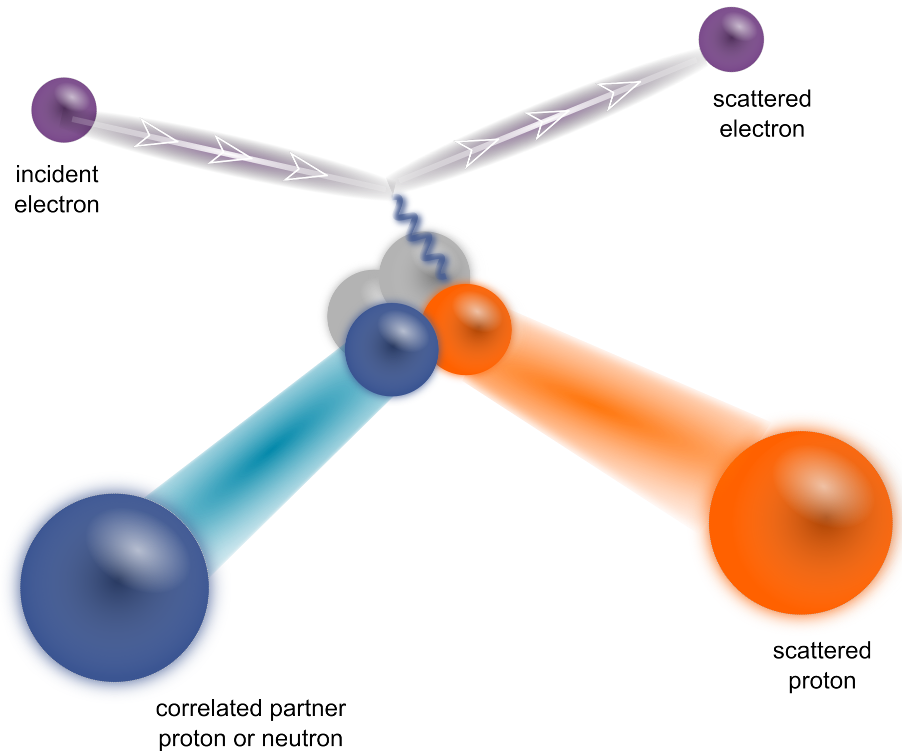
Short-Distance Structure of the Nucleus



Vincent Sulkosky

Longwood University

Physics Department Seminar

April 7th, 2014

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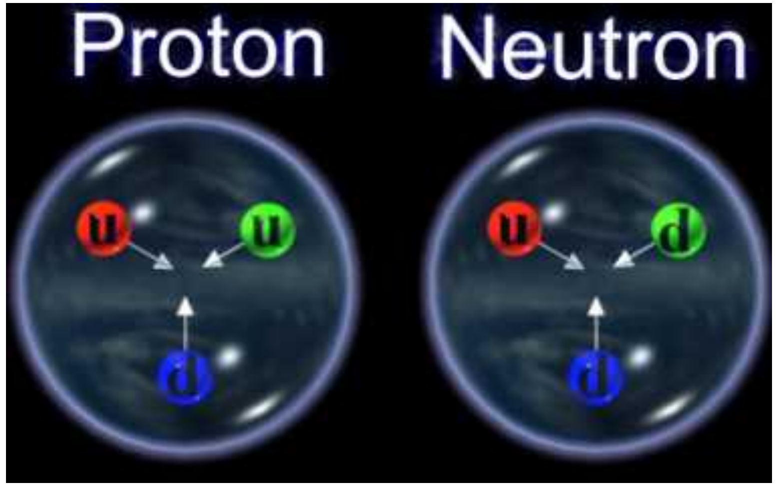
Outline

- 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 Quarks



Nucleons: (Protons and Neutrons)
Building blocks of visible matter
Composed of quarks (bricks) and gluons (mortar).
Structure mostly governed by the strong nuclear force, i.e., **nucleons are a "natural laboratory" to study this interaction**.

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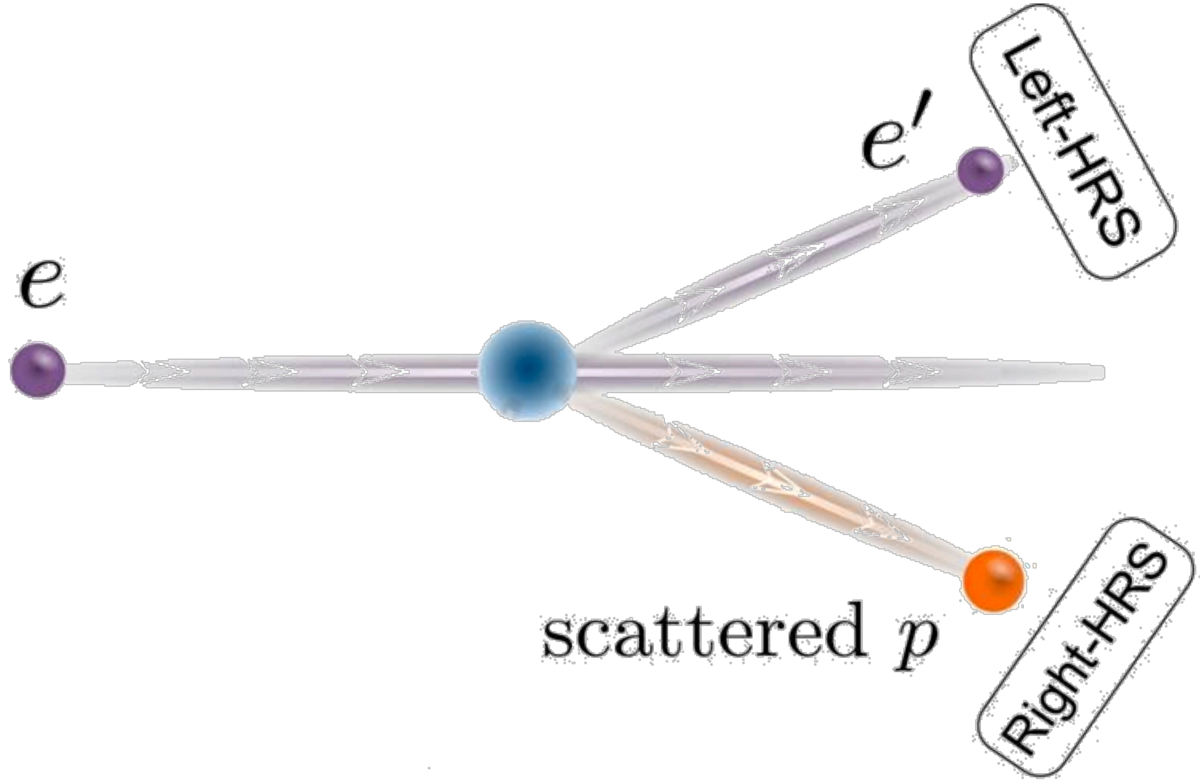
Nucleons in the Nucleus

• How do free nucleons differ from those in nuclei?
• Does the interplay between the attractive long-range 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 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.

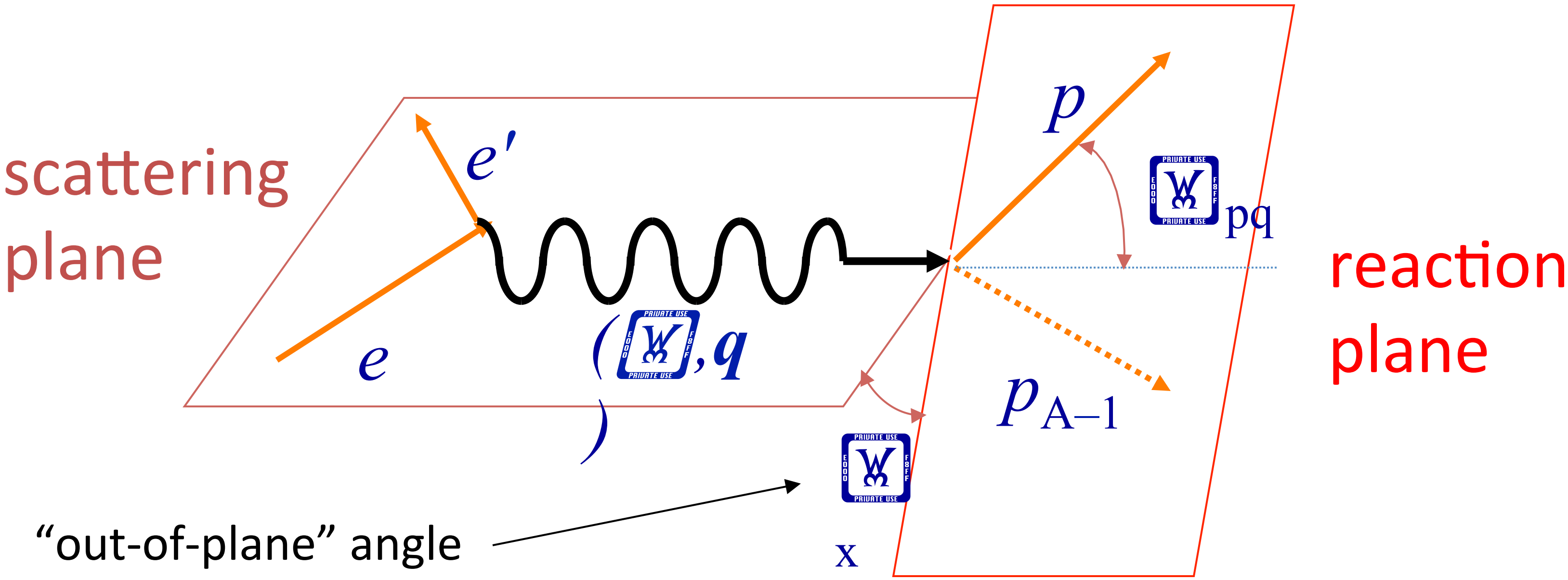
Tools of the Trade

Electron Scattering



Target: electron, proton, or nucleus such as helium or carbon

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



Four-momentum transfer squared: Q^2 [illegible] $- q_{[illegible]} q^{[illegible]} = \mathbf{q}^2 -$ [illegible] ^{2}

Missing momentum: $\mathbf{p}_m = \mathbf{q} - \mathbf{p} = \mathbf{p}_{A-1}$

Difference between transferred and detected momentum

Missing energy: [illegible]$_m =$ [illegible] $- T_p - T_{A-1}$

Difference between transferred and detected energy

Bjorken x: $x_B = Q^2/2m$[illegible] ***(just kinematics!)***

Counts minimum number of nucleons involved

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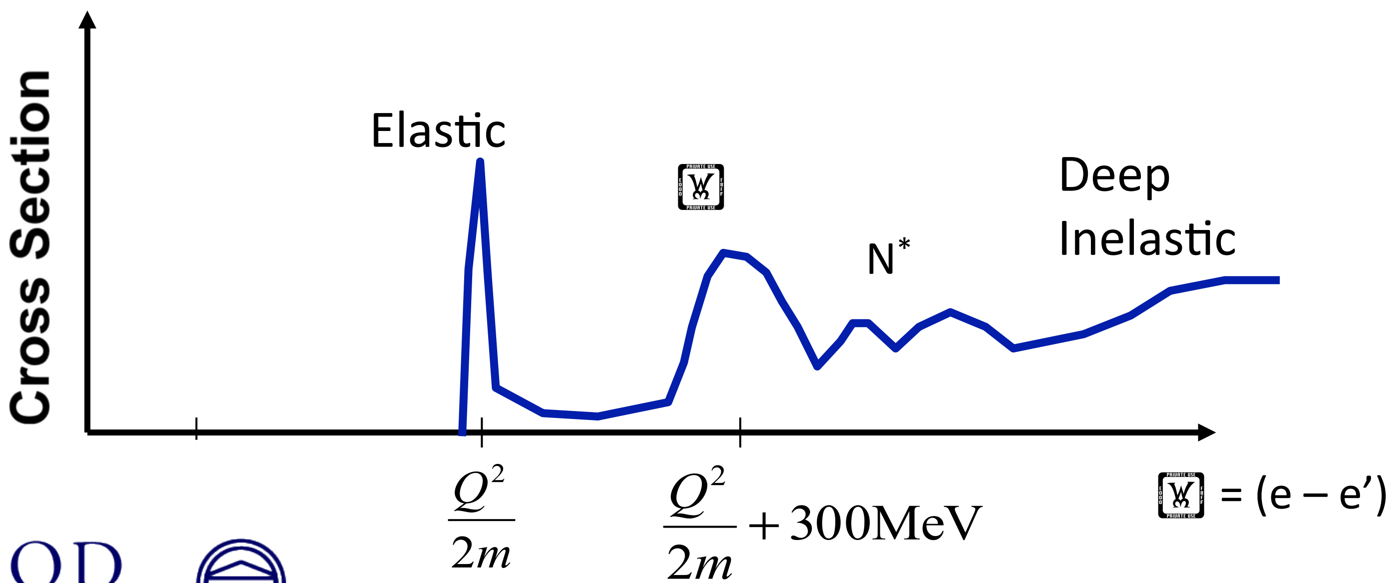
Electron Scattering at Fixed Q^2



Proton

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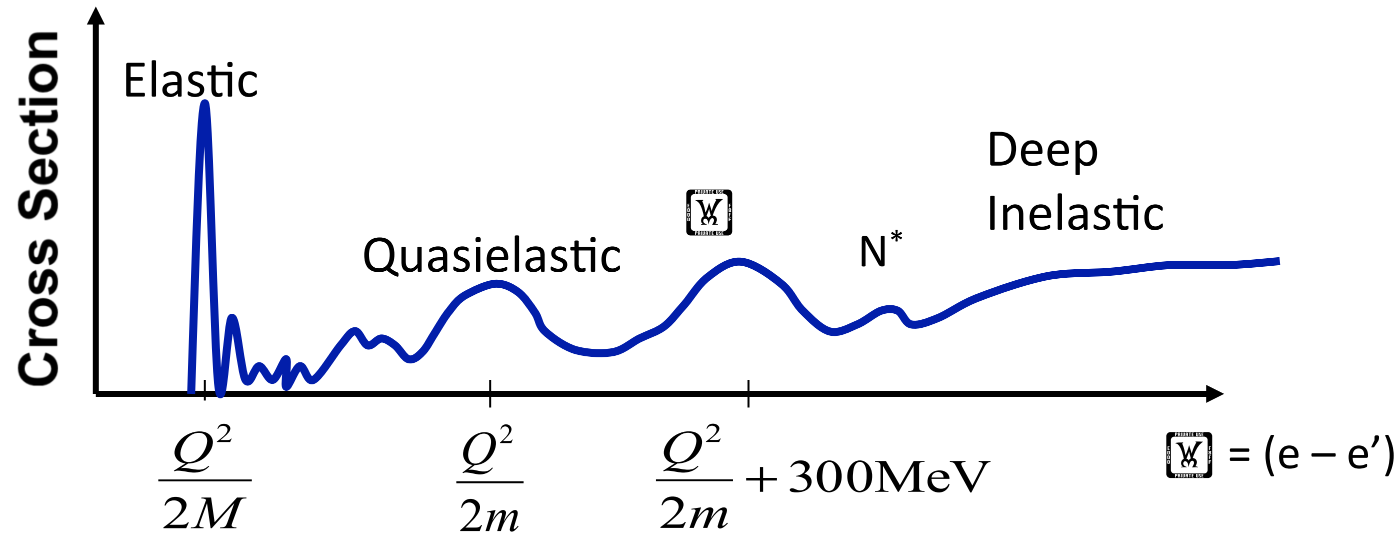
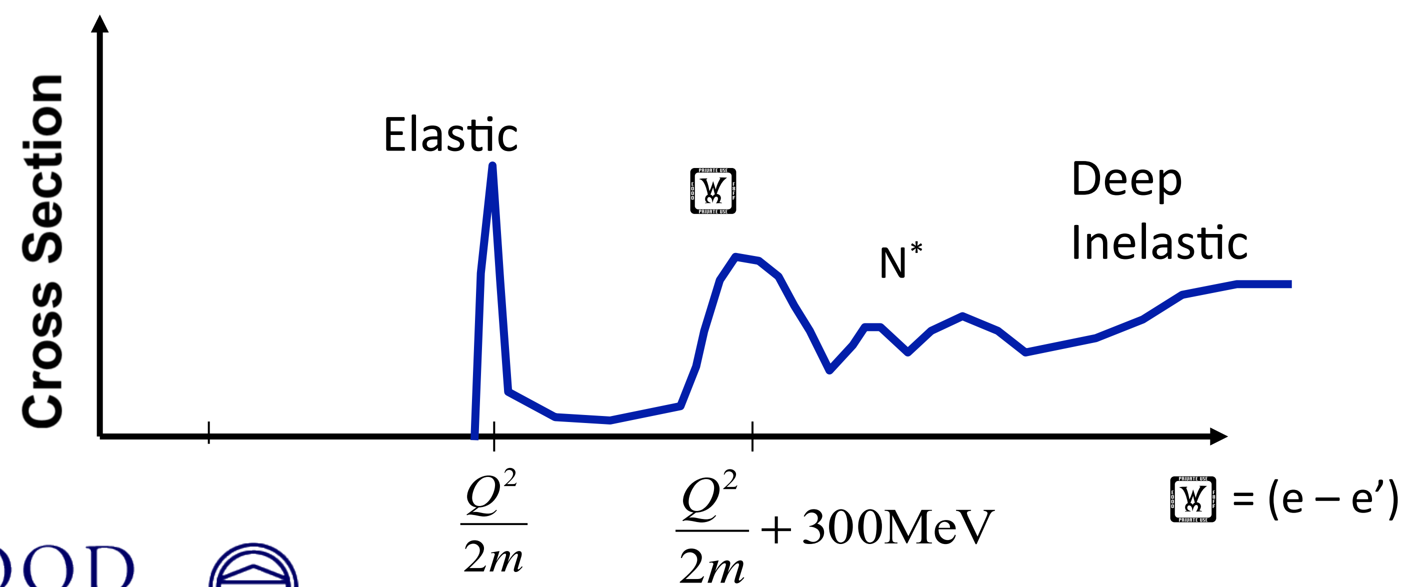
Electron Scattering at Fixed Q^2

Nucleus



Proton



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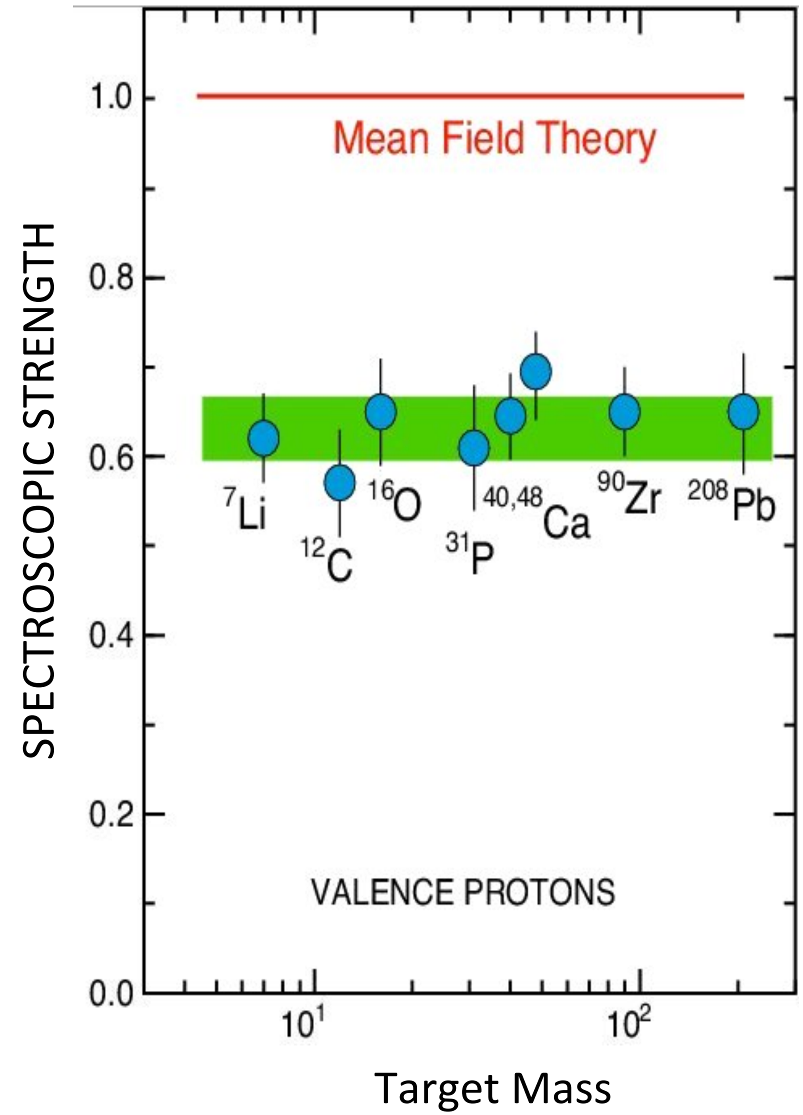
Classic Result from (e,e'p) Measurements

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)



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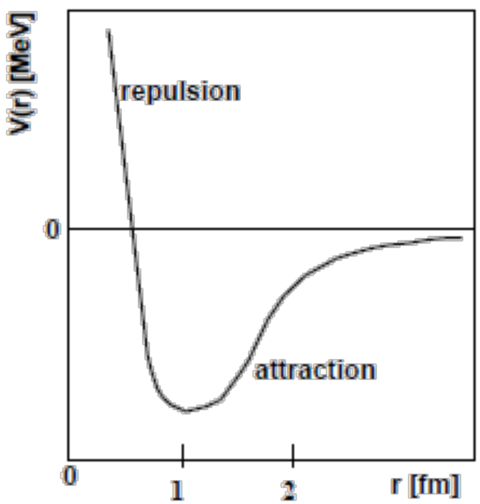
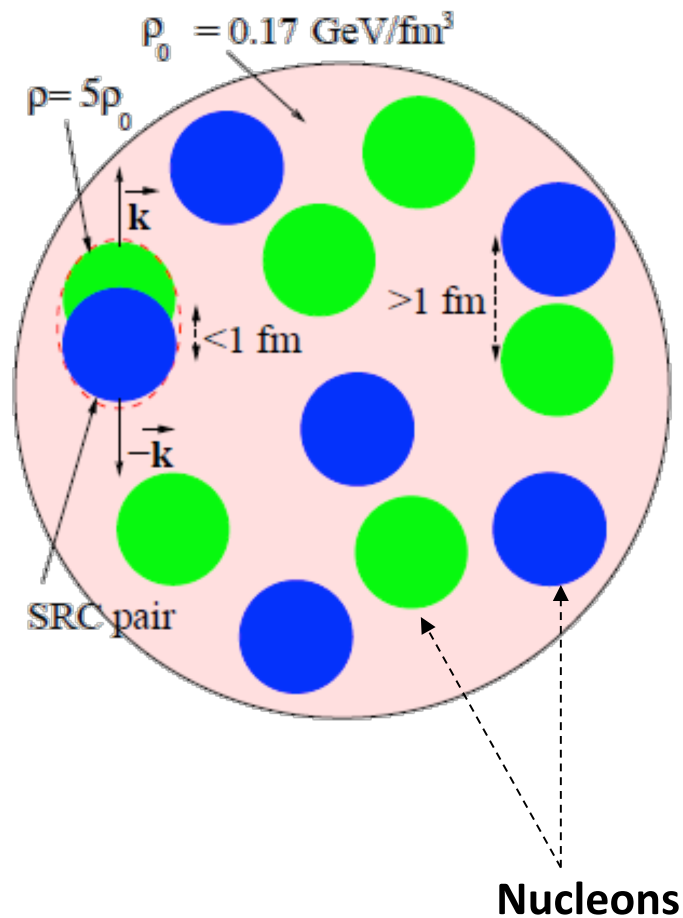
Short-Range Correlations





