Measurement of the Electric Form Factor of the Neutron at High Momentum Transfer

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Overview

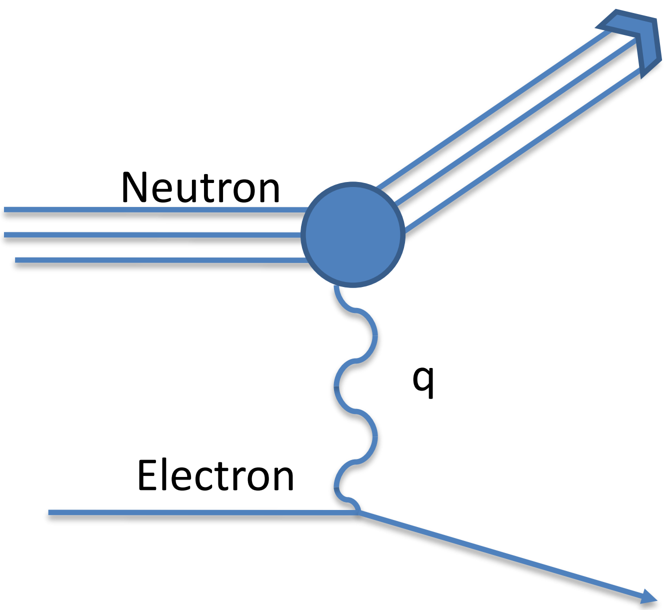
- Neutron Form Factors
- High Q^2 Experiment
- G_E^n Results
- Interpretation
  - Quark Orbital Angular Momentum
  - Quark Form Factors – F_d/F_u
- Conclusions

The Electric Form Factor of the Neutron

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \frac{E_f}{E_i} \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2) \tan^2 \frac{\theta_e}{2} \right] ,$$

$$\tau = \frac{Q^2}{4M^2}$$

Above is the Rosenbluth formula for the differential cross section for a free nucleon. It is difficult to find G_E^n from the cross section because G_E is small compared to G_M for the neutron. The Mott cross section is the cross section for a structureless spin ½ particle.



Sachs form factors are related to the Dirac and Paul form factors and the magnetic moment.

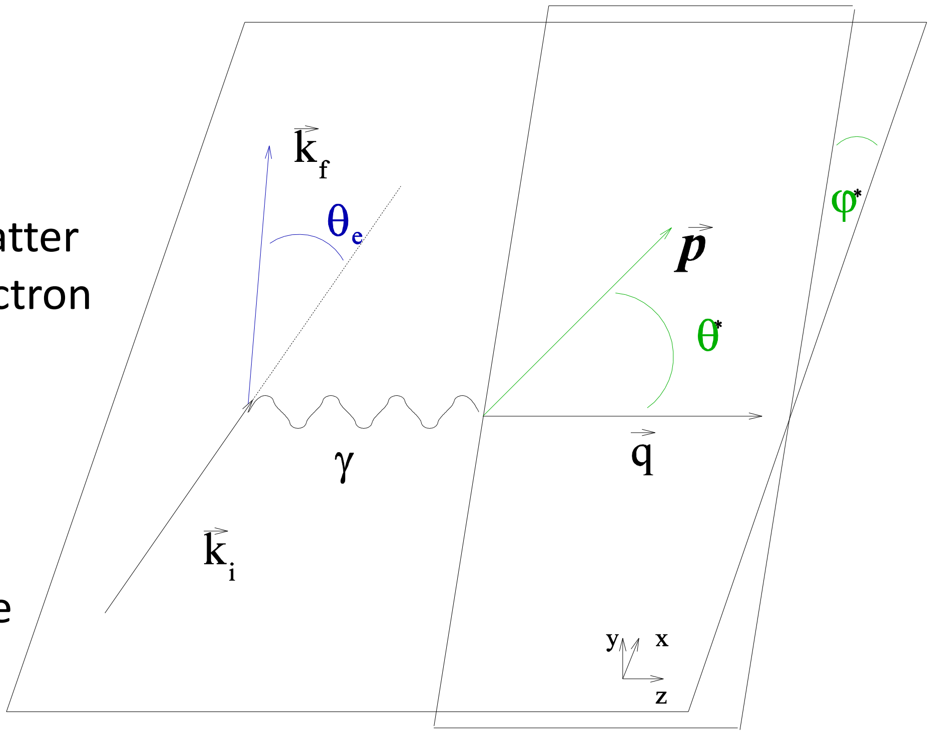
$$G_E^n(0) = 0 \qquad G_E = F_1 - \kappa\tau F_2$$
$$G_M^n(0) = \mu_n \qquad G_M = F_1 + \kappa F_2$$

In these expressions κ is anomalous contribution to the nucleon's magnetic moment.

