Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium

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Outline

1. Scientific Motivation and Previous Measurements.
2. The Ratio Method.
3. Event Selection and Simulations.
4. Corrections and Uncertainties.
5. Summary and Run-Time Estimate.

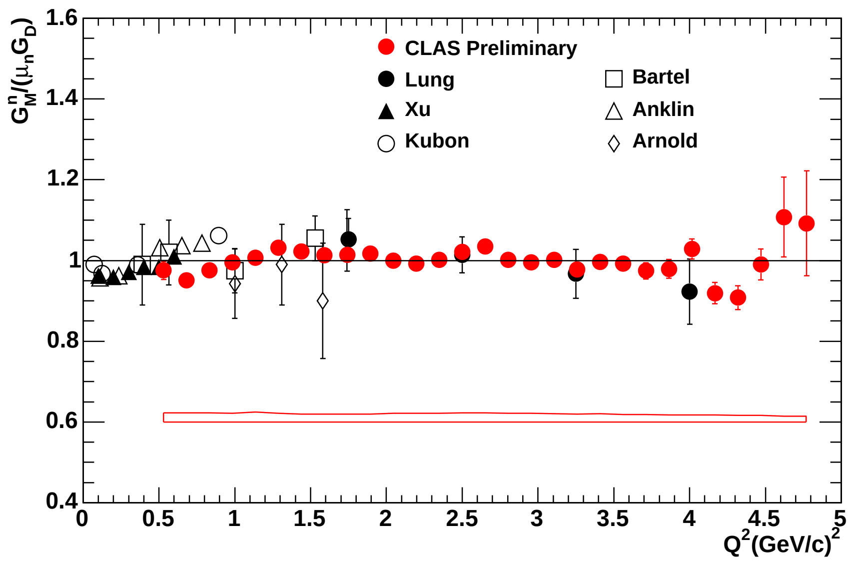
Scientific Motivation

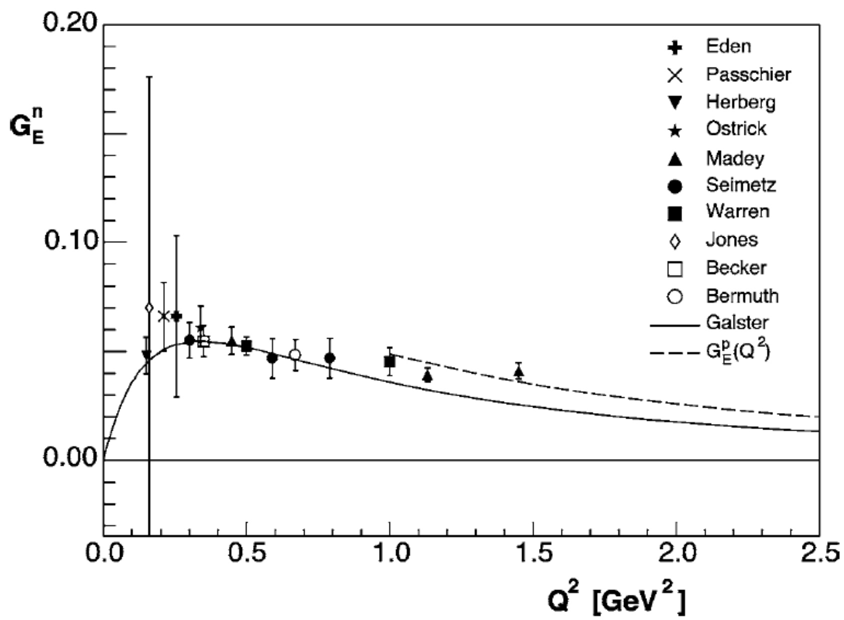
- To explore the ground state structure of the proton and neutron.
- $G_M^n(Q^2)$ is a fundamental observable related to the spatial distribution of the magnetization in the neutron.
- Elastic form factors (G_M^n, G_E^n, G_M^p, and G_E^p) provide key constraints on generalized parton distributions (GPDs) which promise to give us a three-dimensional picture of hadrons.
- Elastic hadronic form factors are a fundamental challenge for lattice QCD.
- Required for extracting the strange quark distributions in the proton.
- Part of a broad effort to understand how nucleons are 'constructed from the quarks and gluons of QCD'. *

* 'Opportunities in Nuclear Science: A Long-Range Plan for the Next Decade', NSF/DOE Nuclear Science Advisory Committee, April, 2002.

Current Status of Neutron Elastic Form Factors

- G_M^n and G_E^n.





C.E. Hyde-Wright and K.deJager, Ann. Rev. Nucl. Part. Sci. **54** (2004) 54 and references therein.

Using The Ratio Method

Outline

- Definition of the ratio and some necessary background.
- Selecting quasielastic events.
- Measuring the neutron and proton detection efficiencies.
- Estimates of uncertainties.

Issues

1. Enables us to use deuterium as a neutron target.
2. Reduces sensitivity to changes in running conditions; goal of 3% systematic uncertainty.
3. Take advantage of the experience from the CLAS measurement of G_M^n.
4. Focus on differences with previous experiment.
5. Importance of *in-situ* calibrations.

Some Necessary Background

- It is convenient to express the cross section in terms of the Sachs form factors.

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\left(G_E^2 + \frac{\tau}{\epsilon}G_M^2\right)\left(\frac{1}{1+\tau}\right)$$

where

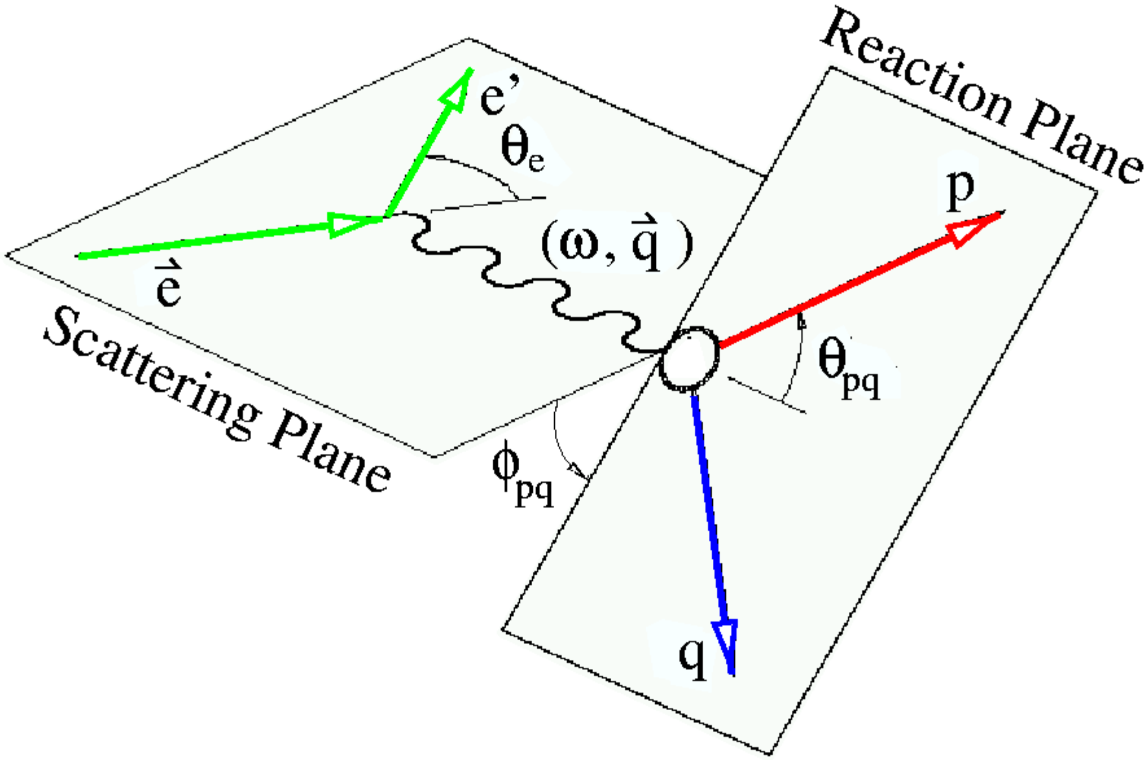
$$\tau = \frac{Q^2}{4M^2} \qquad \epsilon = \frac{1}{1+2(1+\tau)\tan^2(\frac{\theta}{2})} \quad \sigma_{Mott} = \frac{\alpha^2 E' \cos^2(\frac{\theta}{2})}{4E^3 \sin^4(\frac{\theta}{2})} \quad .$$

- We can now take the ratio of the $e-p$ and $e-n$ cross sections (the ratio method).

$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = a(Q^2)\frac{\frac{{G_E^n}^2+\tau {G_M^n}^2}{1+\tau} + 2\tau {G_M^n}^2\tan^2(\frac{\theta}{2})}{\frac{{G_E^p}^2+\tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2\tan^2(\frac{\theta}{2})}$$

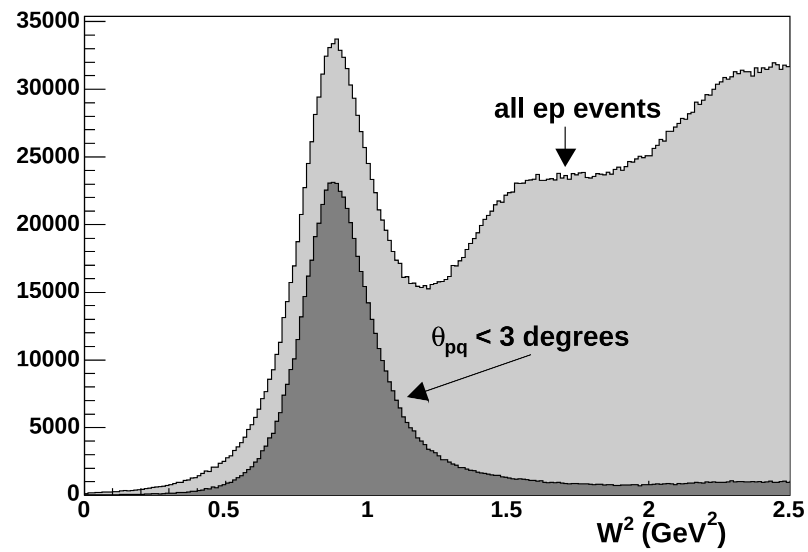
Some More Necessary Background

- To select quasielastic events (more later) we will use a cut on θ_{pq} shown here.



Selecting Quasielastic Events

- Select $e-p$ and $e-n$ events using tracking system electrons and protons, use TOF and calorimeters as independent detectors for neutrons. The main focus here will be on the calorimeters since they are more efficient.
- Quasi-elastic event selection: Apply a maximum θ_{pq} cut to eliminate inelastic events plus $W^2 < 1.2\ (GeV/c^2)^2$. Plot shows the effect of this cut on the CLAS G_M^n measurement at 4 GeV which overlaps with the proposed measurement.



