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

(PR12-07-104)

A New Proposal for the Jefferson Lab 12-GeV Upgrade Program in Hall B

Follow-on to PAC30 Letter of Intent LOI12-06-107

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.

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and the CLAS Collaboration

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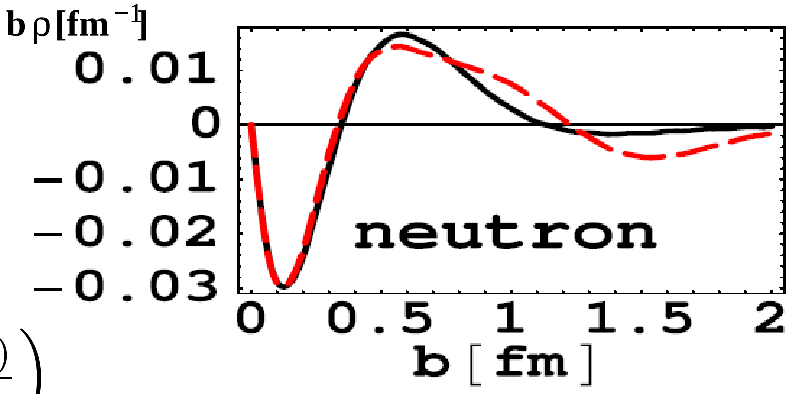
> ‘The physics impact of the experiment is high. The group has already successfully performed similar measurements at 6 GeV. This measurement is an important part of the Jlab program to study the 4 elastic nucleon form factors.’
>
> - PAC30 report on LOI12-06-107

Scientific Motivation

- G_M^n is a fundamental quantity describing the charge and magnetization in the neutron. In the infinite-momentum-frame the parton charge density in transverse space is



$$\rho(b) = \int_0^\infty dQ \frac{Q}{2\pi} J_0(Qb) \times \left(\frac{G_E(Q^2) + \tau G_M(Q^2)}{1+\tau} \right)$$

(G.Miller, arXiv:0705.2409v2 [nucl-th]).

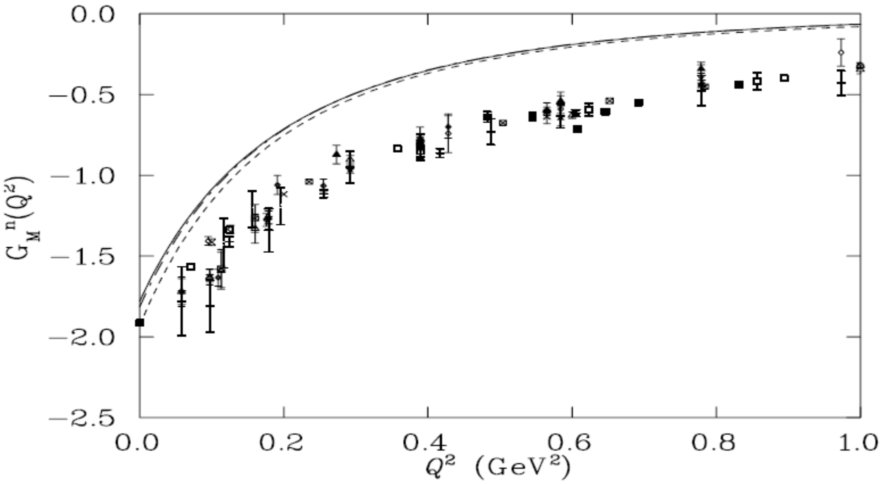
- Measurements at large Q^2 will render the results above 'more precise or potentially change them considerably' (*Ibid.*).

- Elastic form factors (G_M^n, G_E^n, G_M^p, and G_E^p) provide key constraints on the generalized parton distributions (GPDs) which hold the promise of a three-dimensional picture of the nucleon.

> 'High-quality data on the neutron form factors in a wide t range would be highly valuable for pinning down the differences in the spatial distribution of u and d quarks ... drastic differences in the behavior of u and d contributions to the form factors'

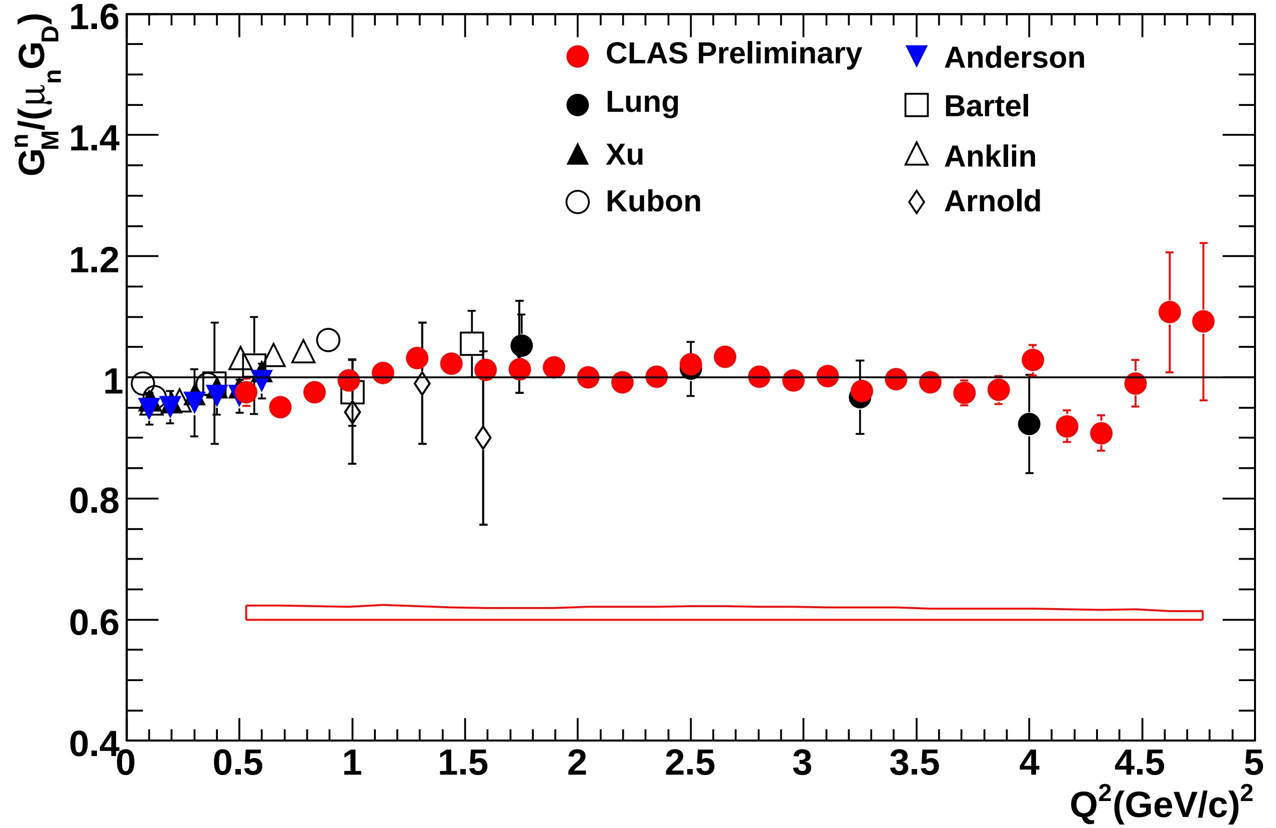
(M.Diehl, Th. Feldmann, R. Jakob, and P.Kroll, hep-ph/0408173v2).

