E02-013: Measurements of the Electric Form Factor of the Neutron in Hall A

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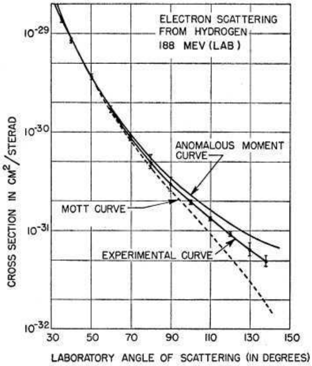
Outline

- Nucleon Form Factor Overview
  - Form Factor Models
  - Form Factor Interpretations
- E02-013
- 12 GeV Plans

Early Efforts

- 1910s - Rutherford discovers positively charged core of atoms
- 1932 - Neutron discovered by James Chadwick
- 1933 - Stern observes anomalous magnetic moment of proton deflection of a beam of hydrogen molecules in an inhomogeneous magnetic field
- 1955 - Hofstadter *et al.* at Stanford discovers protons have size through e scattering - quotes RMS charge radius of 0.74 ± 0.24 fm



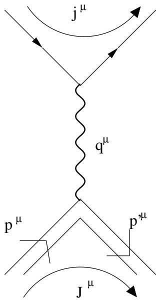
Motivation

- Form factors are a fundamental property of the nucleon
- Provide excellent testing ground for QCD and QCD-inspired models
- Are not yet calculable from first principles

Nucleon Currents

Scattering matrix element, $M \sim \frac{j_\mu J^\mu}{Q^2}$
Generalizing to spin 1/2 with arbitrary structure, one-photon exchange, using parity conservation, current conservation the current parameterized by two form factors

$$J^\mu = e\bar{u}(p')\left[F_1(q^2)\gamma^\nu + i\frac{\kappa}{2M}q_\nu\sigma^{\mu\nu}F_2(q^2)\right]u(p)$$



Form Factors

- Dirac, Chirality Conserving - F_1
- Pauli, Chirality Flip - F_2

Sachs Form Factors

Replace with Sachs Form Factors

$$G_E = F_1 - \kappa\tau F_2$$
$$G_M = F_1 + \kappa F_2, \tau = \frac{Q^2}{4M}$$

Rosenbluth Formula

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{Mott}} \frac{E'}{E}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right]$$

$\lim_{Q^2 \to 0}$

$$G_E^p(0) = 1, \qquad G_M^p(0) = \mu_p = \quad 2.79$$
$$G_E^n(0) = 0, \qquad G_M^n(0) = \mu_n = \quad -1.91$$

Sachs Form Factors

Sachs form factors carry more intuitive interpretation by relating Fourier transforms of electric charge and magnetic moment distributions in "Briet frame" where $\nu = 0$, $\vec{P} = -\vec{P}'$

$$J^0 = e2M\chi'^{\dagger}\chi G_E$$
$$\vec{J} = ie\chi'^{\dagger}(\vec{\sigma} \times \vec{q})\chi G_M$$

For $\lim_{Q^2 \to 0}$, first derivative related to mean squared-radius of the distribution of charge and magnetic moments

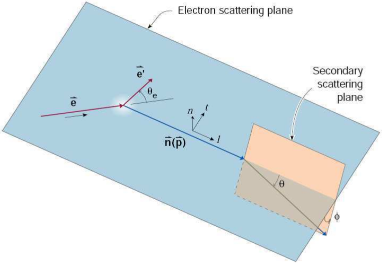
$$\langle r^2_{\mathrm{charge}} \rangle = -6 \frac{dG_E}{dQ^2}\bigg|_{Q^2=0}$$

Measurement through Spin Observables

- Akhiezer and Rekalo (1968) - Polarization experiments offer a better way to obtain G_E
- Polarization observable measurements generally have fewer systematic contributions from nuclear structure and radiative effects

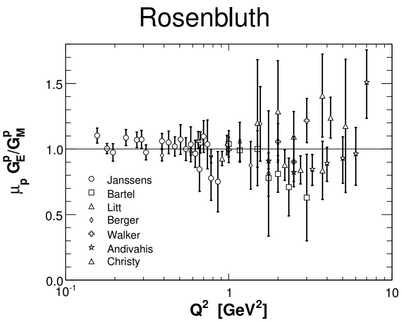
Polarization Transfer

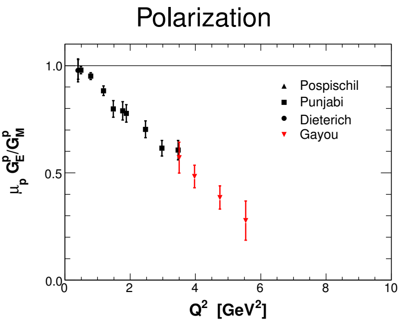
$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})\tan\theta_e/2}{2M}$$



