The Electric and Magnetic Form Factor of the Neutron with Super Bigbite

Seamus Riordan
University of Virginia
spr4y@virginia.edu
Gordon Cates, University of Virginia
Bogdan Wojtsekhowski, Jefferson Lab

for the Super Bigbite, E12-09-016, and E12-09-19 Collaborations

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Outline

- Form Factor Models and Interpretations
- G_E^n to $Q^2 = 10\ \mathrm{GeV}^2$: E12-09-016
- G_M^n to $Q^2 = 13.5\ \mathrm{GeV}^2$: E12-09-019

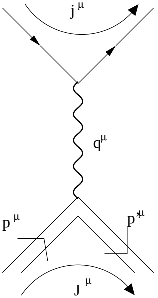
Motivation

- Form factors are a fundamental property of the nucleon
- Provide excellent testing ground for QCD and QCD-inspired models
- Gives constraints on models of nucleon structure
- 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 - F_1, chirality non-flip
- Pauli - F_2, chirality flip

Sachs Form Factors

Replace with Sachs Form Factors

$$G_E = F_1 - \kappa\tau F_2$$
$$G_M = F_1 + \kappa F_2$$

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

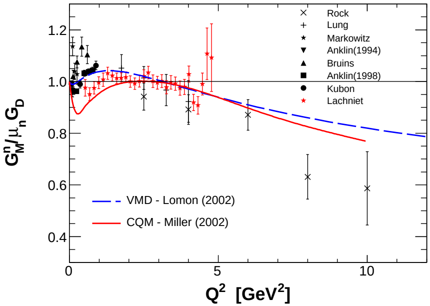
$$G_E^p(Q^2=0) = 1, \qquad G_M^p(Q^2=0) = \mu_p = 2.79$$
$$G_E^n(Q^2=0) = 0, \qquad G_M^n(Q^2=0) = \mu_n = -1.91$$

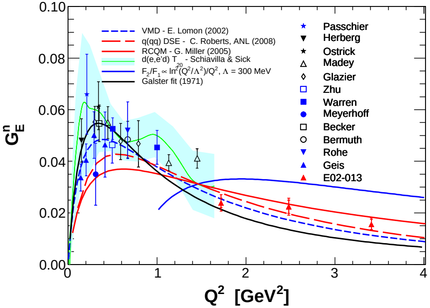
Rosenbluth Formula

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{Mott}} \frac{E'}{E}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right], \tau = \frac{Q^2}{4M^2}$$

Neutron Form Factors

- Typically lag behind proton counterparts
- Neutron studies require nuclear corrections
- G_E^n is small





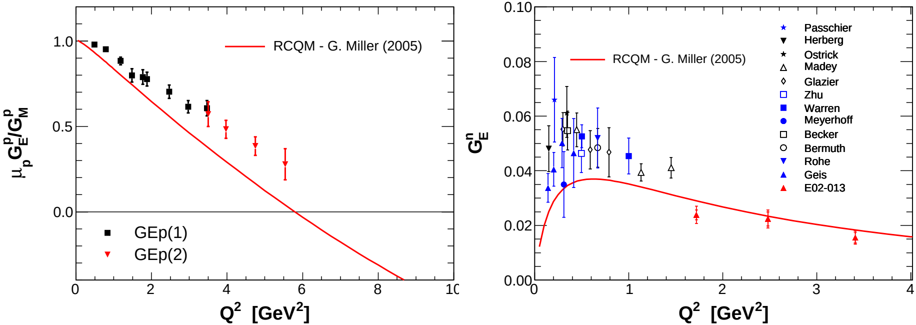
Nucleon Structure Information in Form Factors

- Constituent quark models
- q(qq) Dyson-Schiwinger equations approach
- Charge distributions in the IMF
- QCD motivated fits - VMDs, GPDs
- With proton and neutron form factors - quark flavor and isoscalar/vector decomposition

Constituent Quark Light-Front Cloudy Bag Model

- Constituent quark model - successful for calculation of baryon magnetic moments
- Construct wavefunction for 3 massive quarks, relate current matrix elements to form factors
- Light front dynamics makes boosts to wavefunction easy so relating initial and final states for current matrix element is much easier, but rotations are more difficult
- Form allows for quark orbital angular momentum
- Form is assumed for spatial distribution, confinement size is a free parameter
- Miller includes additional pion cloud effects for low Q^2 behavior