- Acceptance matching: Use the quasi- elastic electron kinematics to predict if the nucleon (proton or neutron) lies in CLAS acceptance. Require both hypotheses to be satisfied.
- Neutrons and protons treated exactly the same whenever possible.
- Impact of inelastic background will be greater at large Q^2 due to increasing width of W^2.

Monte Carlo Simulation

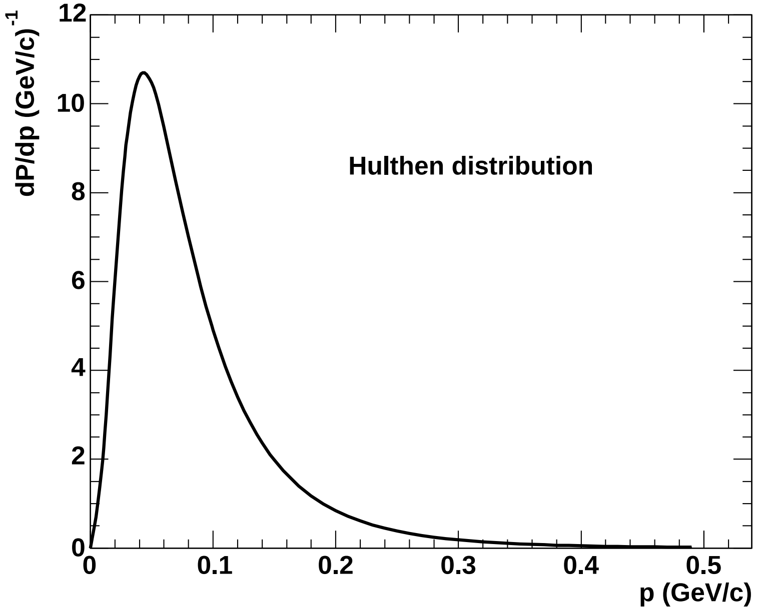
- Study quasielastic and inelastic scattering from both neutron and proton. The inelastic scattering produces a background that overlaps with the quasielastic events.

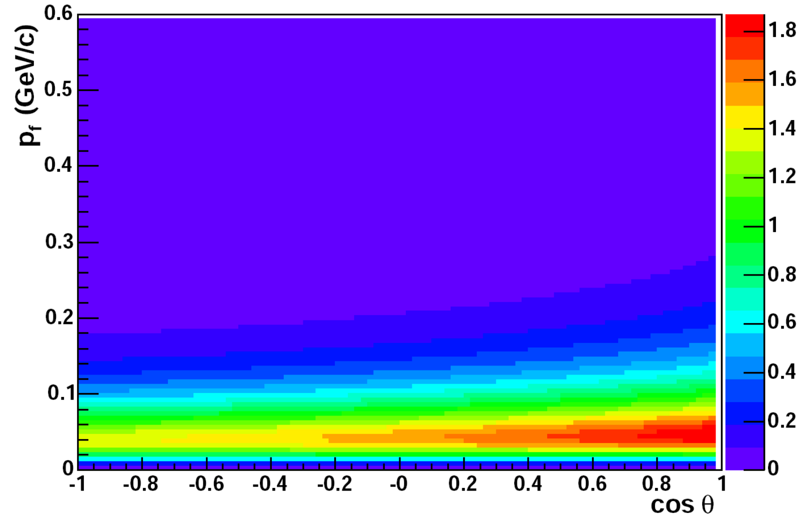
- For quasielastic scattering use the elastic nucleon form factors to get the cross section on the nucleon and then incorporate the effects of the target nucleon's Fermi motion inside the deuteron.

- For inelastic scattering use existing proton and deuteron data to parameterize the cross sections for both protons and neutrons and add the Fermi motion.

Procedure for Quasielastic Simulation

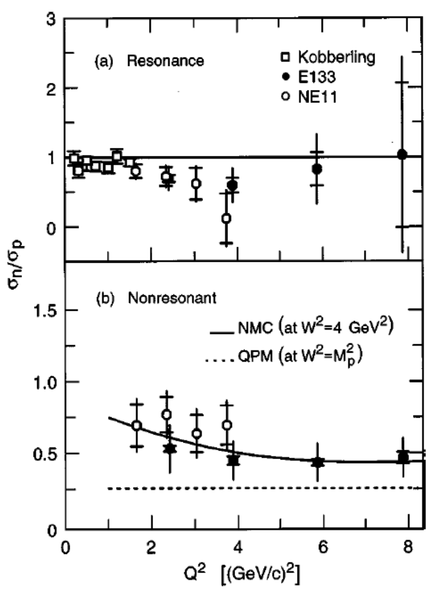
- Pick a Q^2 weighted by the elastic cross section.
- Pick p_f and $\cos\theta$ of the target nucleon weighting it by the combination of the Hulthen distribution and the effective-beam-energy effect.
- Boost to the rest frame of the nucleon and rotate coordinates so the beam direction is along the z axis. Calculate a new beam energy in the nucleon rest frame.
- Choose an elastic scattering angle in the nucleon rest frame using the Brash parameterization.
- Transform back to the laboratory frame.

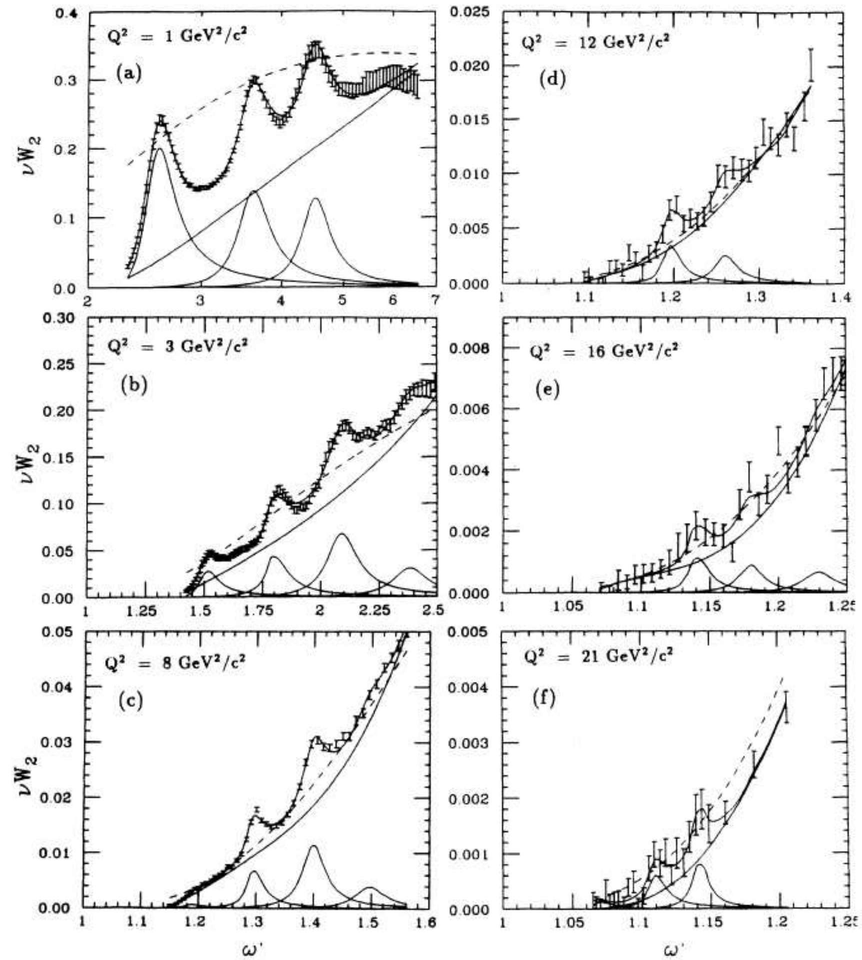




Procedure for Inelastic Simulation - 1

- Use existing measurements of inelastic scattering on the proton (P. Stoler, Phys. Rep., **226**, 103 (1993)).
- For the neutrons use inelastic scattering from deuterium (L.M.Stuart, *et al.*, Phys. Rev. **D58** (1998) 032003). Data don't cover the full CLAS12 range, but $n-p$ ratios are roughly constant.

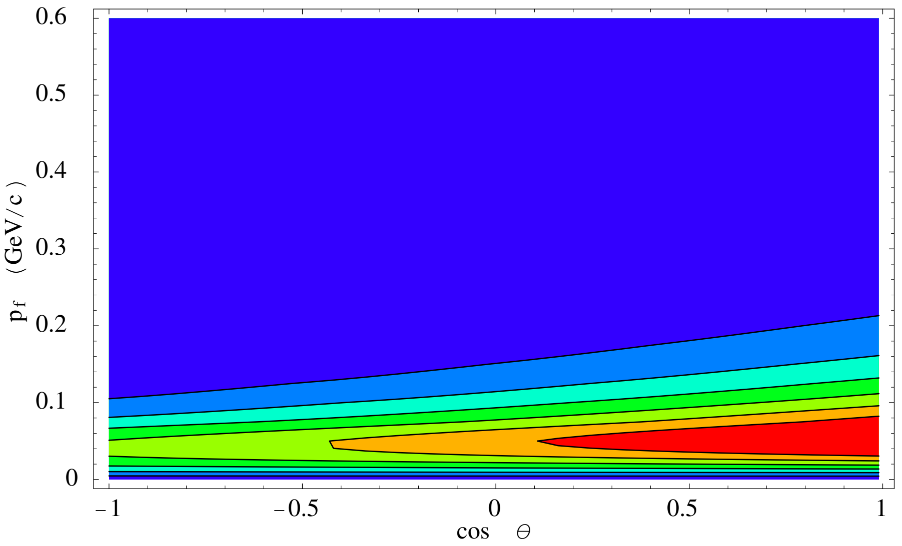




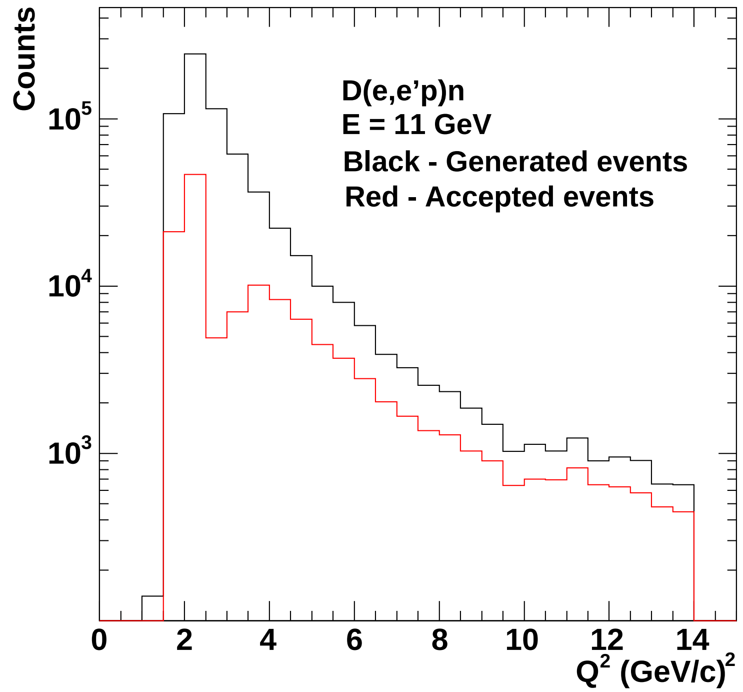
Inelastic cross sections as a function of $\omega' = 1 + W^2/Q^2$.

