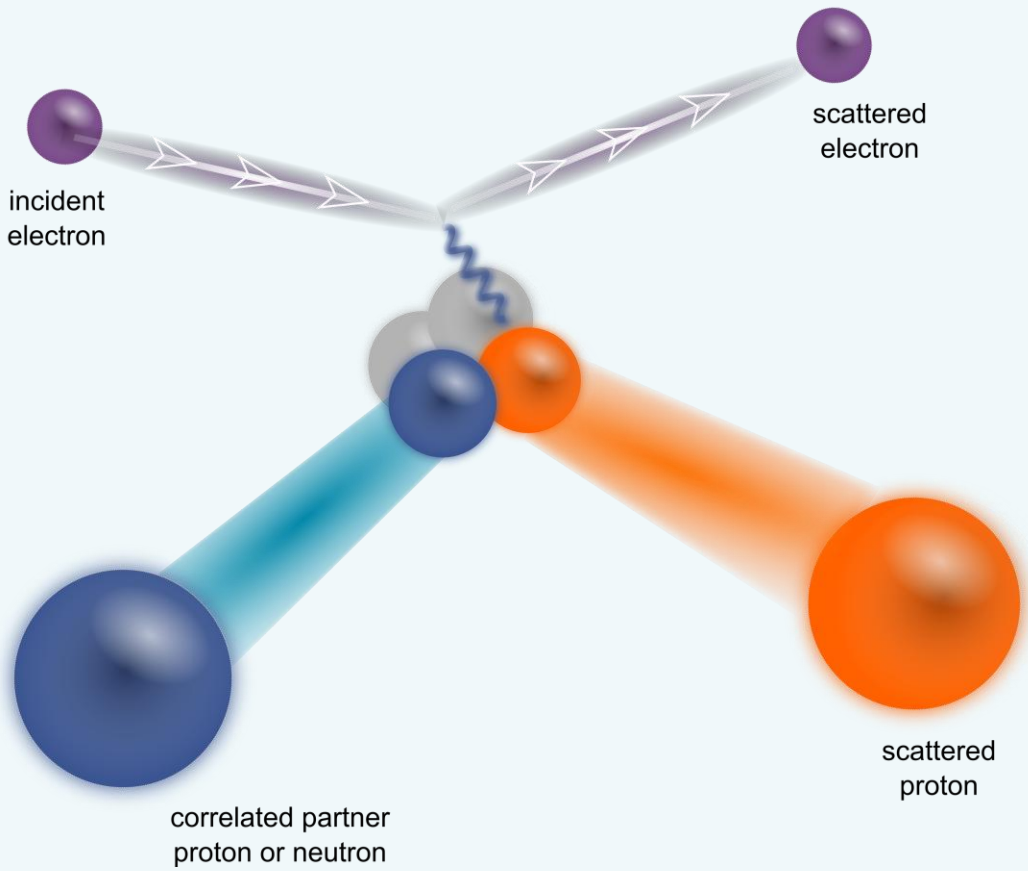
Short-Distance Structure of the Nucleus

Vincent Sulkosky

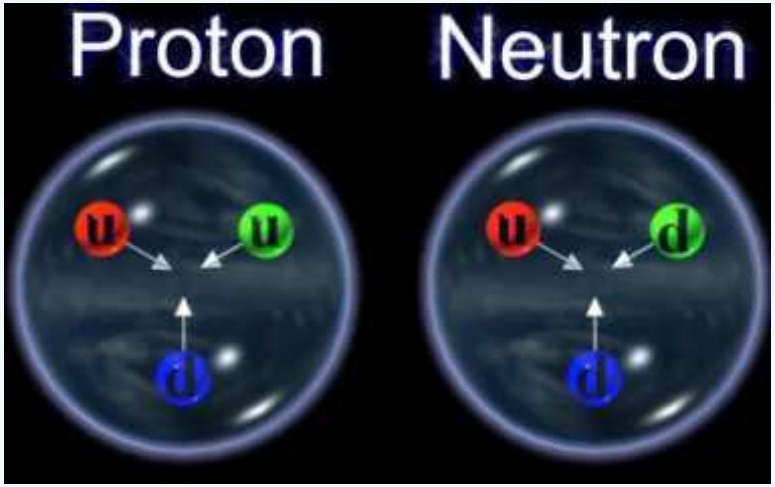
Massachusetts Institute of Technology



Outline

- Introduction
- Short-Range Correlations
- Semi-Inclusive Scattering Results from Nuclei
- Implications from Inclusive Scattering
- Triple Coincidence Measurements
- Current and Future Perspectives
- Summary

Building Nuclei from Nucleons



<u>Nucleons:</u> (Protons and Neutrons)

- The building blocks of visible matter.
- They are composed of quarks (bricks) and gluons (mortar).
- Structure is mostly governed by the strong force, i.e., natural laboratory to study this interaction.

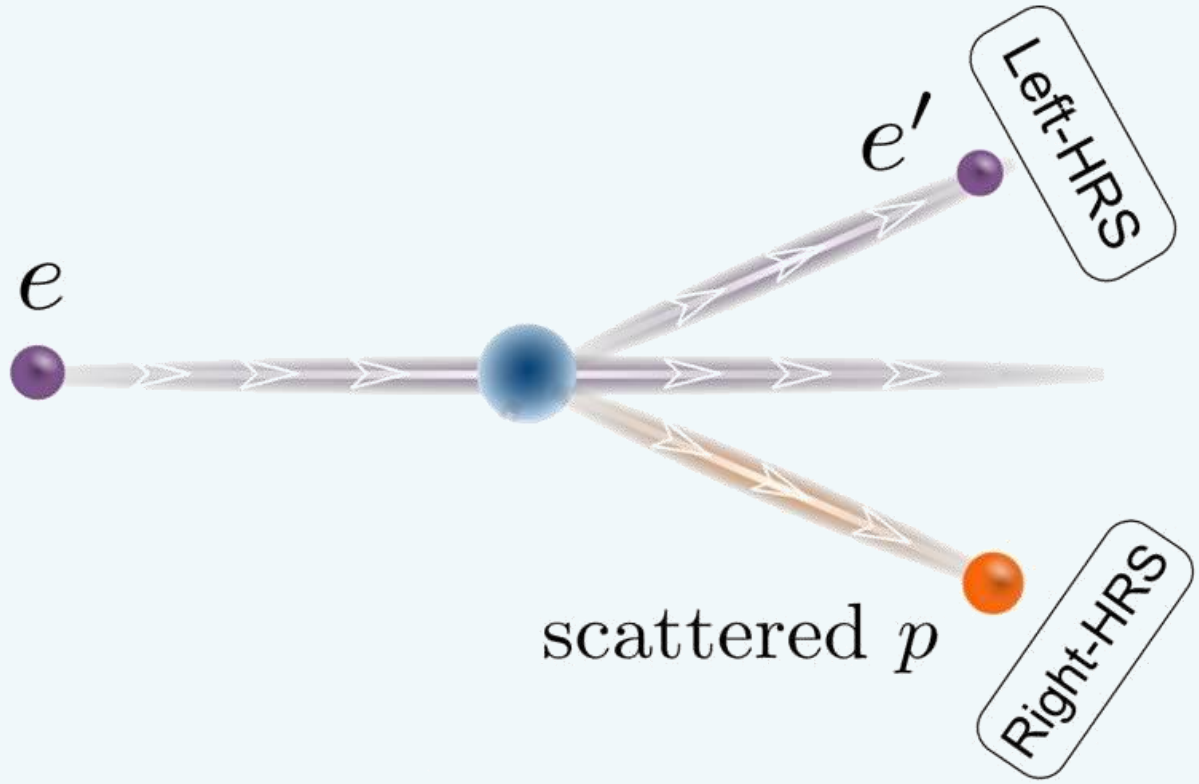
Nucleons in the Nucleus

- How do free nucleons differ from those in nuclei?
- Does the interplay between the attractive and repulsive short-range components of the **nucleon-nucleon (N-N) potential force** cause some of the nucleons inside the nucleus to form pairs?
- Do the correlated pairs favor a particular combination of nucleons: proton-proton, neutron-neutron or proton-neutron?

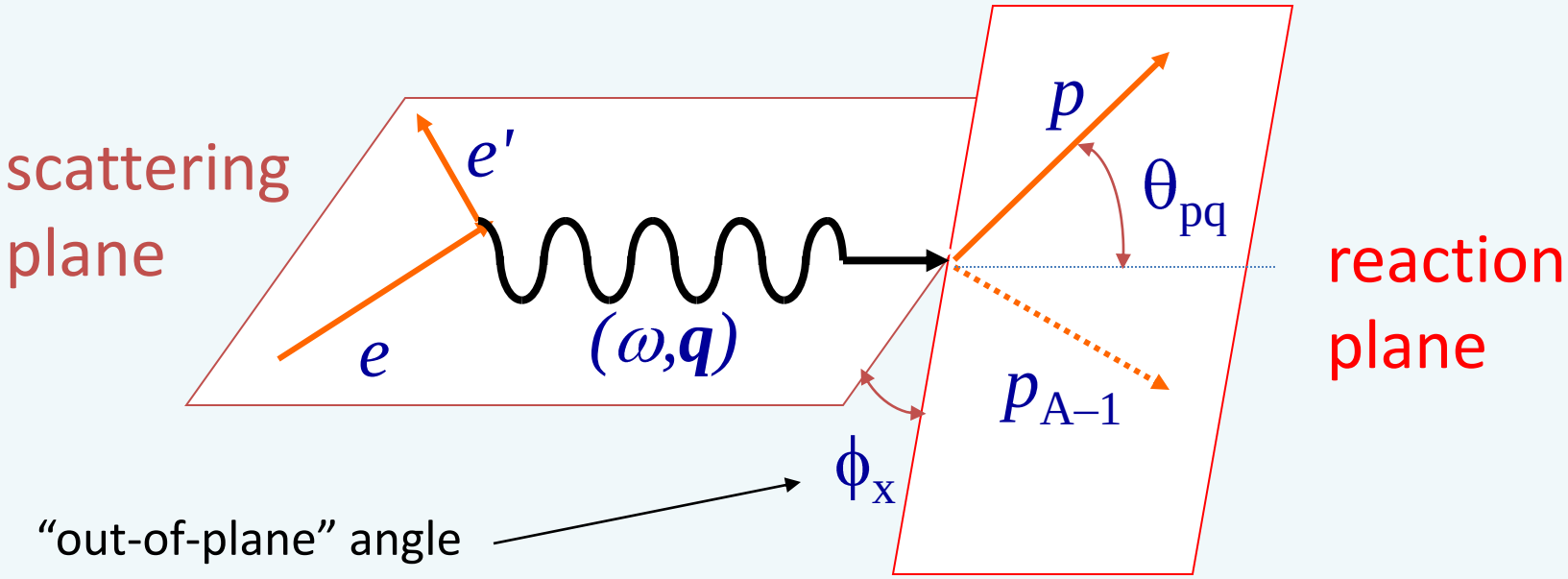
Electron scattering has proven to be a valuable tool to understand and investigate nucleons inside the nucleus.

Tools of the Trade

Electron Scattering



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: $\boldsymbol{p}_m = \boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{A-1}$

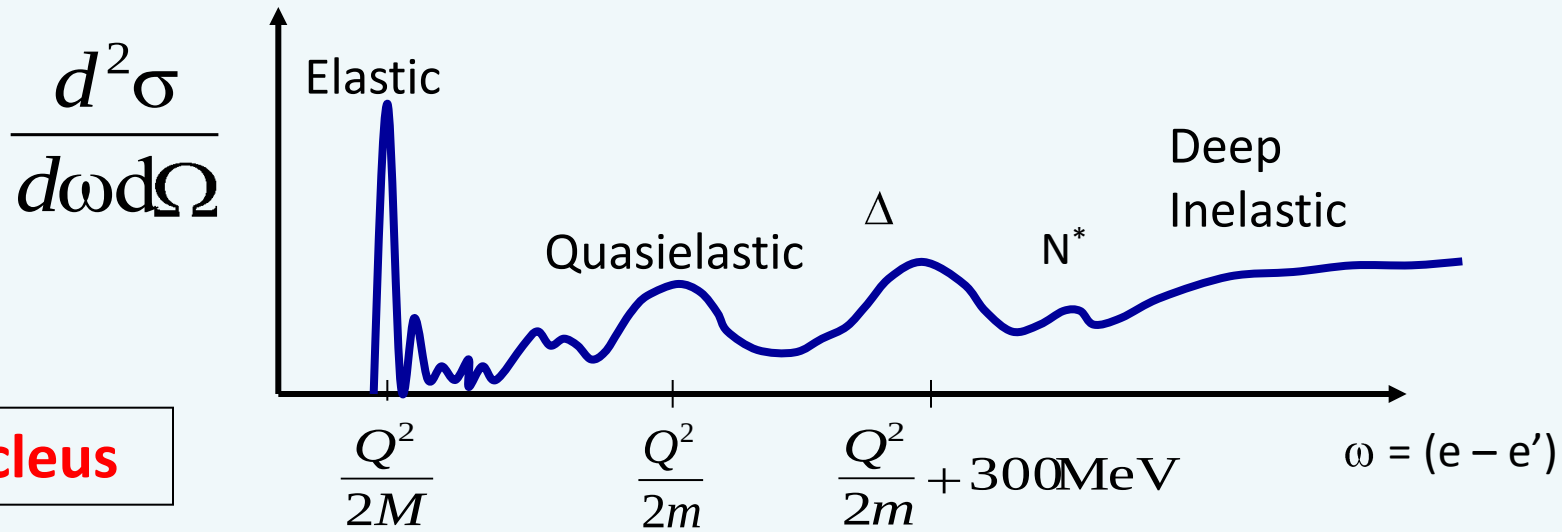
Difference between transferred and detected momentum

Missing energy: $\varepsilon_m = \omega - T_p - T_{A-1}$

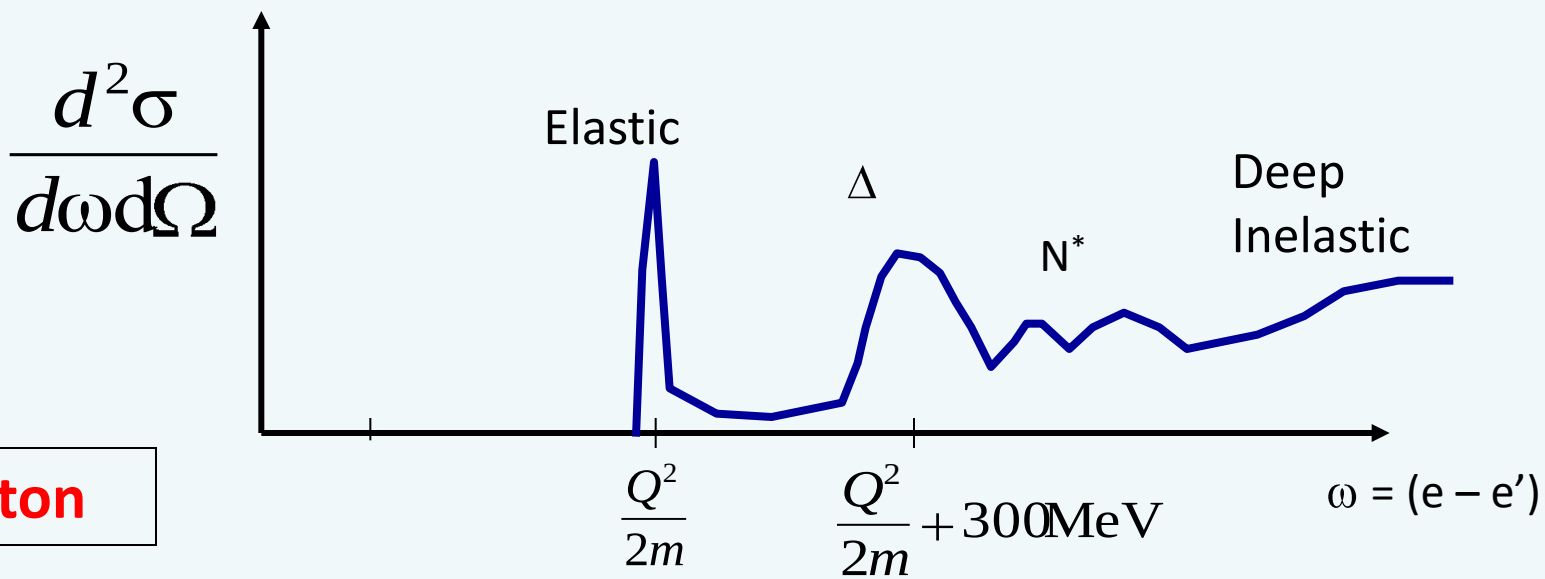
Difference between transferred and detected energy

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

Electron Scattering at Fixed Q^2



Nucleus



Proton

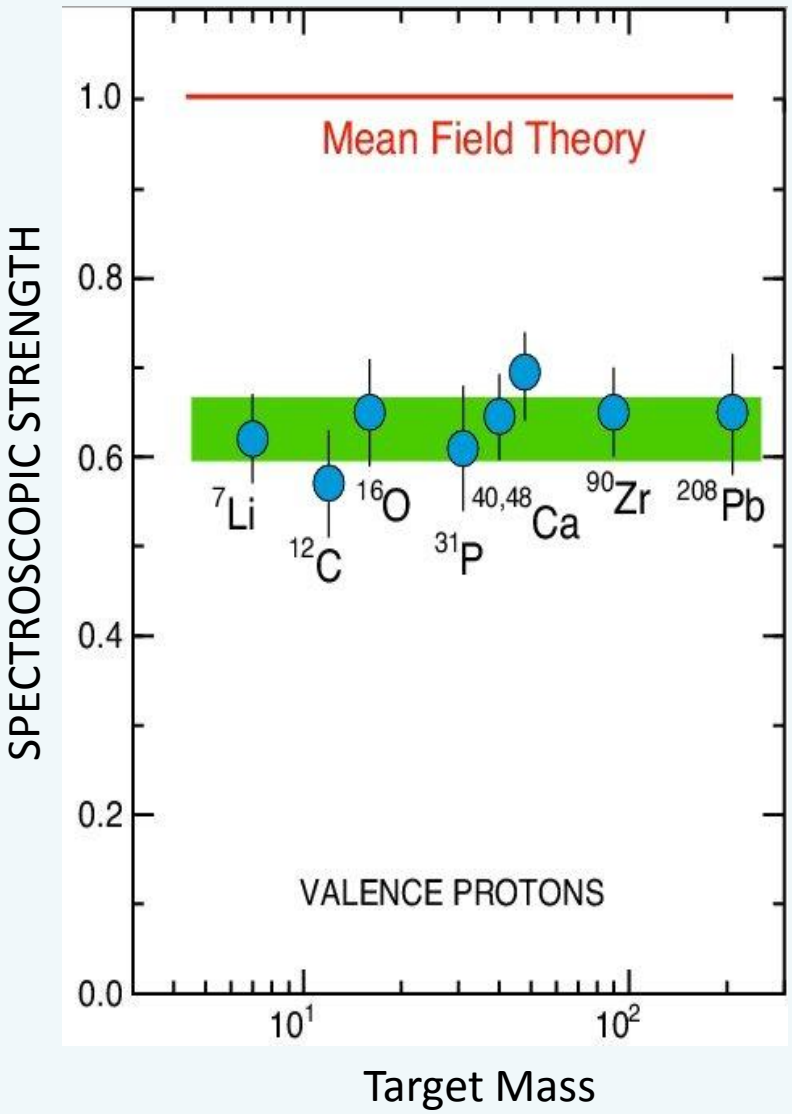
Classic Result from (e,e'p) Measurements

L. Lapikas, Nucl. Phys. A553 (1993) 297.

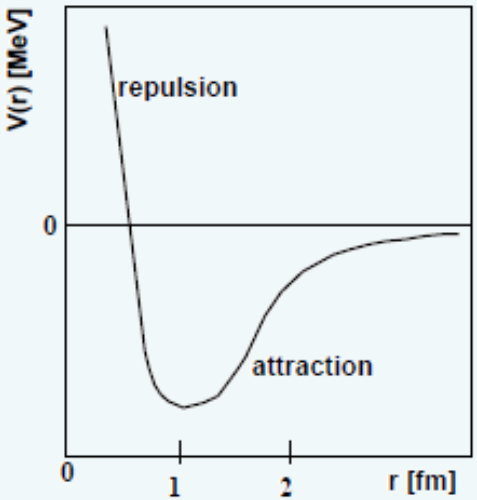
Independent-Particle Shell-Model is based upon the assumption that each nucleon moves independently in an average potential (mean field) induced by the surrounding nucleons

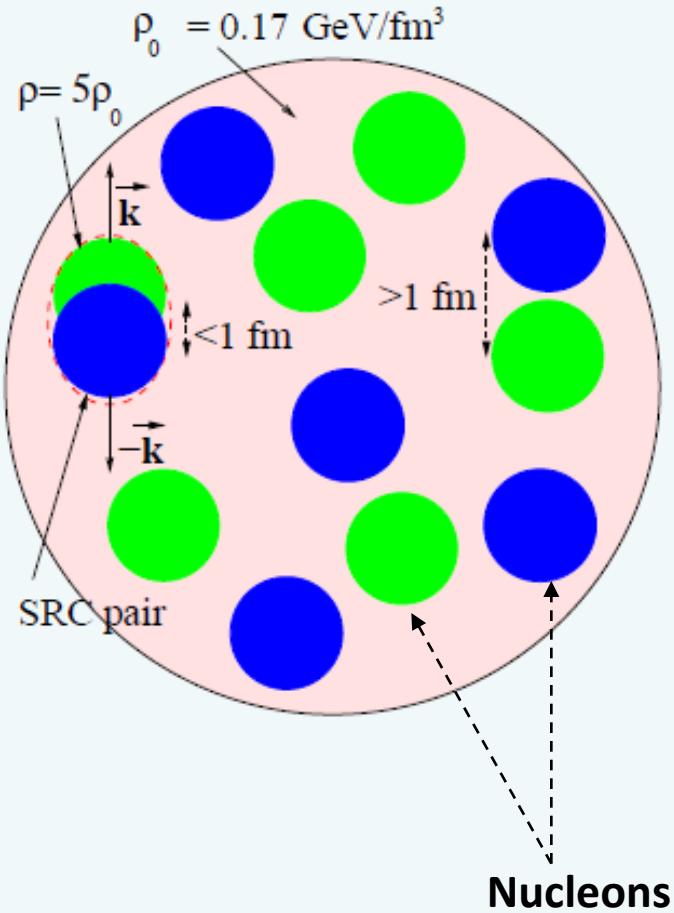
The (e,e'p) data for knockout of valence and deeply bound orbits in nuclei gives spectroscopic factors that are 60 – 70% of the mean field prediction.