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

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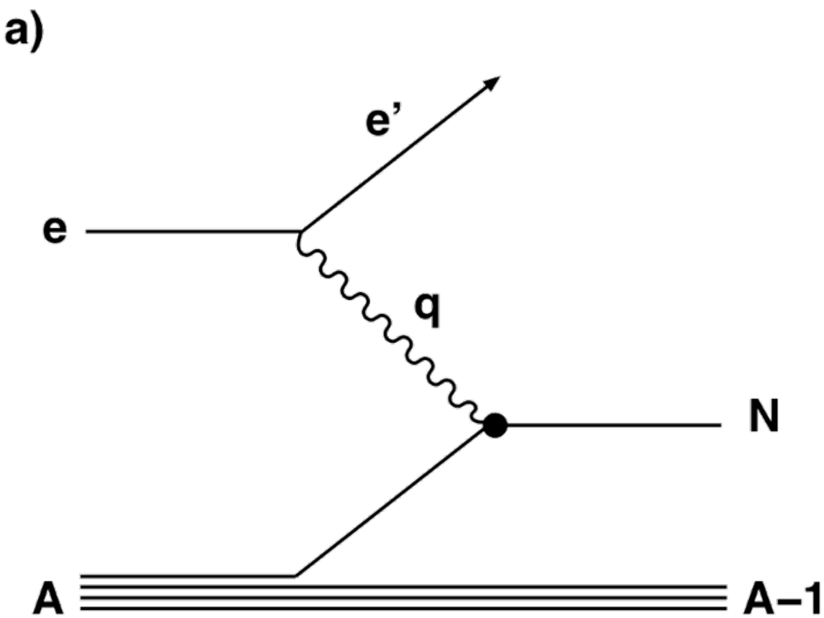
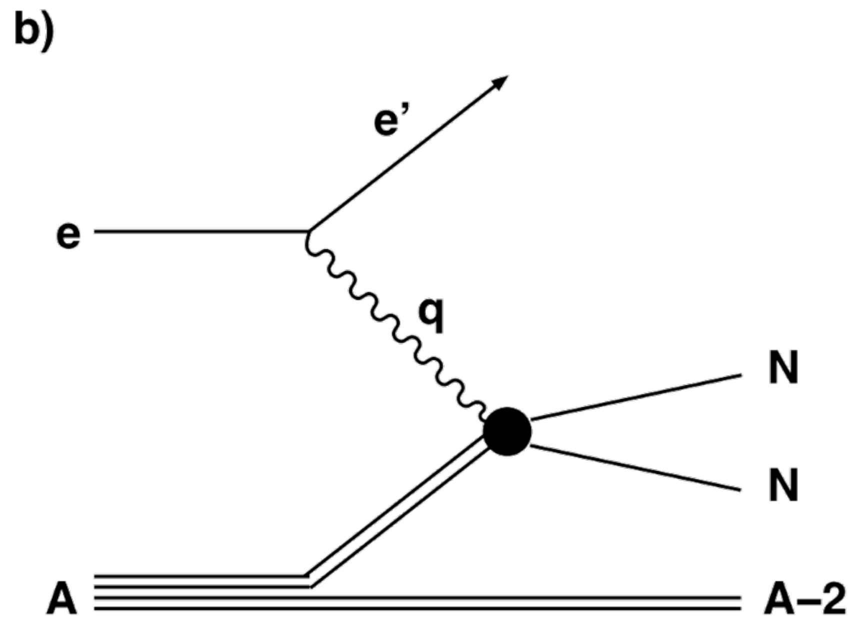
Short-Range Correlations



Single nucleon knock-out



Correlated pair knock-out

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Questions

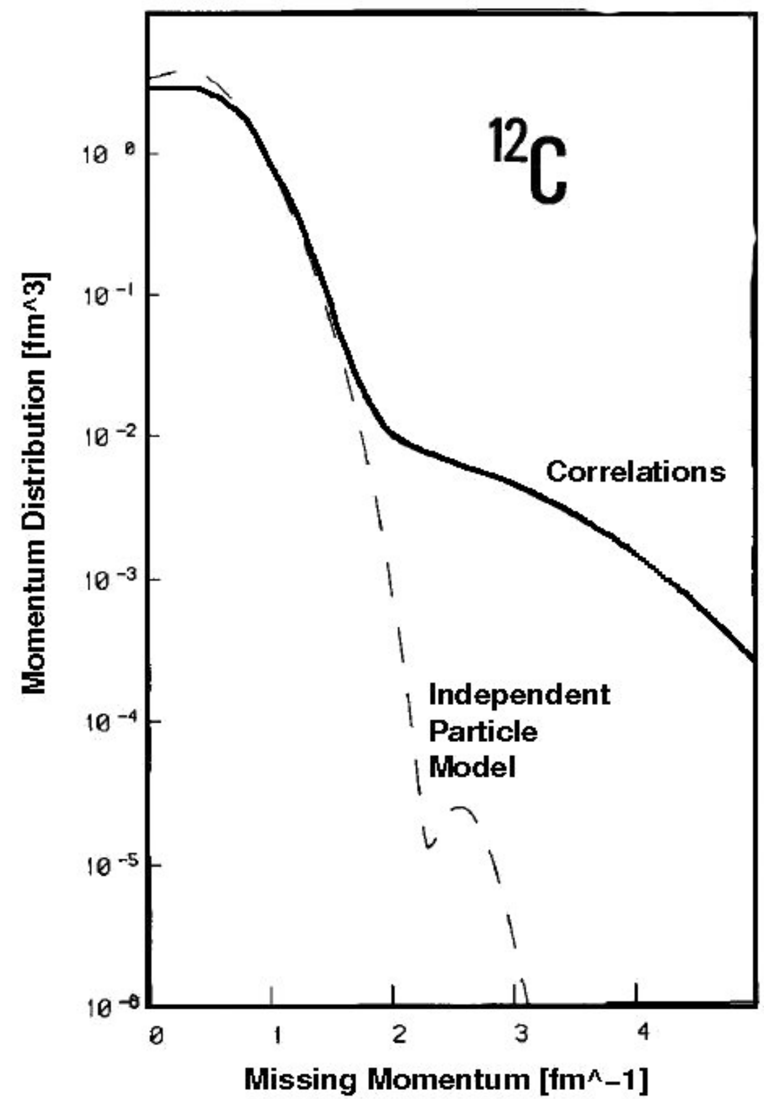
- What fraction of the momentum distribution is due to 2N-SRC?
- What is the relative momentum between the nucleons in the pair?
- What is the ratio of pp to pn pairs?
- Are these nucleons different from free nucleons (e.g. size)?

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 :

$P_{min} > 275$ MeV/c

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



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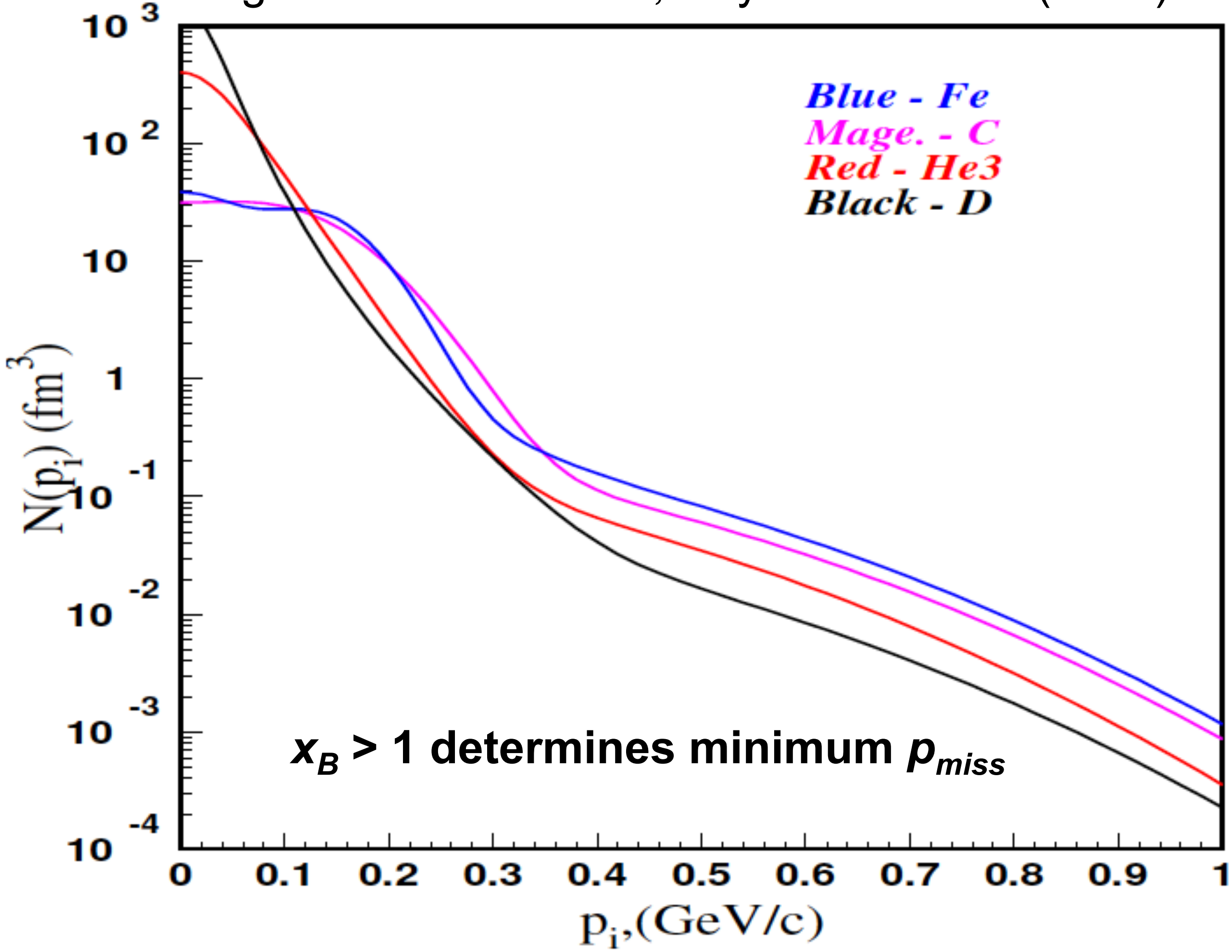
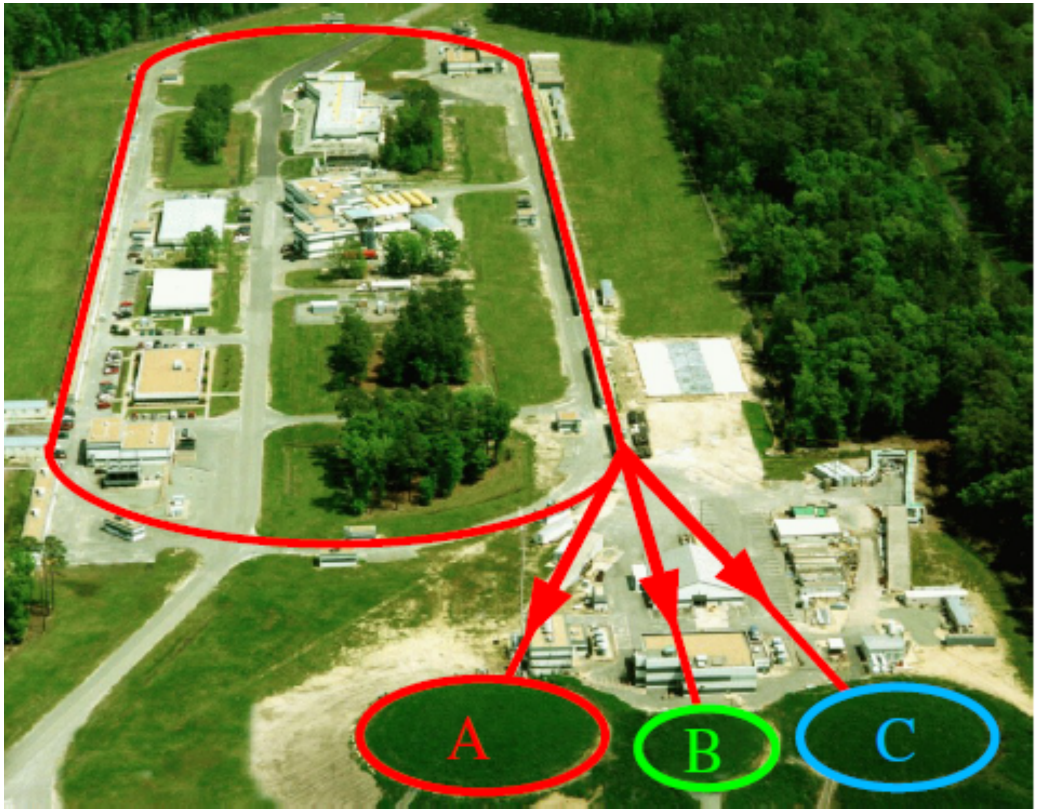
Calculation of Nucleon Initial Momentum

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



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

Jefferson Lab



In Newport News, VA
Continuous electron beam.
Energy: 0.3 to 6 GeV.
3 Experimental Halls.
Polarization: ~ 85–90%.

Beam energy being upgraded to 12 GeV!

International Collaboration

29 different countries representing 120 different institutions

The rest mass energy of an electron is 0.511 MeV.
At 6,000 MeV, the electron is traveling 0.999999996 times the speed of light, or eight 9's.

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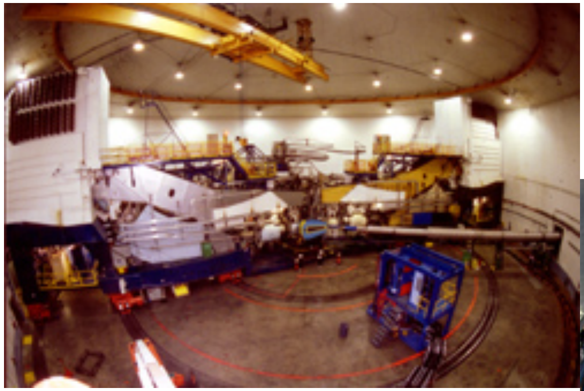
3 Experimental Halls



Hall A

Hall B

Hall C

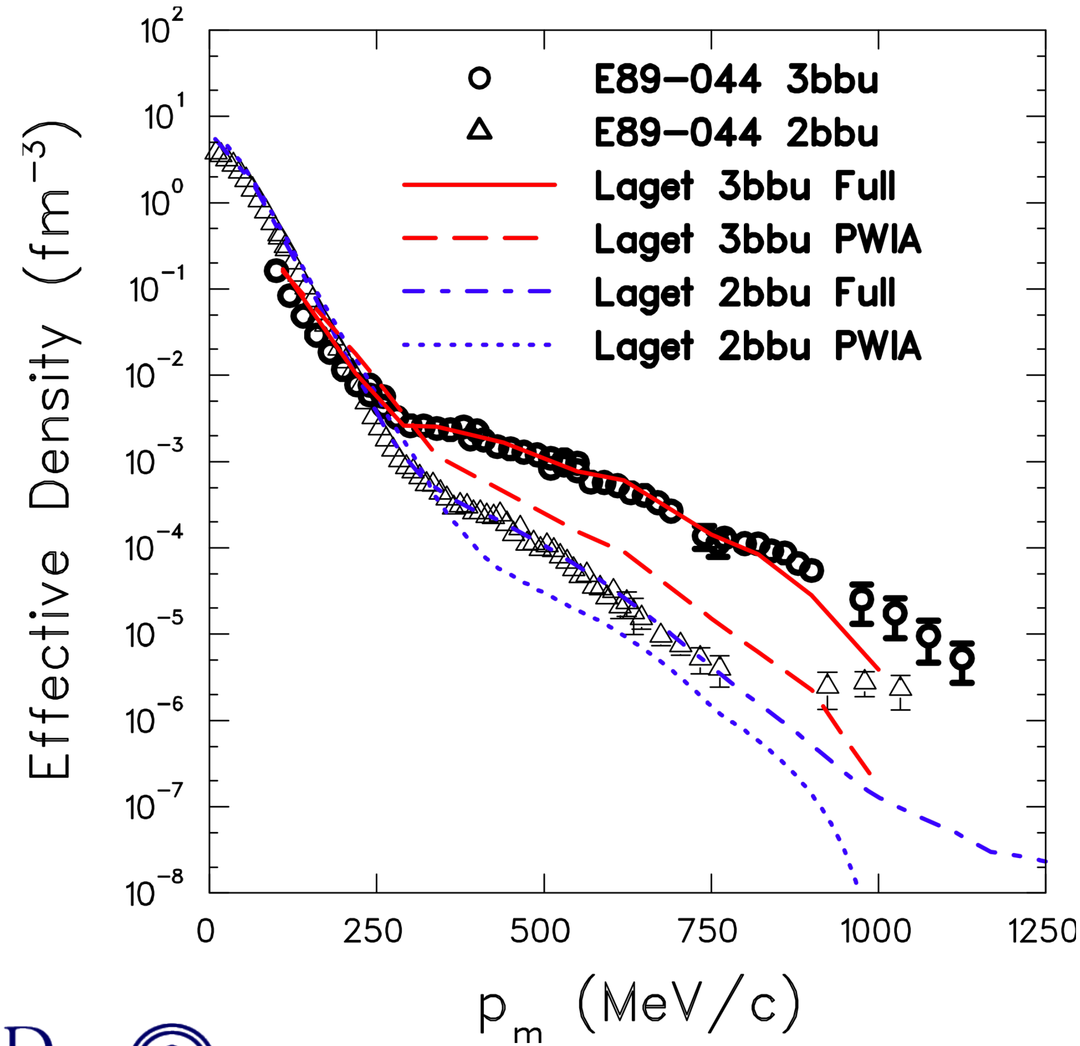
- All halls can take data at the same time.
- Different detectors allow for different types of experiments.

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

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

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

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



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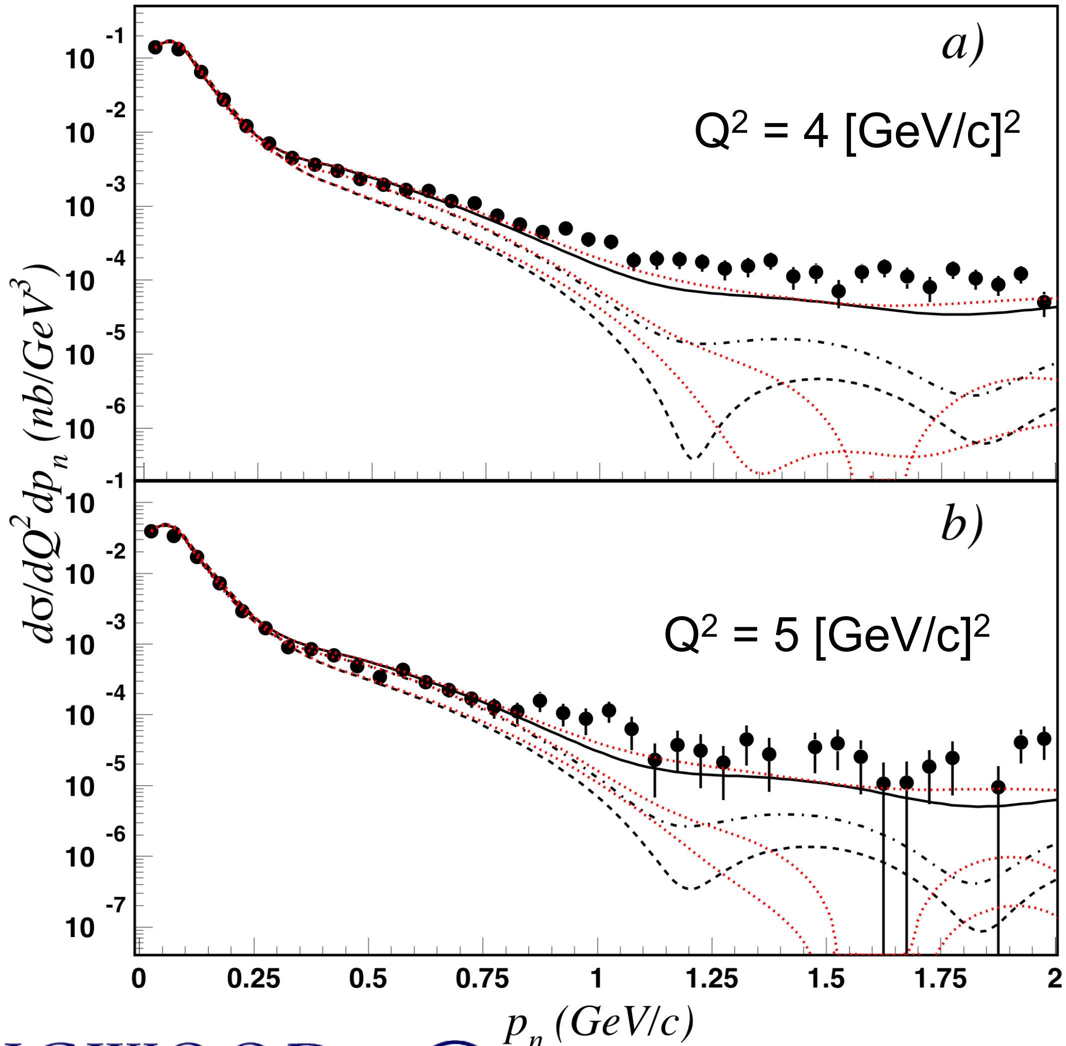
Hall B (CLAS) D(e,e'p)n, x<1 Data

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

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CLAS A(e,e') Data

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

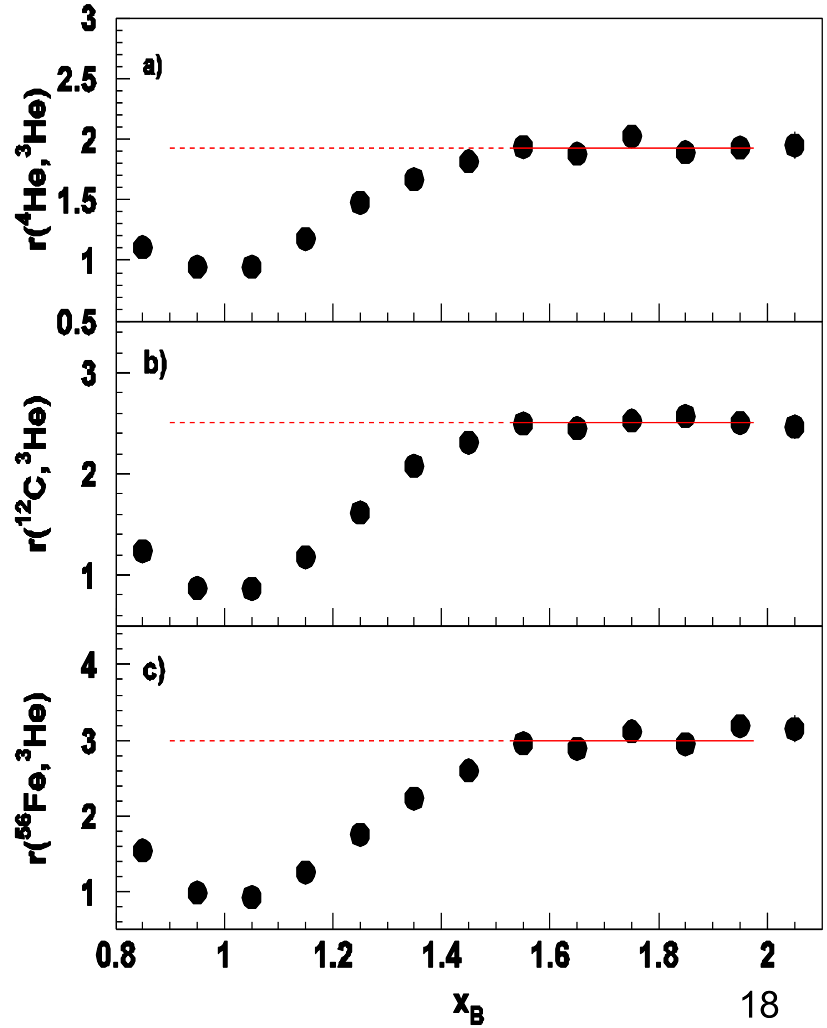
Originally done with SLAC data by D.B. Day *et al.*, Phys. Rev. Lett. 59 (1987) 427.