- Part of a broad effort to understand how nucleons are ‘constructed from the quarks and gluons of QCD’ (NSAC Long Range Plan, April, 2002).
- Fundamental challenge for lattice QCD (J.D. Ashley, D.B. Leinweber, A.W. Thomas and R.D. Young, Eur. Phys. J. A **15**, 487 (2002)).
- There are ‘drastic differences’ in the u and d quark contributions that require high-Q^2 data to sort out (M. Diehl, *et al.* Eur.Phys.J.C **39** (2005) 1).
- Required for extracting the strange quark distributions in the proton.



The magnetic form factor for the neutron extrapolated from lattice data with lattice spacings a = 0.093 fm (single line), a = 0.068 fm (dash-dot line) and a = 0.051 fm (dotted line) and compared to experimental results.

World Data on G_M^n



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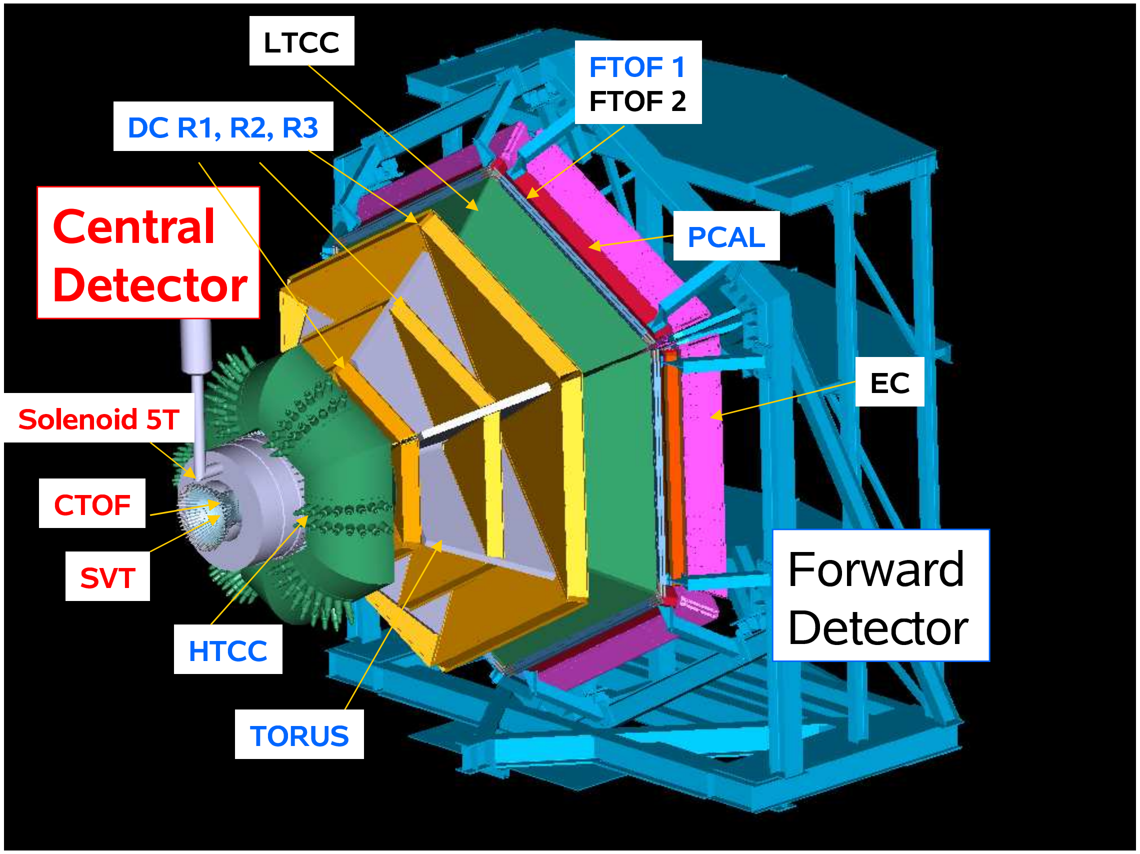
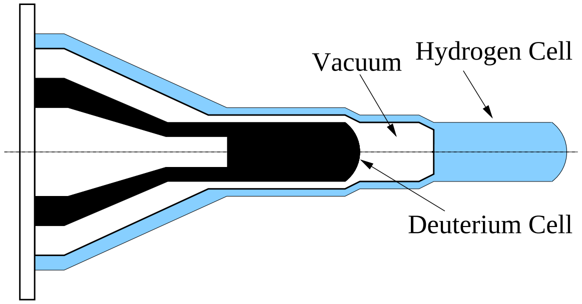
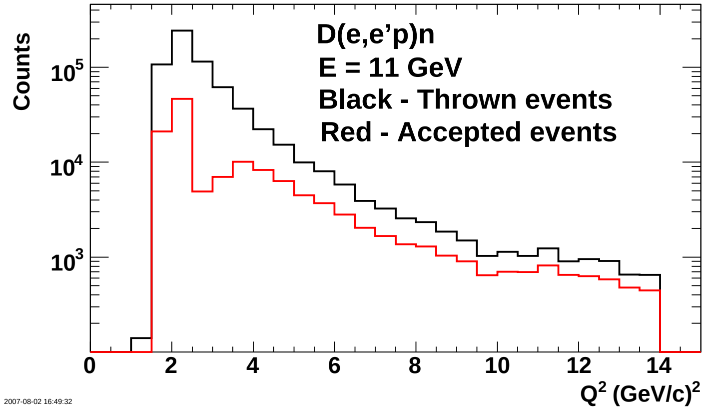
The world data on G_M^n scaled by the dipole approximation where $G_D(Q^2){=}1/(1{+}(Q^2/\Lambda))^2$ and $\Lambda{=}0.71\ (GeV/c)^2$. The proposed measurement will extend the upper limit to $\mathrm{Q}^2{=}14(\mathrm{GeV/c})^2$.

