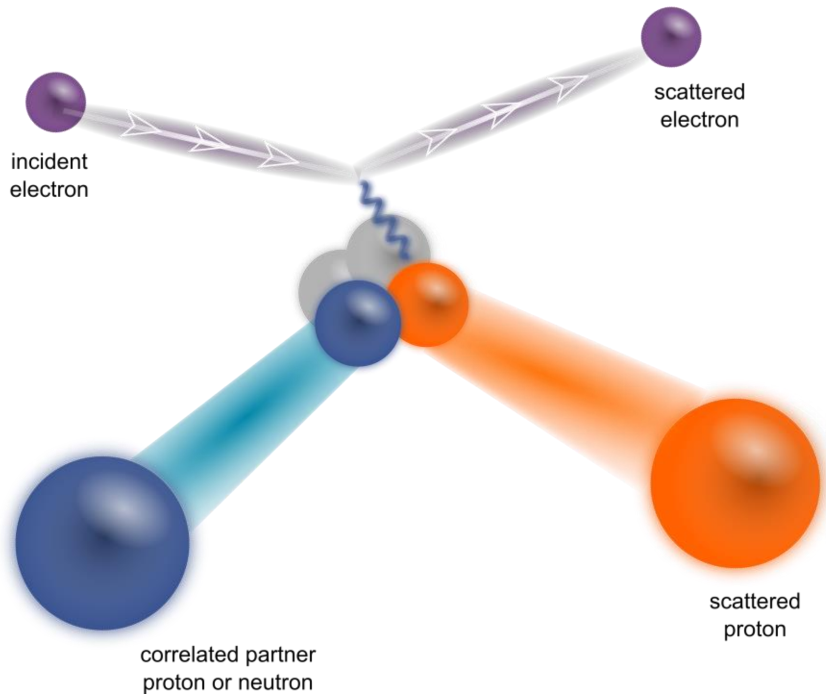
Nucleon Form Factors and the Nuclear Medium



Vincent Sulkosky

University of Virginia

HUGS 2014, Lecture 3

June 12th, 2014

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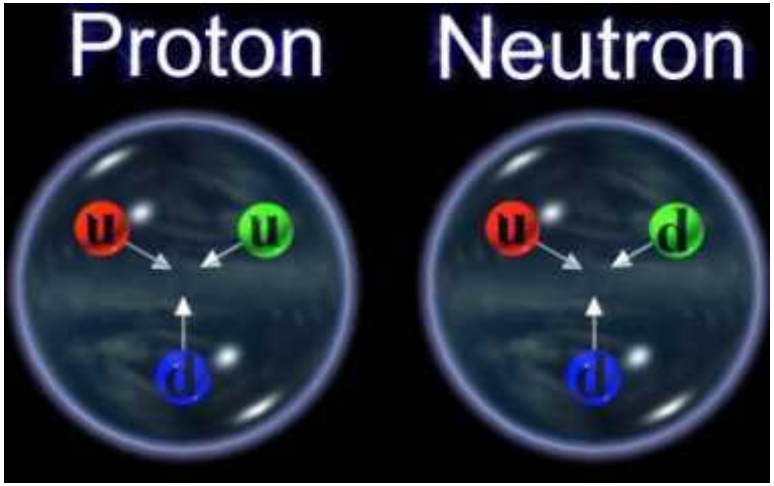
What do we know about their internal structure?



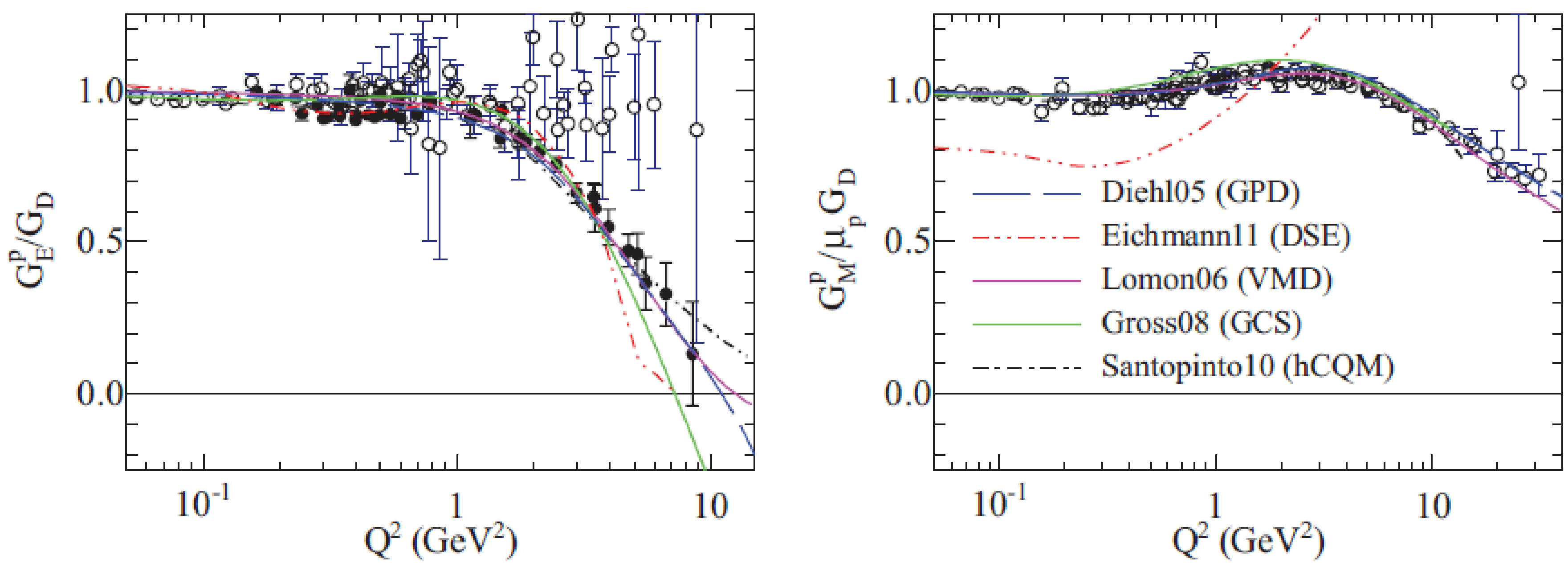
Mass: ~ 940 MeV, but u- and d-quark mass only a few MeV each!

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!

Proton FFs Including JLab Data

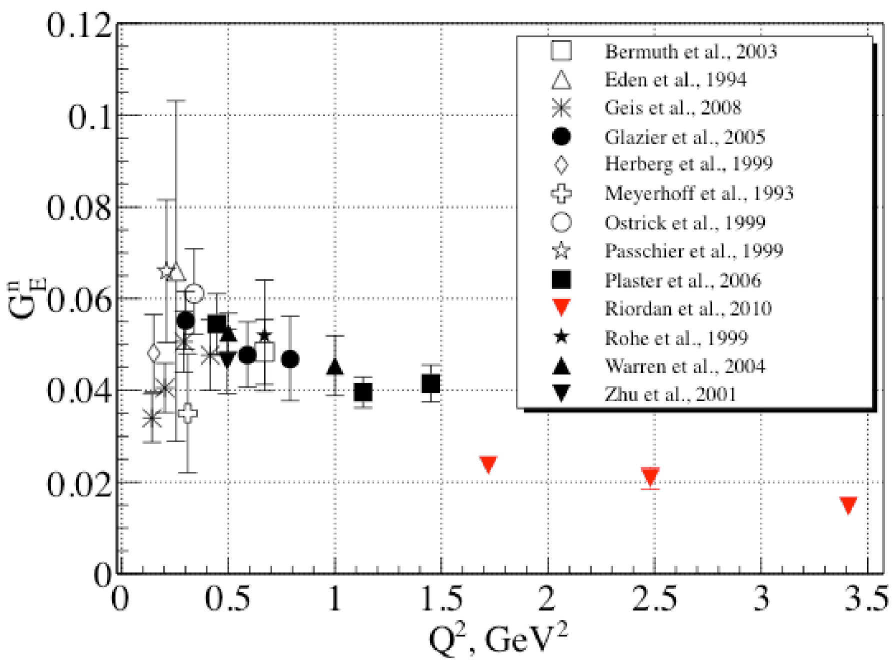


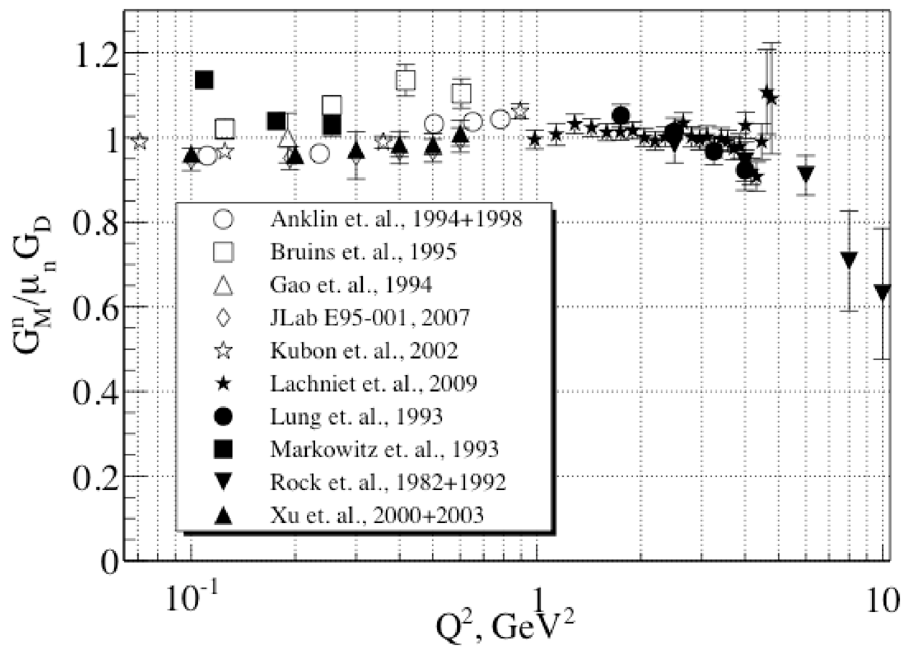
cross-section data: open circles

polarization data: filled circles

Neutron FFs Including JLab Data

G_{En} and $G_{Mn}/\mu \sim G_D$





Requires the use of light nuclei such as the deuteron and ^{3}He

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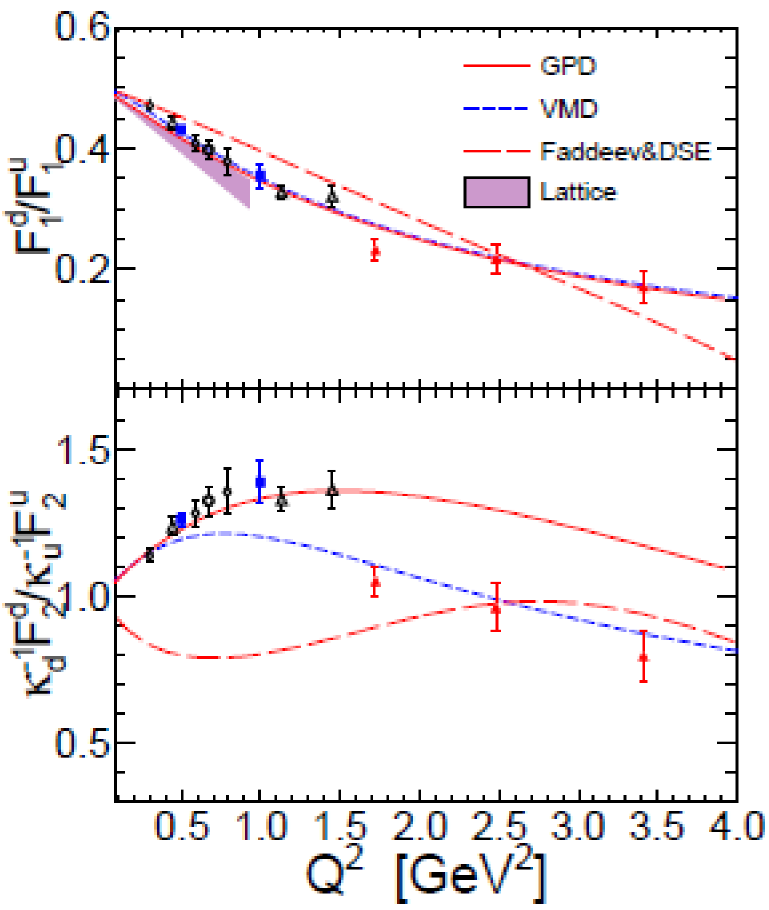
Quark Flavor Decomposition



- General Parton Distribution (GPD) models are constrained by nucleon form factors:

$$F^p_{1,2} = \frac{2}{3}F^u_{1,2} - \frac{1}{3}F^d_{1,2}$$

$$F^n_{1,2} = -\frac{1}{3}F^u_{1,2} + \frac{2}{3}F^d_{1,2}$$

- High Q^2 for G_E^n data allows for quark decomposition
- Lattice QCD is better suited for isovector FF

Lattice: Bratt et al., arXiv: 1001.3620, m_π = 140 MeV

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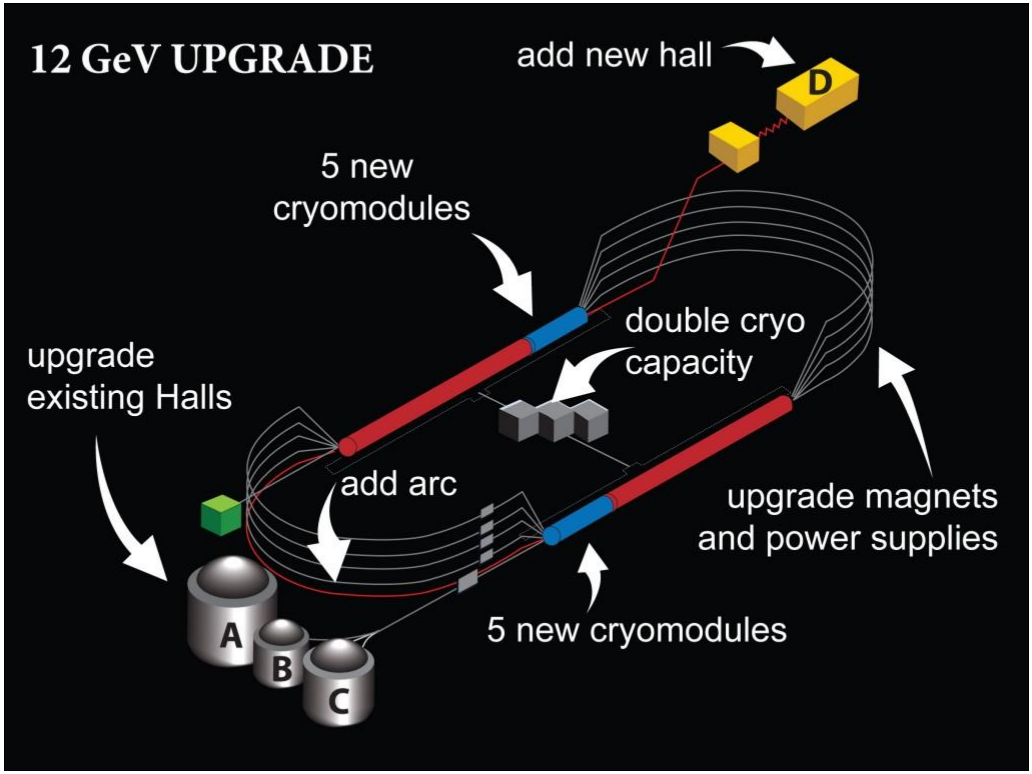
JLab 12 GeV Upgrade

- JLab's 12 GeV upgrade is currently in the construction phase
- Hall D will be added
- The three current experimental halls are being upgraded
- Several new experiments are already approved to run after the 12-GeV upgrade with **6 approved form factor experiments**