Procedure for Inelastic Simulation - 2

- Pick a Q^2 weighted by the measured cross sections.
- Pick p_f and $\cos\theta$ of the nucleon weighted by the Hulthen distribution and the effective-beam-energy effect for inelastic scattering.
- Boost to the rest frame of the nucleon and rotate coordinates so the beam direction is along the z axis. Calculate a new beam energy in the nucleon rest frame.
- Choose the final state using genev (M.Ripani and E.N.Golovach based on P.Corvisiero, et al., NIM A**346**, (1994) 433.).
- Transform back to the laboratory frame.

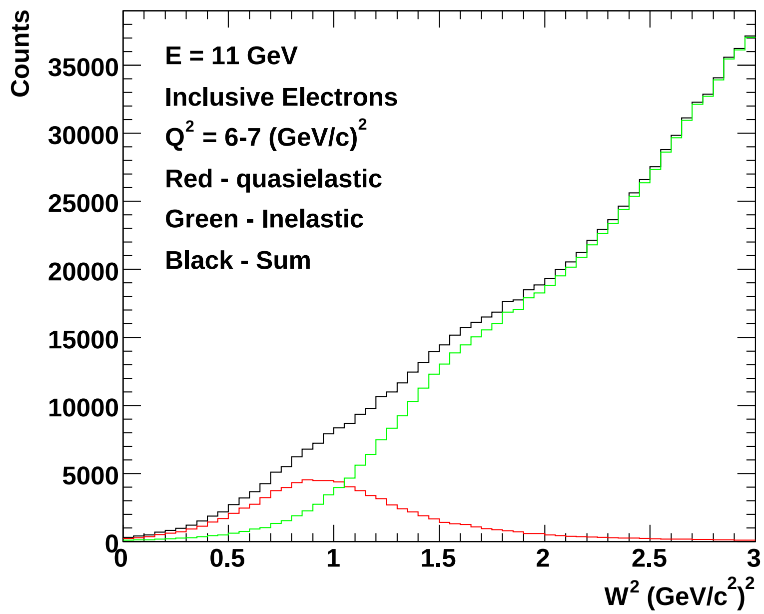


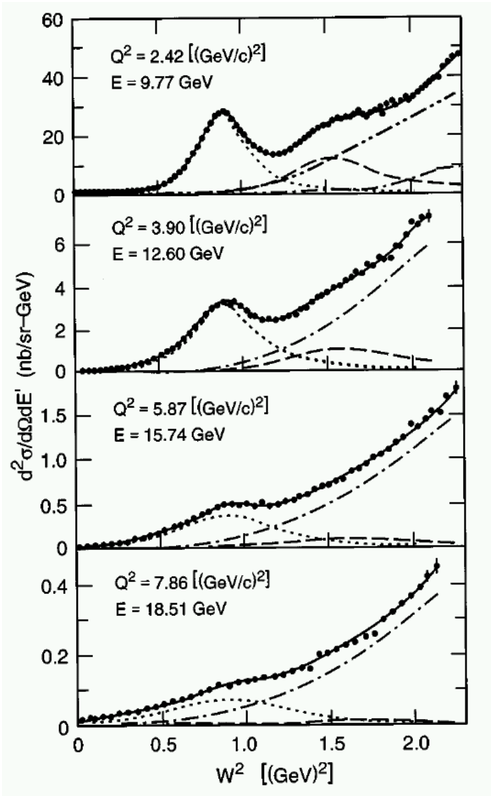
Selecting Quasielastic Protons - Acceptance



Acceptance for the $D(e, e'p)n$ in CLAS12 for 11 GeV. Calculated with FASTMC.

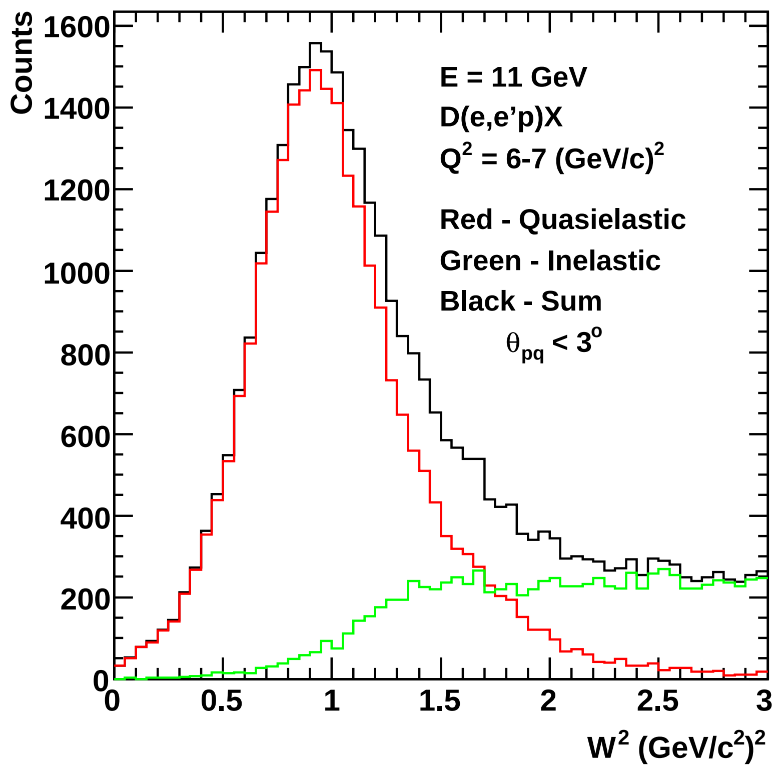
Selecting Quasielastic Protons - Consistency Check

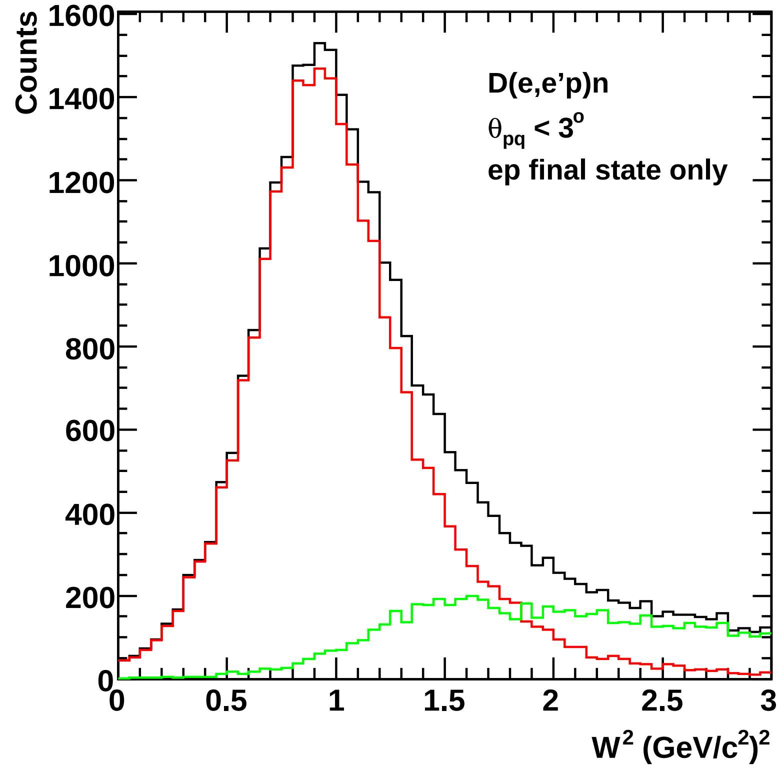




Comparison of the W^2 spectra for simulated inclusive electrons (left-hand panel) from this work and measured inclusive spectra for electron scattering on deuterium (right-hand panel). Inelastic $e - D$ cross sections are shown in the $\Delta(1232)$ resonance region fitted with contributions from quasielastic (dotted line), $\Delta(1232)$ (dashed), and non-resonant (dot-dashed) contributions (L.M.Stuart, *et al.*, Phys. Rev. **D58** (1998) 032003).

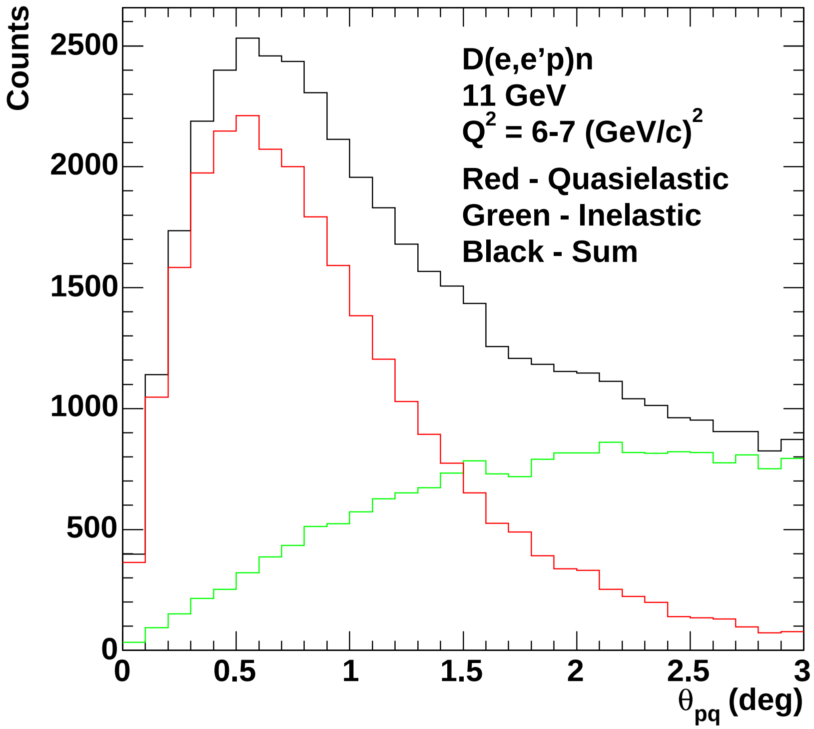
Selecting Quasielastic Protons - W^2 Spectra

