momentum

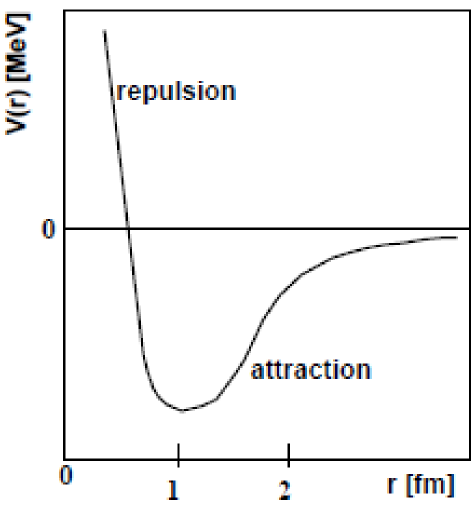
Missing energy: $\varepsilon_{\mathrm{m}} = \omega - T_p - T_{A-1}$

Difference between transferred and detected energy

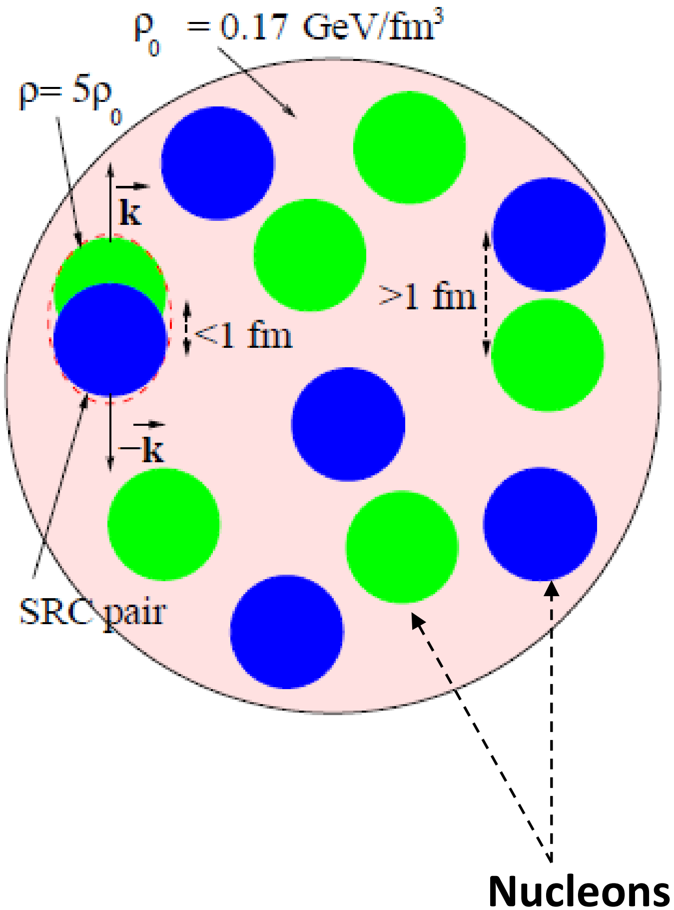
Bjorken x: $x_B = Q^2/2m\omega$ ***(just kinematics!)***

Counts minimum number of nucleons involved

Short-Range Correlations



SRC depletes states below the Fermi sea and makes the states above this level partially occupied.



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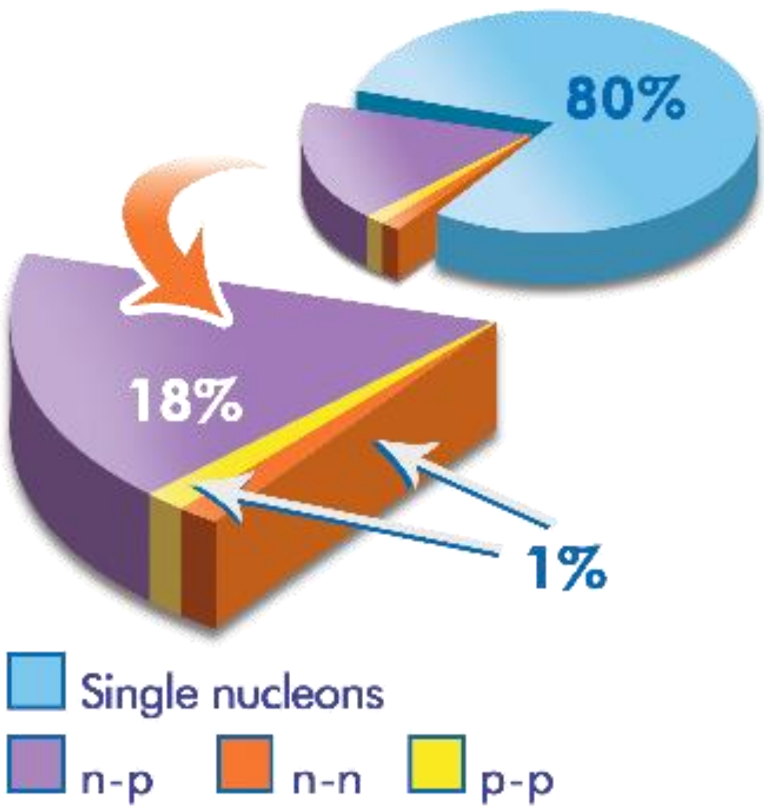
From the (e,e'), (e,e'p), and (e,e'pN) Results

- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - 18% np pairs
  - 1% pp pairs
  - 1% nn pairs (from isospin symmetry)



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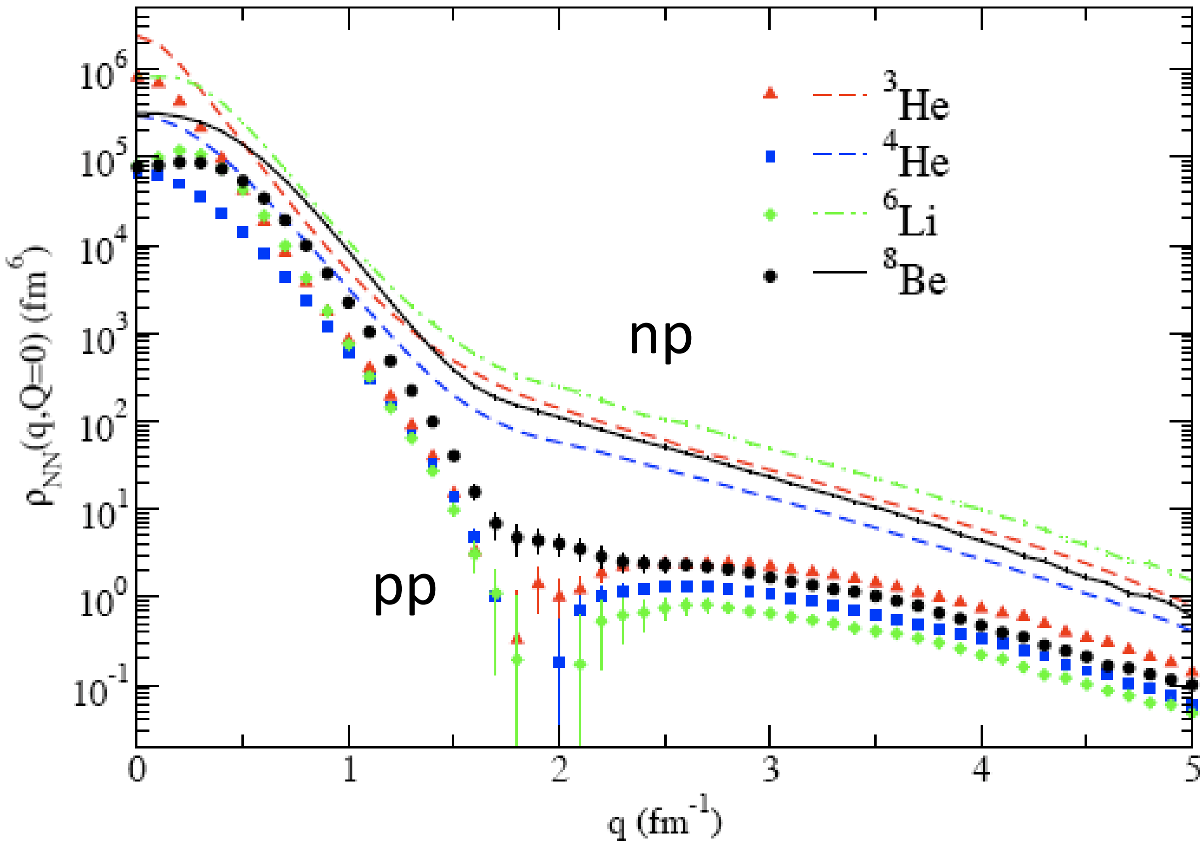
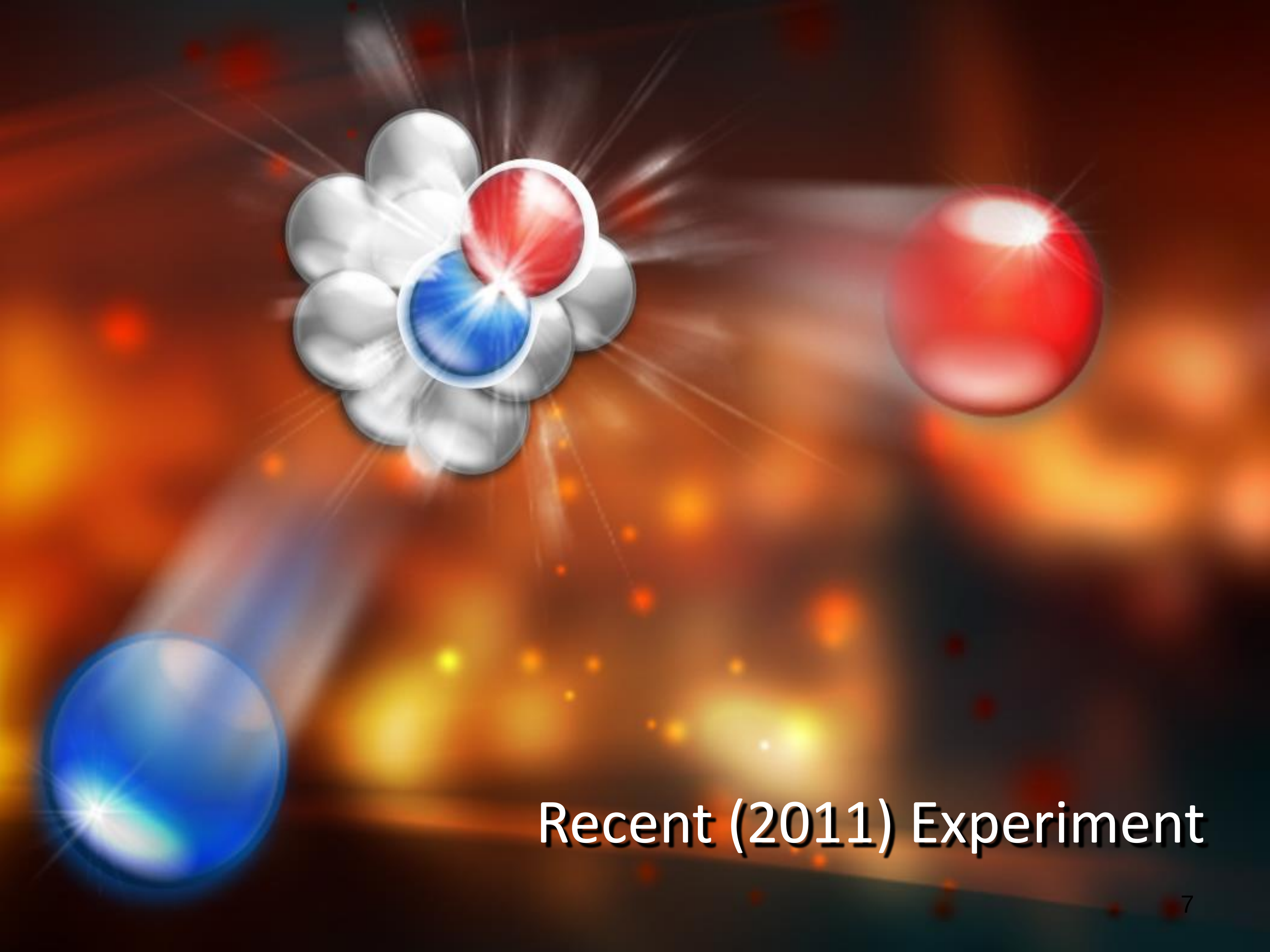
Importance of Tensor Correlations



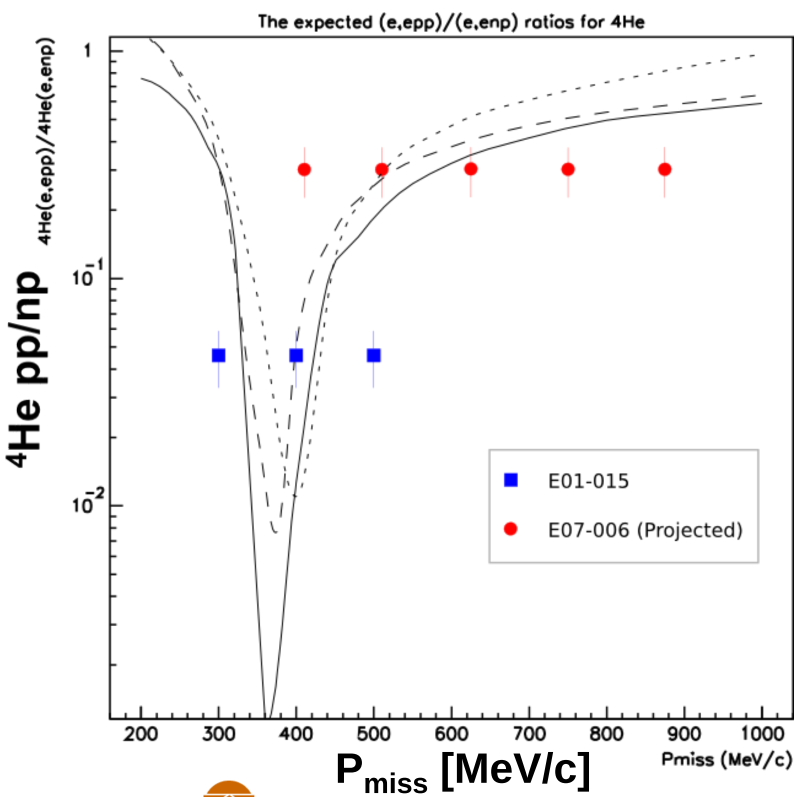
- R. Schiavilla et al., Phys. Rev. Lett. 98 (2007) 132501. [shown above]
- M. Sargsian et al., Phys. Rev. C (2005) 044615.
- M. Alvioli, C. Ciofi degli Atti, and H. Morita, Phys. Rev. Lett. 100 (2008) 162503.