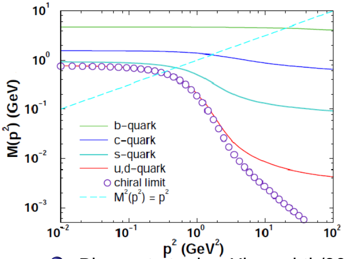
- Results match present G_E^p at higher Q^2

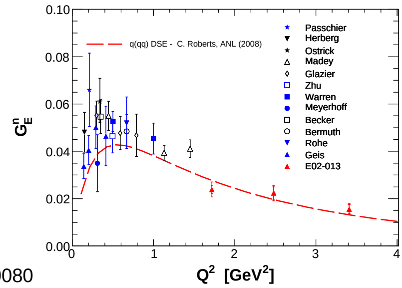


- G_E^p suppression at higher Q^2 due to inclusion of quark orbital angular momentum

Novel DSE/Fadeev q(qq) ANL Calculation

- Poincare covariant model based on QCD's Dyson-Schwinger equations to describe dressed quark propagator
- Uses model where two of three quarks are in diquark state
- Bethe-Salpeter equation describes diquark boundstate
- Fadeev amplitudes describe quark interchanges
- Few free parameters tuned to nucleon properties such as mass and magnetic moments





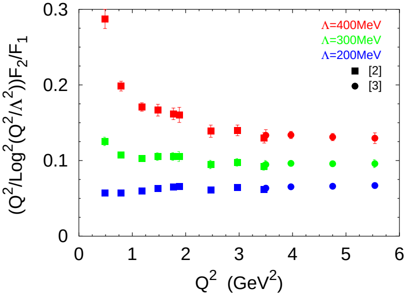
- Bhagwat et. al. arXiv:nucl-th/0610080
- Cloët et. al. arXiv:nucl-th/0804.3118

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 $Q^2 \to \infty$

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

Λ parameter related to size of the nucleon



- Published proton data fits very well at early Q^2

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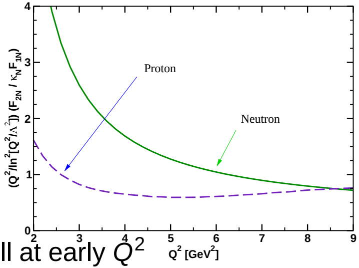
From DSE approach:



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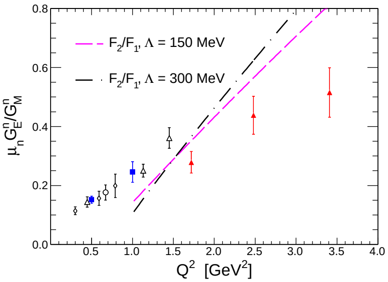


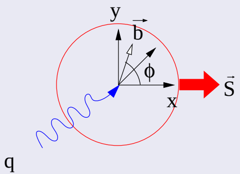
- Published proton data fits very well at early Q^2

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

Unpolarized and Transversely Polarized:

$$\rho_0^N(b) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F_1(Q^2)$$

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

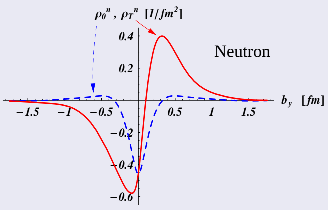


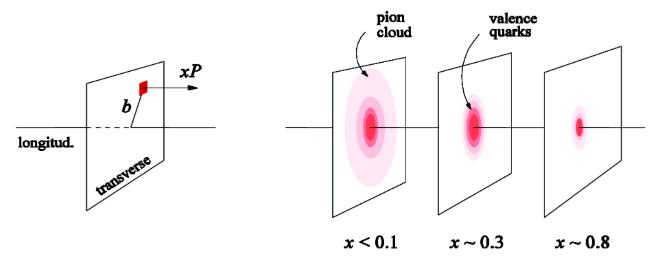
Carlson and Vanderhaeghen, Phys. Rev. Lett. 100, 032004, (2008)

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

- *b* is NOT radial quantity, is taken wrt momentum weighted distribution of all partons in IMF