Double Polarization Method

$$^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)pp$$

In the experiment, polarized electrons scatter from polarized helium-3 and the final electron and hadron are detected.

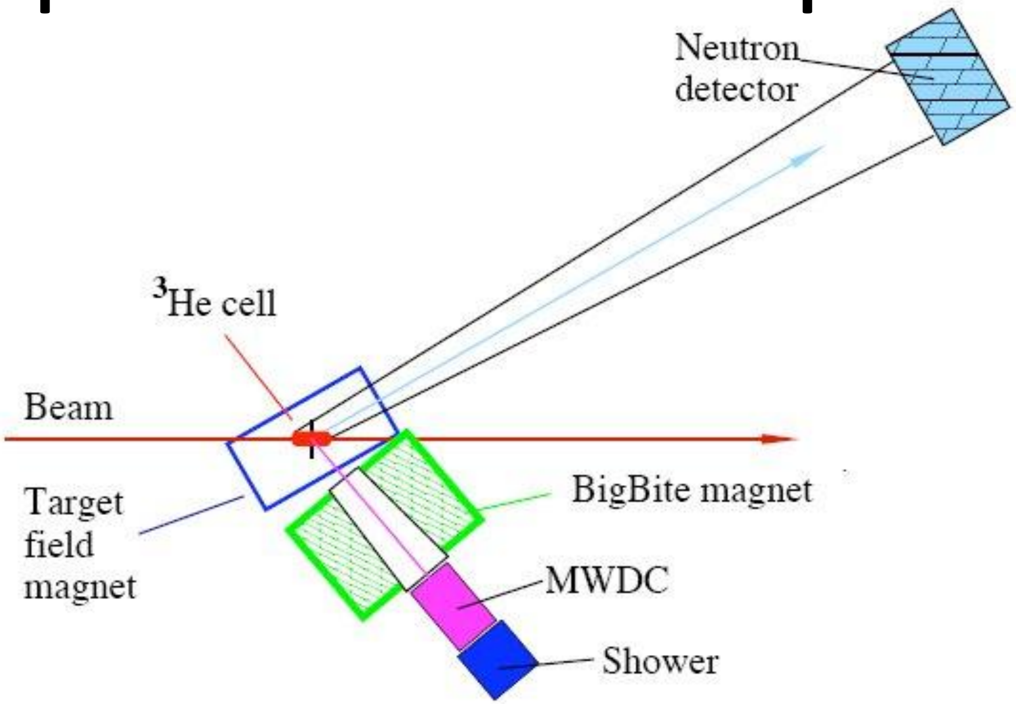


The polarized cross section has helicity dependent term. The asymmetry determined from this is dependent on the form factor ratio and kinematic coefficients.

$$A = \frac{\sigma_{\rightarrow\uparrow} - \sigma_{\rightarrow\downarrow}}{\sigma_{\rightarrow\uparrow} + \sigma_{\rightarrow\downarrow}}$$

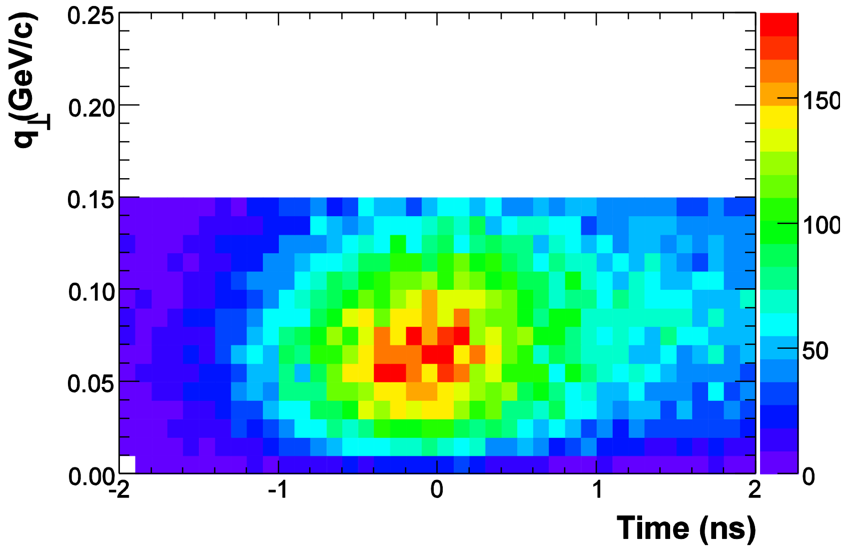
$$= \frac{-\frac{G_E}{G_M} 2\sqrt{\tau(1+\tau)}\tan\left(\frac{\theta_e}{2}\right)\sin\theta^*\cos\phi^* - 2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2\left(\frac{\theta_e}{2}\right)}\tan\left(\frac{\theta_e}{2}\right)\cos\theta^*}{\left(\frac{G_E}{G_M}\right)^2 - \tau + 2\tau(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)}$$