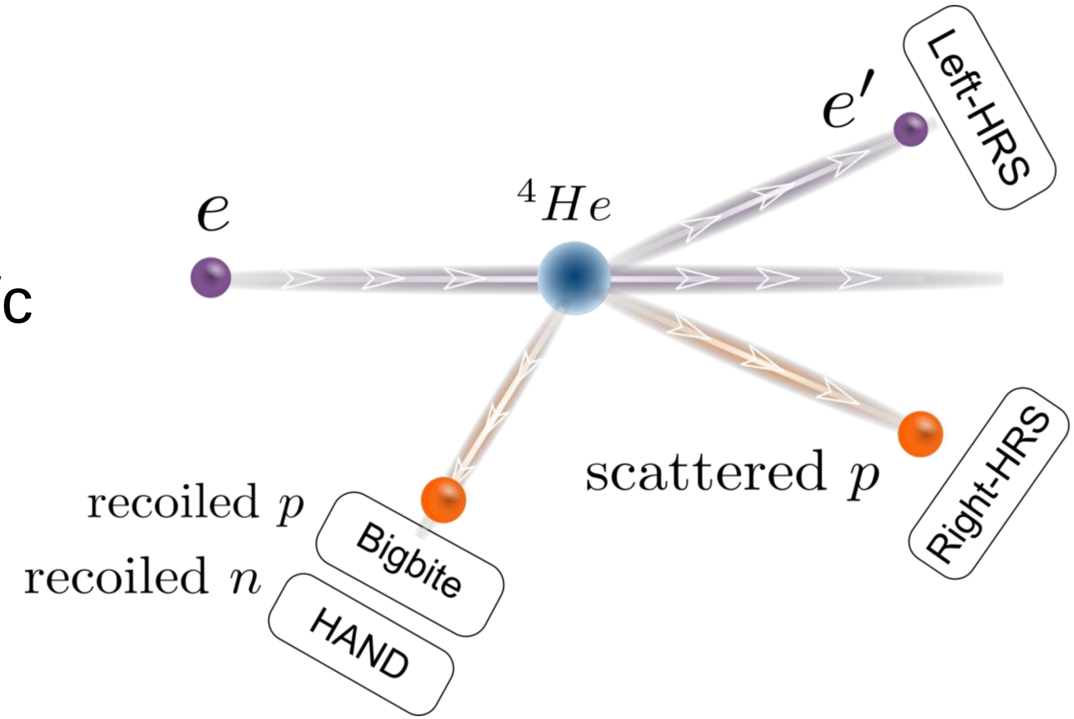


Recent (2011) Experiment

E07-006: ^{4}He(e,e'pN)pn SRC

- ^{4}He Target
  - Dense Nuclear Matter
  - *MF & Exact* Calculations
- P_{miss} from 400 – 800 MeV/c



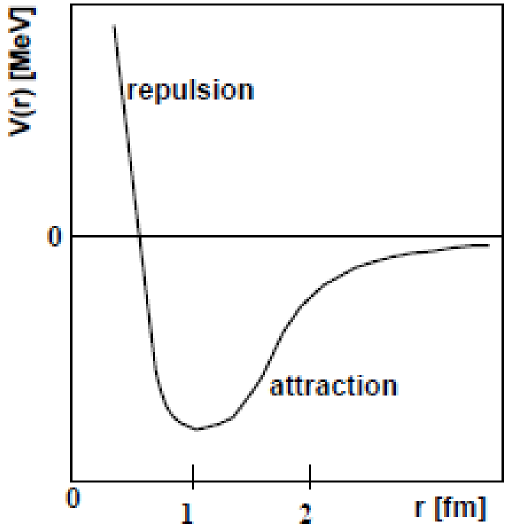


- Pushing the Limits of the NN Potential
  - Long range attraction
  - Short range repulsion

Experiment E07-006

Missing momentum 400 – 800 MeV/c → Tensor to Repulsive Core

E01-015	E07-006
$X_B > 1$, $Q^2 = 2$ [Gev/c]^2	$X_B > 1$, $Q^2 = 2$ [Gev/c]^2
300 – 600 MeV/c	400 – 800 MeV/c
Tensor Force	Tensor to Repulsive core
Target – ^{12}C	Target – ^{4}He (Less FSI)
BigBite and HAND	BigBite with MWDCs Upgraded HAND (new lead wall)



Ran March 13th to April 13th, 2011; May 10th to 13th, 2011

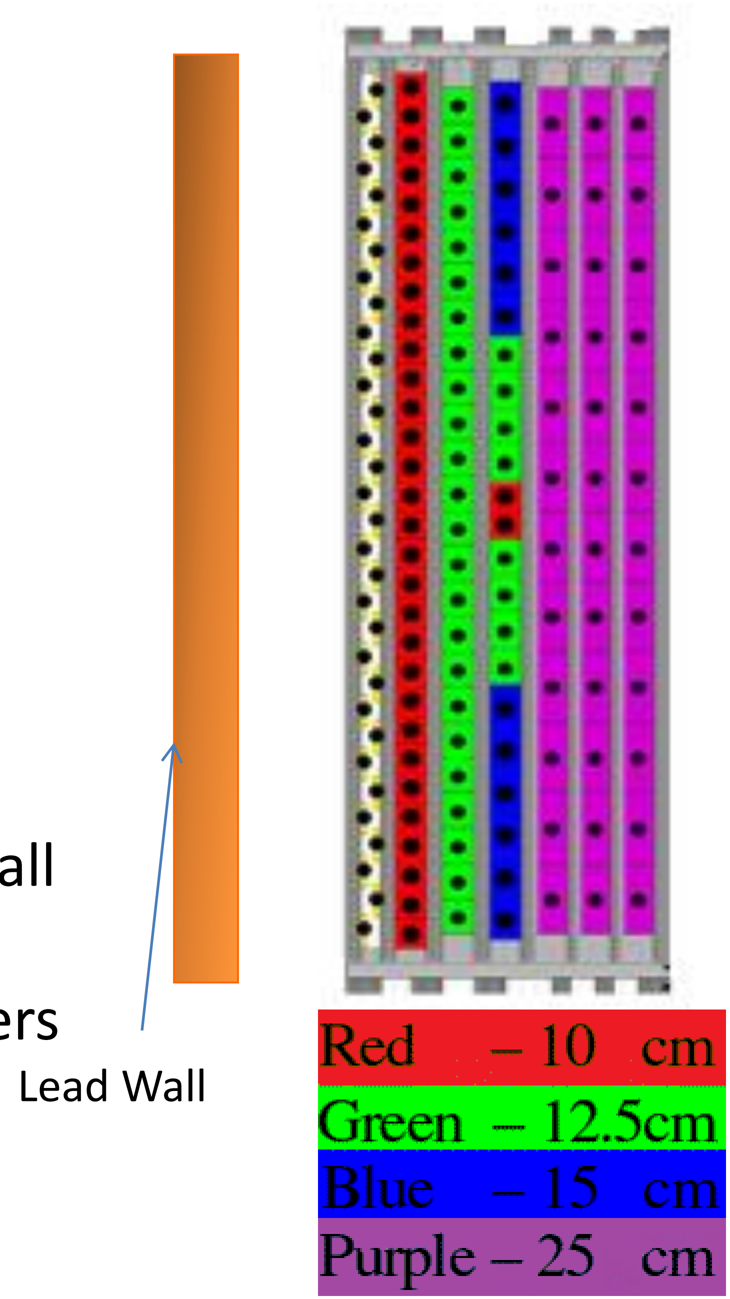
Neuron Array – HAND

Recoil neutron detection:

- Lead wall
- 64 veto bars
- 112 scintillators

Work completed:

- Design and assembly of the new frame
- Design and ordered new Lead wall (**Half as thick!**)
- Expanded HAND from 4 to 6 layers (112 scintillators instead of 88)



Neuron Array – HAND

Recoil neutron detection:

- Lead wall
- 64 veto bars
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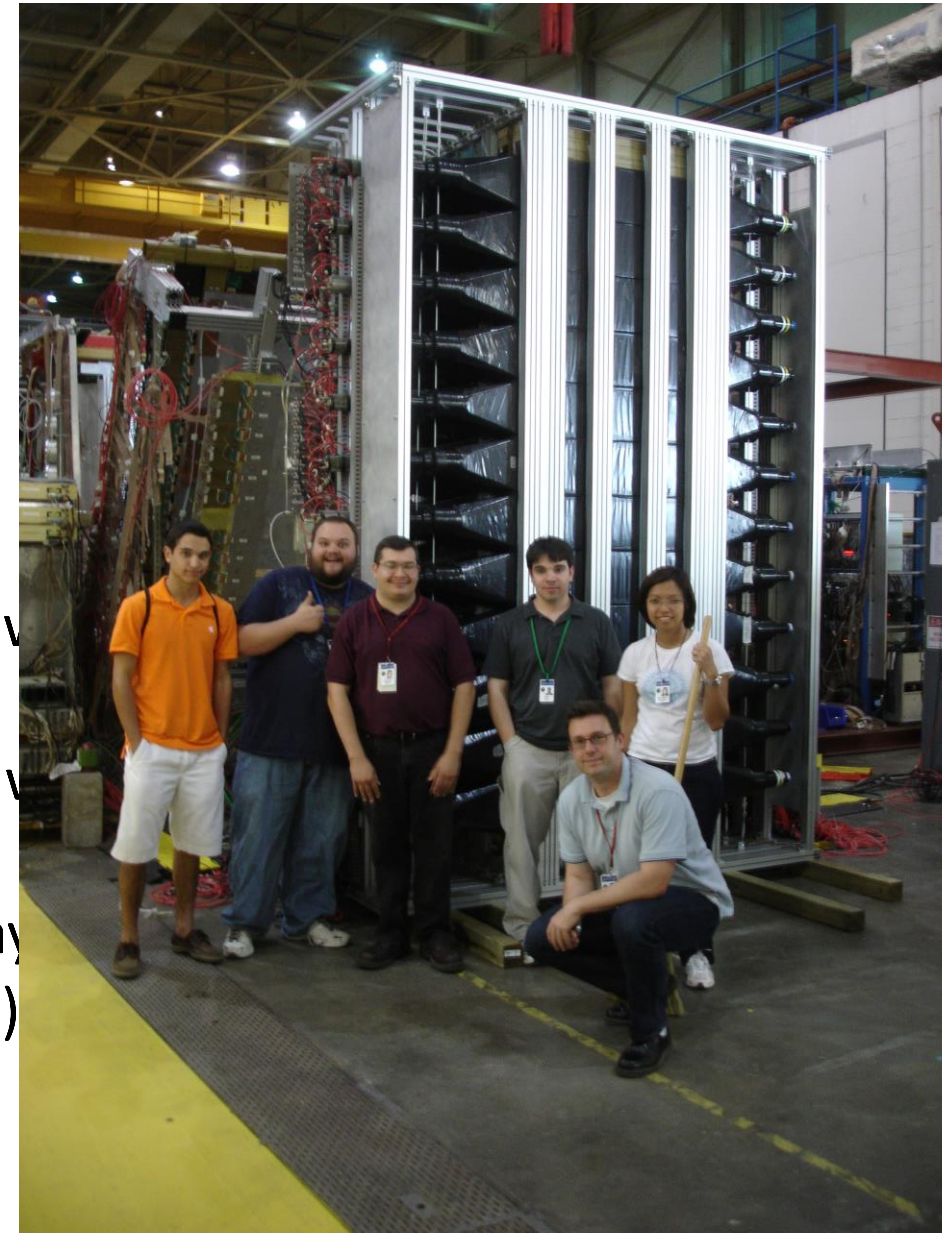