Solution: Correlations Between Nucleons
Long-range (> 2 fm) and short-range (< 1 fm)



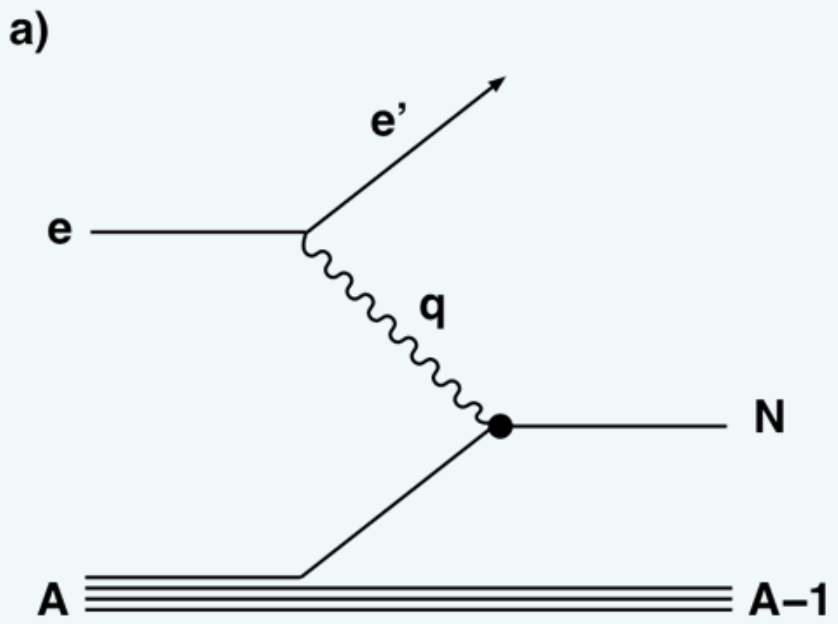
Short-Range Correlations

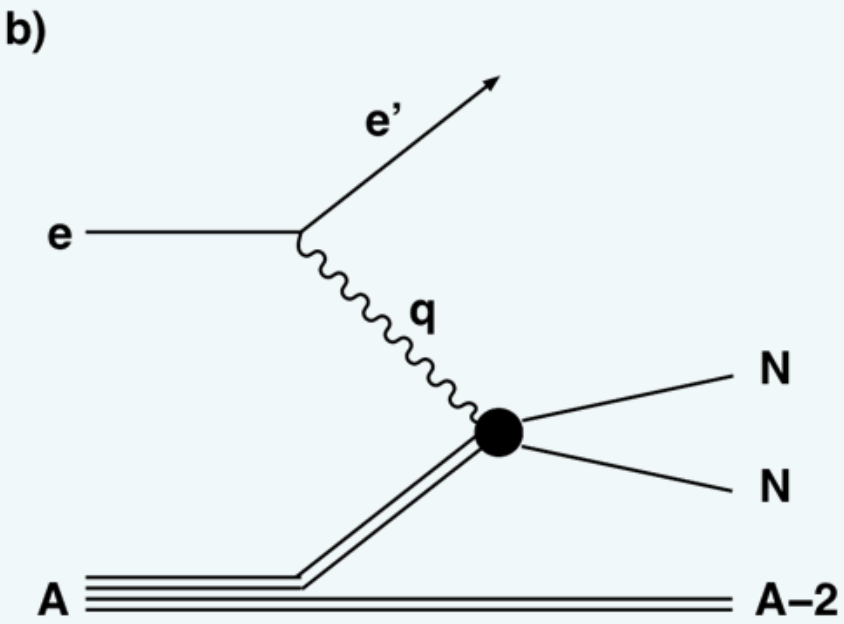




SRC depletes states below the Fermi sea and make the states above this level partially occupied.

Short-Range Correlations





Single nucleon knock-out

Correlated pair knock-out

Questions

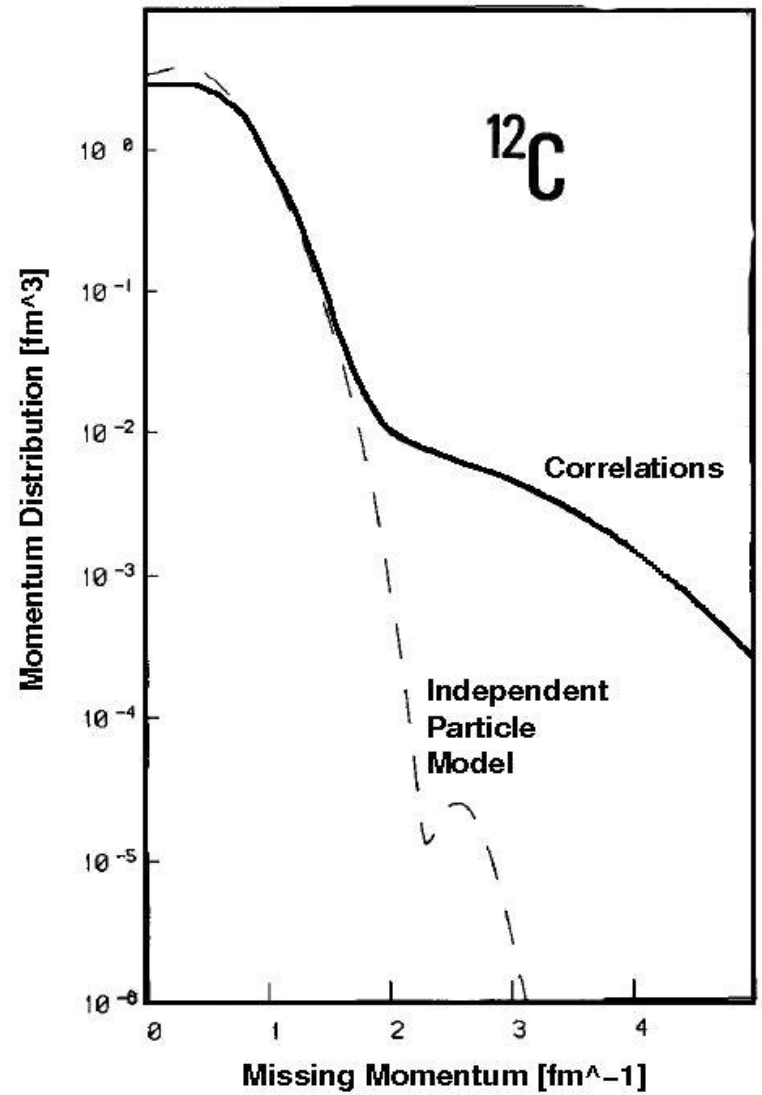
- What fraction of the momentum distribution is due to 2N-SRC?
- What is the relative momentum between the nucleons in the pair?
- What is the ratio of pp to pn pairs?
- Are these nucleons different from free nucleons (e.g. size)?

BUT Other Effects Such As Final State Rescattering Have Masked The Signal In The Past.

To observe the effects of correlations one must probe beyond the Fermi level :

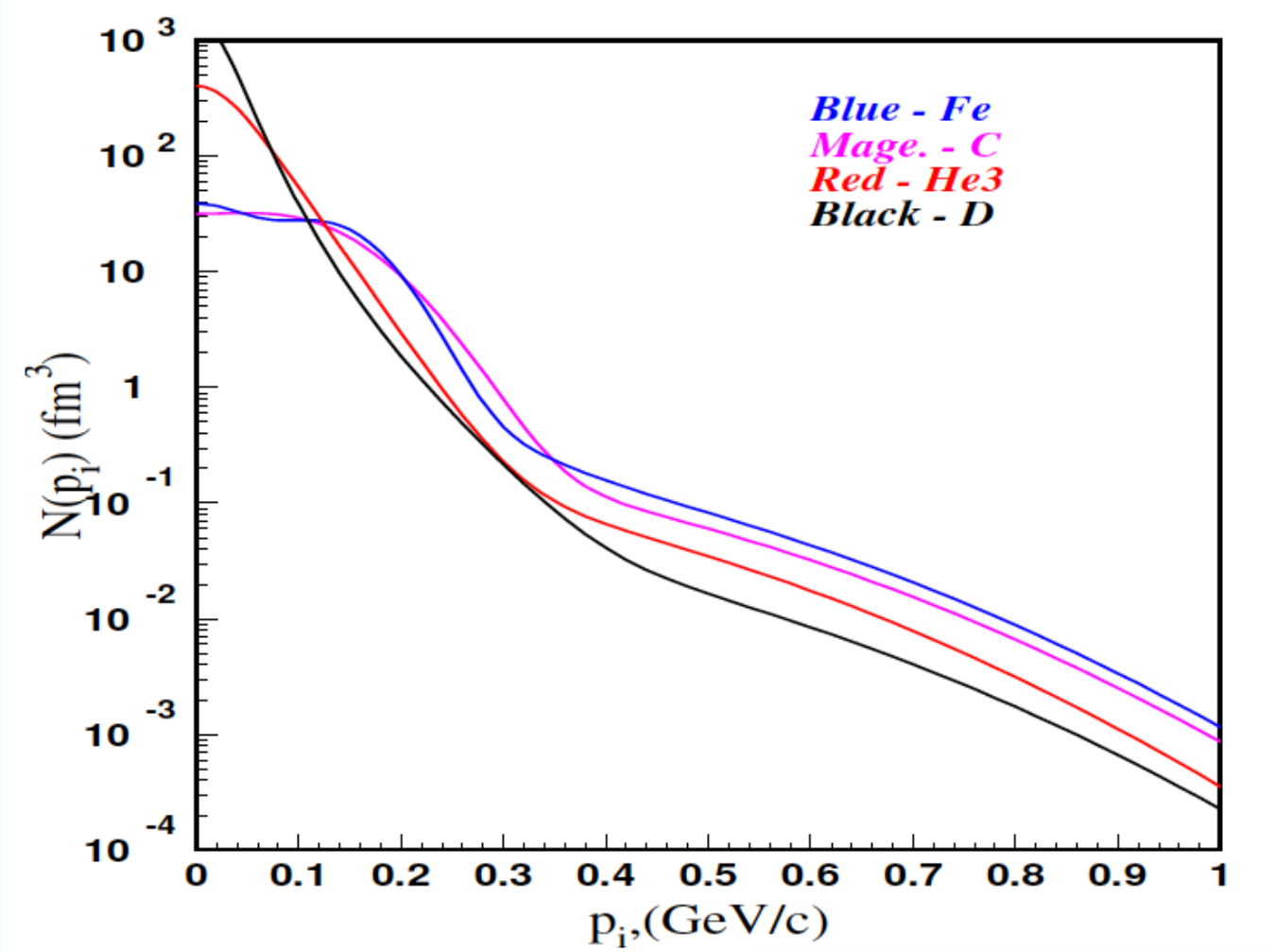
P_{min}> 250 MeV/c

Benhar et al., Phys. Lett. **B** 177 (1986) 135.



Calculation of Nucleon Initial Momentum

C. Ciofi degli Att and S. Simula, Phys. Rev. C **53** (1996) 1689.



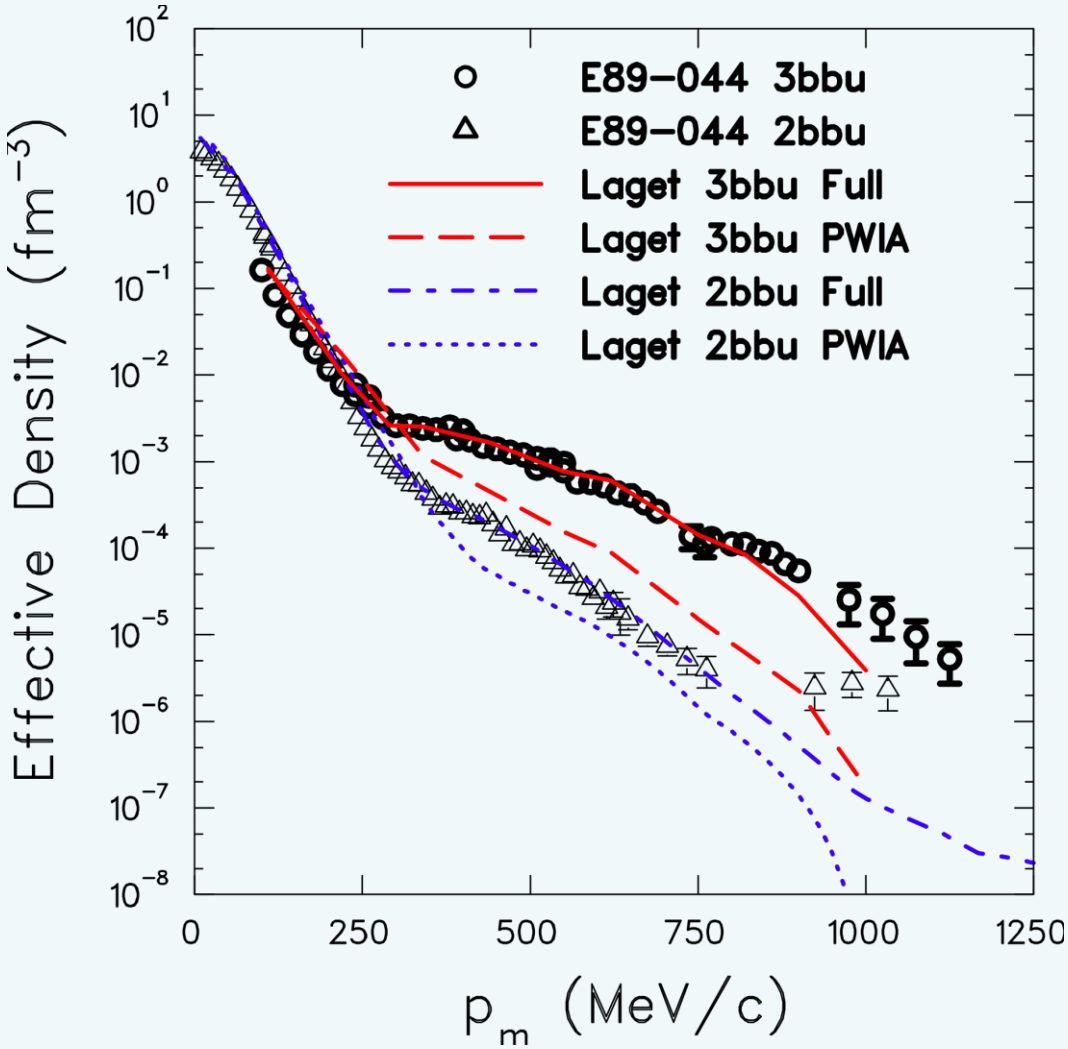
Nuclear Scaling at High Initial Momentums: $n_A(k) = R\, n_D(k)$

^{3}He(e,e'p)d and ^{3}He(e,e'p)np

F. Benmokhtar *et al.*, Phys. Rev. Lett. **95** (2004) 082305.

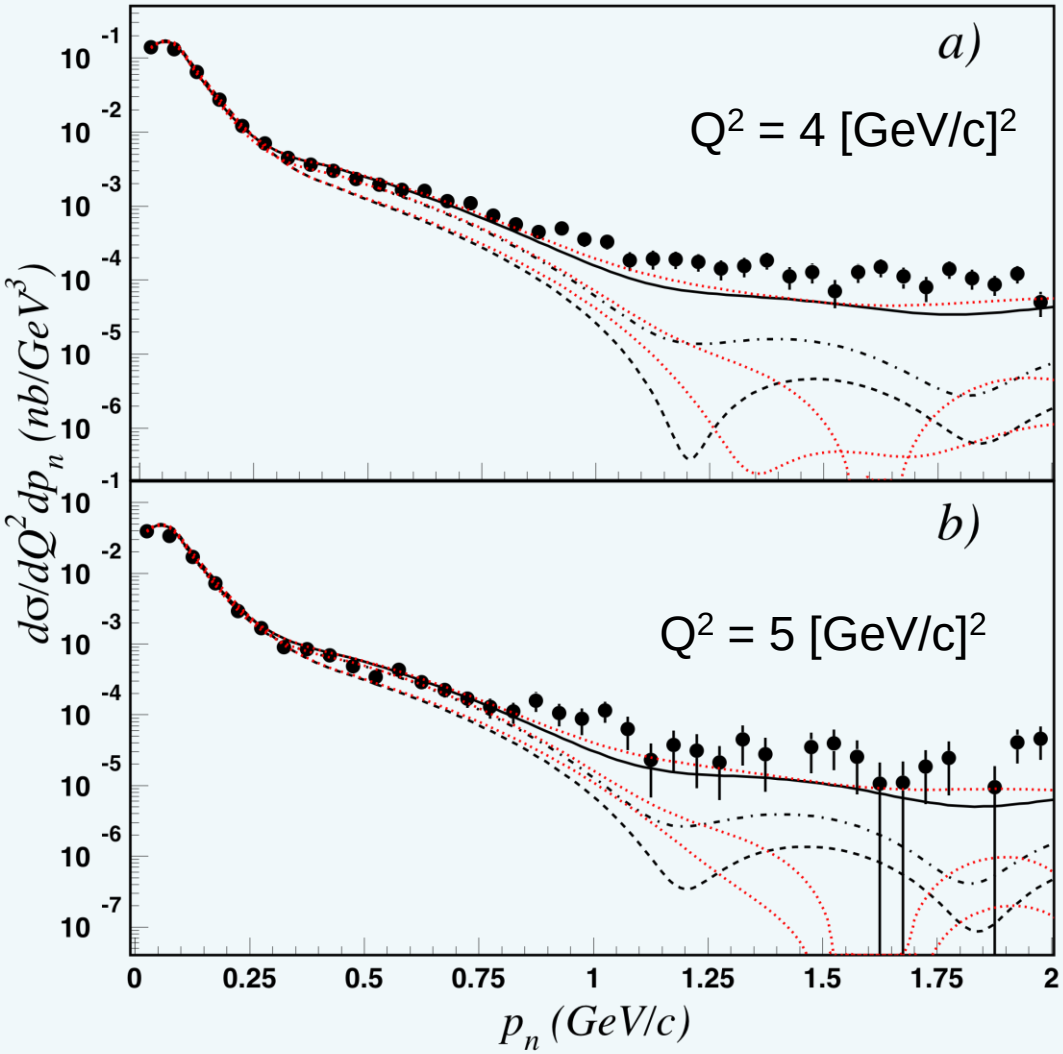
$Q^2 = 1.5\ [\mathrm{GeV/c}]^2$

$x_B = 1$ (Q.E. Peak)



Hall B (CLAS) D(e,e'p)n, x<1 Data

K. Sh. Egiyan *et al.,* Phys. Rev. Lett. **98** (2007) 262502.



Black Paris Potential
Red AV-18 Potential

From Lowest To Highest
PWIA
PWIA+FSI
PWIA+FSI+MEC+NΔ

CLAS A(e,e') Data

K. Sh. Egiyan *et al.,* Phys. Rev. C **68** (2003) 014313.

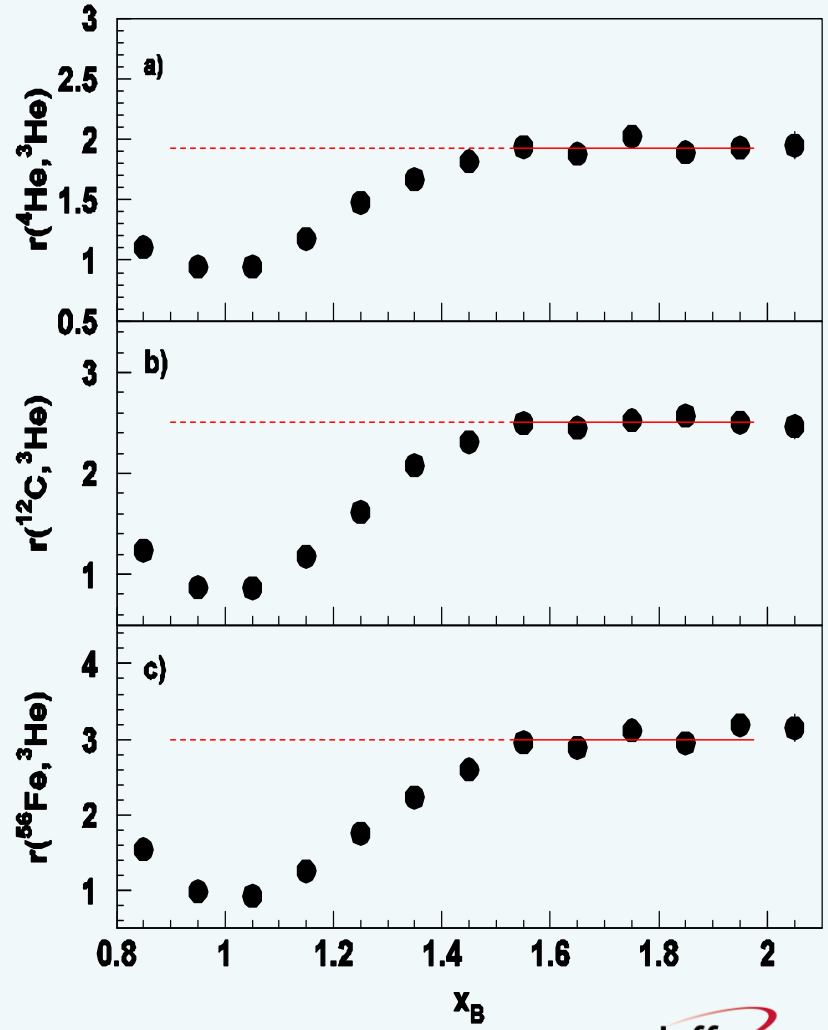
Originally done with SLAC data by D.B. Day *et al.*, Phys. Rev. Lett. 59 (1987) 427.