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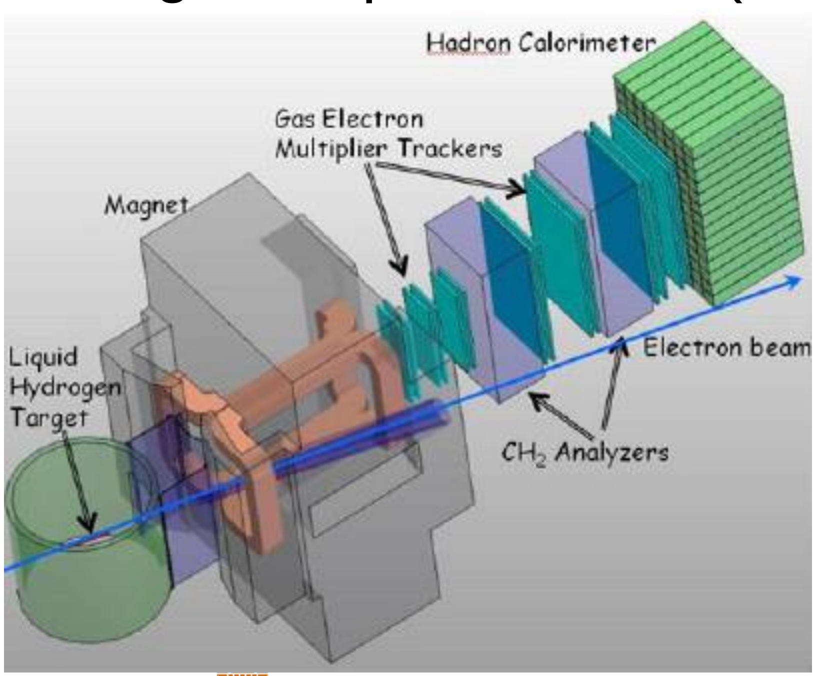
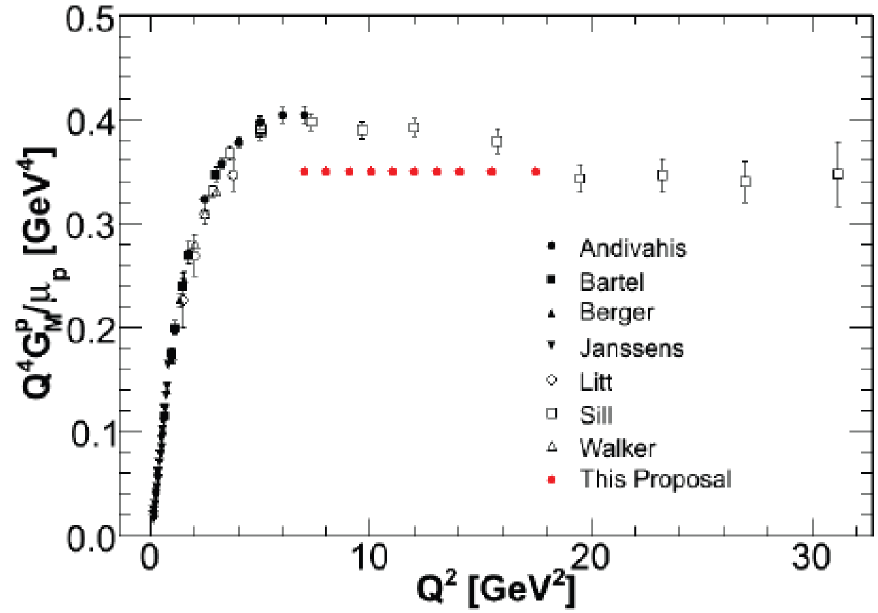
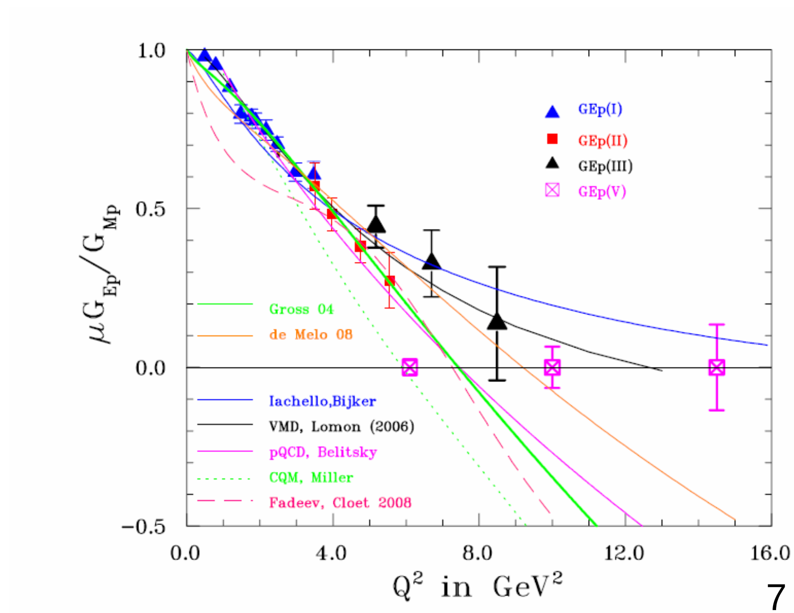
Approved FF Experiments: 12 GeV

Proton

- E12-07-108: elastic cross section experiment H(e,e')p
- E12-07-109: FF ratio experiment using Super BigBite Spectrometer (SBS)







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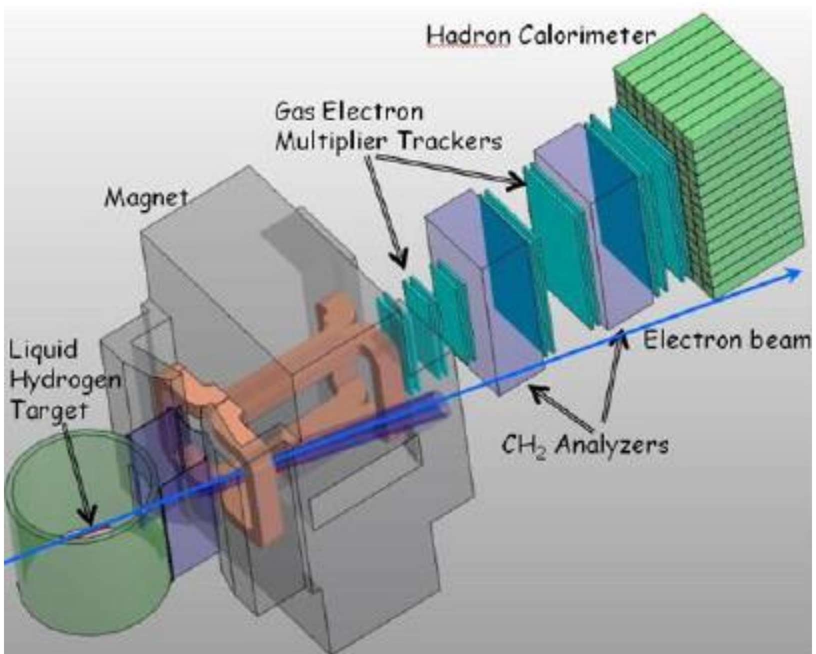
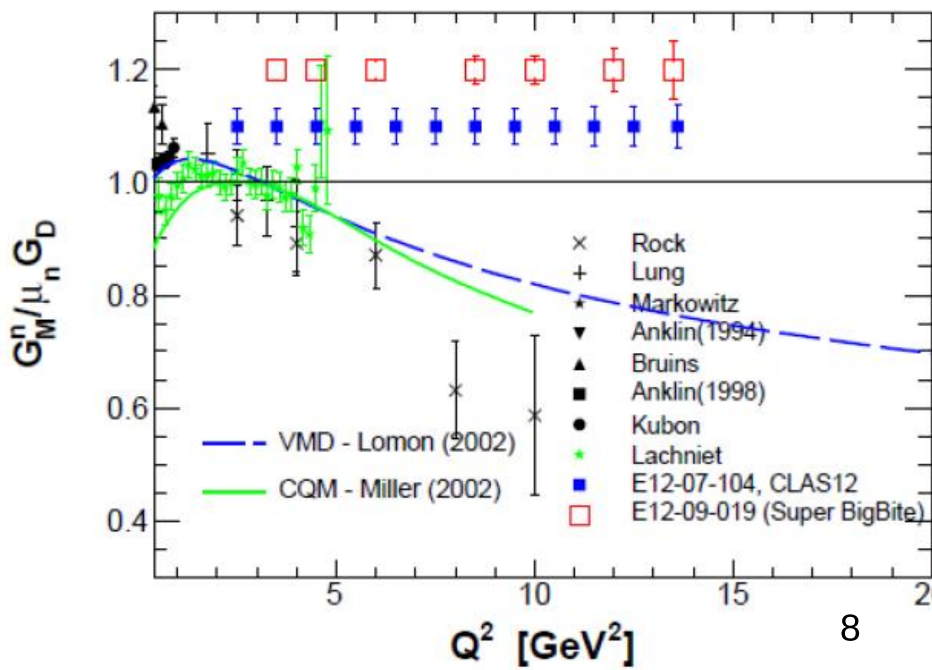


Neutron

- E12-07-108: cross section ratio: $^2H(e,e'n)/^2H(e,e'p)$ to measure G_{Mn} with CLAS12
- E12-09-019: also cross section ratio to measure G_{Mn} using SBS



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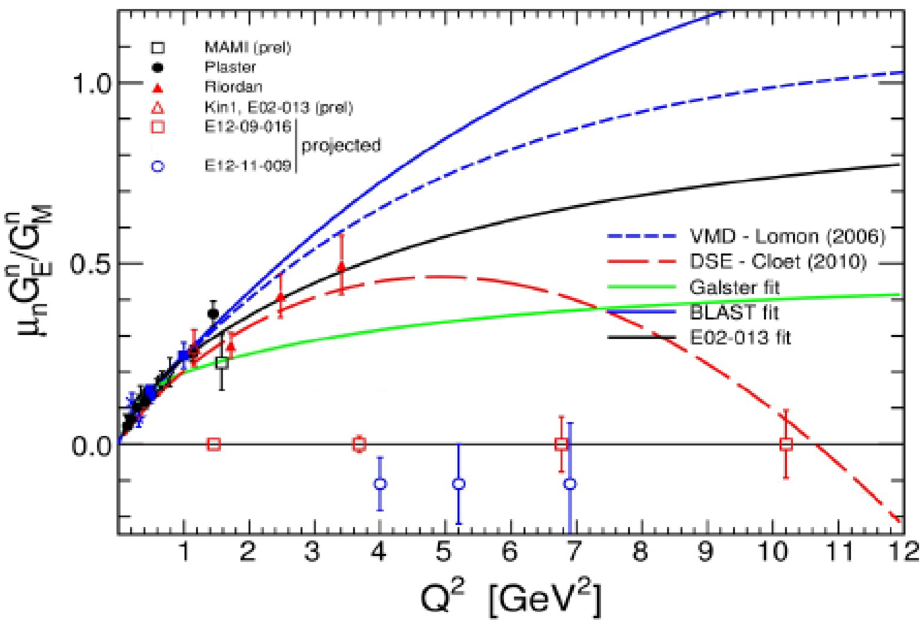


Neutron

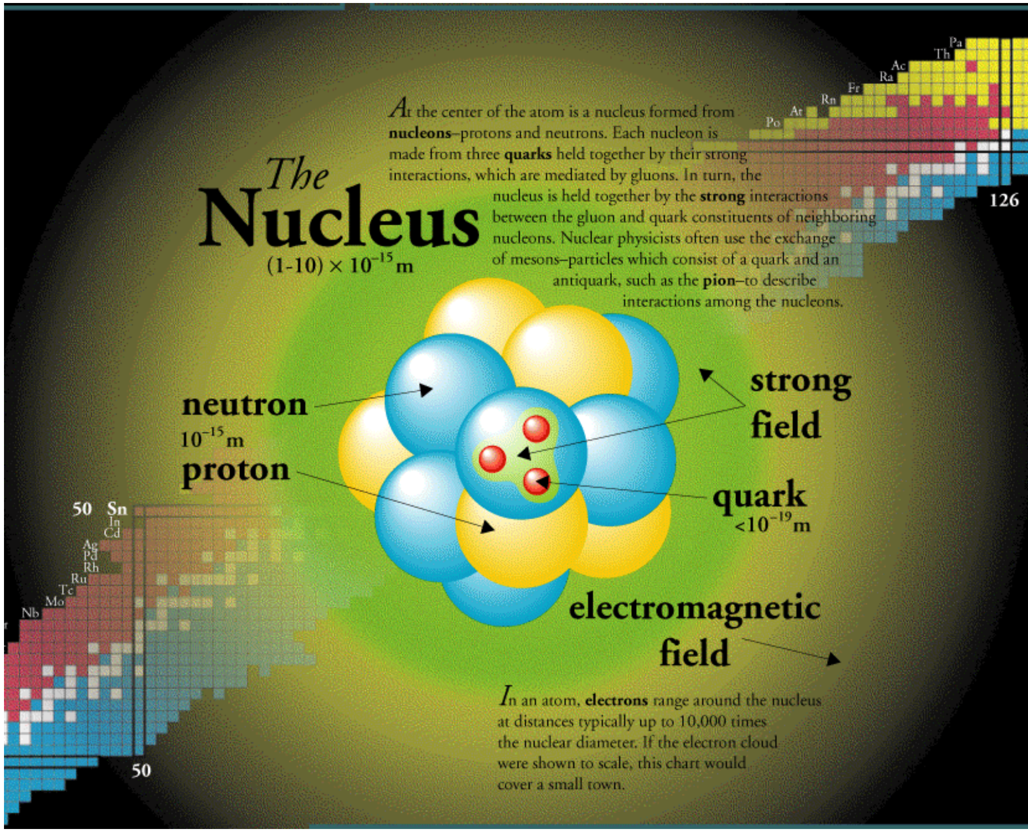
- E12-07-108: cross section ratio: ^{2}H(e,e'n)/^{2}H(e,e'p) to measure G_{Mn} with CLAS12
- E12-09-019: also cross section ratio to measure G_{Mn} using SBS
- E12-09-016 (GEn II): polarized ^{3}He(e,e'n) using SBS, ratio G_{En}/G_{Mn}
- E12-11-009: D(e,e'n) using recoil polarimetry in Hall C to measure ratio G_{En}/G_{Mn}

Motivations to Study FFs

- Form factors are a fundamental property of the nucleon
- Are not yet calculable from first principles
- Provide excellent testing ground for QCD and QCD-inspired models
- Gives constraints on models of nucleon structure
- Electromagnetic form factors of the proton were thought to be well understood prior to Jefferson Lab data:
  - At high Q^2, discovery of significant difference between techniques
  - Proton radius puzzle at low Q^2; experiments at JLab and PSI (MUSE) continue the investigation

Questions to Ponder

1) Do protons and neutrons behave differently inside a nucleus?
2) Do nucleons form pairs inside the nucleus?
3) What can we learn from correlated pairs of protons and neutrons?



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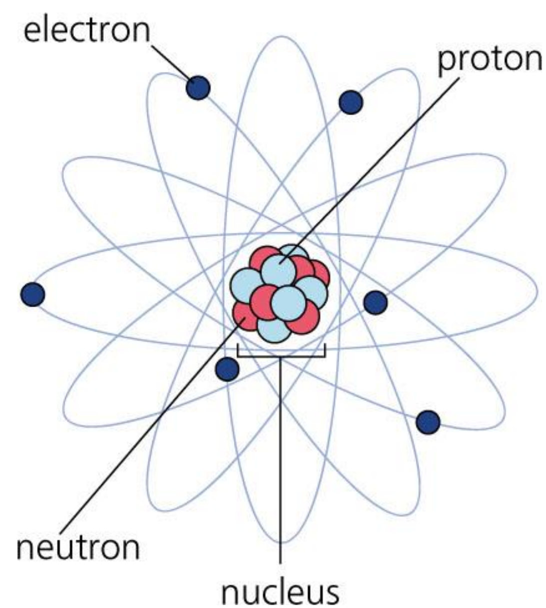
Periodic Table of Elements