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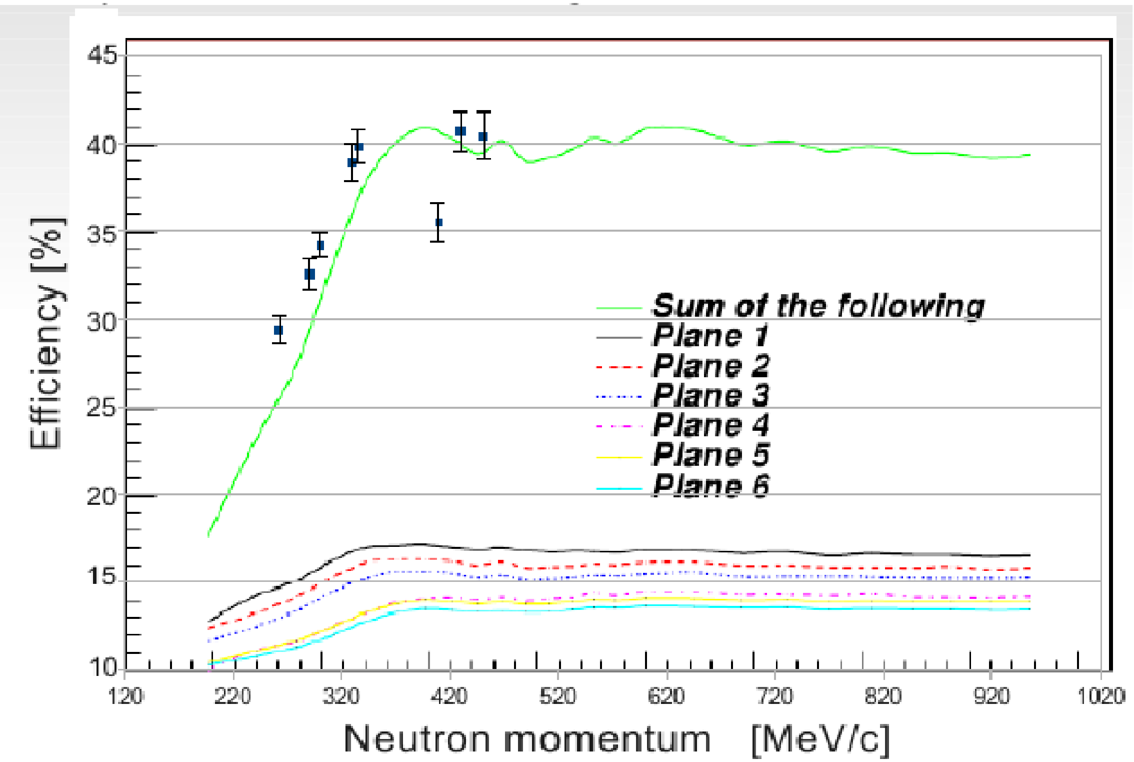
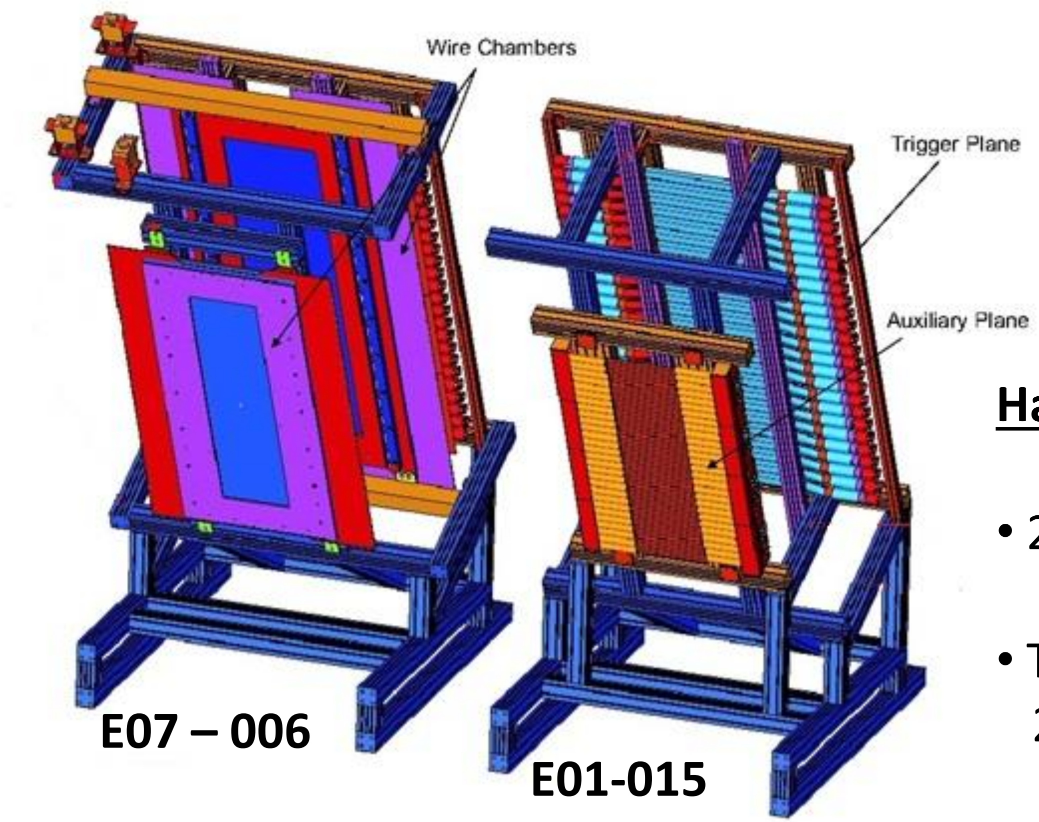
Absolute Neutron Detector Efficiency

- Used HRS quasi-elastic D(e,e'p)n to tag neutrons
- Tested Result Against Neutron Efficiency Code
  – R. A. Cecil, B. D. Anderson, R. Madey, Nucl. Instrum. Meth. 161 (1979) 430.

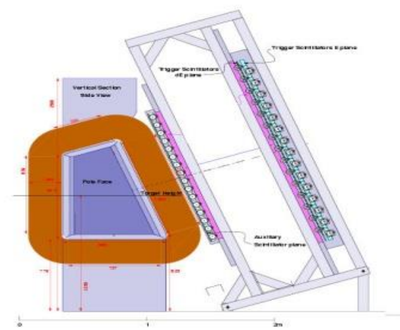


BigBite – Hadron Package

Detection of recoiled protons from SRC pair



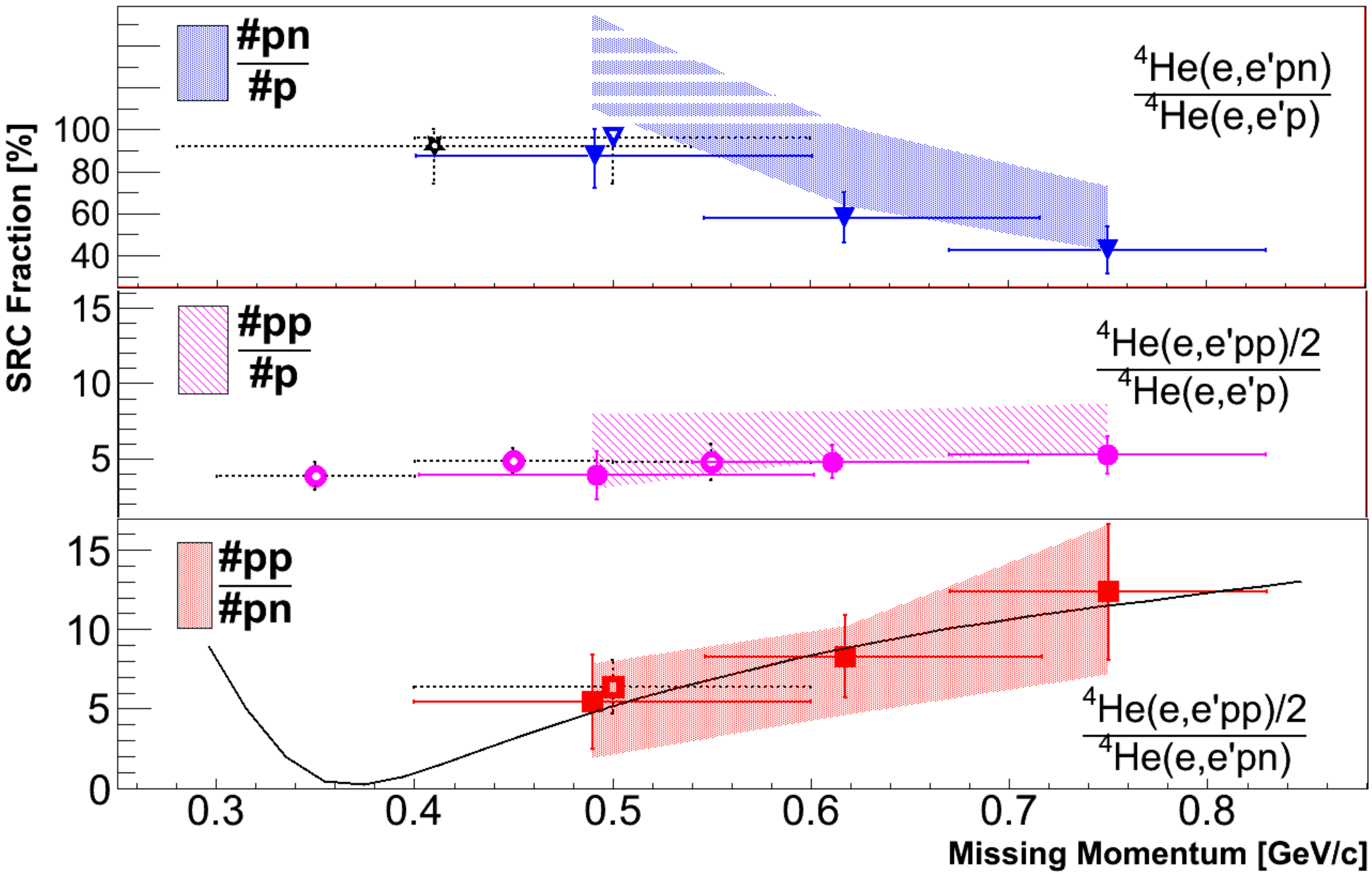
Non focusing dipole



<u>Hadron Package:</u>

- 2 Mulit-Wire Drift Chambers
  - 1% momentum resolution
- Trigger Plane (48 scintillators in 2 layers)

2nd Generation Final Results



Accepted for publication in Phys. Rev. Lett. May 2014

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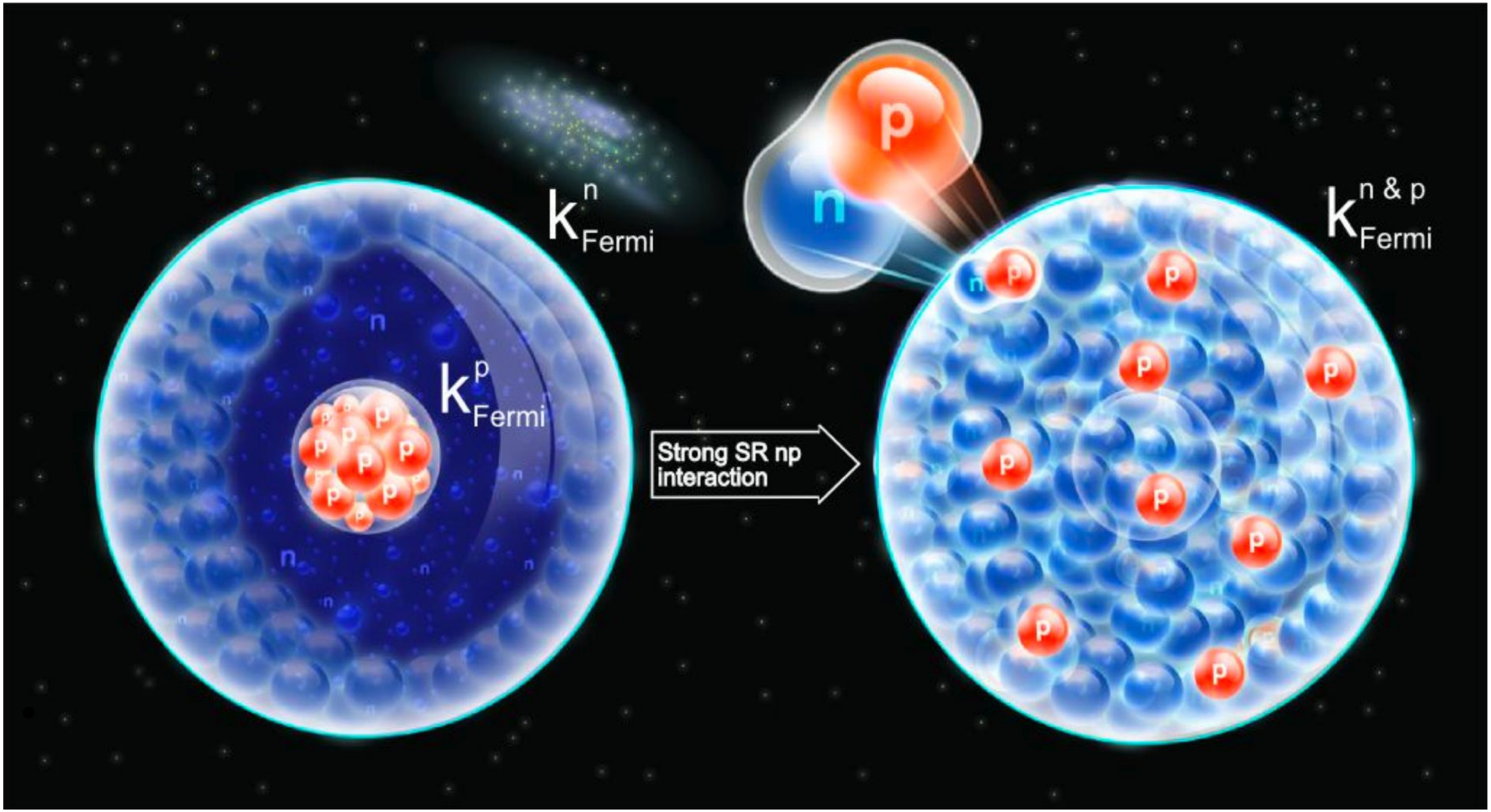
Implications for Neutron Stars



D.Higinbotham, E. Piasetzky, M. Strikman , CERN Courier 49N1 (2009) 22.

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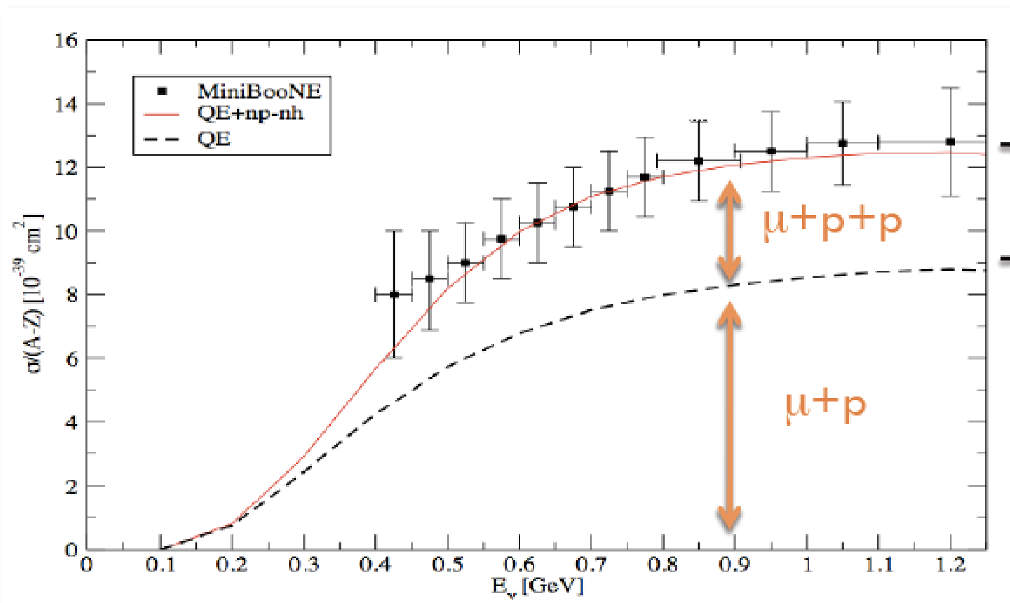
Effect on Neutrino Measurements

Until very recently, the neutrino community's Monte Carlos did not include nuclear effects.