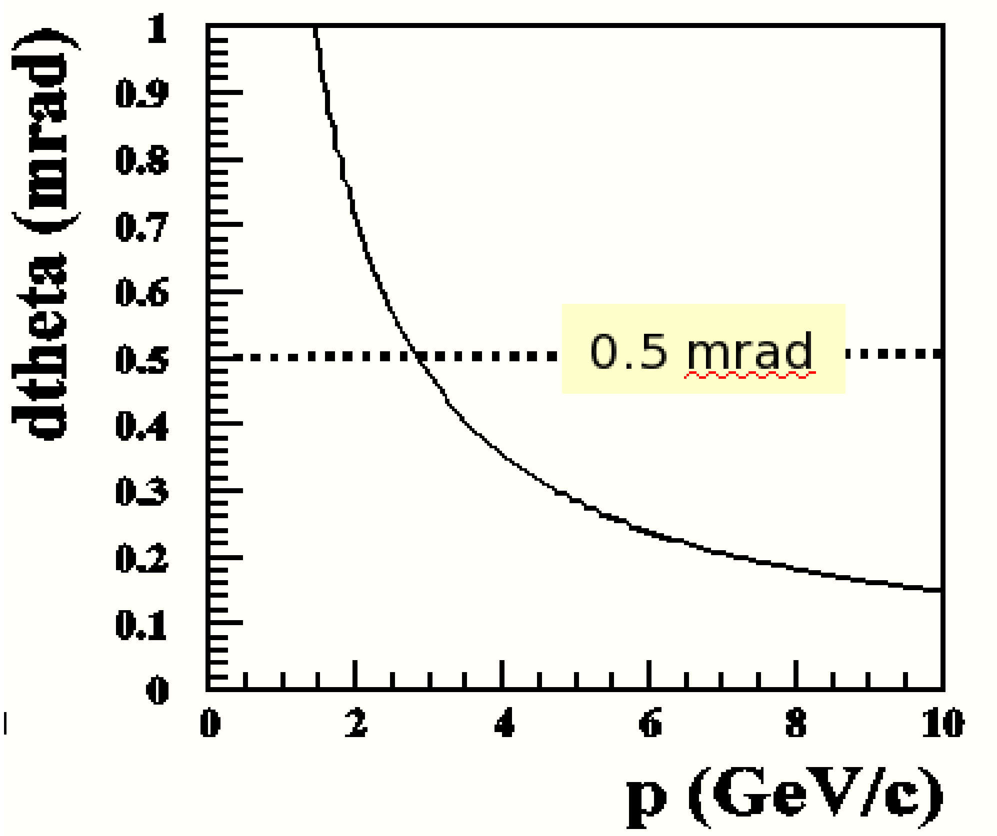




W^2 spectra for the $e - p$ final state. The left-hand panel has $\theta_{pq} < 3^\circ$. The left-hand panel is for $\theta_{pq} < 3^\circ$ and only $e - p$ in the final state.

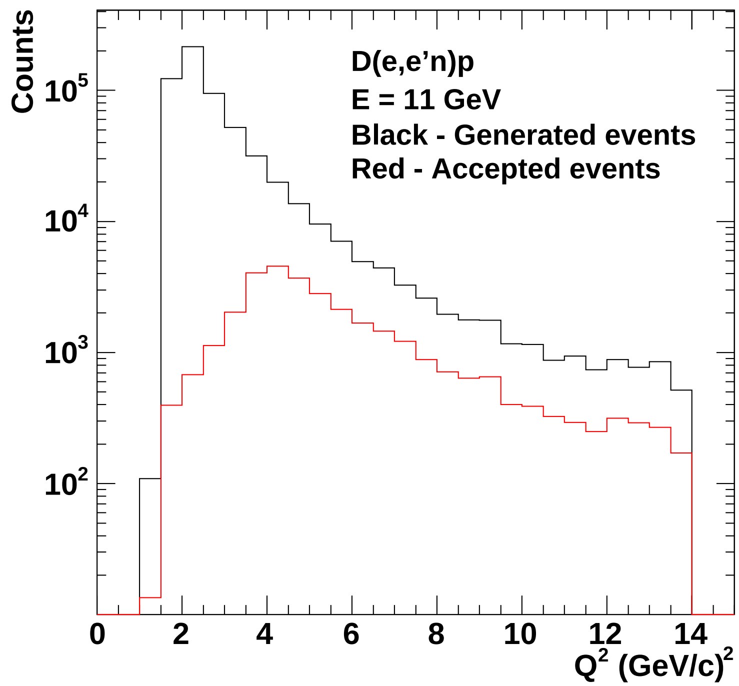
Selecting Quasielastic Protons - Angular Distributions





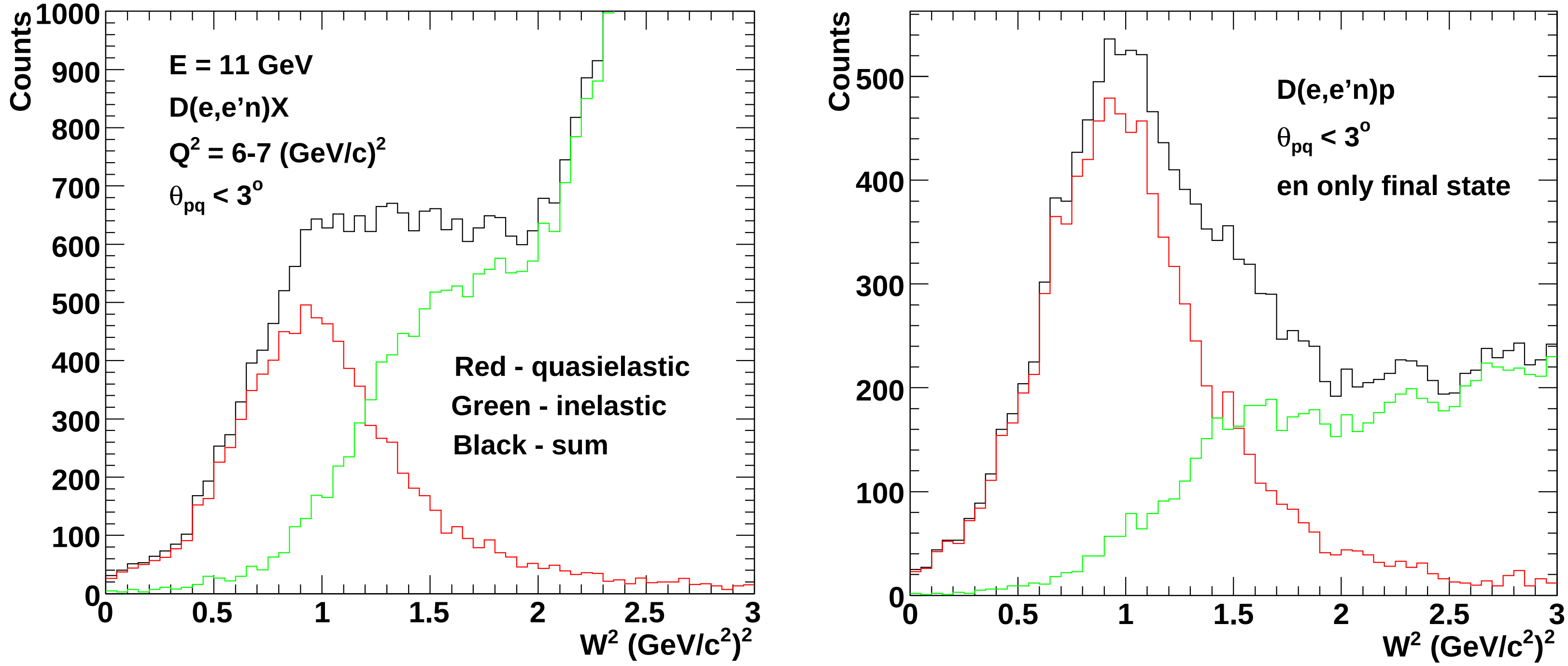
Distribution of θ_{pq} for the simulations and angular resolution of CLAS12 for charged particles in the forward tracking system.

Selecting Quasielastic Neutrons - Acceptance



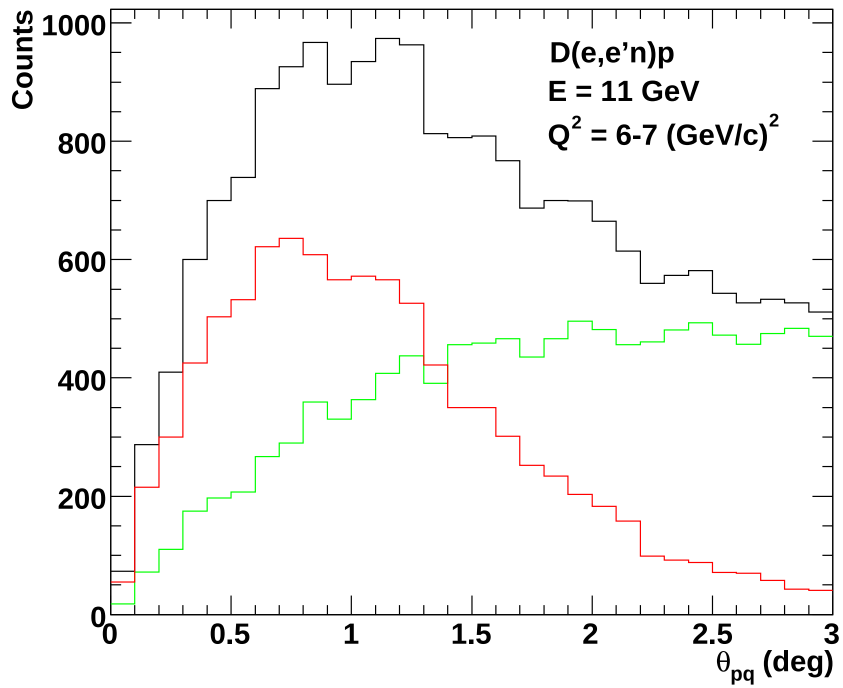
Acceptance for the $D(e, e'n)p$ in CLAS12 for 11 GeV. Calculated with FASTMC.