Key: element name / **atomic number** / symbol / atomic weight (mean relative mass)

hydrogen **1** H 1.0079																		helium **2** He 4.0026
lithium **3** Li 6.941	beryllium **4** Be 9.0122												boron **5** B 10.811	carbon **6** C 12.011	nitrogen **7** N 14.007	oxygen **8** O 15.999	fluorine **9** F 18.998	neon **10** Ne 20.180
sodium **11** Na 22.990	magnesium **12** Mg 24.305												aluminium **13** Al 26.982	silicon **14** Si 28.086	phosphorus **15** P 30.974	sulfur **16** S 32.065	chlorine **17** Cl 35.453	argon **18** Ar 39.948
potassium **19** K 39.098	calcium **20** Ca 40.078		scandium **21** Sc 44.956	titanium **22** Ti 47.867	vanadium **23** V 50.942	chromium **24** Cr 51.996	manganese **25** Mn 54.938	iron **26** Fe 55.845	cobalt **27** Co 58.933	nickel **28** Ni 58.693	copper **29** Cu 63.546	zinc **30** Zn 65.39	gallium **31** Ga 69.723	germanium **32** Ge 72.61	arsenic **33** As 74.922	selenium **34** Se 78.96	bromine **35** Br 79.904	krypton **36** Kr 83.80
rubidium **37** Rb 85.468	strontium **38** Sr 87.62		yttrium **39** Y 88.906	zirconium **40** Zr 91.224	niobium **41** Nb 92.906	molybdenum **42** Mo 95.94	technetium **43** Tc [98]	ruthenium **44** Ru 101.07	rhodium **45** Rh 102.91	palladium **46** Pd 106.42	silver **47** Ag 107.87	cadmium **48** Cd 112.41	indium **49** In 114.82	tin **50** Sn 118.71	antimony **51** Sb 121.76	tellurium **52** Te 127.60	iodine **53** I 126.90	xenon **54** Xe 131.29
caesium **55** Cs 132.91	barium **56** Ba 137.33	**57-70** *	lutetium **71** Lu 174.97	hafnium **72** Hf 178.49	tantalum **73** Ta 180.95	tungsten **74** W 183.84	rhenium **75** Re 186.21	osmium **76** Os 190.23	iridium **77** Ir 192.22	platinum **78** Pt 195.08	gold **79** Au 196.97	mercury **80** Hg 200.59	thallium **81** Tl 204.38	lead **82** Pb 207.2	bismuth **83** Bi 208.98	polonium **84** Po [209]	astatine **85** At [210]	radon **86** Rn [222]
francium **87** Fr [223]	radium **88** Ra [226]	**89-102** **	lawrencium **103** Lr [262]	rutherfordium **104** Rf [261]	dubnium **105** Db [262]	seaborgium **106** Sg [266]	bohrium **107** Bh [264]	hassium **108** Hs [269]	meitnerium **109** Mt [268]	ununnilium **110** Uun [271]	unununium **111** Uuu [272]	ununbium **112** Uub [277]		ununquadium **114** Uuq [289]				

*lanthanoids	lanthanum **57** La 138.91	cerium **58** Ce 140.12	praseodymium **59** Pr 140.91	neodymium **60** Nd 144.24	promethium **61** Pm [145]	samarium **62** Sm 150.36	europium **63** Eu 151.96	gadolinium **64** Gd 157.25	terbium **65** Tb 158.93	dysprosium **66** Dy 162.50	holmium **67** Ho 164.93	erbium **68** Er 167.26	thulium **69** Tm 168.93	ytterbium **70** Yb 173.04
**actinoids	actinium **89** Ac [227]	thorium **90** Th 232.04	protactinium **91** Pa 231.04	uranium **92** U 238.03	neptunium **93** Np [237]	plutonium **94** Pu [244]	americium **95** Am [243]	curium **96** Cm [247]	berkelium **97** Bk [247]	californium **98** Cf [251]	einsteinium **99** Es [252]	fermium **100** Fm [257]	mendelevium **101** Md [258]	nobelium **102** No [259]



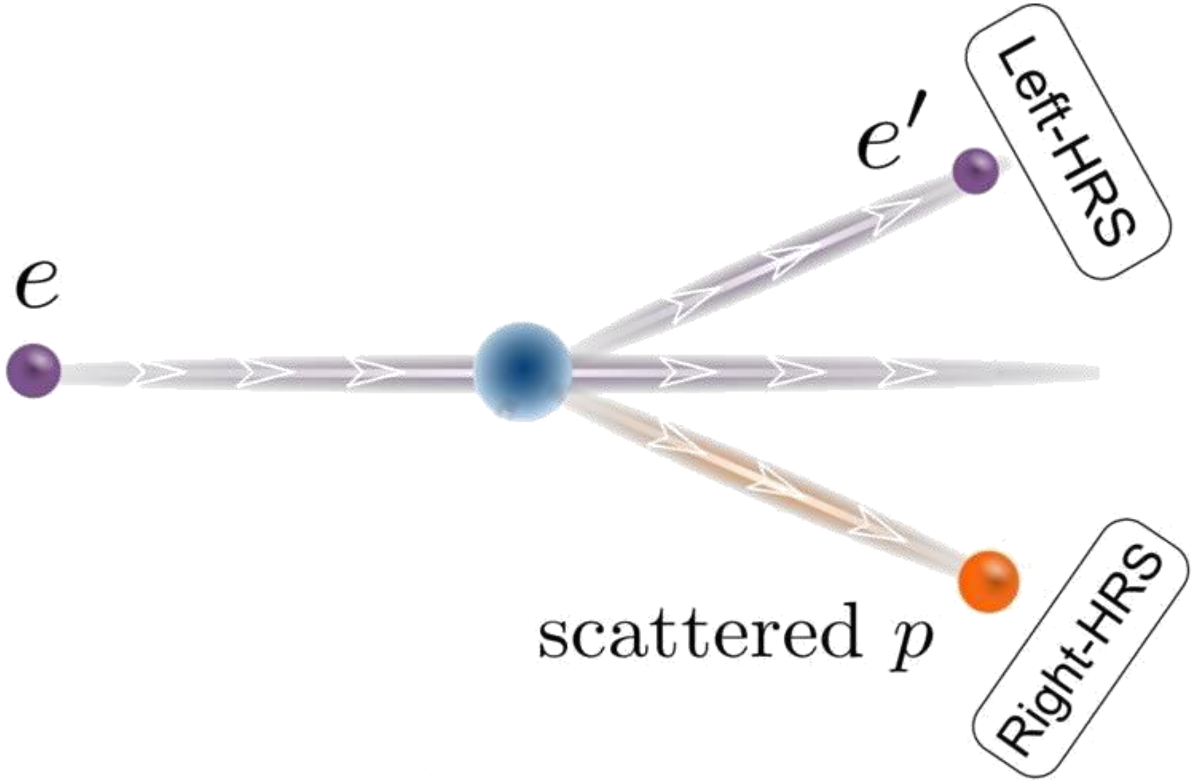
Protons, neutrons, and electrons <u>seem</u> like our fundamental particles.

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?

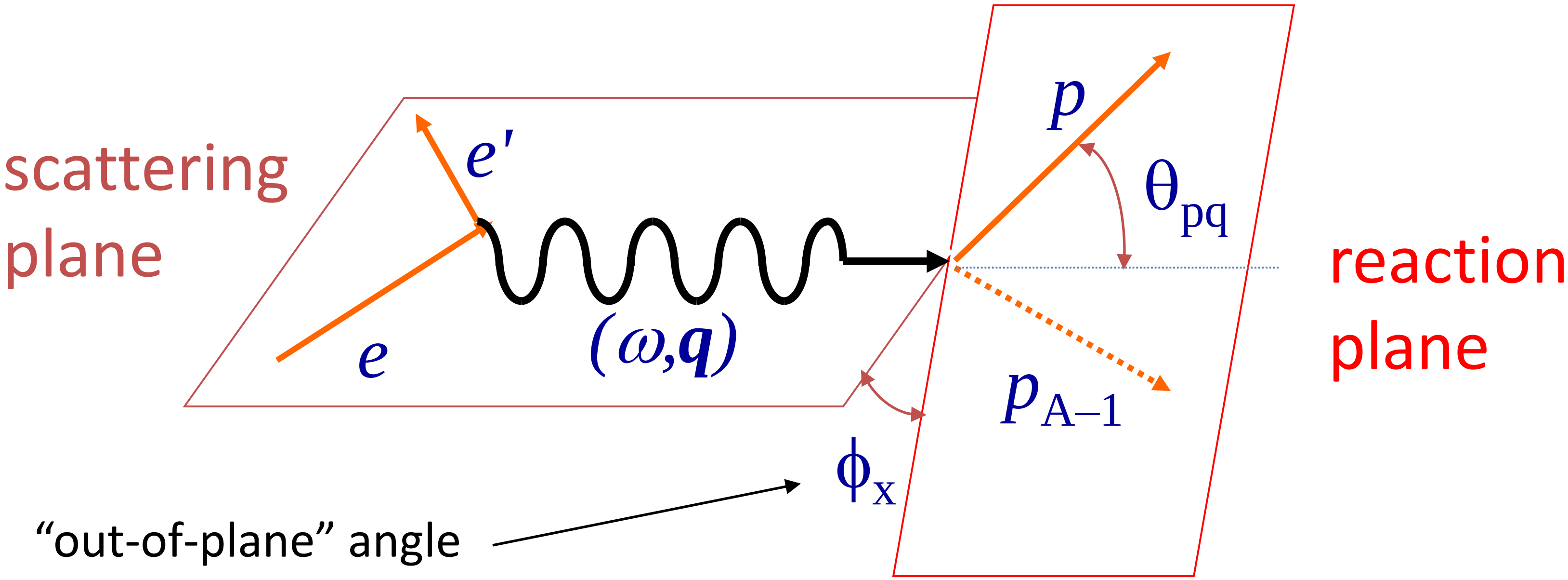
Tools of the Trade

Electron Scattering



Target: nucleus such as helium, carbon or lead

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

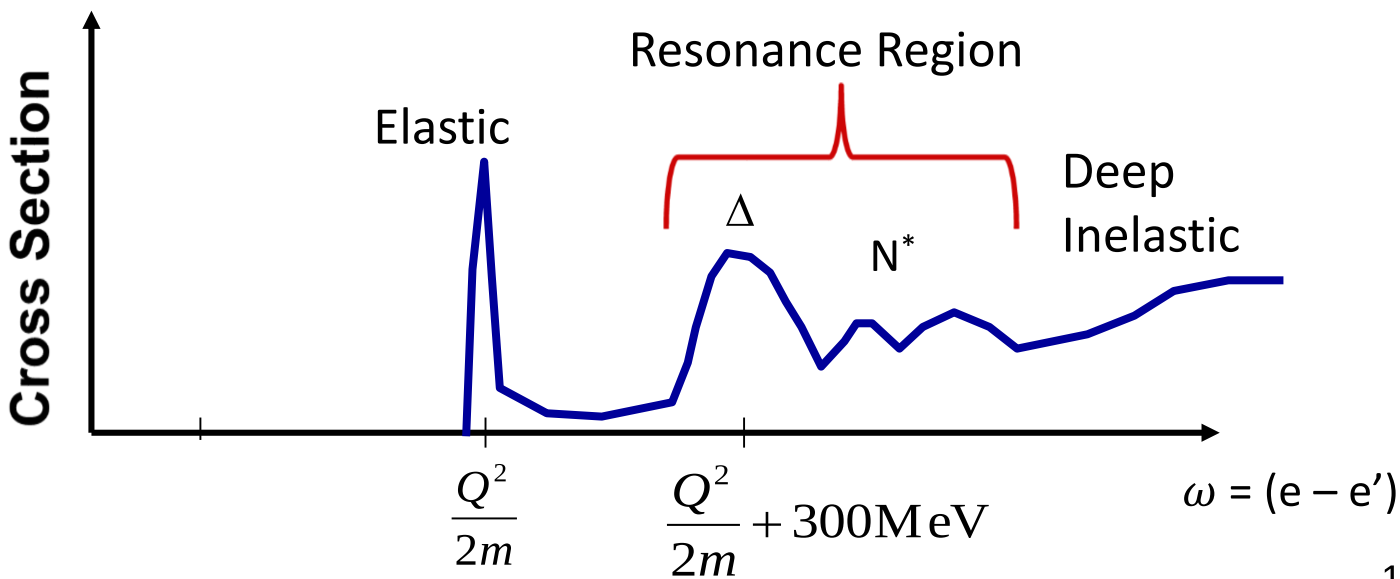
Difference between transferred and detected energy