Proton Polarization Results

- JLab, Gao *et al.*, G_E^p found to be very different from Rosenbluth using this method

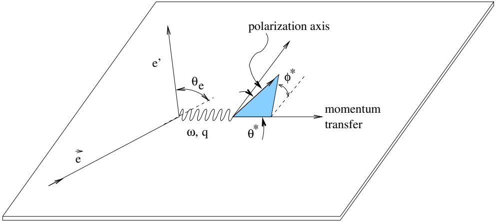




- Discrepancy partially explained by hard two-photon exchange
- New form has implications for interpretation

Polarized Target Measurements

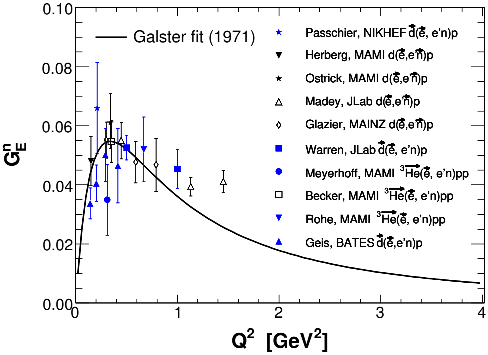
Long. polarized beam/polarized target transverse to $\vec{q}$ in scattering plane



Helicity-dependent asymmetry roughly proportional to G_E/G_M

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = A_\perp = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2) G_E/G_M \hat{n}\cdot(\hat{q}\times\hat{T})}{(G_E/G_M)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))}$$

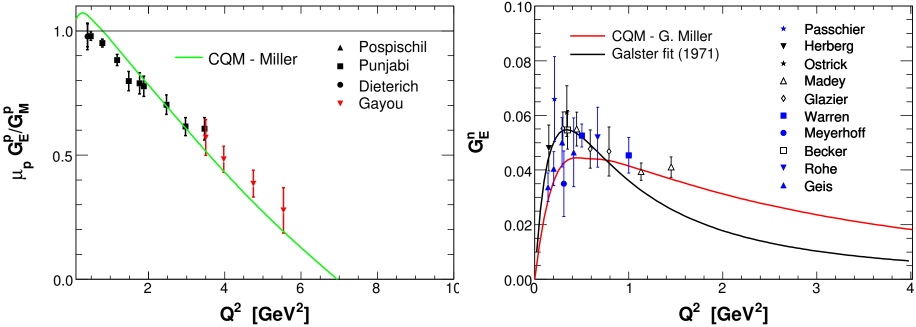
Neutron Electric Form Factor



Polarization measurements allow for precise G_E^n

Constituent Quark Light-Front Cloudy Bag Model

- Results match present G_E^p at higher Q^2!



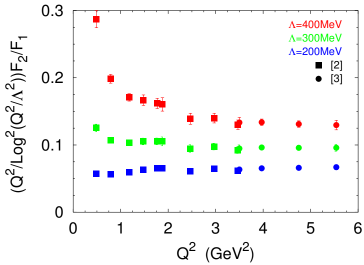
- Suppression at higher Q^2 due to inclusion of quark orbital angular momentum

pQCD

- Can treat with pQCD for large Q^2
- Log order calculations for F_1, F_2 by Belitsky *et al.* (including hadron helicity non-conservation through quark OAM) makes prediction that as $Q^2 \longrightarrow \infty$

$$\frac{Q^2}{\log^2(Q^2/\Lambda^2)}\frac{F_2}{F_1} = \text{const}$$

Λ parameter related to size of the nucleon



- Proton data fits very well, more hints at quark orbital angular momentum

Form Factor Models and Interpretations

- Impact parameter densities in infinite momentum frame
- $\sum_i \vec{b}_i x_i = 0$

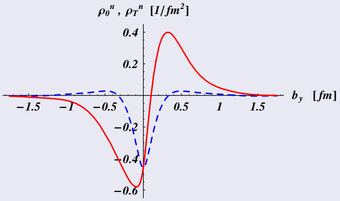
Unpolarized and Polarized:

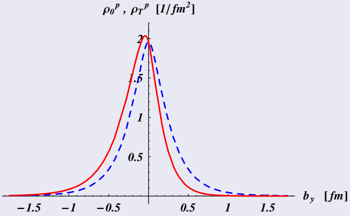
$$\begin{aligned}
\rho_0^N(b) &= \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F_1(Q^2) \\
\rho_T^N(b) &= \rho_0^N(b) - \sin(\phi_b - \phi_S) \\
&\times \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M_N} J_1(bQ) F_2(Q^2)
\end{aligned}$$

Carlson and Vanderhaeghen, Phys. Rev. Lett. 100, 032004, (2008)

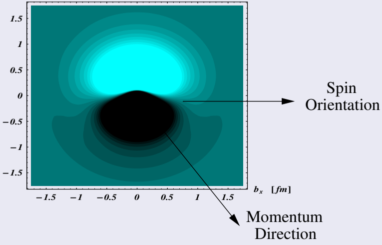
G. Miller, Phys. Rev. C 78, 032201(R) (2008)

Unpolarized





Transversely Polarized Neutron



More hints at orbital angular momentum?

G_E^n Measurements at JLab

- G_E^n least well measured range of Q^2
- More difficult to measure relative to other FFs since
  - G_E^n is intrinsically small compared to G_M^n
  - Neutron is not stable outside nucleus, use targets $^2\mathrm{H}$ and $^3\mathrm{He}$
- Three experiments done at JLab:
  - E93-026 - Warren *et al.* - $\vec{d}(\vec{e},e'n)p$
  - E93-038 - Madey *et al.* - $d(\vec{e},e'\vec{n})p$
  - E02-013 - $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)pp$

E02-013 Collaborators

Spokespeople:

- Bogdan Wojtsekhowski - Jefferson Lab
- Gordon Cates - University of Virginia
- Nilanga Liyanage - University of Virginia

Analysis Coordinator:

- Seamus Riordan - Carnegie Mellon University (graduated 2008), UVA

Ph.D. Students:

- Sergey Abrahamyan - Yerevan, Armenia
- Brandon Craver - University of Virginia
- Aidan Kelleher - College of William and Mary
- Ameya Kolarkar - University of Kentucky (graduated 2007), Boston University
- Jonathan Miller - University of Maryland, College Park

Masters Students:

- Tim Ngo - California State University, Los Angeles (graduated 2007)

Postdocs:

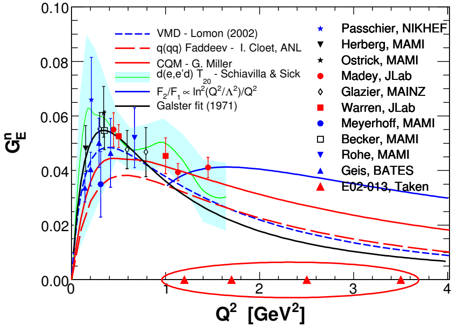
- Rob Feuerbach - JLab, College of William and Mary (-2007)

Over 100 collaborators

Hall A, E02-013

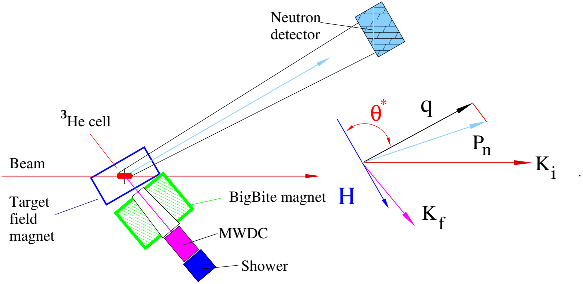
- Most recent measurement in Hall A, E02-013 through $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)pp$

Q^2 [GeV^2]	E_{beam} [GeV]	Avg. θ_e [deg]	Q_{beam} [C]
1.2	1.519	56.26	1.2
1.7	2.079	51.59	2.2
2.5	2.640	51.59	5.5
3.5	3.291	51.59	11.4



Experimental Setup

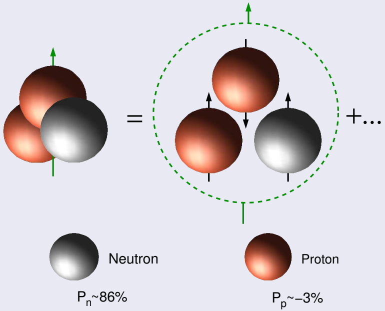
- Polarized ^{3}He target acts as effective free neutron source
- Two arms to measure coincidence e' and n, allow for cuts on $p_{\mathrm{miss},\perp}$ to suppress FSI