- while traditional nuclear effects <u>decrease</u> the σ, there are processes that can <u>increase</u> the total yield …



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

add'l nuclear processes contribute ~40% more σ at these ν energies and produce a multi-nucleon final state ($\mu+p+p$)

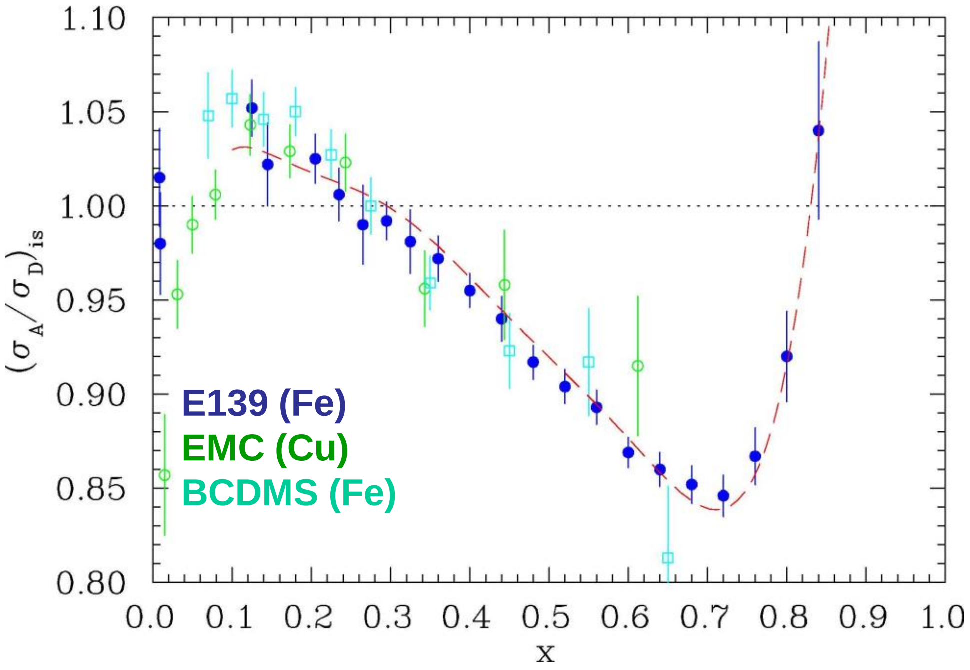
- together account for MB

(*these two final states are indistinguishable in MB and in Cerenkov detectors in general*)

S. Zeller, PANIC, July 26, 2011

The EMC Effect

- Nuclear structure: $\sigma_A \neq Z.\sigma_p + N.\sigma_n$
  - Effects found in several experiments at CERN, SLAC, DESY
- Same x-dependence in all nuclei
  - Shadowing: $x<0.1$
  - Anti-shadowing: $0.1<x<0.3$
  - EMC effect: $x>0.3$
- The size of the effect is a function of A



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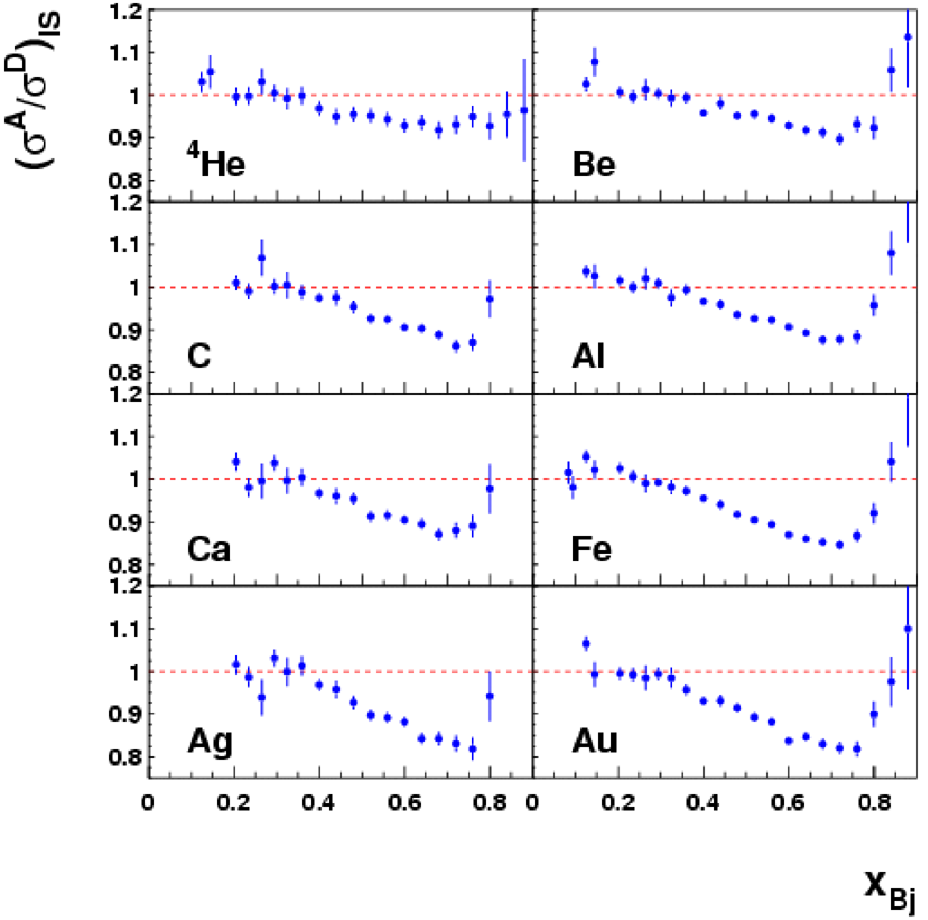
Existing EMC Data

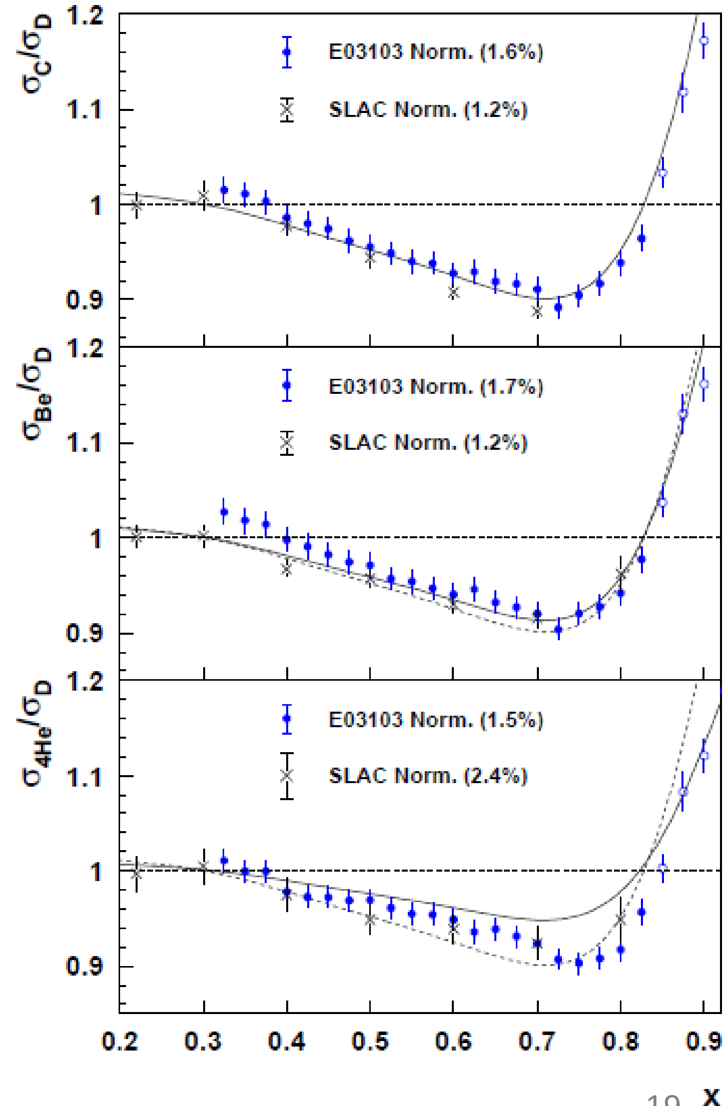
- SLAC E139 most extensive and precise data set for $x_B > 0.2$

- **σ_A/σ_D for A=4 to 197**
  - Size at fixed x_B varies with A, but shape is nearly constant



Hall C Results on The EMC Effect

J. Seely, et al., PRL **103** (2009) 202301.



- Experiment E03-103 improved with
  - Higher precision data for ^{4}He
  - Addition of ^{3}He data
  - Precision data at large x and on heavy nuclei
  - **Lower Q^2 to reach high x region**

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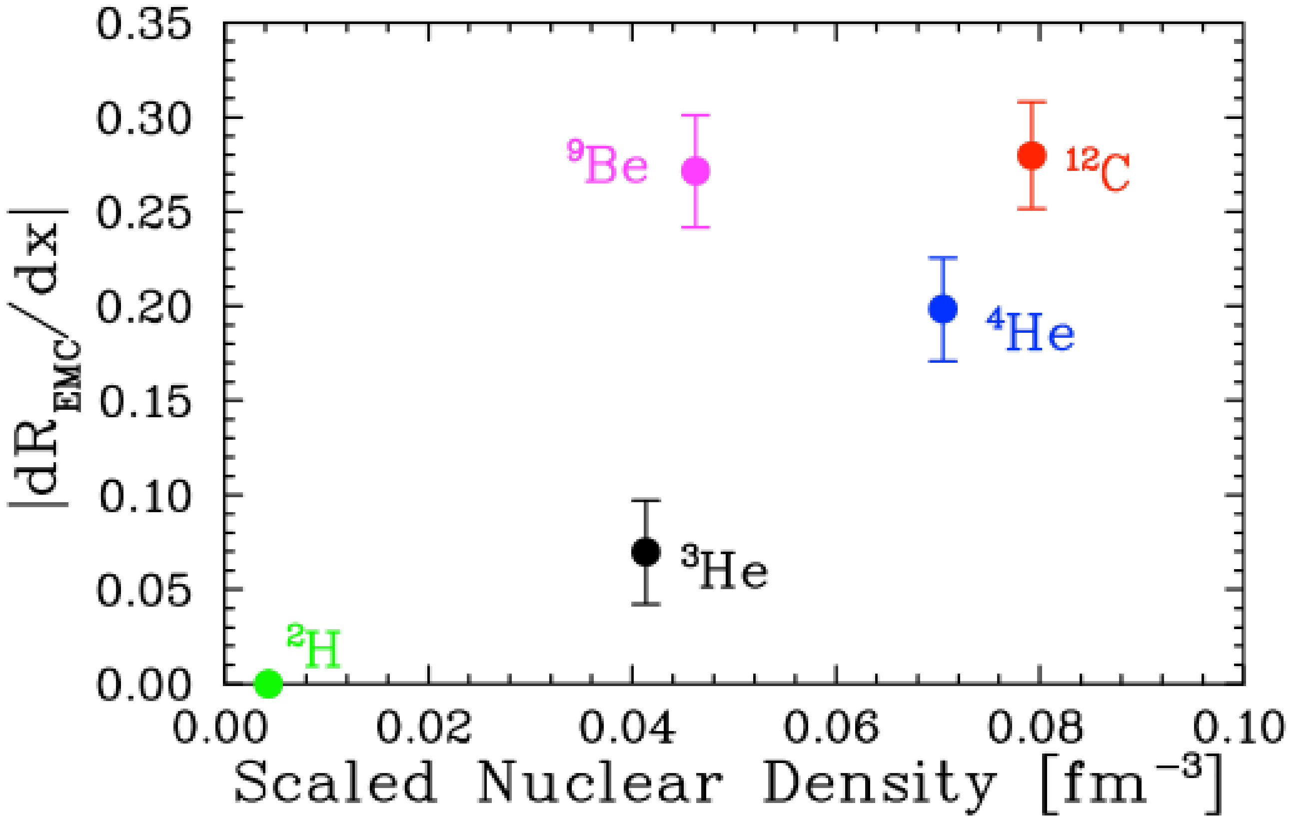
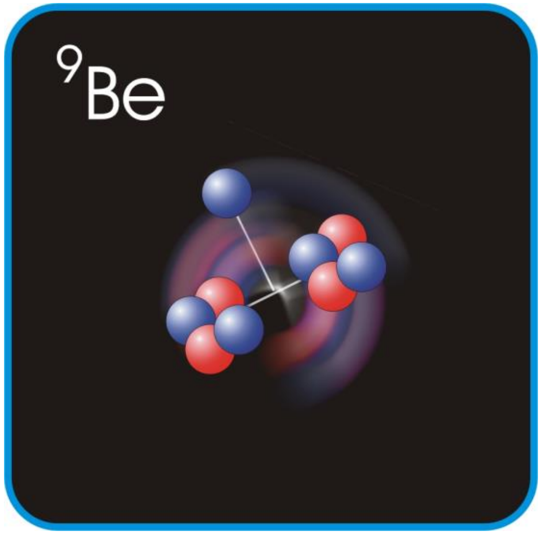
Jefferson Lab EMC Effect Data

