The Electric Form Factor of the Neutron to High Q^2

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Outline

- Form Factor Introduction
- E02-013 - G_E^n to $Q^2 = 3.4\ \mathrm{GeV}^2$
- Form Factor Models and Interpretations
- 12 GeV JLab Plans - Q^2 to 10 GeV^2

Motivation

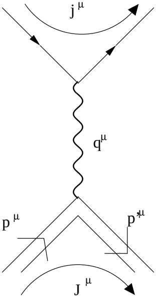
- Form factors are a fundamental property of the nucleon
- Provide excellent testing ground for QCD and QCD-inspired models
- Gives constraints on models of nucleon structure
- Are not yet calculable from first principles

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

$$\begin{aligned} G_E &= F_1 - \kappa\tau F_2 \\ G_M &= F_1 + \kappa F_2 \end{aligned}$$

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

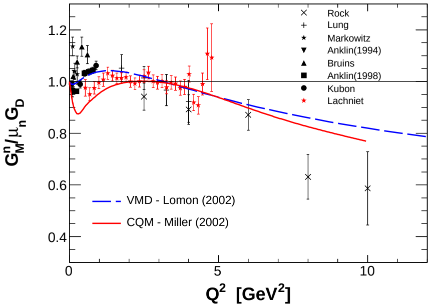
$$\begin{aligned} G_E^p(Q^2=0) = 1, \qquad & G_M^p(Q^2=0) = \mu_p = \quad 2.79 \\ G_E^n(Q^2=0) = 0, \qquad & G_M^n(Q^2=0) = \mu_n = \quad -1.91 \end{aligned}$$

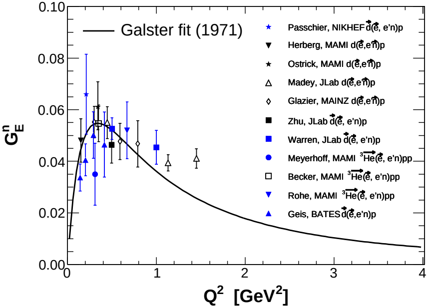
Rosenbluth Formula

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

Neutron Form Factors

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



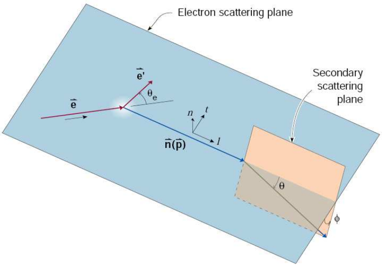


Extending G_E^n with Spin Observables

- 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

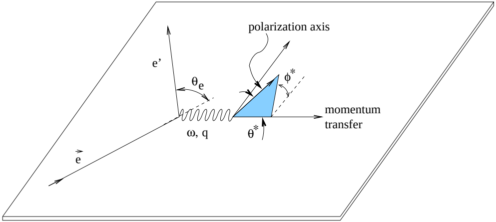
Polarization Transfer

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



Polarized Target Measurements

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



Helicity-dependent asymmetry nearly 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 - $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)pp$, $Q^2 = 0.4 - 1.0\ \mathrm{GeV}^2$

E02-013 Collaborators

Over 100 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 (graduated 2009)
- Ameya Kolarkar - University of Kentucky (graduated 2007), Boston University
- Jonathan Miller - University of Maryland, College Park (graduated 2009)

Masters Students:

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

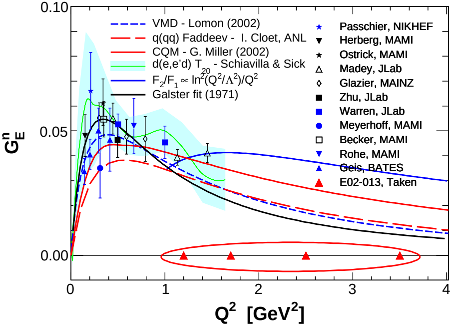
Postdocs:

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

Hall A, E02-013

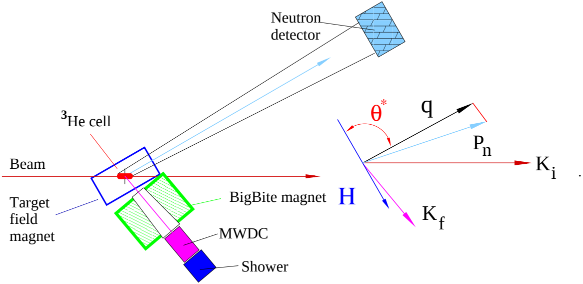
- Highest Q^2 measurement in Hall A, E02-013 through $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)pp$

Q^2 $[\mathrm{GeV}^2]$	E_{beam} [GeV]	Cen. 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
3.4	3.291	51.59	11.4



Experimental Setup

- Polarized $^3\mathrm{He}$ 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, reconstructs $\vec{e}'$
- Neutron arm - matches BB acceptance, measures neutron momentum through ToF, performs nucleon charge ID

Polarized ^{3}He Target

Developed at W&M, UVA, JLab

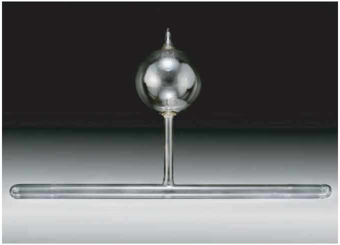
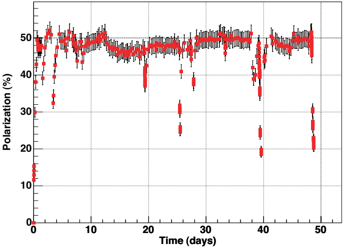


Photo Credit: A. Gavalya



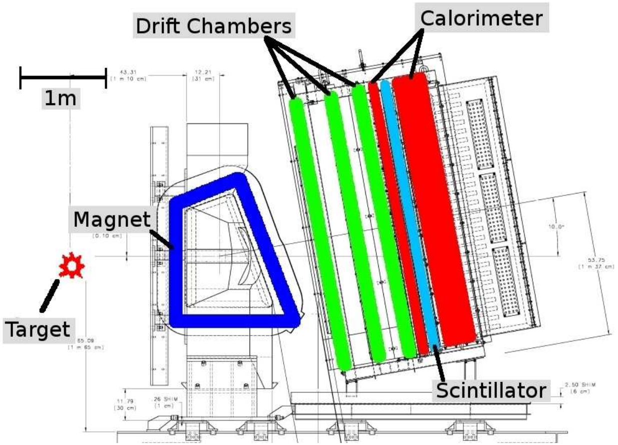
- Spin-exchange optical pumping polarization transfer:
  - $\vec{\gamma} \longrightarrow \mathrm{Rb}$
  - $\mathrm{Rb} \longrightarrow \mathrm{K}$
  - $\mathrm{K} \longrightarrow {}^3\mathrm{He}$ (hyperfine int.)

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

BigBite Spectrometer

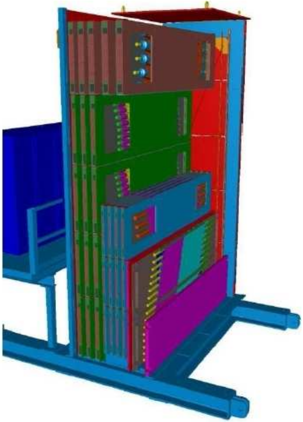
- Non-focusing large angular and momentum acceptance spectrometer
- Approximately 76 msr solid angle for 40 cm target
- Single dipole magnet of field integral approximately 1.0 $\mathrm{T}\cdot\mathrm{m}$
    - Momentum resolution of $\sigma_p/p \approx 1\%$ for accepted electrons
- Accepting electrons between 0.6$\sim$1.5 GeV/c
- Total luminosity $5 \times 10^{36}\ \frac{\mathrm{Hz}}{\mathrm{cm}^2}$
- Specially constructed detector package first used for E02-013

BigBite Detector Set



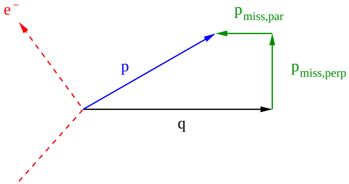
Neutron Arm

- Neutron arm detects recoiling proton/neutron, $\eta \sim 50\%$
- Measures momentum through ToF, charge through veto layers
- Time resolution $\sigma_t = 300\,\mathrm{ps}$, nucleon momentum resolution $\sigma_p \approx 300\,\mathrm{MeV}$ for $Q^2 = 3.4\,\mathrm{GeV}^2$ point
- Covers 5m × 1.6m about about 10m away - Matches BigBite acceptance for QE electrons