$$x = \frac{Q^2}{2M\omega} > 1.5 \quad \text{and} \quad Q^2 > 1.4\ [\mathrm{GeV/c}]^2$$

then

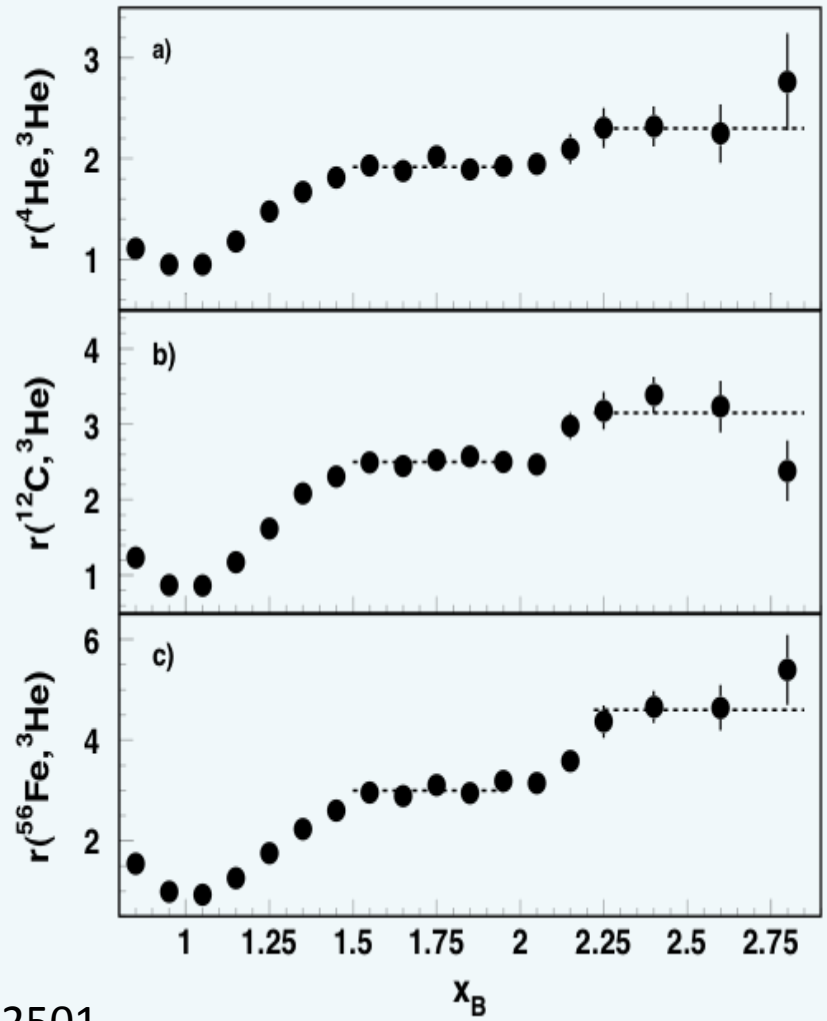
$$r(A,{}^3He) = a_{2n}(A)/a_{2n}({}^3He)$$

The observed *scaling* means that the electrons probe the high-momentum nucleons in the 2N-SRC phase, and the scaling factors determine the per-nucleon probability of the 2N-SRC phase in nuclei with A>3 relative to ^{3}He



Estimate of ^{12}C Two and Three Nucleon SRC

- K. Egiyan *et al*. related the known correlations in deuterium and previous r(^{3}He,D) results to find:
- ^{12}C 20% two nucleon SRC
- ^{12}C <1% three nucleon SRC



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

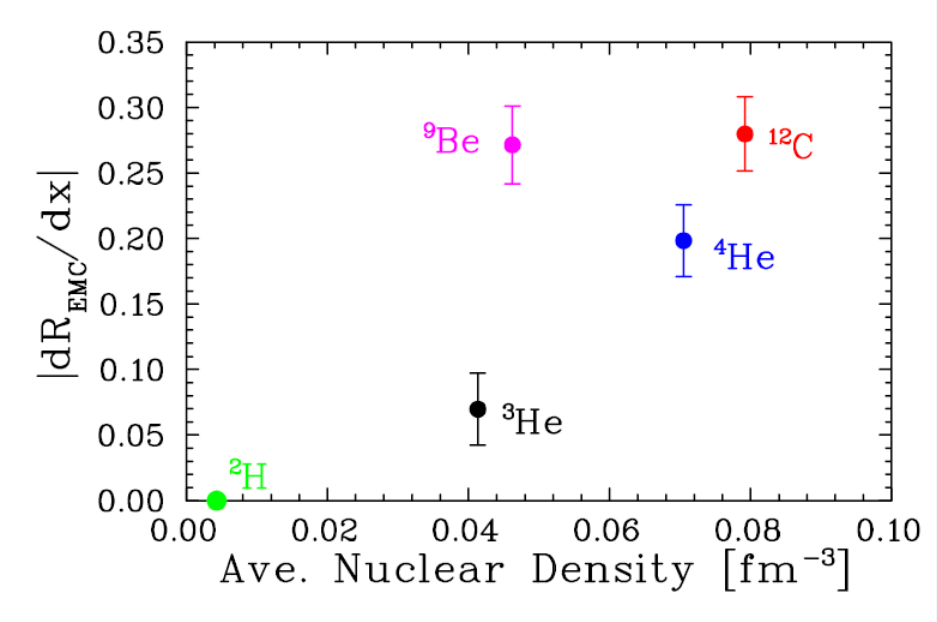
^{12}C From the (e,e') and (e,e'p) Results

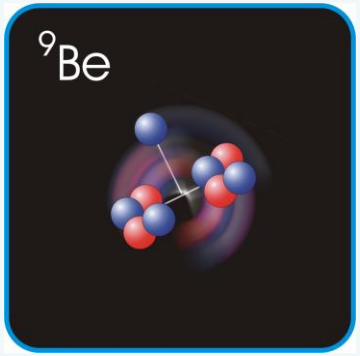
- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - Hall C (e,e') Ratios Coming from Nadia Fomin
    - No Q^2 Dependence Of 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

EMC Effect and EMC Slopes

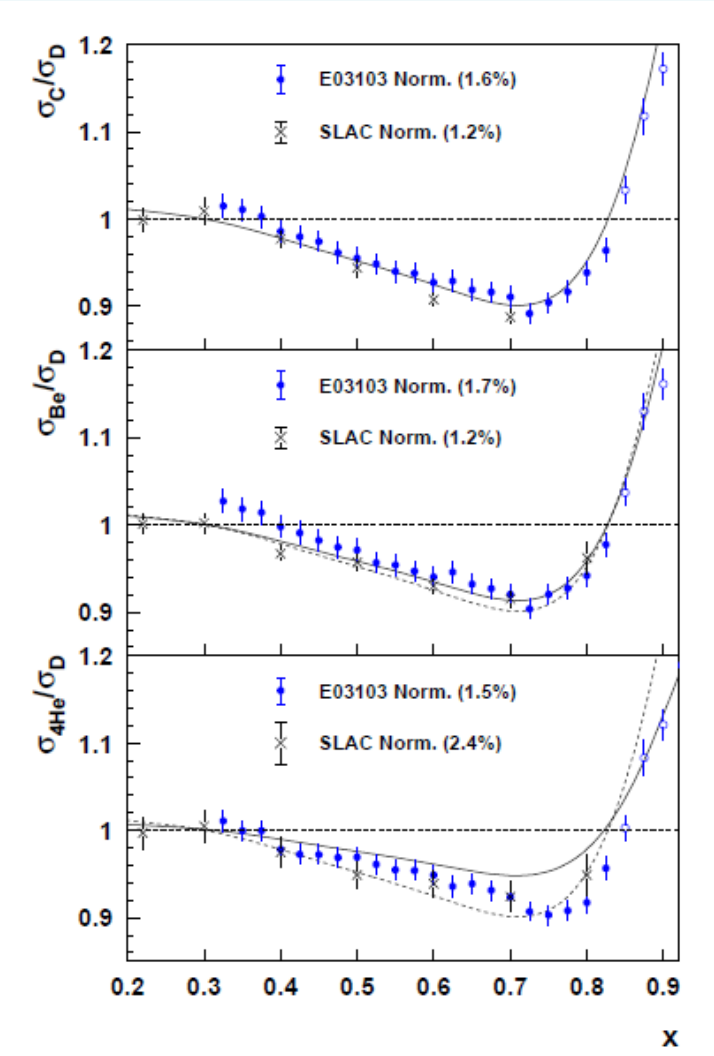
Indication that the EMC effect scales with the local environment of the nucleons

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





- Difference between ^{3}He and ^{4}He rules out A-dependent fits
- Large EMC effect in ^{9}Be contradicts a simple density-dependent effect

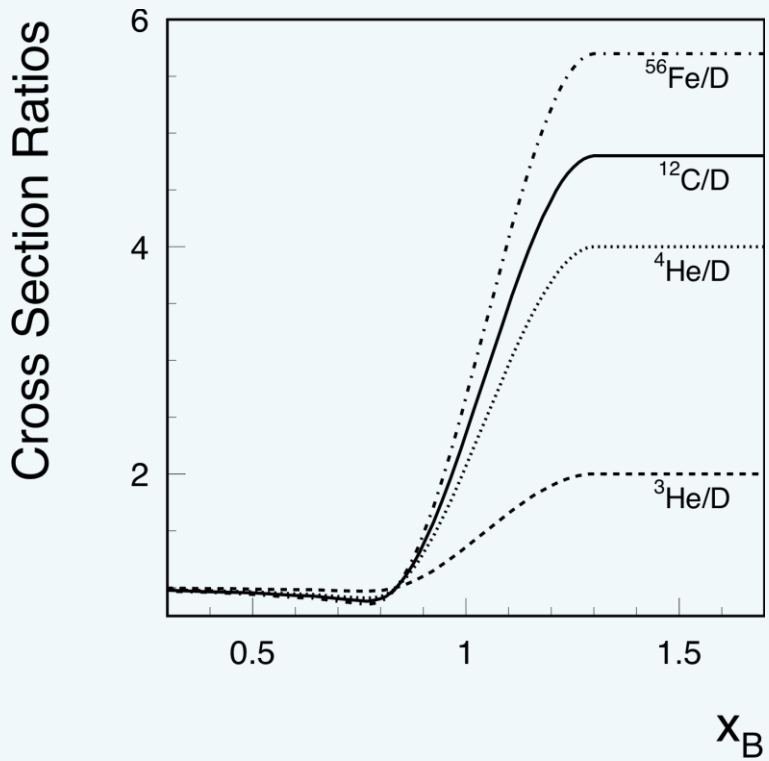


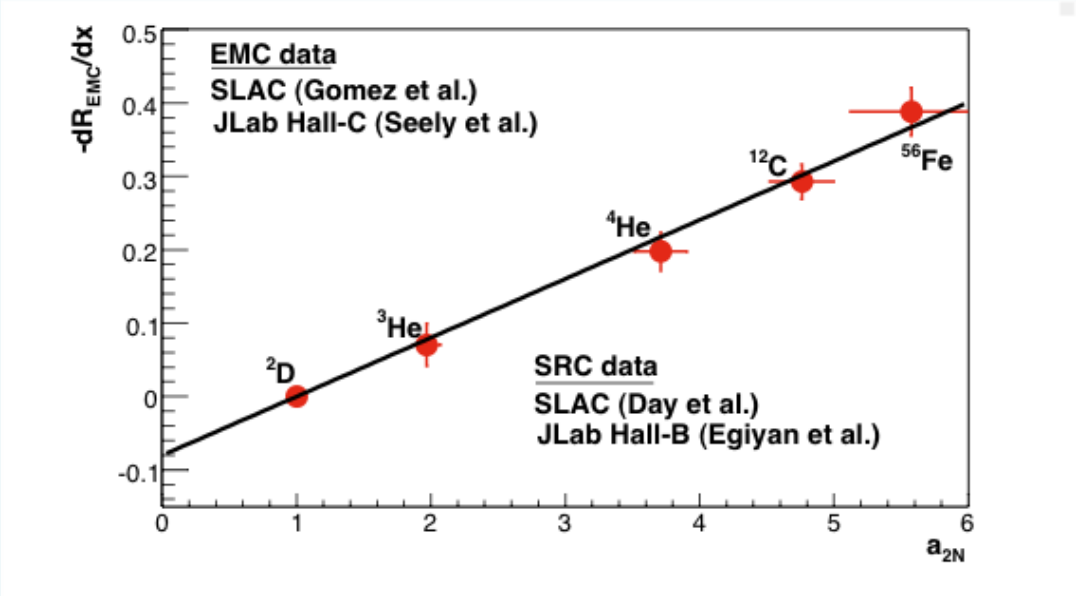
SRC Ratios and x>0.3 EMC Slopes

Both Local Density Effects?

Note: Q^2=50 GeV/c ^{56}Fe(e,e')/D(e,e') data extends smoothly into the x>1 region

A. C. Benvenuti, et al., Z. Phys. **C63** (1994) 29.





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

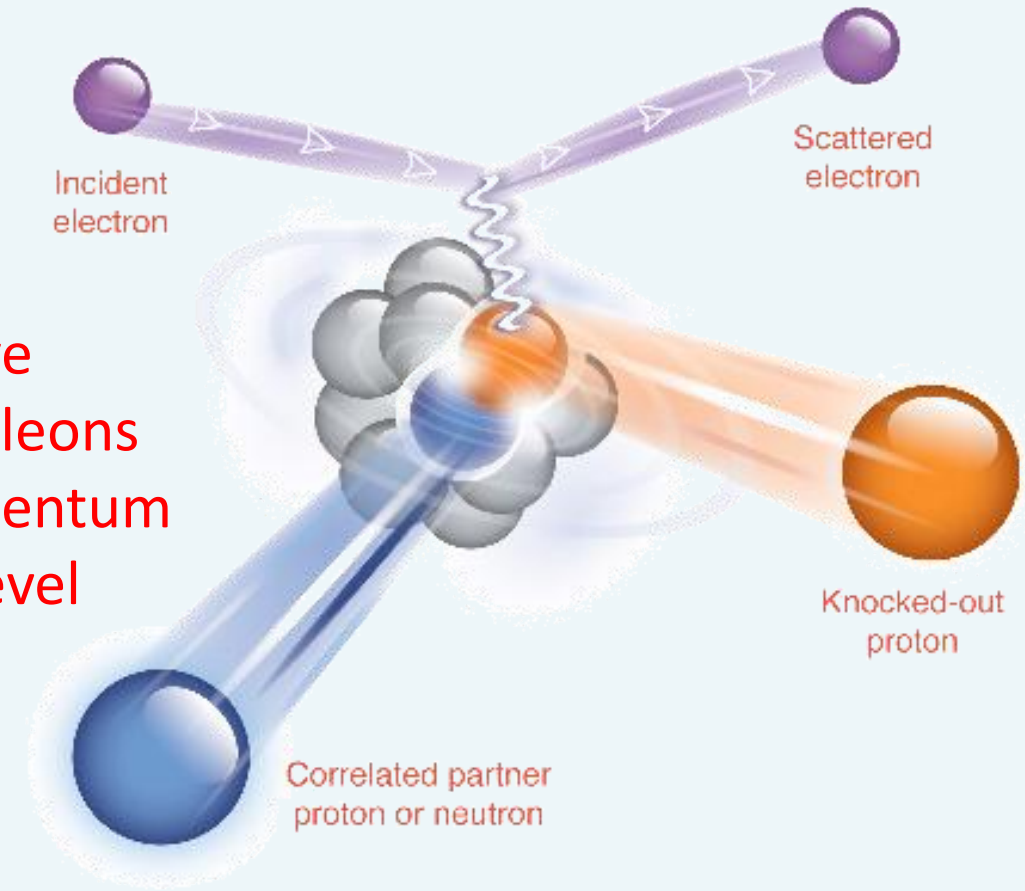
Ratio of EMC Slopes Seems To Follow Ratio of SRC Plateaus

Customized (e,e'pN) Measurement

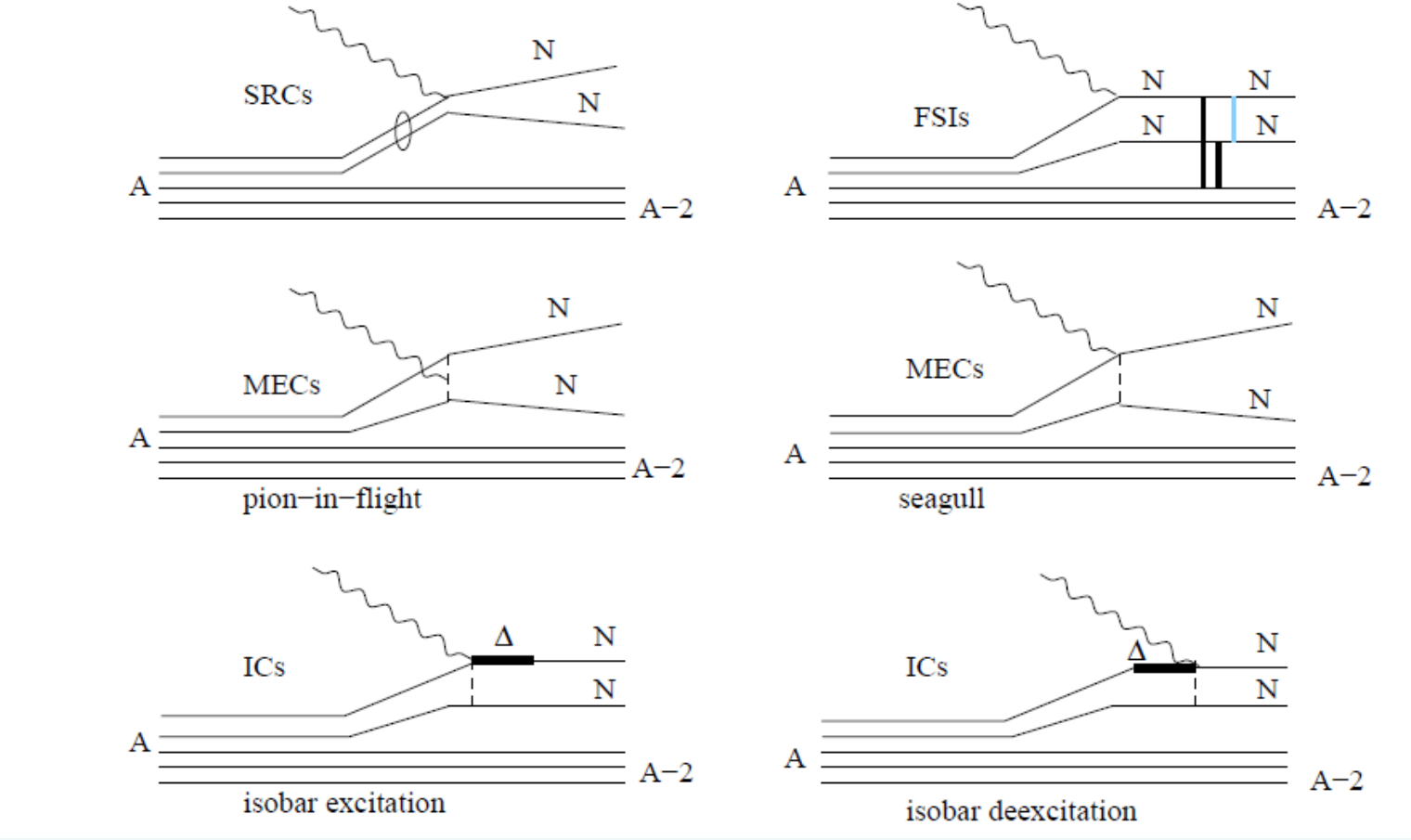
To study nucleon pairs at close proximity and their contributions to the large momentum tail of nucleons in nuclei.