J. Seely *et al.*, Phys, Rev. Lett. **103** (2009) 202301.

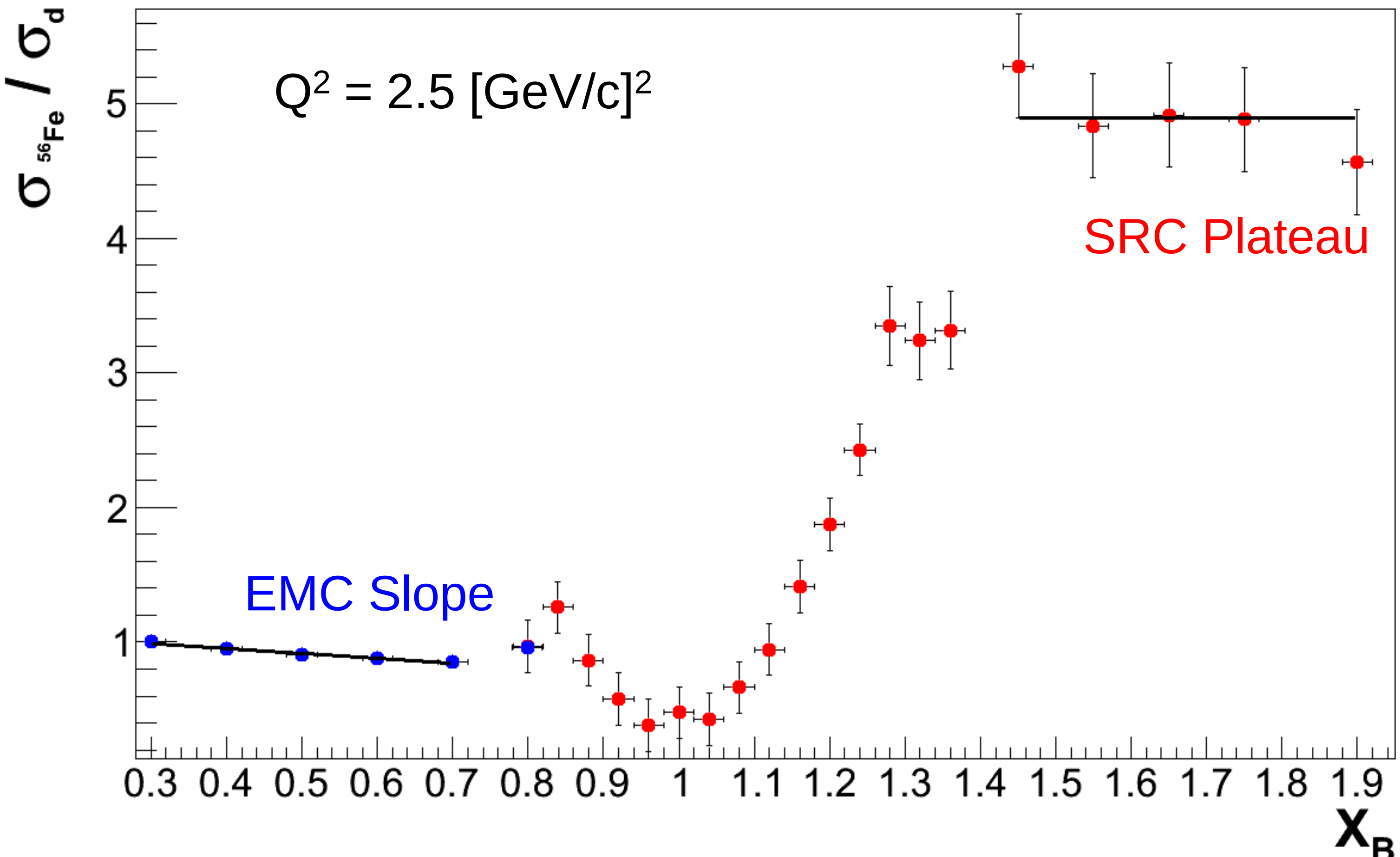




- Plot shows slope of ratio σ_A/σ_D in the EMC region.
- EMC effect correlated with **local density** not average density.

Holistic View of the EMC & SRC Data

D. Higinbotham *et al.*, arXiv:1003.4497.



- Scaling plateaus are likely due to proton-nucleon **local density** correlations
- So could the **EMC** slopes (x_B<0.7) and **SRC plateaus** (x_B>1.5) correlated?!

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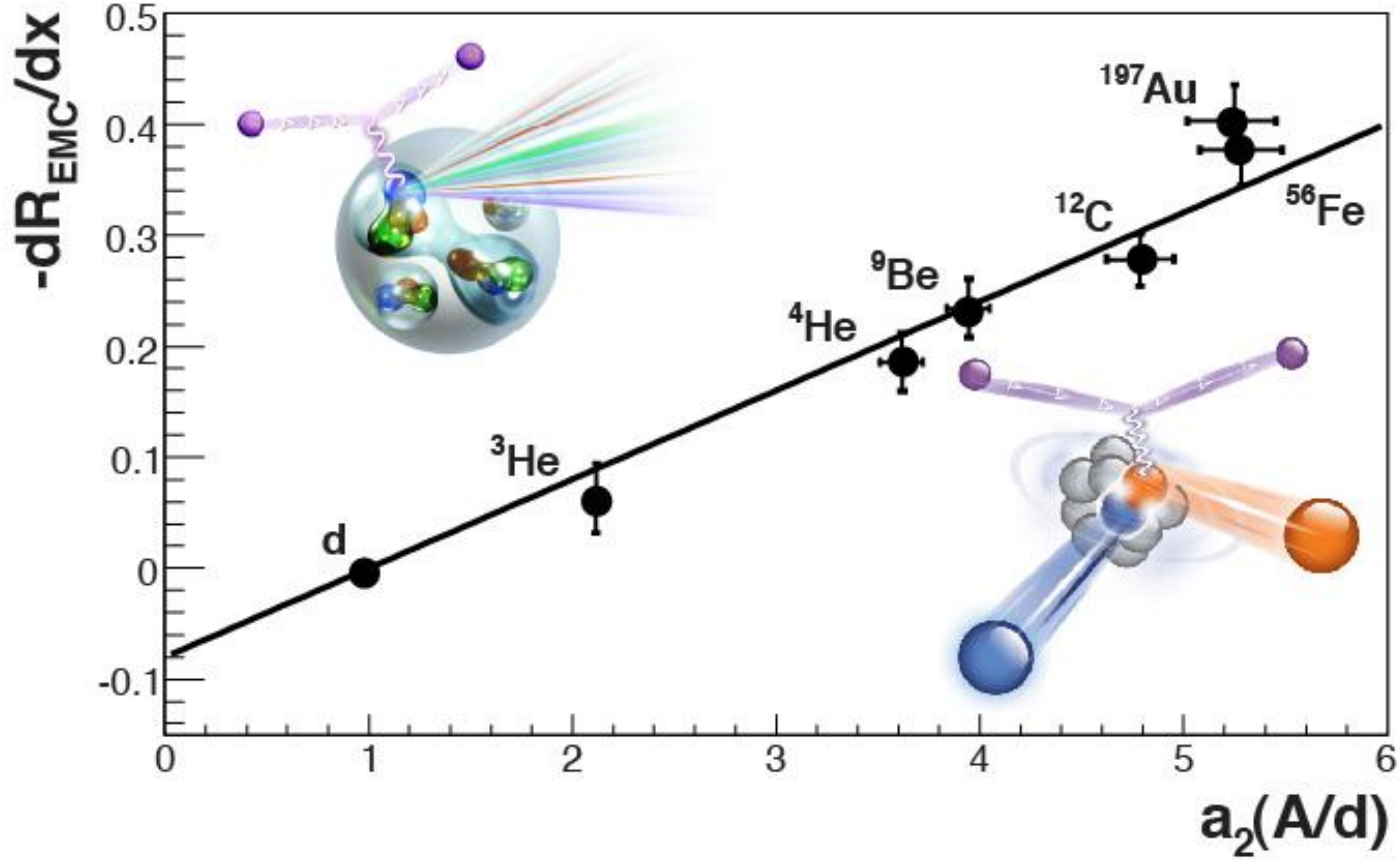
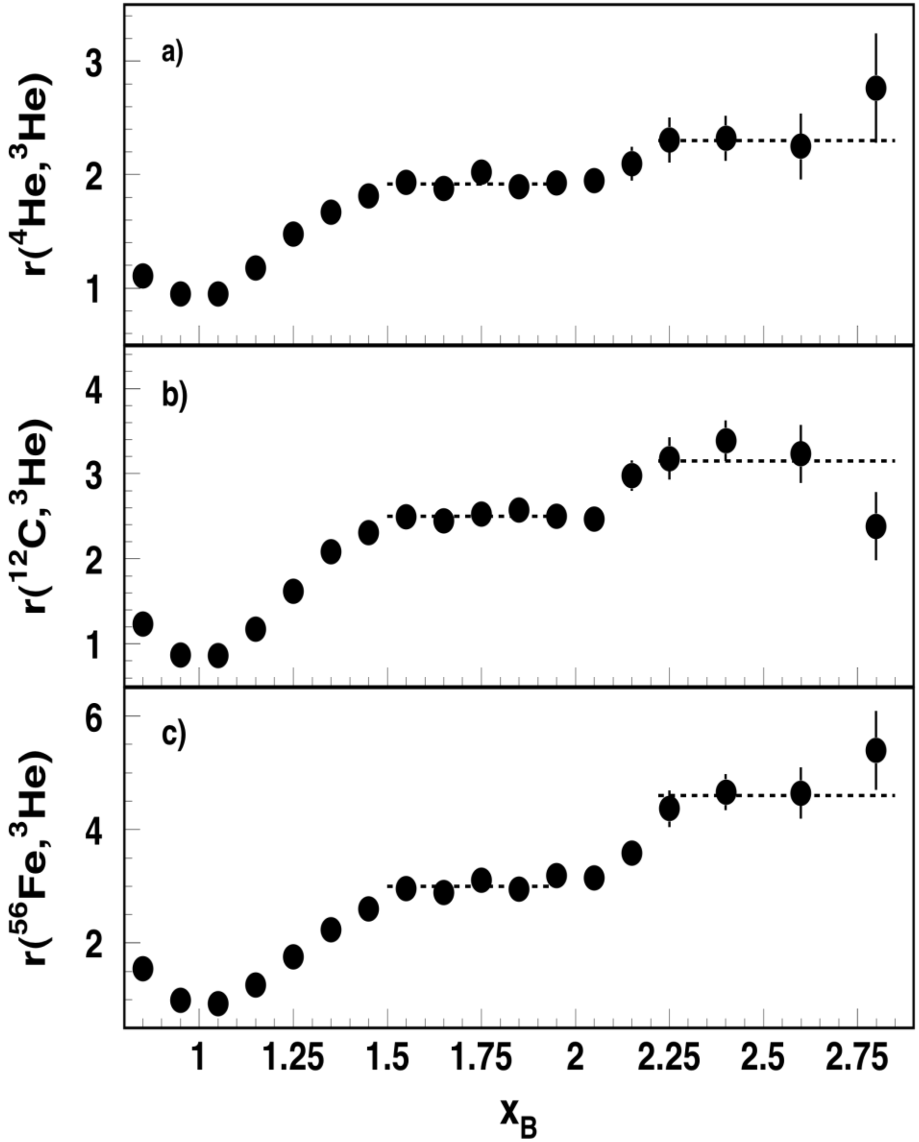
x>1 Ratios and EMC Slope Correlation

L. Weinstein *et al.*, Phys. Rev. Lett. **106** (2011) 052301.



Three Nucleon Correlations

K. Sh. Egiyan *et al.,* Phys. Rev. Lett. **96** (2006) 082501.



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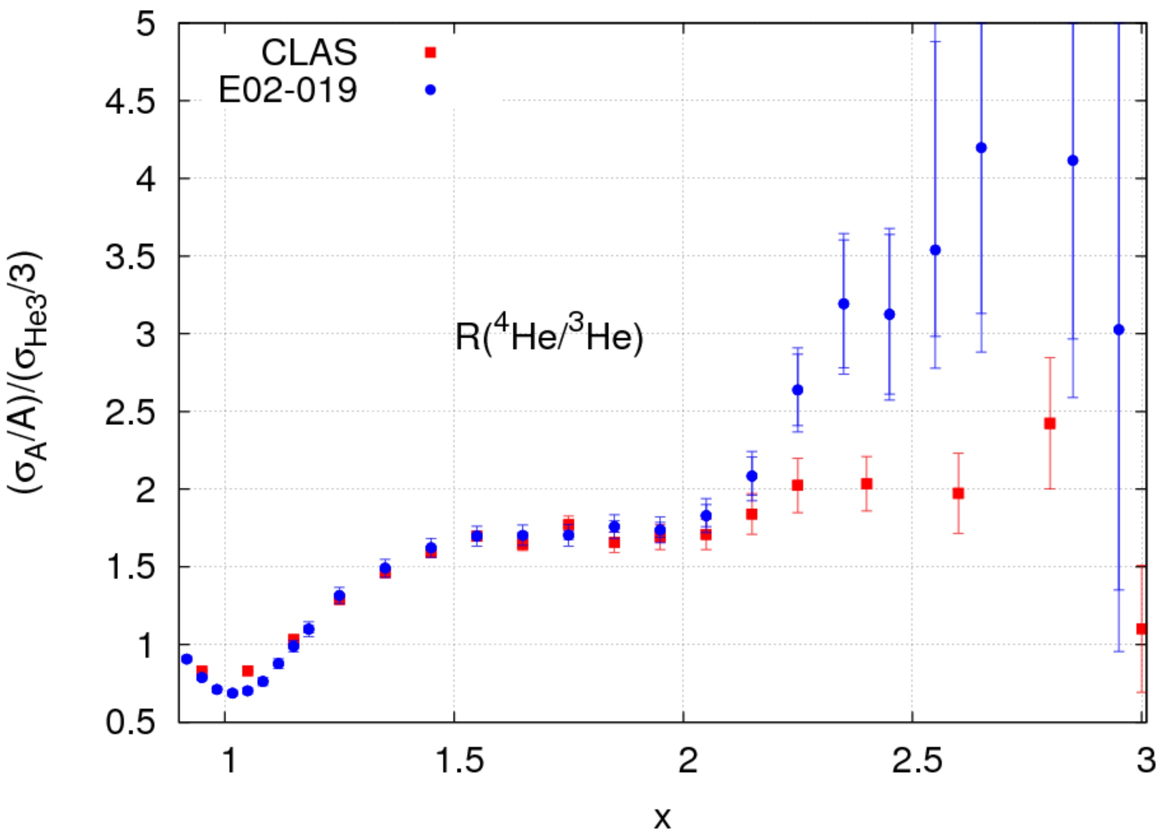
Results on ^{12}C From the (e,e') and (e,e'p)

- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - No Q^2 Dependence Of Ratio Magnitude Q^2: 1 to 4 GeV to few percent
  - Plateaus Start When Minimum Missing Momentum > Fermi Momentum
- Less than 1% multi-nucleon correlations