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

Counts minimum number of nucleons involved

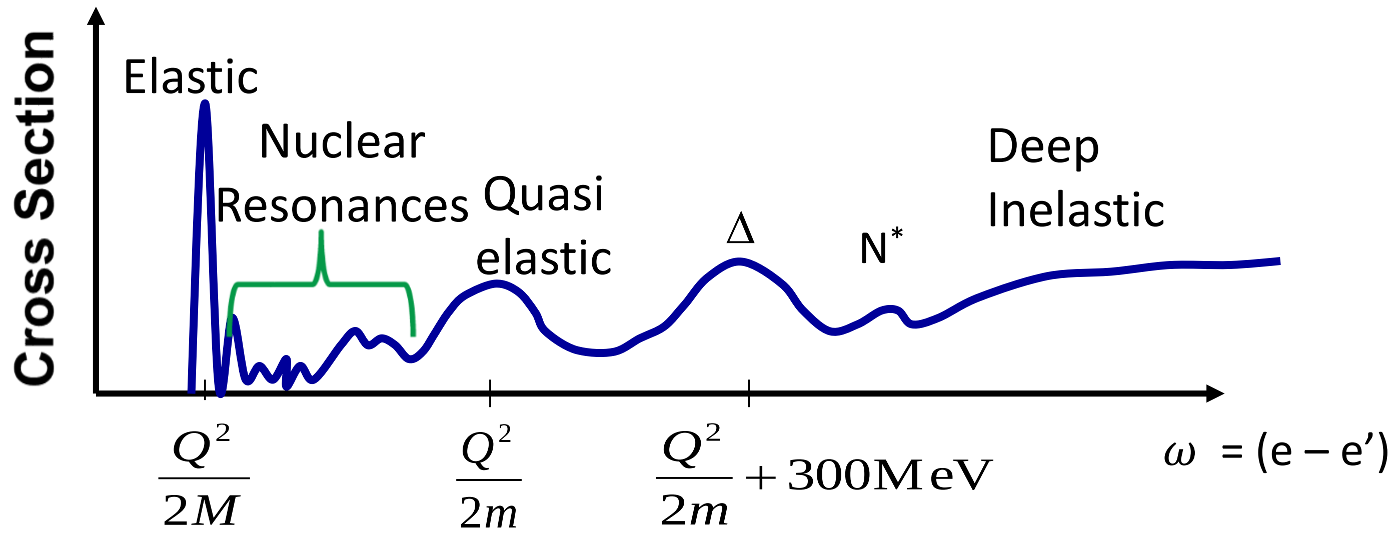
Electron Scattering at Fixed Q^2

Electon-Nucleon

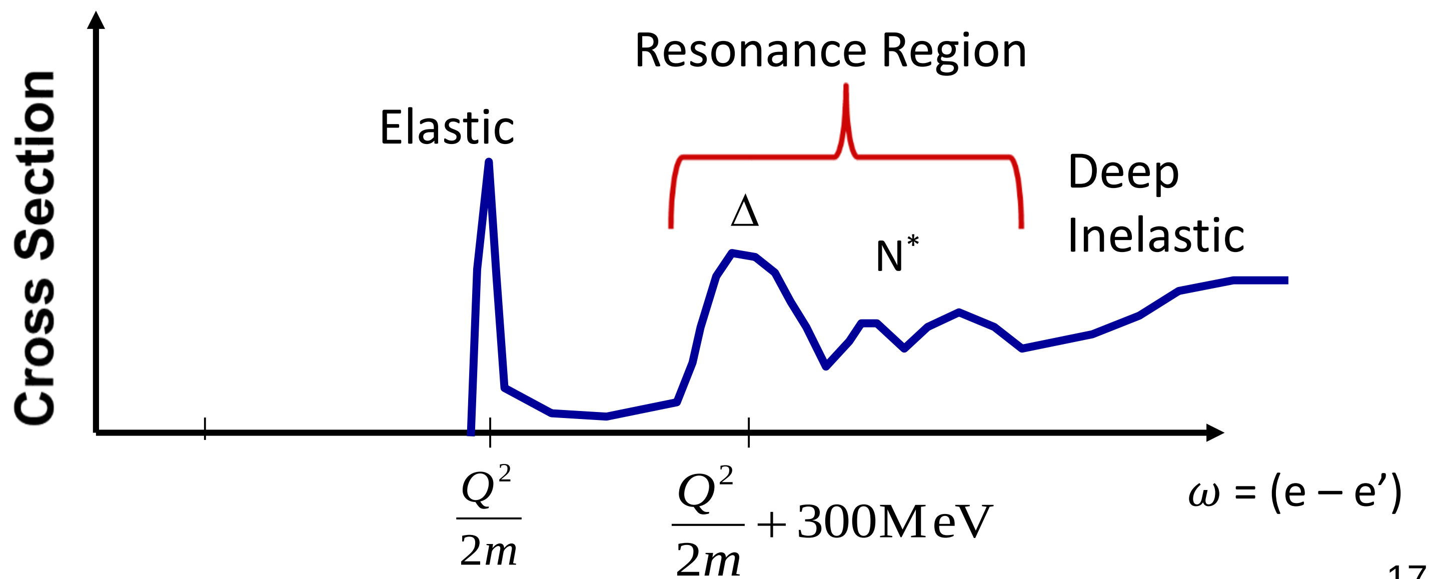


Electron Scattering at Fixed Q^2

Electron-Nucleus

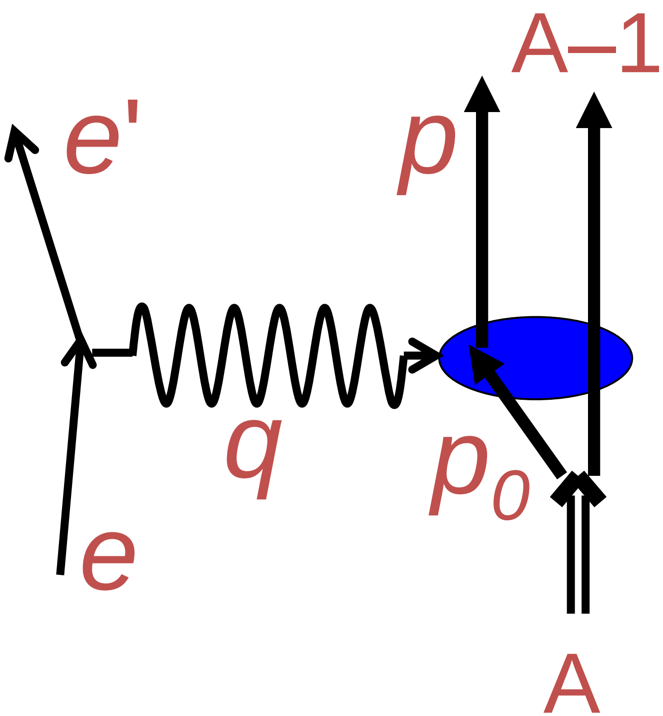


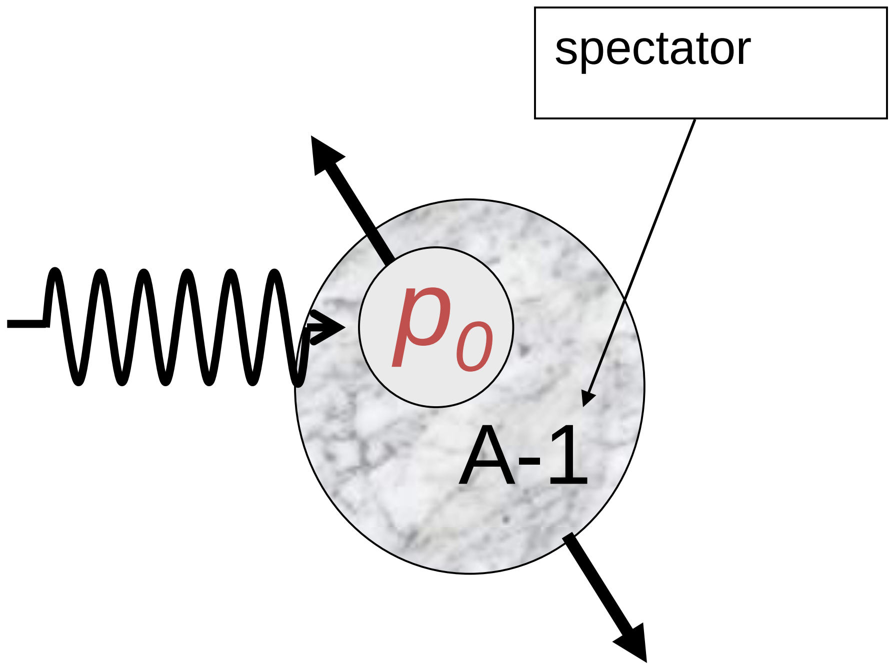
Electon-Nucleon



Simple Theory Of Nucleon Knock-out

Plane Wave Impulse Approximation (PWIA)





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

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Spectral Function

In nonrelativistic PWIA:

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

e-p cross section

nuclear spectral function

For bound state of recoil system:

proton momentum distribution

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

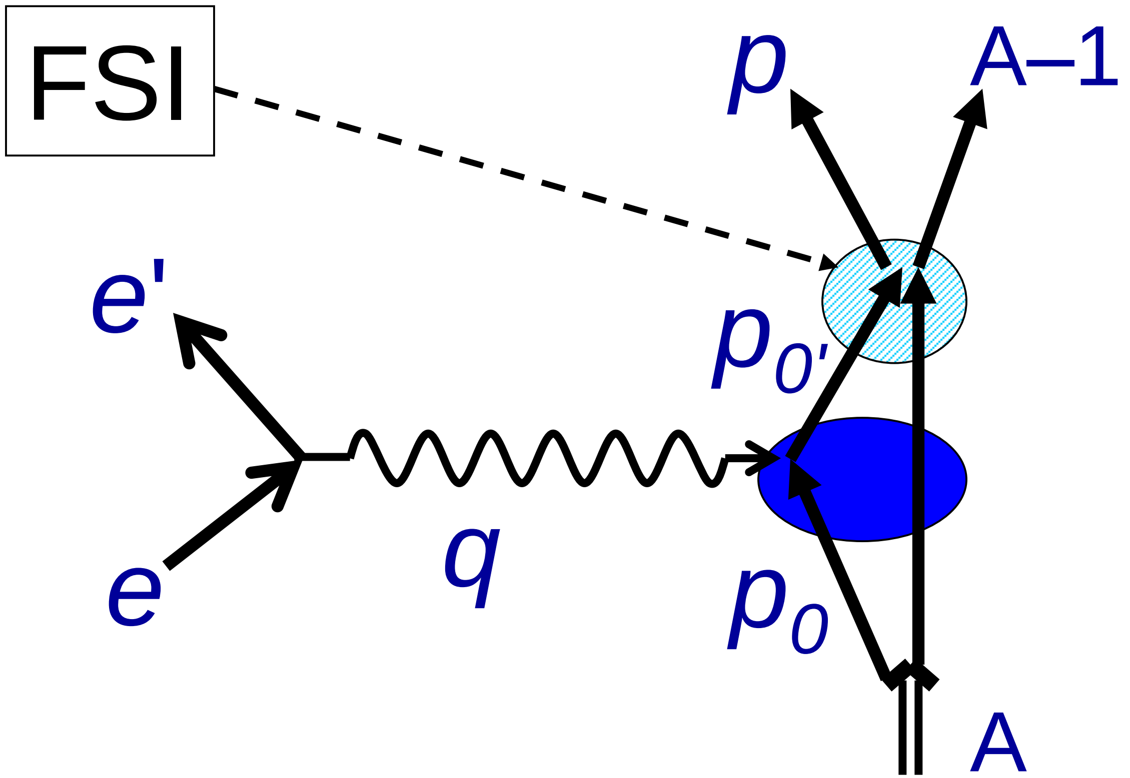
Reaction Mechanisms in (e,e'p)

A more accurate description of the (e,e'p) reaction includes:

- Final-State Interactions:
  Interactions of the extracted proton with the residual nucleus.
- Coulomb Distortion and Internal Radiative Corrections:
  The momentum of the electrons at the reaction point is different to their asymptotic measured values.
- External Effects (From atomic interactions in the target):
  Energy Loss, External Radiative Corrections, Straggling, Proton Absorption.
- Meson Exchange Currents (MEC)
- Intermediate excited nucleonic configurations:
  e.g. Delta-isobar contributions

Reaction Mechanisms

Example: Final State Interactions (FSI)



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

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Improve Theory

Distorted Wave Impulse Approximation (DWIA)

This is modeled by an optical potential from elastic (p,p) data.
Proton is described by Distorted Waves.

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

"Distorted" spectral function

DWIA: If the struck nucleon re-interacts with the rest of the nucleus, then the cross section still factorizes (mostly) but we measure a distorted spectral function.

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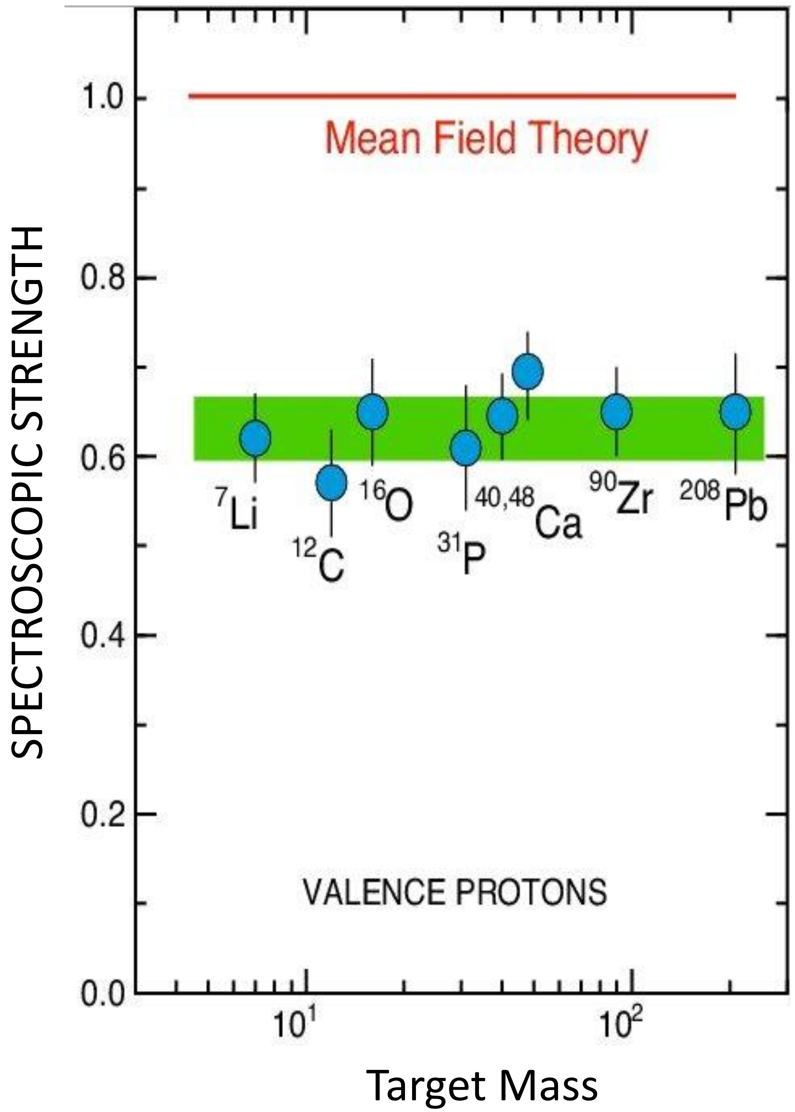
Classic Result from (e,e'p) Measurements

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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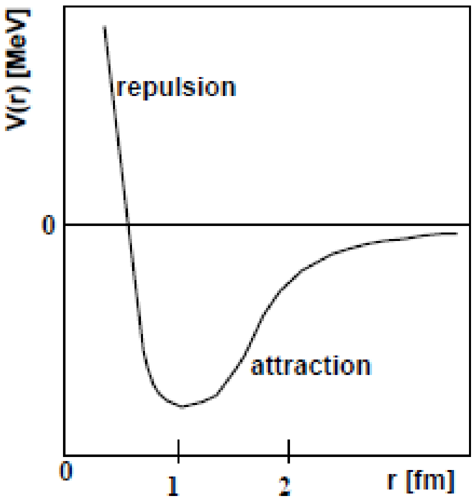
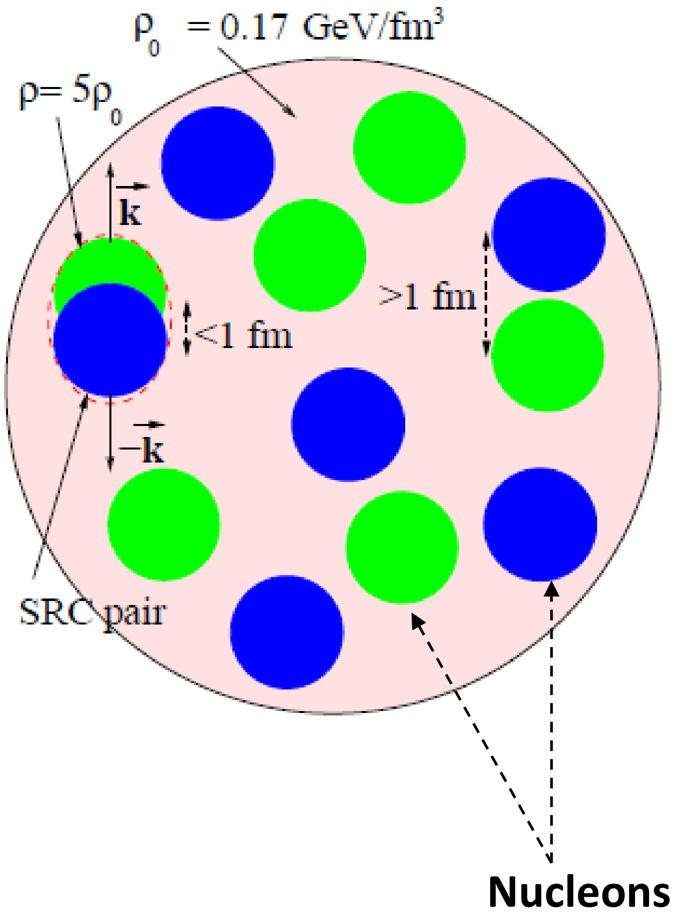
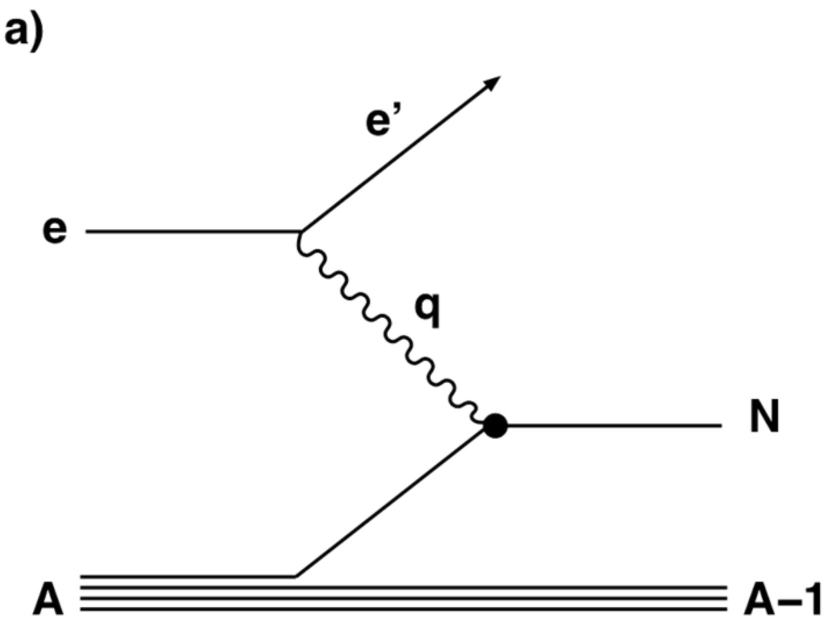
Short-Range Correlations



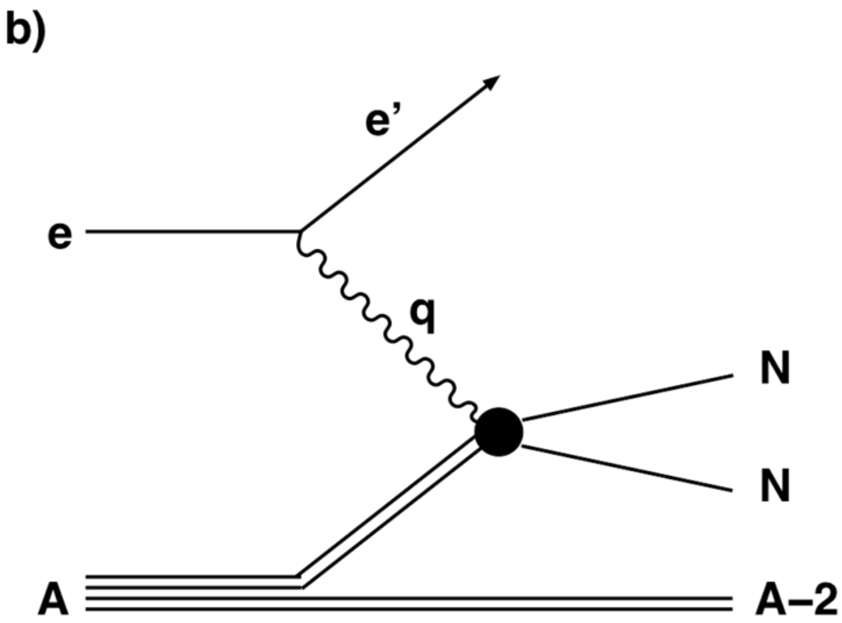


SRC depletes states below the Fermi sea and makes the states above this level partially occupied.