Quasielastic Selection

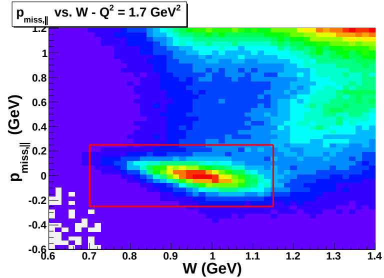
Need to reliably separate neutral QE events



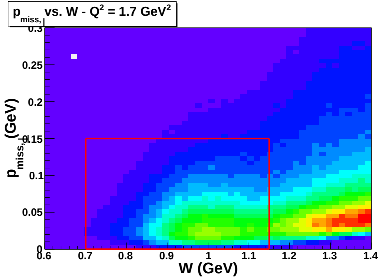
- Invariant mass assuming free stationary nucleon target
- Missing mass of $^3\mathrm{He}(e,e'n)X$

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

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



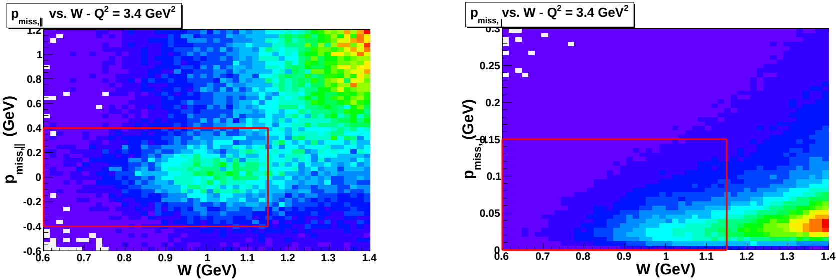
$p_{\mathrm{miss},\perp}$ vs W



$Q^2 = 3.4\ \mathrm{GeV}^2$ Quasielastic Selection

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

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



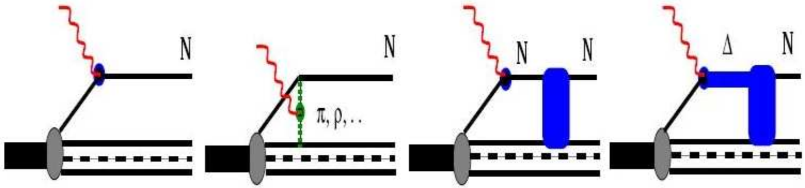
- Momentum resolution degraded due to shorter time-of-flight

Corrections

- Beam polarization $\sim 85\%$, target polarzation $\sim 45-50\%$
- Accidental Background, $< 1\%$ correction
- Nitrogen dilution, $\sim 5\%$ correction
- Misidentified protons, $\sim 20\%$ correction
    - Evaluated through data using H_2, N_2, and $^3\mathrm{He}$
    - Also evaluated through Geant4 monte carlo - in good agreement with data
- Inelastic Events, $< 5\%$ correction
    - Evaluated through Geant4 monte carlo + MAID
    - Asymmetry was generally close to QE asymmetry, so correction was not large
- Nuclear effects + FSI

FSI Contributions, n polarization

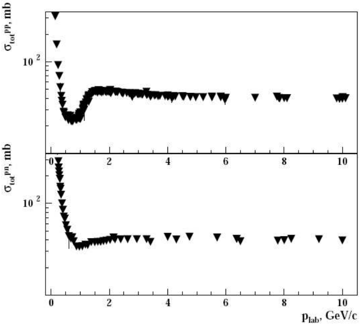
- Nuclear effects evaluated by M. Sargsian in Generalized Eikonal Approximation
    - Determine effective neutron/proton polarization
    - Evaluate rescattering effects on asymmetry
- Considers four main diagrams