The CLAS12 Detector and Dual Target Cell





The dual target enables us to collect high-precision, consistent calibration data so systematic uncertainties $\leq 3\%$.



CLAS12 acceptance for quasi-elastic $e-p$ events calculated with FASTMC (CLAS12 parameterized simulation). Range is $\mathrm{Q}^2 = 2 - 14(\mathrm{GeV/c})^2$.

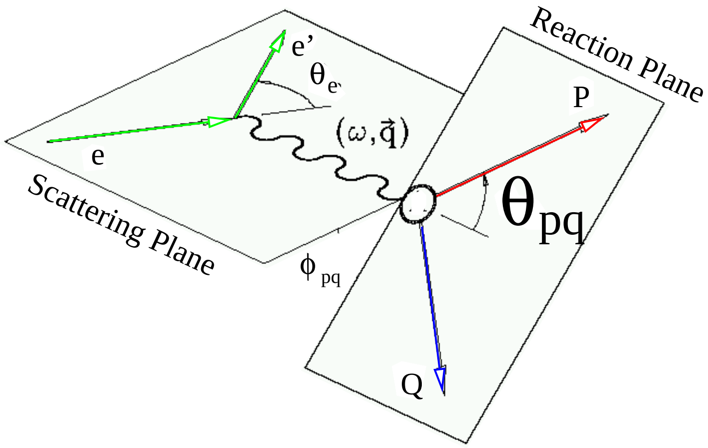
The Ratio Method - Some Necessary Background

- Express the cross section in terms of the Sachs form factors.

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

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

- Kinematic definitions - The angle θ_{pq} is between the virtual photon direction and the direction of the ejected nucleon.



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

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

The Ratio Method - Outline and Advantages

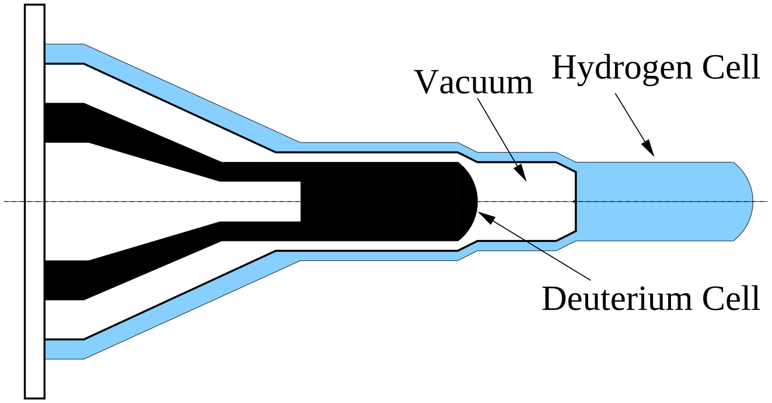
Outline

1. Selecting quasielastic events: inelastic background, acceptance matching.
2. Neutron detection efficiency.
3. Proton detection efficiency.
4. Estimates of uncertainties.

GOAL: 3% systematic uncertainty

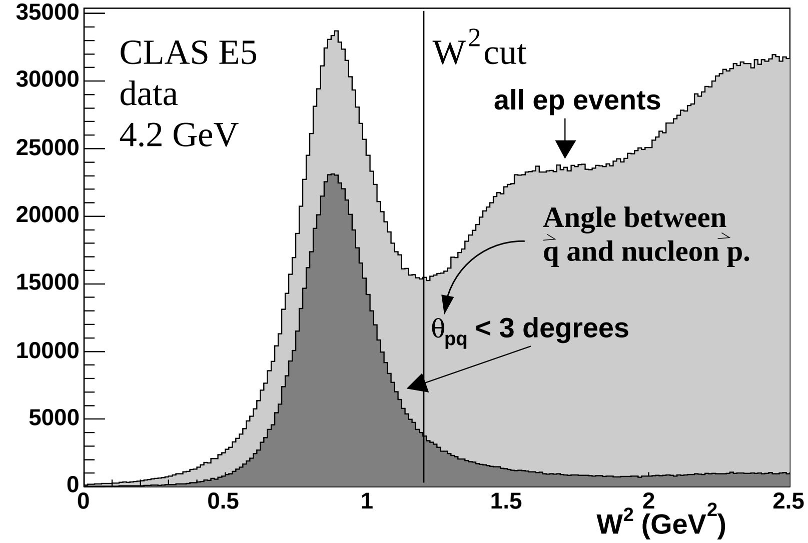
Advantages

- Use deuterium as a neutron target.
- Reduces sensitivity to changes in running conditions, nuclear effects, radiative corrections, Fermi motion corrections.
- Importance of *in-situ* calibrations of neutron and proton detection efficiencies .
- Take advantage of the experience from the CLAS measurement of G_M^n.