Unpolarized, polarized $\phi = 90^\circ$





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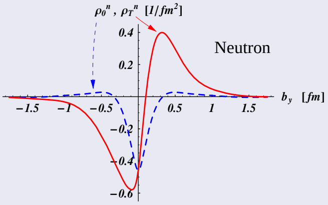
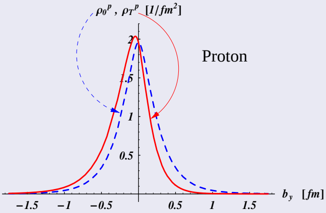
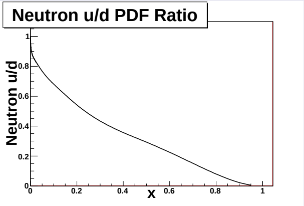


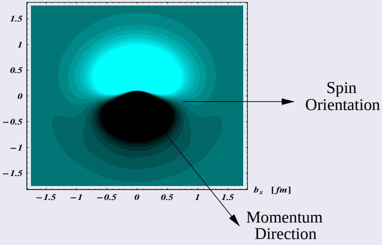


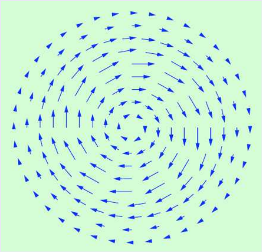
- Neutron has negative density at $b = 0$
- Large x, d quarks dominate in neutron



Transversely Polarized Transverse Density

Transversely Polarized





- In IMF quarks which are rotating towards/away from photon are enhanced across polarization-q plane
- Suggestive of orbital angular momentum (M. Burkardt)

GPD Parameterization - Diehl et al.

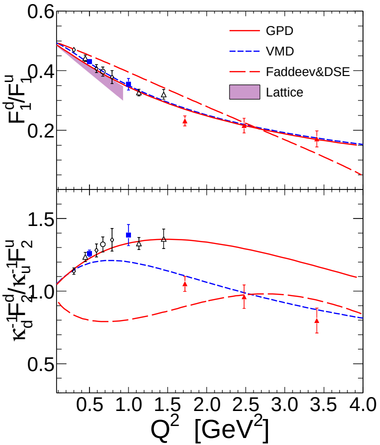
- Non-skewed moments of GPDs yield form factors

$$F_1^p = \int_{-1}^{1} dx \left(\frac{2}{3} H^u(x, \xi = 0, t, \mu^2) - \frac{1}{3} H^d(x, \xi = 0, t, \mu^2) \right)$$
$$F_2^p = \int_{-1}^{1} dx \left(\frac{2}{3} E^u(x, \xi = 0, t, \mu^2) - \frac{1}{3} E^d(x, \xi = 0, t, \mu^2) \right)$$

- Form factors can be used to constrain GPD models
- Parameterization from Diehl et al:

$$H_v^q(x,t) = \left(\frac{x_0}{x}\right)^{\alpha(0)} exp\left[\left(\alpha' \log\frac{x_0}{x} + b_0\right) t\right]$$
$$E_v^q(x,t) = N_q \kappa_q x^{-\alpha}(1-x)^{\beta_q} \times$$
$$\exp\left[t\alpha'(1-x)^3 \log\frac{1}{x} + D_q(1-x)^3 + C_q x(1-x)^2\right]$$

Quark Flavor Decomposition



Lattice: Bratt et al., arXiv:1001.3620, $m_\pi = 140$ MeV

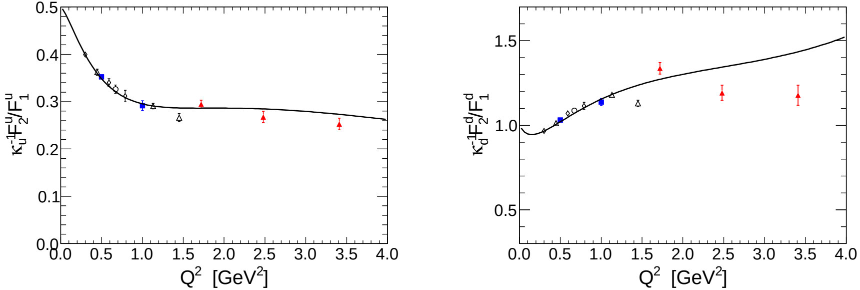
$$F^p_{1,2} = \frac{2}{3}F^u_{1,2} - \frac{1}{3}F^d_{1,2}$$

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

- High Q^2 for G^n_E data allows for quark decomposition
- GPDs formulated for quark flavors
- Lattice is better suited for isovector FF, scaling behavior