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

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



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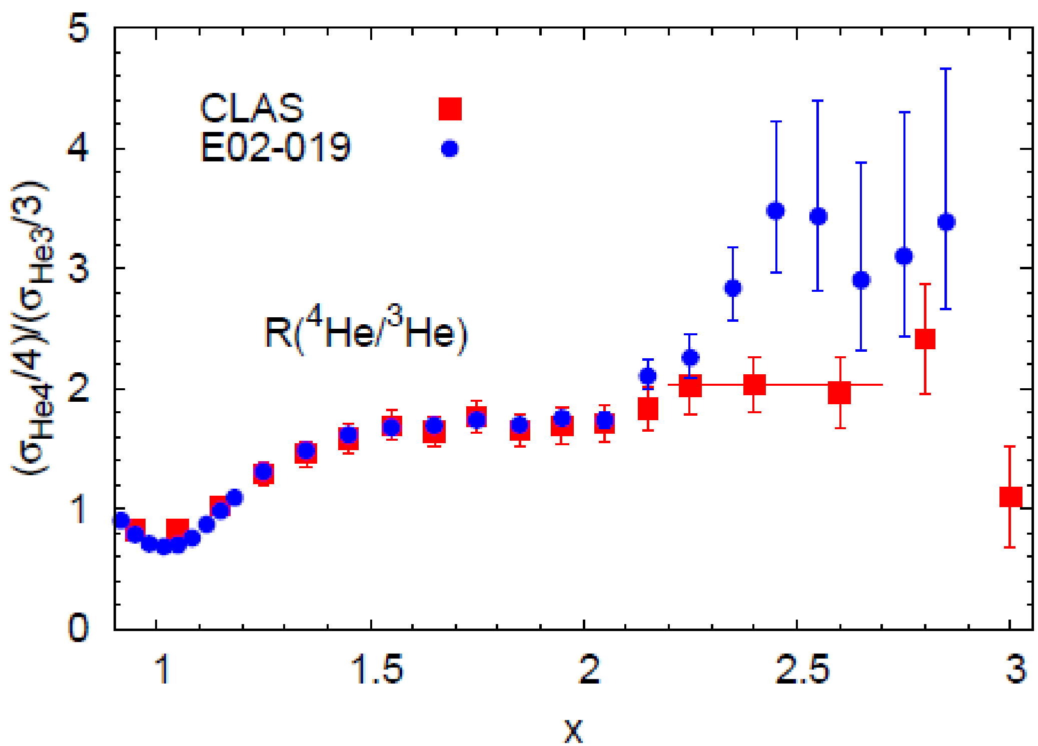
Estimate of ^{12}C Two and Three Nucleon SRC

- K. Egiyan *et al*. related the known correlations in deuterium and previous r (^3He,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

N. Fomin *et al*.**,** Phys. Rev. Lett. 108 (2012) 092502

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

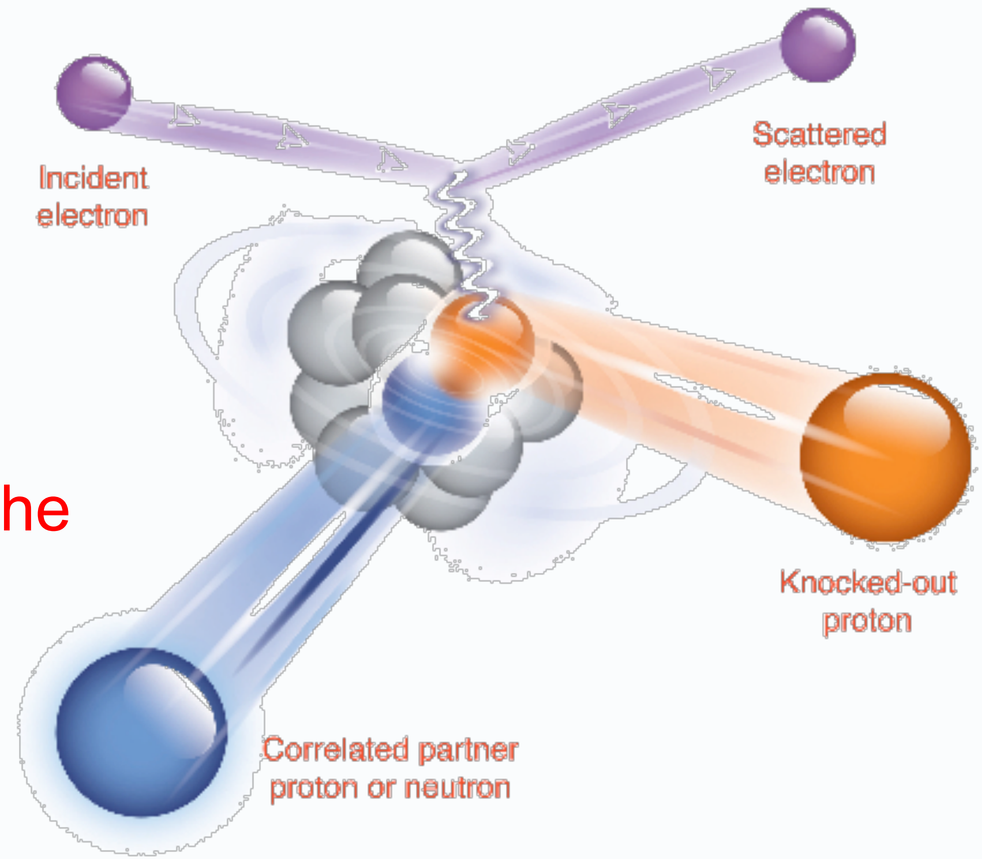
- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - No Q^2 Dependence Of Ratio Magnitude Q^2: 1 to 4 GeV to few percent
  -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

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:

~ 275 MeV/c



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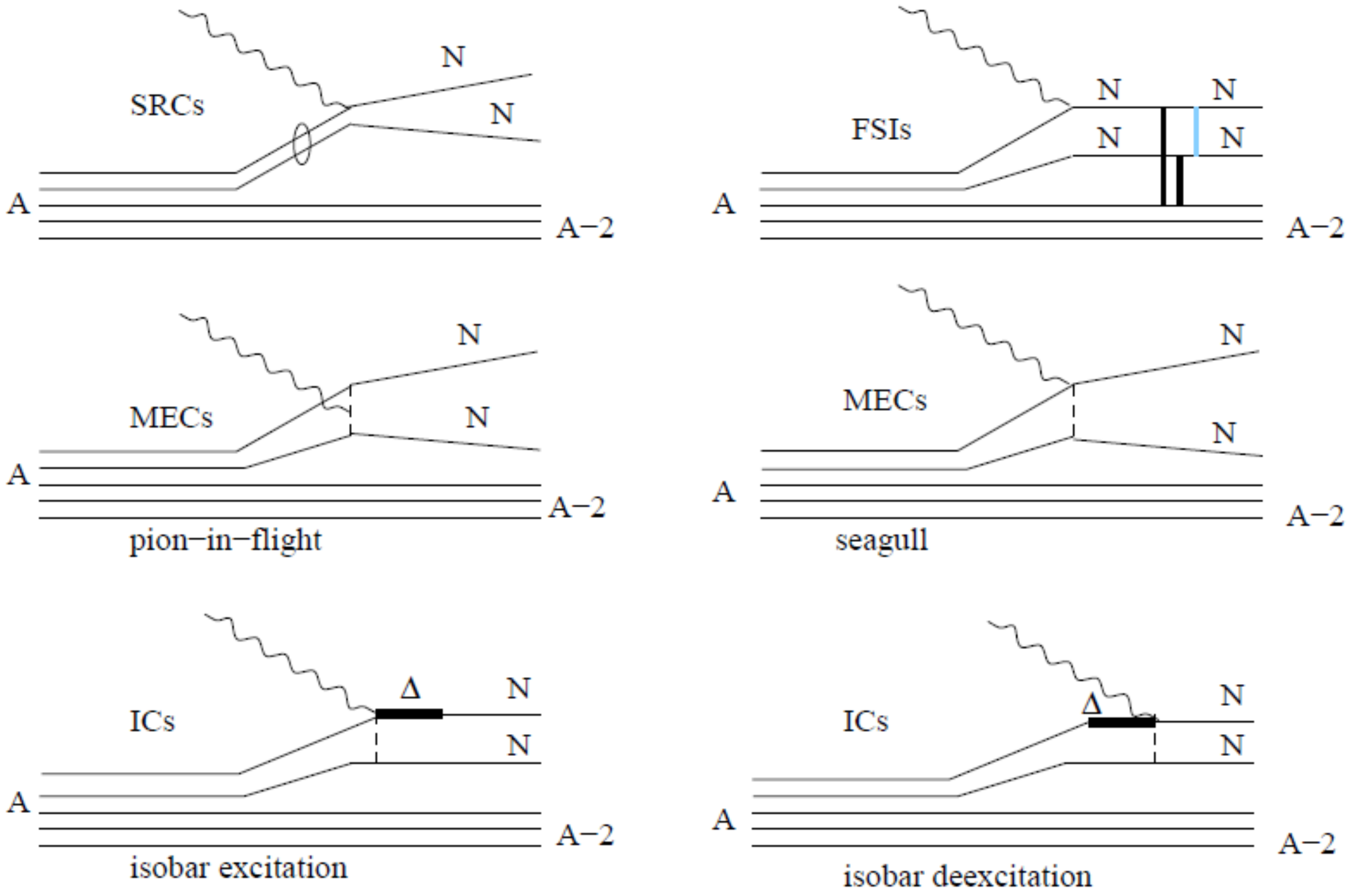
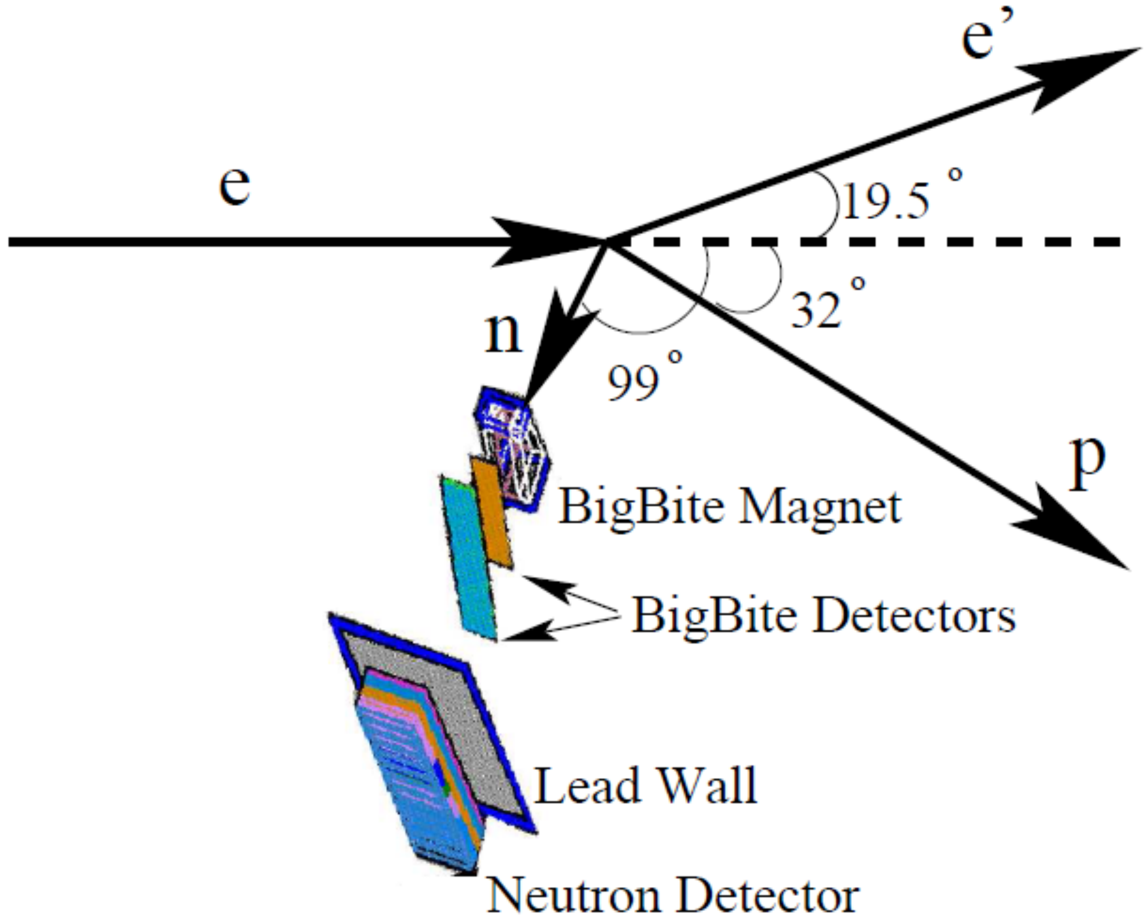
Suppression of Non-SRC Two Body Effects



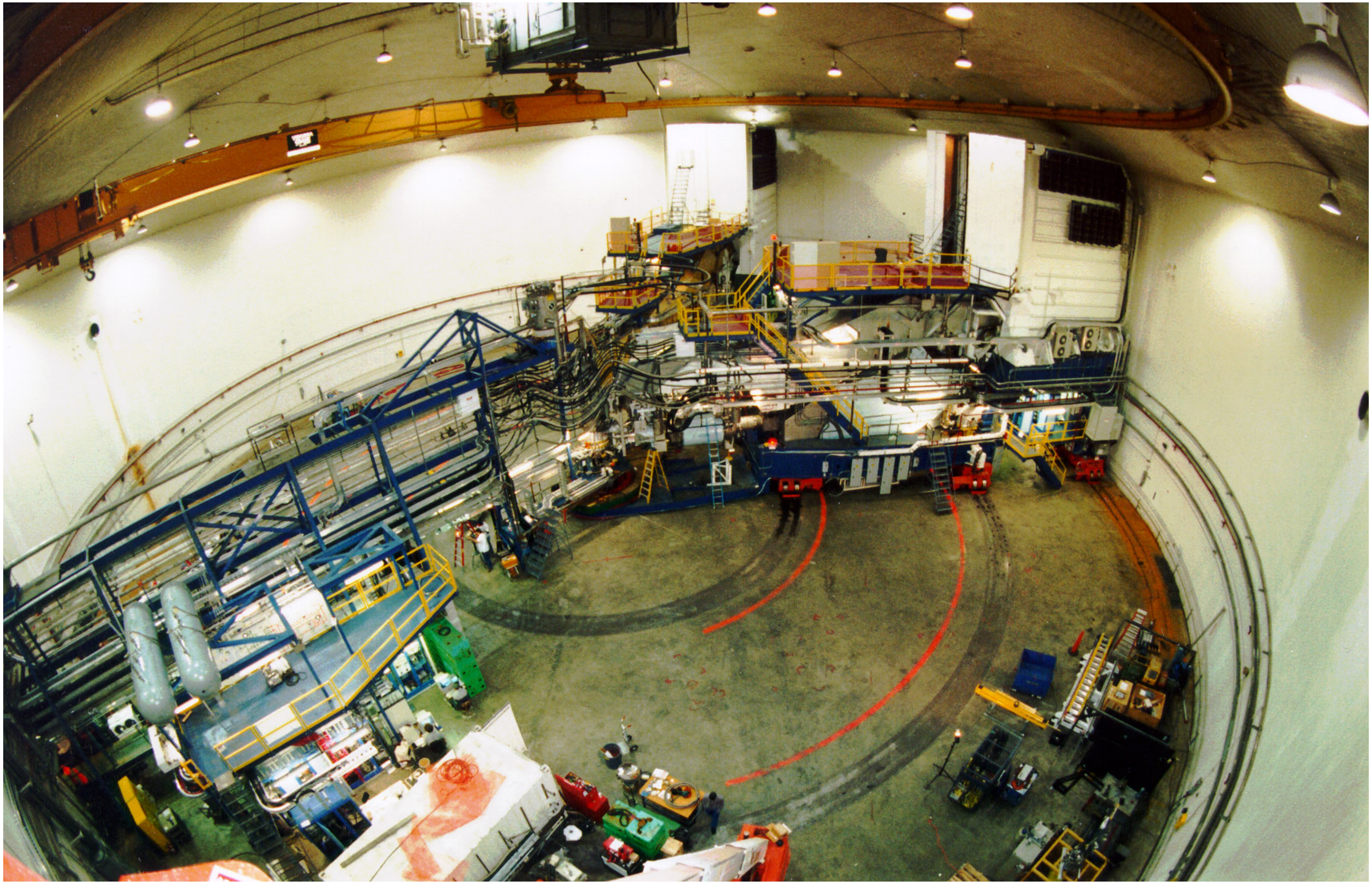
- High Q^2 to minimize MEC ($1/Q^2$) and FSI
- x>1 to suppress isobar contributions

Kinematics



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

Experimental Hall A



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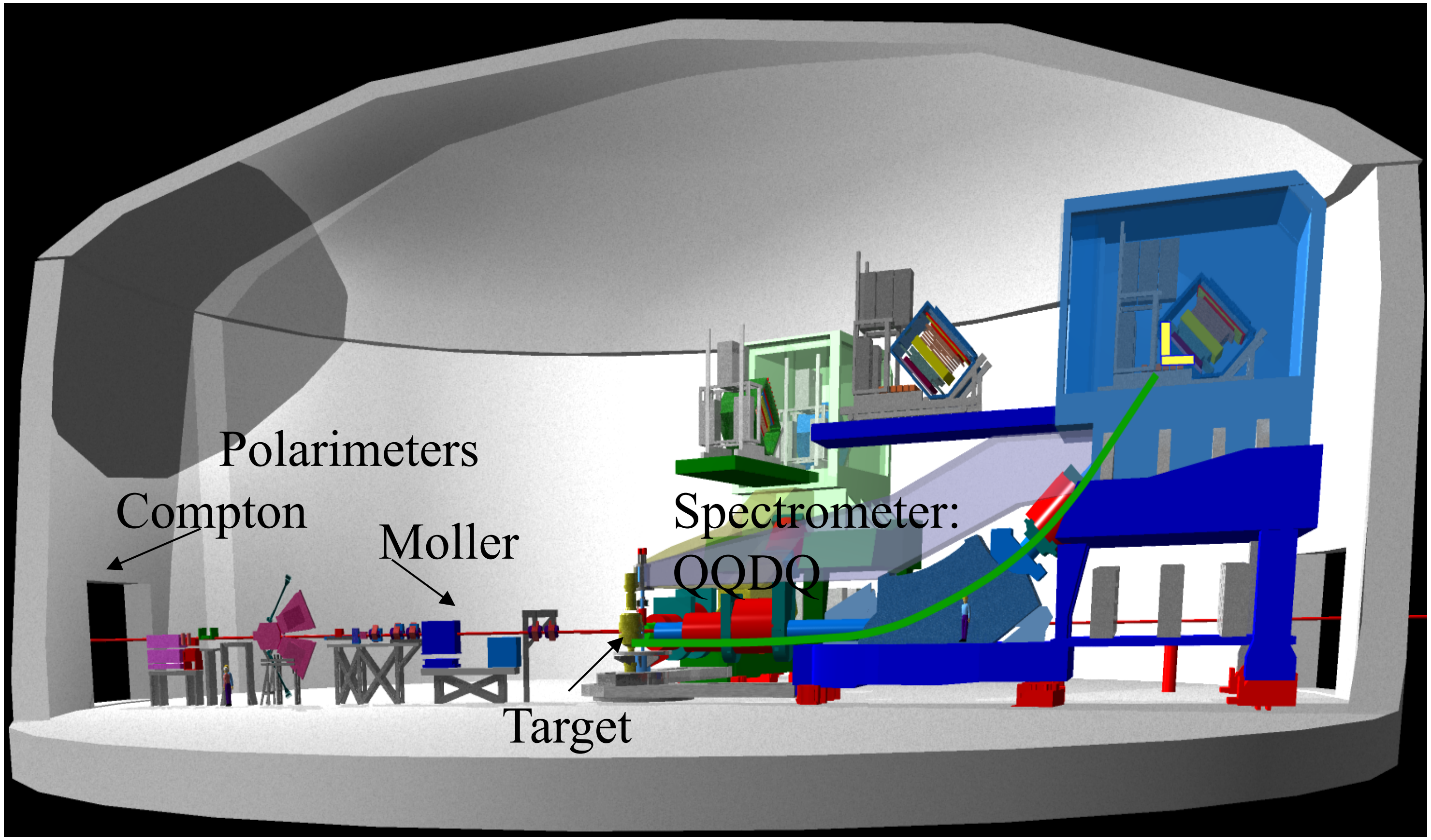
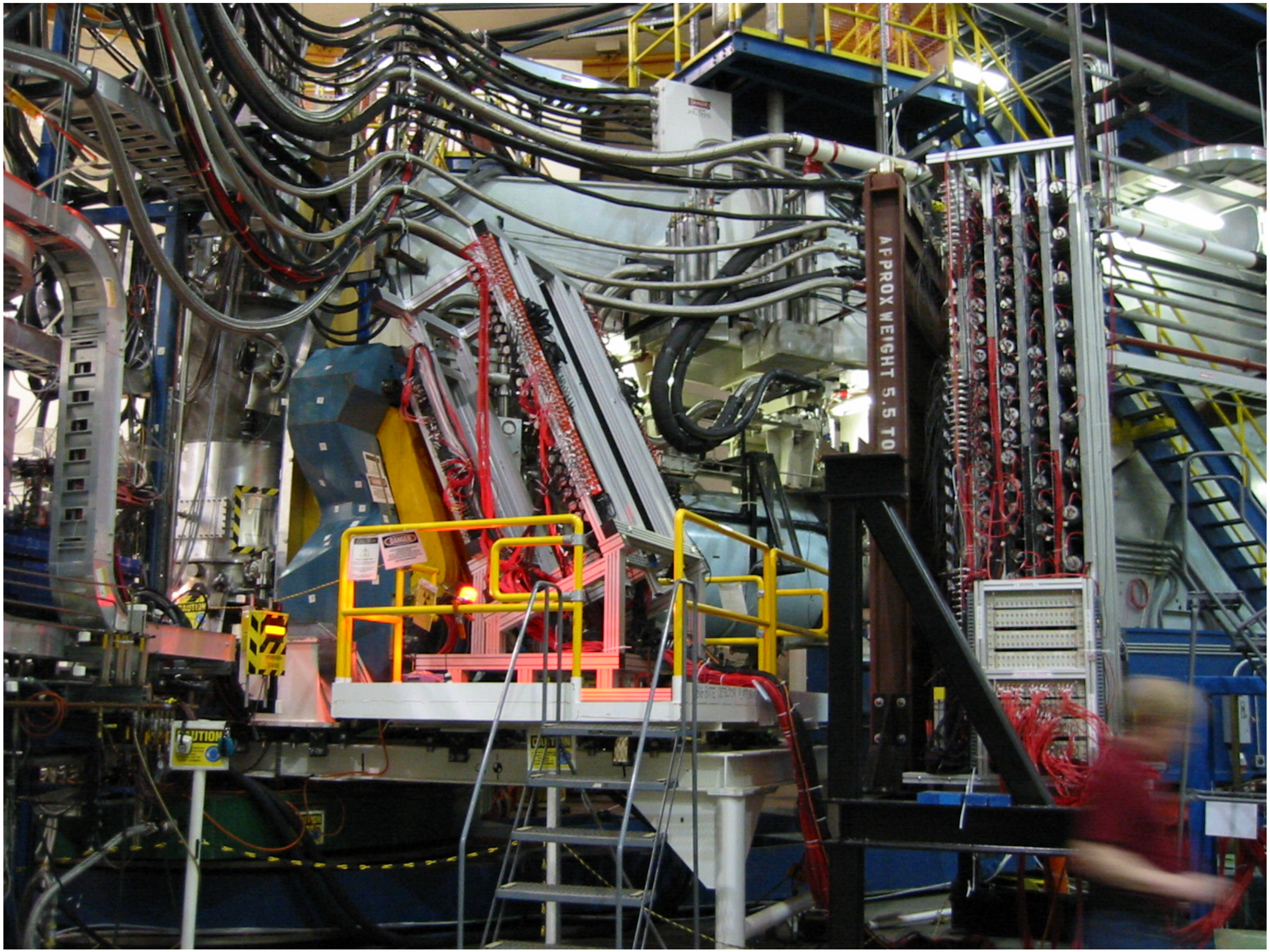
Experimental Hall A



- Hall A's two High resolution Spectrometers can detect scattered electrons with momentum up 4 GeV/c with a resolution of 10^{-4}.
- Can detect particles scattered from 6° to 120°.

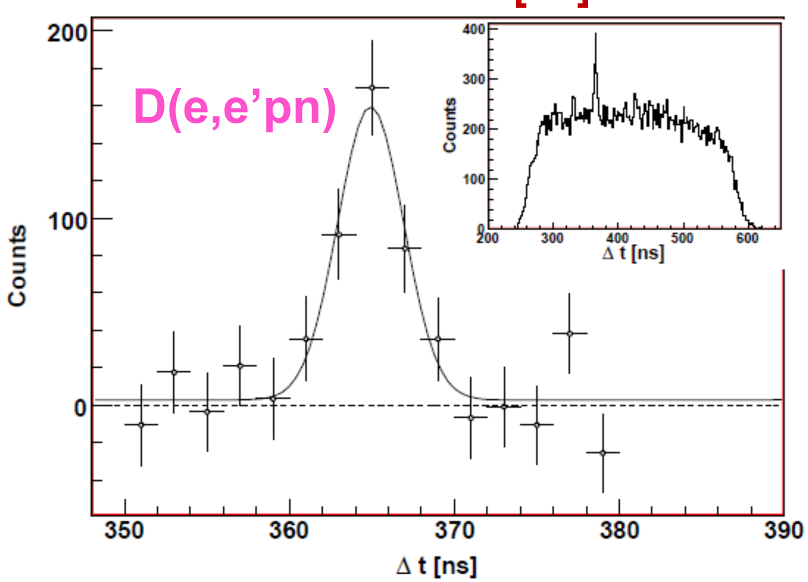
Add BigBite and Neutron Detector



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.