Selecting Quasielastic Events

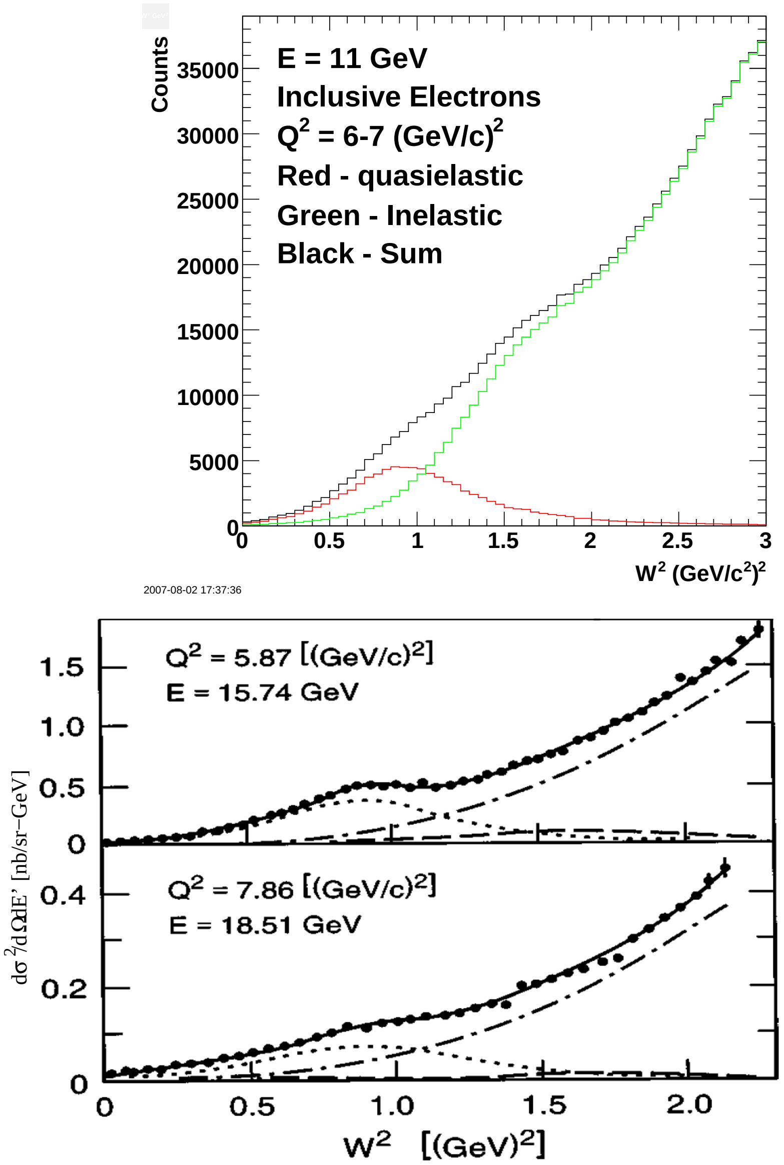
- Select $e - p$ events using the CLAS12 tracking system for electrons and protons.
- Use TOF and calorimeters as independent detectors for neutrons. The main focus here will be on the calorimeters since they are more efficient.
- Apply a θ_{pq} cut to select quasi-elastic events plus $W^2 < 1.2\ (GeV/c^2)^2$.



- Match acceptances using quasi- elastic electron kinematics to determine if the nucleon lies in CLAS12 acceptance.
- Neutrons and protons treated exactly the same whenever possible.
- The CLAS G_M^n measurement at 4 GeV overlaps the proposed measurement to provide a consistency check.
- Impact of inelastic background will be greater at large Q^2 due to increasing width of W^2 requiring simulation.