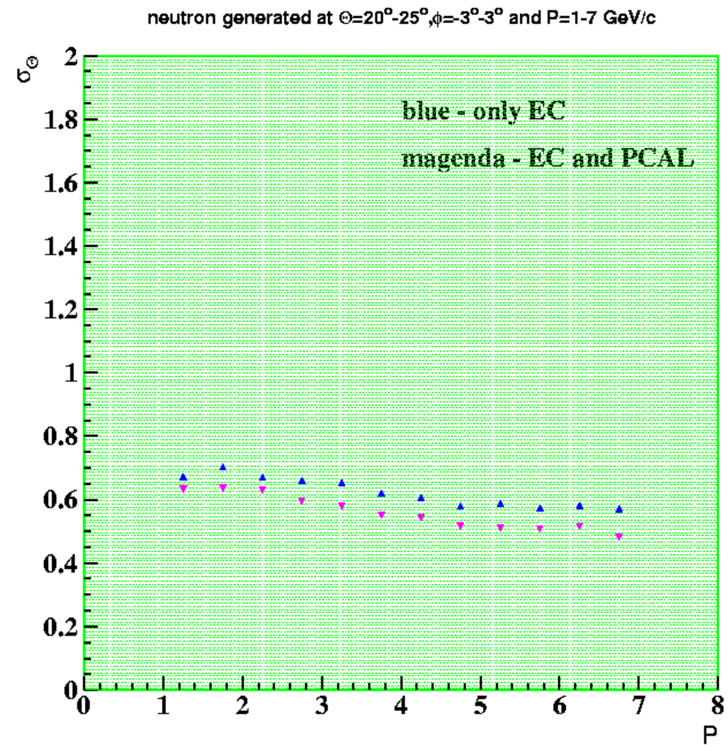
Selecting Quasielastic Neutrons - W^2 Spectra



Comparison of the simulated W^2 spectra for the $D(e, e'n)X$ (left-hand panel) and $D(e, e'n)p$ reactions (right-hand panel).

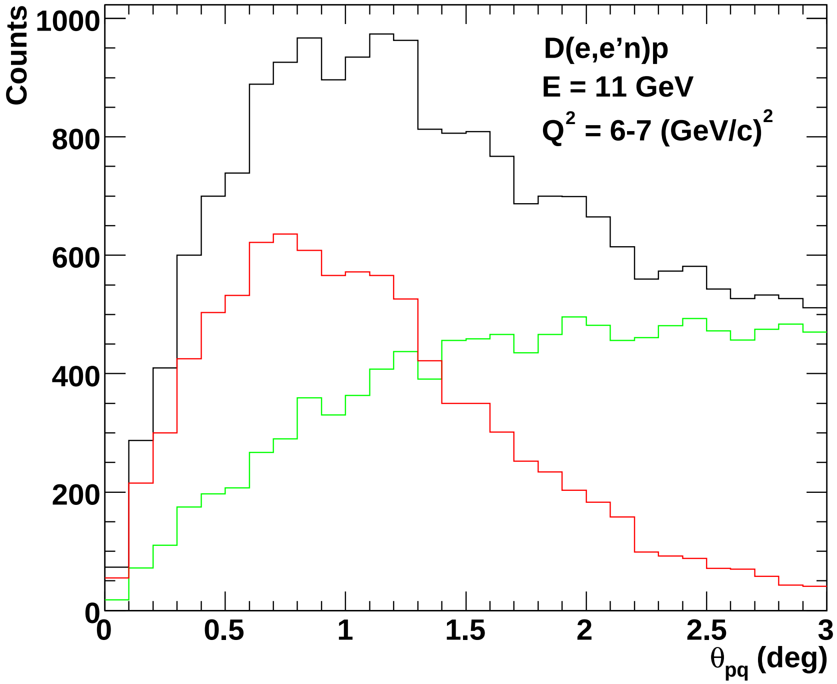
Selecting Quasielastic Neutrons - Angular Distributions

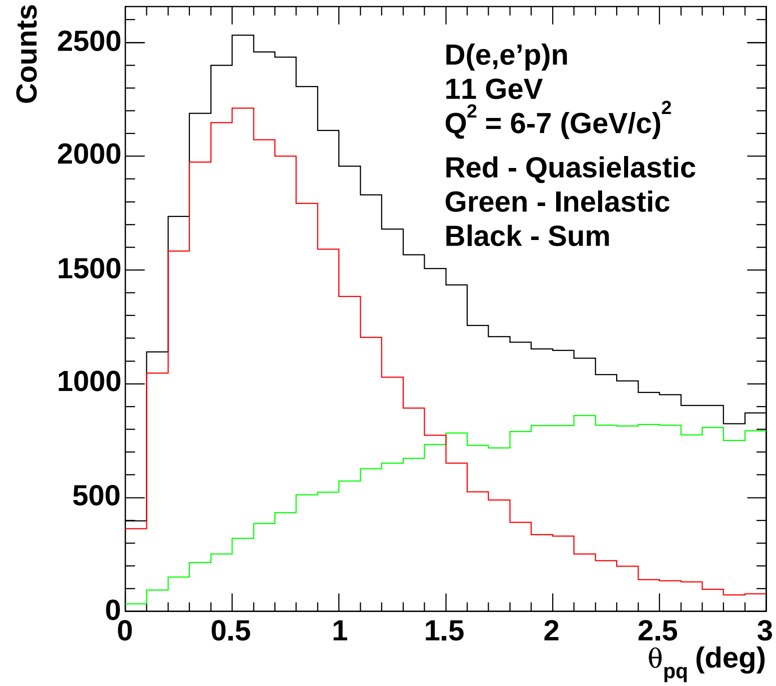




Angular distribution of θ_{pq} for the quasielastic (red), inelastic (green), and total (black) contributions (left-hand panel) and a GSIM12 simulation of the angular resolution of CLAS12 for neutrons in the forward tracking system (right-hand panel).

Selecting Quasielastic Neutrons - Angular Distributions - 2



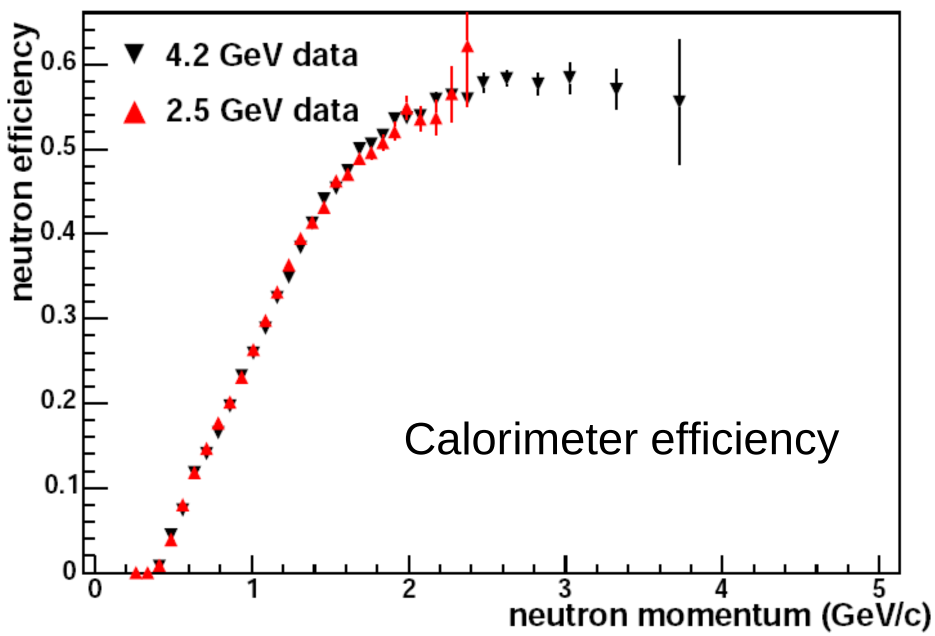


Angular distribution of θ_{pq} neutrons (left-hand panel) for the quasielastic (red), inelastic (green), and total (black) contributions (left-hand panel) and protons (right-hand panel).

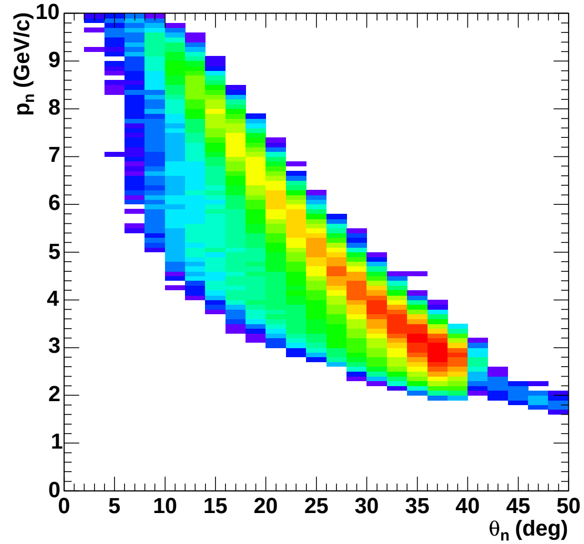
Ratio Method Calibrations - Neutron Detection Efficiency

Neutron detection efficiency:

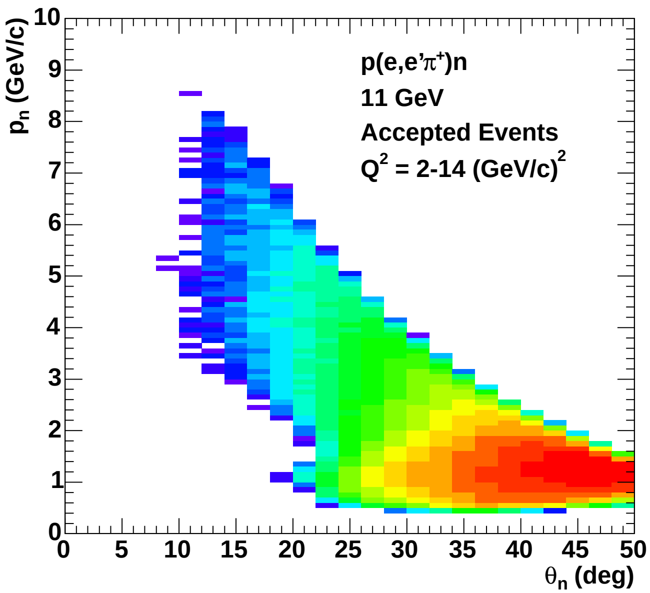
1. Use the $ep \to e'\pi^+ n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.
2. Use CLAS12 tracking for electron selection.
3. For π^+, use positive tracks, cut on the difference between β measured from tracking and from time-of-flight to reduce photon background.
4. For neutrons, $ep \to e\pi^+ X$ for $0.9 < m_X < 0.95\ \mathrm{GeV/c^2}$.
5. In the calorimeter use the neutron momentum $\vec{p}_n$ to determine the location of a hit in the fiducial region (reconstructed event) and search for that neutron (a found event if it's there). Plot shows the results of the CLAS G_M^n measurement.