BUT Hall C $x_B > 2$ *Plateaus* Different

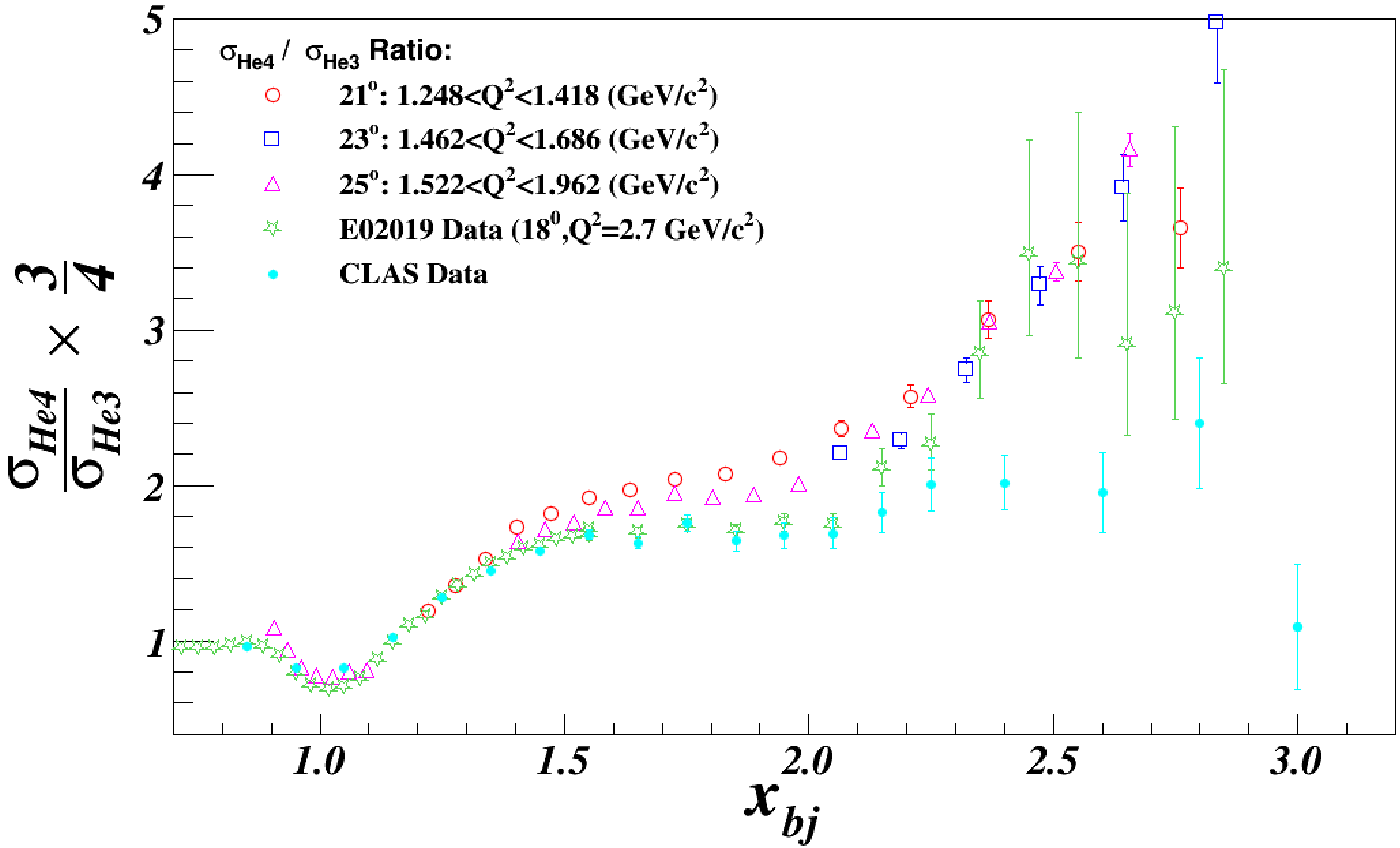


CLAS: 1.4 - 2.6 [GeV/c]^2
Hall C: 2.5 – 3.0 [GeV/c]^2

- Excellent agreement for $x \leq 2$
- Very different shape and **error bars** in the $x>2$ region
- Time for a third measurement!

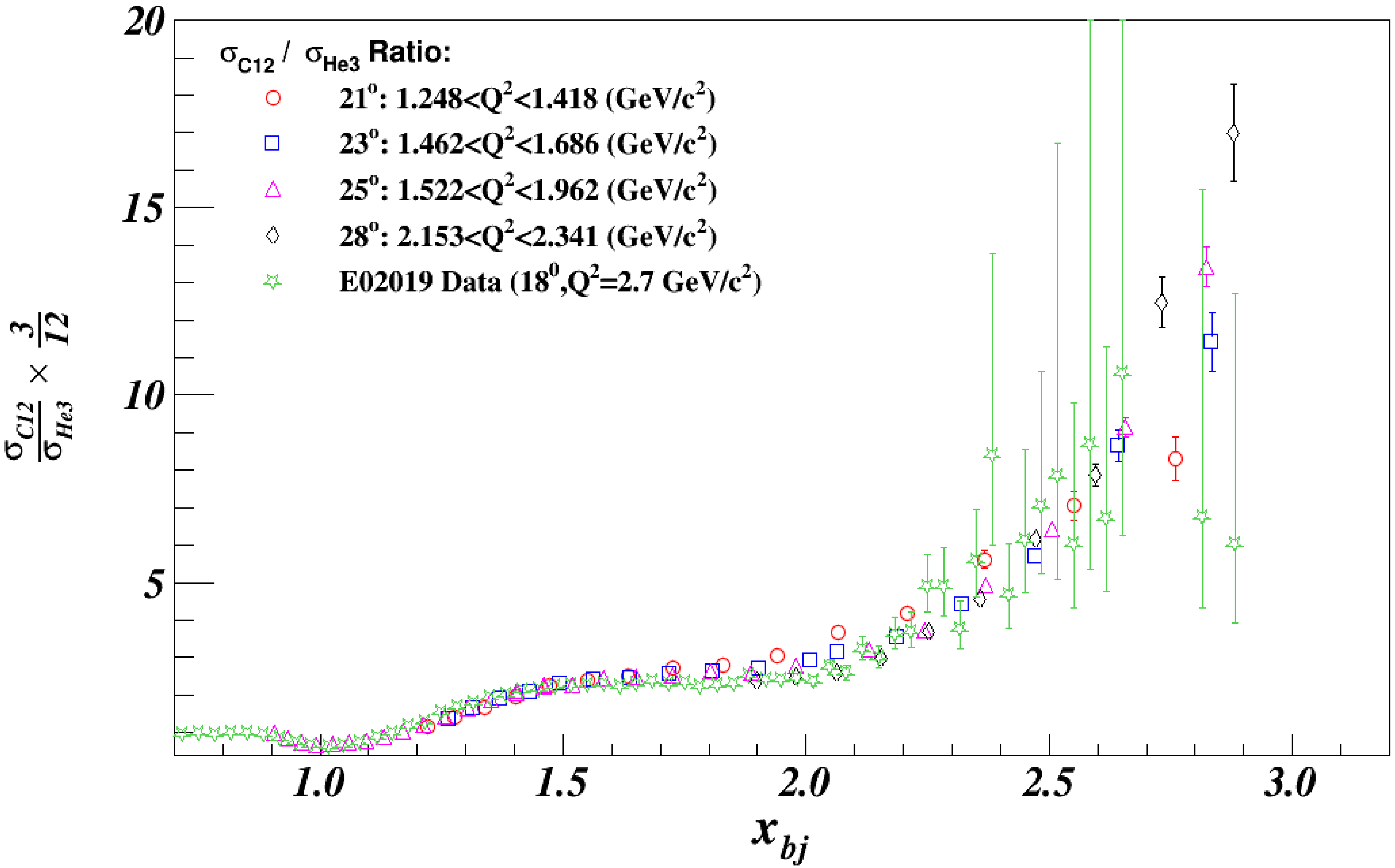
Preliminary Hall A Data with B & C

Analysis done by Zhihong Ye.



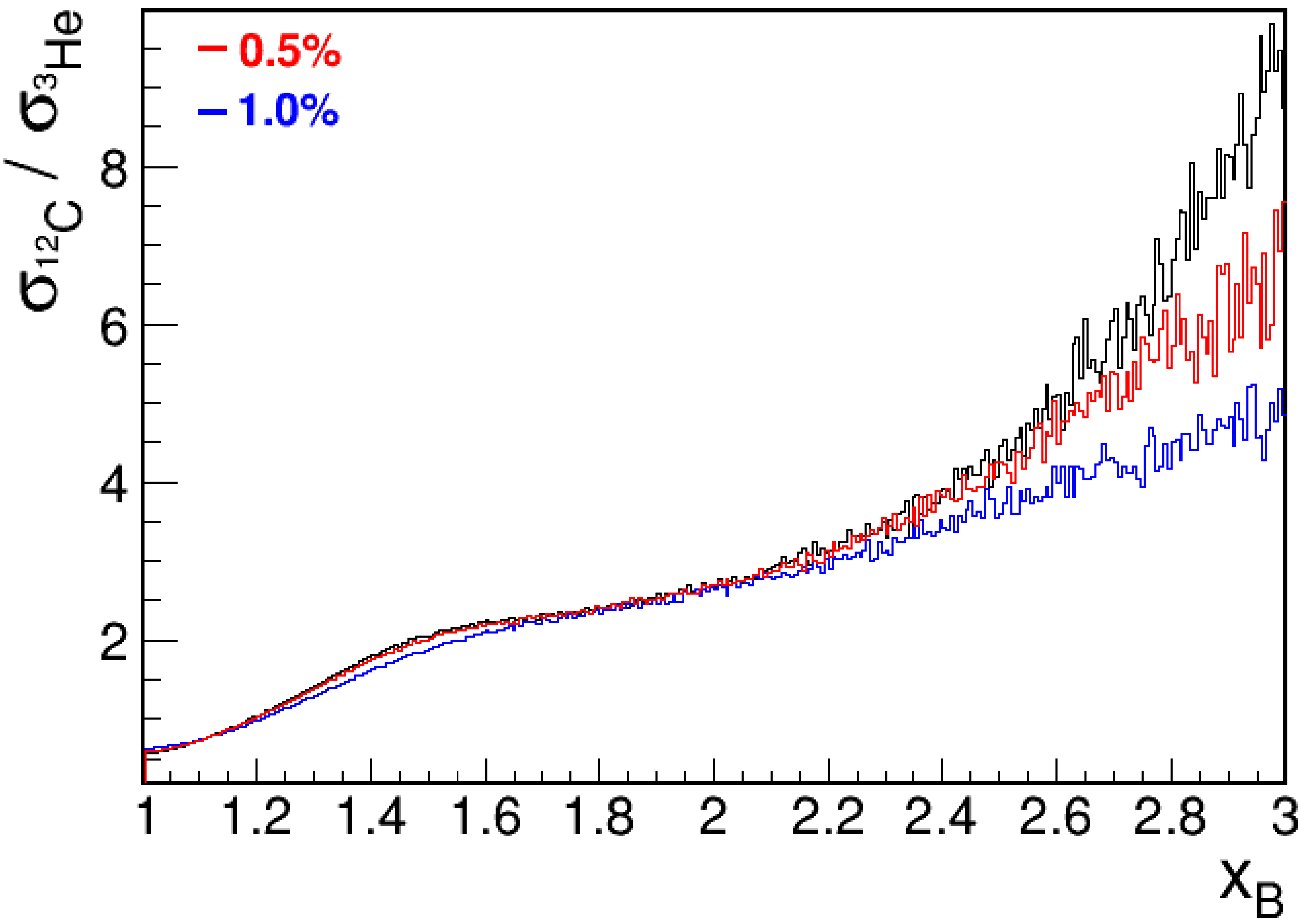
Preliminary Hall A Results

Analysis done by Zhihong Ye.



Monte Carlo Test Of Resolution Effects

O. Hen and D.Higinbotham using XEMC code for (e,e') cross sections.



Isospin Effect of SRCs

^{40}Ca versus ^{48}Ca

- Assuming Isospin-independence in inclusive measurements:

$$R = \frac{\sigma_{48\mathrm{Ca}}/48}{\sigma_{40\mathrm{Ca}}/40} = \frac{(20\sigma_p + 28\sigma_n)/48}{(20\sigma_p + 20\sigma_n)/40}$$

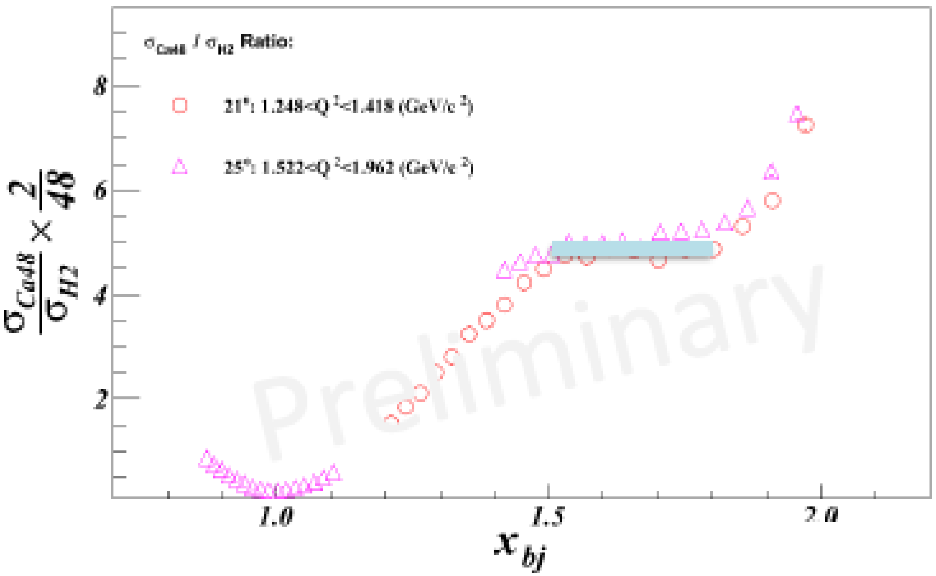
Using $\sigma_p \approx 3\sigma_n$, R= **0.92**

- For 2N-SRC, n-p pairs dominate:

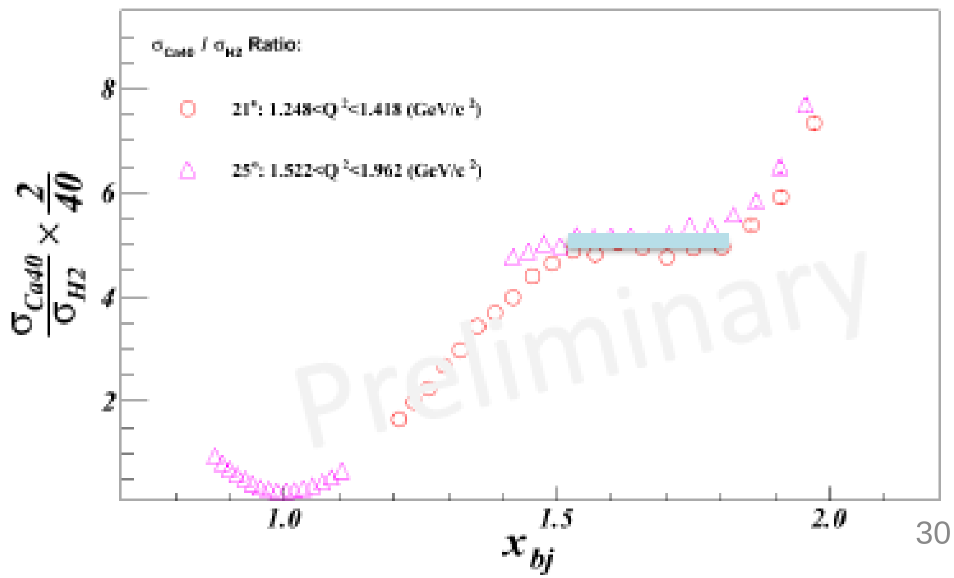
$$R = \frac{\sigma_{48\mathrm{Ca}}/48}{\sigma_{40\mathrm{Ca}}/40} = \frac{(20 \times 28)/48}{(20 \times 20)/40} \rightarrow \mathbf{1.17}$$