Short-Range Correlations



Single nucleon knock-out



Correlated pair knock-out

Realistic Momentum Distribution

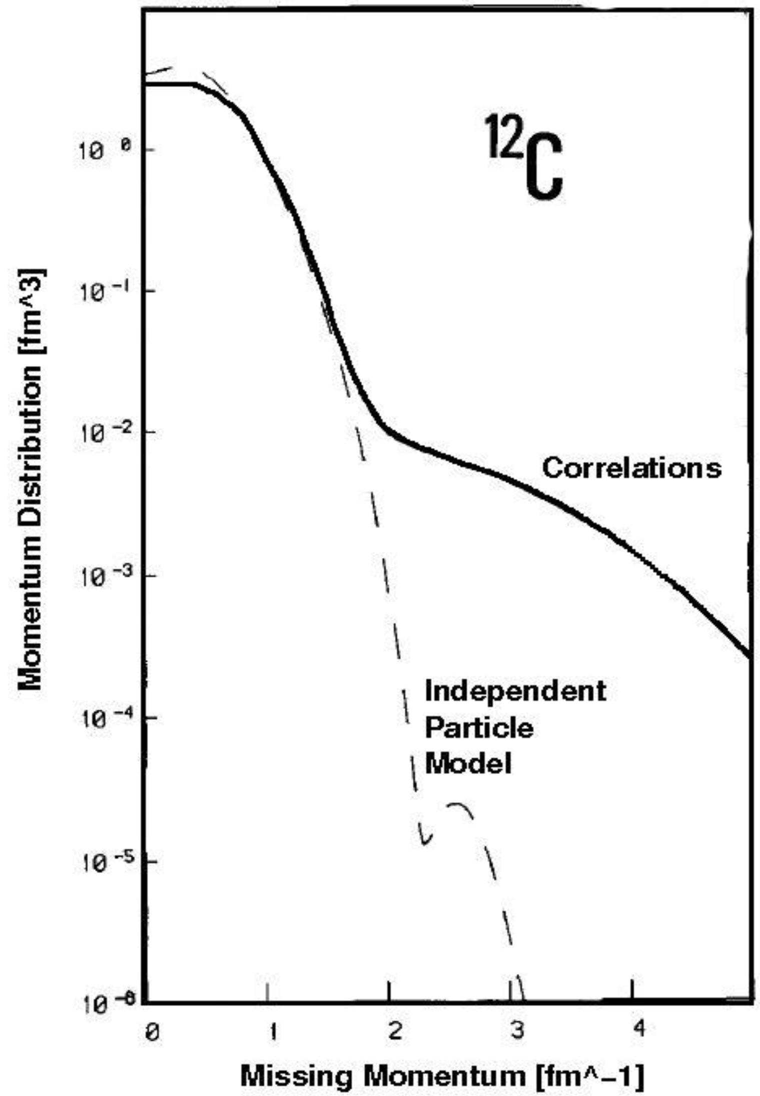
- What fraction of the momentum distribution is due to 2N-SRC?
- What is the relative momentum between the nucleons in the pair?
- What is the ratio of pp to pn pairs?
- Are these nucleons different from free nucleons (e.g. size)?

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

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



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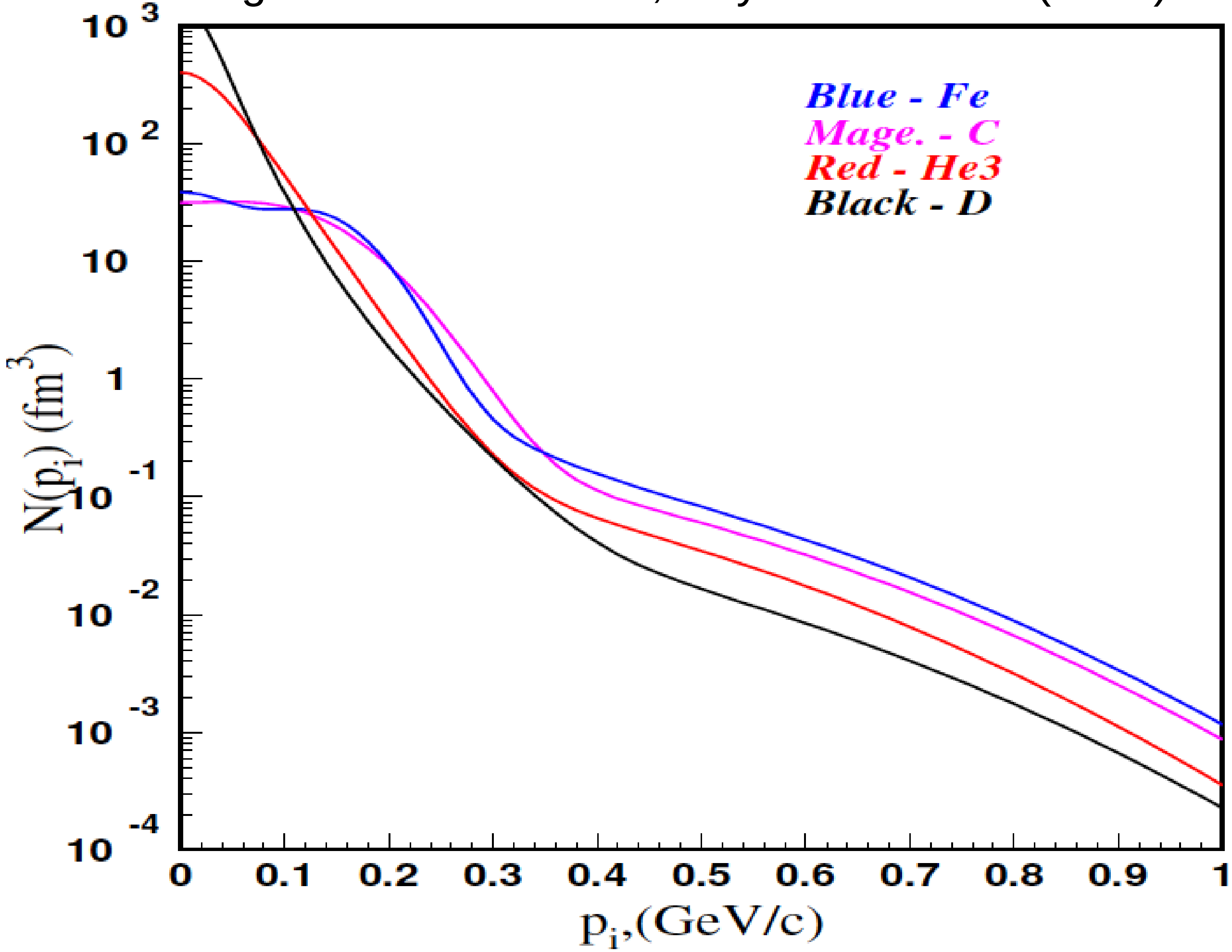
Calculation of Nucleon Initial Momentum

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



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

Inclusive Scattering at Large x_B

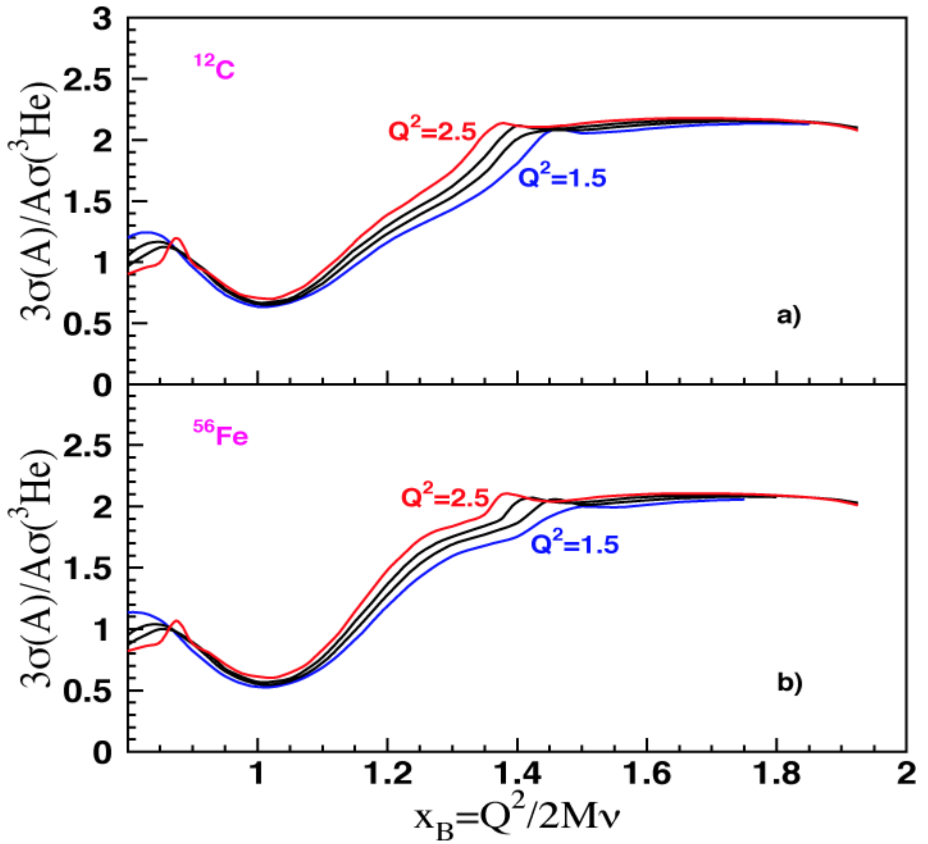
Define y as the x_B-value at which the minimum p_{miss} exceeds k_F

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



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SRC Signature from Inclusive Measurements

- Inclusive Cross Section involving SRC:
  - k > k_F for x_B > 1.3, so QE electron-nucleus scattering probes SRC:

$$\sigma_A(x_B, Q^2) = \sum_{j=2}^{A} \frac{A}{j} a_j(A)\sigma_j(x_B, Q^2) = \frac{A}{2} a_2(A)\sigma_2(x_B, Q^2) + \frac{A}{3} a_3(A)\sigma_3(x_B, Q^2) + \ldots,$$

  - $a_j(A)$: the probability of a nucleon in a jN-SRC
  - $\sigma_j(A)$: the cross section of an electron scattering off a nucleon in a jN-SRC
- Ratios:
  - a_2 and a_3 are independent of x_B and Q^2, and only depend on A $\rightarrow$ **Scaling plateau**

2N-SRC (1.3 < x_B < 2)

$$a_2(A,D) = \frac{2}{A}\frac{\sigma_A(x,Q^2)}{\sigma_D(x,Q^2)},$$

3N-SRC (2 < x_B < 3)

$$a_3(A,{}^3He) = K \cdot \frac{3\sigma_A}{A\sigma_{{}^3He}}$$

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

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

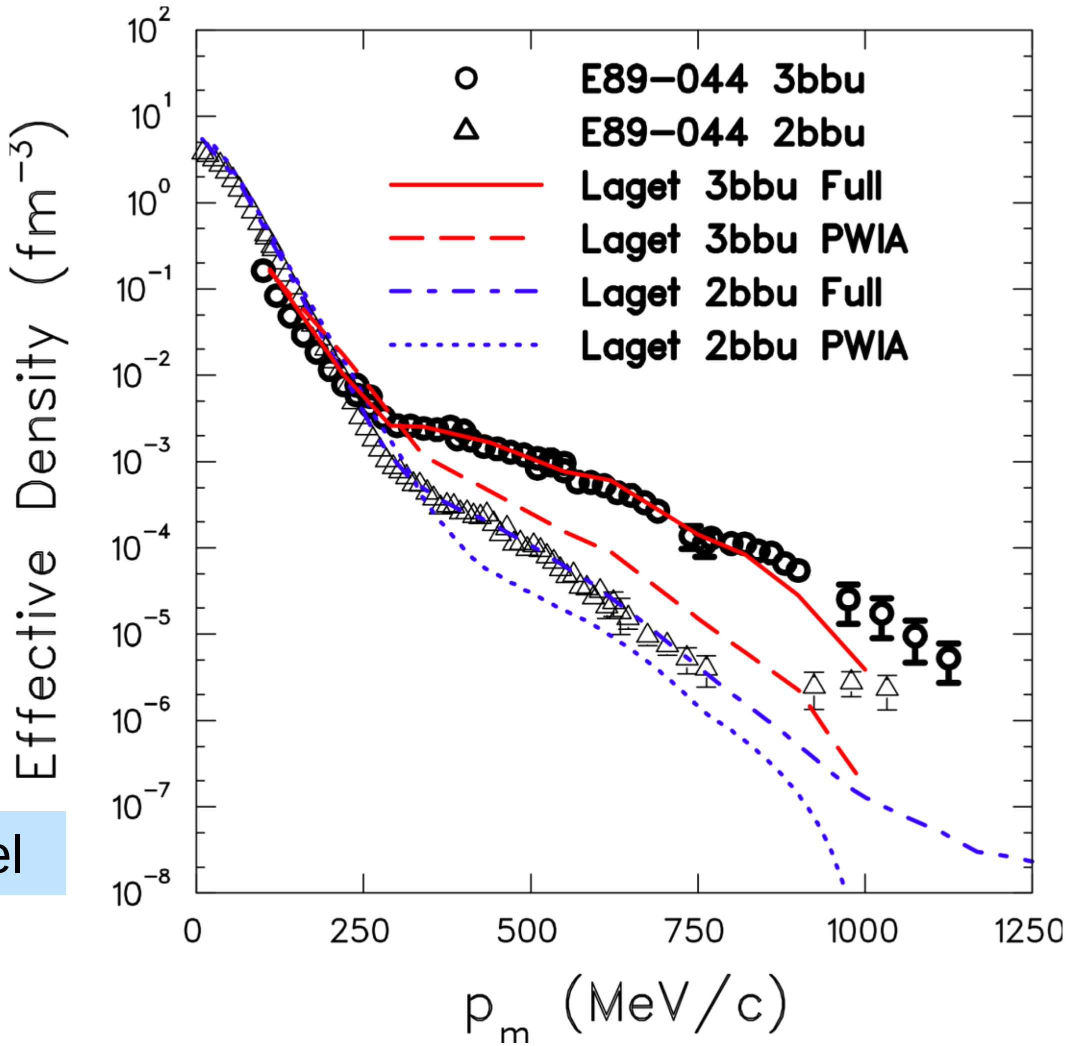
Q^2 = 1.5 [GeV/c]^2

x_B = 1 (Q.E. Peak)

$$\frac{d^6\sigma}{dE_e dE_p d\Omega_e d\Omega_p} = K \cdot \sigma_{ep} \cdot S^D(E_m, p_m)$$

$$\eta(p_m) = \int \left(\frac{d^6\sigma}{dE_e dE_p d\Omega_e d\Omega_p} / K \cdot \sigma_{ep}\right) dE_m$$

Compare $S^D(E_m,p_m)$, $n(p_m)$ to model



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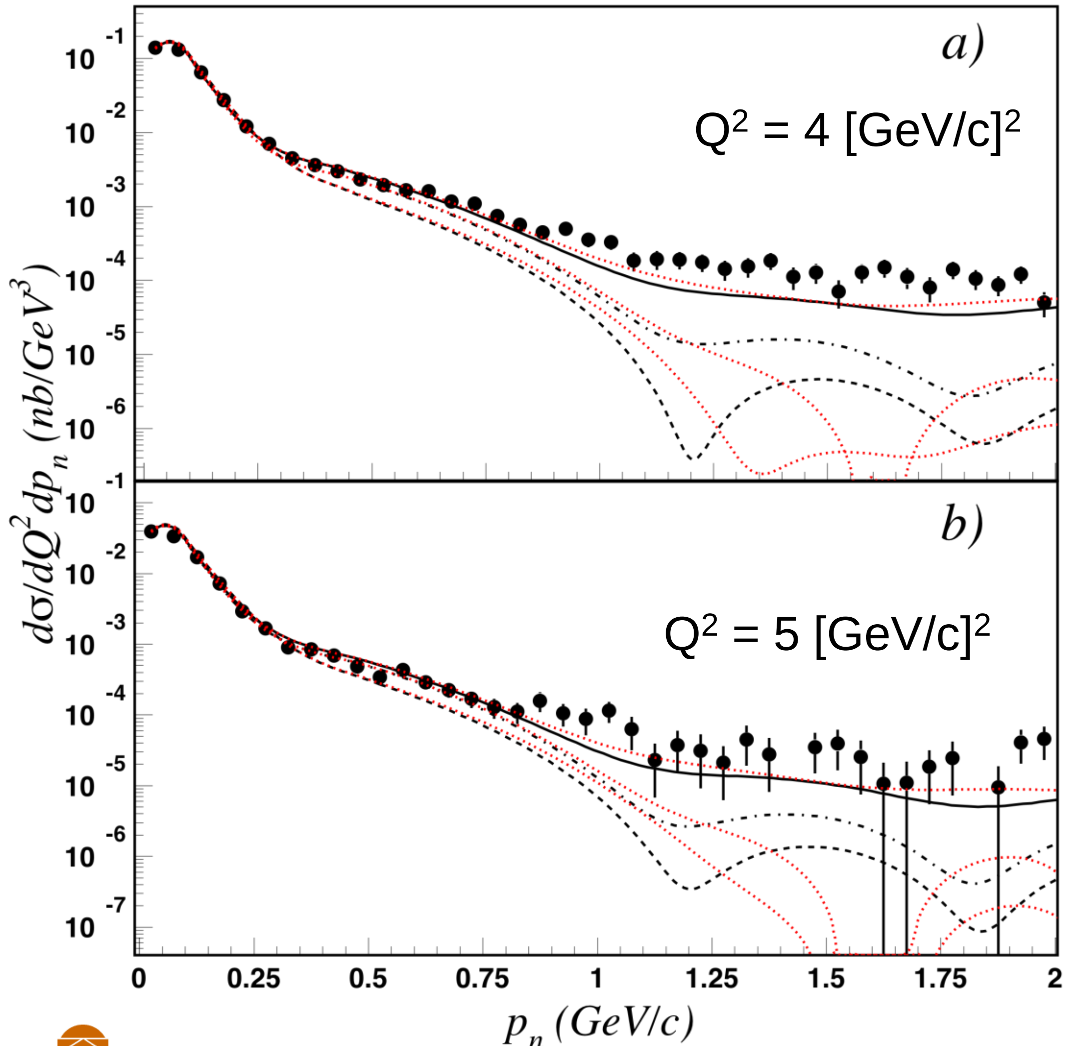
Hall B (CLAS) D(e,e'p)n, x<1 Data

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.