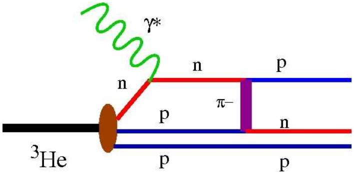


- PWIA, MEC, FSI, IC

FSI Contributions

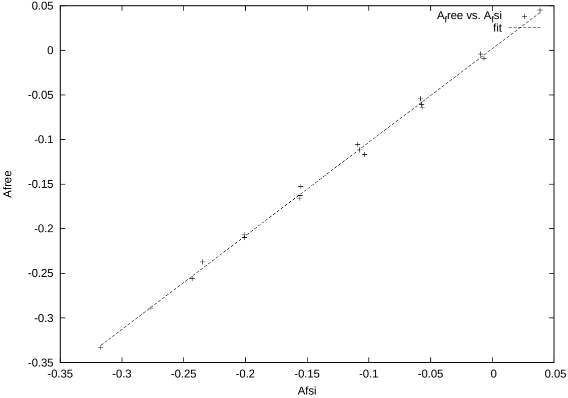
- MEC and IC become suppressed at higher Q^2
- At high p, total cross sections for σ_{pp}, σ_{pn} becomes roughly constant
- Charge exchange can modify final asymmetry



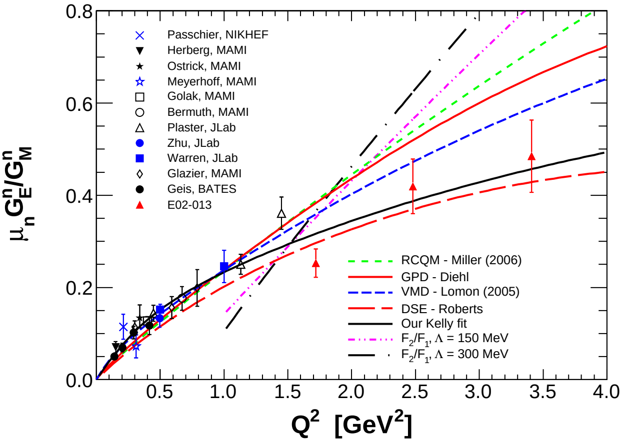


FSI Results

- Effective neutron polarization dependent on missing momentum cuts
- Very different from 86% inclusive assumption, $P_n >\sim 95\%$
- For our detector acceptances and cuts:



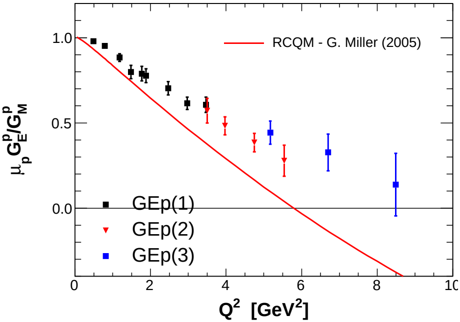
Results

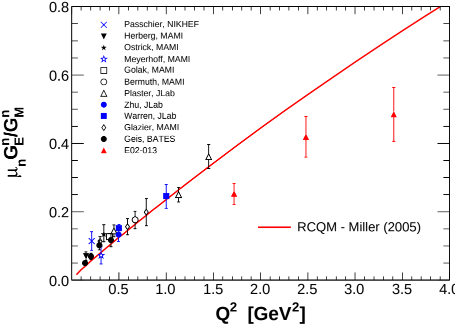

Passchier, NIKHEF
Herberg, MAMI
Ostrick, MAMI
Meyerhoff, MAMI
Golak, MAMI
Bermuth, MAMI
Plaster, JLab
Zhu, JLab
Warren, JLab
Glazier, MAMI
Geis, BATES
E02-013
RCQM - Miller (2006)
GPD - Diehl
VMD - Lomon (2005)
DSE - Roberts
Our Kelly fit
F_2/F_1, Λ = 150 MeV
F_2/F_1, Λ = 300 MeV
$\mu_n G_E^n/G_M^n$
0.0
0.2
0.4
0.6
0.8
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Q^2 [GeV^2]

Nucleon Structure Information in Form Factors

- Constituent quark models
- q(qq) Dyson-Schwinger equations approach
- pQCD
- QCD motivated fits - GPDs
- With proton and neutron form factors - quark flavor and isoscalar/vector decomposition