Neutron TOF [ns]



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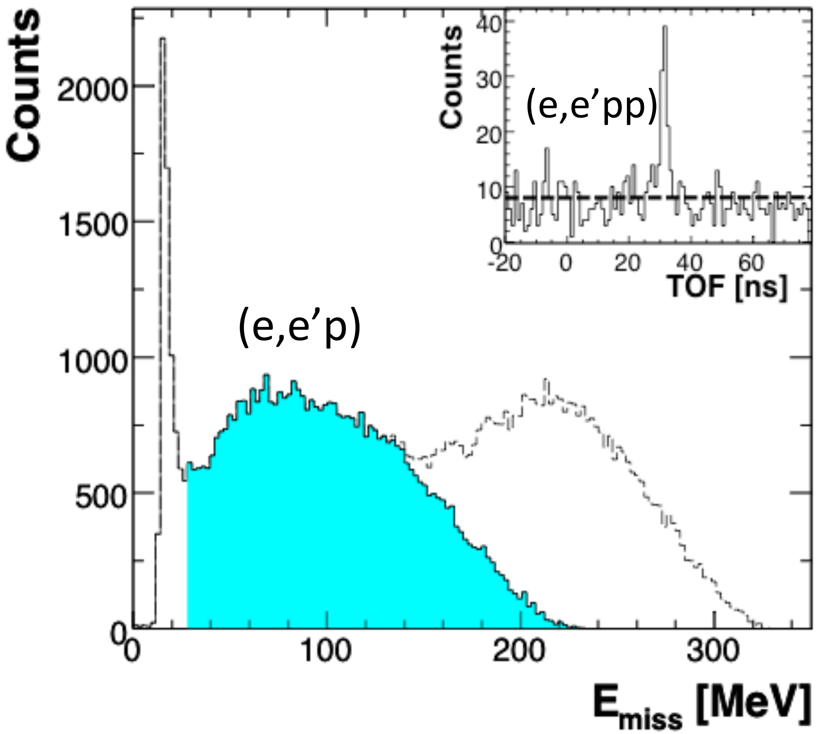
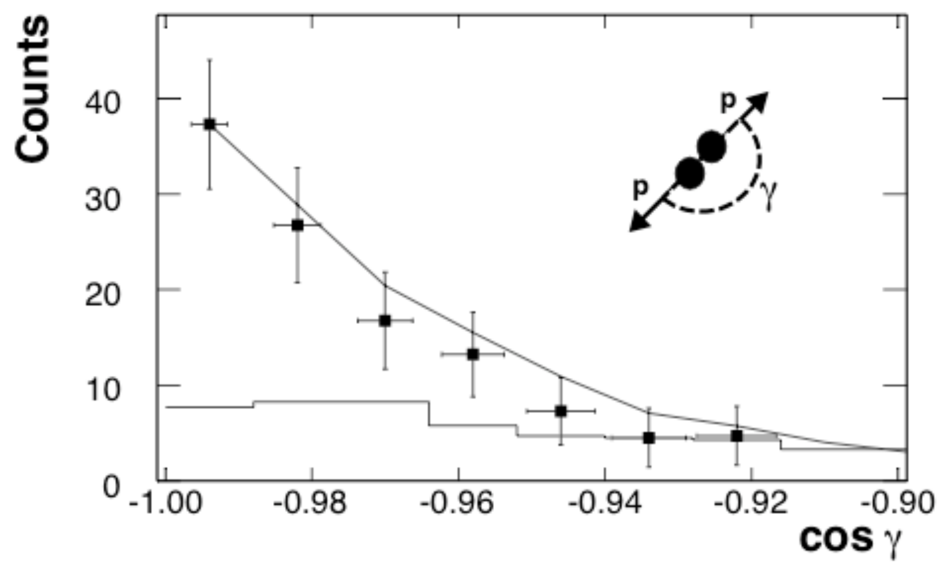
(e,e'p) & (e,e'pp) Data





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.

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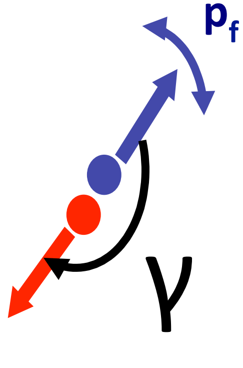
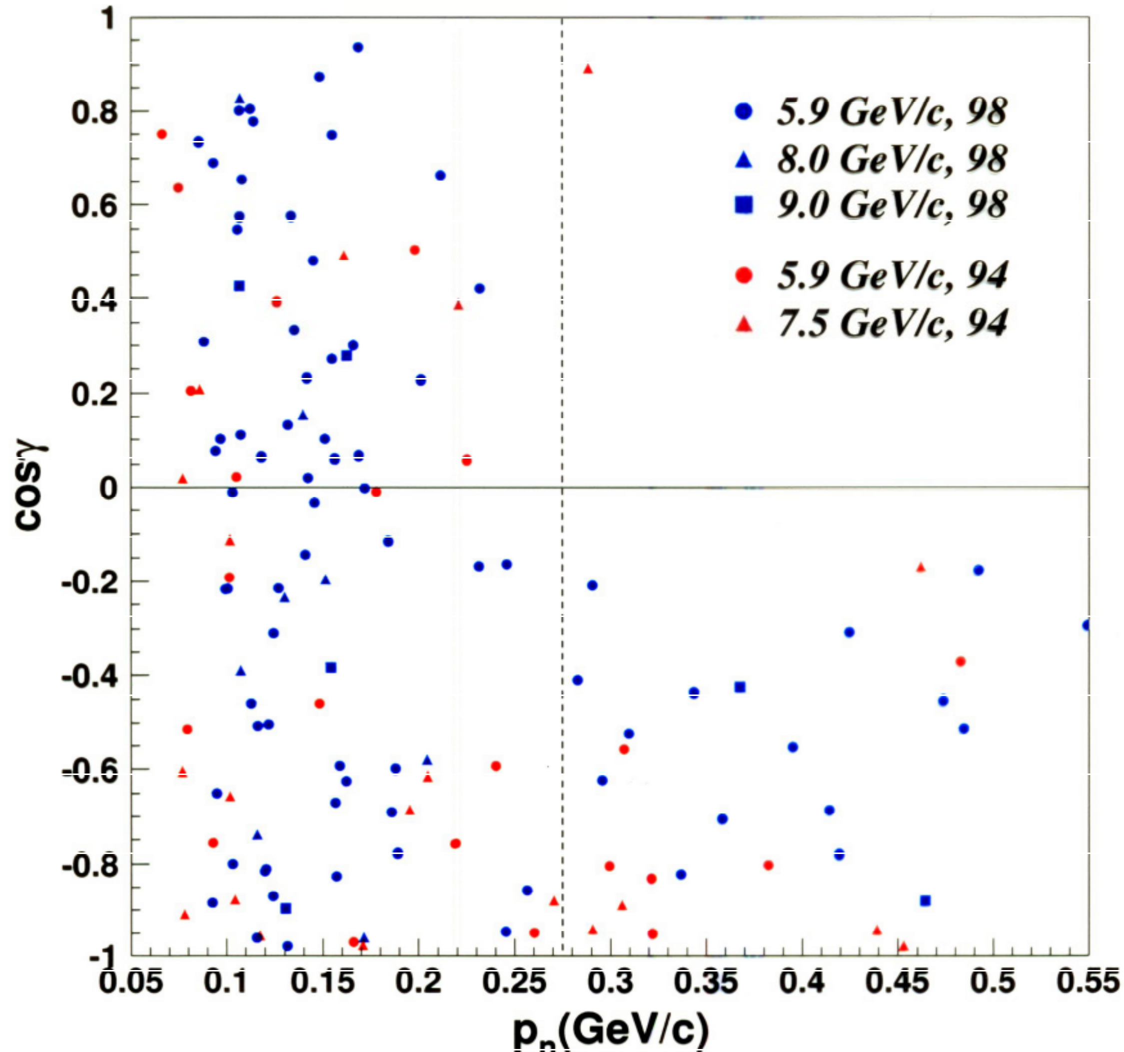
Brookhaven EVA Collaboration Result

$^{12}C(p,2p+n)$ **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.

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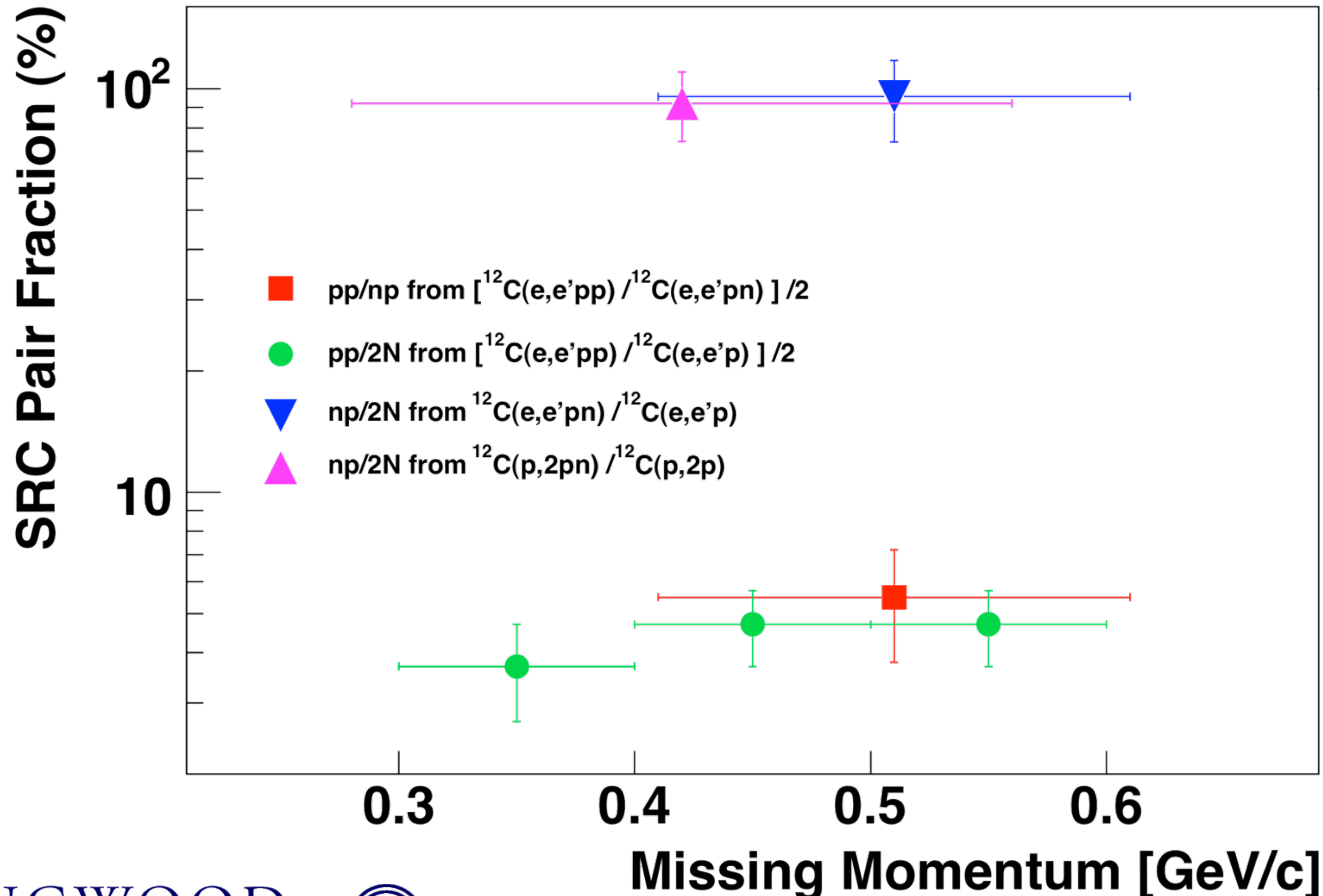
Correlated Pair Factions from ^{12}C

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



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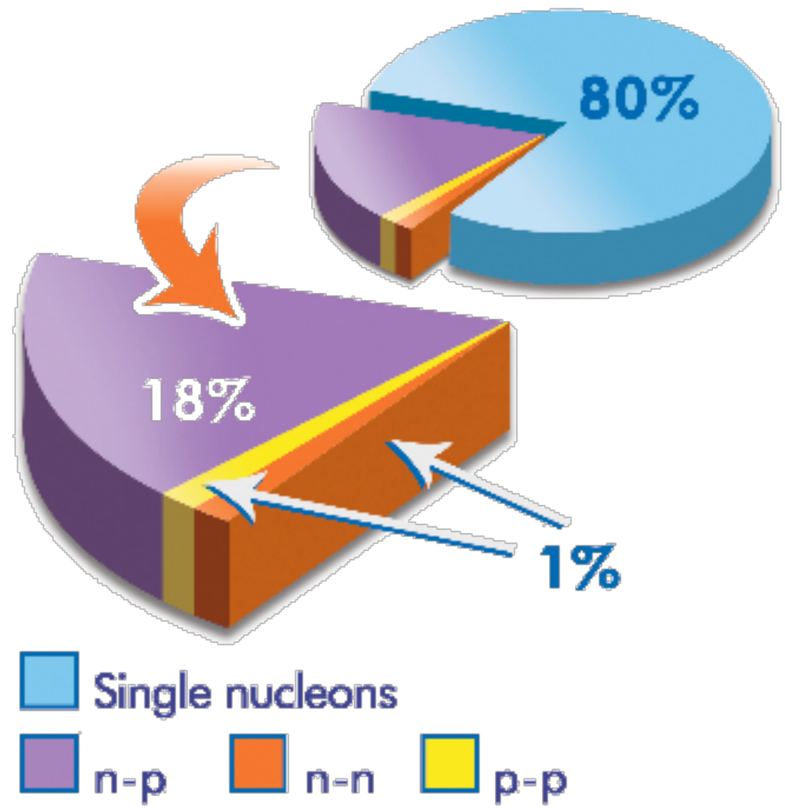
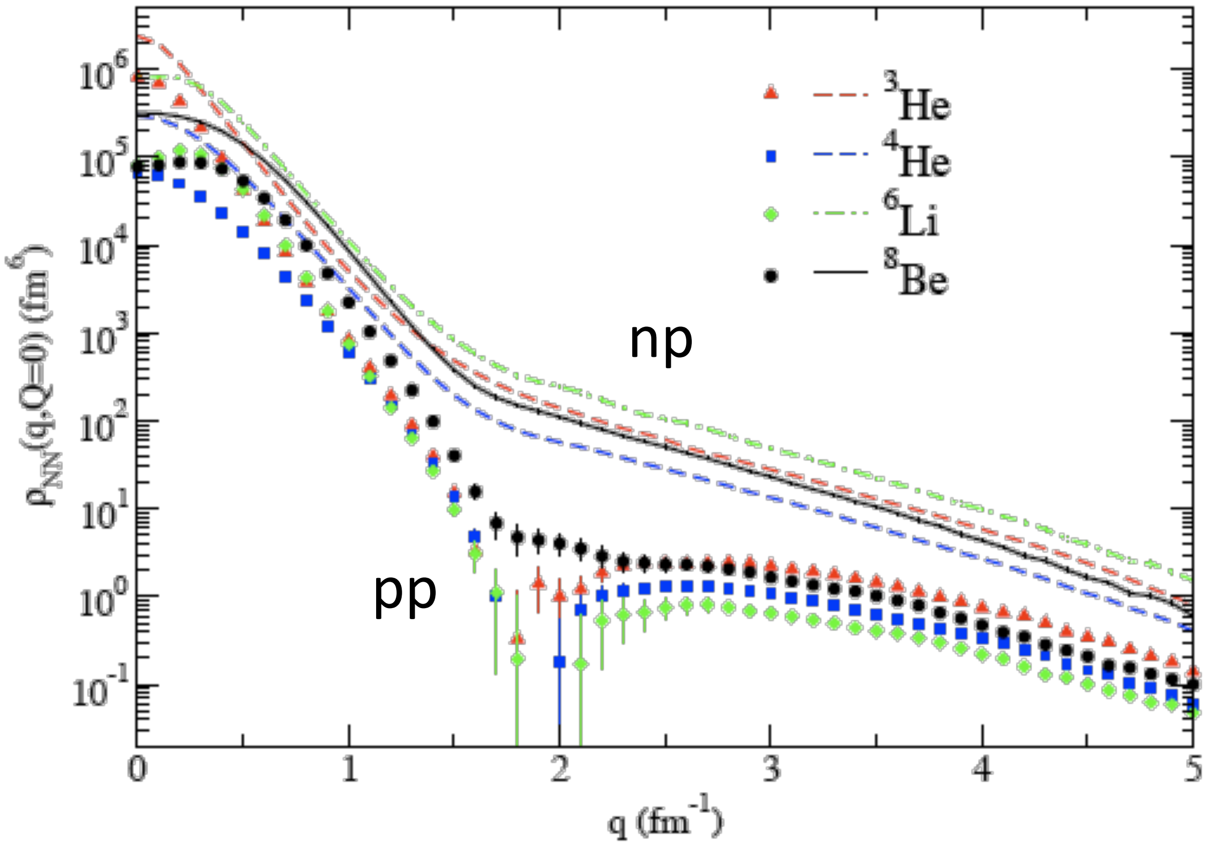
From the (e,e'), (e,e'p), and (e,e'pN) Results

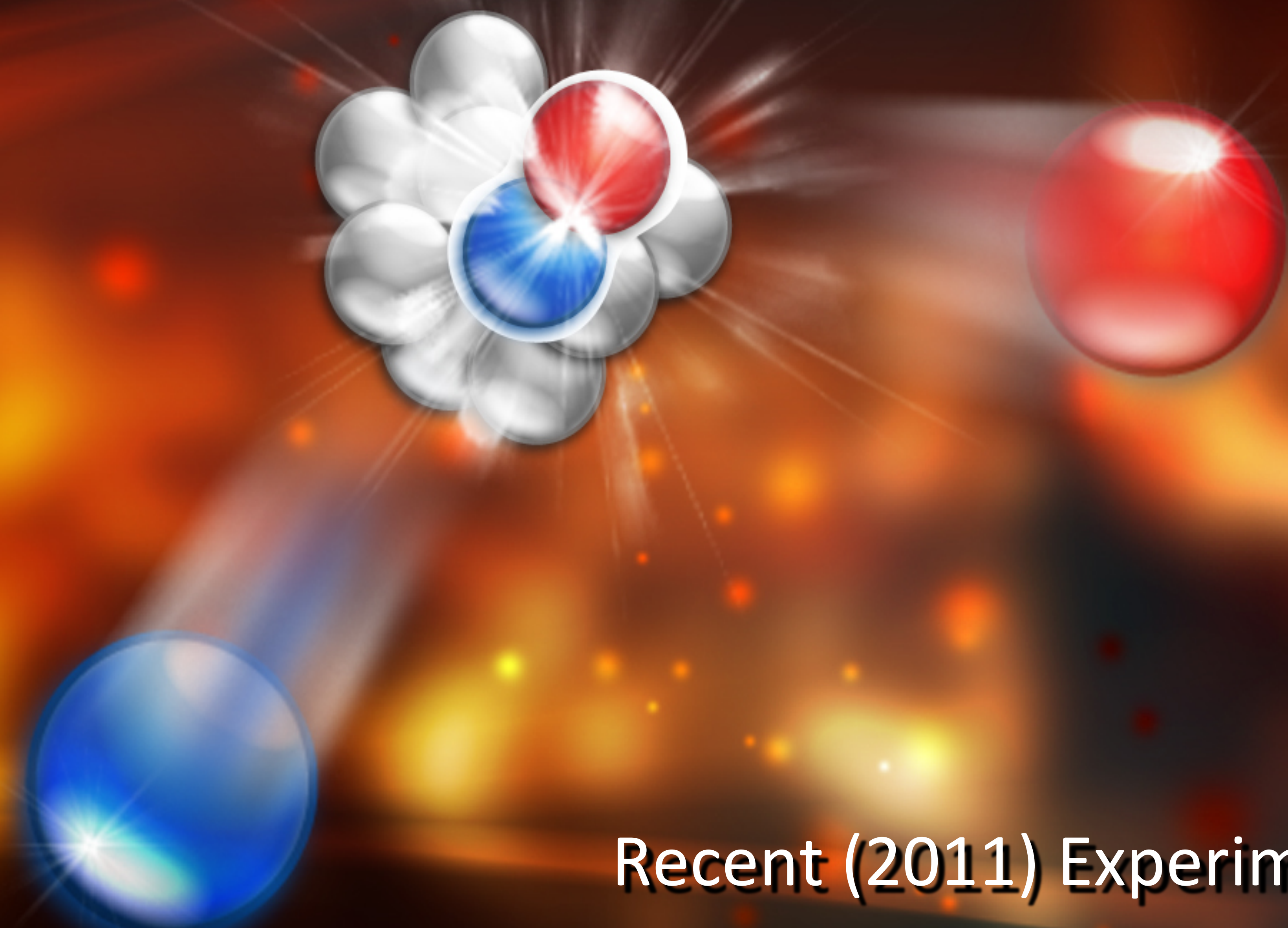
- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - 18% np pairs
  - 1% pp pairs
  - 1% nn pairs (from isospin symmetry)
-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

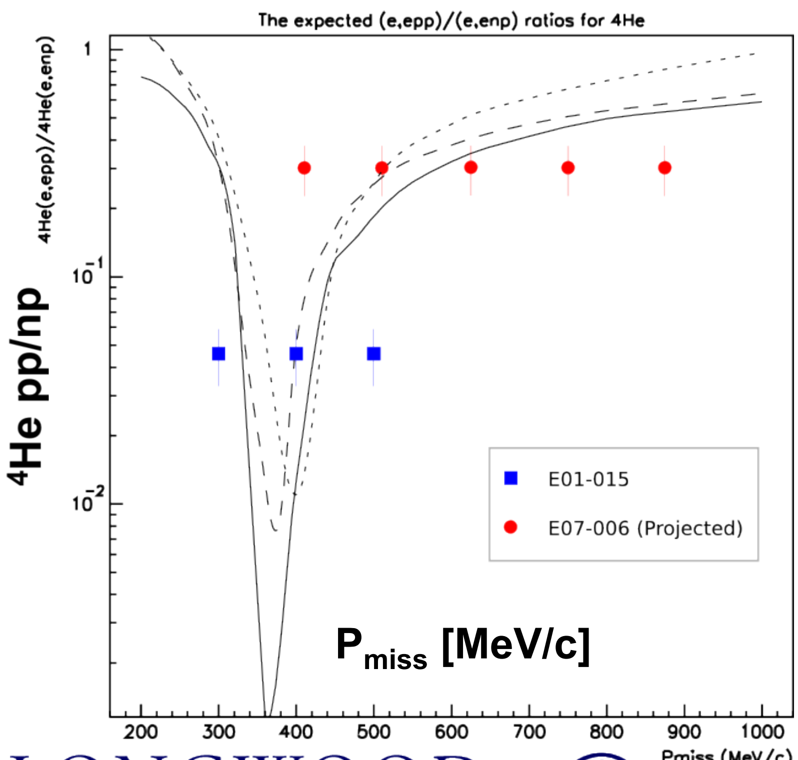


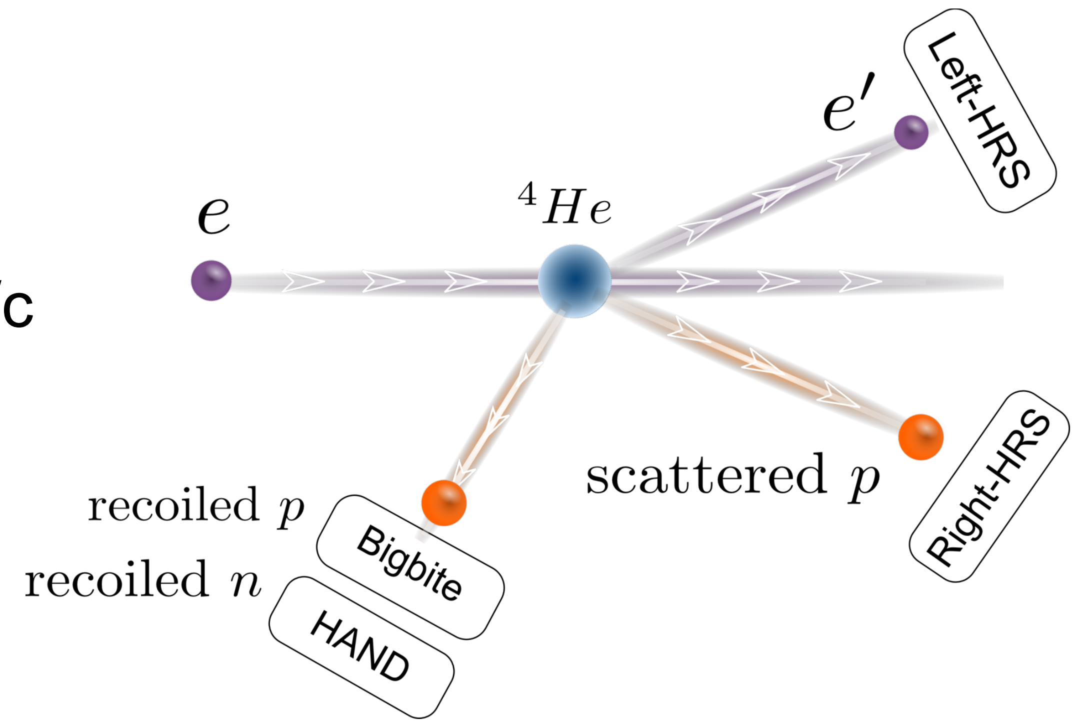
Recent (2011) Experiment

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_{miss} from 400 – 800 MeV/c



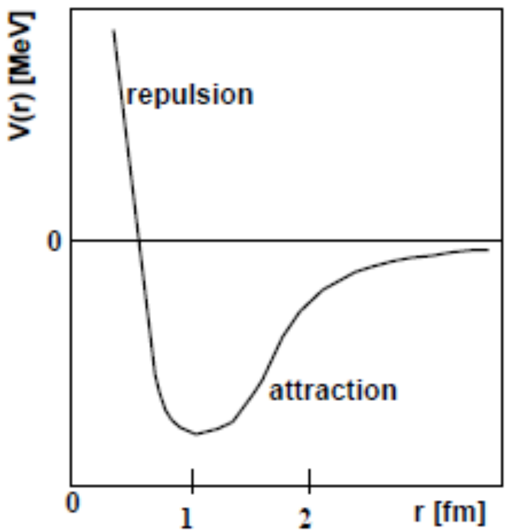


- Pushing the Limits of the NN Potential
  - Long range attraction
  - Short range repulsion