- BigBite - large acceptance spectrometer, measures $\vec{e}'$
- Neutron arm - matches BB acceptance, measures neutron momentum through ToF, performs nucleon charge ID

Polarized ^{3}He Target

- ^{3}He is spin 1/2, 3 body calculations describe polarization as

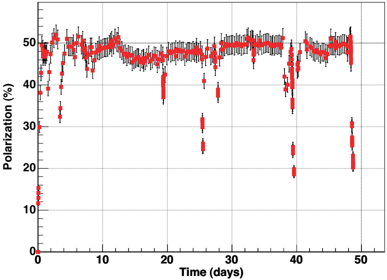


Polarization is carried mostly in *n*, protons are mostly unpolarized

- SEOP polarization transfer: $\vec{\gamma} \longrightarrow \mathrm{Rb} \longrightarrow \mathrm{K} \longrightarrow {}^3\mathrm{He}$

E02-013

Polarized $^3\mathrm{He}$ Target

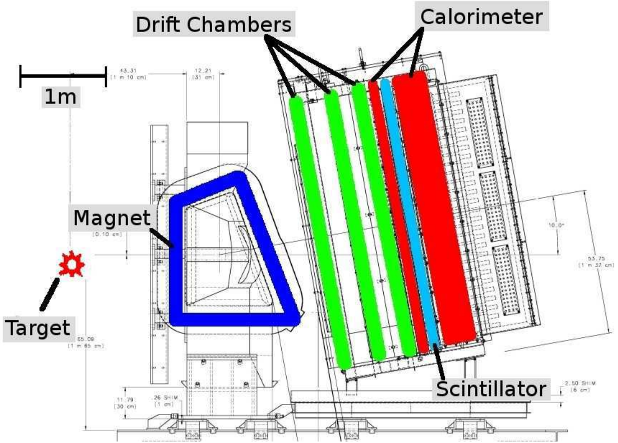


- Measure polarization through NMR/EPR
- Achieved polarization of about 45∼50%
- Luminosity of $L \sim 10^{36}\mathrm{Hz/cm}^2$

BigBite Spectrometer

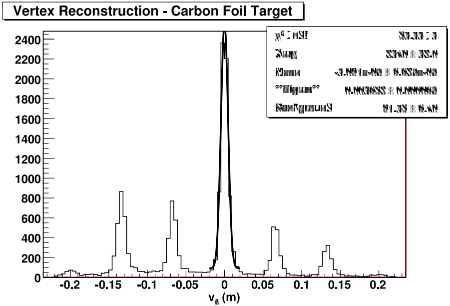
- Non-focusing large angular and momentum acceptance spectrometer
- Approximately 76 msr solid angle for 40 cm target
- Single dipole magnet of field integral approximately 1.0 $\mathrm{T} \cdot \mathrm{m}$
  - Momentum resolution of $\sigma_p / p \approx 1\%$ for accepted electrons
- Accepting electrons between 0.6$\sim$1.5 GeV/c
- Specially constructed detector package first used for E02-013

BigBite Detector Set

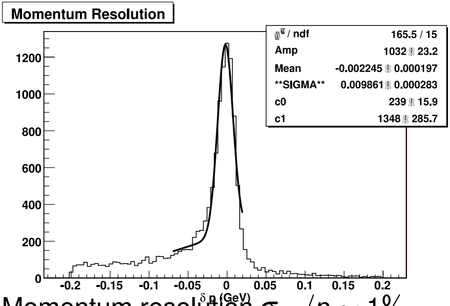


Drift Chamber Optics and Performance

- Wire positions and TDC offsets calculated and optimized - $\sigma \sim 200\ \mu\mathrm{m}$ resolution per plane
- Using optics model treating interaction at effective bend plane with first order corrections



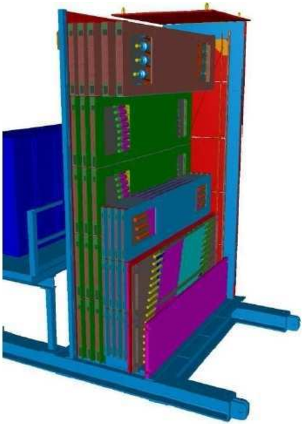
Resolution of about $\sigma_{v_z} = 5\ \mathrm{mm}$