Constituent Quark Light-Front Cloudy Bag Model

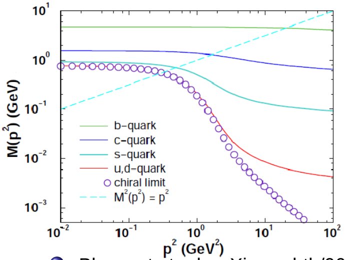


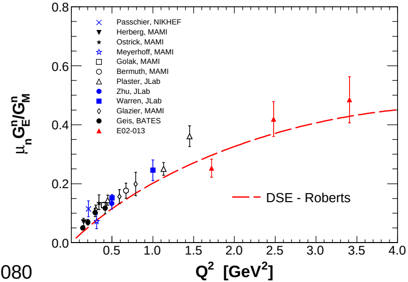


- G_E^p suppression at higher Q^2 due to inclusion of quark orbital angular momentum

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





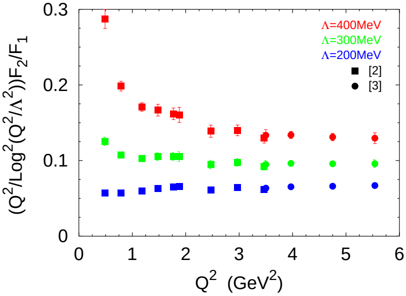
- Bhagwat et. al. arXiv:nucl-th/0610080
- Cloët et. al. arXiv:nucl-th/0804.3118

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 $Q^2 \longrightarrow \infty$

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

Λ parameter related to size of the nucleon



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

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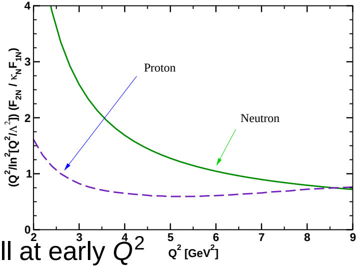
From DSE approach:



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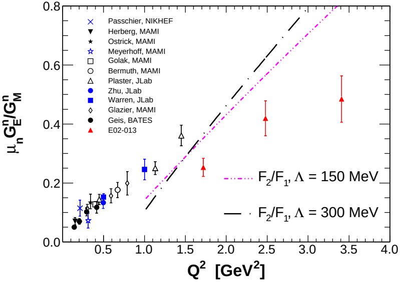

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GPD Parameterization - Diehl et al.

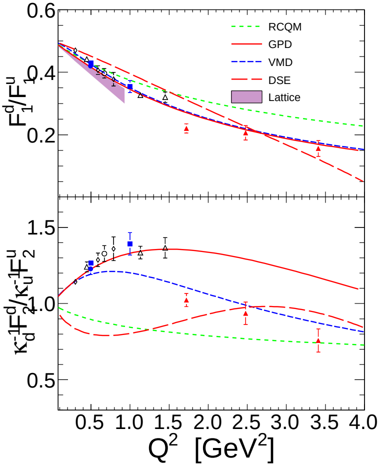
- Non-skewed moments of GPDs yield form factors

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

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

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

Quark Flavor Decomposition



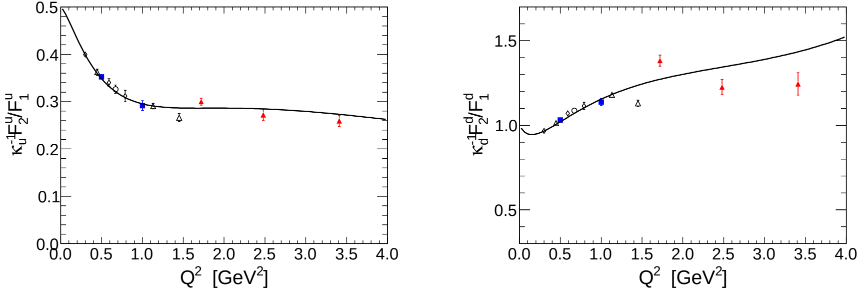
Lattice: Bratt et al., arXiv:1001.3620, $m_\pi = 140\ \mathrm{MeV}$

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

- High Q^2 for G_E^n 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 F_2/F_1 distributions do not appear to follow $1/Q^2$