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

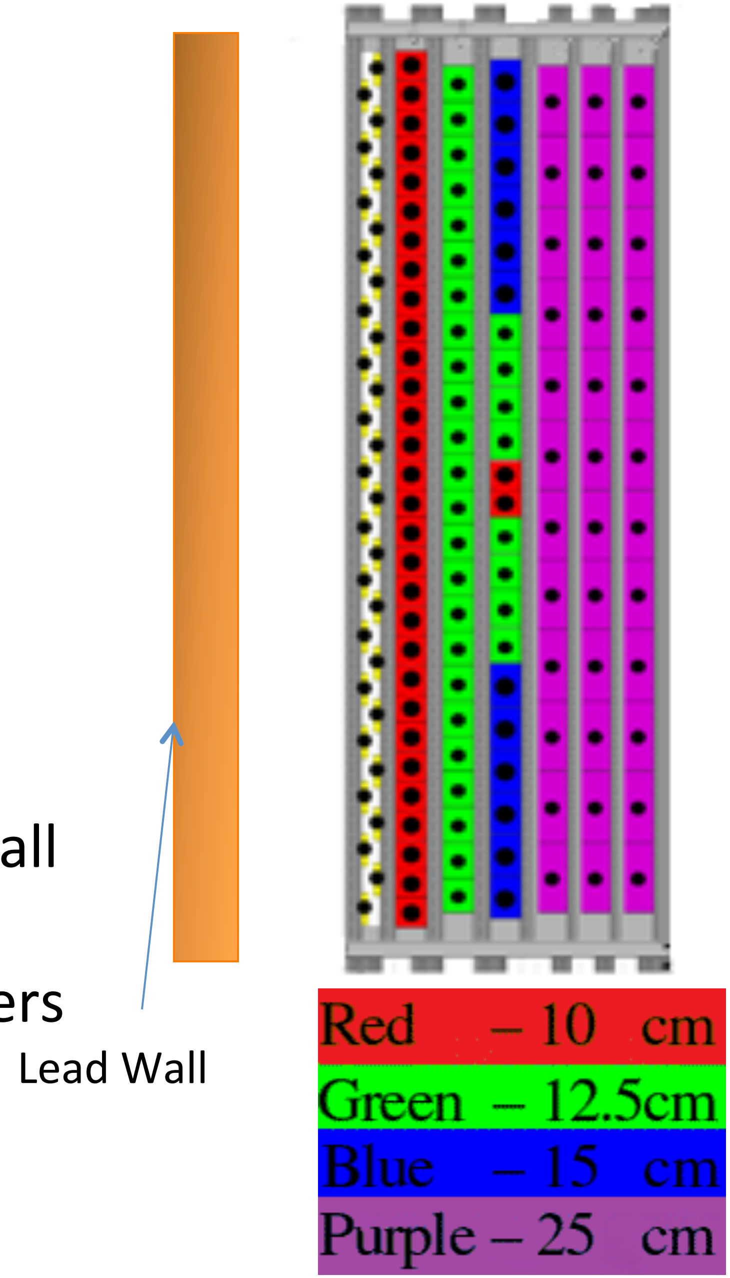
Neuron Array – HAND

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)



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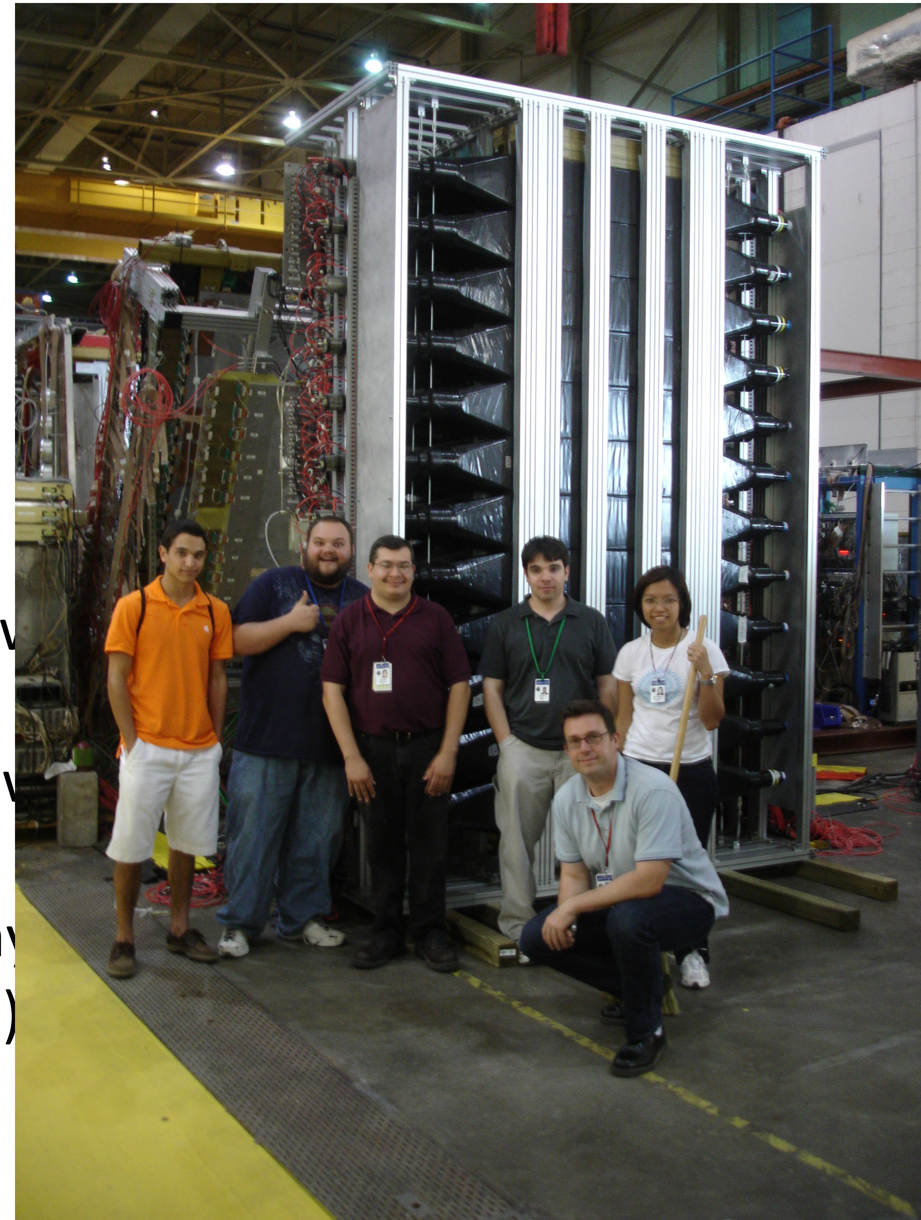
Neuron Array – HAND

Recoil neutron detection:

- Lead wall
- 64 veto bars
- 112 scintillators



Work completed:

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

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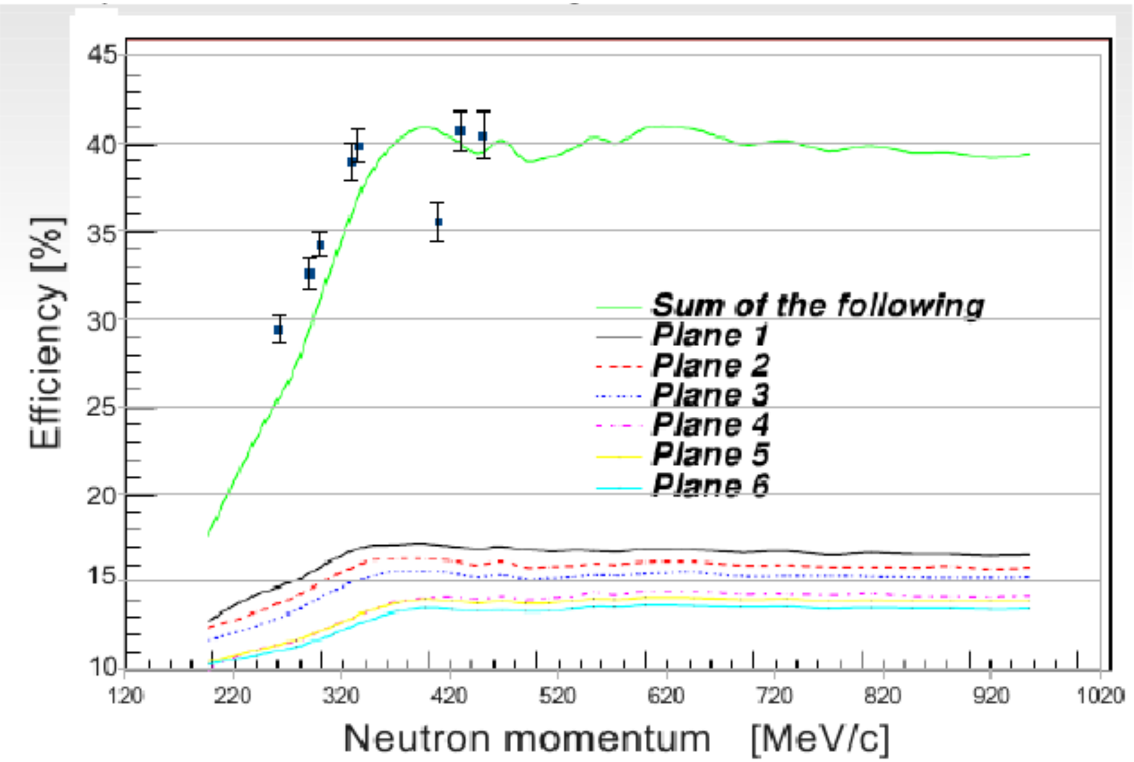
Absolute Neutron Detector Efficiency

- 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.



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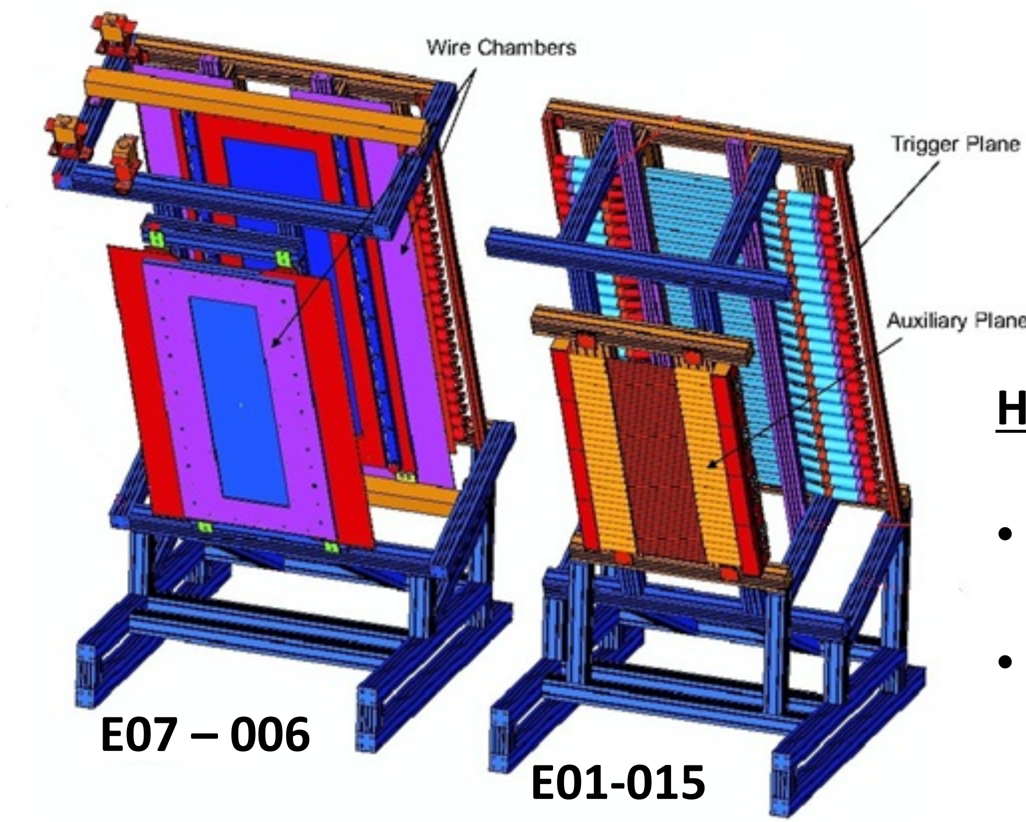
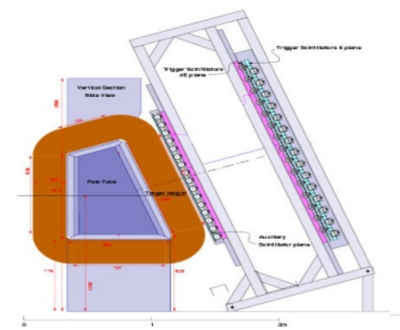
BigBite – Hadron Package

Detection of recoiled protons from SRC pair

Non focusing dipole

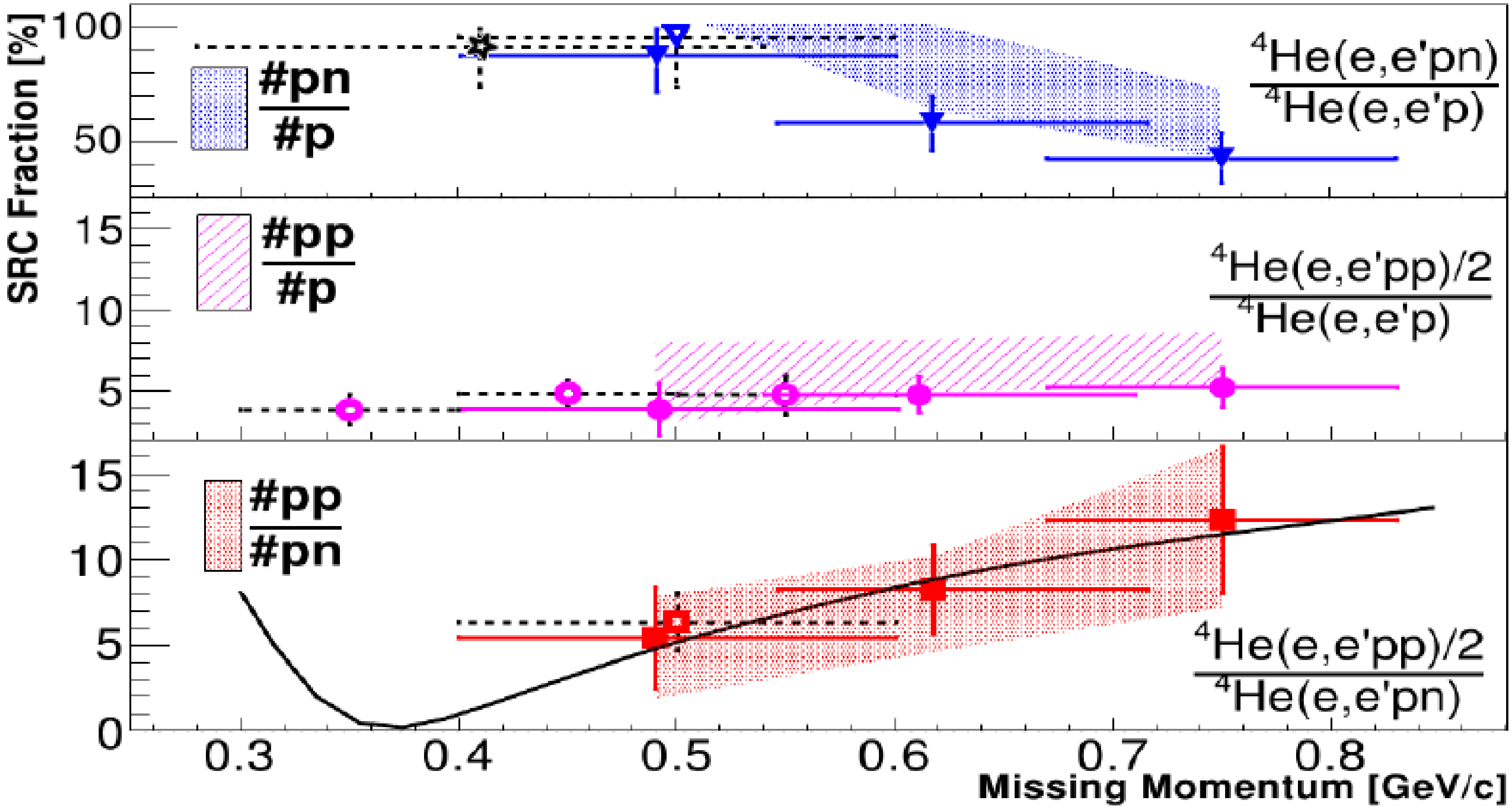




<u>Hadron Package:</u>

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

Final Ratio Results



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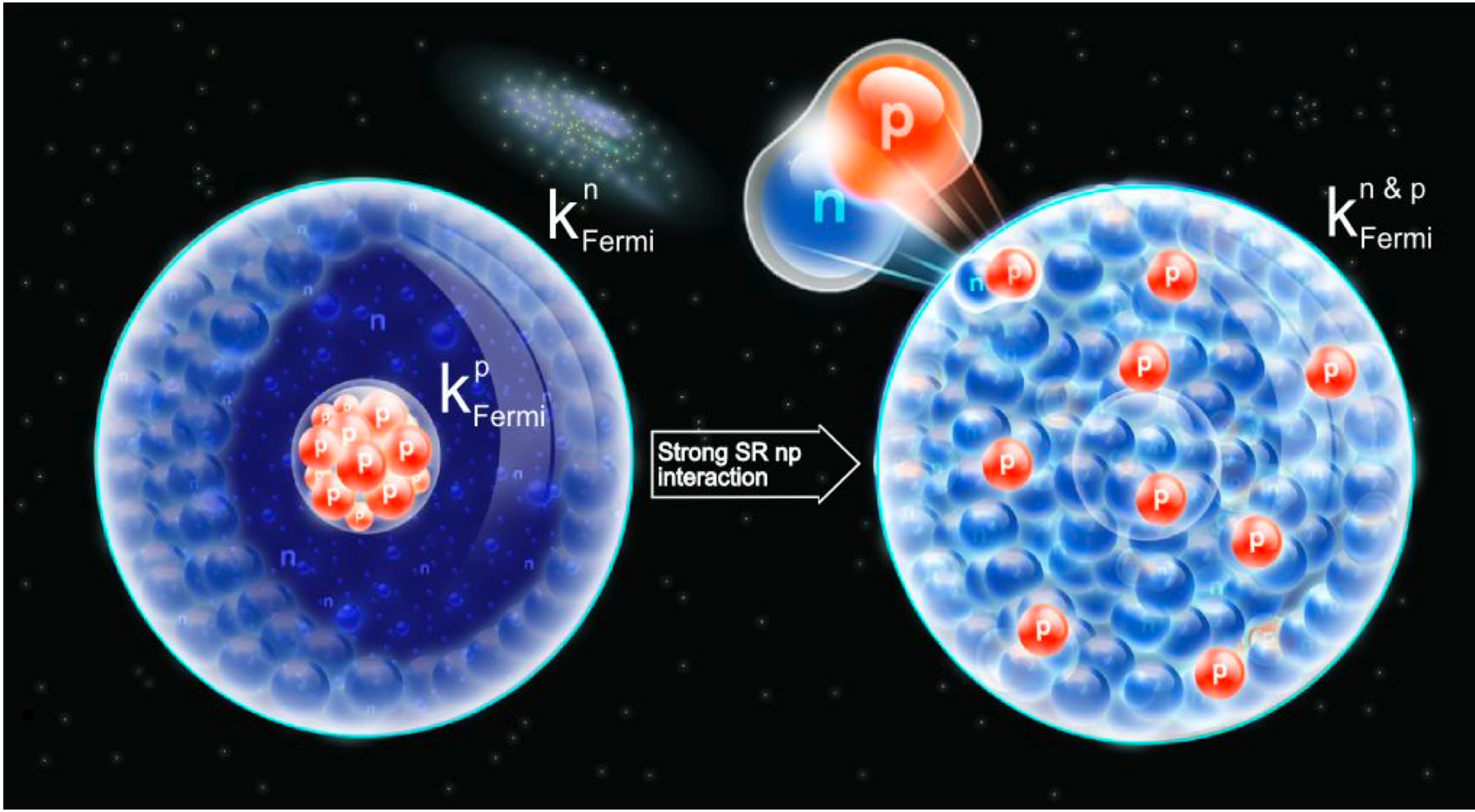
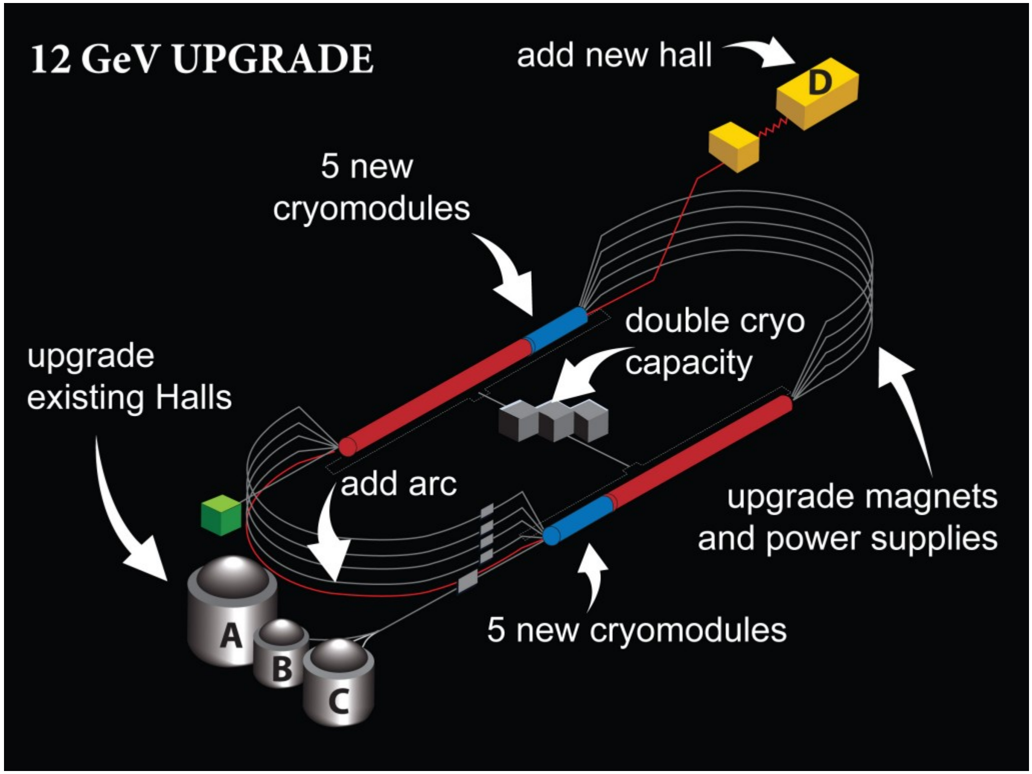
Implications for Neutron Stars



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

JLab 12 GeV Upgrade

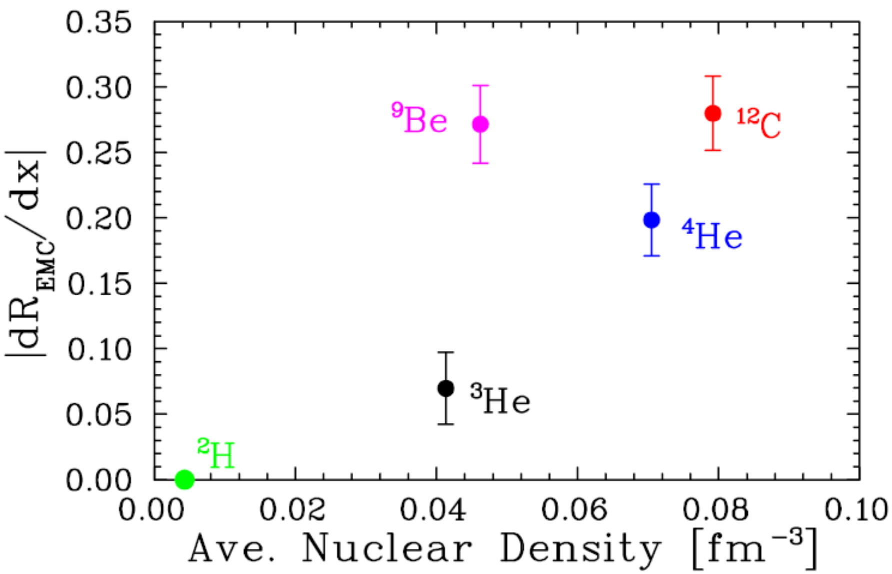
- JLab's 12 GeV upgrade is currently in the construction phase
- A fourth hall will be added
- The three current halls are being upgraded
- Several new experiments are already approved to run after the 12-GeV upgrade with **5 approved N-N Correlation experiments**