Experimental Setup

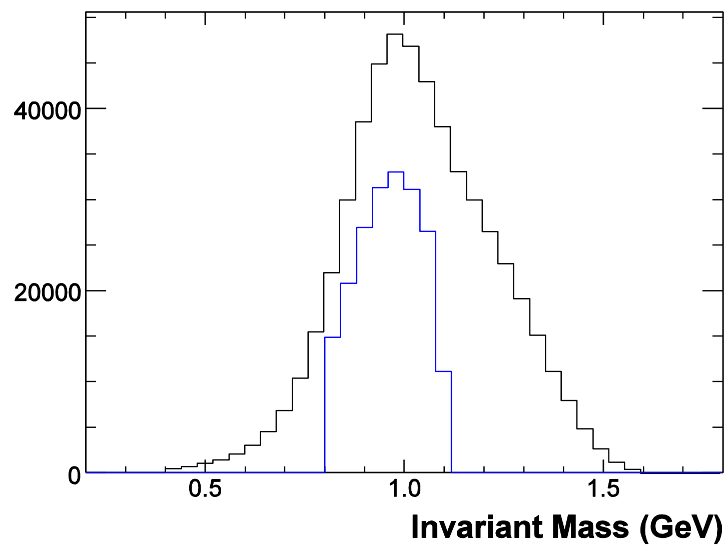


- CEBAF provides a polarized (83%) electron beam.
- The polarized ^{3}He (45-50% polarization) acts as a free polarized neutron target.
- Big Bite is a large acceptance spectrometer for scattered electrons.
- The Neutron Arm, with an 11m^2 active area, detects and identifies protons and neutrons at a path length of up to 12m.