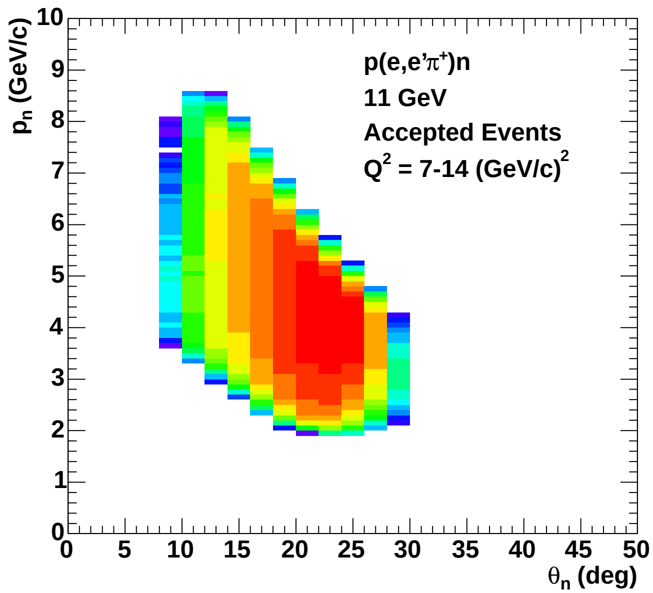


6. Acceptance for neutrons in $D(e,e'n)p$.



7. Acceptance for neutrons in $p(e,e'\pi^+)n$.

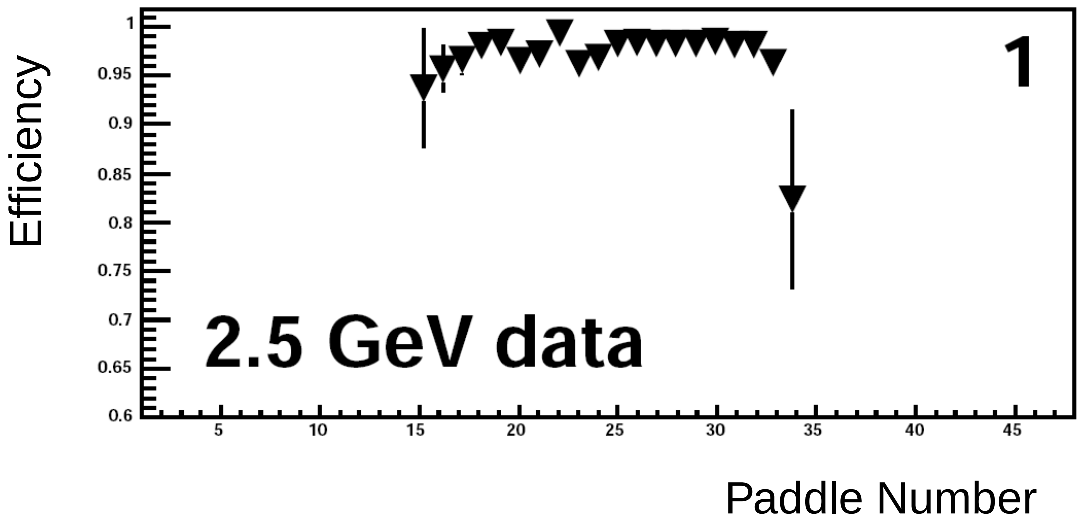




Ratio Method Calibrations - Proton Detection Efficiency

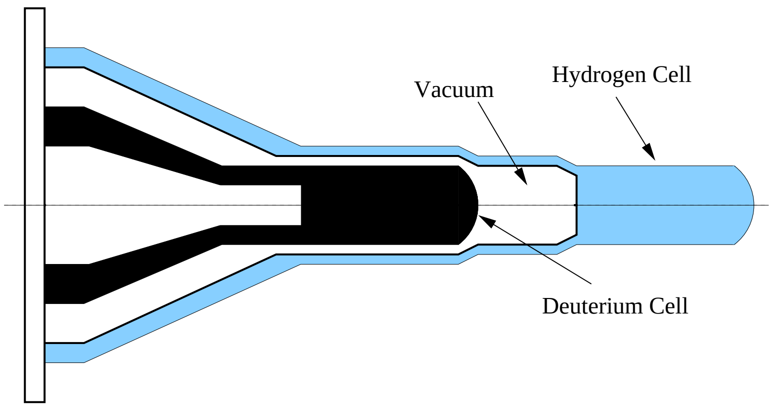
Proton detection efficiency:

1. Use $ep \rightarrow e'p$ elastic scattering from hydrogen target as a source of tagged protons.
2. Select elastic $e-p$ eveants with a W^2 cut.
3. Protons were identified as positive tracks with a coplanarity cut applied.
4. Use the missing momentum from $ep \rightarrow e'X$ to predict the location of the proton (a reconstructed event). Search the the TOF paddle or an adjacent one for a positively-charged particle (a found event if it's there). Results below are for sector 1 in the CLAS G_M^n measurement.



Ratio Method Calibrations - Conceptual Target Design

- Dual target cell with two, 2-cm cells containing liquid hydrogen and deuterium. The hydrogen cell is downstream and separated from the deuterium target by 1.0-cm gap. Enables us to perform *in situ* calibrations during data collection.
- Modeled after E5 target used in CLAS G_M^n measurement.



The Ratio Method - Systematic Errors

- The goal is a systematic uncertainty of 3%.
- Use the CLAS G_M^n measurement for guidance.

Quantity	$\delta G_M^n/G_M^n \times 100$	Quantity	$\delta G_M^n/G_M^n \times 100$
Neutron efficiency parameterization	< 1.5	θ_{pq} cut	< 1.0
proton σ	< 1.5	G_E^n	< 0.7
neutron accidentals	< 0.3	Neutron MM cut	< 0.5
neutron proximity cut	< 0.2	proton efficiency	< 0.4
Fermi loss correction	< 0.9	Radiative corrections	< 0.06
Nuclear Corrections	< 0.2		

Upper limits on estimated systematic error for different contributions for the CLAS G_M^n measurement ($\Delta G_M^n/G_M^n = 2.7\%$).

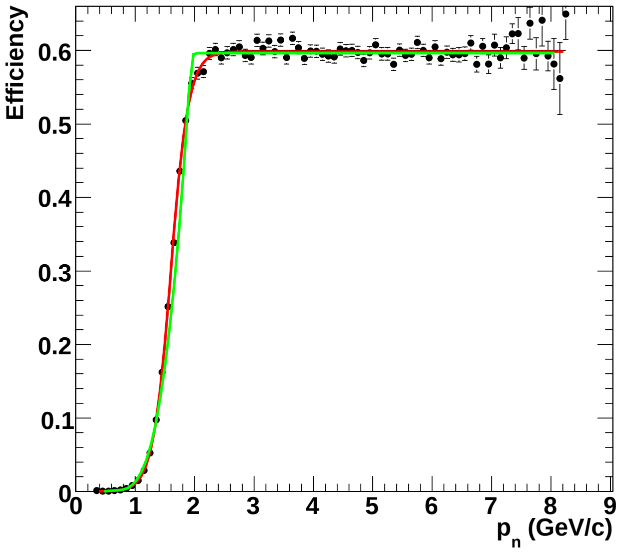
Systematic Uncertainties - Neutron Detection Efficiency

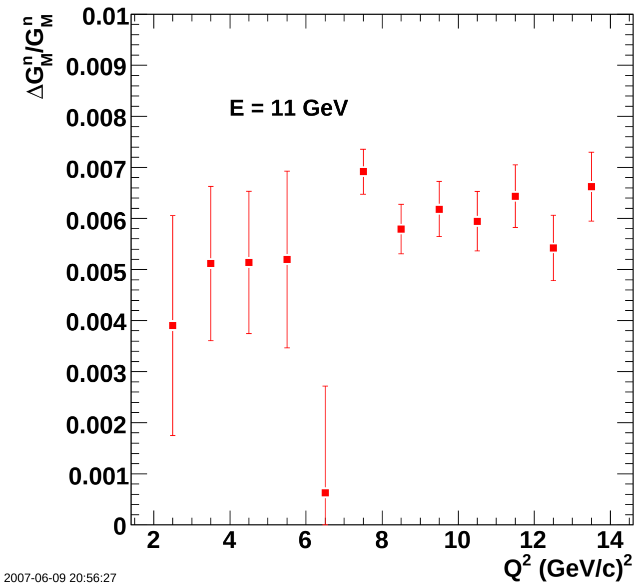
- Characterize the neutron detection efficiency ϵ_n with the expression

$$\epsilon_n = S \times \left(1 - \frac{1}{1 + \exp(\frac{p_n - p_0}{a_0})}\right)$$

where S is the height of the plateau in ϵ_n for $p_n > 2\, GeV/c$, p_0 is a constant representing the position of the middle of the rapidly rising portion of the ϵ_n, and a_0 controls the slope of the ϵ_n in the increasing ϵ_n region.

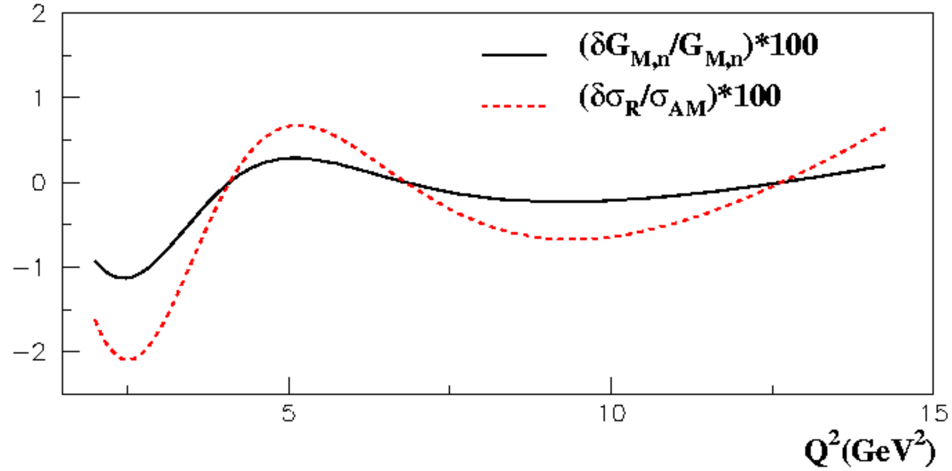
- Fit the ϵ_n with a third-order polynomial and a flat region.
- Use the original ϵ_n and the fit in reconstructing the neutrons and compare.