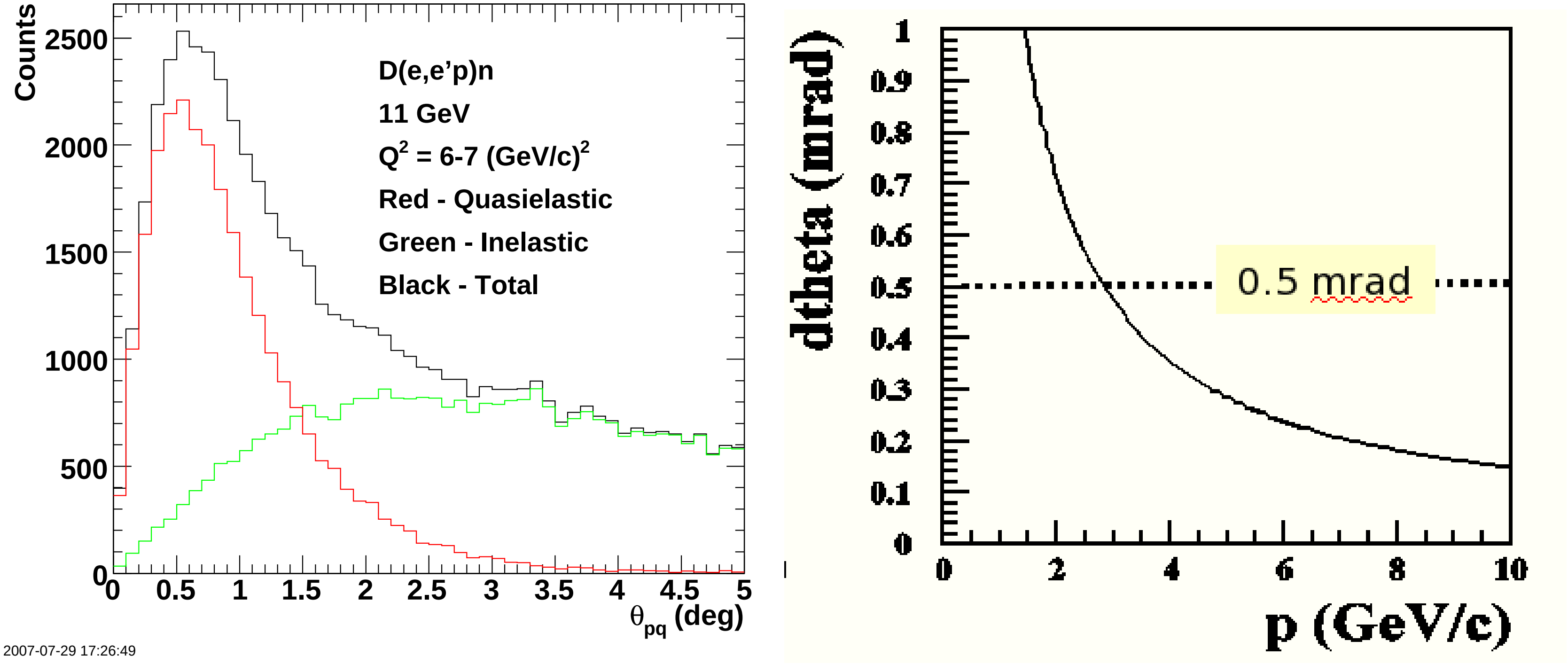
Monte Carlo Simulation

1. Quasielastic events ⟶ elastic form factors.
2. Inelastic events ⟶ proton and deuteron data (P. Stoler, Phys. Rep., **226**, 103 (1993), L.M.Stuart, *et al.*, Phys. Rev. **D58** (1998) 032003).
3. For exit channel use elastic form factors and the `genev` program (for inelastic events) (M.Ripani and E.M.Golovach based on P.Corvisiero, *et al.*, Nucl. Instr. and Meth., **A346**, 433 (1994)).
4. Use FASTMC (CLAS12 parameterized Monte Carlo) to simulate the CLAS12 response.
5. Validate the Monte Carlo simulation.



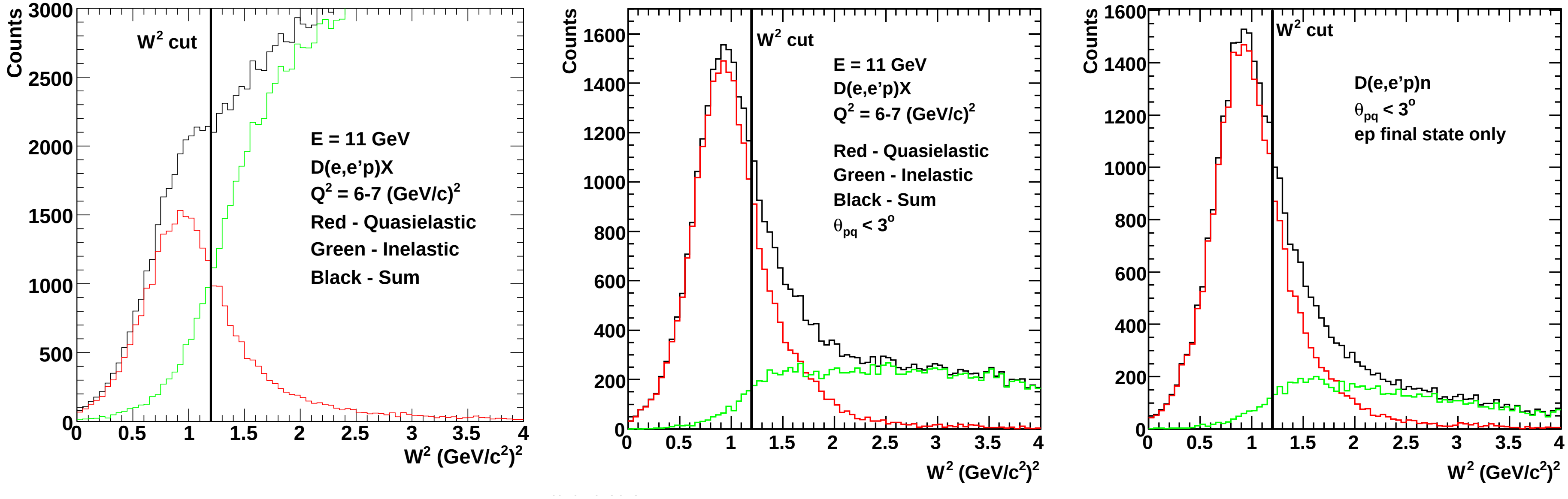
Simulated (top panel) and measured (lower panel) inclusive electron spectra (L.M.Stuart, *et al.*, Phys. Rev. **D58** (1998) 032003).

Selecting Quasielastic Protons - The θ_{pq} Cut



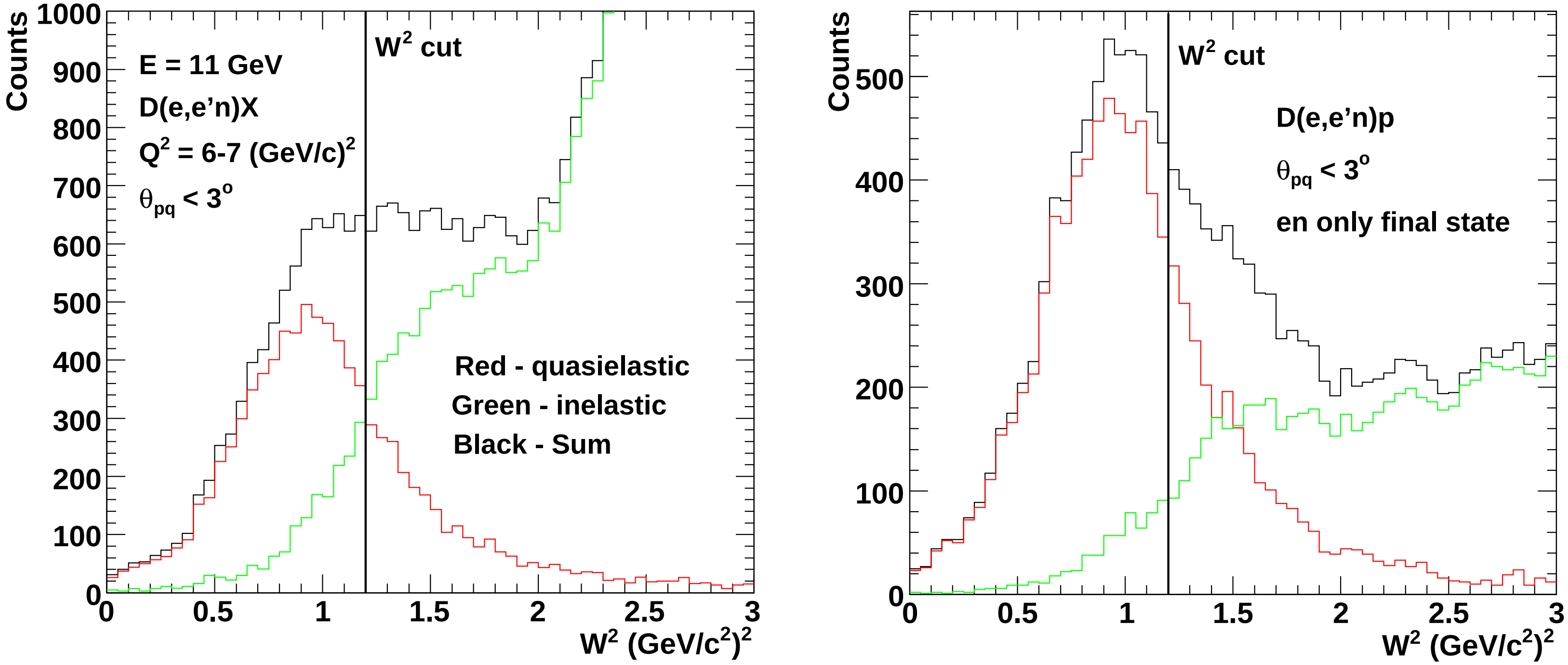
Distribution of θ_{pq} for the simulations and angular resolution of CLAS12 for charged particles in the forward tracking system from GSIM12.