Preliminary Ratio Results (Ca to D)

^{40}Ca/D and ^{48}Ca/D ratios: (statistical errors only)

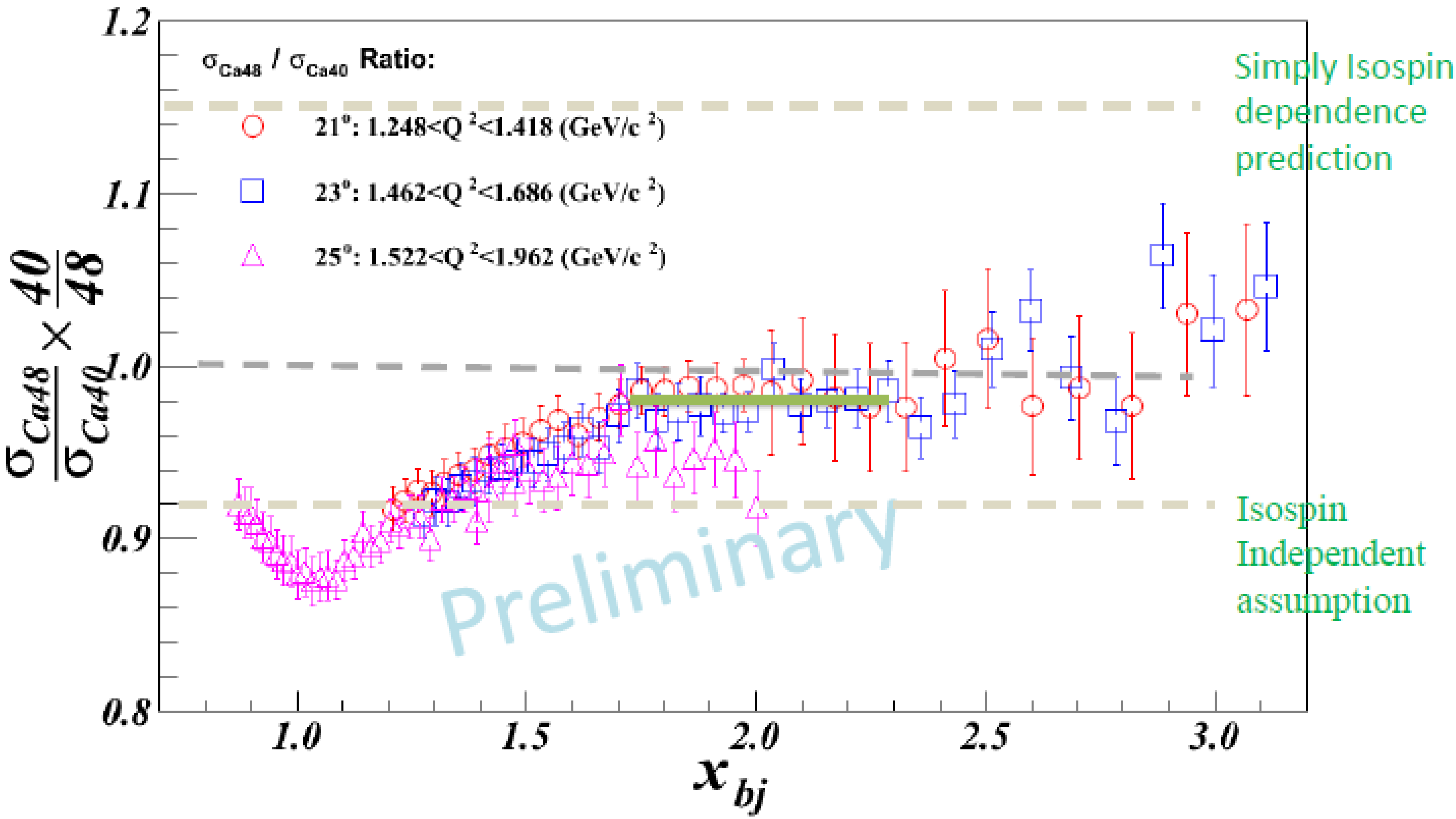


Very first High Q^2 ^{40}Ca and ^{48}Ca cross section results



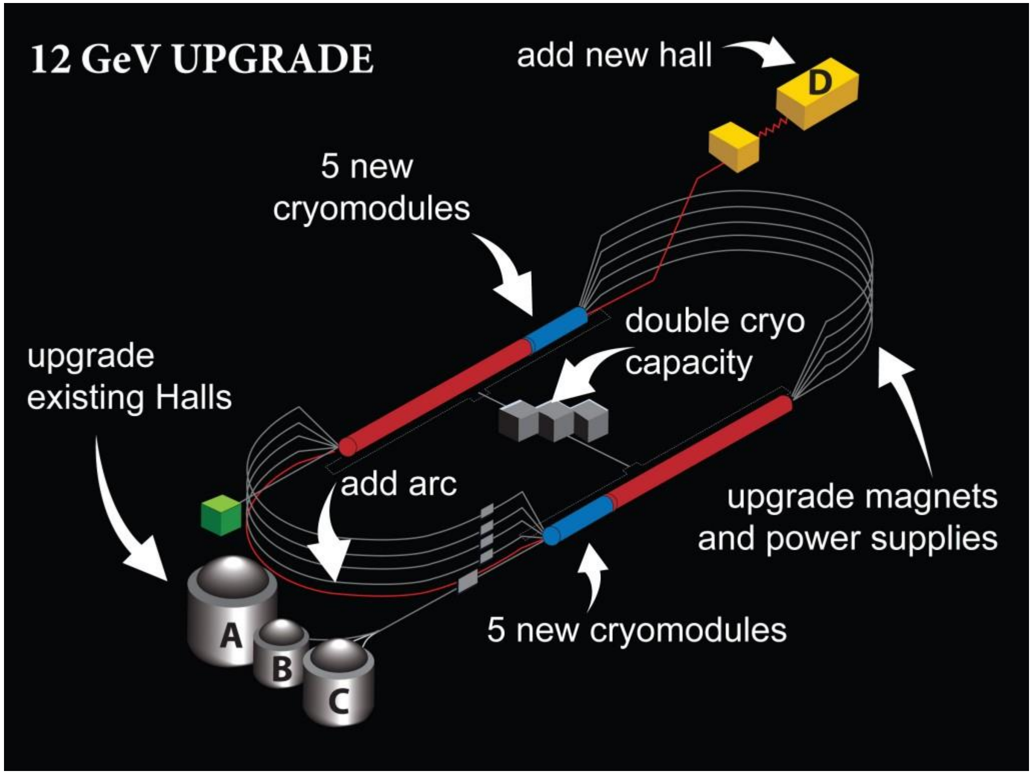
Preliminary Ratio Results (^{48}Ca to ^{40}Ca)

(statistical errors only)



JLab 12 GeV Upgrade

- JLab's 12 GeV upgrade is currently in the construction phase
- A fourth hall will be added
- The three current halls are being upgraded
- Several new experiments are already approved to run after the 12-GeV upgrade with **5 approved N-N Correlation experiments**



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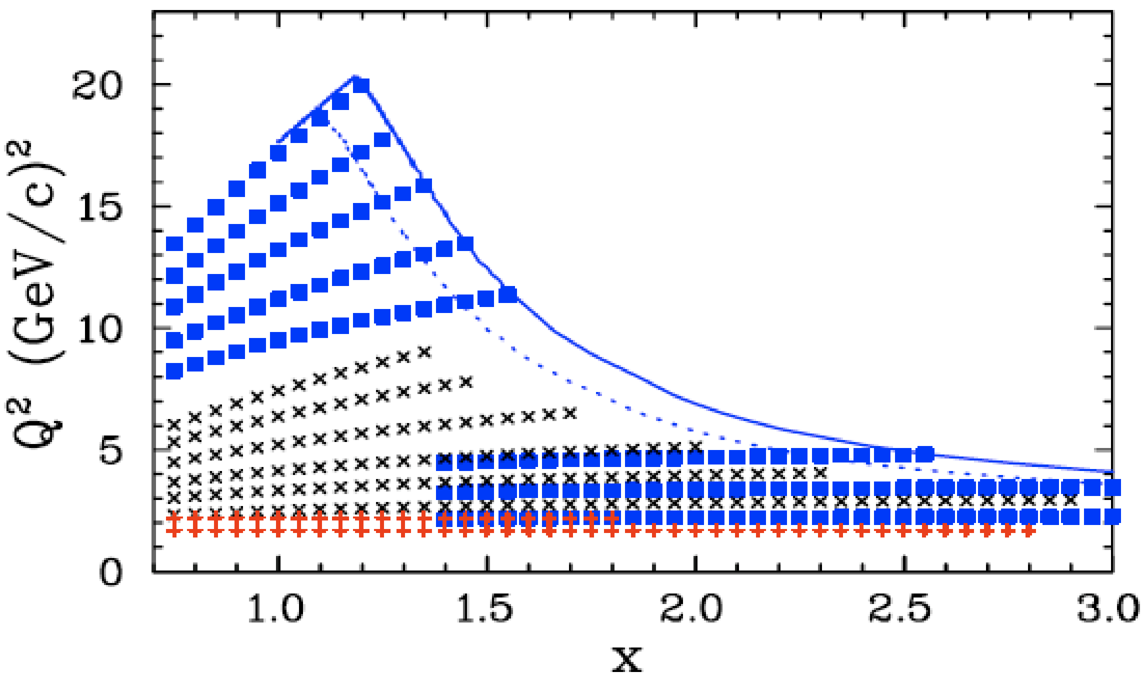
PR12-06-105: (e,e') x>1



11 GeV Beam

θ (deg)	E' settings (GeV)	x	Q^2 GeV^2
8.0	10.6	0.7-4.0	2.1-2.3
10.0	10.4	0.7-3.0	3.0-3.5
12.0	9.8	0.7-2.6	4.0-5.0
22.0	5.7,7.0	0.7-1.55	8.1-12
26.0	4.8,6.0	0.7-1.45	9.5-14
32.0	3.3,3.9,4.6	0.7-1.35	11-17
40.0	2.4,2.8,3.3	0.7-1.25	12-18
55.0	1.5,1.7,2.0	0.7-1.20	13-20

Red is the range of CLAS Data
Black is the range of 6 GeV Data
Blue is 11 GeV Proposed Data
Solid Line = 10% Uncertainty; Dashed Line = 5% Uncertainty

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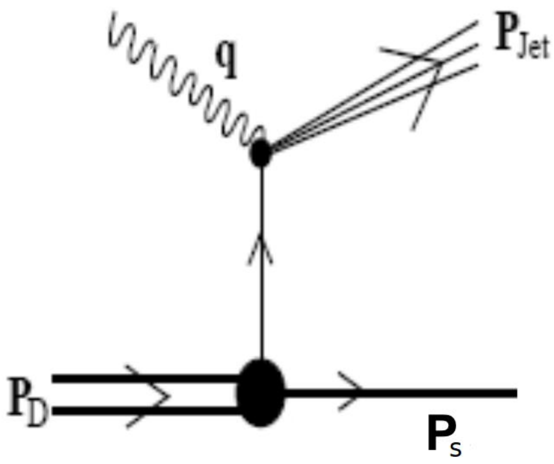
E12-11-107

In Medium Nucleon Structure Function, SRC and the EMC Effect

Goal: Measure DIS off high momentum nucleons



- Spectator tagging $D(e,e'N_s)$:
  - DIS in coincidence with a fast, backwards recoil nucleon.
  - Selects DIS off high momentum (high virtuality) nucleons

$$x' = \frac{Q^2}{2 p_\mu q^\mu}$$

- Cross Section ratio:

$$\boxed{\frac{\sigma_{DIS}\left(x'_{high}, Q_1^2, \vec{p}_s\right)}{\sigma_{DIS}\left(x'_{low}, Q_2^2, \vec{p}_s\right)}} \cdot \boxed{\frac{\sigma_{DIS}^{free}\left(x_{low}, Q_2^2\right)}{\sigma_{DIS}^{free}\left(x_{high}, Q_1^2\right)} \cdot R_{FSI}} = \frac{F_2^{bound}\left(x'_{high}, Q_1^2, \vec{p}_s\right)}{F_2^{free}\left(x_{high}, Q_1^2\right)}$$