A pair with "large" relative momentum between the nucleons and small center of mass momentum Relative to the Fermi-sea level

~ 250 MeV/c

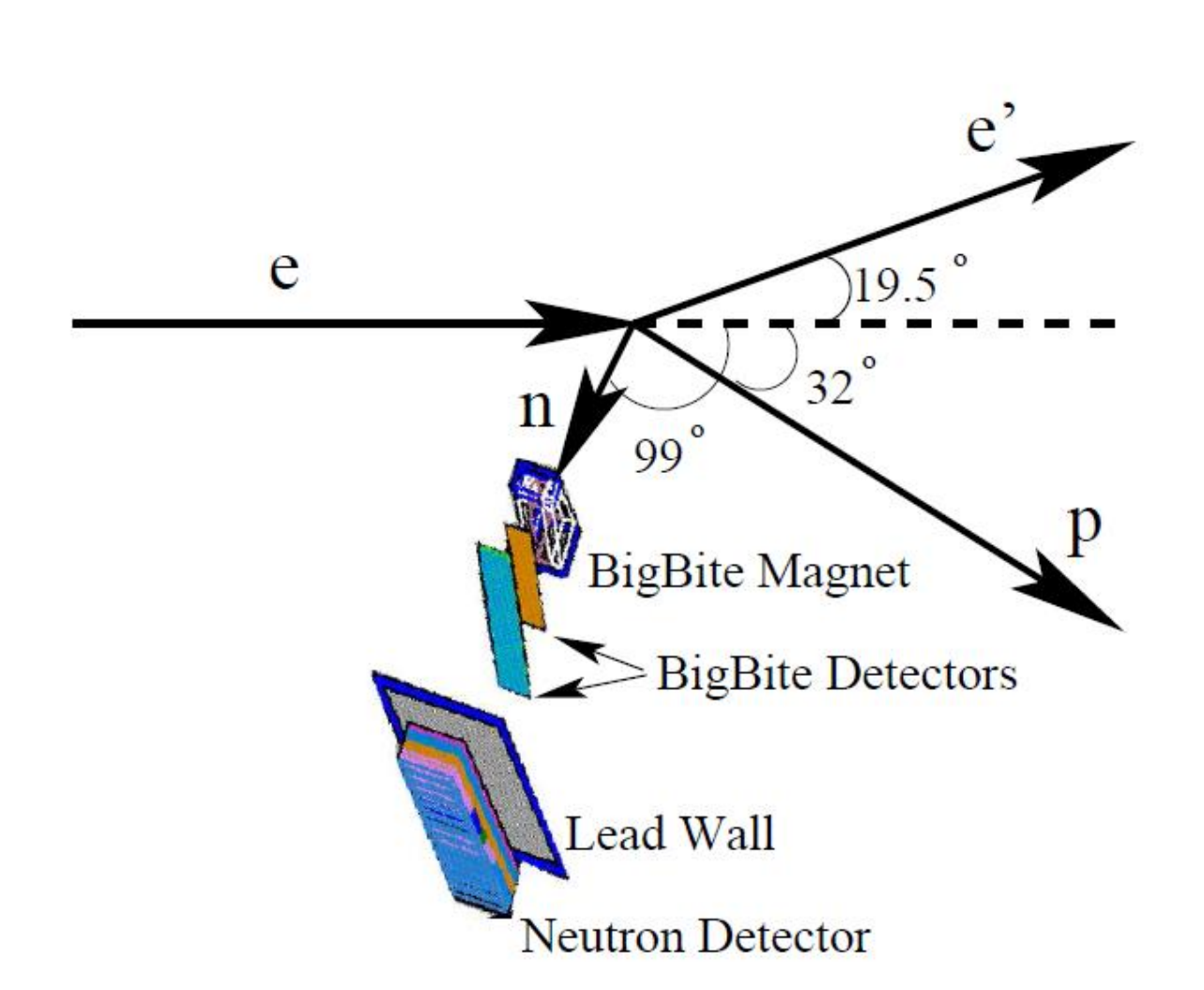


Suppression of Non-SRC Two Body Effects

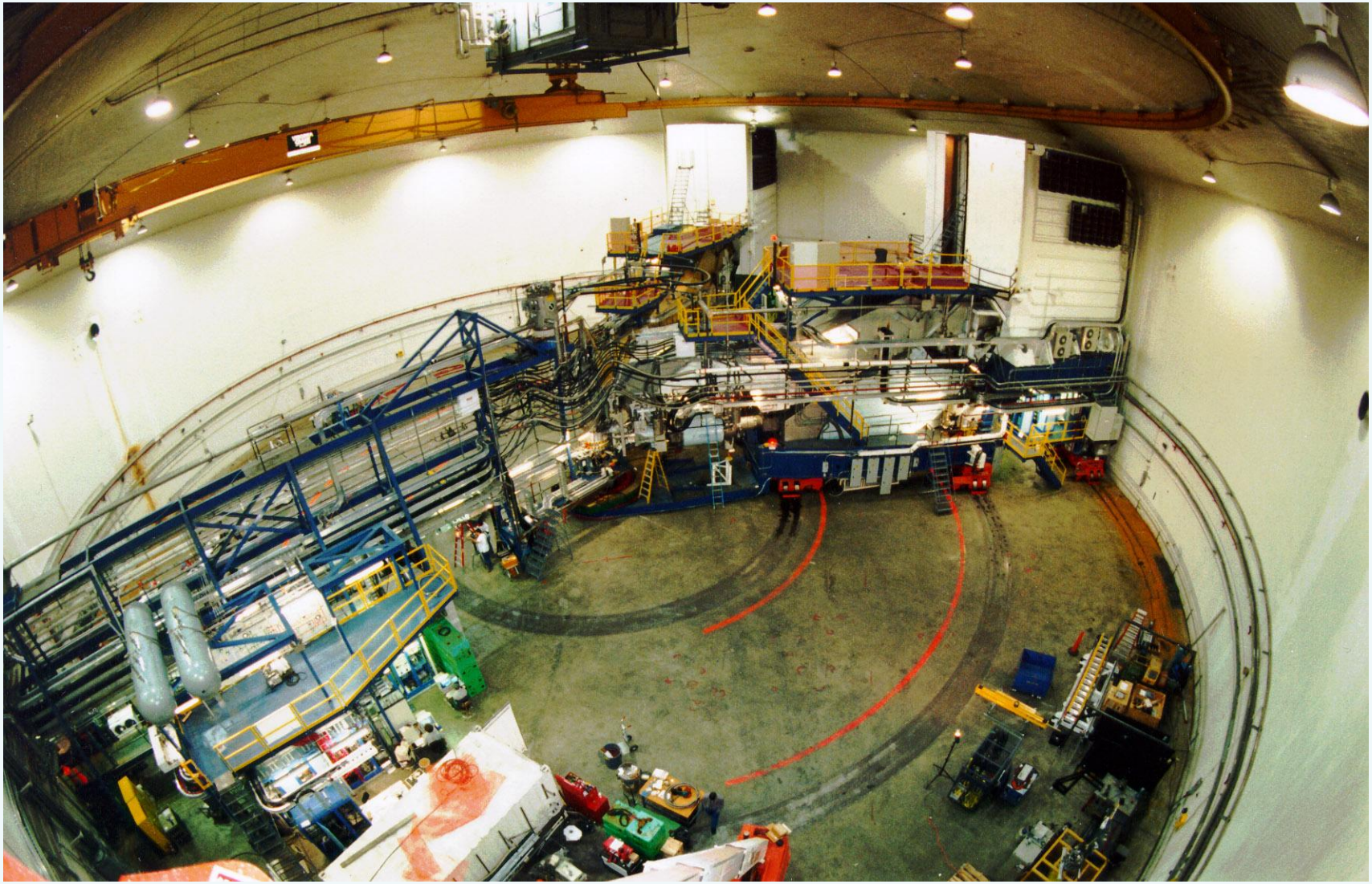


- High Q^2 to minimize MEC ($1/Q^2$) and FSI
- x>1 to suppress isobar contributions

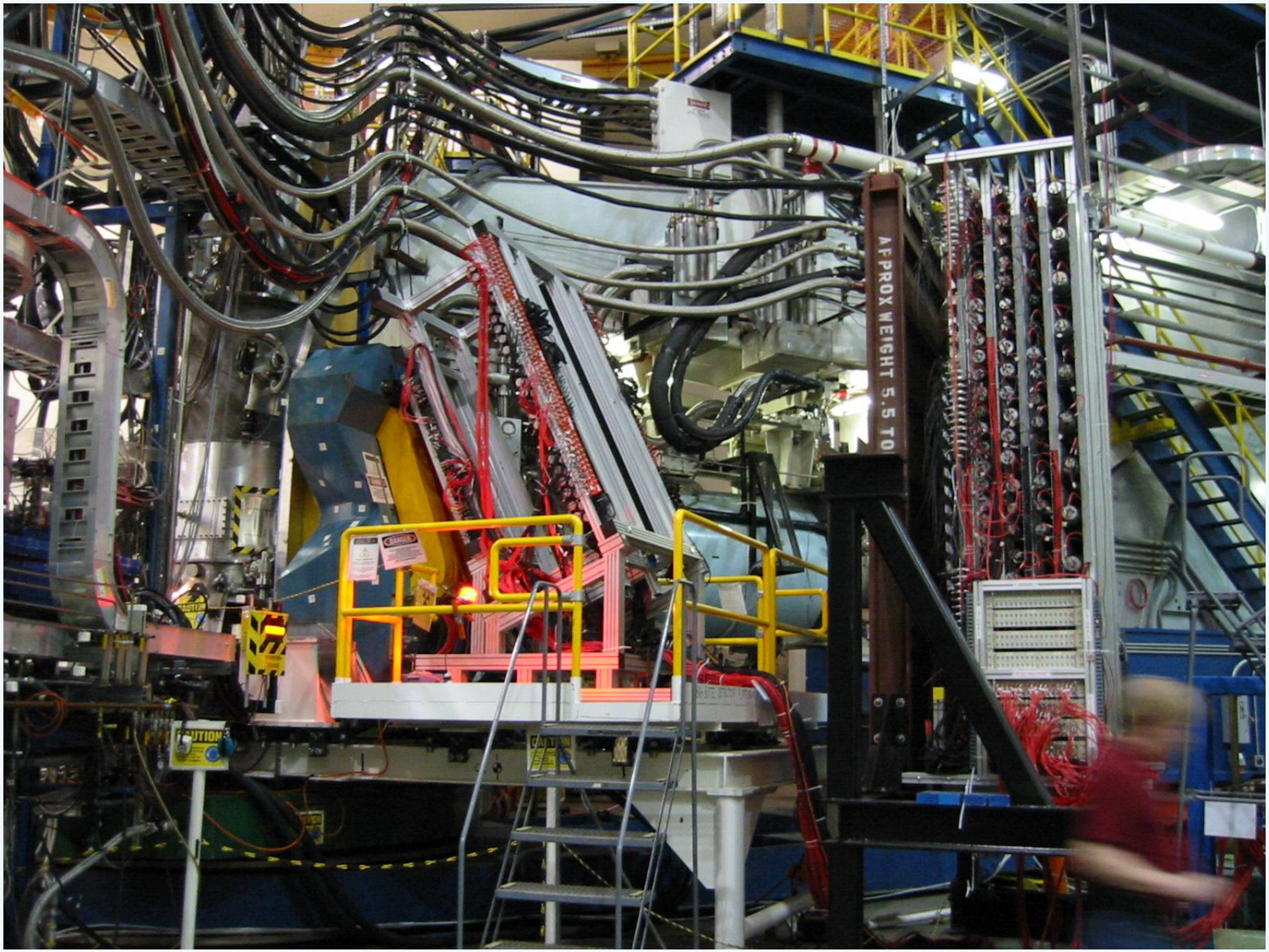
Kinematics


e'
e
19.5 °
32 °
n
99 °
p
BigBite Magnet
BigBite Detectors
Lead Wall
Neutron Detector

Jefferson Lab's Hall A

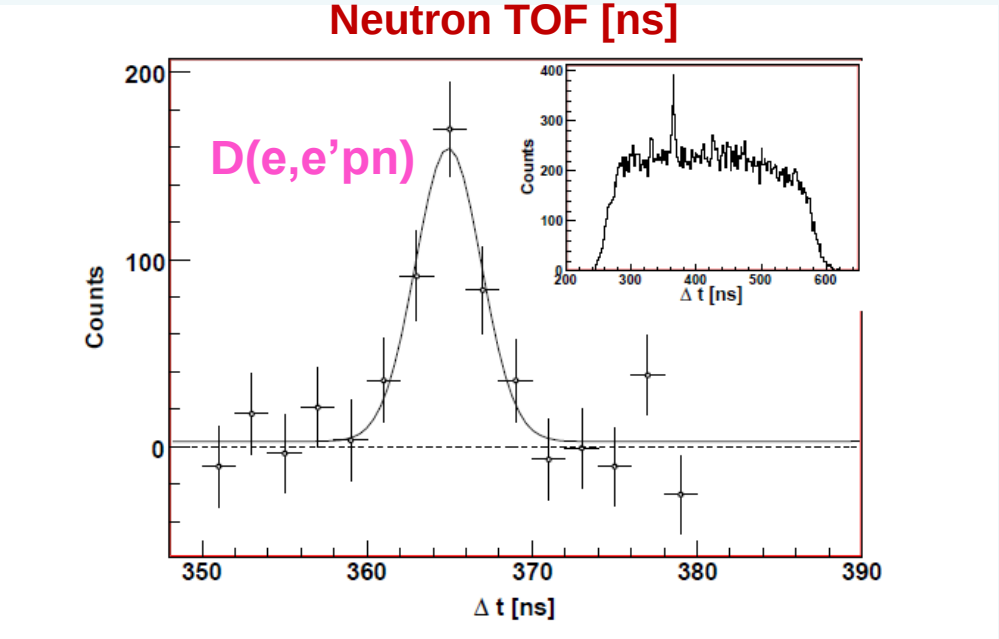


Add BigBite and Neutron Detector



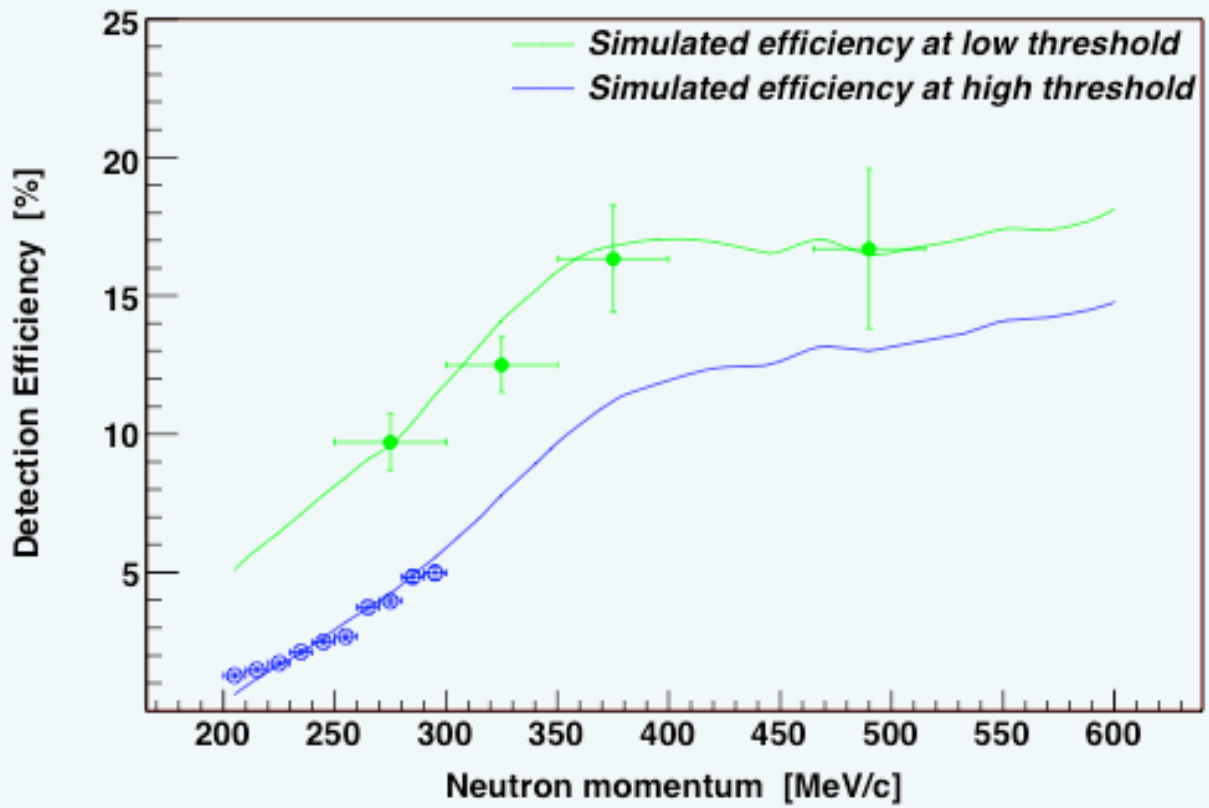
HAND

- Hall A Neutron Detector
- First Neutron Detector in Hall A
- Measuring D(e,e'p) and detecting the neutron, the detector was tested and calibrated.

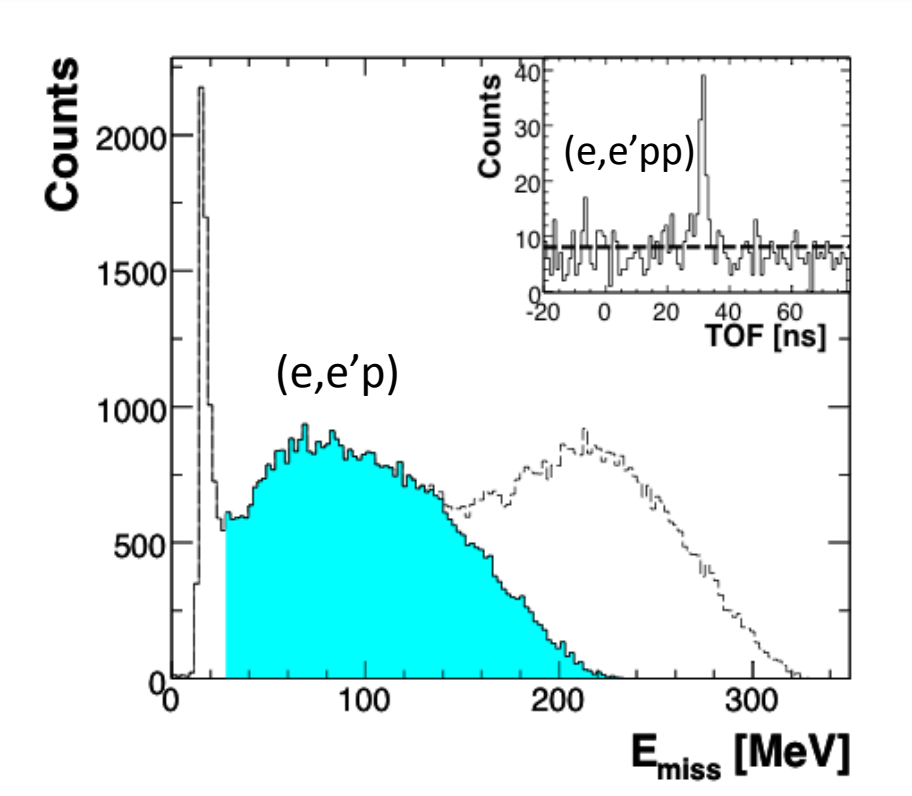


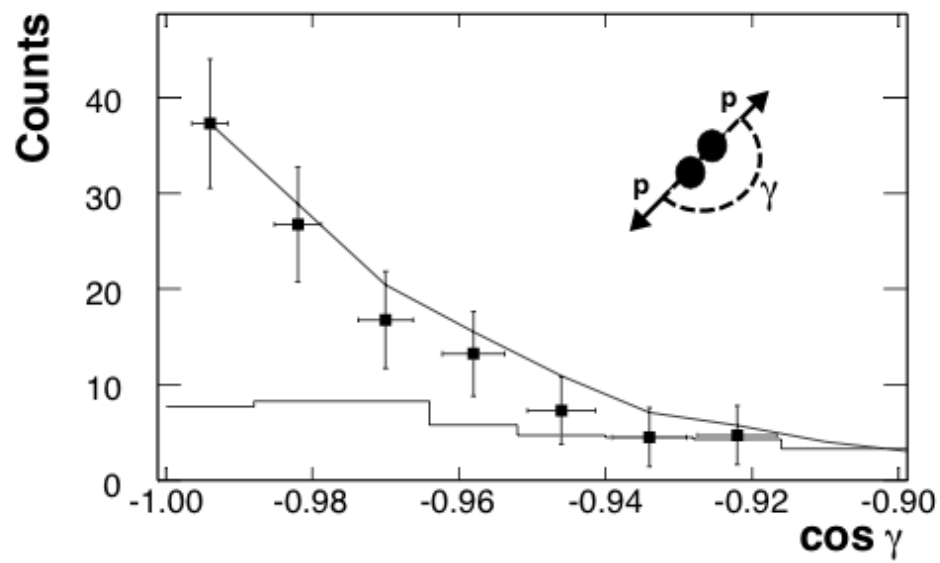
Absolute Neutron Detector Efficiency

- 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.
  - Blue data using 2.3 GeV beam, Green data with 4.6 GeV beam



(e,e'p) & (e,e'pp) Data





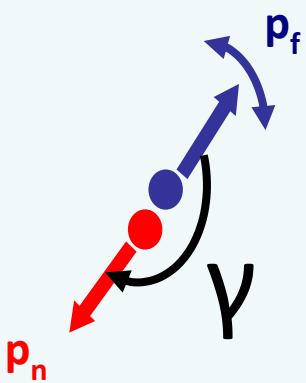
Strong back-to-back correlation!