Quark Flavor Decomposition

- Up and down quark F2/F1 distributions do not appear to follow $1/Q^2$



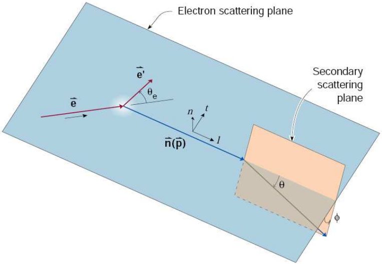
- G_E^n data with Kelly paramterization for remaining FFs
- Curve - Kelly parameterization

Extending G_E^n to $Q^2 = 10\ \mathrm{GeV}^2$ - Spin Observables

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

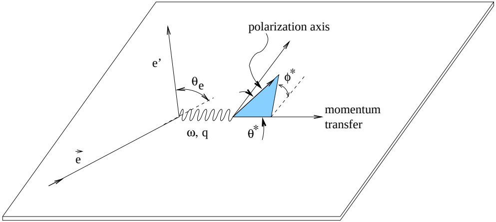
Polarization Transfer

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



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

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx A_\perp = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2) G_E/G_M}{(G_E/G_M)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))}$$

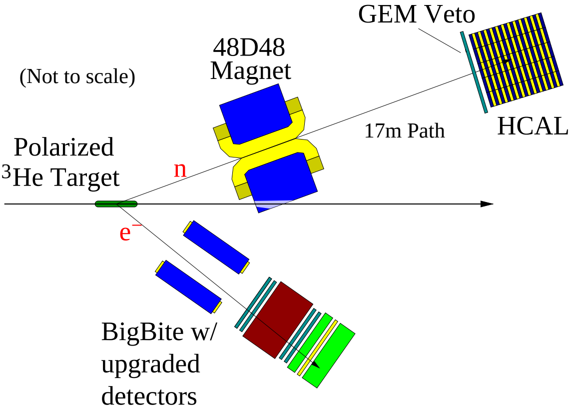
G_E^n Measurements at JLab

- 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 $^3\mathrm{He}$
- Four experiments done at JLab:
  - Hall C - E93-026 - Zhu *et al.*, Warren *et al.* - $\vec{d}(\vec{e},e'n)p$, $Q^2 = 0.5, 1.0\ \mathrm{GeV}^2$
  - Hall C - E93-038 - Madey *et al.* - $d(\vec{e},e'\vec{n})p$, $Q^2 = 0.4 - 1.5\ \mathrm{GeV}^2$
  - Hall A - E02-013 - $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)pp$, $Q^2 = 1.2 - 3.4\ \mathrm{GeV}^2$
  - Hall A - E05-102 - $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)pp$, $Q^2 = 0.4 - 1.0\ \mathrm{GeV}^2$

Goals

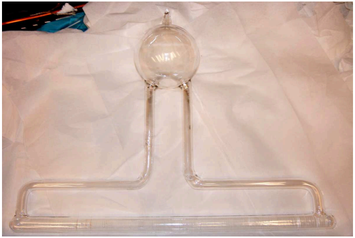
- Bring G_E^n up to similar range as G_E^p
- Challenges:
  - Cross section falls with Q^2, factor of ~ 100 $Q^2 = 3.4 \rightarrow 10\mathrm{GeV}^2$
  - Polarization transfer difficult with high nucleon momentum
- Strategy:
  - Measure polarized target asymmetry
  - Increase luminosity - upgrade detectors/target
  - Increase target polarization - narrow width laser, hybrid alkalai
  - Improve PID from electron and nucleon arm

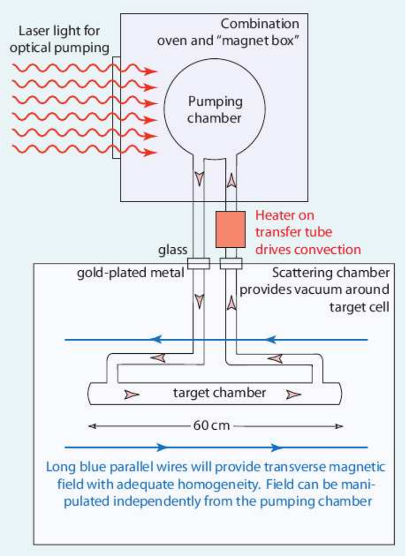
High Q^2 G_E^n Experimental Layout



- Upgraded Bigbite detector stack for higher rates, better PID
- Hadron calorimeter at 17 m, additional GEM veto
- Place magnet $B \cdot dl = 1.7\ \mathrm{T} \cdot \mathrm{m}$ in front to deflect protons - reduces background by factor of 5