Selecting Quasielastic Protons - W^2 Spectra



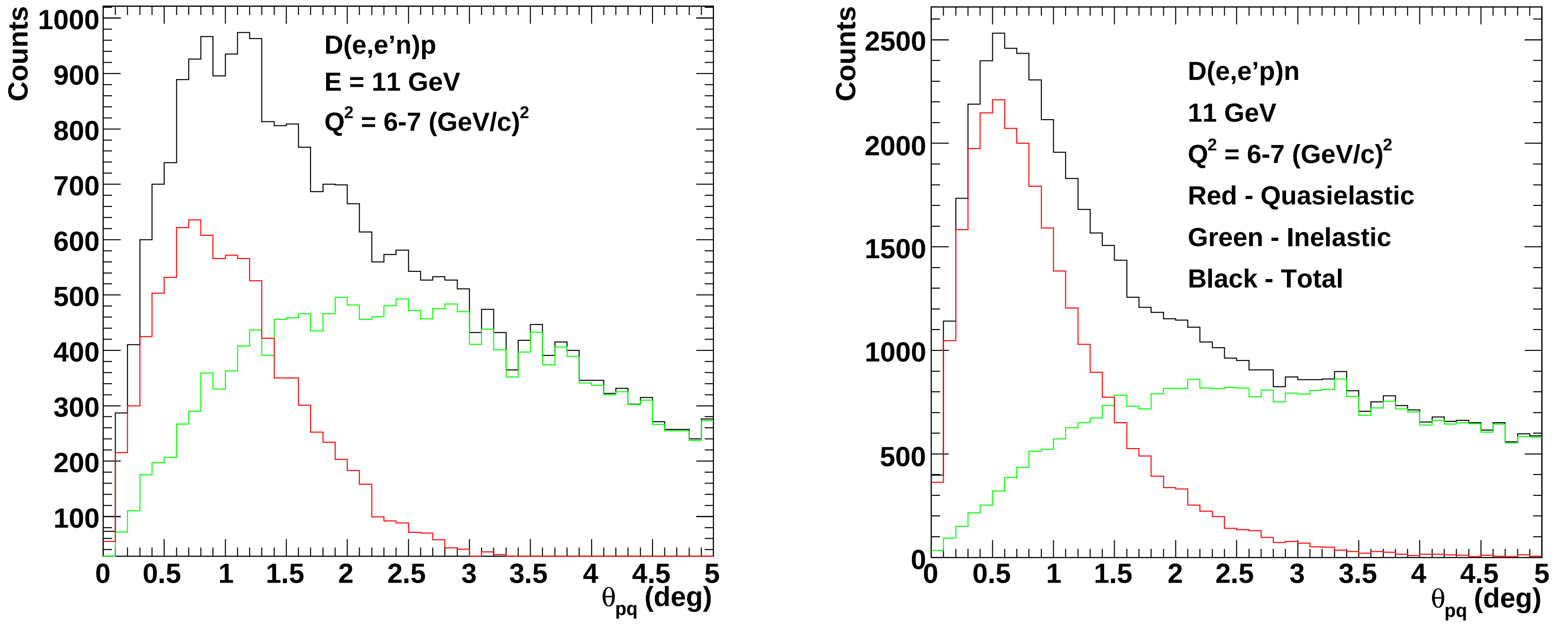
W^2 spectra for the $e-p$ final state. The left-hand panel has no θ_{pq} cut and the middle panel shows the effect of requiring $\theta_{pq} < 3^\circ$. The right-hand panel is for $\theta_{pq} < 3^\circ$ and only $e-p$ in the final state (the multi-particle veto).

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) with $\theta_{pq} < 3^\circ$ in both.