- $^{12}C(e,e'p)$
- Quasi-Elastic Shaded In Blue
- Resonance Even at $x_B>1$

R. Shneor *et al.*, Phys. Rev. Lett. **99** (2007) 072501.

Brookhaven EVA Collaboration Result

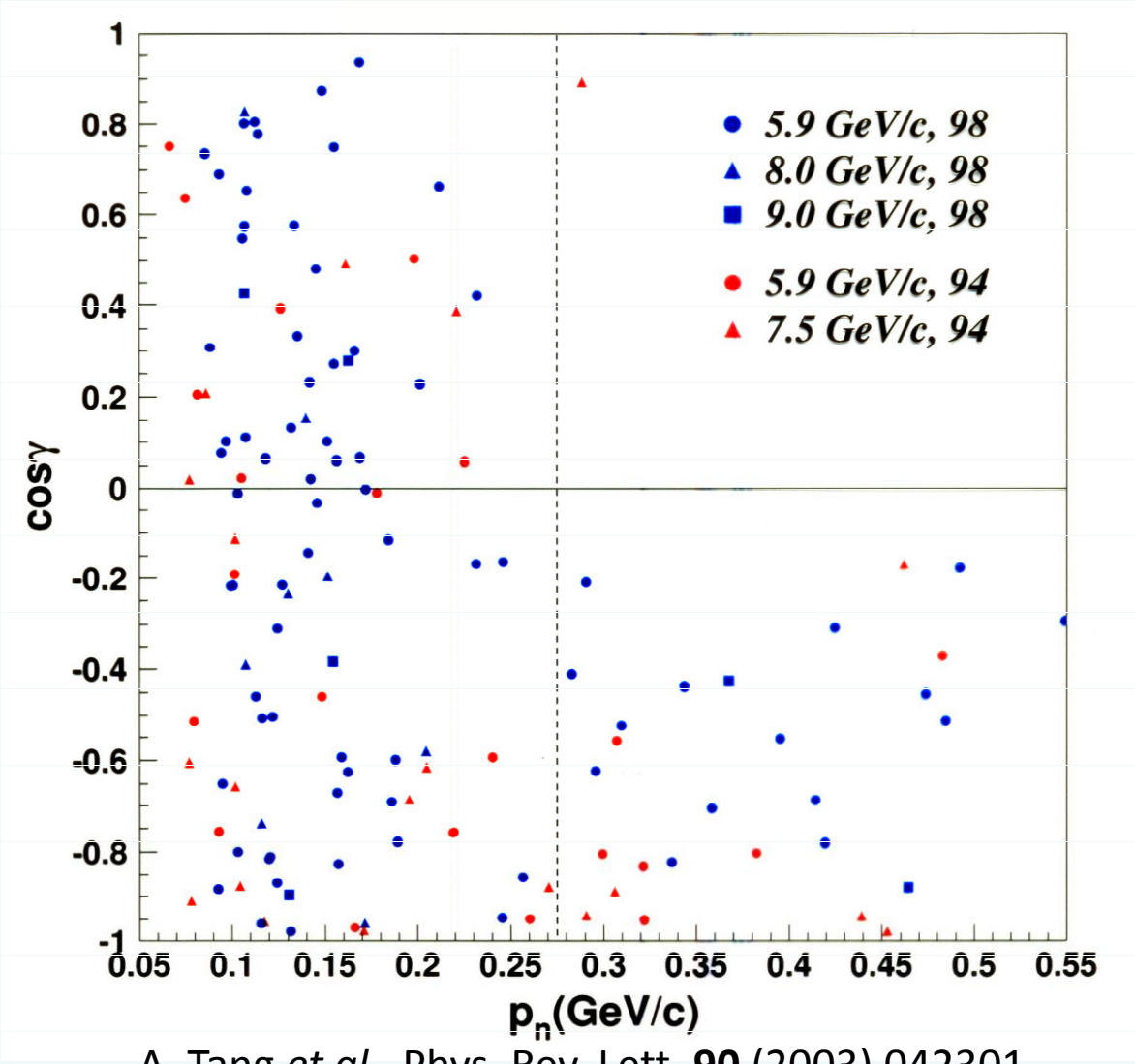
^{12}C(p,2p+n) Reaction



$p_f = p_1 + p_2 - p_0$

p_0 = incident proton

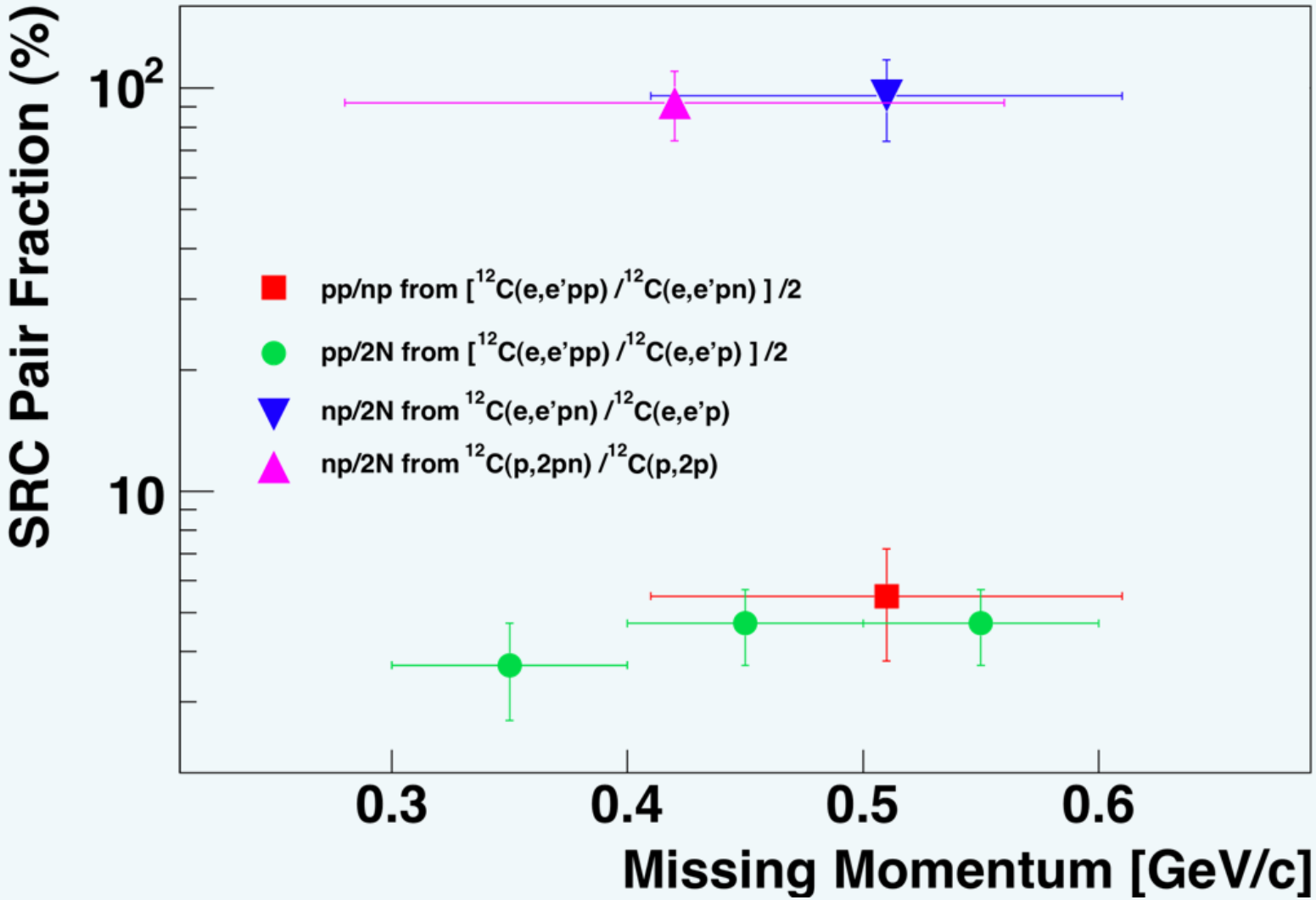
p1 and p2 are detected



A. Tang *et al.*, Phys. Rev. Lett. **90** (2003) 042301.

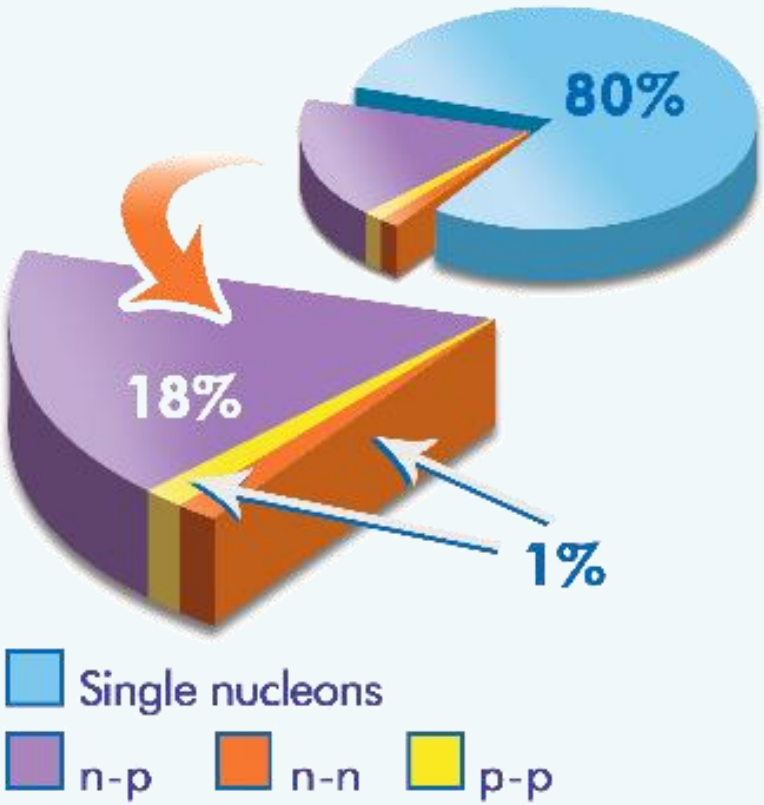
Correlated Pair Factions from ^{12}C

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

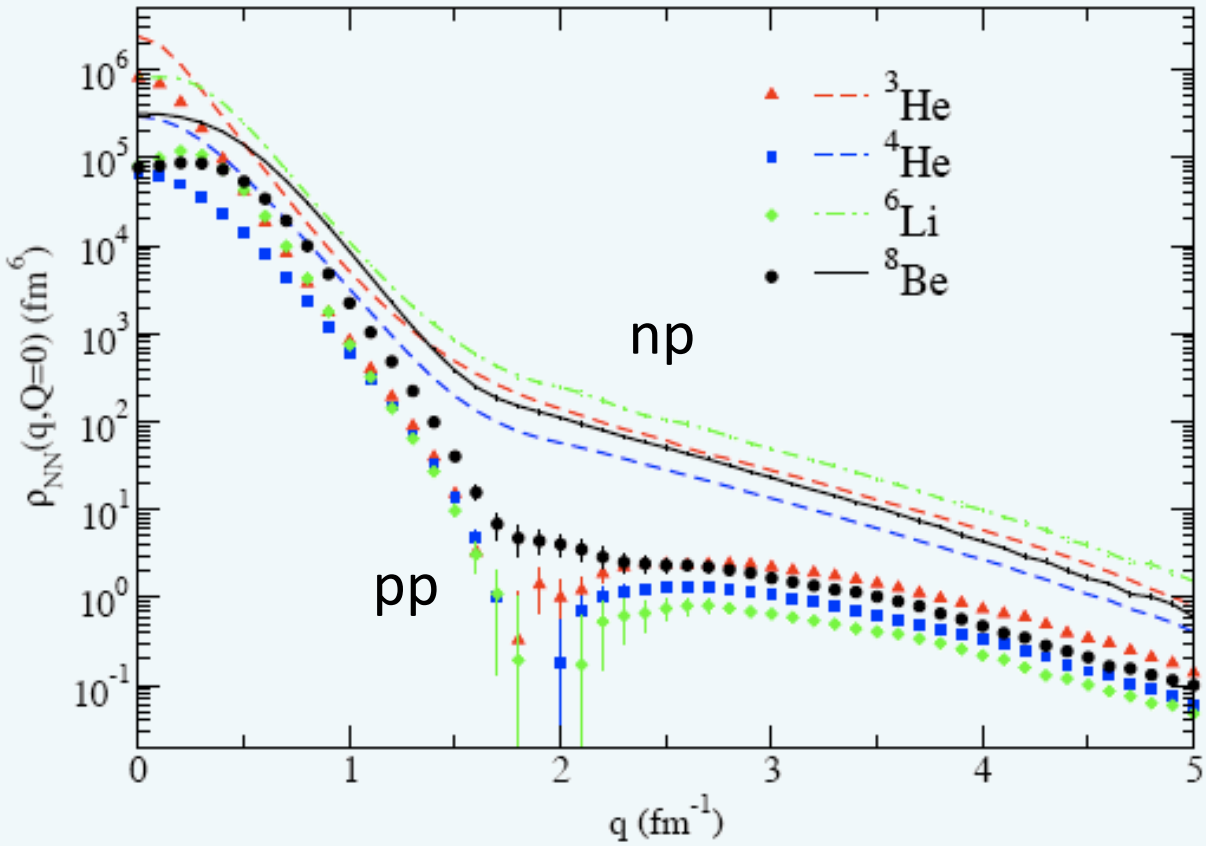


From the (e,e'), (e,e'p), and (e,e'pN) Results

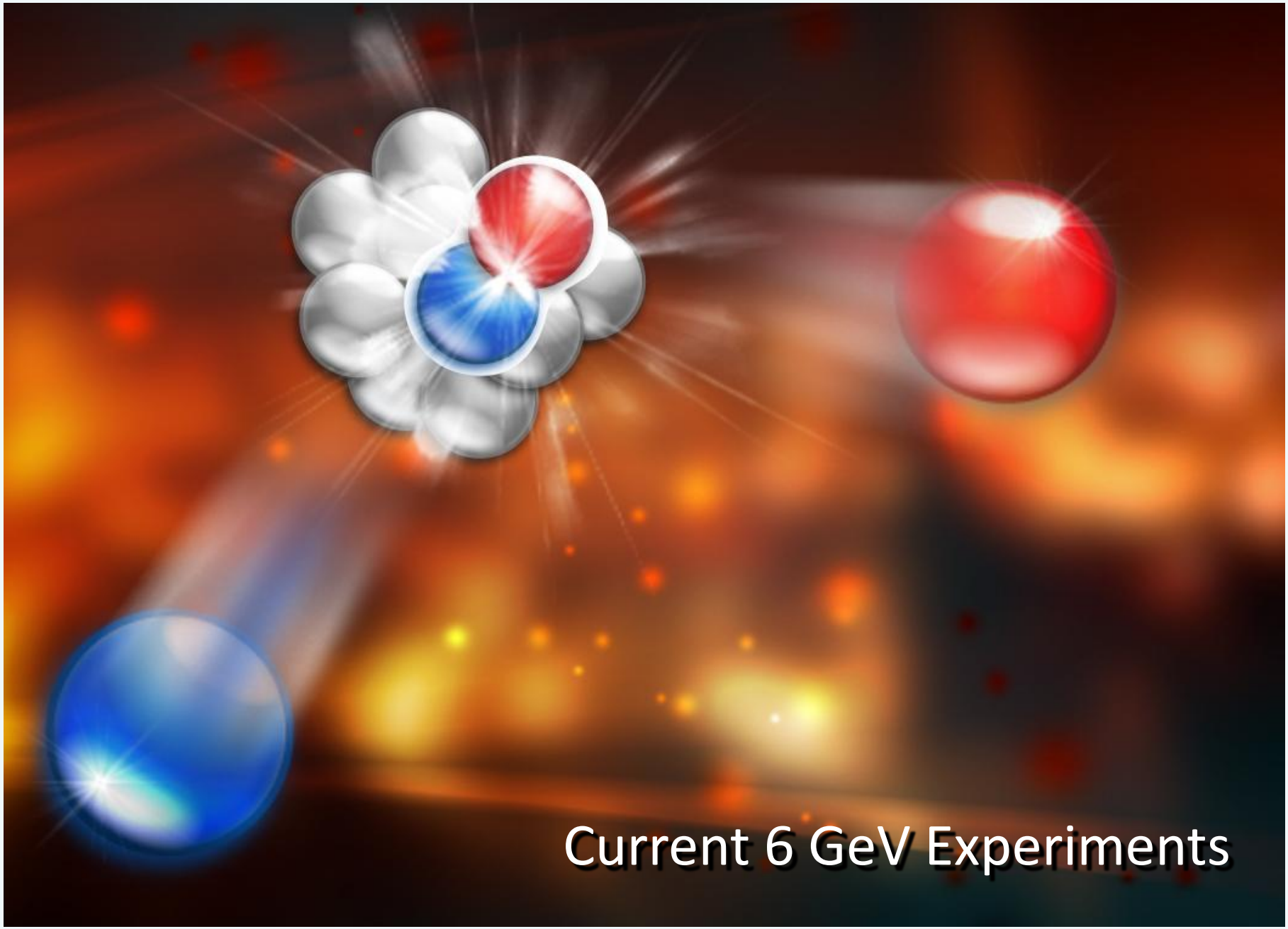
- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - 18% np pairs
  - 1% pp pairs
  - 1% nn pairs (from isospin symmetry)
-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



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.

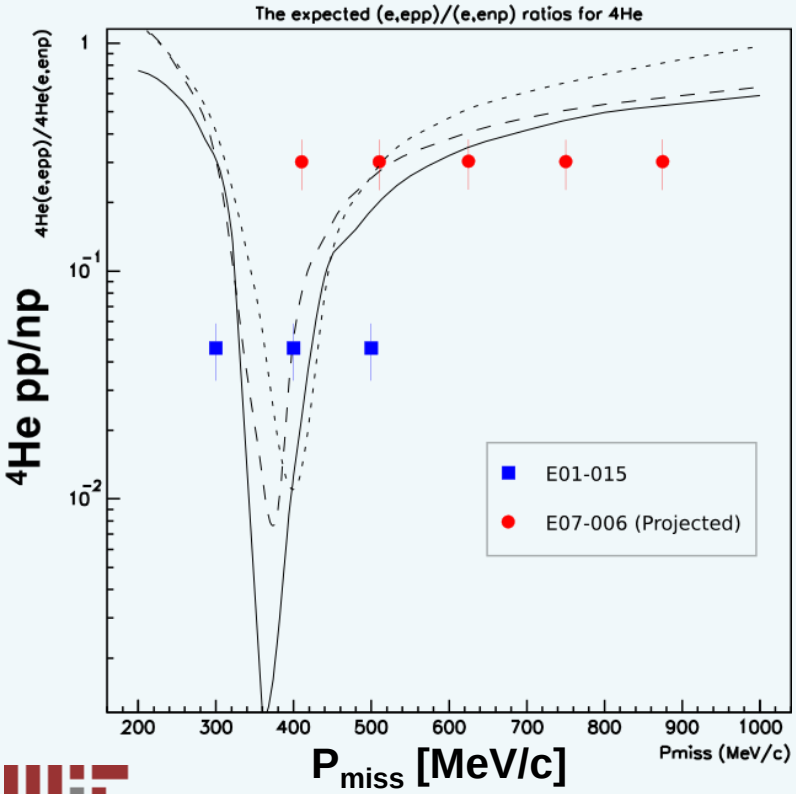


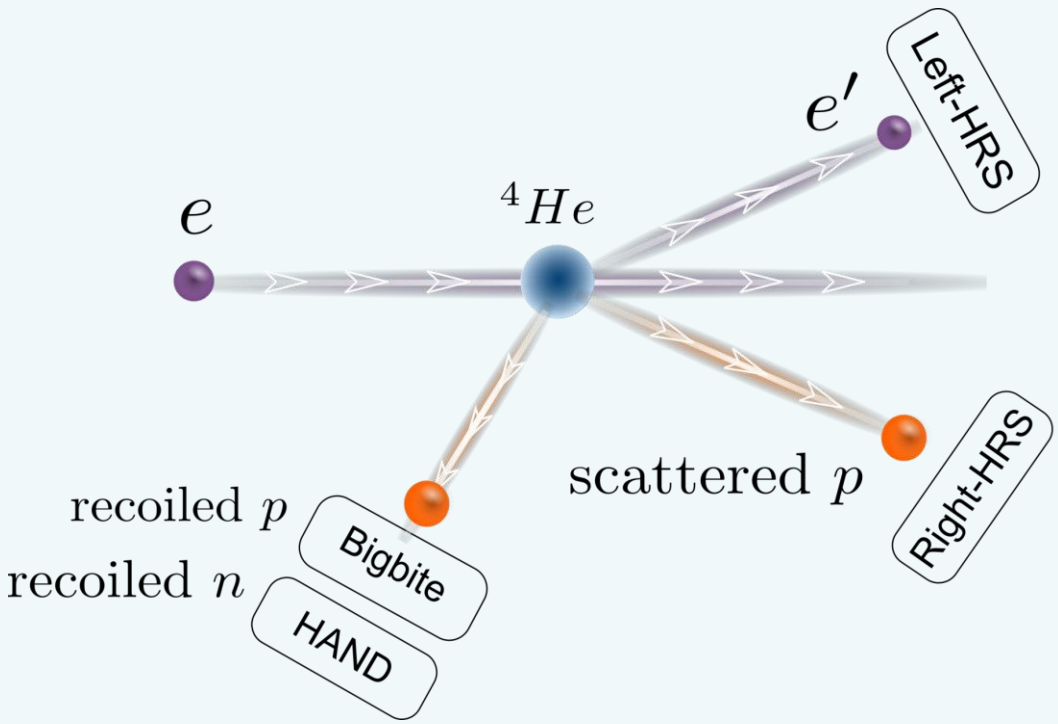
Current 6 GeV Experiments

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

Spokespersons: S. Gilad, D. Higinbotham, E. Piasetzky, **V. Sulkosky** and J. Watson

- ^{4}He Target
  - Dense Nuclear Matter
  - *MF & Exact* Calculations
- P_m from 400 – 900 MeV
- 25 PAC Days



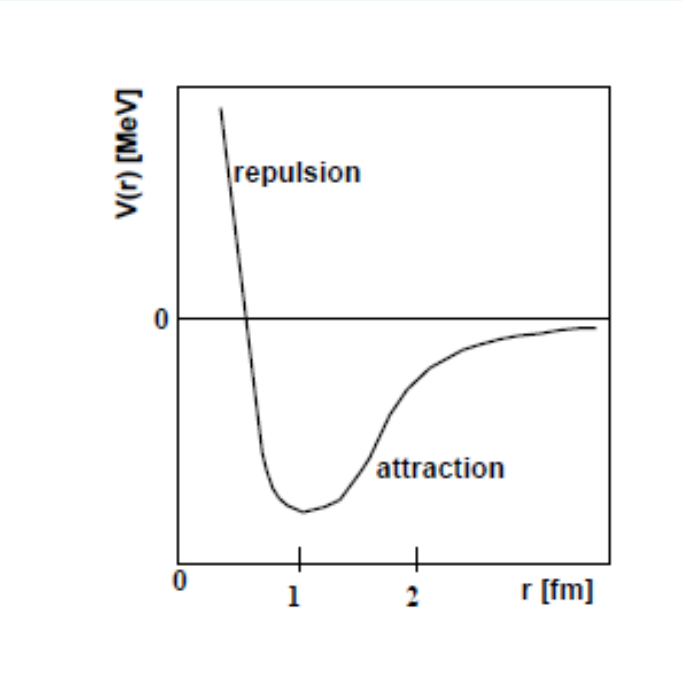


- Pushing Limits of NN Potential
  - Long range attraction
  - Short range repulsion

Experiment E07-006 vs E01-015

Missing momentum 400 – 900 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 – 900 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)