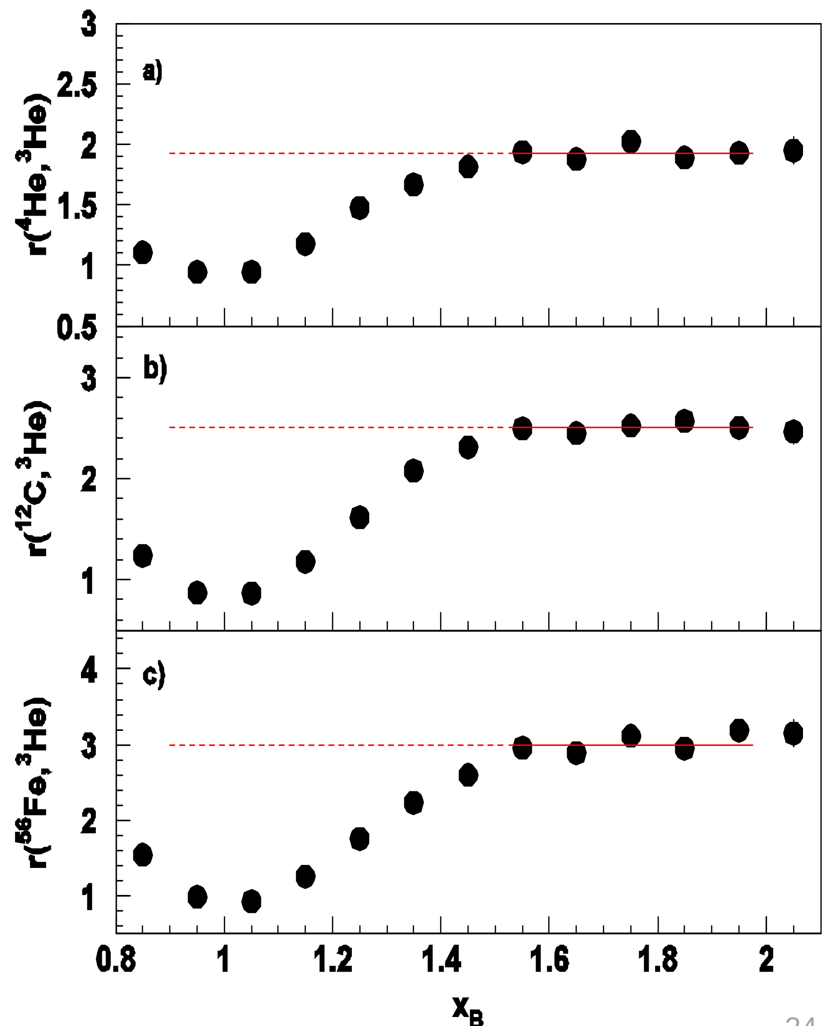
Originally done with SLAC data by D.B. Day *et al.*, Phys. Rev. Lett. 59 (1987) 427.

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

then

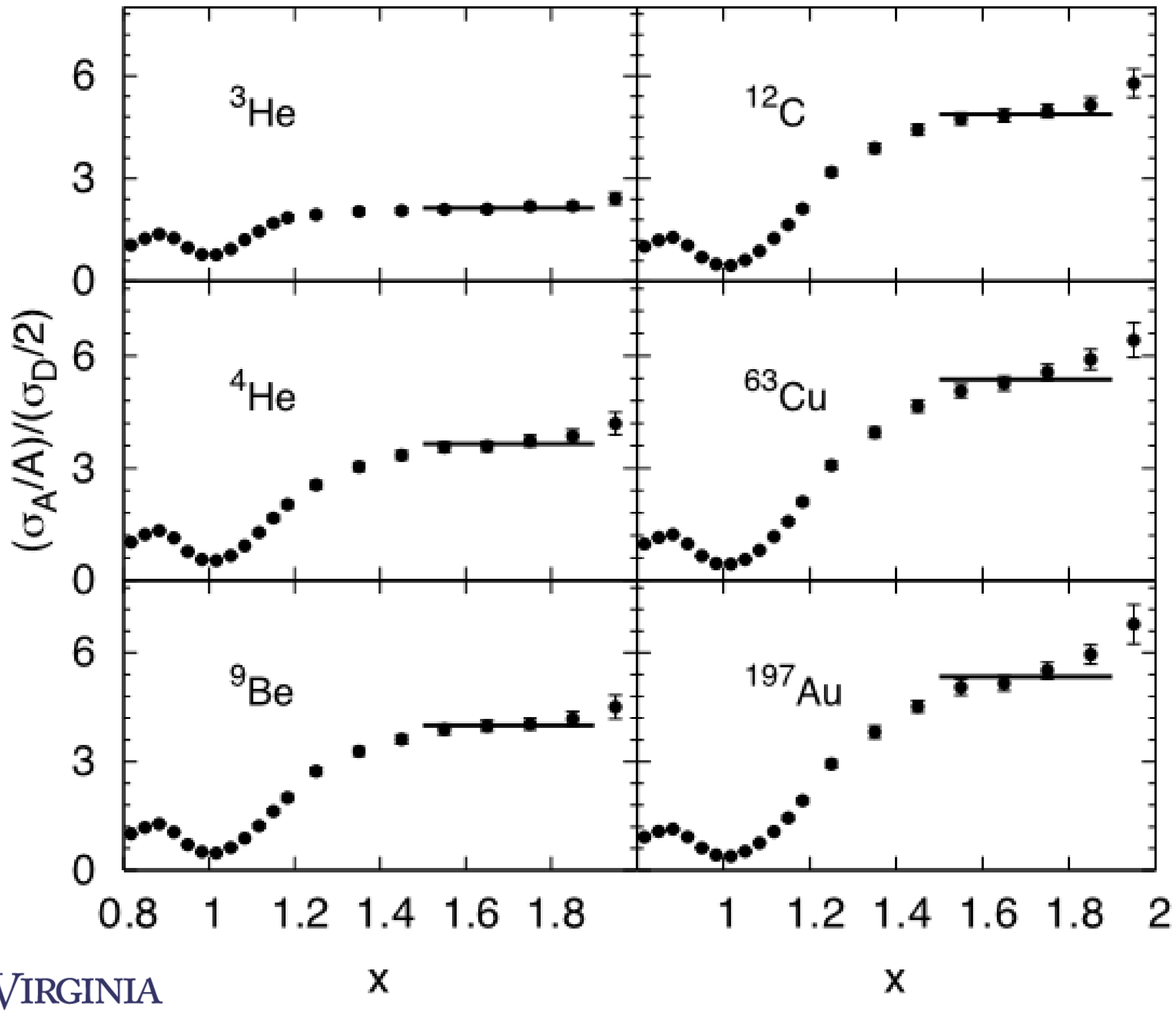
$$r(A,{}^3\mathrm{He}) = a_{2n}(A)/a_{2n}({}^3\mathrm{He})$$

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



Results From JLab Hall-C

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



Estimate of ^{12}C Two-Nucleon SRC

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

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

- K. Egiyan *et al*. related the known correlations in deuterium and previous r(^{3}He,D) results to find:
- ^{12}C, 20% of nucleons are in a 2-N SRC

$$a_2(^3\mathrm{He}) = 1.7 \pm 0.3$$
$$a_2(^4\mathrm{He}) = 3.3 \pm 0.5$$
$$a_2(^{12}\mathrm{C}) = 5.0 \pm 0.5$$
$$a_2(^{27}\mathrm{Al}) = 5.3 \pm 0.6$$
$$a_2(^{56}\mathrm{Fe}) = 5.2 \pm 0.9$$
$$a_2(^{197}\mathrm{Au}) = 4.8 \pm 0.7$$

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

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

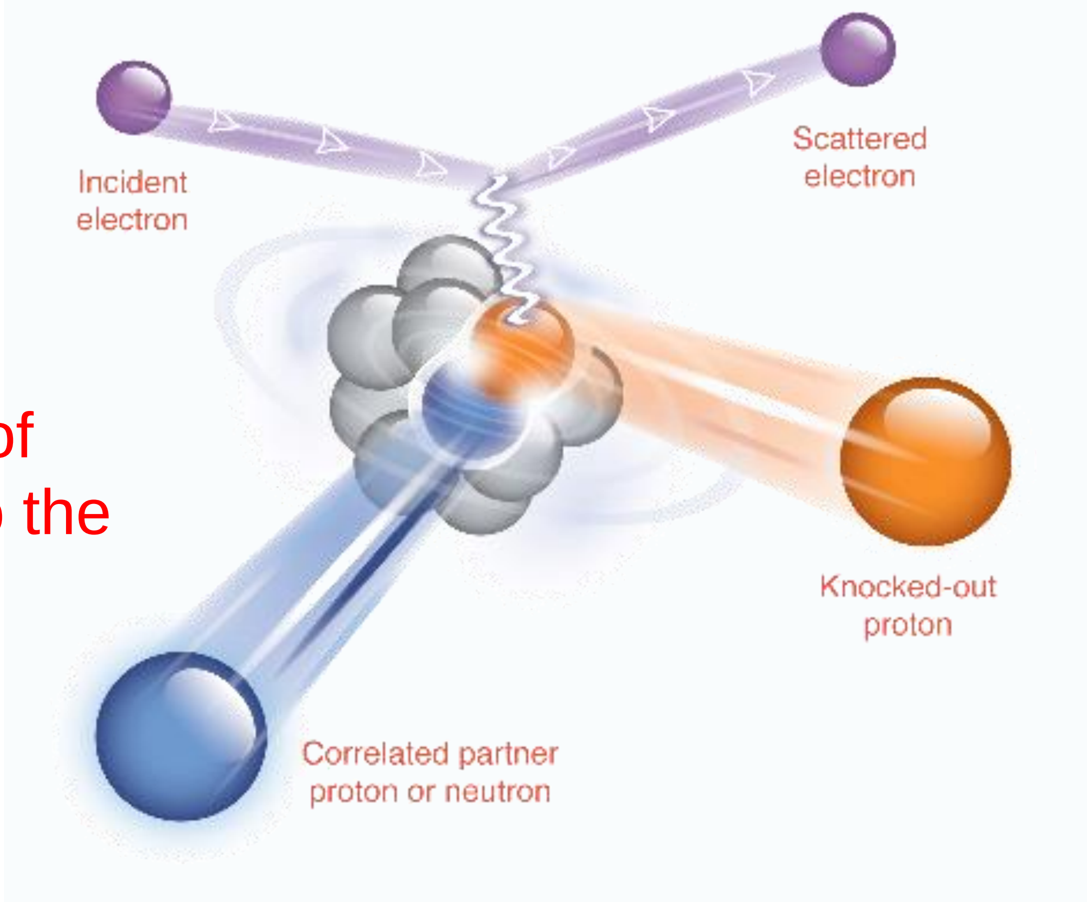
- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - No Q^2 Dependence Of Ratio Magnitude Q^2: 1 to 4 GeV to few percent
  -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

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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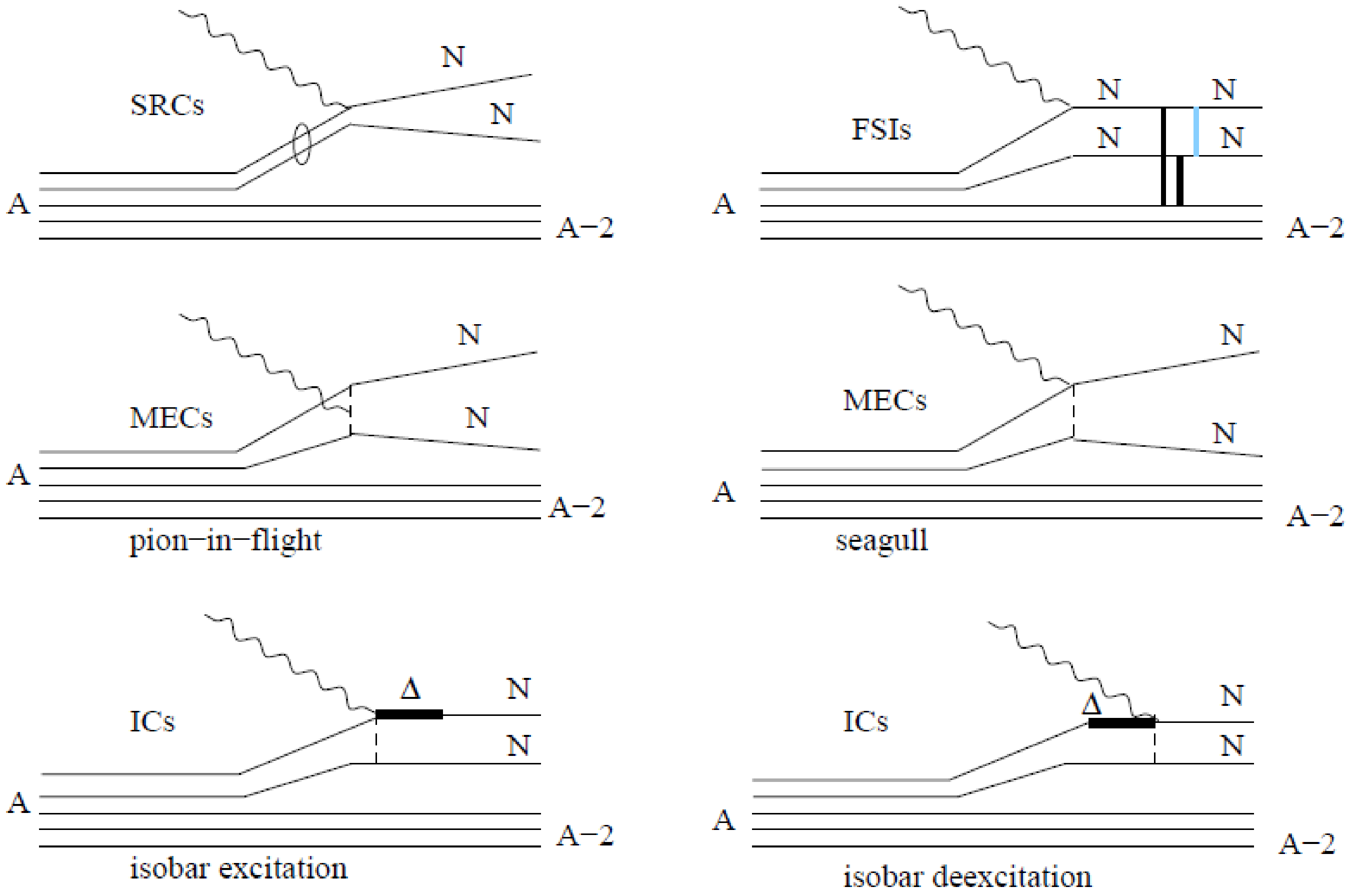
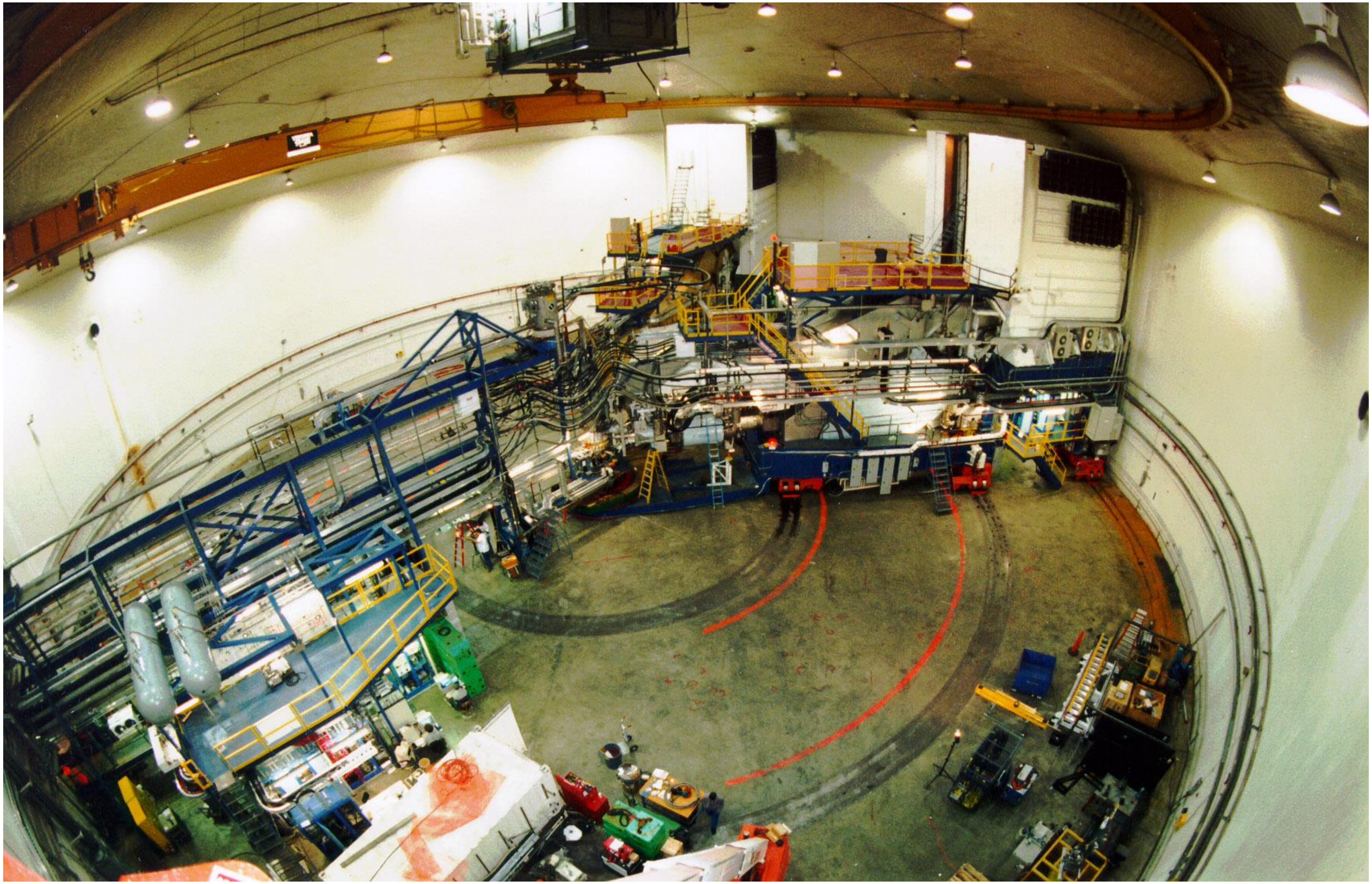
Suppression of Non-SRC Two Body Effects