Selection of Quasi-elastic Events at Q^2=2.5



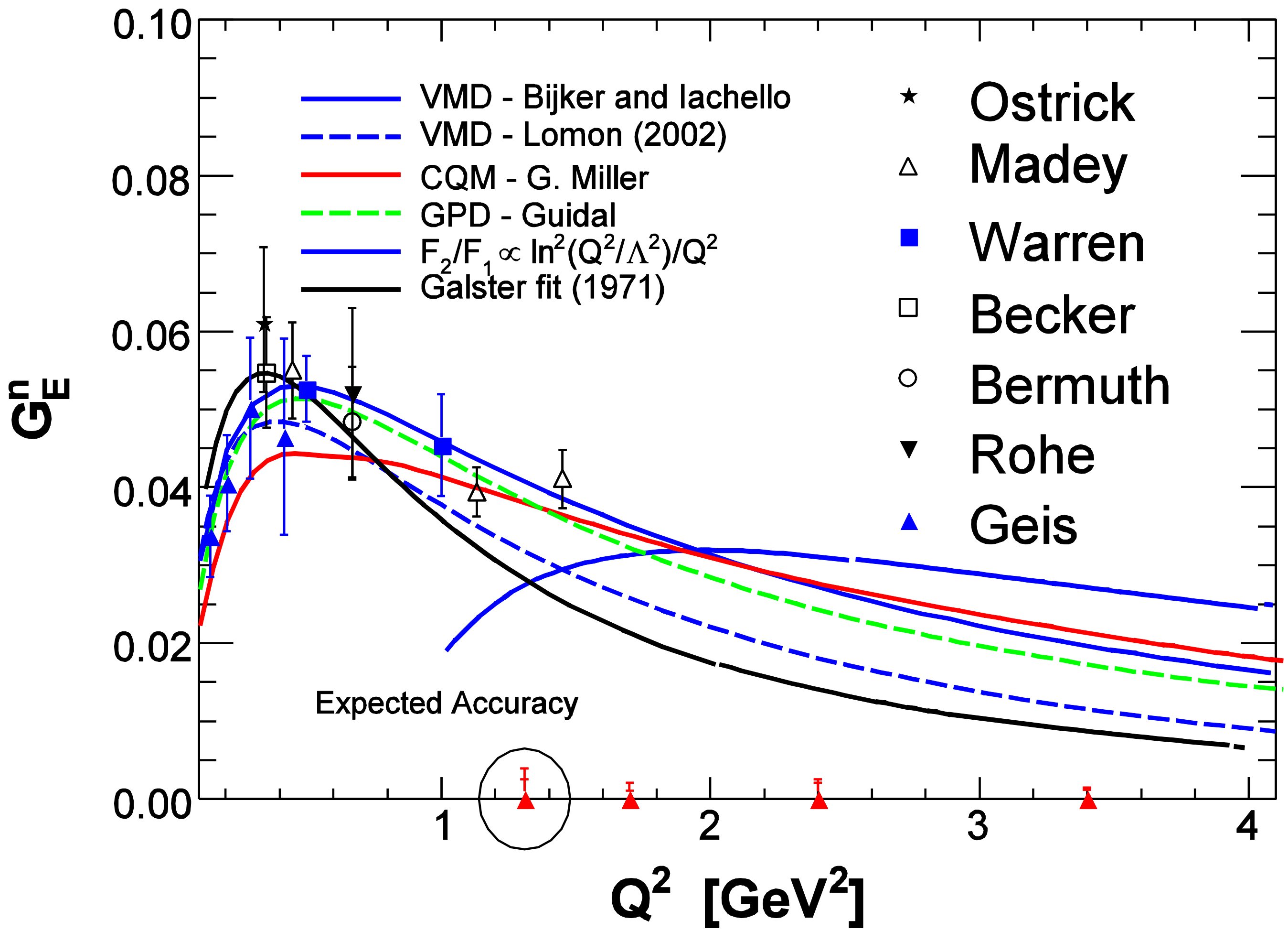
Events are selected so that they are in time and so that they are parallel to the q. In black below is the invariant mass of charged events with only good events cuts while in blue is the quasi-elastic events.



Additionally, cuts on perpendicular missing momentum to suppress Final State Interactions (FSI).