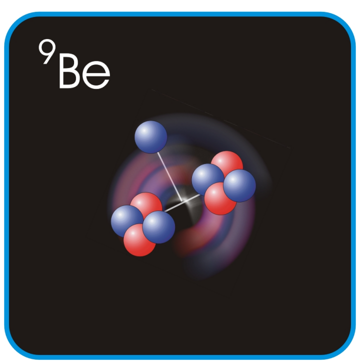


EMC Effect and EMC Slopes

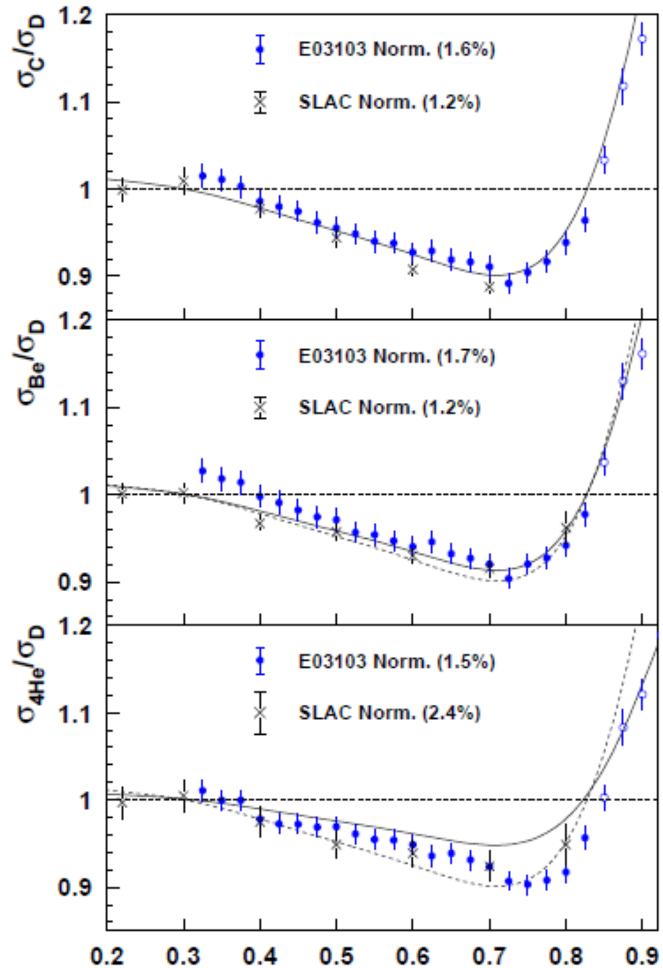
Indication that the EMC effect scales with the local environment of the nucleons

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



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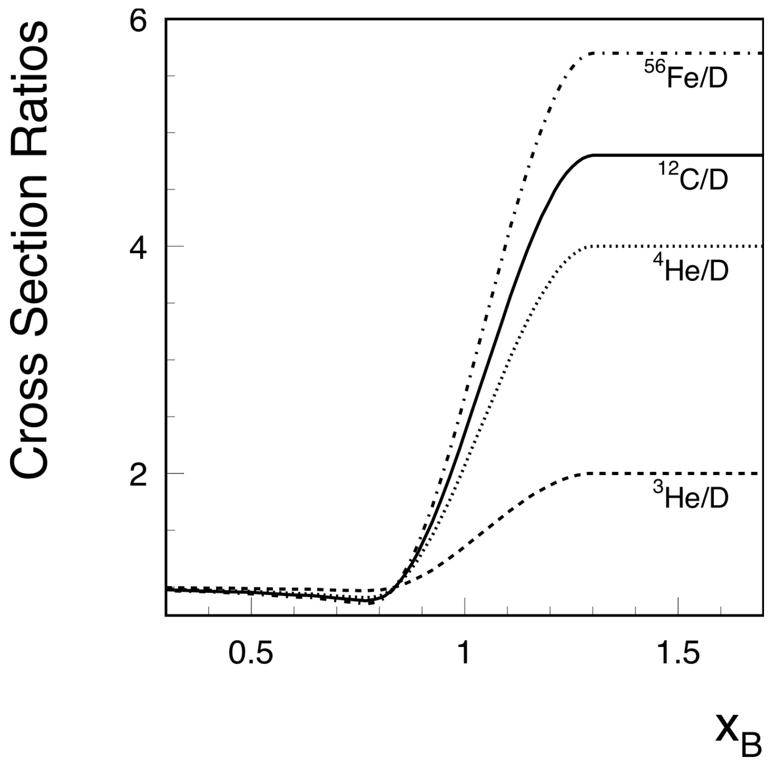
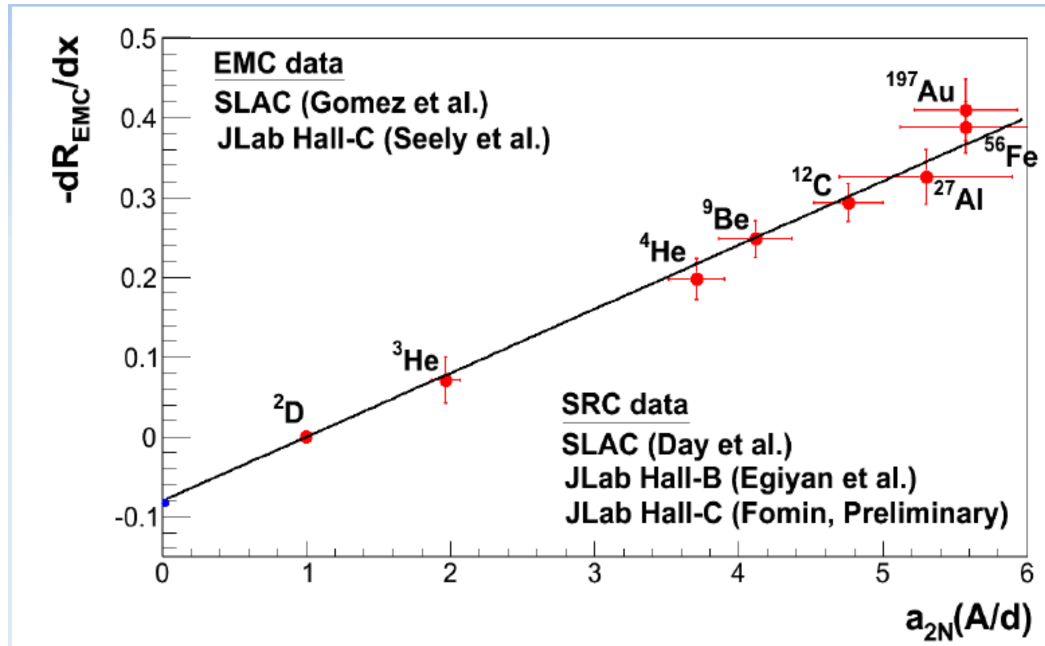
SRC Ratios and x>0.3 EMC Slopes

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

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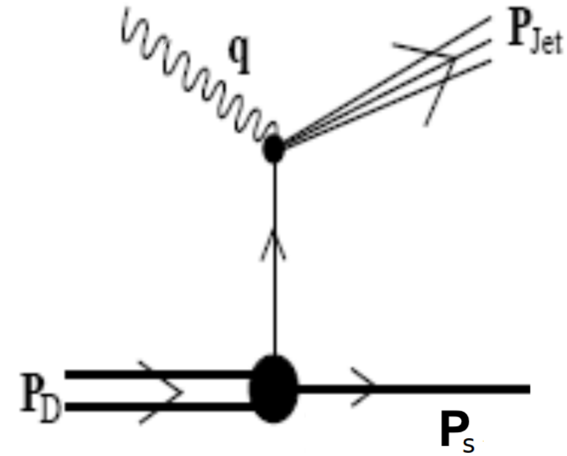
E12-11-107

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:

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

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

R_{FSI} is the FSI correction factor

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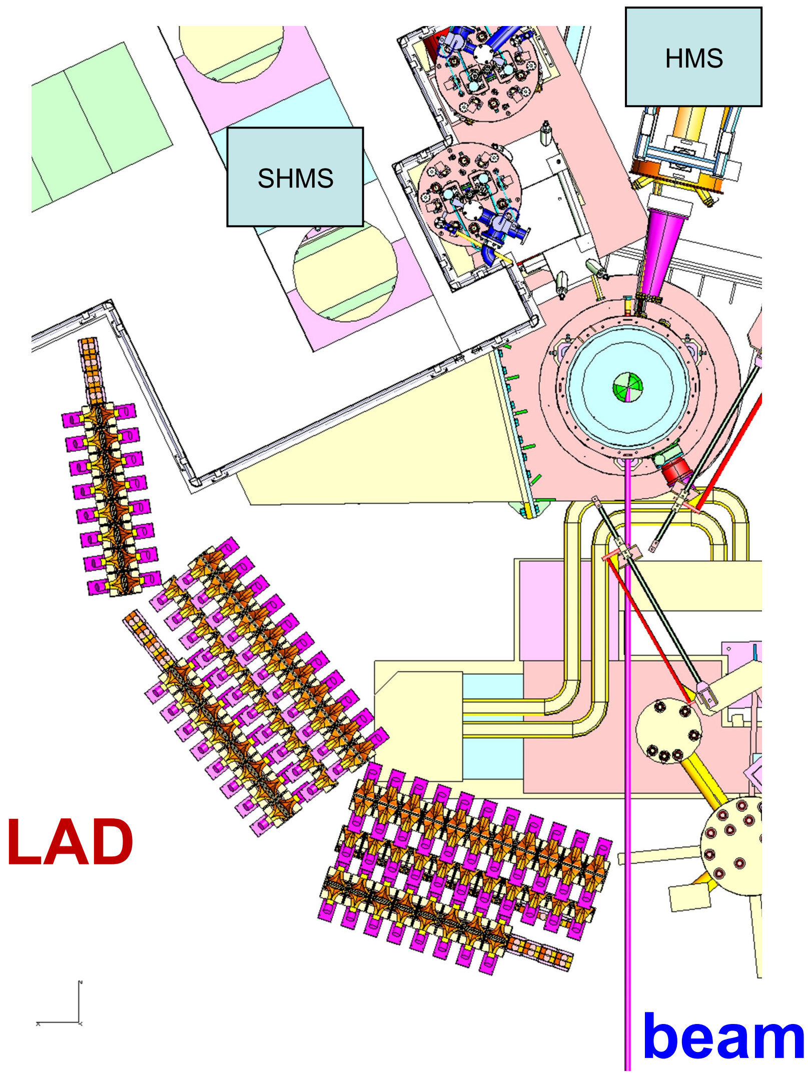
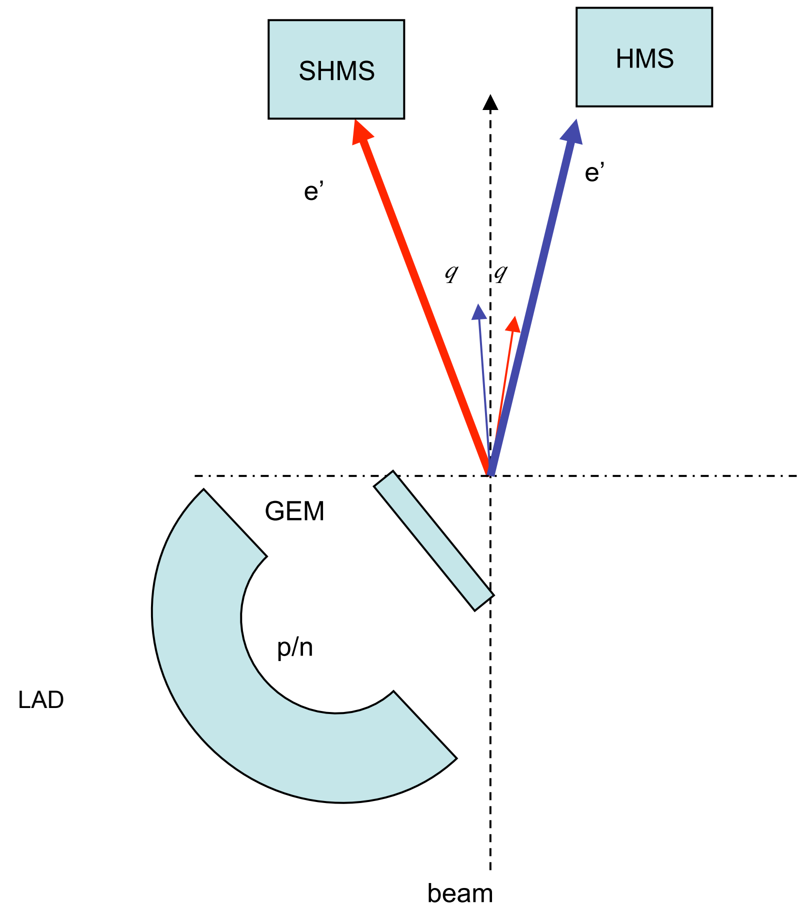
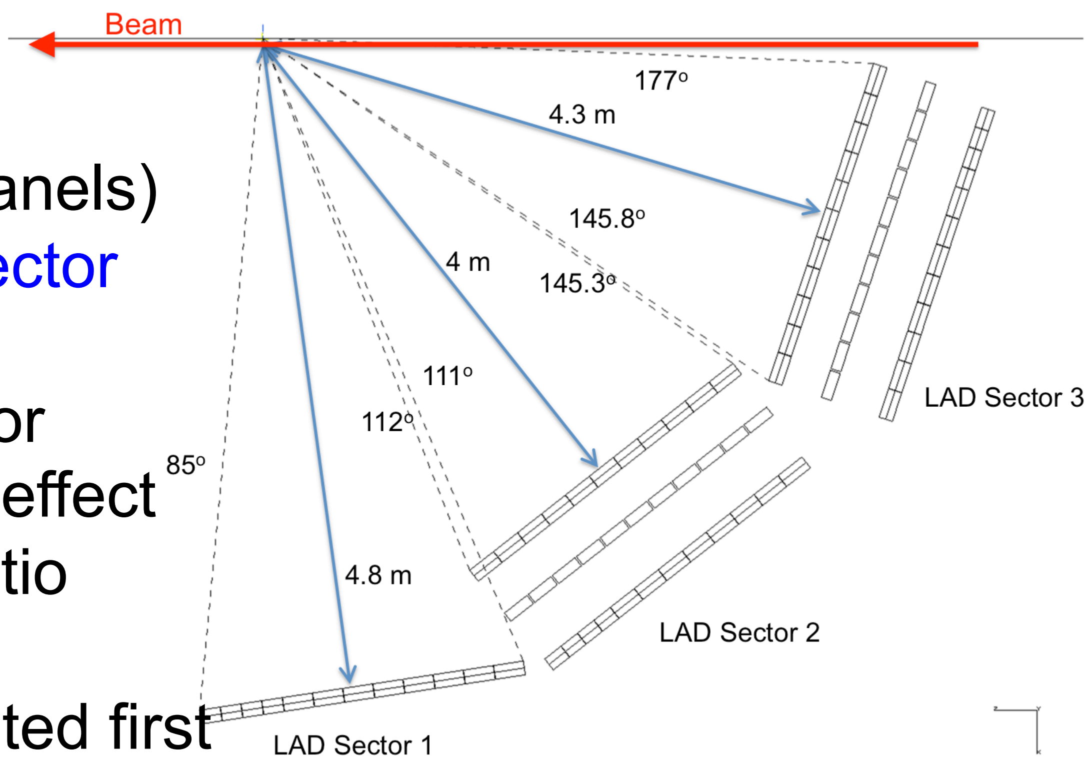
Experimental Setup





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)



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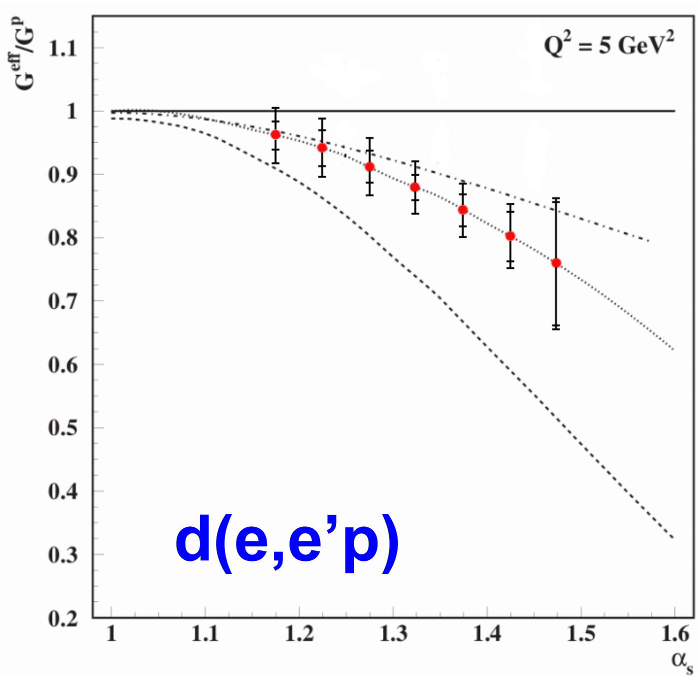
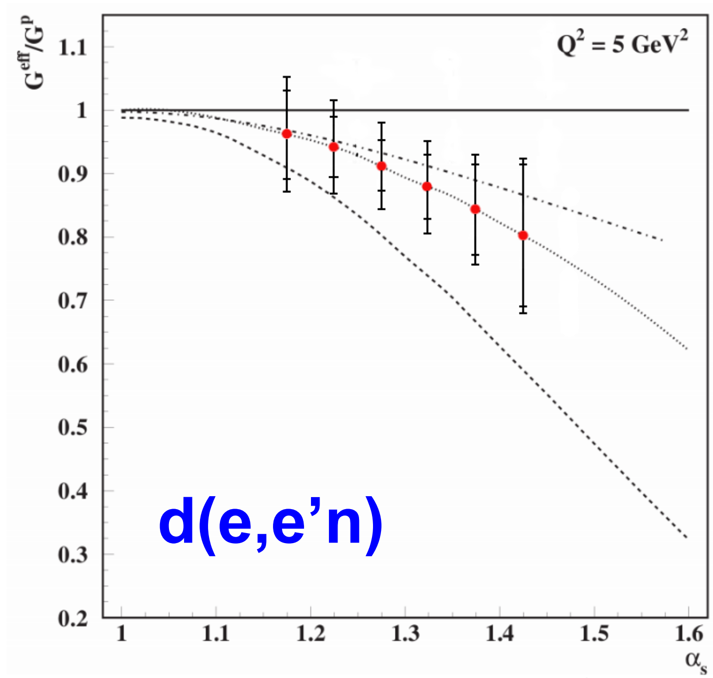
Expected Results

- 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

$$\alpha_s = (E_s - p_s^z) / m_s$$





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

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

Summary

- At JLab, we study the strong and weak interactions, proton/ neutron and nuclear structure, …
- 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!

Acknowledgements

- **Duke University:**
  - Zhihong Ye (formally UVA)
- **Hebrew University:**
  - Or Hen
  - Aidan Kelleher (formally)
- **JLab:**
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  - Patricia Solvignon-Slifer
- **Kent State:**
  - Larry Selvy (formally)
  - John Watson
- **Longwood:**
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- **MIT:**
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  - Shalev Gilad
  - Navaphon (Tai) Muangma
- **ODU:**
  - Larry Weinstein
- **Saint Mary's:**
  - David Anez
- **Tel Aviv University:**
  - Igor Korover
  - Eli Piasetzky
  - Ran Shneor
- **UVa:**
  - Charles Hanretty

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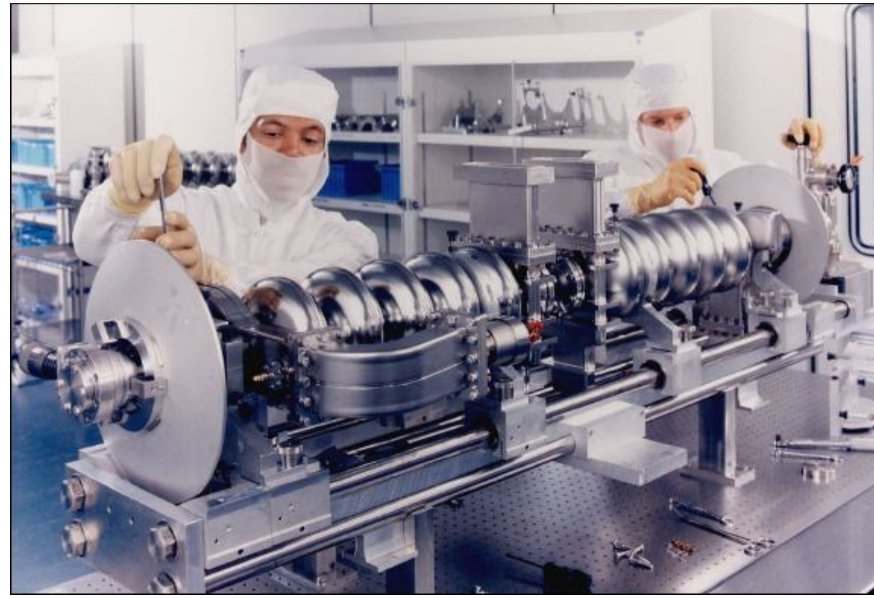
Polarized Electron Beam

- Circularly polarized laser light knocks electrons off of a photocathode
- The Superlattice Photocathode
  - New photocathode made with a thin layers of gallium arsenide grown atop layers of gallium arsenide phosphide.
- New technique allows 85-90% beam polarization.

Polarized beams probe protons and neutrons in a different way

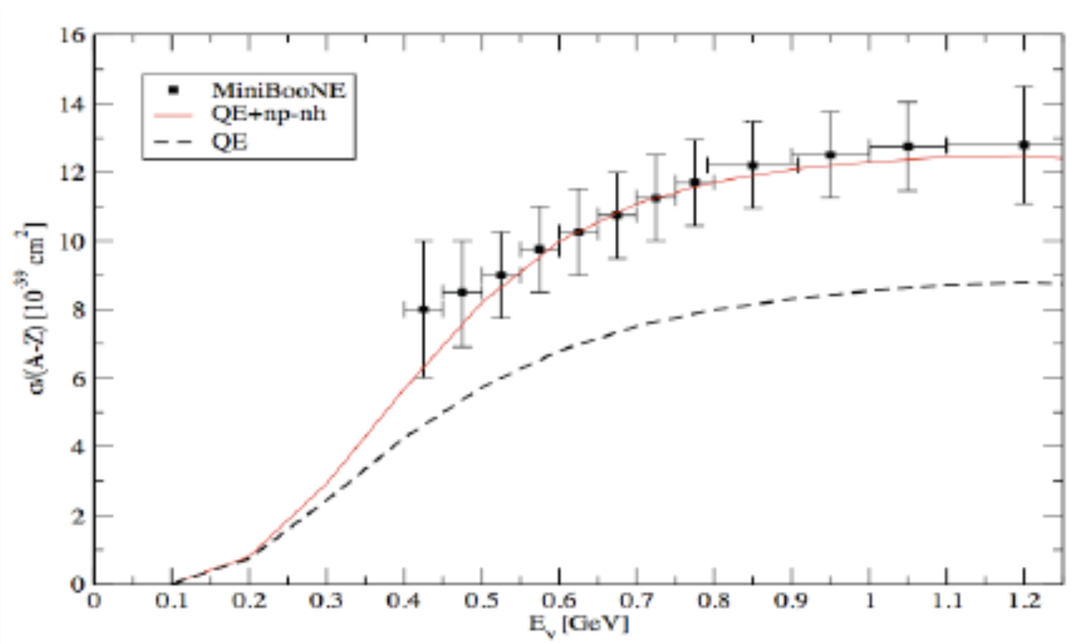
Electron Beam Acceleration



- Niobium cavities are placed in cryomodules and cooled with liquid helium to 2 K so that they become superconductors.
- An RF electric field travels with the electron around the accelerator.