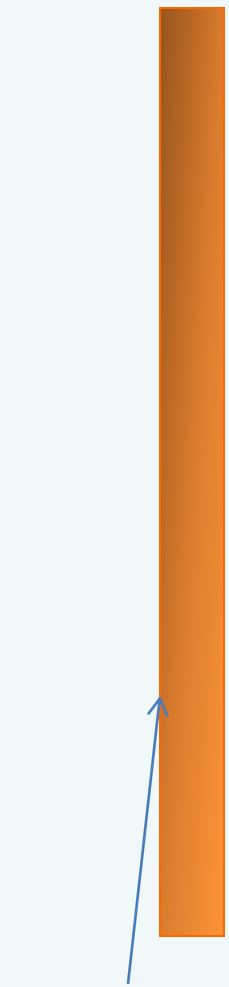
Neuron Array – HAND

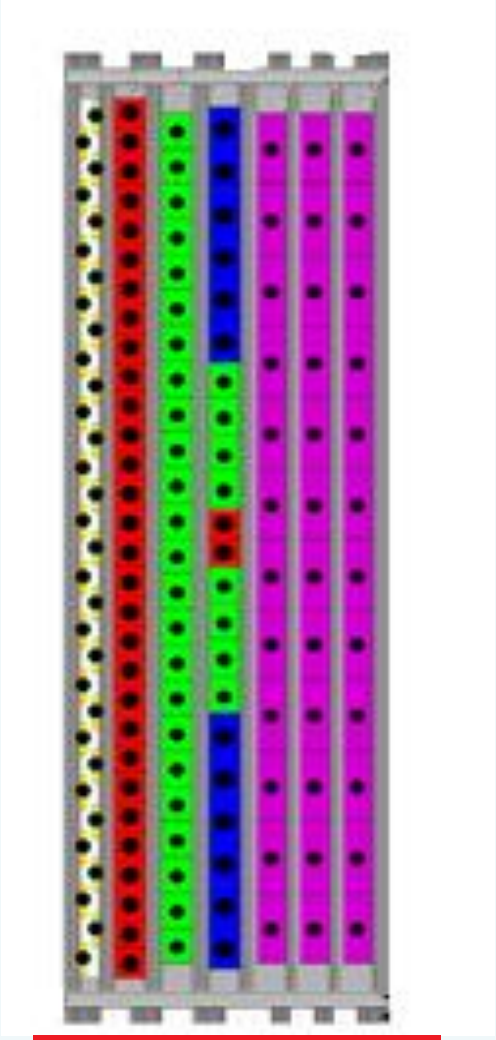
Recoil neutron detection:

- Lead wall
- 64 veto bars
- 112 scintillators

Work completed:

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





Red – 10 cm
Green – 12.5cm
Blue – 15 cm
Purple – 25 cm

Neuron Array – HAND

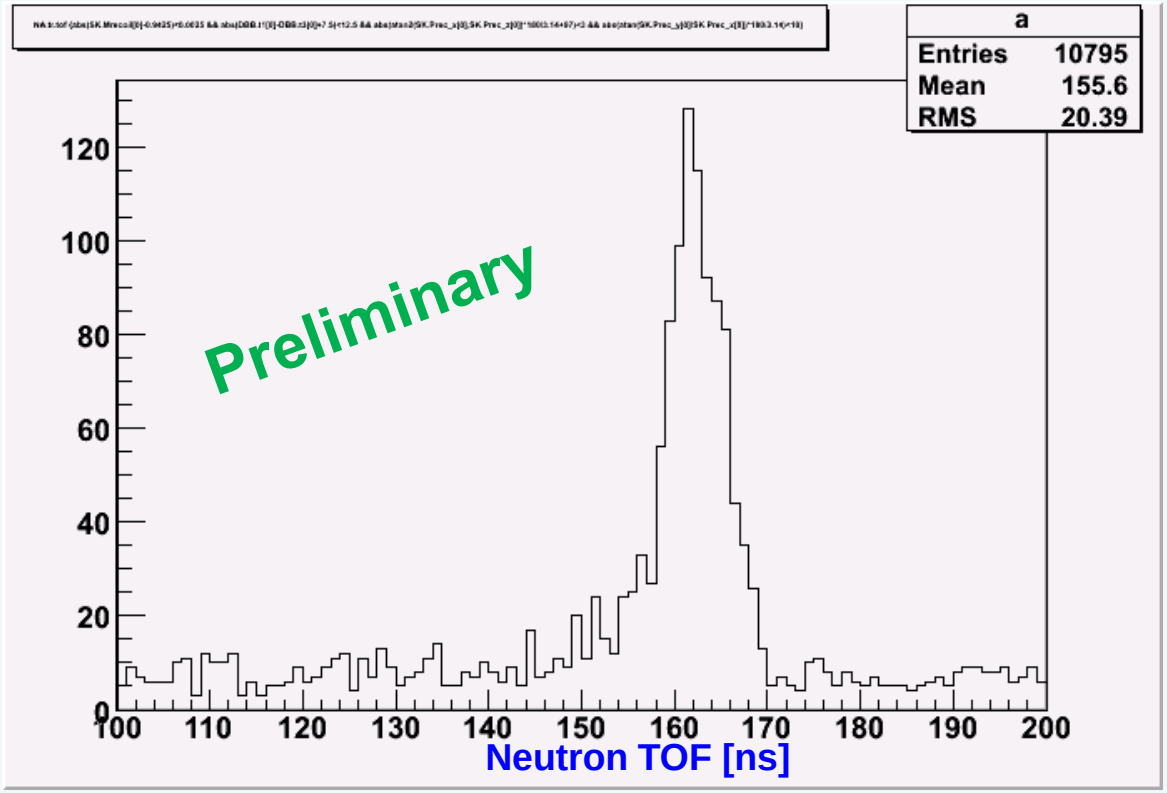
Recoil neutron detection:

- Lead wall
- 64 veto bars
- 112 scintillators

Work completed:

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

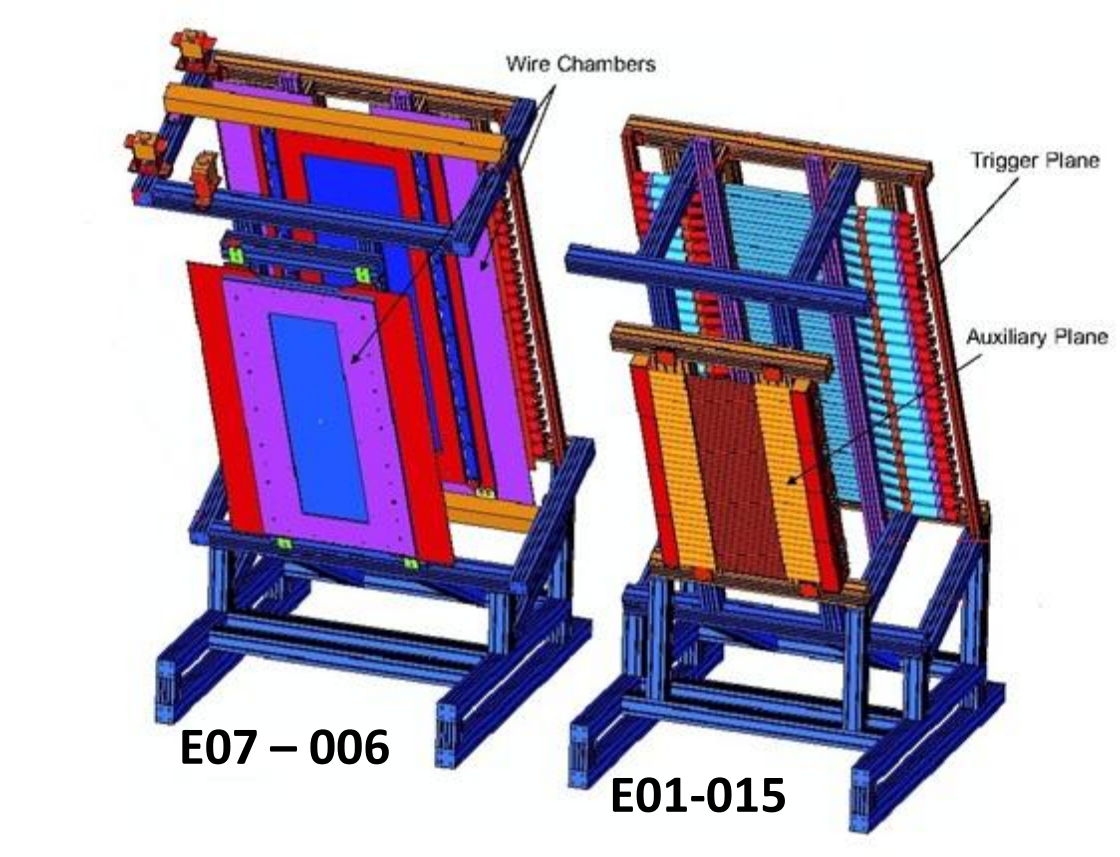
HAND Commissioning Results



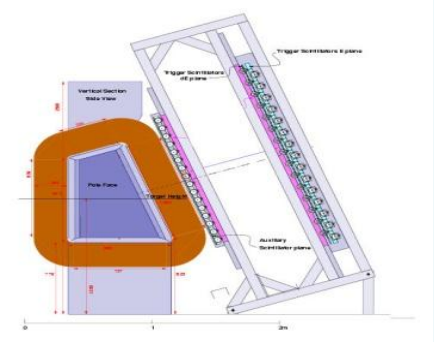
Momentum [MeV/c]	Threshold [mV]	Efficiency [%]
300	-50	10
300	-30	15
400	-30	22

BigBite – Hadron Package

Detection of recoiled protons from SRC pair



Non focusing dipole

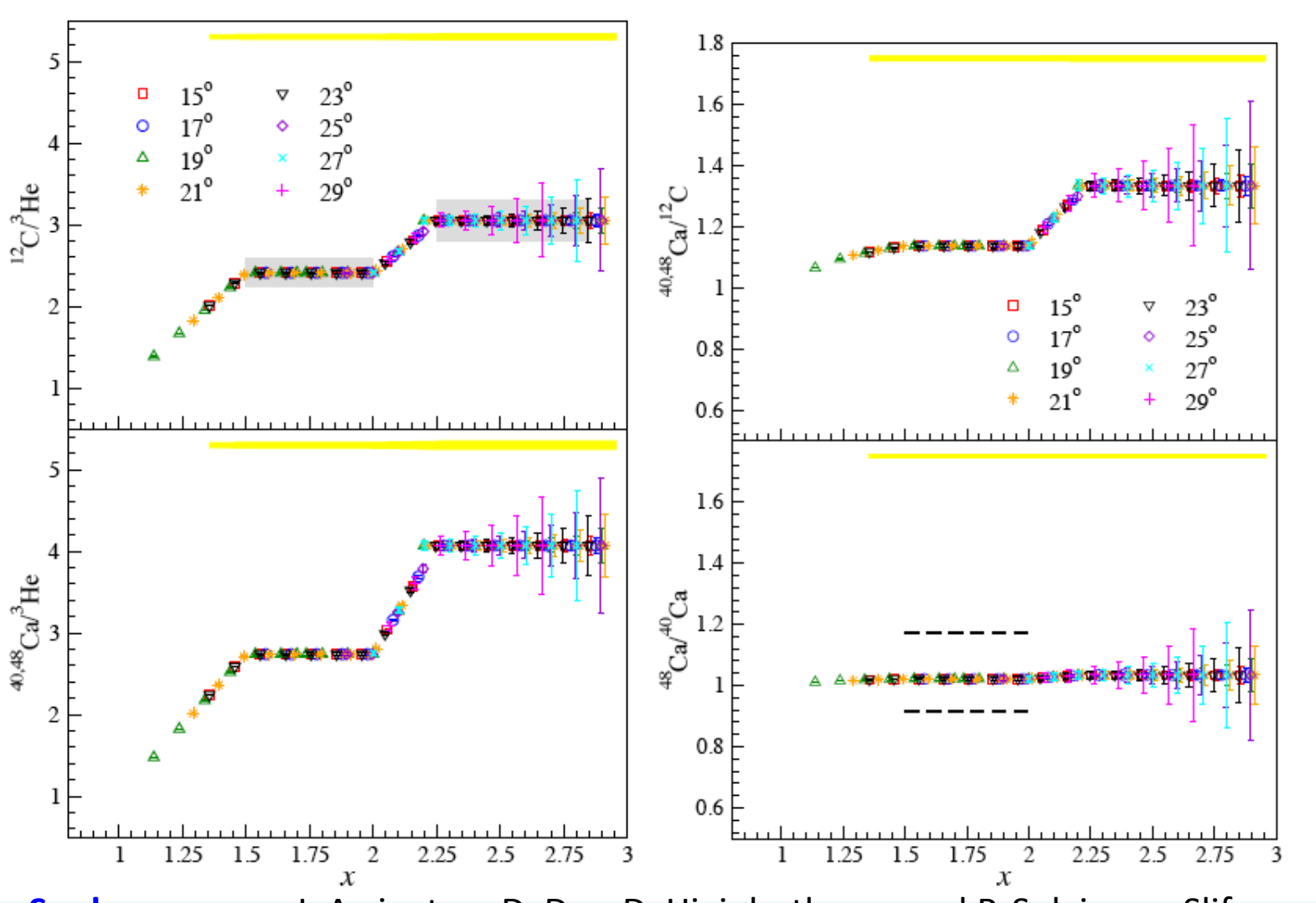


Hadron Package:

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

E08-014: A(e,e') x>2 High Stat. Data

D, ^{3}He, ^{4}He, C, ^{40}Ca, ^{48}Ca Targets **Scheduled April 18th to May 13th 2011**



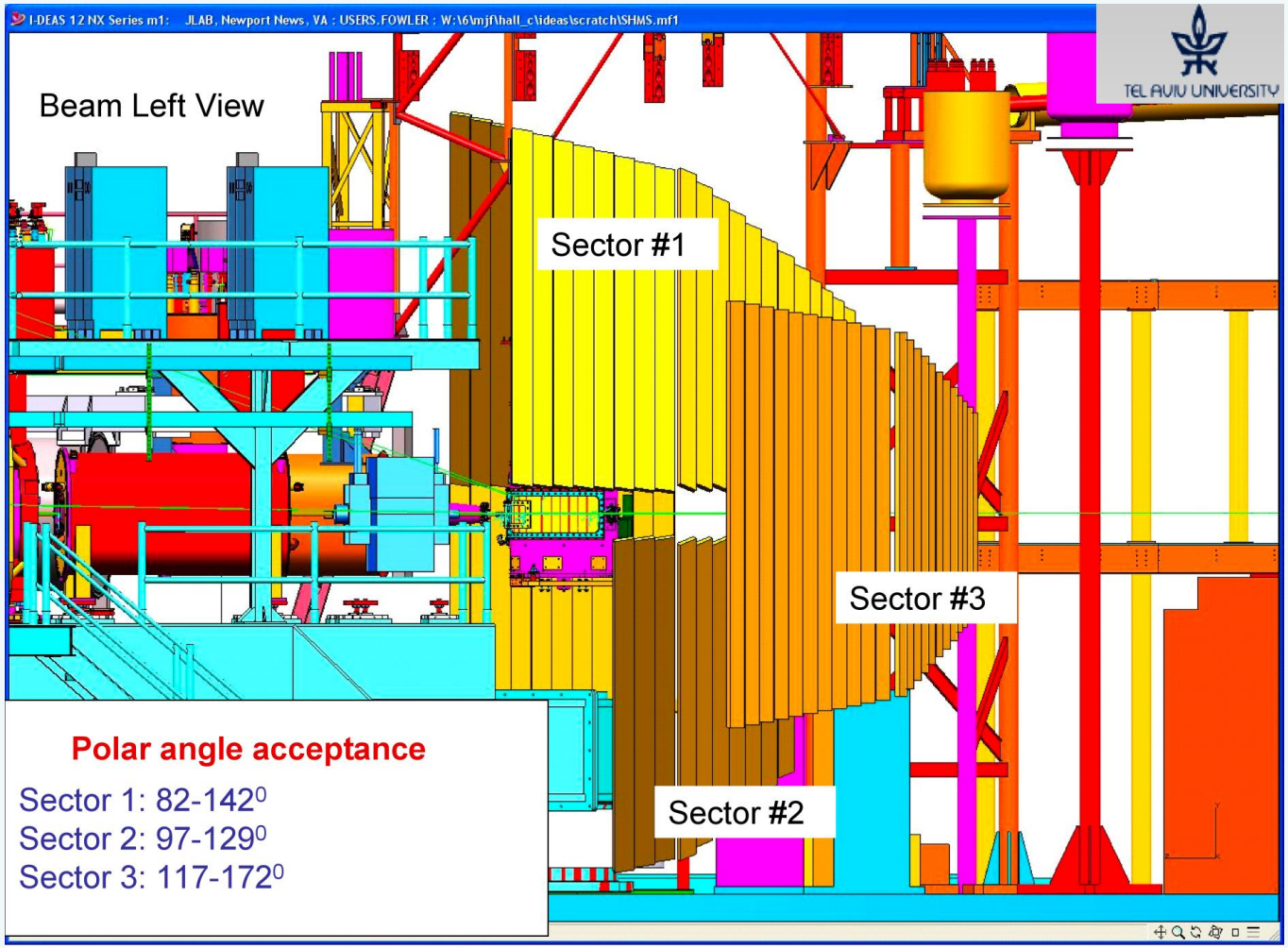
Spokespersons: J. Arrington, D. Day, D. Higinbotham, and P. Solvignon-Slifer

Future 12 GeV Experiments

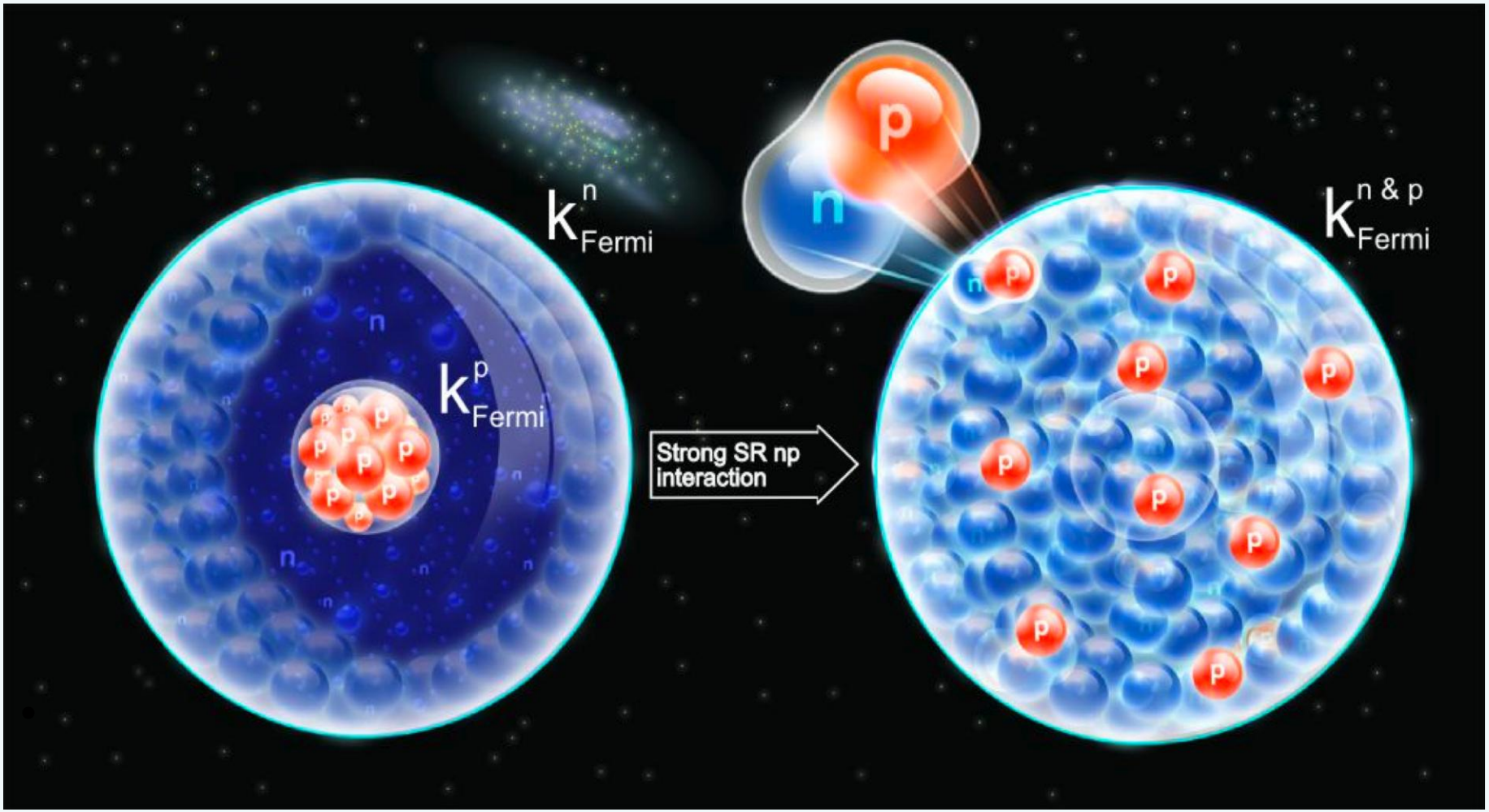
New Idea: Large Acceptance Device

Letter of Intent at Jefferson Lab Program Advisory Committee Meeting (PAC 35)

Spokespersons: D. Higinbotham, R. Shneor, **V. Sulkosky** and J. Watson



Implications for Neutron Stars



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

Summary and Outlook

- Shell Model (the mean behavior of nucleons in nucleus)
- 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, $x_B>1$ and $Q^2>1$ $[GeV/c]^2$ we seem to finally be cleanly probing 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.
- With the JLab 12 GeV upgrade, high Q^2 $[GeV/c]^2$ in $x>1$ kinematics, the experiments will push the limits of modern NN potentials and enhance our understanding of the nature of these correlations.