Upgraded ^{3}He Target

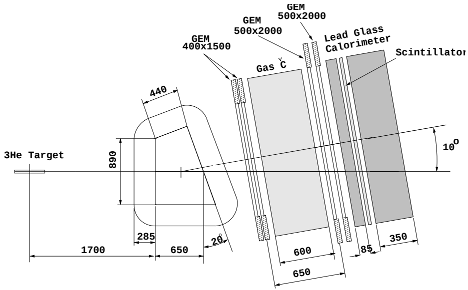




- Simulations show sustainable polarization of 62% with $I = 60\ \mu\text{A}$
- Overall effective luminosity gain of 15

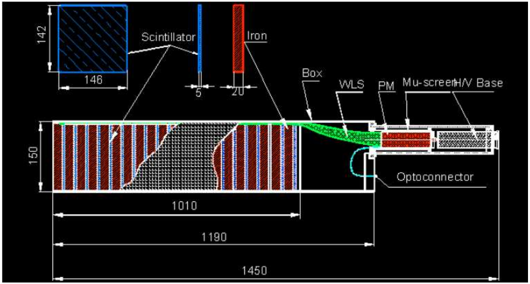
Upgraded BigBite Components

- Estimated rates are 60 $\mathrm{kHz/cm^2}$ - current drift chambers replaced by GEM chambers
- GEM detectors shown to work up to 2500 $\mathrm{kHz/cm^2}$ at CERN
- Momentum resolution of $\sigma_p/p \sim 0.5\%$ for e^- of $3-4$ GeV
- BigBite Cerenkov+preshower pushes pion contributions $< 0.1\%$



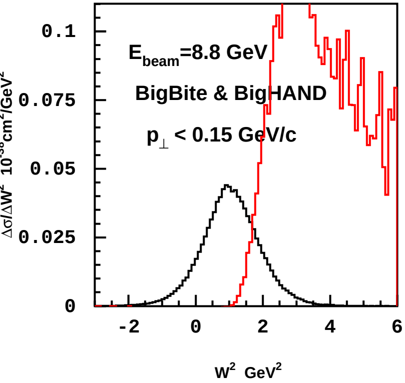
Hadron Calorimeter, HCAL

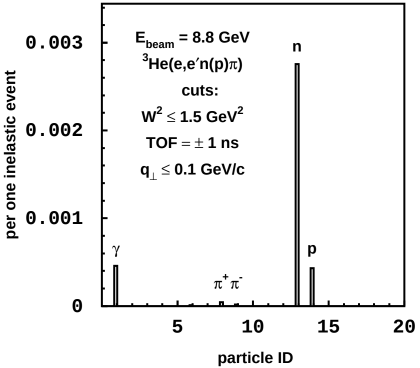
- HCAL based on COMPASS design



- Threshold can be set dramatically higher than original neutron arm, 50 kHz with 50 MeV threshold
- High detection efficiency, $> 95\%$
- Acceptance can be configured to match QE nucleon profile
- Time-of-flight resolution comparable to neutron arm with optimized readout scheme (300 ps was achieved with E864 calorimeter at AGS)

- Cuts on missing momenta, invariant mass allow for suppression of inelastic events
- Inelastics can be corrected using Monte Carlo with MAID or sideband subtraction

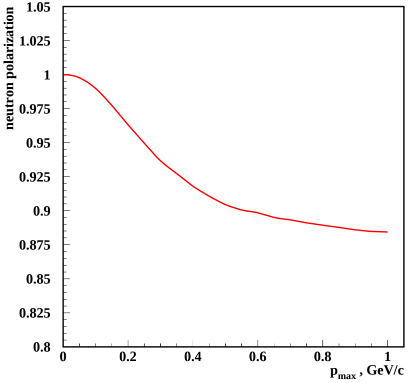




- With bending magnet and GEM veto, proton contamination will be negligable

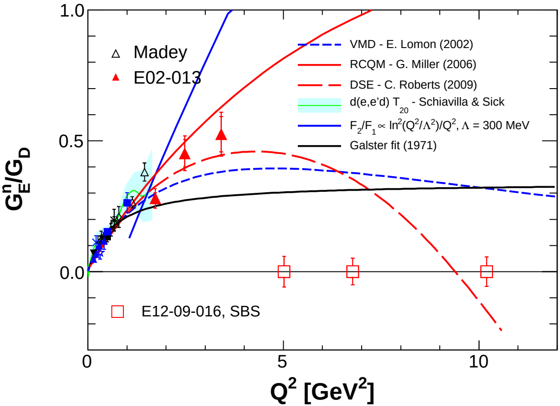
FSI Contributions

- Nuclear effects evaluated through GEA by M. Sargsian
- Effective polarization highly dependent on missing momentum cuts
- Different from 86% inclusive assumption
- For our detector acceptances and cuts, effective polarization $90 - 100\%$