SRC Impact on Neutrino Cross Sections

- *possible explanation*: extra contributions from multi-nucleon correlations in the nucleus (all prior calcs assume indep particles)



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

- large enhancement from short range correlations (SRC) and 2-body currents
- can predict MiniBooNE data without having to increase M_A (here, M_A=1.0 GeV)

from Dr. Sam Zeller, PANIC 2011

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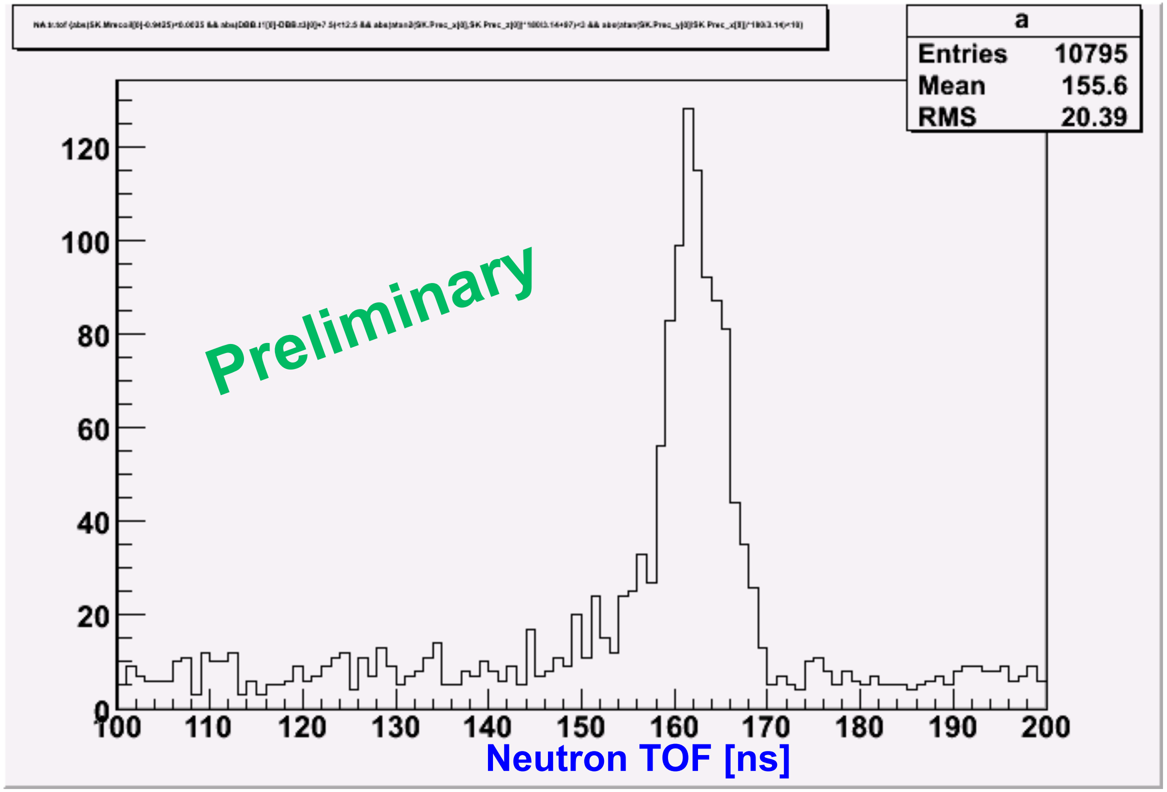
HAND Commissioning Results



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

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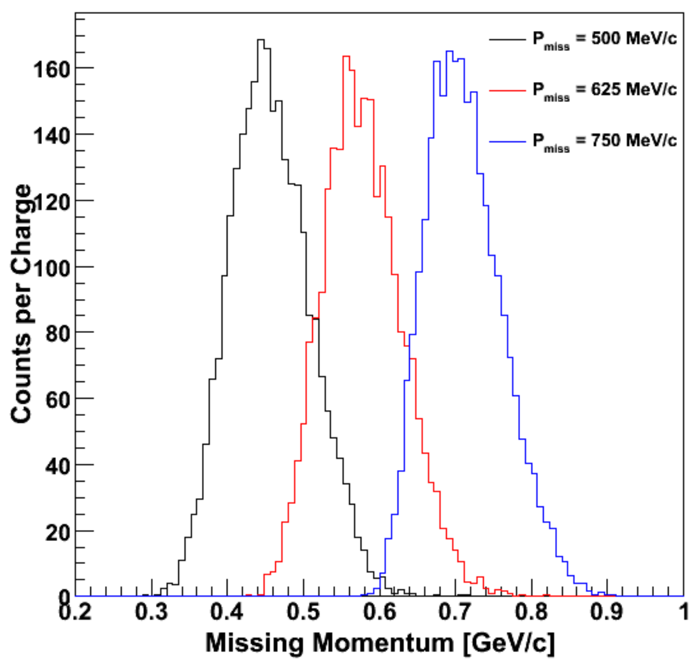
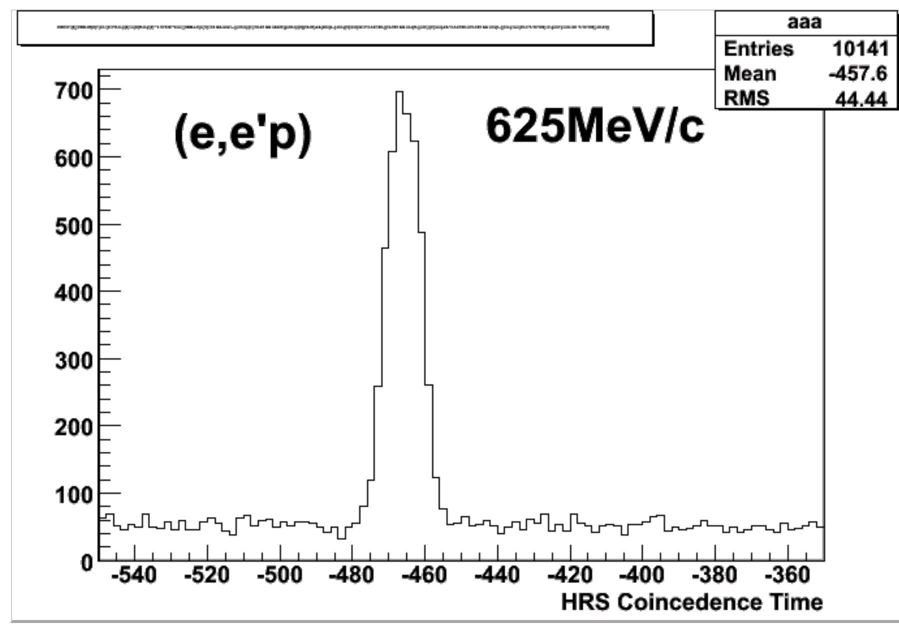
Very Preliminary Results

P_{miss} [GeV/c]	Charge [C]	Raw Counts ^{4}He(e,e'p)
500	2.0	5400
625	2.5	5100
755	3.9	8800





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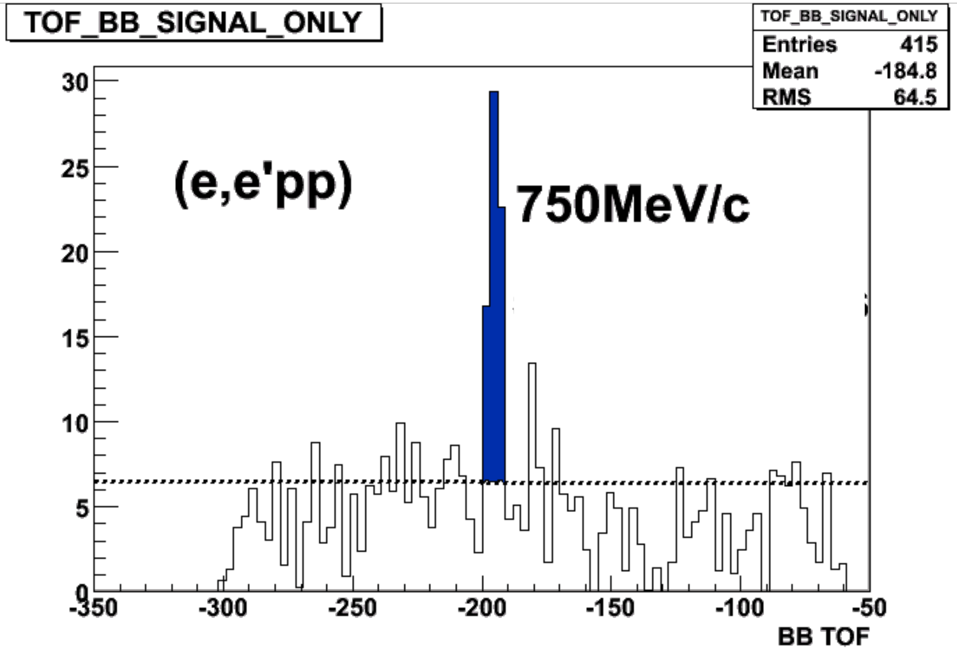
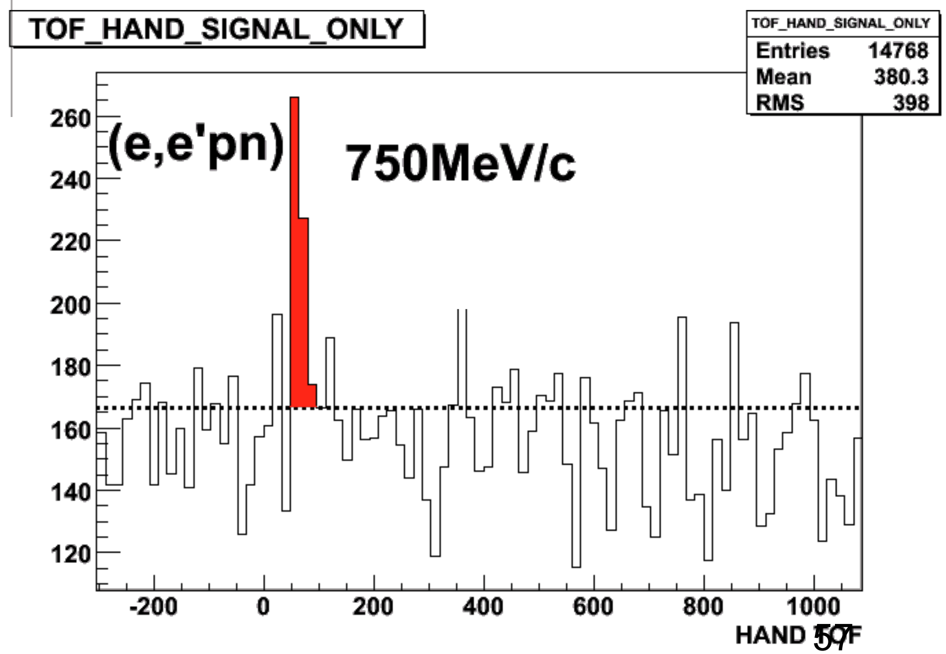
Very Preliminary (e,e'pp) and (e,e'pn) TOF



Current Analysis Status:

- Detector calibrations underway
- BPM and BCM calibrations completed
- ^{4}He target density calculated for each run
- Aiming for *preliminary* ^{4}He(e,e'p_{recoil}) cross sections by mid-November



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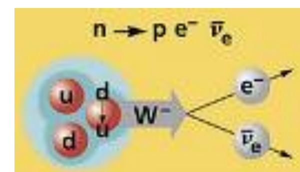
Future 12 GeV Experiment

Fundamental Forces in Nature

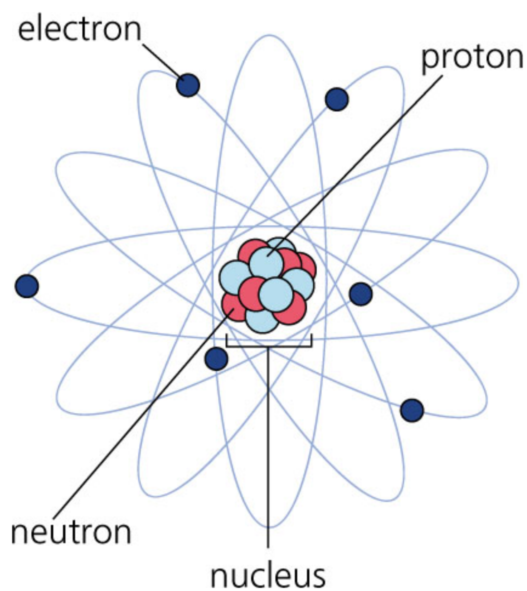


<u>Four Forces:</u>

- Strong Nuclear: short range (10^{-15} m)
- Electromagnetism: long range
- Weak Nuclear: short range (10^{-18} m)
- Gravitation: long range

- Gravity, EM and weak: **adequate description** (within experimentally accessible range)
- Strong: **analytical description** only in a **small fraction of the experimentally accessible range**

Properties of Protons and Neutrons



Mass : ~ 940 MeV: majority of the visible mass in the universe (> 99%); neutron mass > proton mass (1.3 MeV)

1 MeV = 1.602 x 10^{-13} J

a 150-g baseball has a mass ~ 10^{28} MeV

Charge: proton, +1; neutron, 0

Magnetic moment

Spin-1/2

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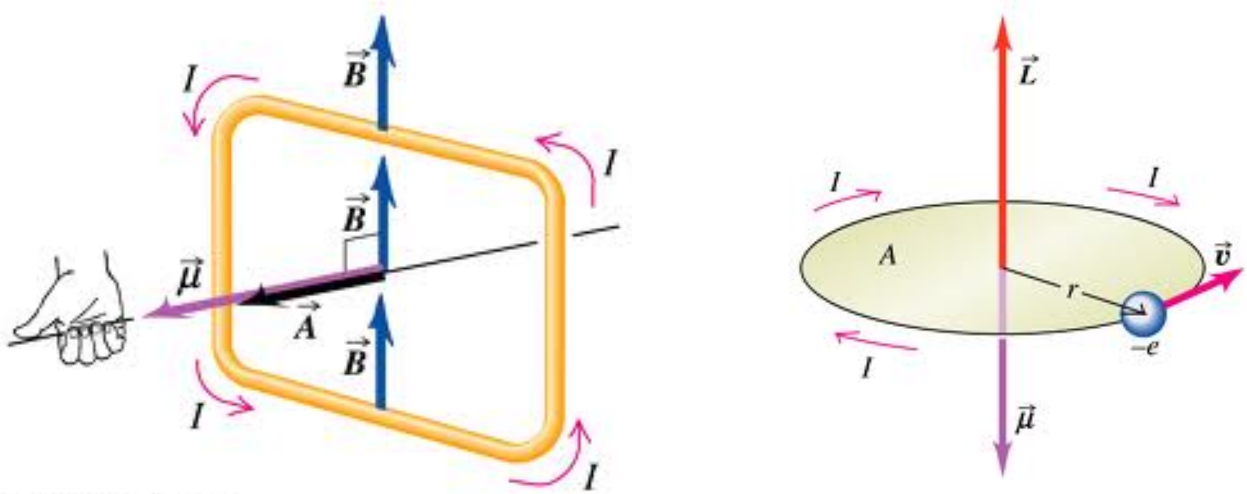
Magnetic Moments

- An electric current in a wire produces a magnetic field that curls around the wire.
- The **magnetic moment** ($\mu = IA$) quantifies the strength of the magnet; points from the south to the north pole of a magnet.
- An electron in a circular orbit around a nucleus has a magnetic moment that is proportional to its orbital angular momentum:
$\mu = IA = (e/2m)L$



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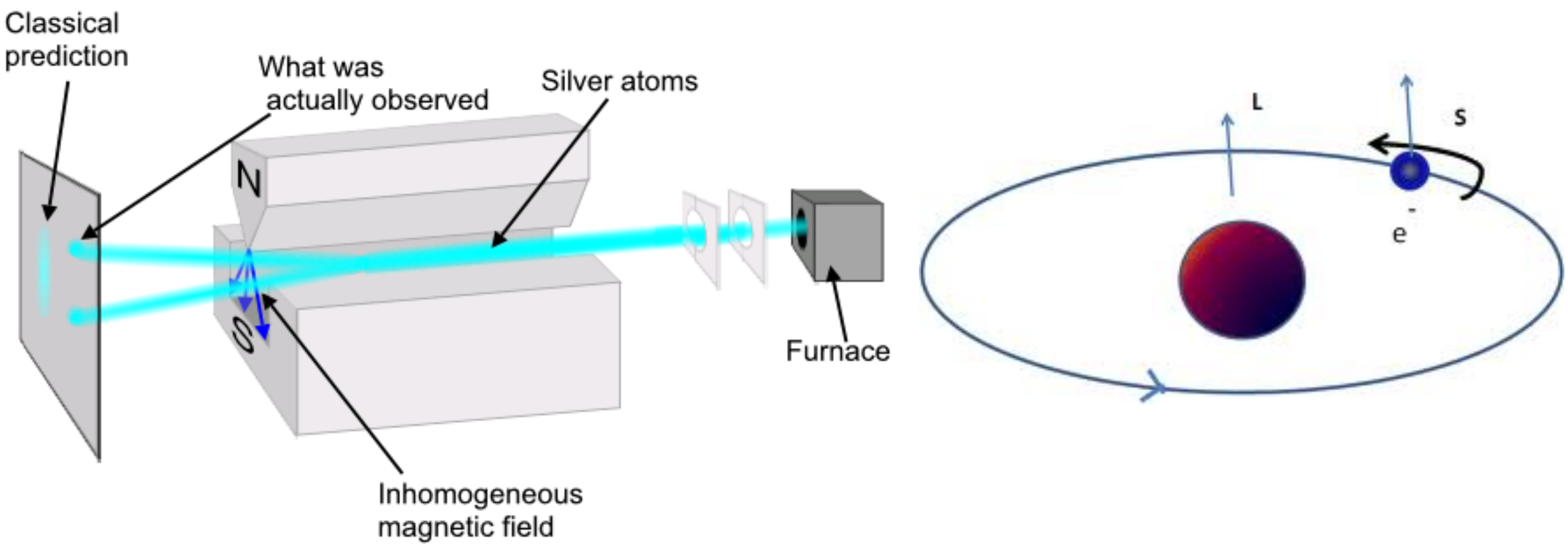
Spin

- In 1922, Stern and Gerlach discovered that the electron has an intrinsic property: **spin**, either up or down for electrons.



- Spin behaves like angular momentum.
- A particle's spin can be related to its **magnetic moment**:

$$\boldsymbol{\mu} = e\boldsymbol{Q}/M\,\boldsymbol{S}$$

Nucleon Magnetic Moments

Nucleon is not a Dirac particle (*point-like* particle)

spin $\frac{1}{2}$ $\mu = \frac{e\hbar}{2mc}$

$\mu_p = +2.79\ \mu_N$ *Frisch and Stern (1933)*

$\mu_n = -1.91\ \mu_N$ should be 0

→ **per-se indication of internal structure**

$$\kappa_p = \frac{\mu_p - \mu_N}{\mu_N} = +1.79 \qquad \kappa_n = \frac{\mu_n - 0}{\mu_N} = -1.91$$

- First hint that the **proton and neutron are composite particles**.
- In 1933, Estermann and Stern discovered that the proton has a large **anomalous magnetic moment**: κ.

Why use electron scattering?

1) Scattering experiments reveal the proton's and neutron's internal structure.
2) Electrons are point particles and their interactions are understood from the theory of electromagnetism (Quantum Electrodynamics).

Electron scattering has proven to be a valuable tool to understand and investigate nucleon structure.

History of Electron Nucleon Scattering

- 1930s proton anomalous magnetic moment was discovered (O. Stern), direct indication of proton internal structure.

$$\mu_p \approx 2.793(\mu_B) \neq 1(\mu_B)$$

- Nobel Prize 1943

- Pioneered by Hofstadter *et. al* at Stanford in 1950s, first proton form factor measurement reported in 1955.

- Nobel Prize 1961

- DIS of electrons from protons by Friedman, Kendall and Taylor unravels the underlying quark structure of the proton at SLAC .

- Noble Prize 1990

- While QCD has been tested well in the asymptotic region (David J. Gross, H. David Politzer, Frank Wilczek), understanding hadron structure in confinement region still challenging.

- Noble Prize 2004

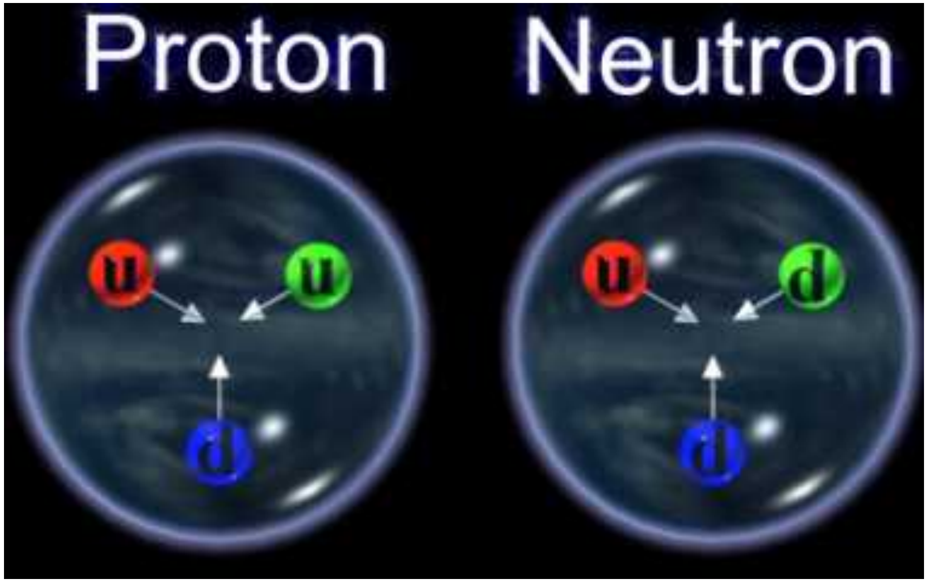
So what are we really made of?

Experimental results can be explained using quarks

- **Basic Quark model**:
  - Protons are made of two up quarks and one down quark
  - Neutrons are made of two down quarks and one up quark
- So it seems **we are made of up quarks, down quarks, and electrons**.

Subatomic world:

Scale: 10^{-15} m = 1 fm



Four forces describe all interactions:

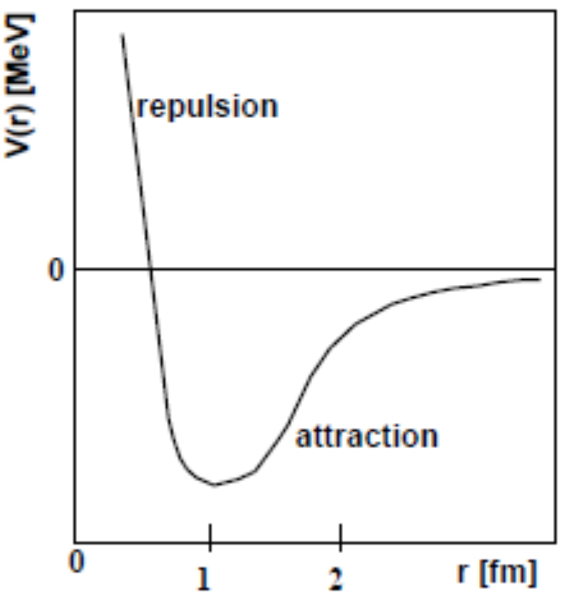
gravity, **electromagnetism**, **weak nuclear** and **strong nuclear**

Strong Nuclear Force

- The theory is known as Quantum Chromodynamics (QCD)
- Holds nucleons and quarks together: **confinement**
- Difficult to solve mathematically, since gluons carry color charge and interact with themselves

- Options:
  - Model with a computer (Lattice QCD)
  - Make simplifications:
    High Energy (Perturbation theory)
    Low Energy (Chiral Perturbation theory)

- Theory should explain the internal dynamics of protons and neutrons and their global properties.



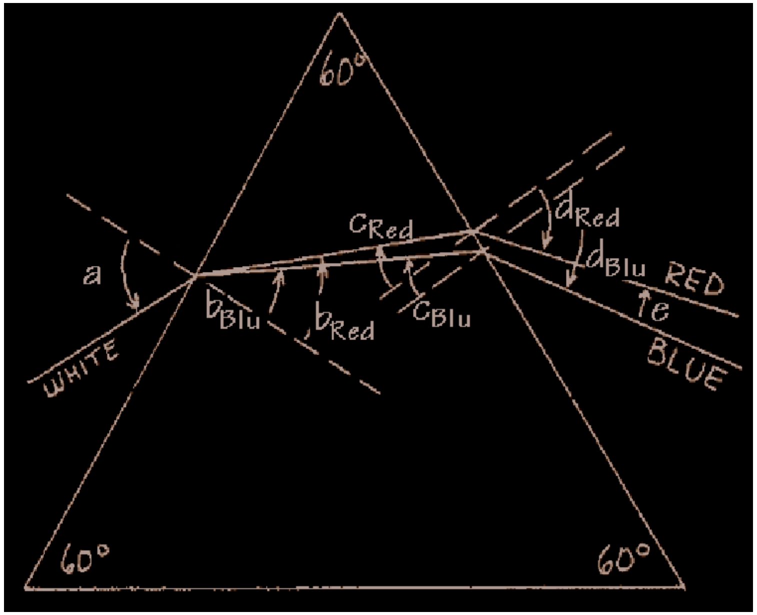
Effective Theories

When complexity makes the basic degrees of freedom too complicated to handle, effective theories can be used.

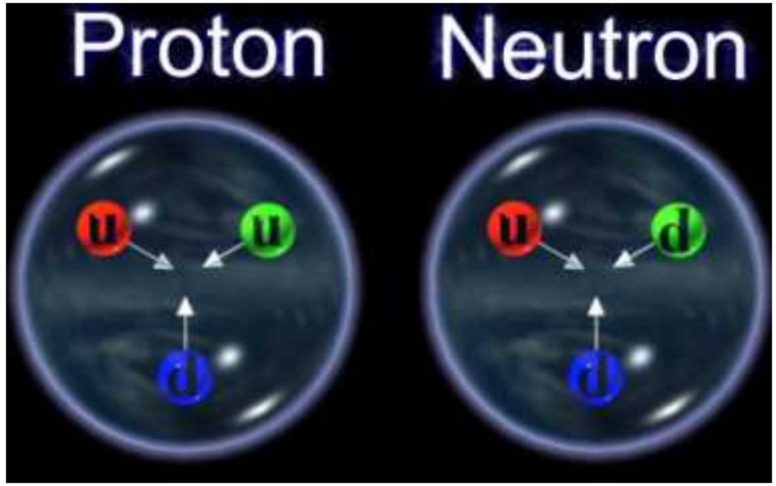
Legitimately a part of our description of Nature as long as connections with the fundamental theory are known.

A standard procedure in science:

e.g., geometric optics → electromagnetism,
thermodynamics → statistical mechanics



What do we know about their internal structure?



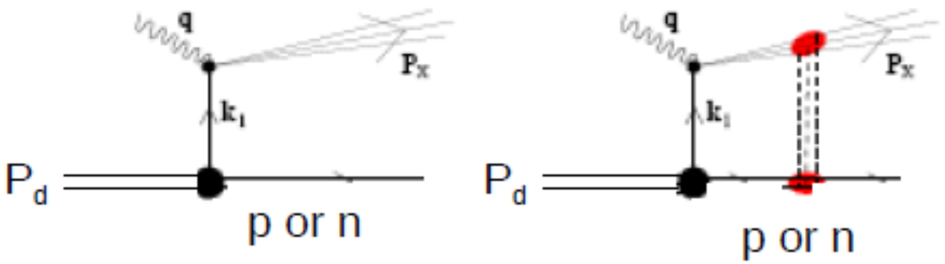
Mass: ~ 940 MeV, but u- and d-quark mass only a few MeV each!