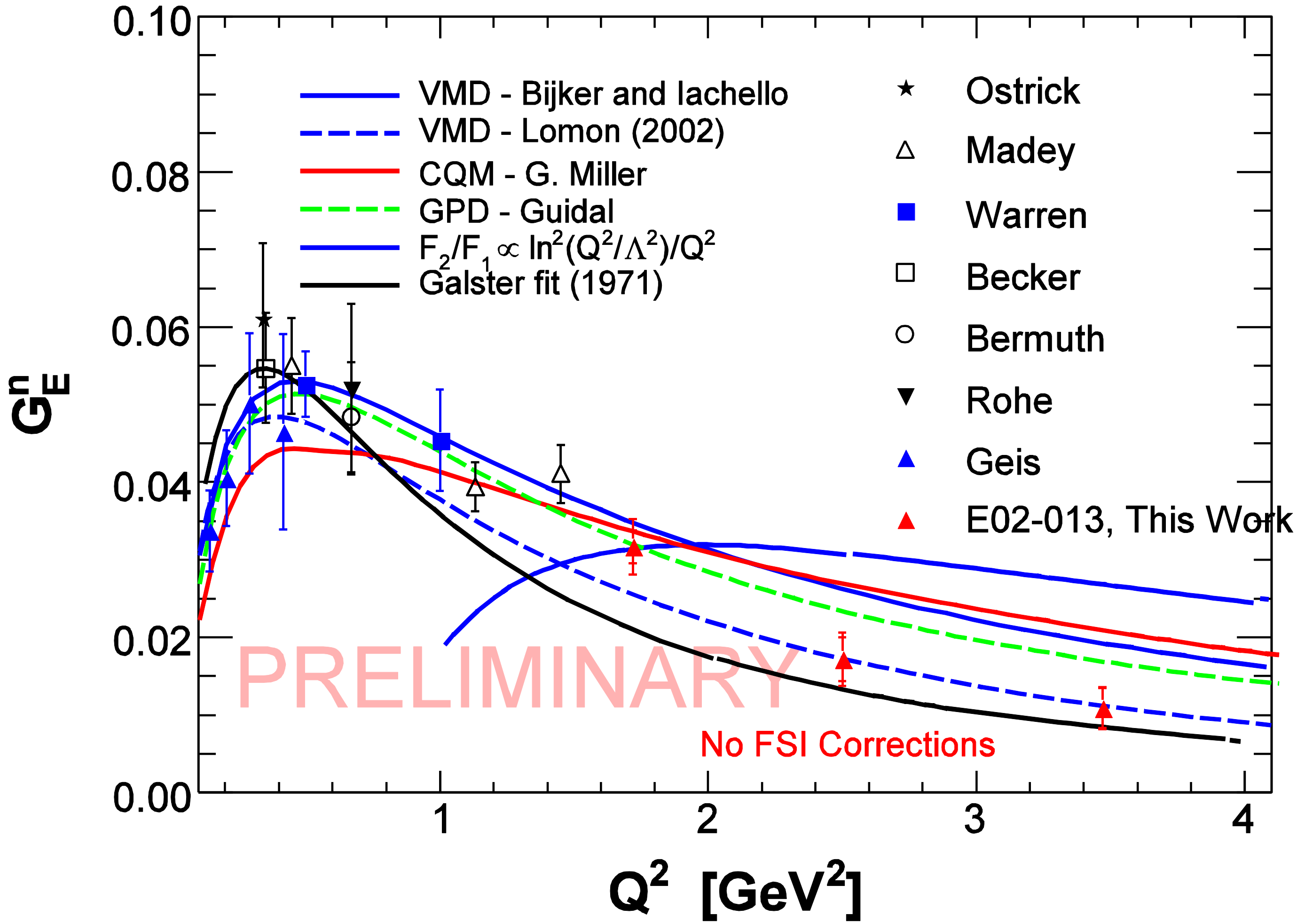
$$\overrightarrow{p}_{\perp} = \hat{q} \times \overrightarrow{p}$$

Electric Form Factor of the Neutron



The electric form factor of the neutron pre E02013 data. Circled is what will not be presented here.

Electric Form Factor of the Neutron

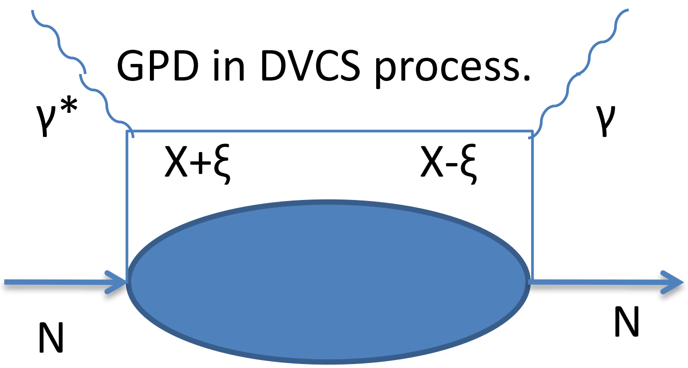


New experimental data significantly lower than favored predictions.

Generalized Parton Distributions

GPDs provide the quark contribution at a given x to the form factors:

$$F_1^q(t) = \int_0^1 dx H^q(x,\xi,t)$$
$$F_2^q(t) = \int_0^1 dx E^q(x,\xi,t)$$



$$t = -Q^2$$

GPDs parameterize the non-forward elements of the light cone operators. There is a GPD for every quark flavor. GPDs are functions of x which is the longitude momentum fraction, ξ which is the skewness or longitude momentum asymmetry, and t which is the transferred momentum squared.

For Form Factors and orbital angular momentum, we can let $\xi = 0$

Classes of processes:
- DIS
- Elastic Scattering
- DVCS

GPD Model

$$E^q(x,t) = \frac{\kappa_q}{N_q}(1-x)^{\eta_q} q_v(x) x^{-\alpha(1-x)t}$$

$$H^q(x,t) = q_v(x) x^{-\alpha(1-x)t}$$

Guidal, Polyakov, Radyushkin, and Vanderhaeghen
Phys Rev D 72, 054013 (2005)

- Model depends on 3 parameters and the form of the q(x).
- α is the Regge parameter defined by the Dirac mean squared radius of the proton.
- The η are determined from the neutron and proton FF data, in the original parameters only the proton was used.
- The model contains an extra (1-x) dependence for E compared to H because E scales faster with t at x≈1.
- N is a normalization constant resulting from this (1-x) dependence.