Selecting Quasielastic Events - Angular Distributions



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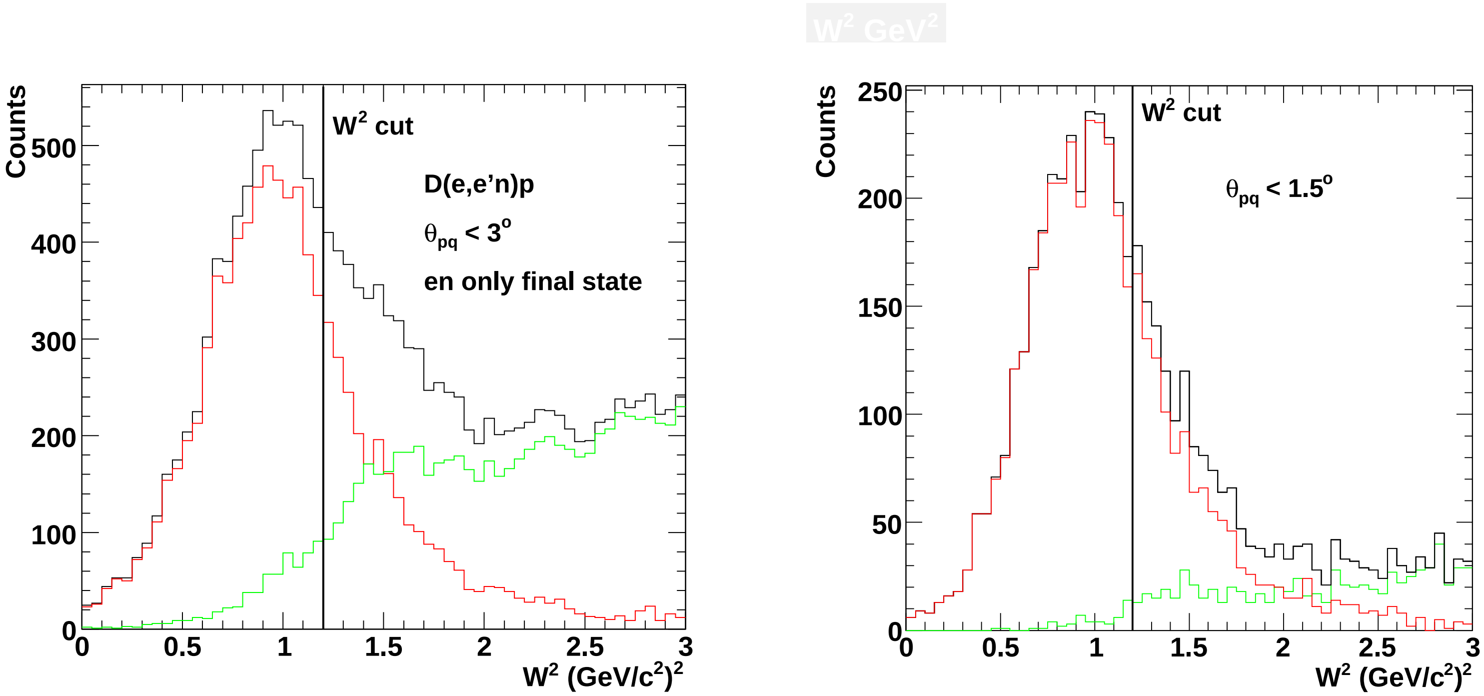
Angular distribution of θ_{pq} neutrons (left-hand panel) for the quasielastic (red), inelastic (green), and total (black) contributions (left-hand panel) and protons (right-hand panel).

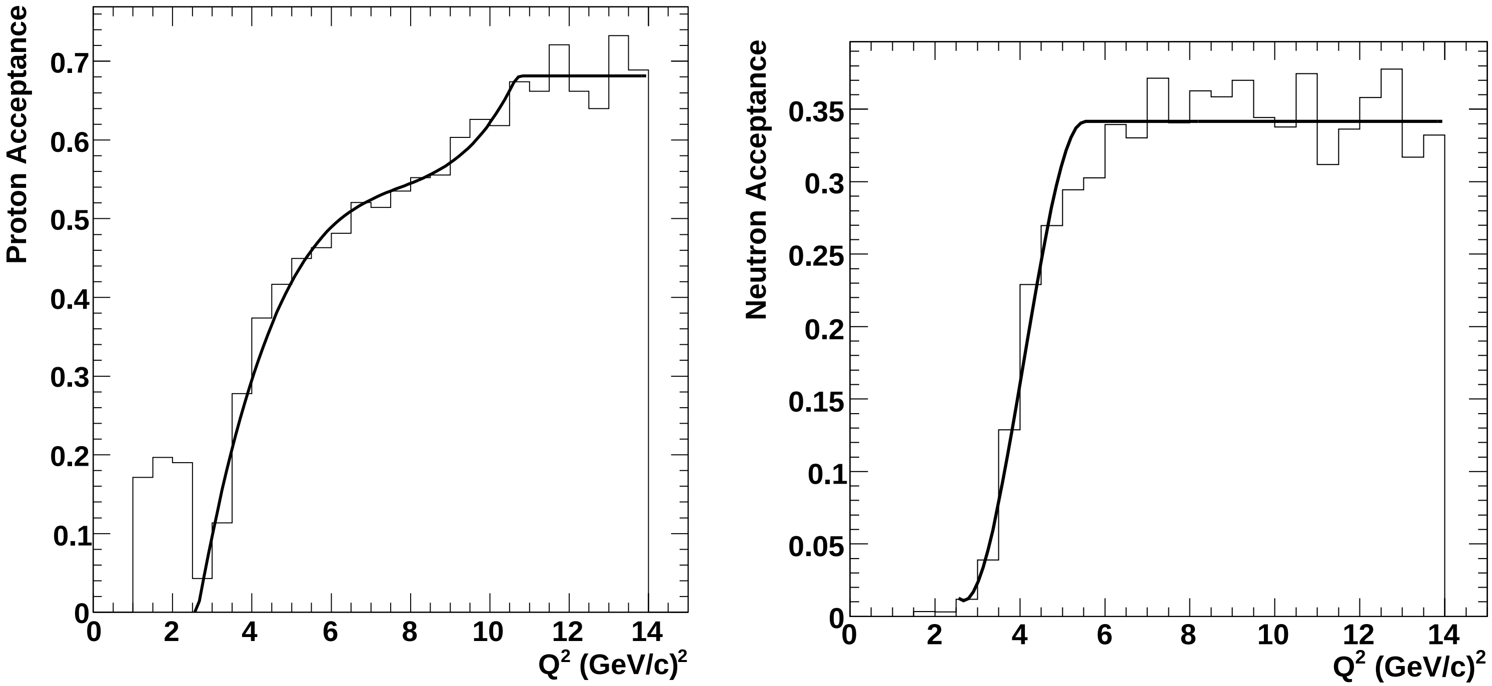
Suppressing the Inelastic Background

- Reduce the maximum value of θ_{pq}. Plots below show effect of reducing the maximum angle from 3.0° (left-hand panel) to 1.5° (right-hand panel) for $\mathrm{Q}^2 = 6 - 7(\mathrm{GeV/c})^2$.