Momentum resolution $\sigma_{\delta p}/p \sim 1\%$

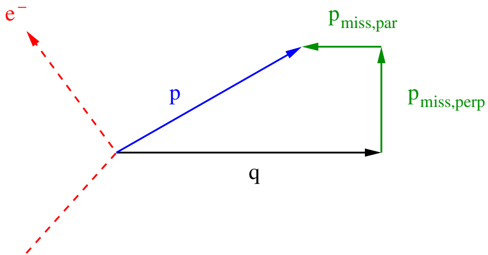
Neutron Arm

- Neutron arm detects recoiling proton/neutron
- Measures momentum through ToF, charge through veto layers
- Optimized to have neutron/proton momentum resolution $\sigma_p \approx 300\ \mathrm{MeV}$ for $Q^2 = 3.5\ \mathrm{GeV}^2$ point
- Covers 5m $\times$ 1.6m about about 10m away - Matches BigBite acceptance for QE protons/neutrons



Quasielastic Selection

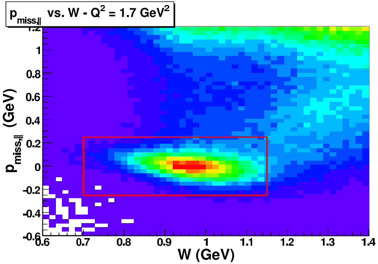
Need to reliably separate neutral QE events



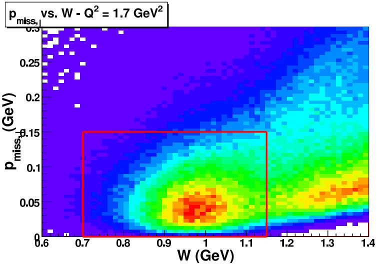
- Invariant mass assuming free stationary nucleon target
- Missing mass of $^3\mathrm{He}(e, e'n)X$

$Q^2 = 1.7\ \mathrm{GeV}^2$ Quasielastic Selection

$p_{\mathrm{miss},\parallel}$ vs W

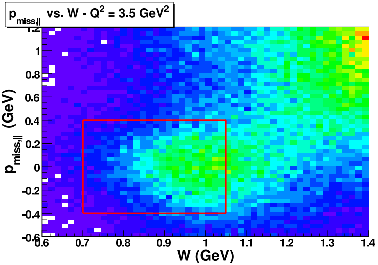


$p_{\mathrm{miss},\perp}$ vs W

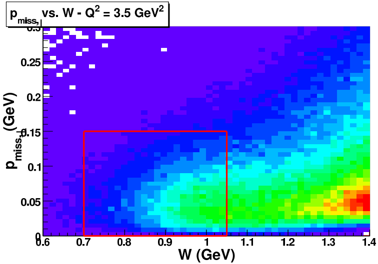


$Q^2 = 3.5\ \mathrm{GeV}^2$ Quasielastic Selection

$p_{\mathrm{miss},\parallel}$ vs W



$p_{\mathrm{miss},\perp}$ vs W



- Momentum resolution degraded due to shorter time-of-flight

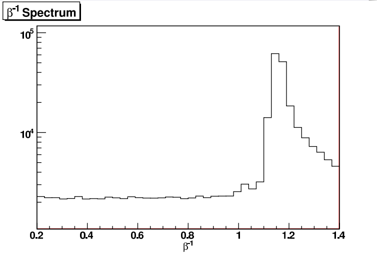
Asymmetry Dilutions and Corrections

Asymmetry is corrected for:

- N_2 in target
- Target polarization
- Beam polarization

Accidental Background

Evaluated by looking at out-of-time events



Proton Contamination

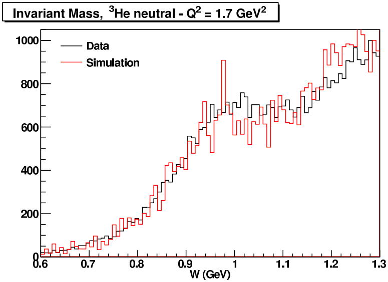
- Evaluated through uncharged/charged ratios of $\mathrm{H_2}$, $\mathrm{^3He}$, $\mathrm{N_2}$
  - e.g. $\frac{\mathrm{N_{p\to n}}}{\mathrm{N_{p\to p}}} = \frac{N_{\mathrm{un}}}{N_{\mathrm{ch}}}\Big|_{\mathrm{H_2}}$