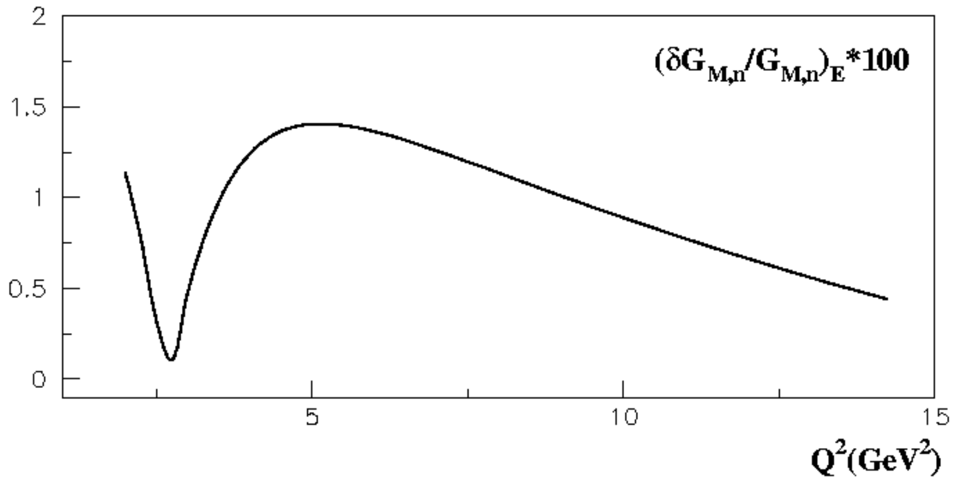


Systematic Uncertainties - Other Elastic Form Factors

- Systematic uncertainty ($\Delta G_M^n / G_M^n \times 100$) based on differences in the proton reduced cross section parameterizations of Bosted and Arrington-Melnitchouk.



- Systematic uncertainty ($\Delta G_M^n / G_M^n \times 100$) based on differences in G_E^n parameterizations of Kelly and BBBA05.



Systematic Uncertainties - Summary

Quantity	$\delta G_M^n / G_M^n \times 100$	Quantity	$\delta G_M^n / G_M^n \times 100$
Neutron efficiency parameterization	< 0.7(1.5)	θ_{pq} cut	< 1.0(1.7)
proton σ	< 1.5(1.5)	G_E^n	< 0.7(0.5)
neutron accidentals	< 0.3	Neutron MM cut	< 0.5
neutron proximity cut	< 0.2	proton efficiency	< 0.4
Fermi loss correction	< 0.9	Radiative corrections	< 0.06
Nuclear Corrections	< 0.2		

Summary of expected systematic uncertainties for CLAS12 G_M^n measurement ($\Delta G_M^n / G_M^n = 2.7\%$(2.7)). Red numbers represent the previous upper limits from the CLAS measurement.

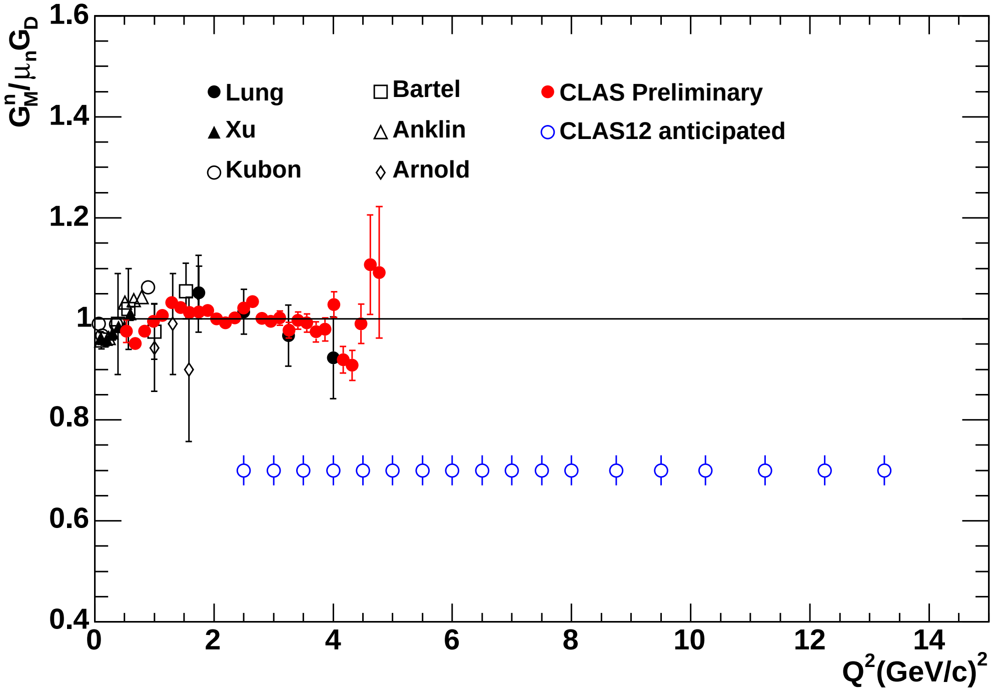
Run Statistics

2.5	0.2566	1.3384	0.499×10^6	0.142	0.26×10^7	0.062
3.5	11.7592	1.8455	0.229×10^8	0.021	0.36×10^7	0.053
4.5	4.9359	1.4266	0.960×10^7	0.032	0.28×10^7	0.060
5.5	1.8363	0.6011	0.357×10^7	0.053	0.12×10^7	0.093
6.5	0.7002	0.2103	0.136×10^7	0.086	0.41×10^6	0.156
7.5	0.2829	0.0816	0.550×10^6	0.135	0.16×10^6	0.251
8.5	0.1236	0.0342	0.240×10^6	0.204	0.66×10^5	0.388
9.5	0.0595	0.0152	0.116×10^6	0.294	0.29×10^5	0.583
10.5	0.0303	0.0070	0.590×10^5	0.412	0.14×10^5	0.857
11.5	0.0144	0.0033	0.280×10^5	0.598	0.65×10^4	1.242
12.5	0.0069	0.0016	0.135×10^5	0.860	0.31×10^4	1.784
13.5	0.0034	0.0008	0.657×10^4	1.234	0.15×10^4	2.554

Rates and statistical uncertainties for quasielastic scattering. All bins are $\pm 0.5\ (GeV/c)^2$. Based on 45 PAC days of beam time and a luminosity per nucleon of $0.5 \times 10^{35}\ cm^{-2}s^{-1}$.

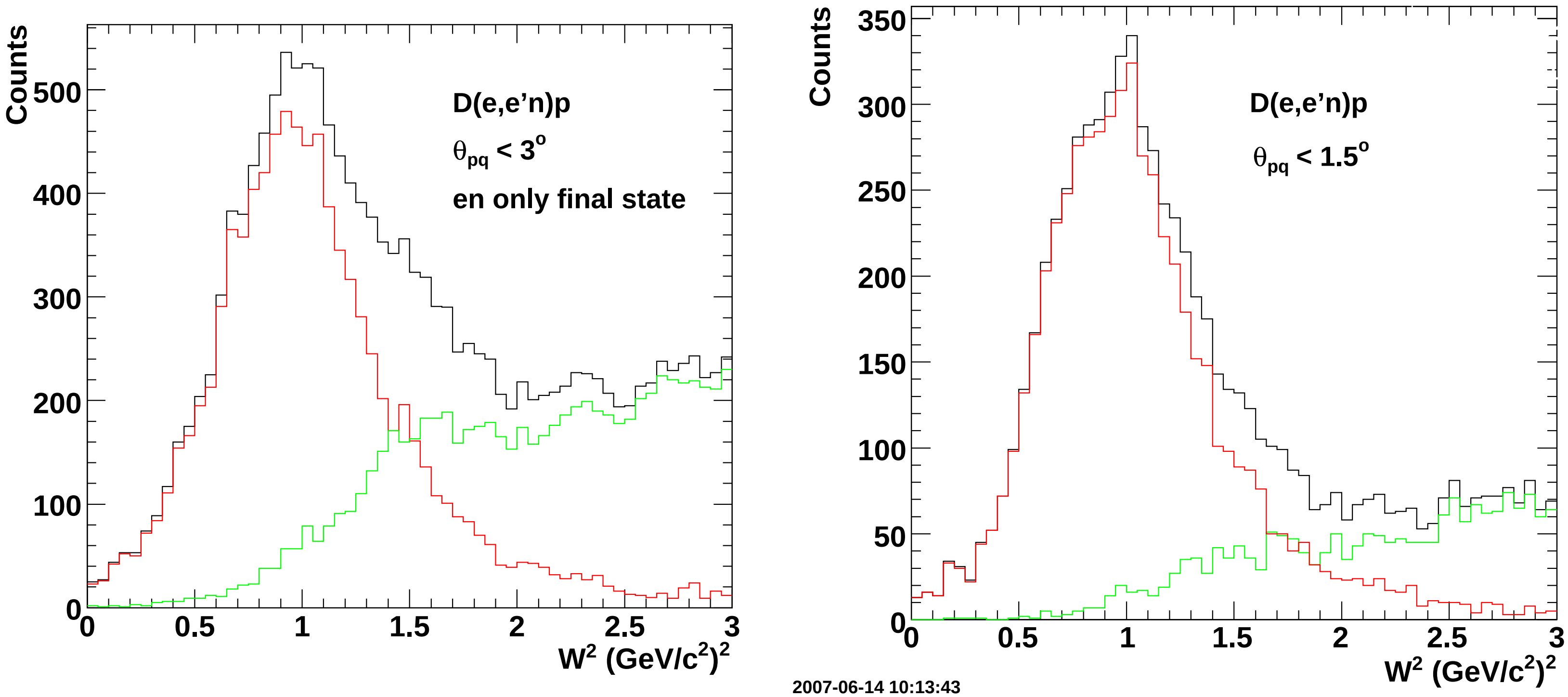
Anticipated Results and Beam Request

- The expected Q^2 range and systematic uncertainty of less than 3% are shown belong along with the world data for G_M^n. We will more than double the Q^2 range of the current knowledge of the neutron magnetic form factor.



- We request 45 PAC days of beam time at 11 GeV in order to obtain statistical precision as good as the anticipated systematic uncertainty.