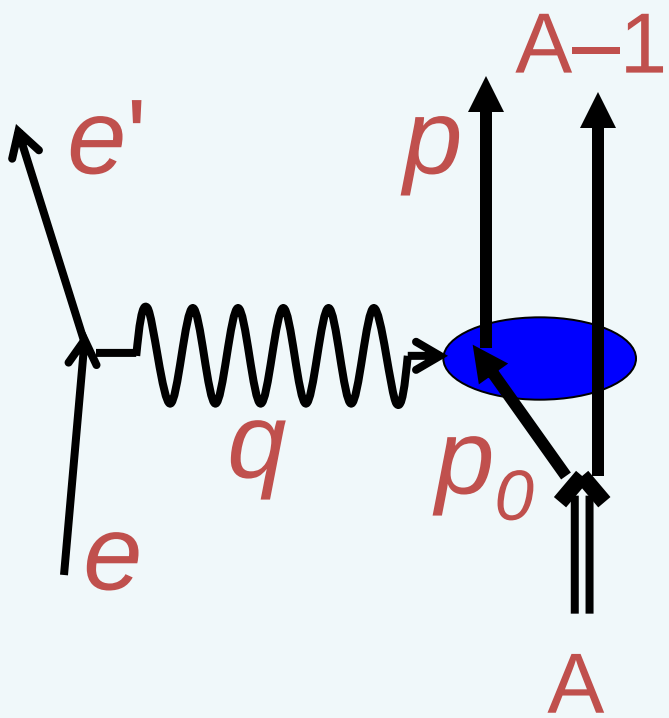
Acknowledgements

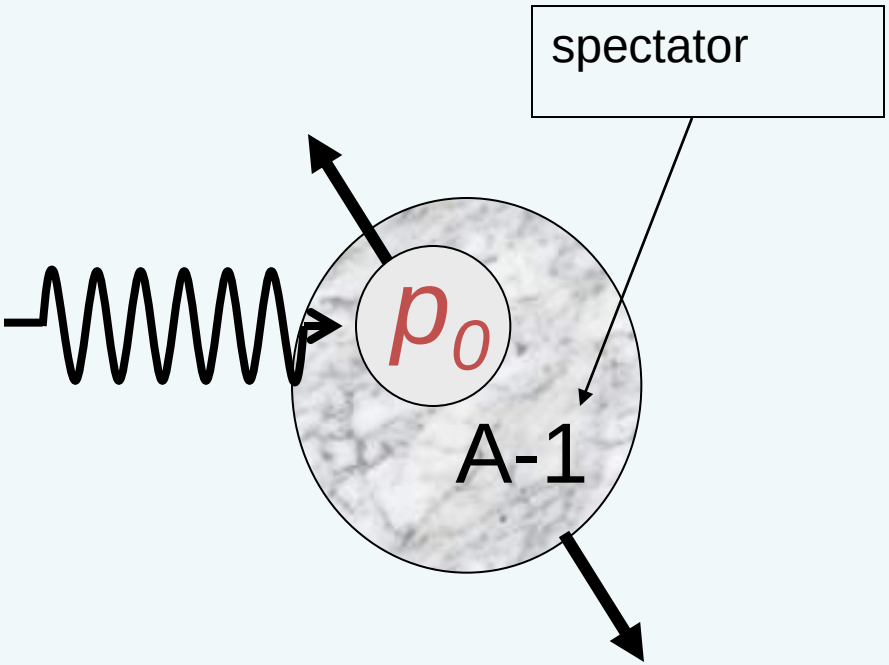
- **Spokespersons**:
  - Shalev Gilad (MIT)
  - Douglas Higinbotham (JLab)
  - Eli Piasetzky (Tel Aviv)
  - Vincent Sulkosky (MIT)
  - John Watson (Kent State)
- **Postdocs**:
  - Aidan Kelleher (MIT)
  - Charles Hanretty (Uva)
  - Ran Shneor (Tel Aviv)
- **Graduate Students**:
  - David Anez (Saint Mary's)
  - Or Chen (Tel Aviv)
  - Igor Korover (Tel Aviv)
  - Navaphon (Tai) Muangma (MIT)
  - Larry Selvy (Kent State)
  - Zhihong Ye (Uva)

Thank You!

Simple Theory Of Nucleon Knock-out

Plane Wave Impulse Approximation (PWIA)





$$\boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{A\text{-}1} = \boldsymbol{p}_m = -\boldsymbol{p}_0$$

Spectral Function

In nonrelativistic PWIA:

$$\frac{d^6\sigma}{d\omega d\Omega_e dp d\Omega_p} = K \sigma_{ep} S(p_m, \varepsilon_m)$$

e-p cross section

nuclear spectral function

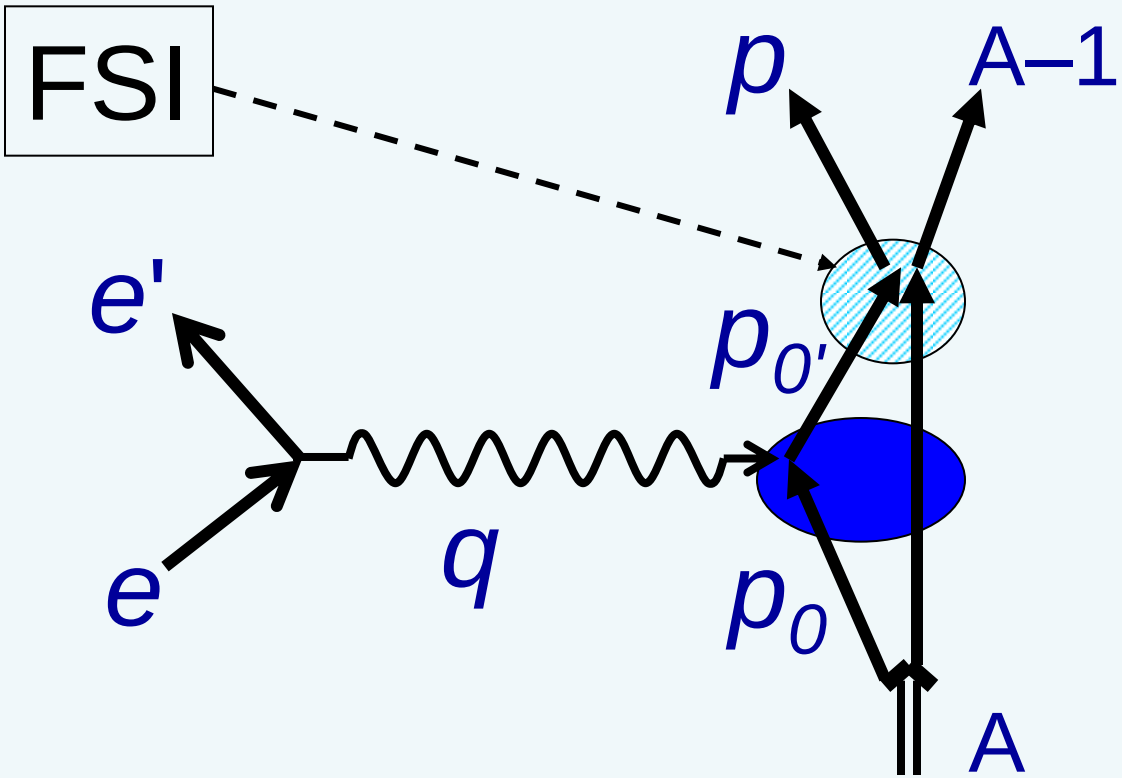
For bound state of recoil system:

proton momentum distribution

$$\rightarrow \frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} = K' \sigma_{ep} \left|\Phi(p_m)\right|^2$$

Reaction Mechanisms

Example: Final State Interactions (FSI)



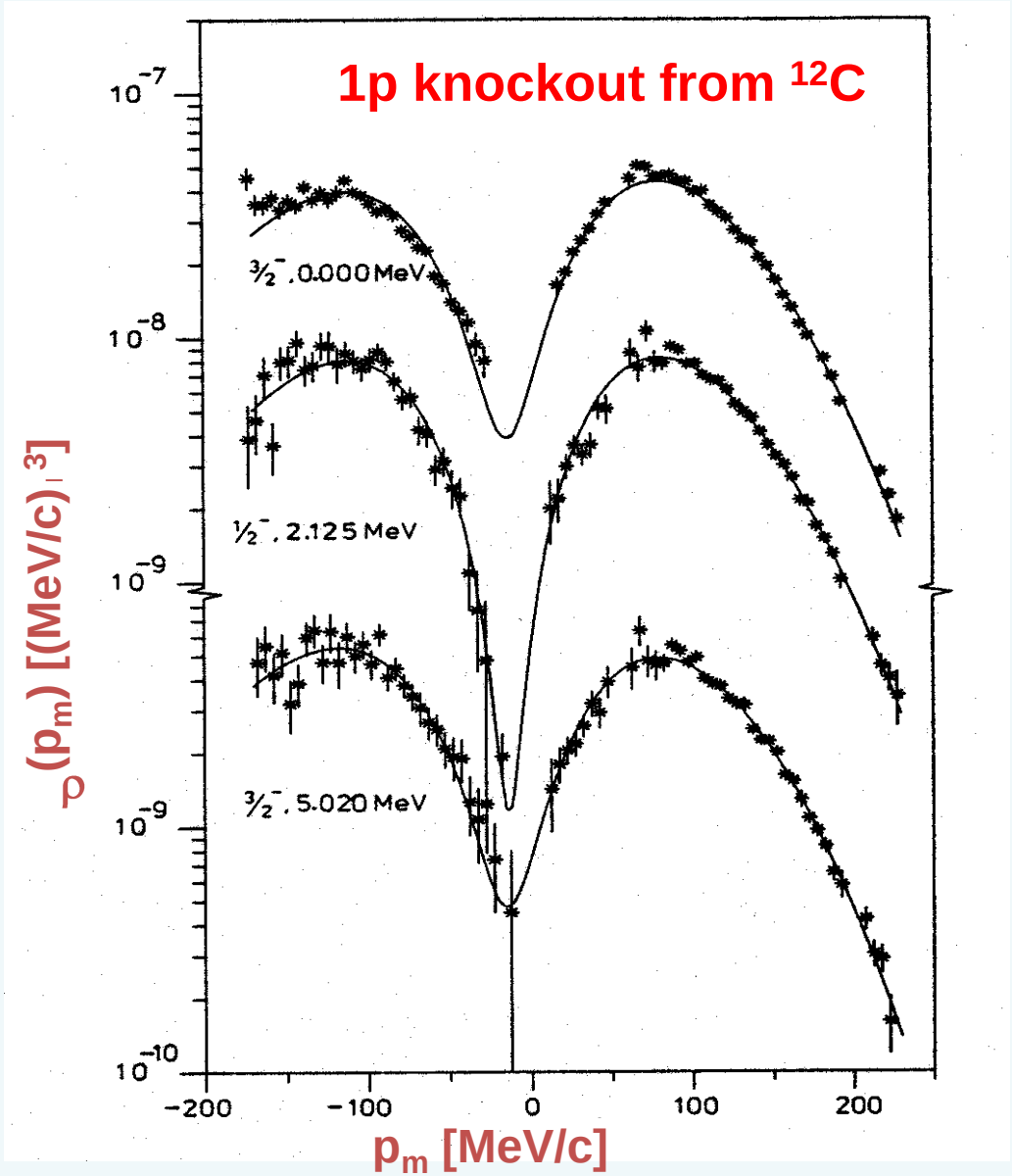
$$\vec{q} - \vec{p} = \vec{p}_{A-1} \neq \vec{p}_0$$

Improve Theory

Distorted Wave Impulse Approximation (DWIA)

$$\frac{d^6\sigma}{d\Omega_e d\Omega_p dp d\omega} = K\,\sigma_{ep}\,\boxed{S^D(p_m, \varepsilon_m, p)}$$

"Distorted" spectral function



$^{12}C(e,e'p)^{11}B$

DWIA calculations give correct shapes, but:

Missing strength observed.

NIKHEF

G. van der Steenhoven, *et al.*, Nucl. Phys. **A480**, 547 (1988).

Inclusive scattering at large x

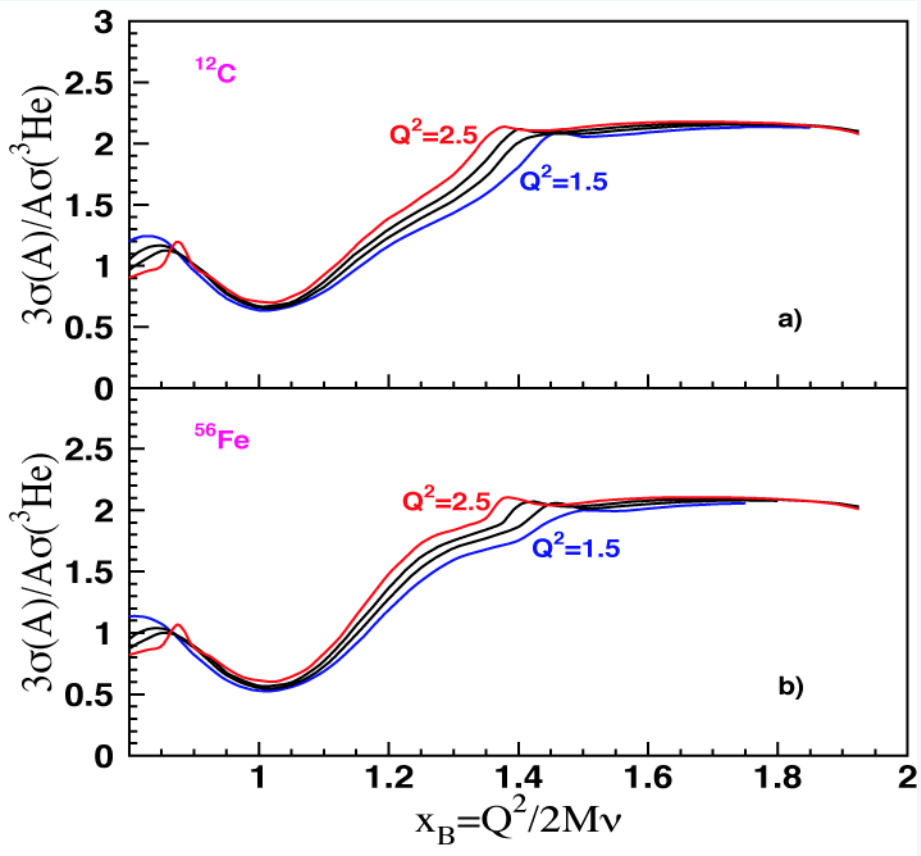
Define y as the x_B-value at which the minimum p_{miss} exceeds p_{Fermi}

SRC model predicts:

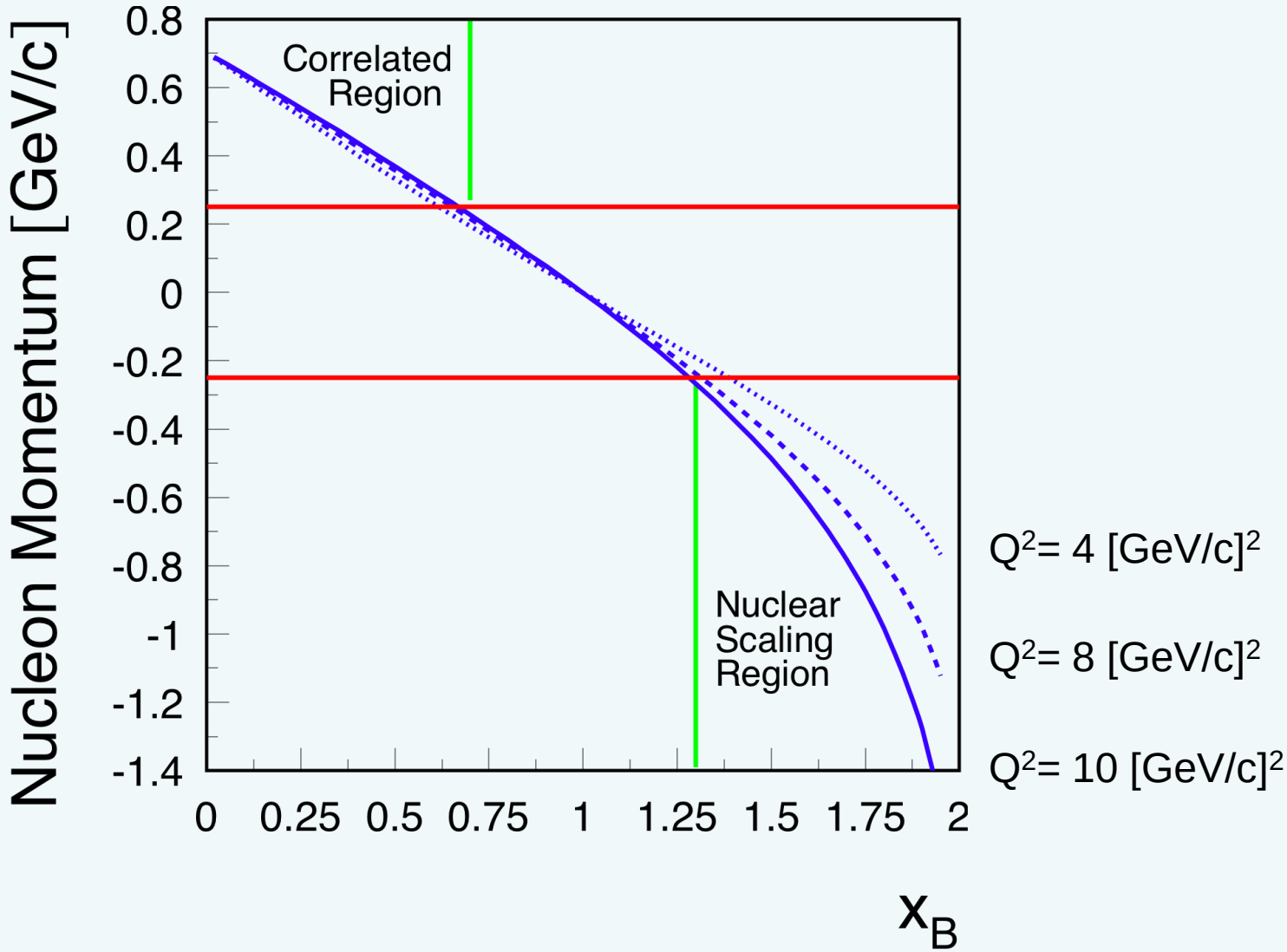
- Scaling for $x_B > y$ and $Q^2 > 1.5$ GeV^2
- No scaling for $Q^2 < 1$ GeV^2
- In scaling regime ratio Q^2-independent and only weakly A-dependent

Glauber Approximation predicts:

- No scaling for $x_B < 2$ and $Q^2 > 1$ GeV^2
- Nuclear ratios should vary with A and Q^2

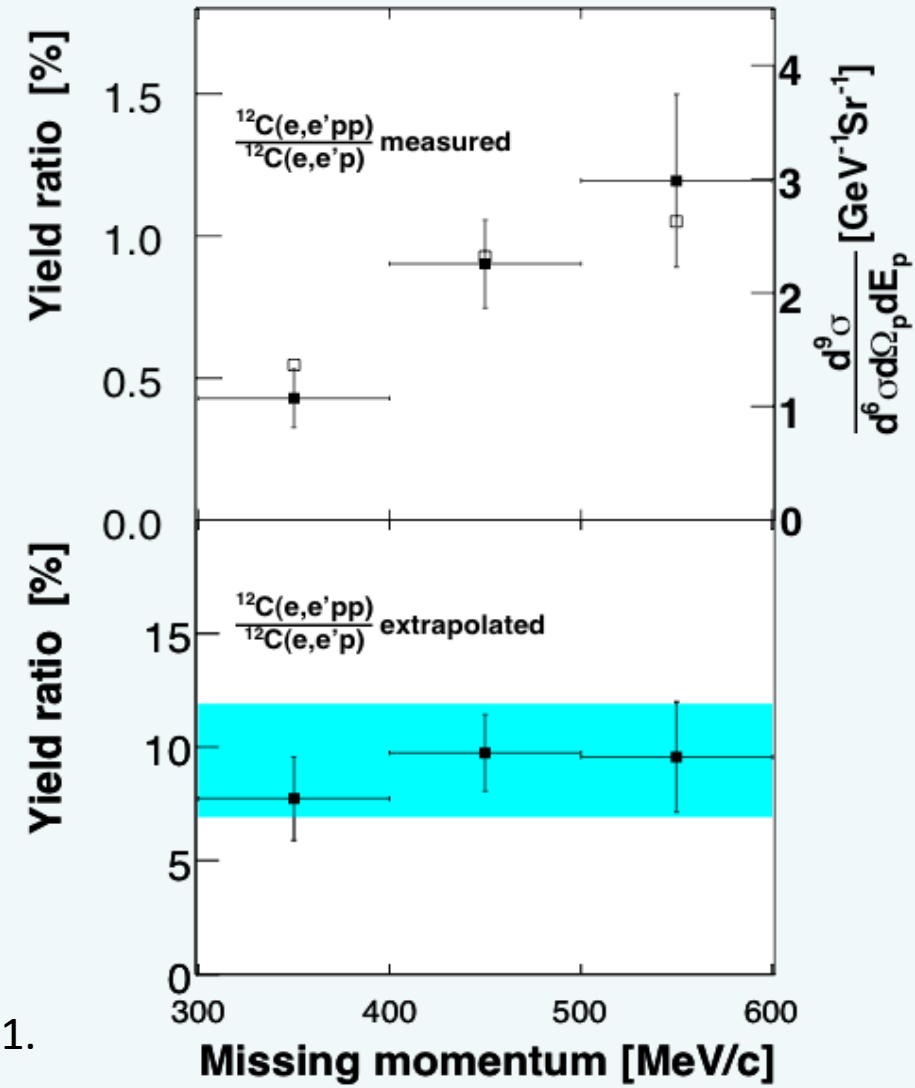


D(e,e')pn Reaction As Function of x_B



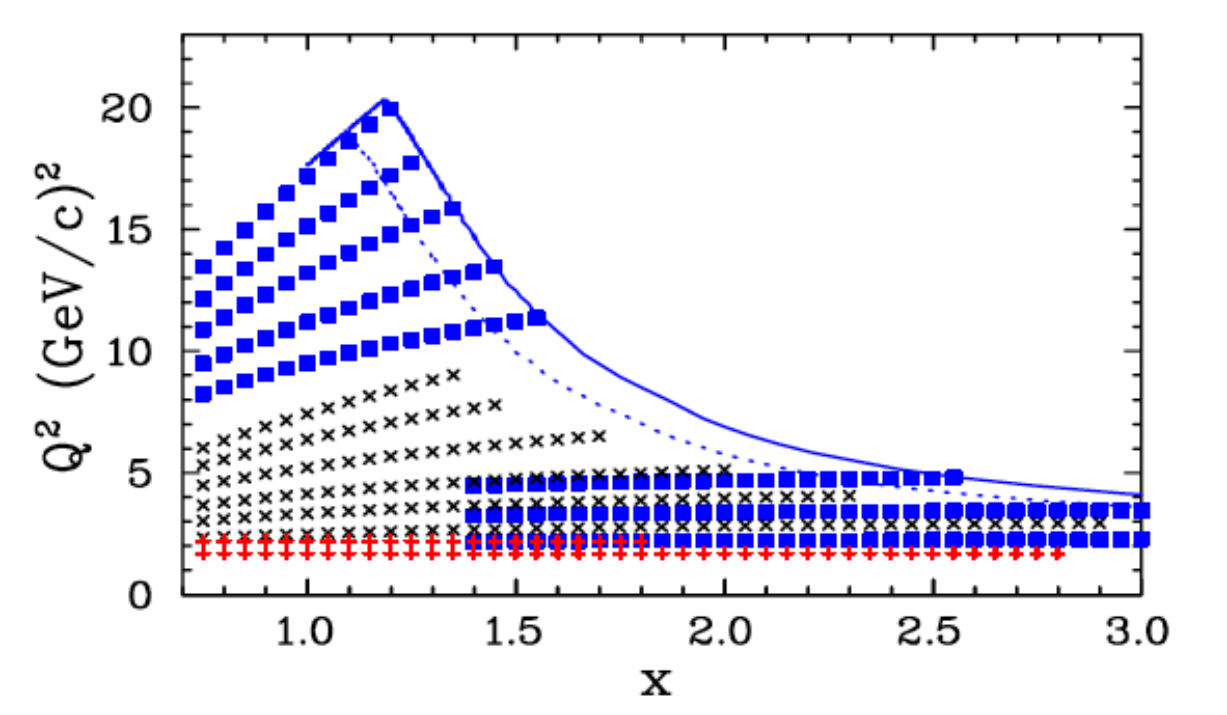
Ratio of $^{12}C(e,e'pp)$ to $^{12}C(e,e'p)$