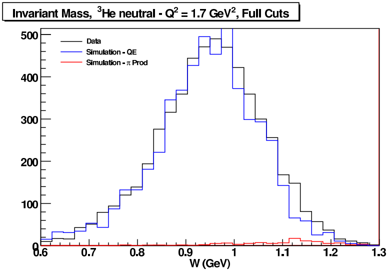
$$D_p = \frac{1}{1 + \frac{\mathrm{N_{p\to n}}}{\mathrm{N_{n\to n}}}}$$

- Monte Carlo simulations generally in agreement
- Evaluated to be 10-25% with systematic error of few percent
- Small proton asymmetry contributions are taken into account

Inelastic Contributions

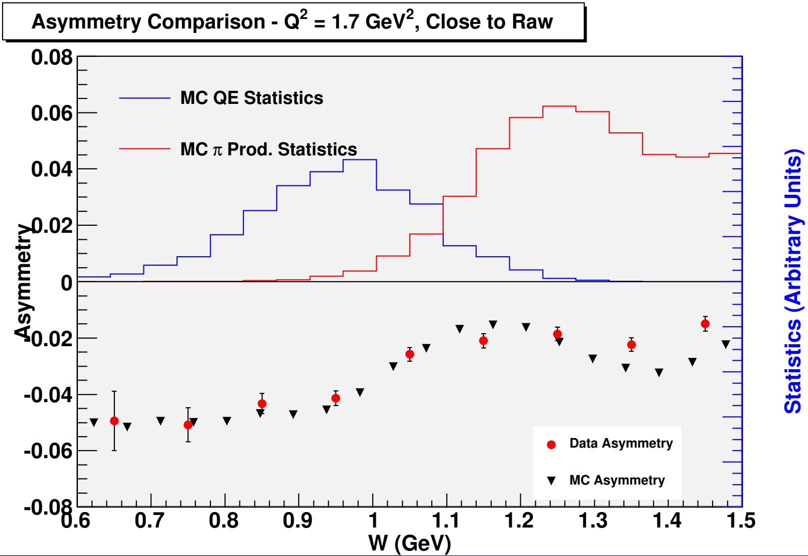
- π electroproduction contributions evaluated using MC with MAID data
- Allows us to evaluate cross sections and production asymmetry





Inelastic contribution $< 1\%$

Inelastic Contributions

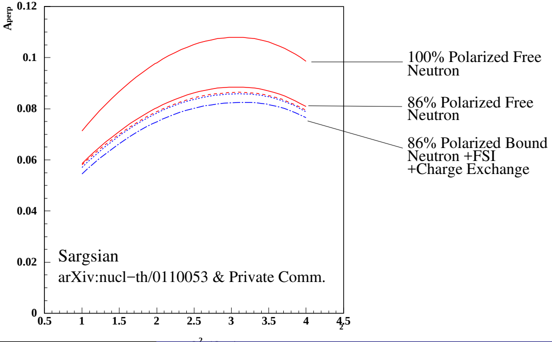


FSI Contributions

Final state interactions modify final asymmetry

- Charge exchange can drive measured asymmetry down
- Narrow missing momentum can drive asymmetry up

Preliminary GEA calculations show decrease of A by $\sim 5-10\%$



Results

12 GeV Plans

- Polarized 12 GeV beam offers new opportunities to go to higher Q^2
- Two experiments at PAC34 approved
  - E12-09-006, B. D. Anderson, J. Arrington, S. Kowalski, R. Madey, B. Plaster, A.Yu. Semenov
    - Hall C, similar concept as earlier Madey experiment, E93-038
    - $^2\mathrm{H}(\vec{e}, e'\vec{n})p$
    - $Q^2 = 2.2, 4.0, 5.2, 6.9\ \mathrm{GeV}^2$
  - E12-09-016, B. Wojtsekhowski, G. Cates, S. Riordan
    - Super-BigBite Family (see G. Cates, 2:30 today)
    - $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)pp$
    - $Q^2 = 5.0, 6.8, 10.2\ \mathrm{GeV}^2$

Goals

Brings GEn up to similar range as other form factors

Conclusion

- Electromagnetic form factors provide a fundamental way to measure nucleon structure
- Measurements at Jefferson Lab have more than double the measured Q^2 range of G_E^n up to $Q^2 = 3.5\ \mathrm{GeV}^2$
- Experiments approved for the 12 GeV upgrade will push measurements of G_E^n further to $Q^2 = 10\ \mathrm{GeV}^2$