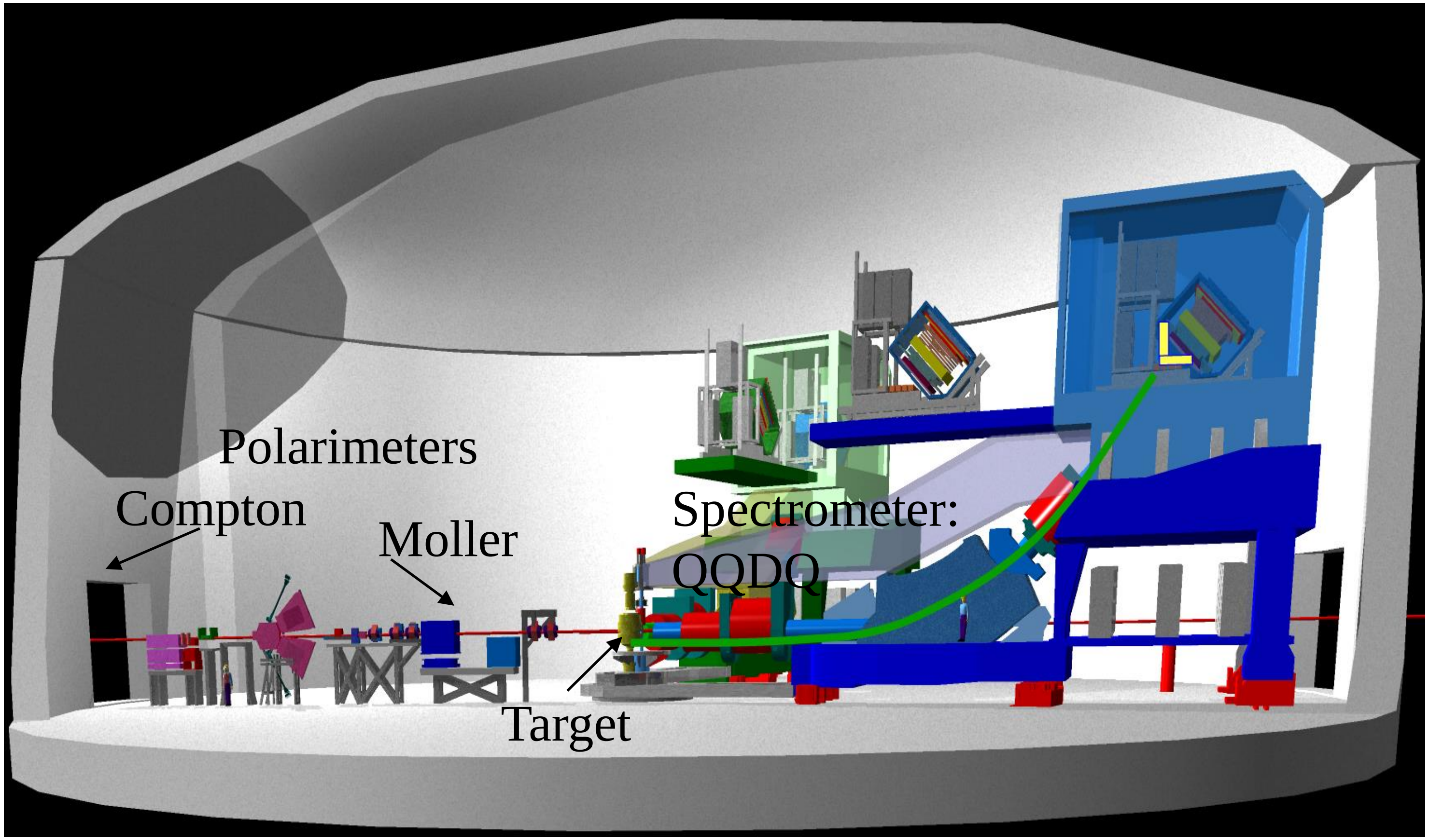


- High Q^2 to minimize MEC ($1/Q^2$) and FSI
- x>1 to suppress isobar contributions

Experimental Hall A

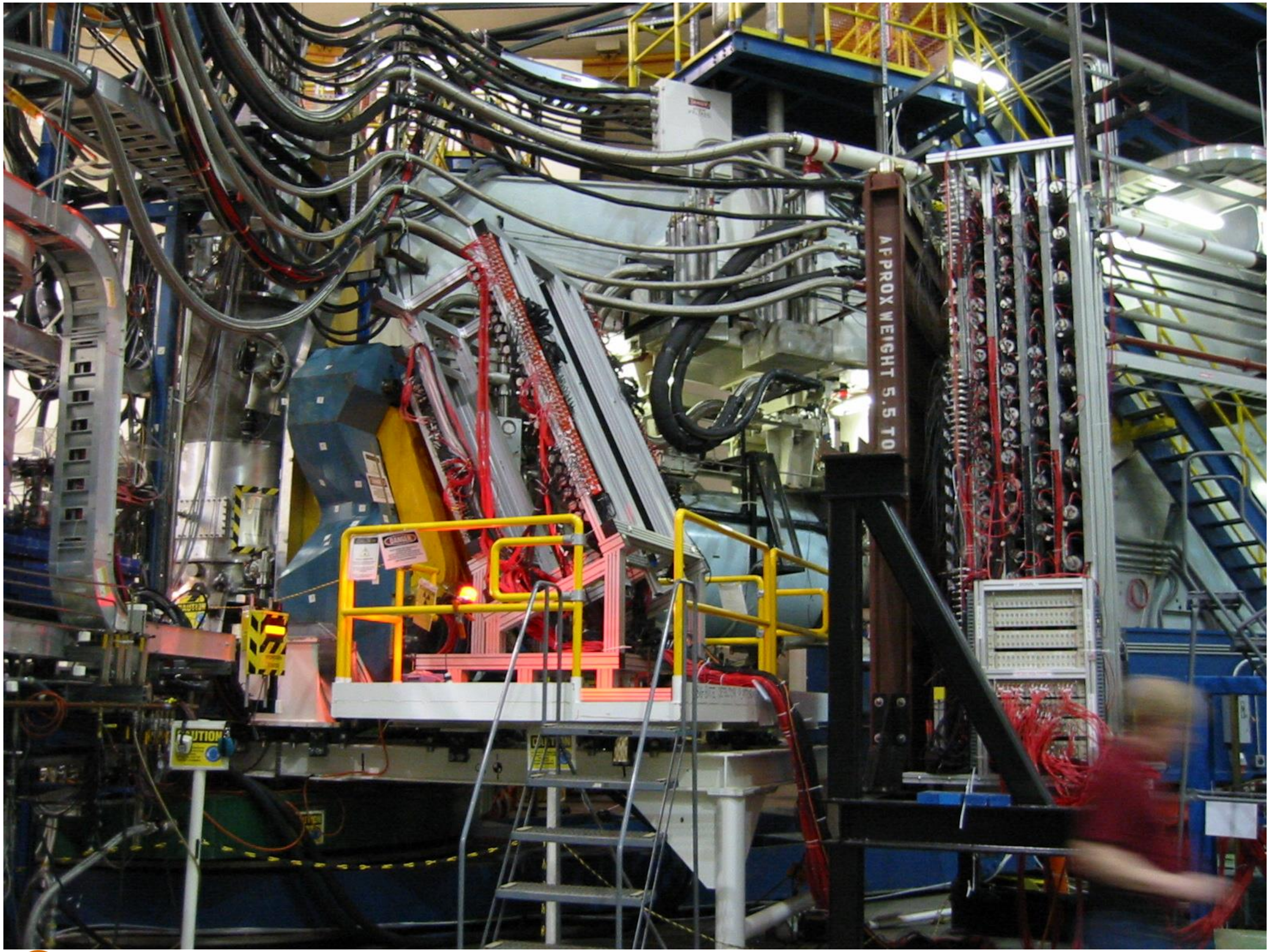


Experimental Hall A

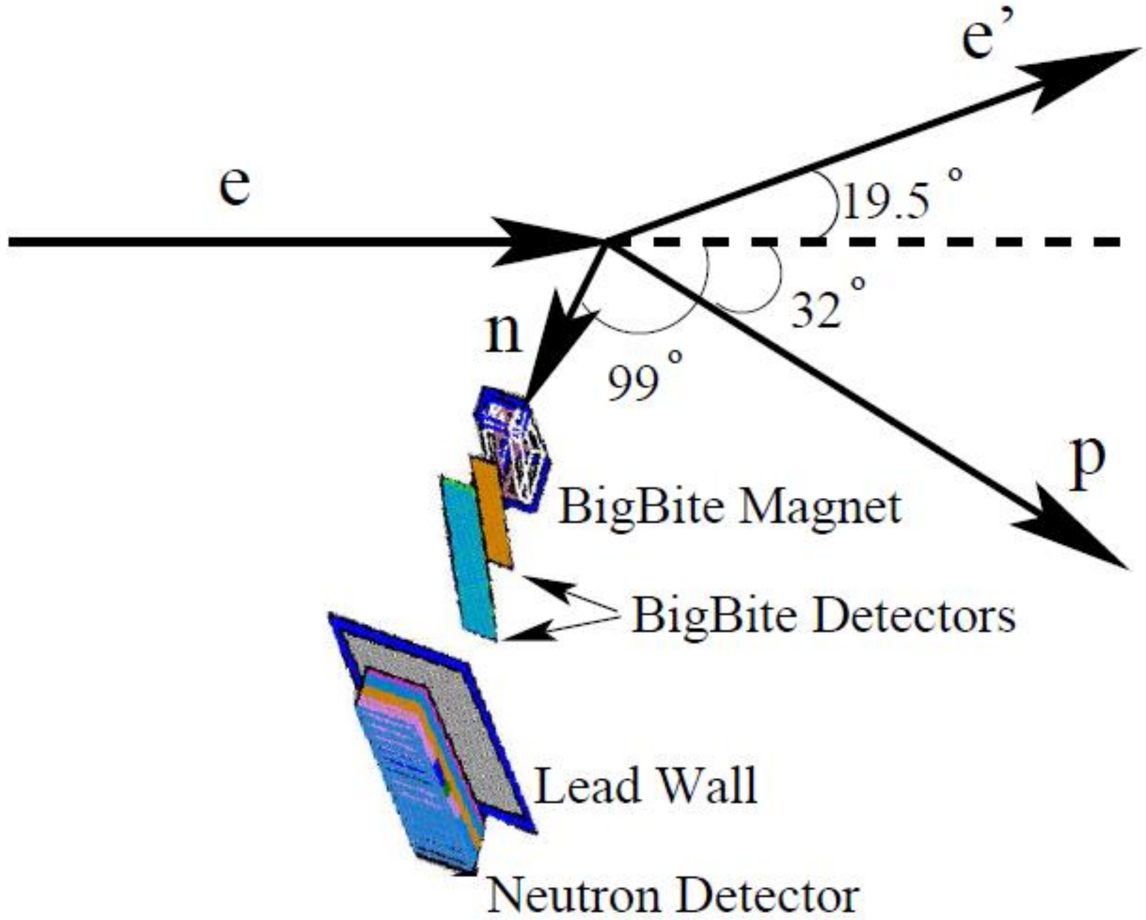


- Hall A's two High resolution Spectrometers can detect scattered electrons with momentum up 4 GeV/c with a resolution of 10^{-4}.
- Can detect particles scattered from 6° to 120°.