$x'_{high} \geq 0.45$ $\quad$ $0.25 \geq x'_{low} \geq 0.35$

R_{FSI} is the FSI correction factor

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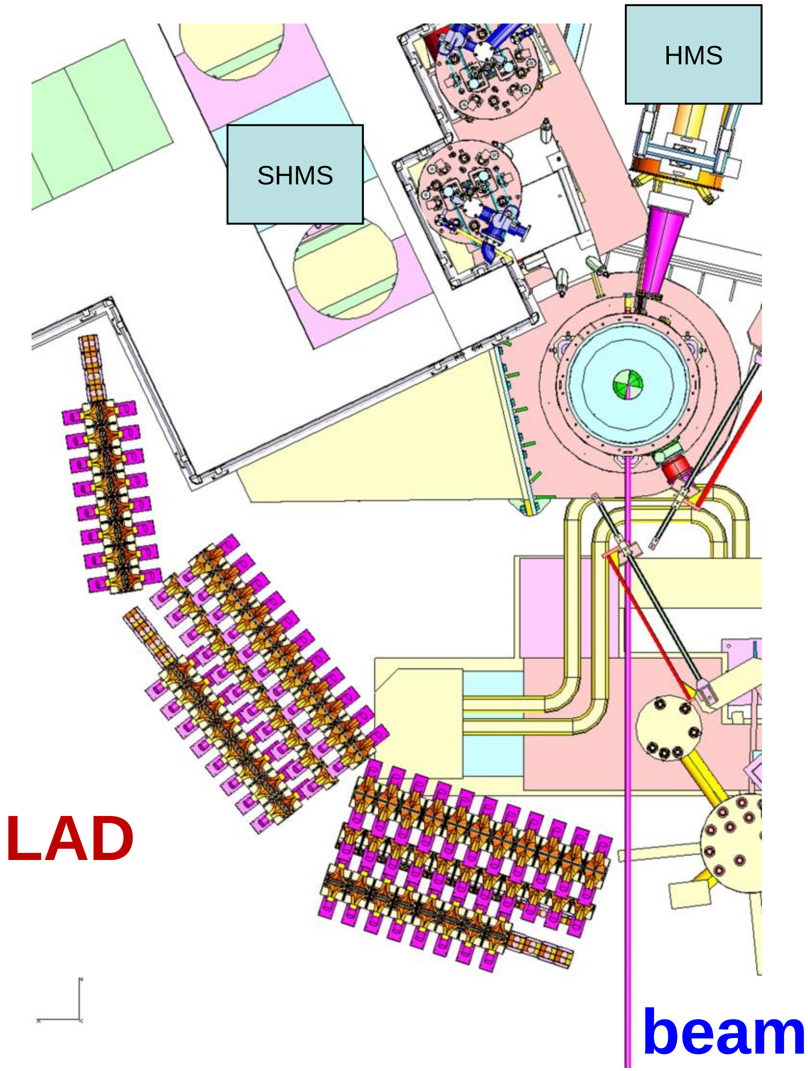
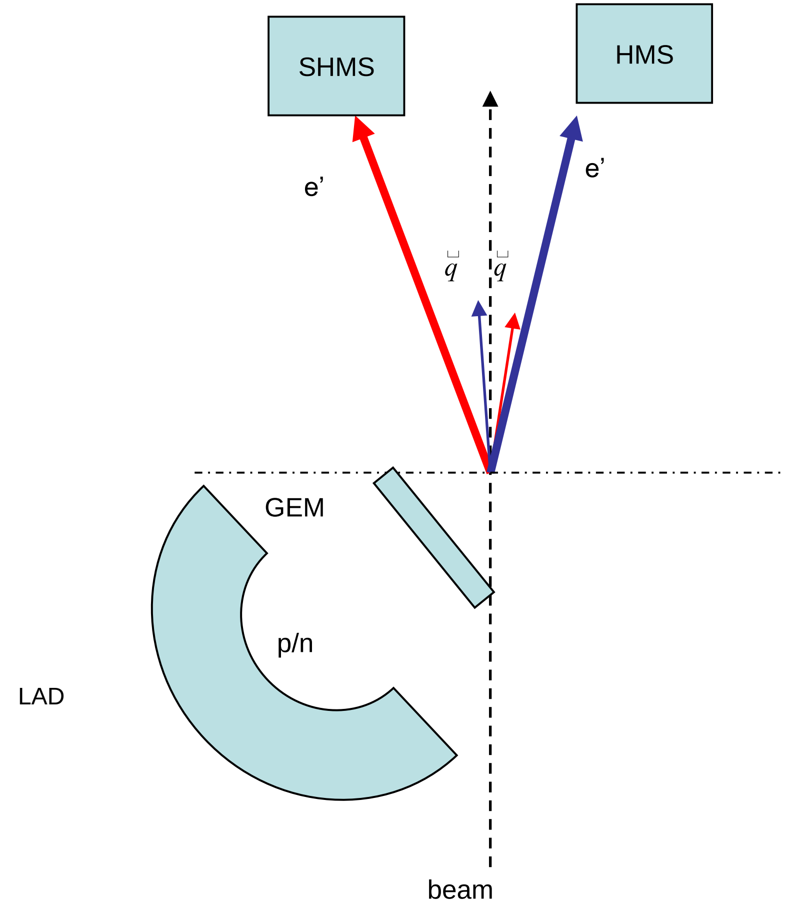
Experimental Setup

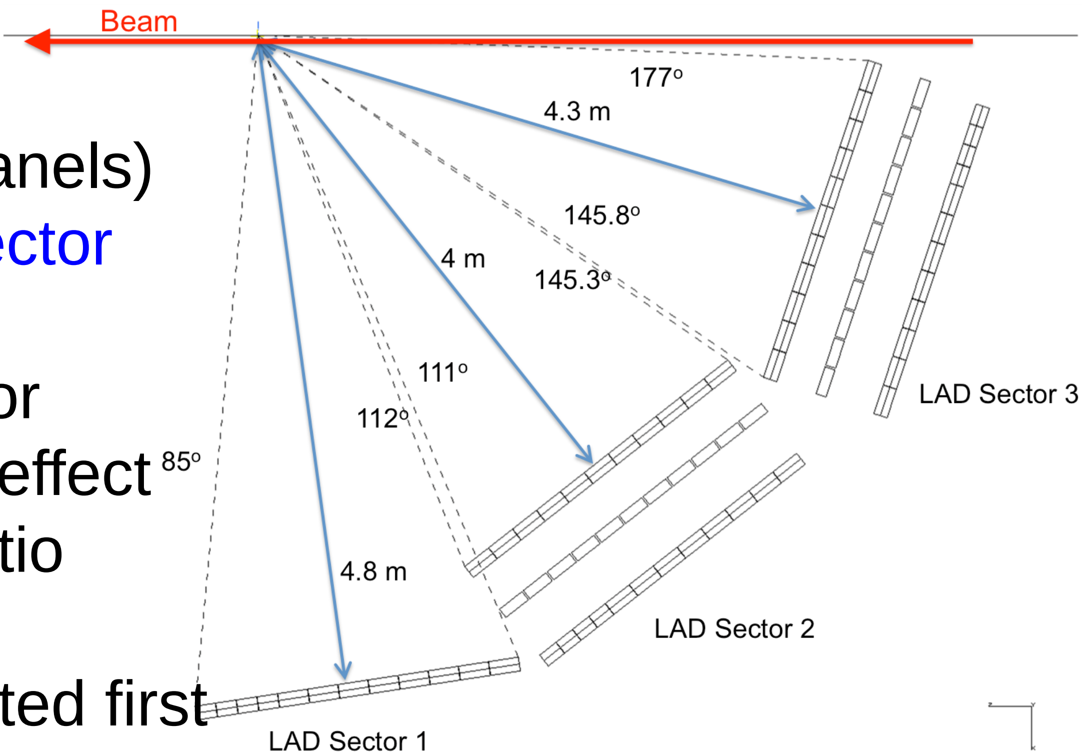




Large Acceptance Detector (LAD)

- Use retired CLAS-6 TOF Counters
- 5-cm thick counters (12 panels)
- 1.5 Sr, ~20% neutron detector efficiency
- Also planned to be used for **LOI-11-104:** tagged EMC effect ^{4}He(e,e'N_s) to D(e,e'N_s) ratio measurements
- Technique being investigated first with E07-006 data

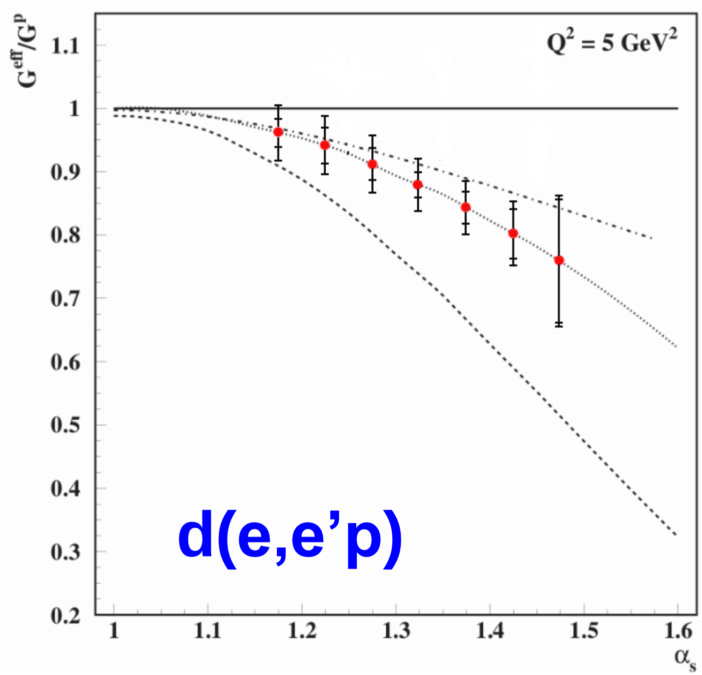
  (Ph.D. work of Tai Muangma)

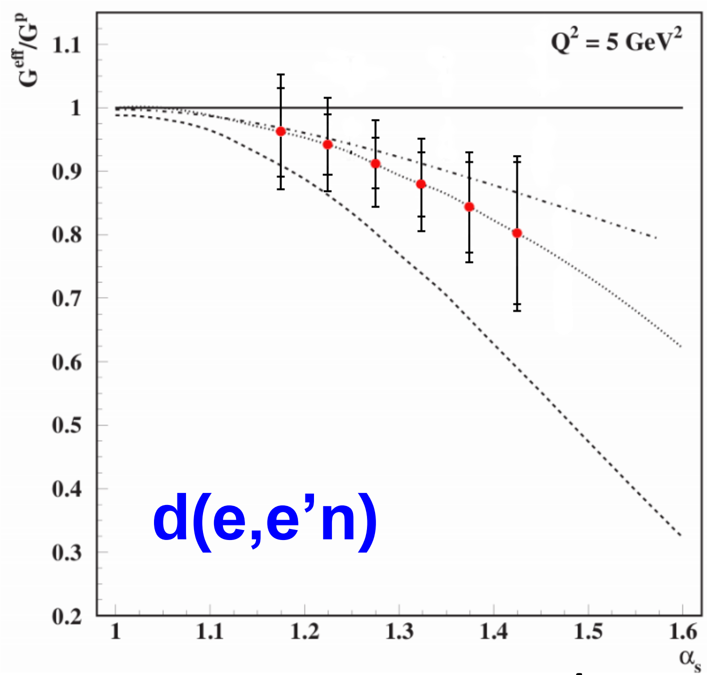


Expected Results

- Direct measurement of the nucleon structure function in the nuclear medium as a function of light-cone variable
- Approved for 40 days in Hall C

$$a_s = (E_s - p_s^z)/m_s$$



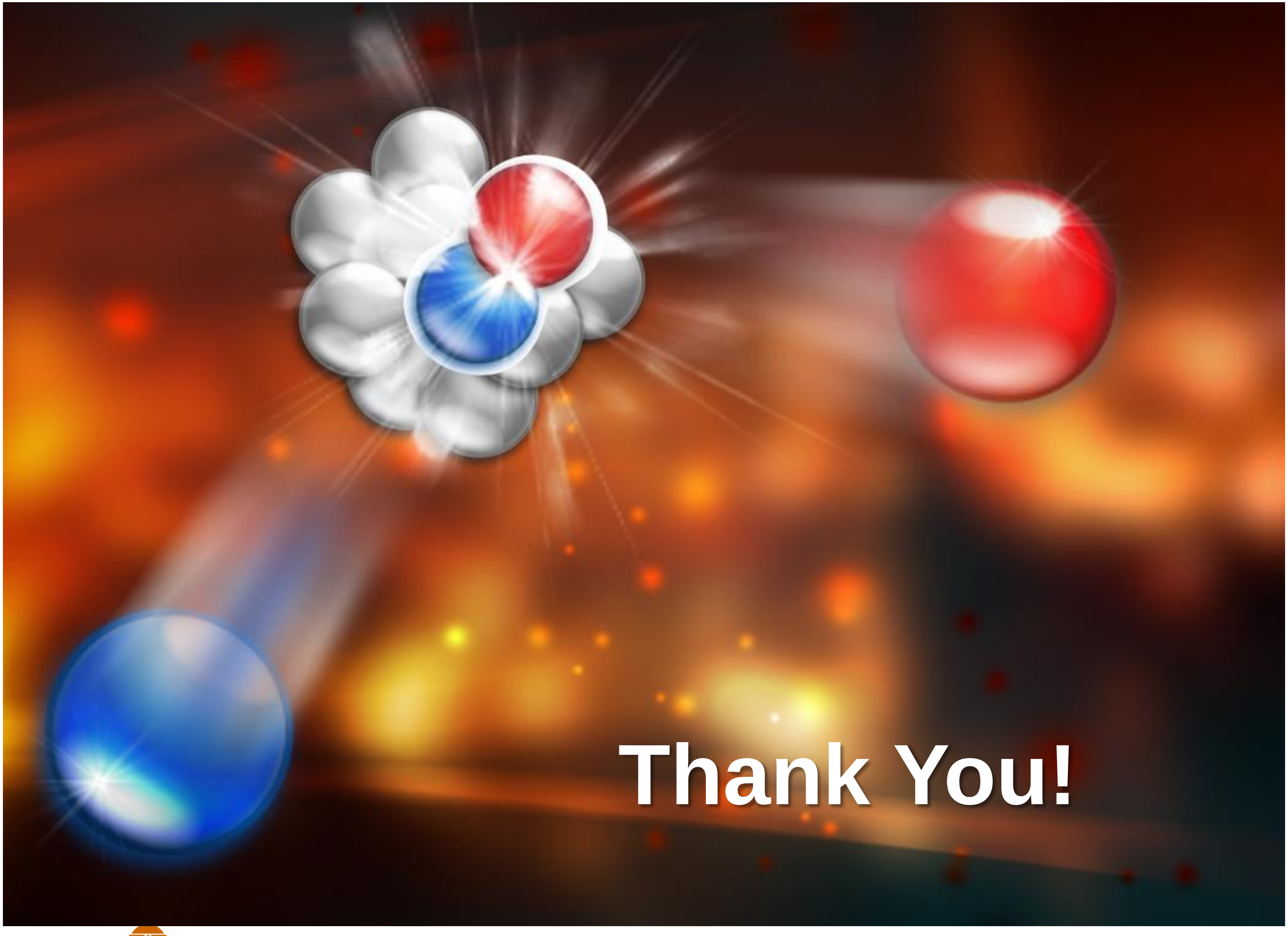


Dashed: PLC suppression; Dotted: rescaling; Dot-dashed: binding/off-shell

Spokespersons: S. Gilad, O. Hen, L. Weinstein and S. Wood

SRC Motivation and Summary

- Short-Range Nucleon-Nucleon Correlation Experiments:
  - Goal to probe the repulsive part of the nucleon-nucleon potential
  - Long History of Reaction Mechanisms Dominating Cross Section
- With high luminosity and the right kinematics, we seem to finally be cleanly probing the short distance behavior.
- Many other new results compliment what has been shown.
- The high luminosity and precision available at JLab has made these measurements possible.
- **The Jefferson Lab 12-GeV energy upgrade will allow us to explore and discover new insights and challenges.**


Thank You!