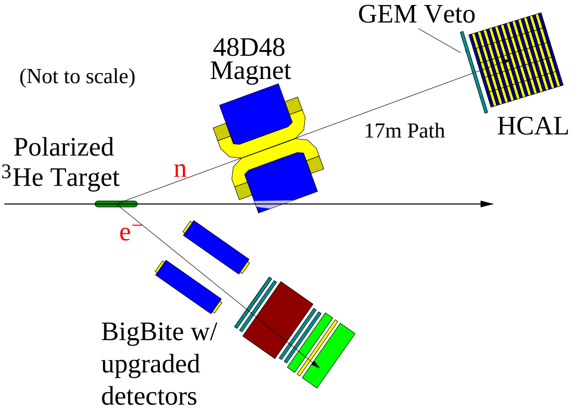


- G_E^n data with Kelly paramterization for remaining FFs
- Curve - Kelly parameterization

12 GeV JLab 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

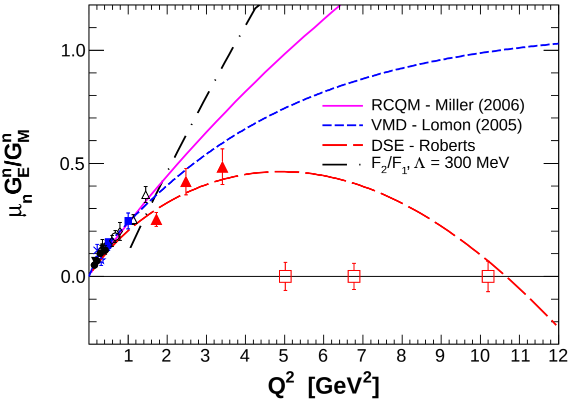
High Q^2 G_E^n Experimental Layout



- 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

Anticipated Results

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

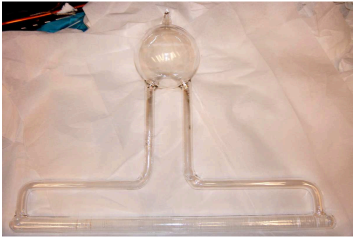


- Strong divergence between different model predictions
- DSE predicts zero crossing

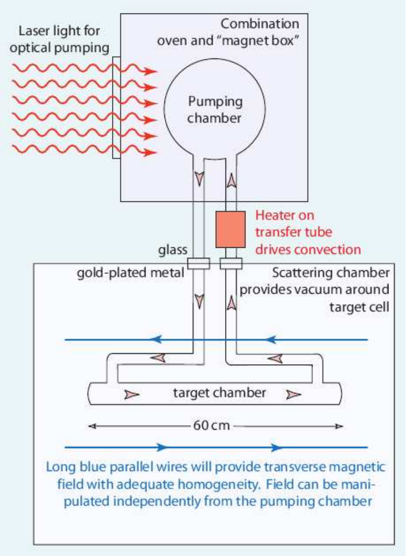
Conclusion

- Measuring the electric form factor of the neutron to high Q^2 helps "complete" our picture of the nucleon
- E02-013 has more than doubled the previously measured Q^2 range for G_E^n
- Super Bigbite allows us to take form factor measurements to very high Q^2 will allow for differentiation between several popular form factor models

Upgraded ^{3}He Target

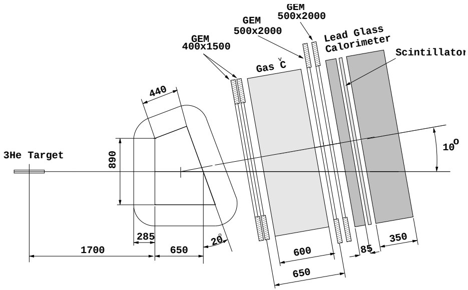


- Simulations show sustainable polarization of 62% with $I = 60\ \mu\mathrm{A}$
- Overall effective luminosity gain of 15



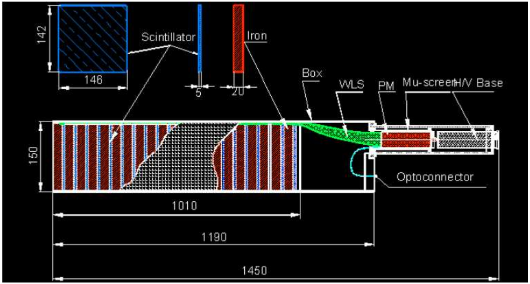
Upgraded BigBite Components

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