Add BigBite and Neutron Detector



Kinematics

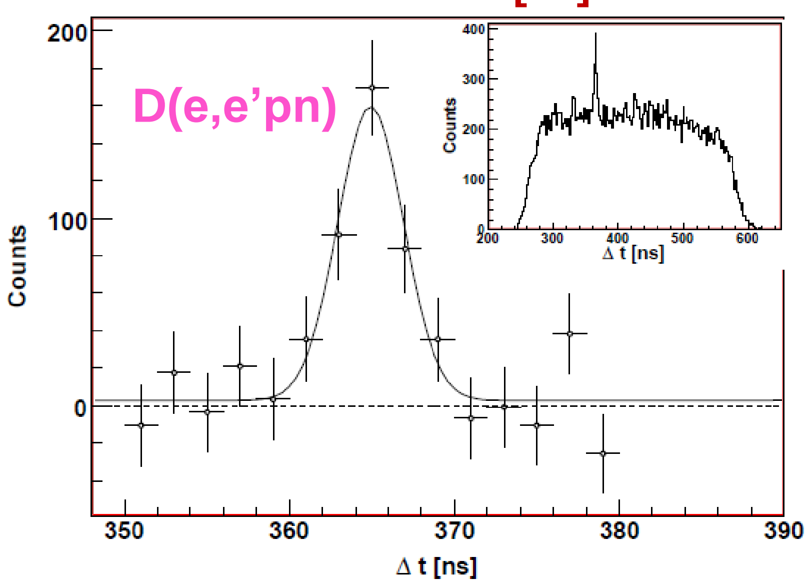


e'
e
19.5 °
32 °
n
99 °
p
BigBite Magnet
BigBite Detectors
Lead Wall
Neutron Detector

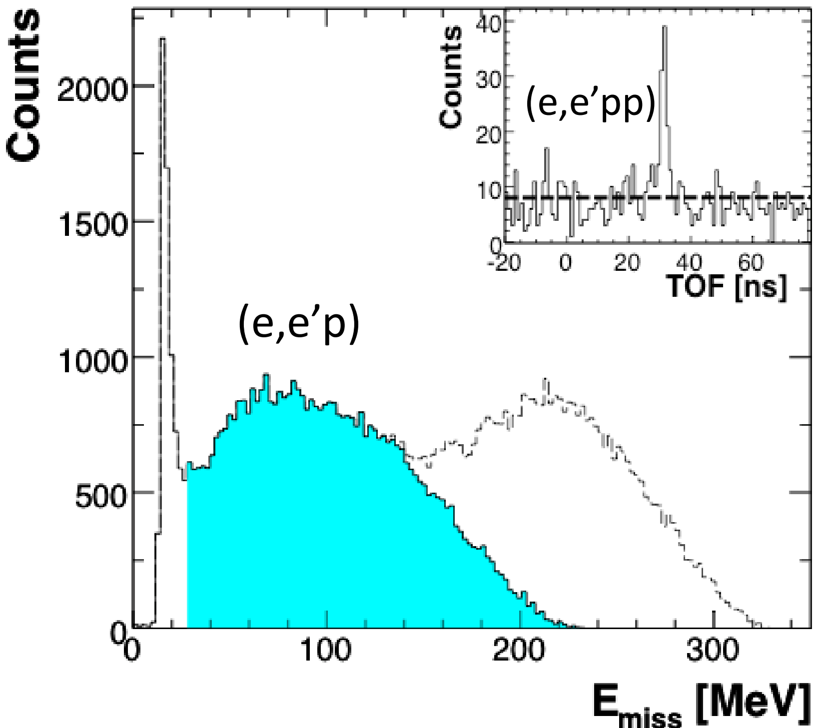
HAND

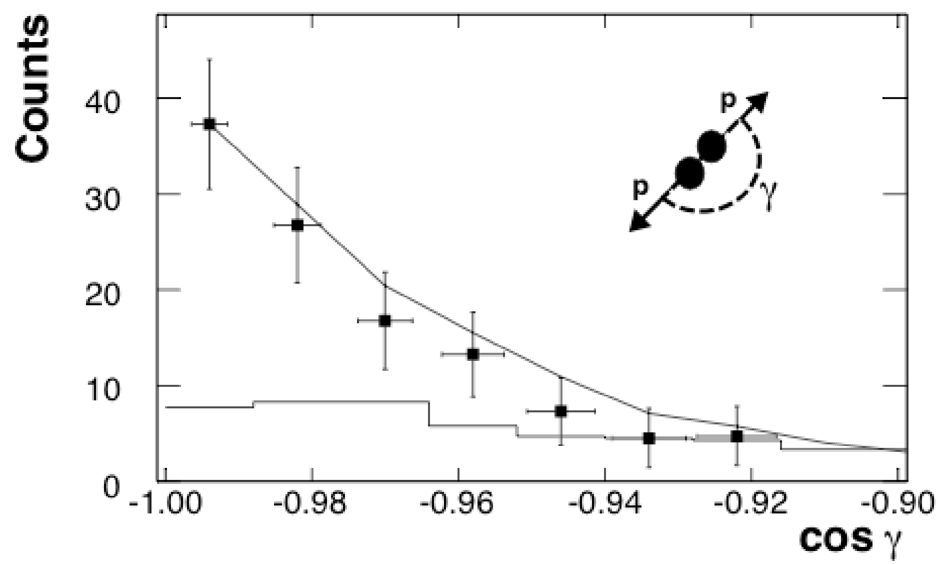
- Hall A Neutron Detector
- First Neutron Detector in Hall A
- Measuring D(e,e'p) and detecting the neutron, the detector was tested and calibrated.

Neutron TOF [ns]



(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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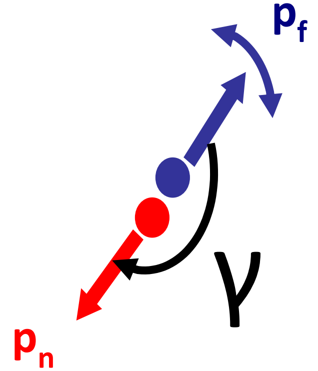
Brookhaven EVA Collaboration Result

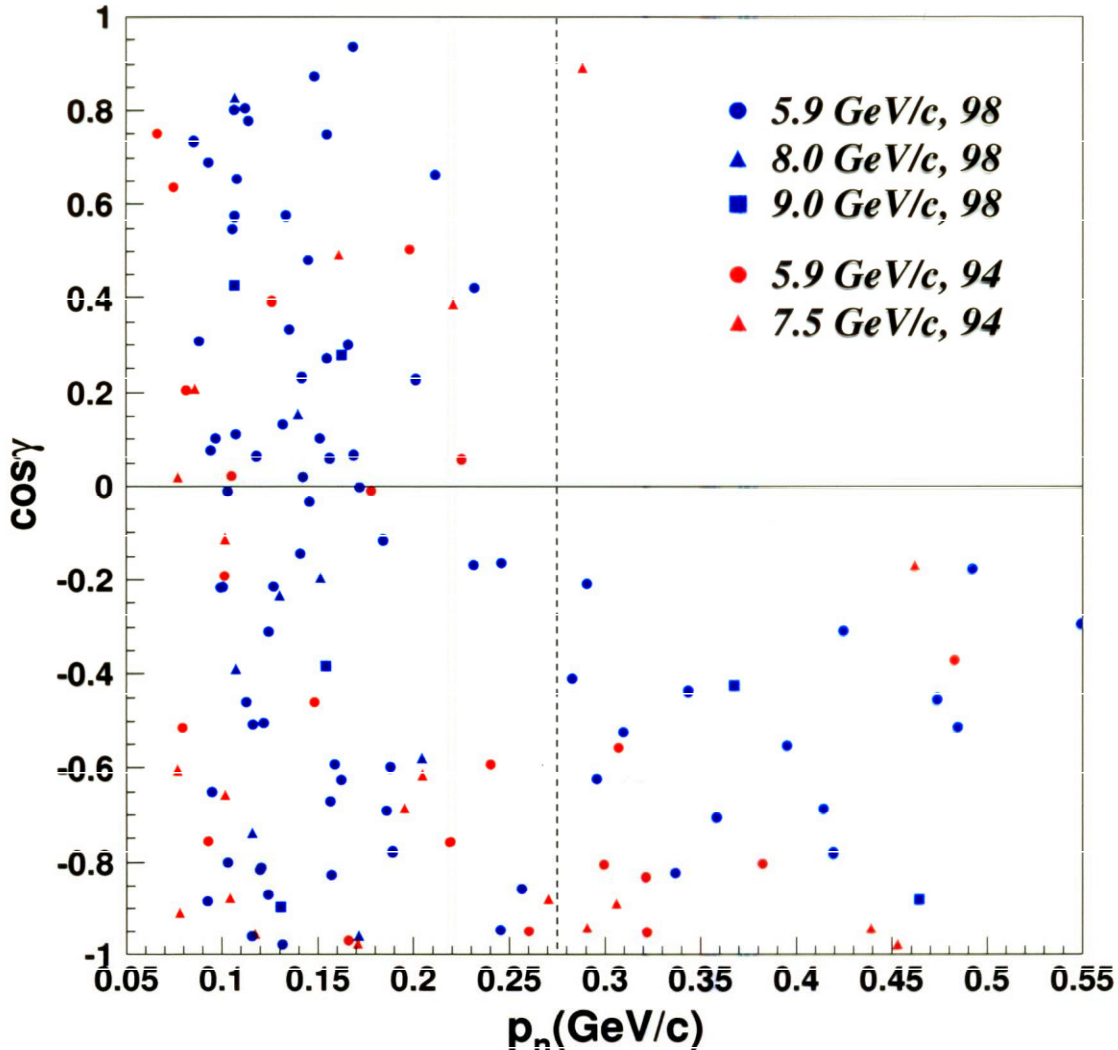
$^{12}C(p,2p+n)$ Reaction



$p_f = p_1 + p_2 - p_0$

p_0 = incident proton

p1 and p2 are detected



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

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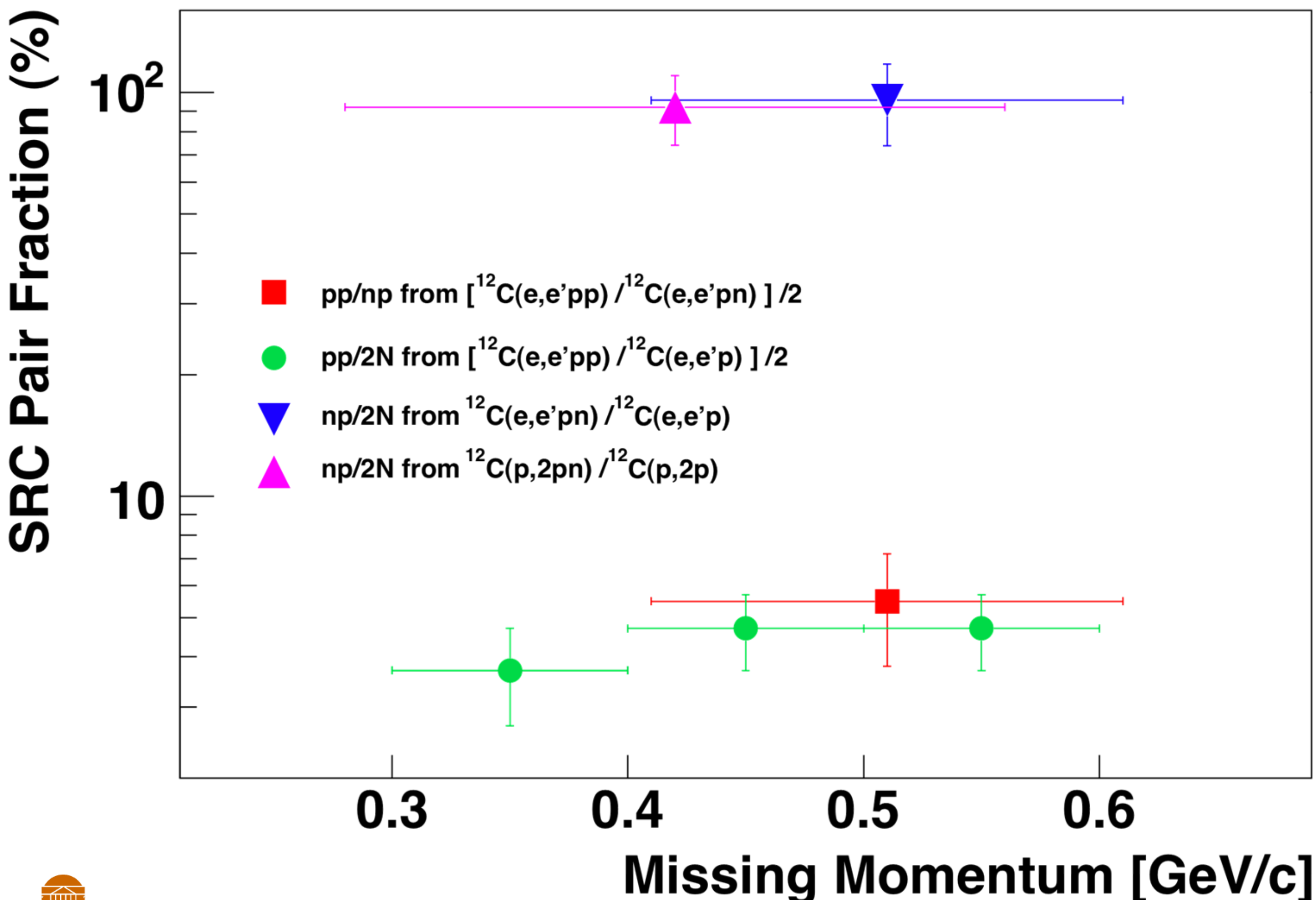
Correlated Pair Factions from ^{12}C

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



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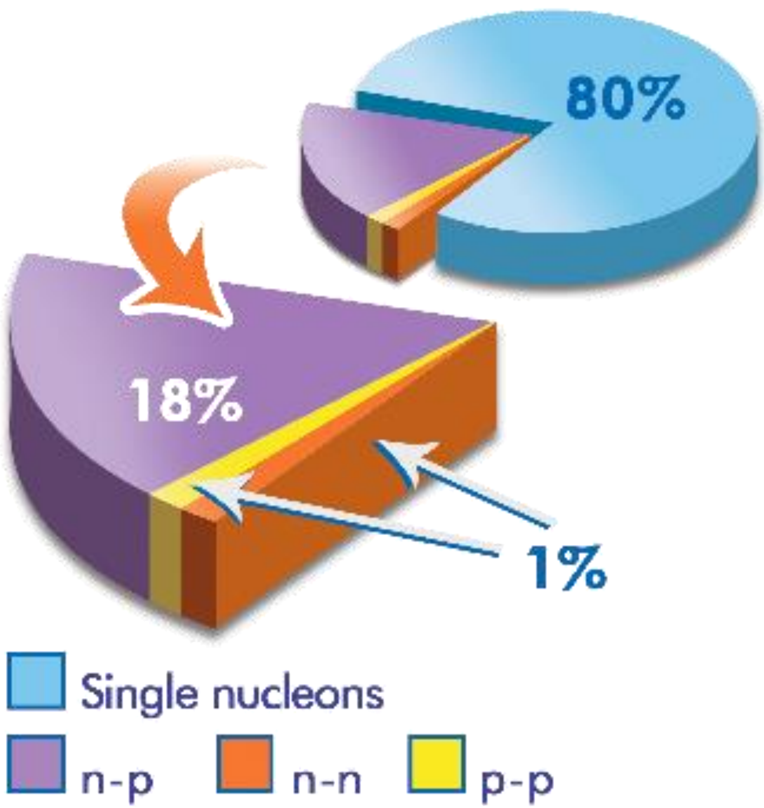
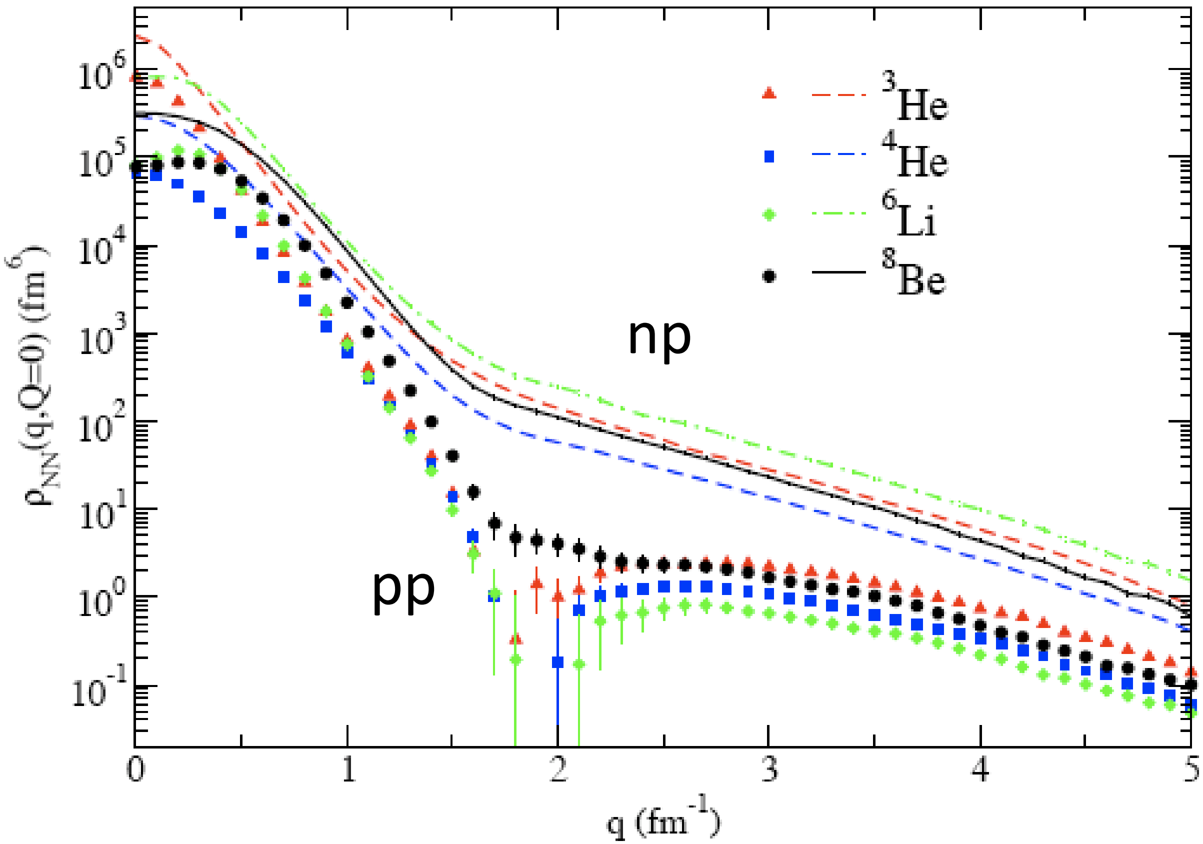
From the (e,e'), (e,e'p), and (e,e'pN) Results

- 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)



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.