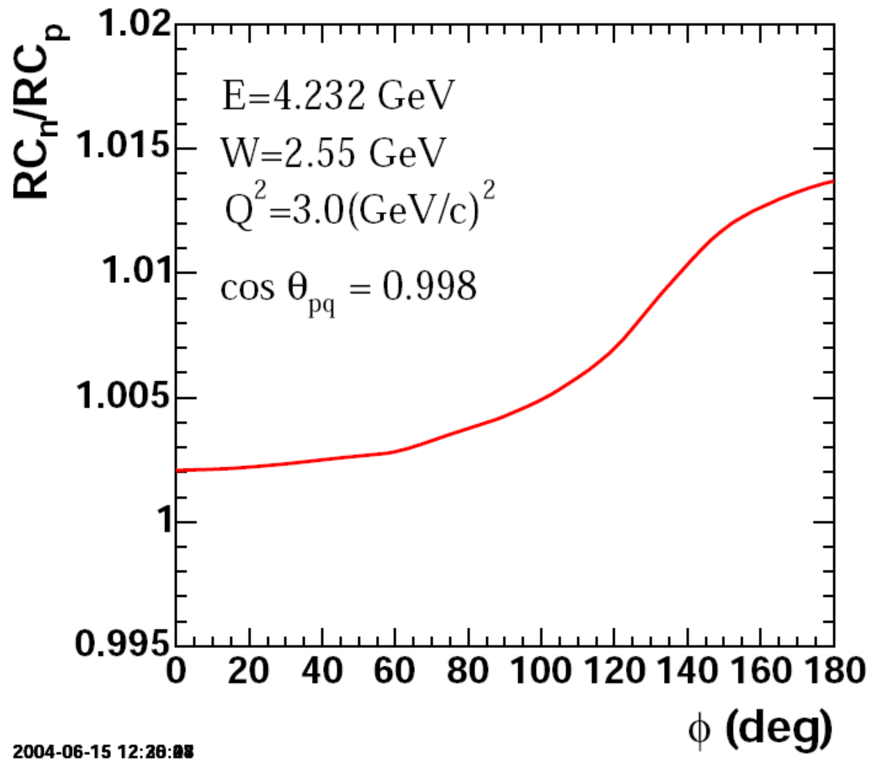
Selecting Quasielastic Neutrons - W^2 Spectra - 2



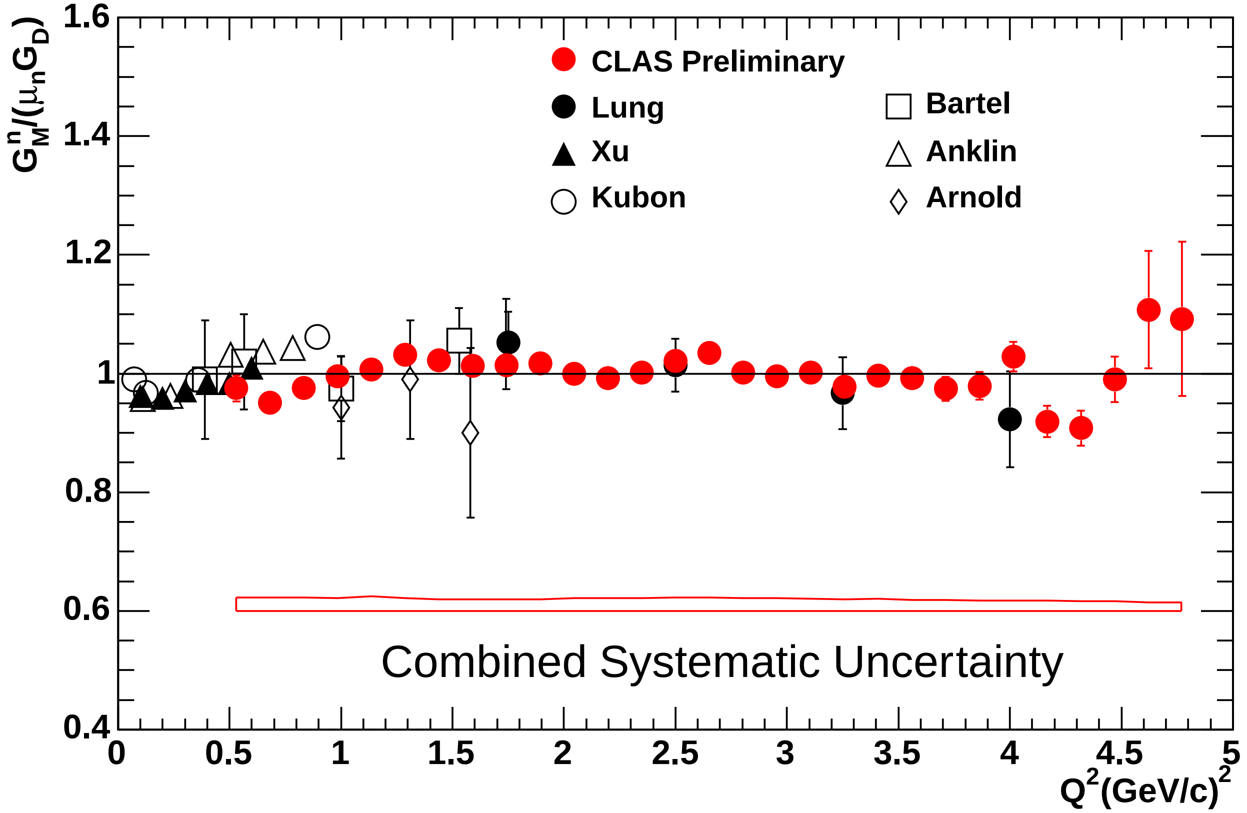
Simulated W^2 spectra for the $D(e,e'n)p$ with θ_{pq} cut reduced from 3° (left-hand panel) to 1.5° (right-hand panel).

The Ratio Method - Corrections

- Nuclear effects: The $e-n/e-p$ ratio for free nucleons can be altered here because we measure the quasielastic scattering from bound nucleons. This factor $a(Q^2)$ was calculated and we compared results from Jeschonnek and Arenhoevel. Where the calculations overlap in Q^2, the average correction to R is 0.994 and we assigned a systematic uncertainty of 0.6%.
- Radiative corrections: Calculated for exclusive $D(e,e'p)n$ with the code EXCLURAD by Afanasev and Gilfoyle (CLAS-Note 2005-022). The ratio of the correction factors for $e-n/e-p$ events is close to unity.

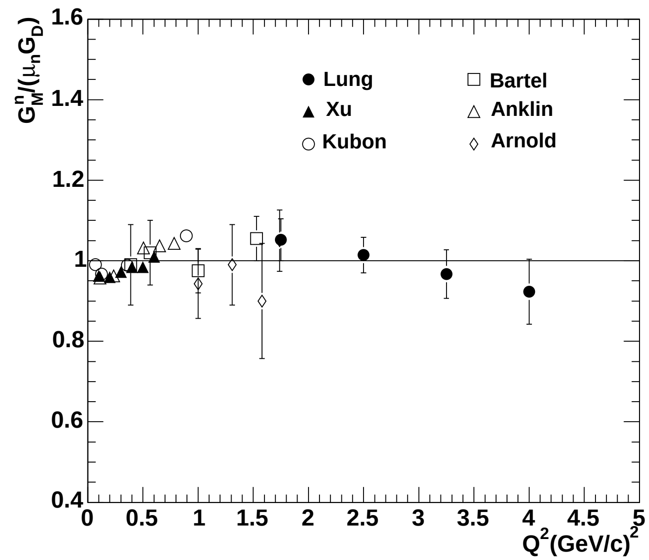


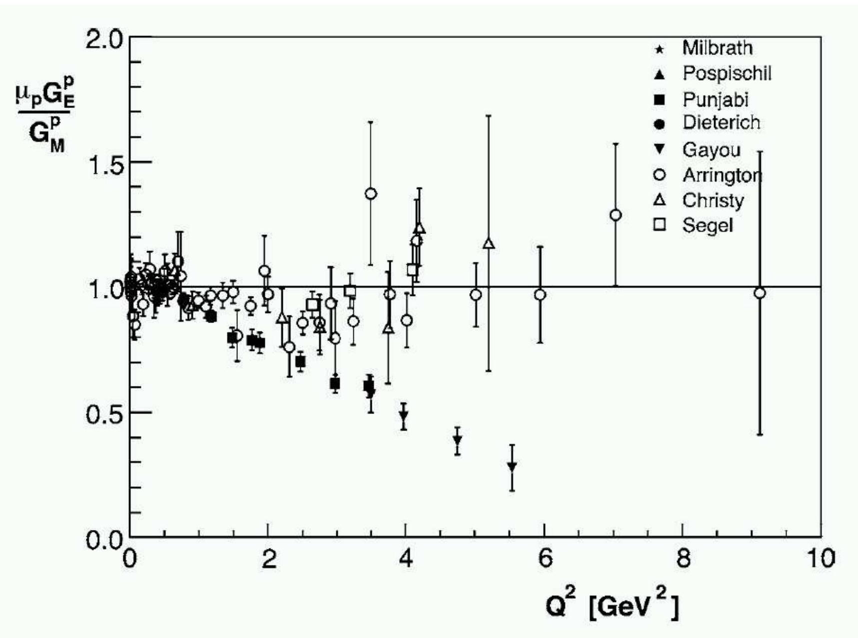
Results - Comparison with Existing Data

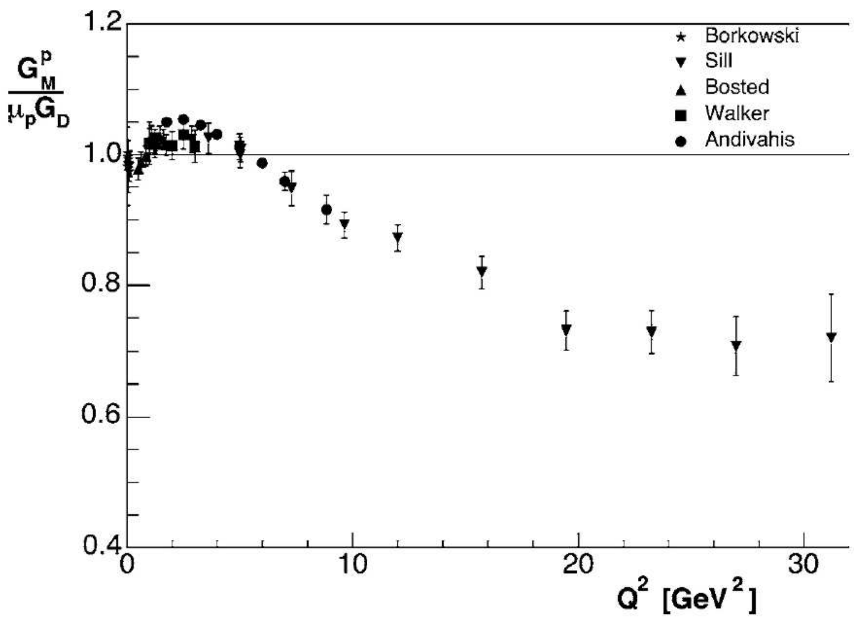


Published Measurements of Elastic Form Factors

- G_M^n
- G_M^p
- G_E^p/G_M^p







C.E. Hyde-Wright and K.deJager, Ann. Rev. Nucl. Part. Sci. **54** (2004) 54 and references therein.