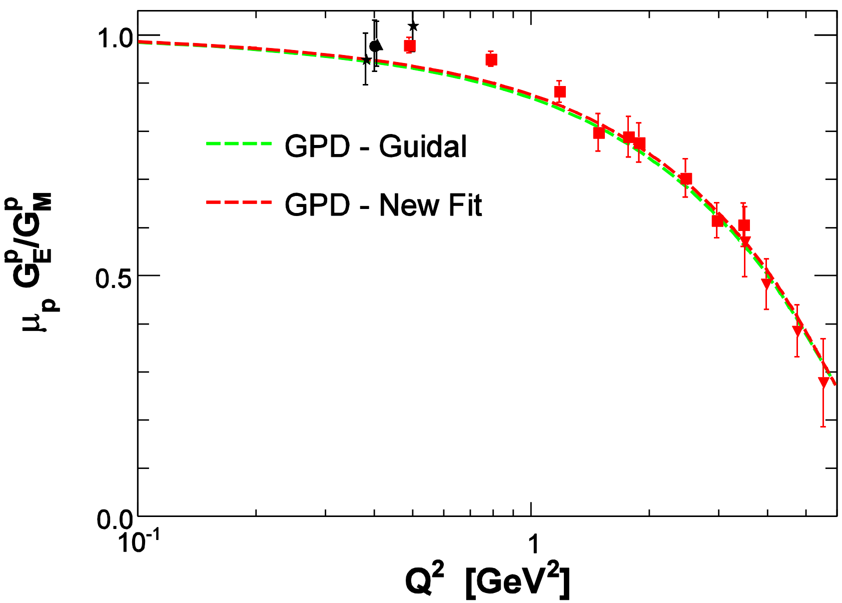
Original Parameters

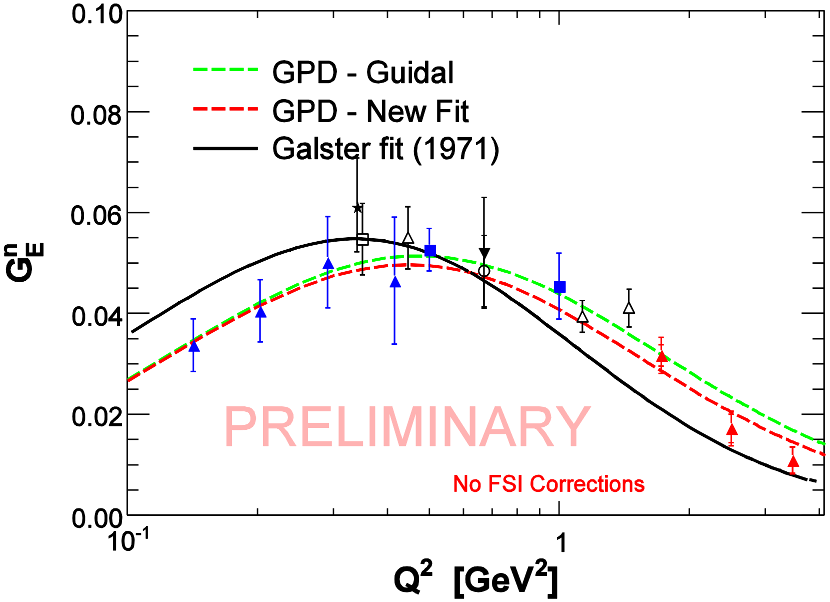
$$\eta_u = 1.34$$
$$\eta_d = 1.34$$

Fit to current data

$$\eta_u = 1.23$$
$$\eta_d = 1.80$$

New Fit of η Parameters





The new fit is in agreement with both the proton and neutron data, while the previous was not in agreement with the neutron data.