- Top plot shows the raw measured ratio
- Bottom plot shows the extrapolated where the finite acceptance of BigBite and pair center of mass motion has been taken into account.
- Determined pair cm motion to be 136+/-20 MeV/c and blue band indication two-sigma around this value.
- Note Brookhaven found 143+/-17 MeV/c



R. Shneor *et al.*, Phys. Rev. Lett. **99** (2007) 072501.

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

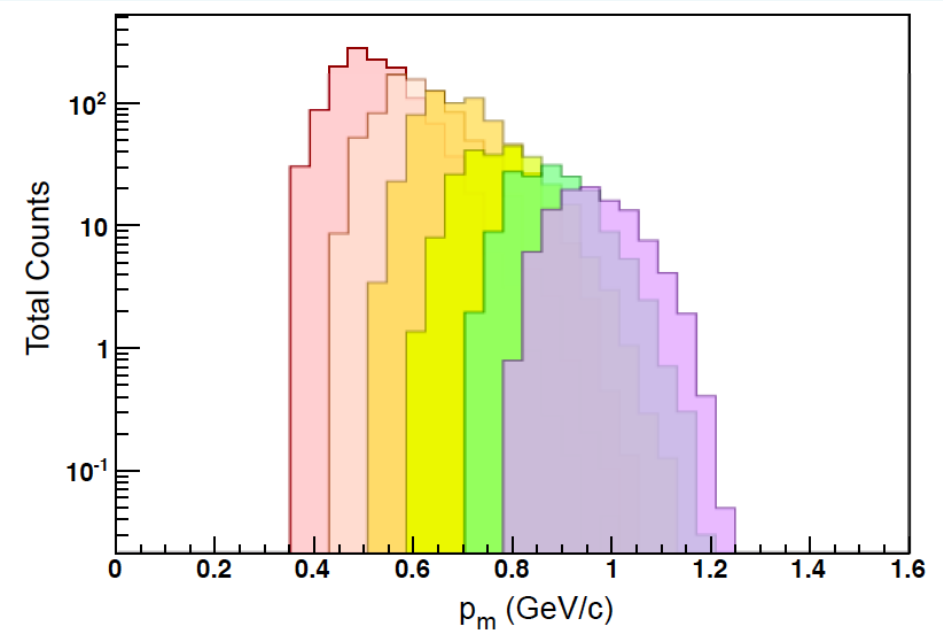


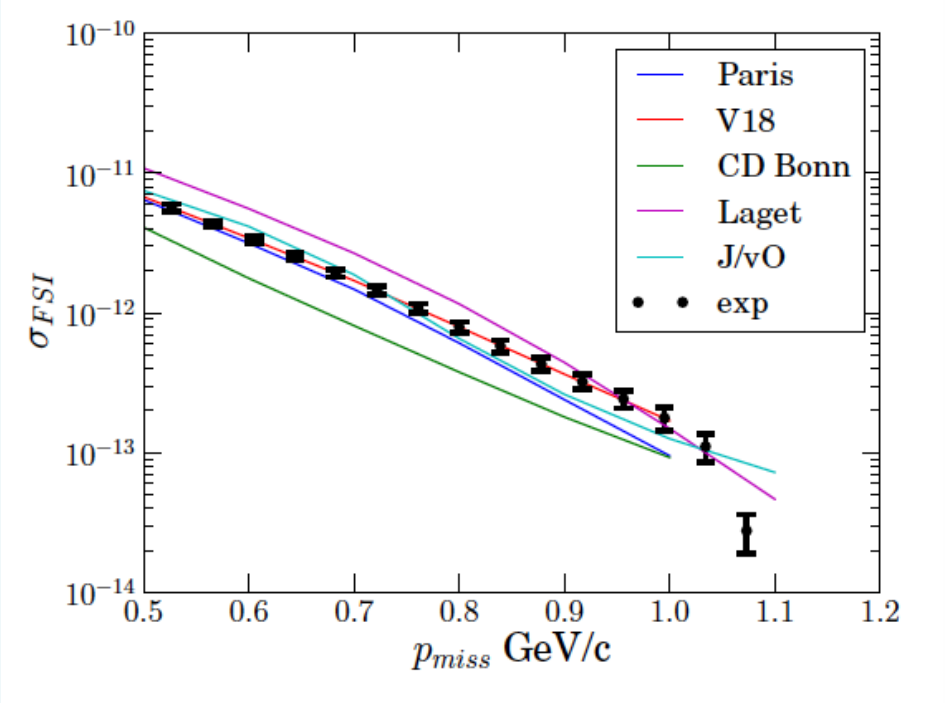
Red is the range of CLAS Data
Black is the range of 6 GeV Data
Blue is 11 GeV Proposed Data
Solid Line = 10% Uncertainty;
Dashed Line = 5% Uncertainty

- With 11 GeV Beam:
  - Verify the relative strength of 3N correlations in a variety of nuclei: H, D, ^{3}He, ^{4}He, Be, Cu and Au.
  - Make improved measurements up to x = 3.
  - Observe possible dominance of scattering from alpha-clusters (4N correlations).
  - Study parton distributions at x > 1 (superfast quarks in nuclei).

PR12-10-003: D(e,e'p)n at x>1, Q^2=4 GeV/c

21 PAC Days, 11 GeV beam and Hall C with 6 settings of the spectrometers





^{3}He(e,e'p)d deviated from conventional theory at around 800 MeV/c

Making BigBite & Neutron Detector

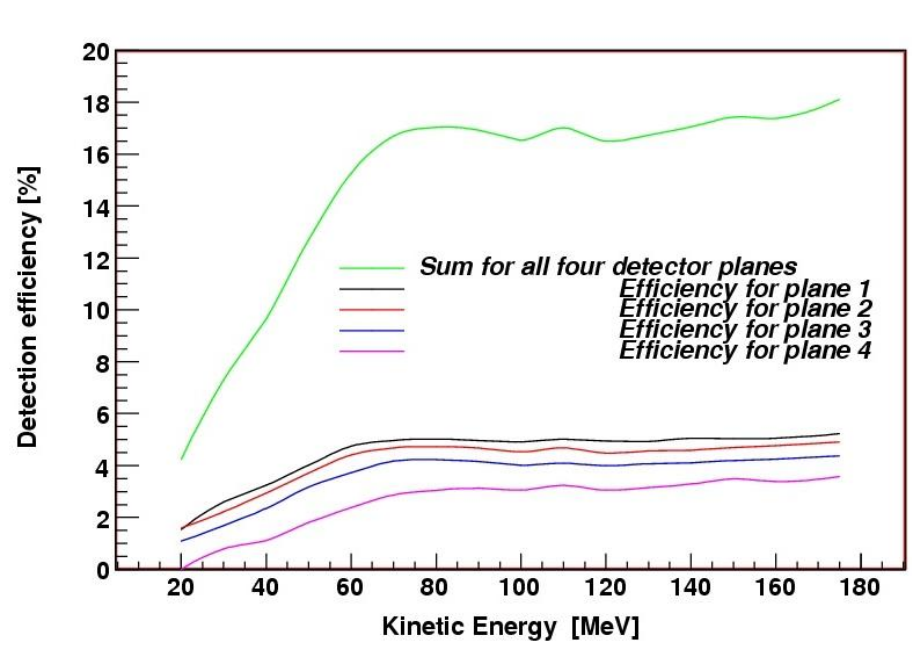
- JLab from NIKHEF – BigBite Magnet
- Tel Aviv - Auxiliary Plane
- Glasgow - Trigger Plane
- UVa MRI - Scattering Chamber
- Kent State – Most of the Neutron Detectors
- Wire Chambers also from UVa MRI

HAND Detection Efficiency

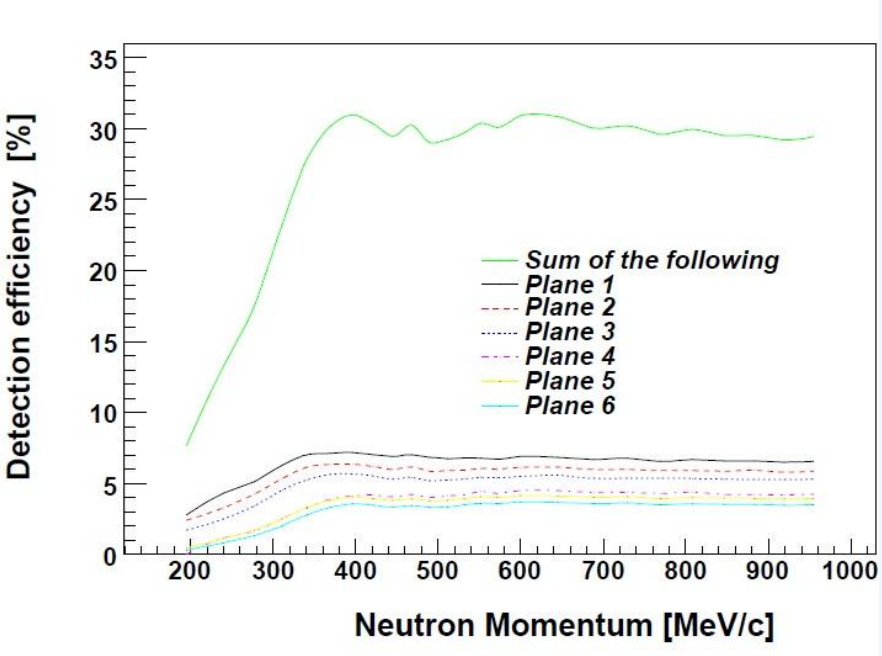
- Two additional Layers in HAND
- Lead wall:
  2.5 cm lead instead of 5 cm lead + 2.5 cm Fe

→ **Increased neutron detection efficiency**

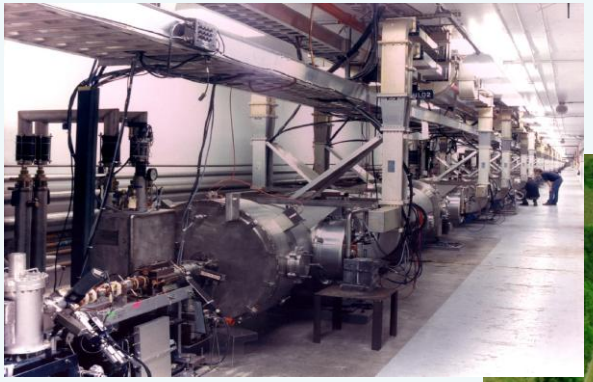
E01-015

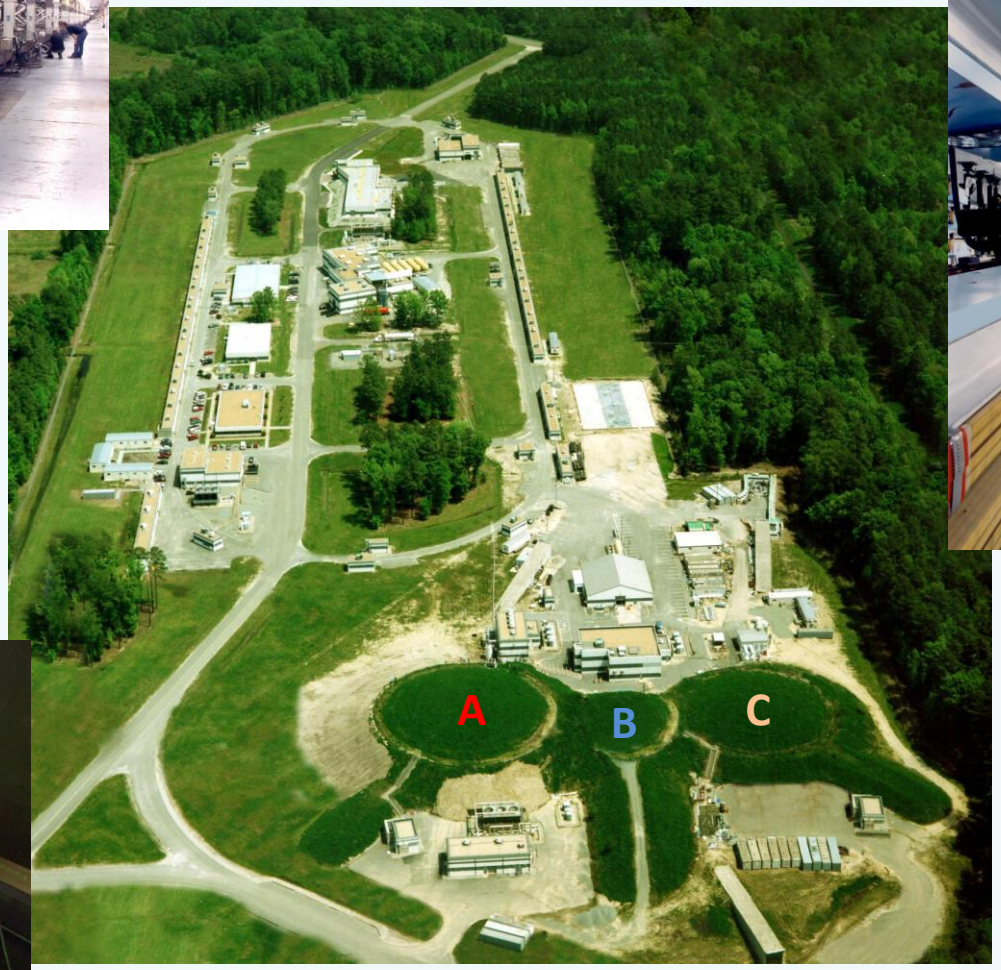


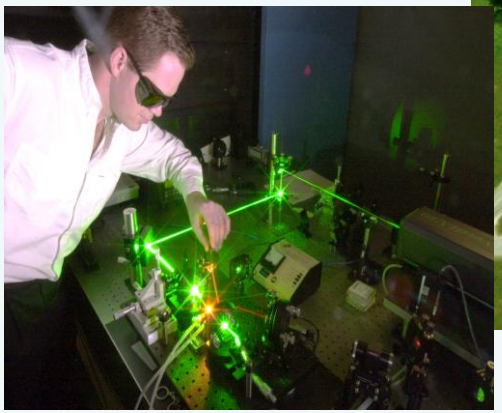
E07-006



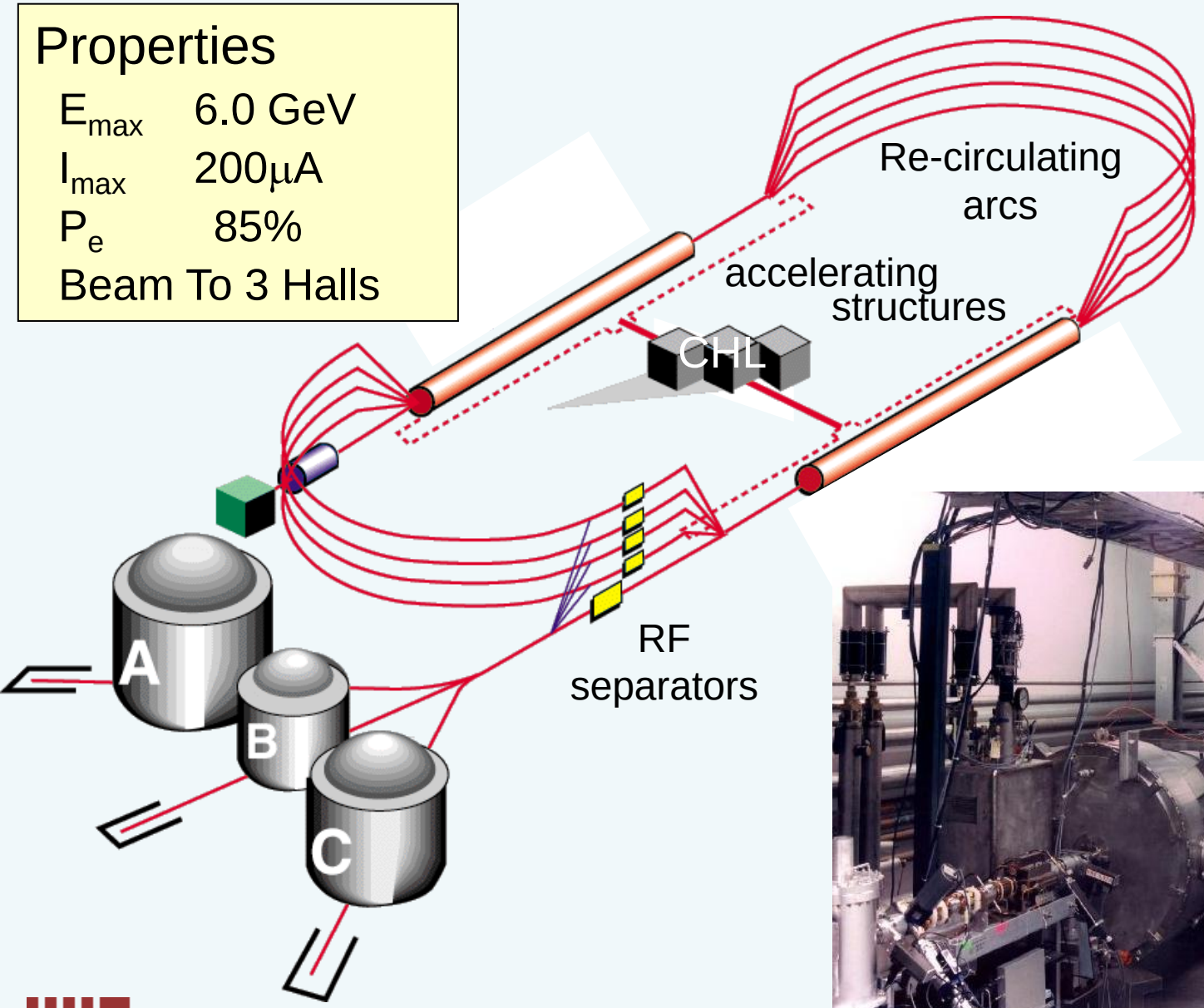
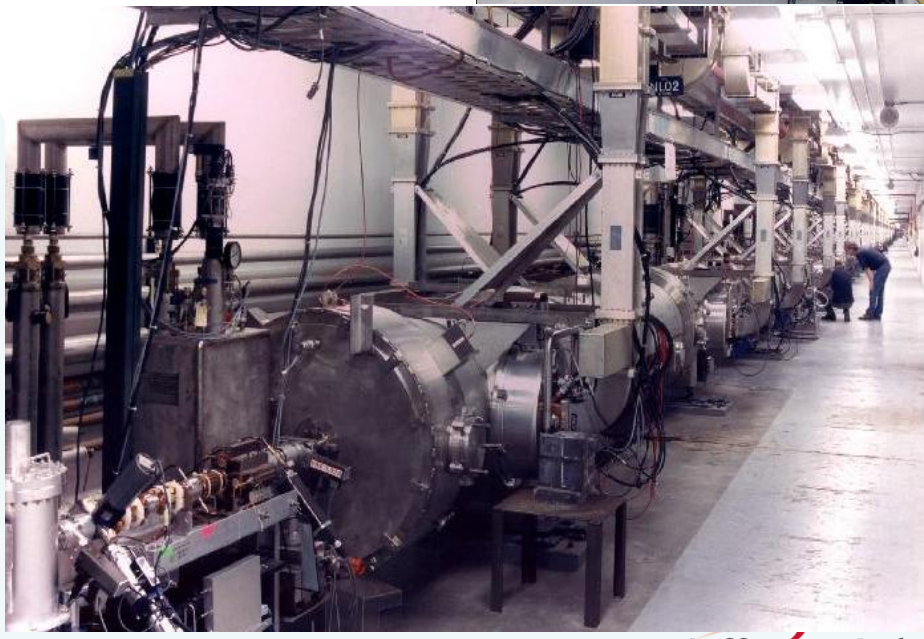
Jefferson Lab CEBAF







CEBAF: Continuous Electron Beam Accelerator Facility

Properties

E_{max}	6.0 GeV
I_{max}	200μA
P_e	85%
Beam To 3 Halls