Anticipated Results

Brings G_E^n up to similar level as other form factors in 50 days beamtime



- Strong divergence between different model predictions
- DSE predicts zero crossing

Extending G_M^n to $Q^2 = 14\ \mathrm{GeV}^2$

Ratio technique to extract G_M^n from relative differential cross section to G_M^p

$$R'' = \frac{\frac{d\sigma}{d\Omega}|_{\mathrm{d(e,e'n)}}}{\frac{d\sigma}{d\Omega}|_{\mathrm{d(e,e'p)}}} \to \frac{\frac{d\sigma}{d\Omega}|_{\mathrm{n(e,e')}}}{\frac{d\sigma}{d\Omega}|_{\mathrm{p(e,e')}}} = \frac{\eta \frac{\sigma_{\mathrm{Mott}}}{1+\tau}\left((G_E^n)^2 + \frac{\tau}{\varepsilon}(G_M^n)^2\right)}{\frac{d\sigma}{d\Omega}|_{\mathrm{p(e,e')}}}$$

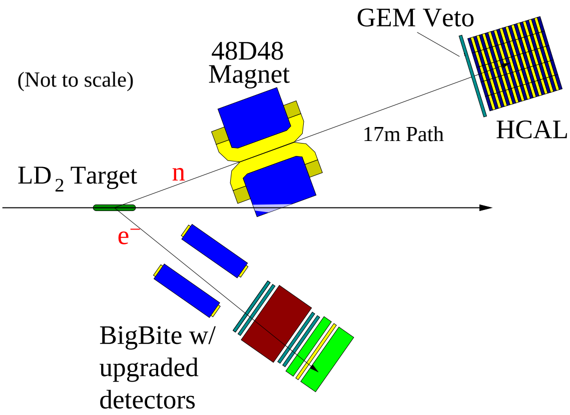
$$\to \frac{\eta\sigma_{\mathrm{Mott}}\frac{\tau/\varepsilon}{1+\tau}(G_M^n)^2}{\frac{d\sigma}{d\Omega}|_{\mathrm{p(e,e')}}} = R$$

$$\eta = E'/E, \varepsilon = \left(1 + \vec{q}^2/Q^2 \tan^2(\theta/2)\right)^{-1}$$

- Not as sensitive for corrections for nuclear structure ($< 1\%$)
- Not very sensitive to G_E^n
- Need to know nucleon detection efficiencies, calibrate on H_2
- Need for extracting G_E^n from measured ratio G_E^n/G_M^n

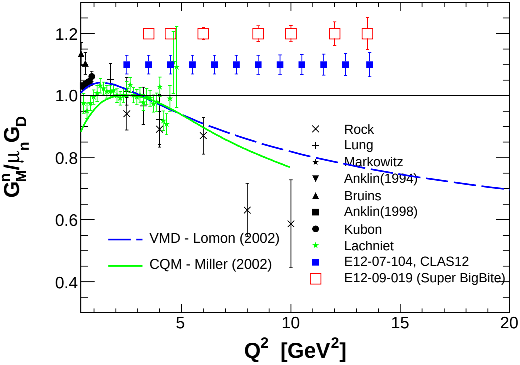
G_M^n Setup

- 7 Q^2 points ranging from 3.5 GeV^2 to 13.5 GeV^2
- Setup similar to G_E^n with LD_2 target



Antipated Results

- Approved beam of 25 days
- Total error on $G_M^n \sim 4\%$ at $Q^2 = 13.5\ \mathrm{GeV}^2$
- G_M^n calculated using conservative Bodek parameterization



- CLAS12 G_M^n points shown for 56 days proposed (30 approved)

Conclusion

- Measuring the electric and magnetic form factors of the neutron to high Q^2 helps "complete" our picture of the nucleon
- Super Bigbite allows us to take form factor measurements to very high Q^2 with relative errors comparable to previous measurements
- Will allow for differentiation between several popular form factor models