Quark Orbital Angular Momentum

$$2J^q = \int_{-1}^{1} dx x [H^q(x,0,0) + E^q(x,0,0)]$$

$$= M_2^q + \int_0^1 dx x E^q(x,0) \qquad 2J^q = \Delta q + 2L^q$$

Quark	Δq	M	Integral	2J Guidal	2J New Fit	2L New Fit
u	0.6	0.37	0.238	0.595	0.600	0.00
d	-0.25	0.20	-0.207	-0.031	-0.016	0.234
s		0.04	0	0.04	0.04	
Total		0.61		0.568	0.624	

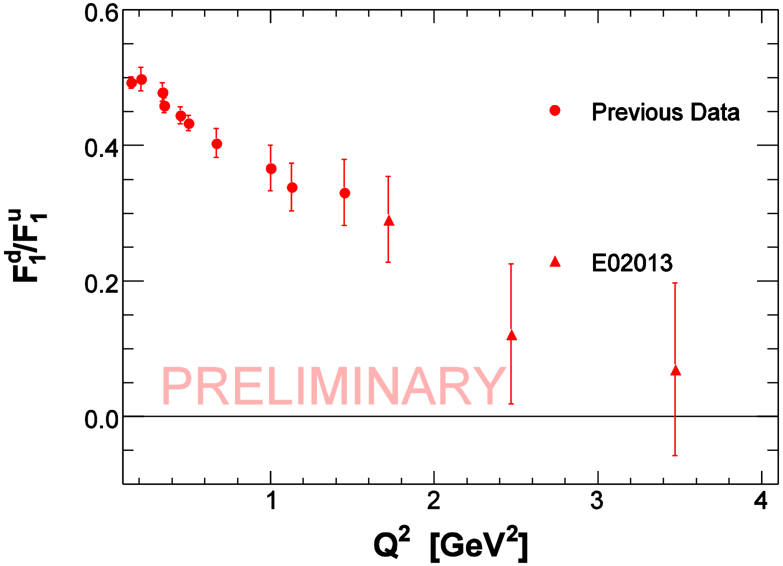
The values of M are calculated according to the NNLO fit.

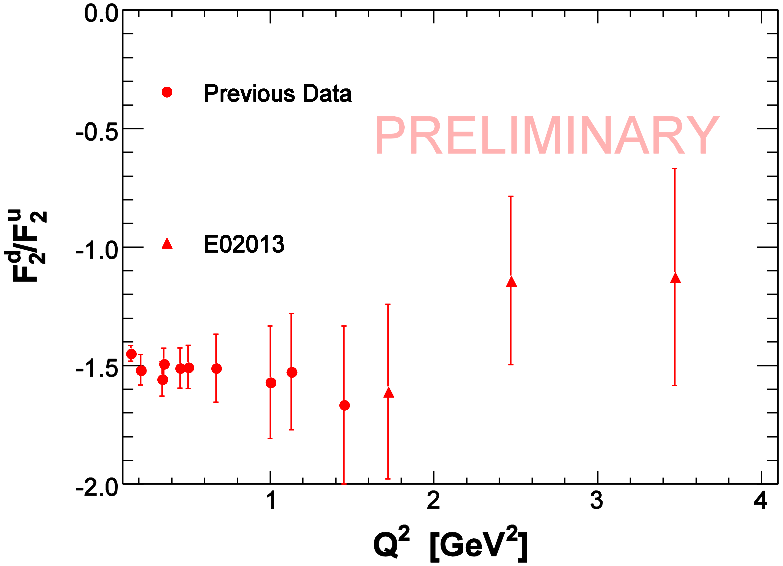
In the framework of this GPD model, Ji's sum rule can be evaluated.

Here the antiquark contributions are ignored.

Quark Form Factors

$$F^n_{1,2} = e_d F^u_{1,2} + e_u F^d_{1,2} \qquad F^p_{1,2} = e_u F^u_{1,2} + e_d F^d_{1,2}$$





Using measurements of the G_E^n including our data and traditional parameterizations for the form factors: $G_M^n = \mu_n G_D$, $G_e^p = (1.06\text{-}0.14\ t)\ G_D$, , and $G_M^p = \mu_p G_D$, we calculated the up and down quark form factors.

Conclusions

- The E02013 collaboration has measured G_E^n at Q^2 up to 3.5 GeV^2, more than doubling the range covered.
- Our measurement provides new input for models to describe the physics of nucleon structure.
- Including our data in a GPD model, we extracted the orbital angular momentum of the down quark and up quark, found to be 0.23 and 0 respectively.