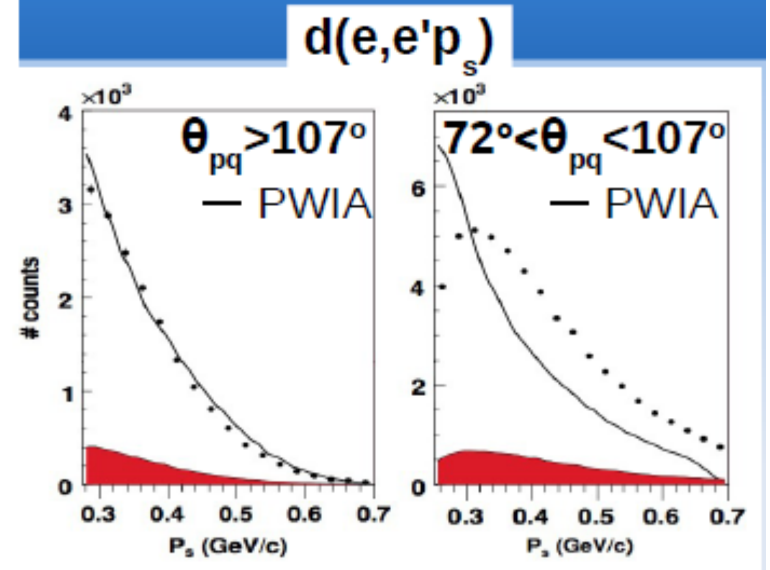
1 MeV = 1.602 x 10^{-13} J

Charge: proton, +1; neutron, 0
Magnetic moment: large part is anomalous, > 150%!
Spin-1/2: but total quark spin contributes only ~ 30%!

Sum of the parts is not equal to the whole!

Obstacles (FSI)





DEEPS, PRC 73, 035212 (2006)

What do we know about FSI:

Decrease with Q^2

Increase with W'

Not sensitive to x'

Small for θ_{pq}>107°

How are we going to minimize (correct for) FSI:

* Collect data at very large recoil angles (small FSI) and at ~90⁰ (large FSI)

* look at ratios of two different x'

* Use the low x' large phase space to check / adjust the FSI calculations (Study the dependence of FSI on Q^2, W' and θ_{pq})

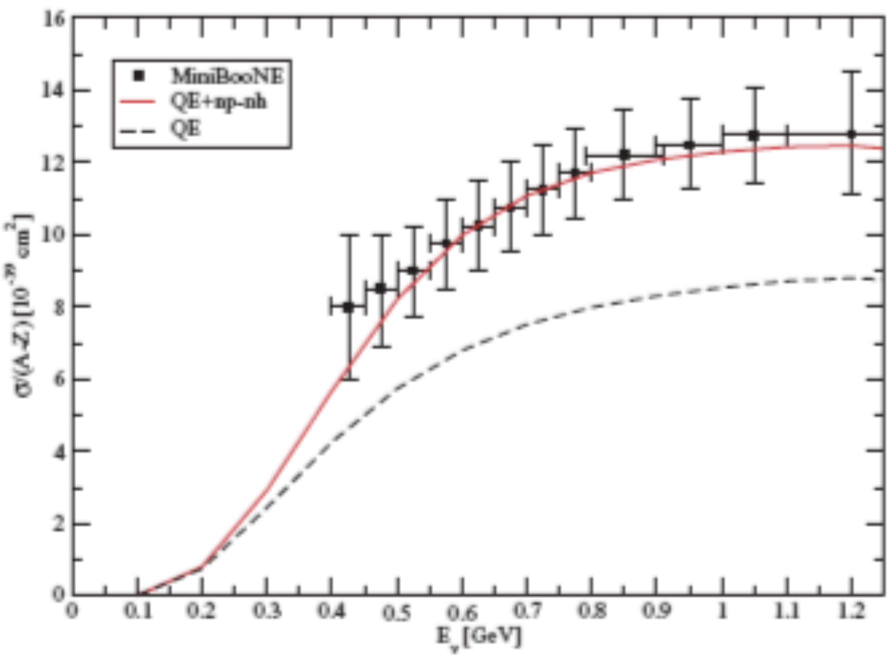
* Large involvement of theoretical colleagues at all stages of proposal, measurement, and analysis

22

Even More Surprising - Theoretical Support

M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PHYS. REV. **C 80**, 065501 (2009)

They use M_A=1.03 GeV, in an RPA formalism

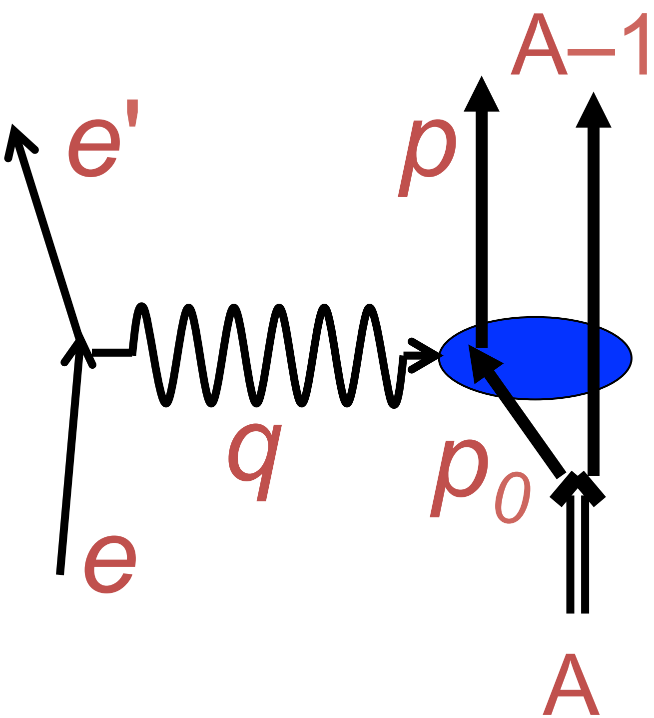


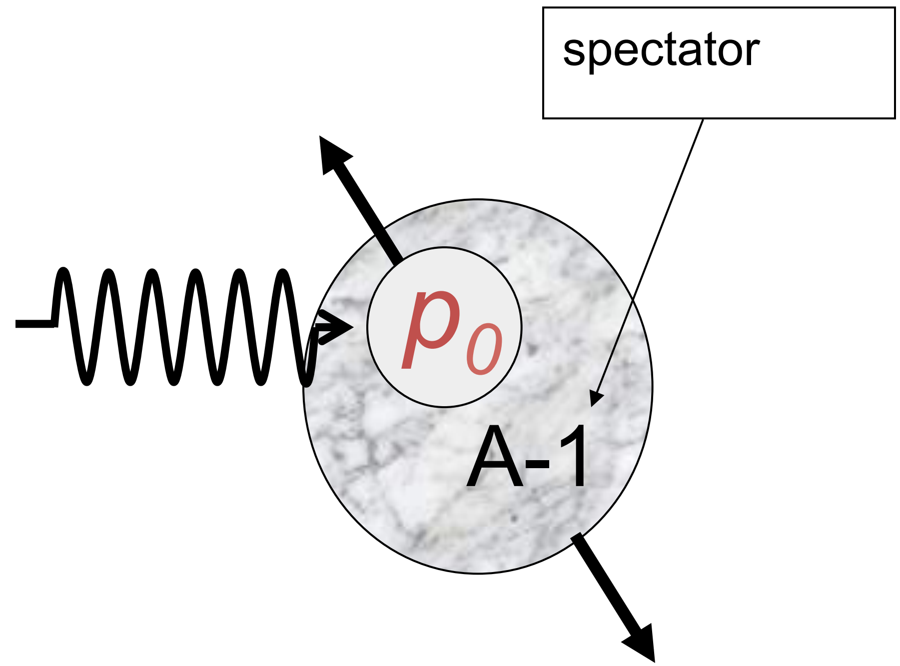
"We suggest that the proposed increase of the axial mass from the standard value to a larger one to account for the quasielastic data, reflects the presence of a polarization cloud, mostly due to tensor interaction, which surrounds a nucleon in the nuclear medium. It translates into a final state with ejection of two nucleons, which in the present stage of the experiments is indistinguishable from the quasielastic final state."

$$\sigma_{\nu(\bar{\nu})} \approx V_L^2 + V_T^2 + (-)2V_T A_T + A_T^2$$

Simple Theory Of Nucleon Knock-out

Plane Wave Impulse Approximation (PWIA)





$$q - p = p_{A-1} = p_m = - p_0$$

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

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

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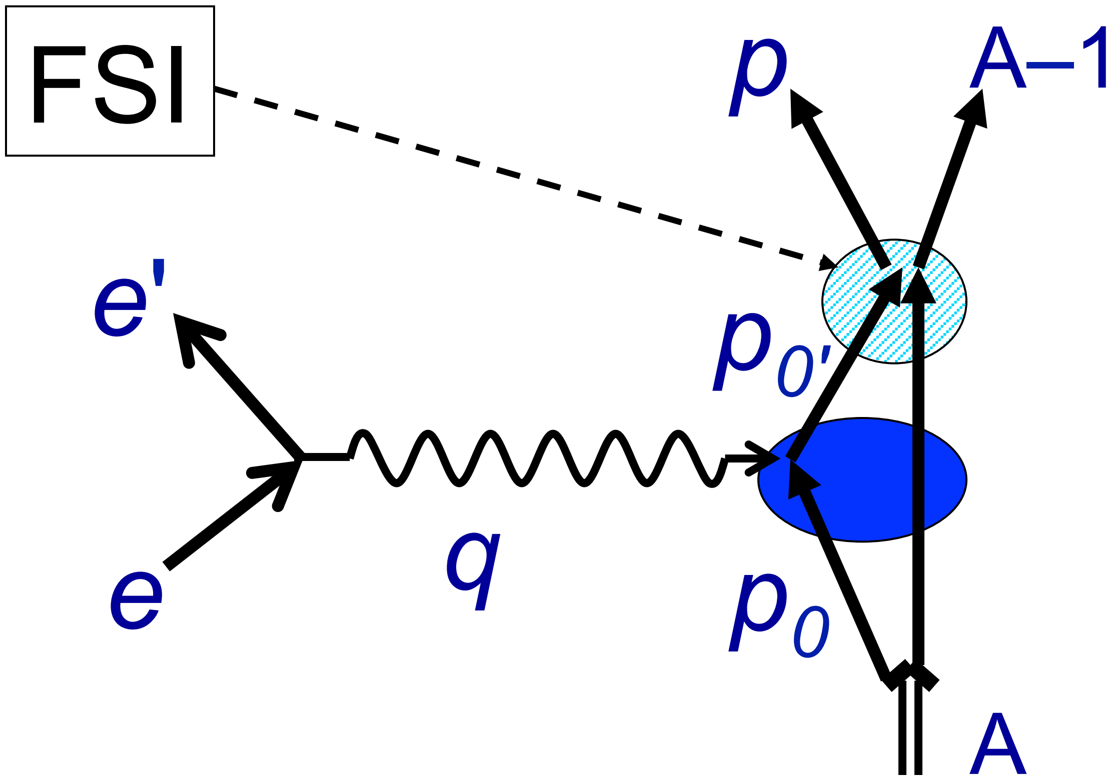
Reaction Mechanisms

Example: Final State Interactions (FSI)



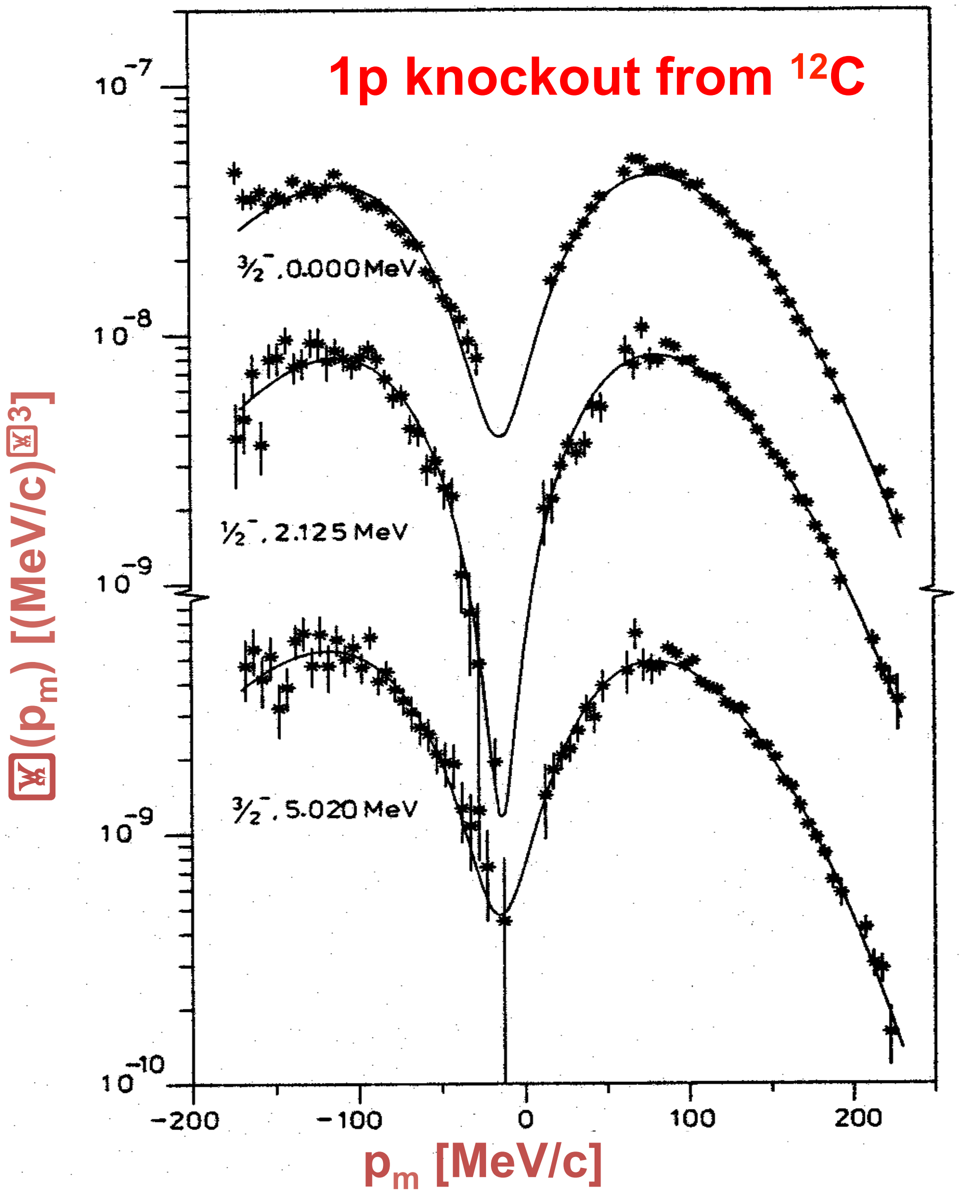
$$\vec{q} - \vec{p} = \vec{p}_{A-1} \neq \vec{p}_0$$

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).

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Inclusive Scattering at Large x

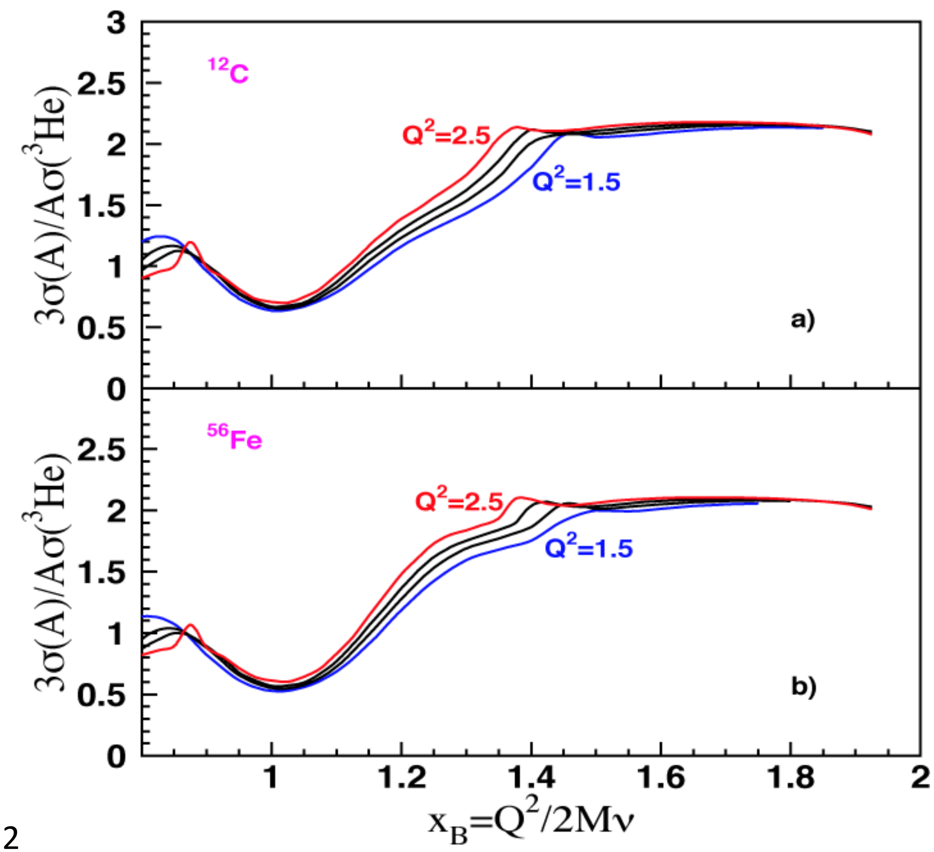
Define y as the x_B-value at which the minimum p_{miss} exceeds p_{Fermi}

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



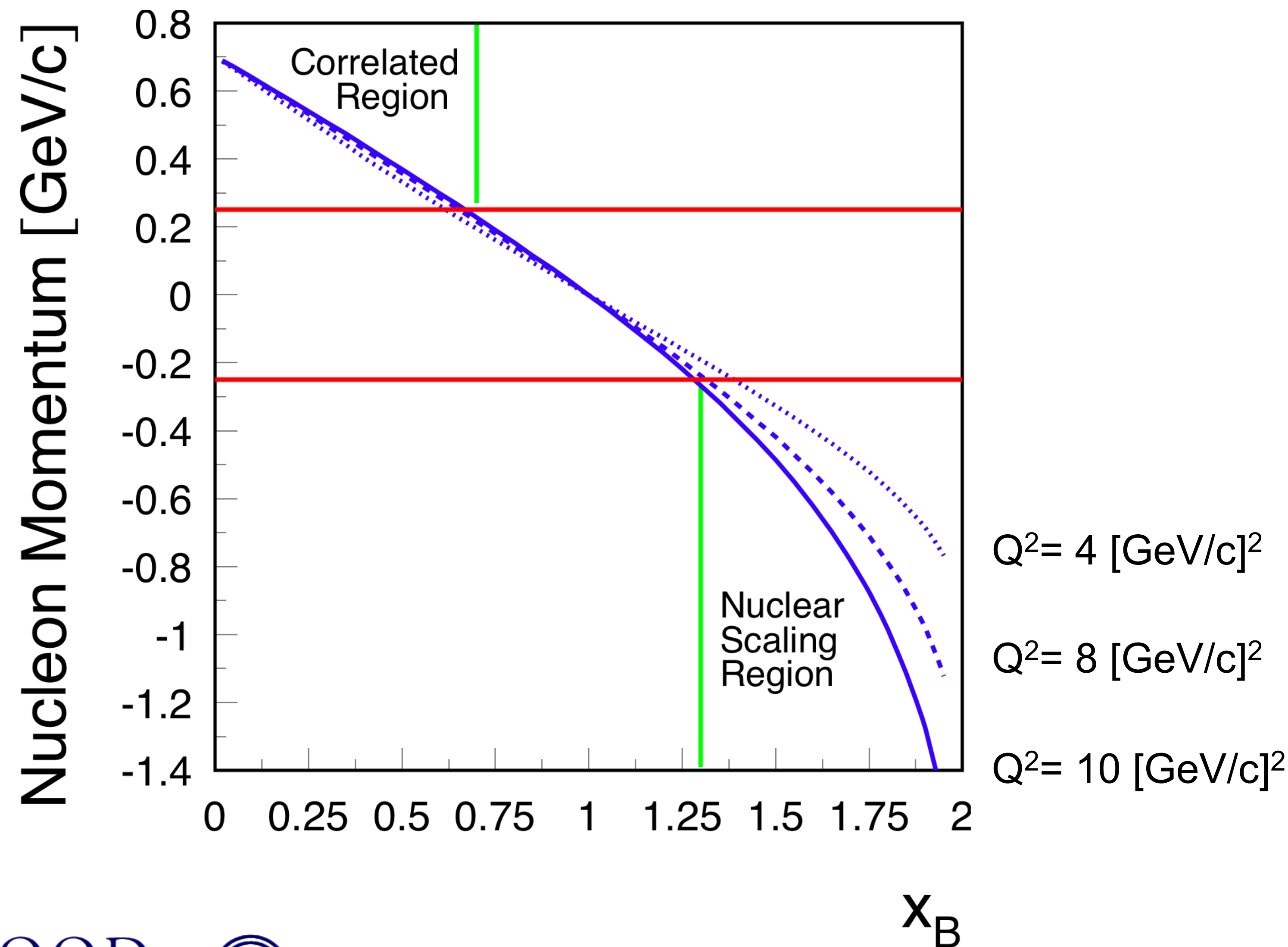
SRCs From Inclusive Measurements

- Scaling onset corresponds to $P_{min} \approx 275$ MeV/c

$$\int_0^\infty n_d(k)k^2\,dk = 100\% \implies \int_{P_{min}}^\infty n_d(k)k^2\,dk = 4\%$$

- In nuclei with A > 12, 2N-SRC account for:
  - ~20% of the nucleons in the nuclei
  - ~80% of the kinetic energy carried by the nucleons
- 3N-SRC are an order of magnitude less abundant then 2N-SRC

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



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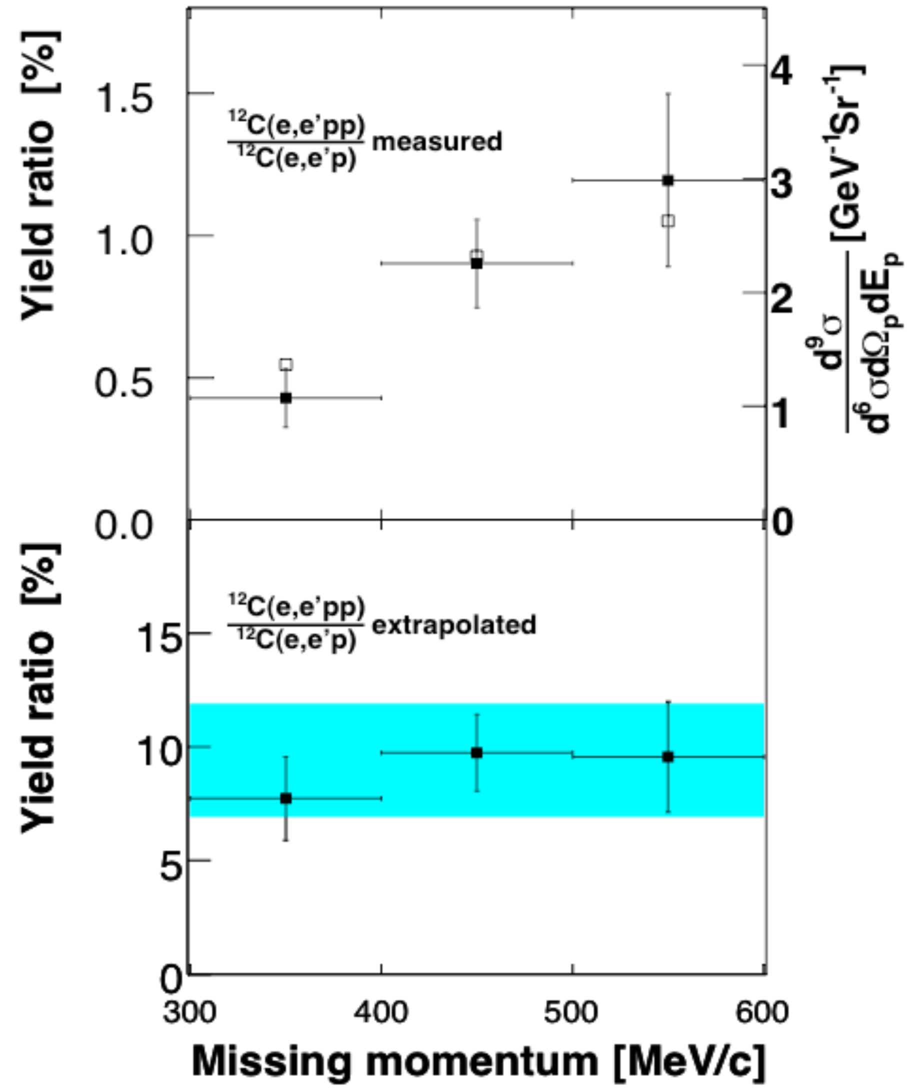
Ratio of $^{12}C(e,e'pp)$ to $^{12}C(e,e'p)$

- 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



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