List of Collaborators/Thanks

- Spokespeople
  - Bogdan Wojtsekhowski – Jefferson Lab
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  - Nilanga Liyanage – University of Virginia
- Post Docs
  - Seamus Riordan – 2008-Present – University of Virginia
  - Robert Feurbach – 2006-2007 – William and Mary and Jefferson Lab
- Students
  - Seamus Riordan – Carnegie Mellon University
  - Jonathan Miller – University of Maryland
  - Tim Ngo – California State University, Los Angeles
  - Aidan Kelleher – William and Mary
  - Ameya Kolarkar – University of Kentucky
  - Brandon Craver – University of Virginia
  - Sergey Abrahamyan – Yerevan Physics Institute

Quark Form Factors

Q^2 (GeV^2)	F_1^p	F_1^n	F_2^p	F_2^n
1.72		-0.034 ±0.022		-0.139 ±0.046
2.47		-0.032 ±0.019		-0.065 ±0.027
3.47		-0.020 ±0.014		-0.033 ±0.015

Q^2 (GeV^2)	F_1^u	F_1^d	F_2^u	F_2^d
1.72	0.233 ±0.025	0.066 ±0.045	0.105 ±0.047	-0.157 ±0.091
2.47	0.135 ±0.020	0.020 ±0.038	0.068 ±0.028	-0.063 ±0.054
3.47	0.082 ±0.015	0.011 ±0.029	0.037 ±0.016	-0.030 ±0.029

*J. J. Kelly, Phys. Rev. C 70, 068202 (2004)

Experiment Overview

Beam Energy (GeV)	Q^2 (GeV^2)	Statistical Expected
1.519	1.2	0.0025
2.079	1.7	0.0011
2.638	2.5	0.0015
3.290	3.5	0.0012

Measurements were undertaken at four different energies, included to the right was the expected statistical precision. Below the components to systematic uncertainty are tabulated as a fraction of G_E^n.

Analysis Element	1.7 (GeV^2)	2.5 (GeV^2)	3.5 (GeV^2)
Proton Contamination	0.035		0.057
Target Polarization	0.063		0.035
Beam Polarization	0.020		0.011
Acc. Back. Contamination	0.018		0.017
Neutron Polarization	0.035		0.019
Nitrogen Contamination	0.003		0.010
FSI Corrections	0.080		0.043

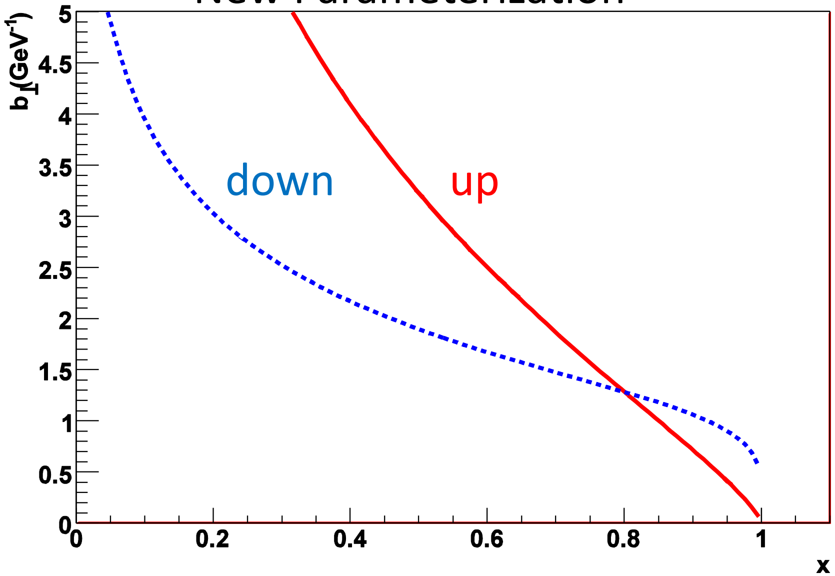
S. Riordan. PhD thesis, Carnegie Mellon University, unpublished (2008).

Tomographic Picture of the Neutron

$$\rho_{\perp}^{N}(\vec{b}) = \sum_{q} e_{q} \int dx \rho_{\perp}^{q}(\vec{b}, x) = \int \frac{d^{2}q}{(2\pi)^{2}} F_{1}^{N}(\vec{q}^{2}) e^{-i\vec{q}\cdot\vec{b}}$$

The transverse density of the nucleon is related to both the form factor of the nucleon and the quark density, which can be calculated from model dependent GPDs. Below is the region of parameter space allowed by positivity constraint.

New Parameterization



Old Parameterization