- Calculate the background using the dependence of the spectra on the maximum θ_{pq}, multiple-particle veto, and other kinematic quantities to tune the simulation.

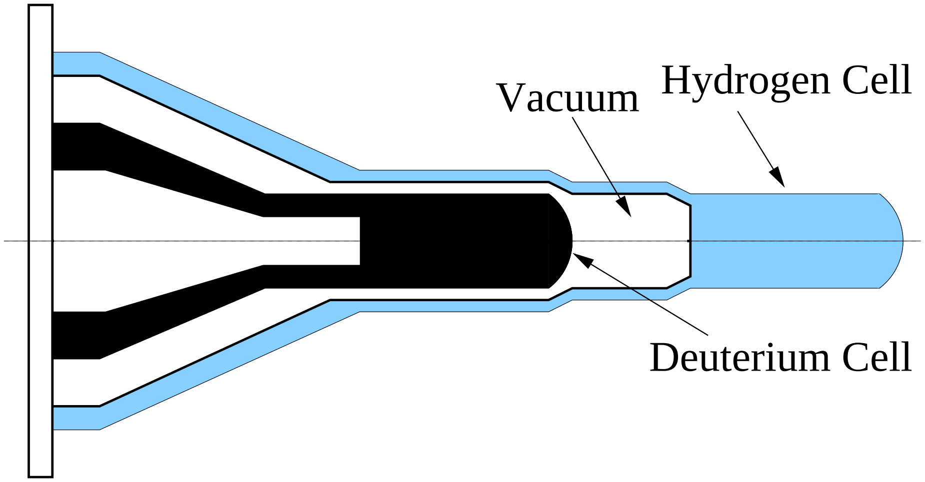
Selecting Quasielastic Events - Acceptances



Acceptance for the $D(e,e'p)n$ (left-hand panel) and $D(e,e'n)p$ (right-hand panel) in CLAS12 (forward EC only) for 11 GeV. Calculated with FASTMC (parameterized Monte Carlo simulation of CLAS12).

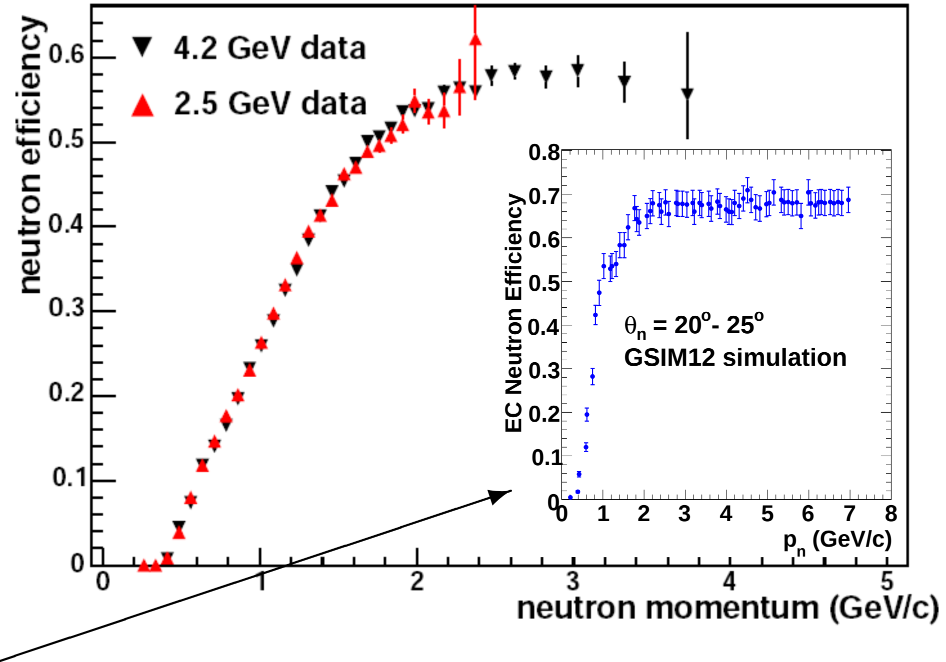
Ratio Method Calibrations - Proton Detection Efficiency

1. Use $ep \longrightarrow e'p$ elastic scattering from hydrogen target as a source of tagged protons.
2. Select elastic $e - p$ events with a W^2 cut.
3. Identify protons as positive tracks with a coplanarity cut applied.
4. Use the missing momentum from $ep \longrightarrow e'X$ to predict the location of the proton and search the TOF paddle or an adjacent one for a positively-charged particle.
5. Calibration data taken simultaneously with production data using the dual-cell target shown here.



Ratio Method Calibrations - Neutron Detection Efficiency

1. Use the $ep \rightarrow e'\pi^+n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.
2. For electrons, use CLAS12 tracking. For π^+, use positive tracks, cut on the difference between β measured from tracking and from time-of-flight to reduce photon background.
3. For neutrons, $ep \rightarrow e\pi^+X$ for $0.9 < m_X < 0.95\ \mathrm{GeV/c^2}$.
4. Use the predicted neutron momentum $\vec{p}_n$ to determine the location of a hit in the fiducial region and search for that neutron.
5. The CLAS G_M^n results.
6. GSIM12 simulation results for CLAS12 are shown in the inset. Proposed measurement will extend to higher momentum where the efficiency is stable.


Calorimeter efficiency

The Ratio Method - Systematic Errors

- G_M^n is related to the $e-n/e-p$ ratio R by

$$G_M^n = \pm\sqrt{\left[R\left(\frac{\sigma^p_{mott}}{\sigma^n_{mott}}\right)\left(\frac{1+\tau_n}{1+\tau_p}\right)\left({G_E^p}^2+\frac{\tau_p}{\varepsilon_p}{G_M^p}^2\right)-{G_E^n}^2\right]\frac{\varepsilon_n}{\tau_n}}$$

where the subscripts refer to neutron (n) and proton (p).

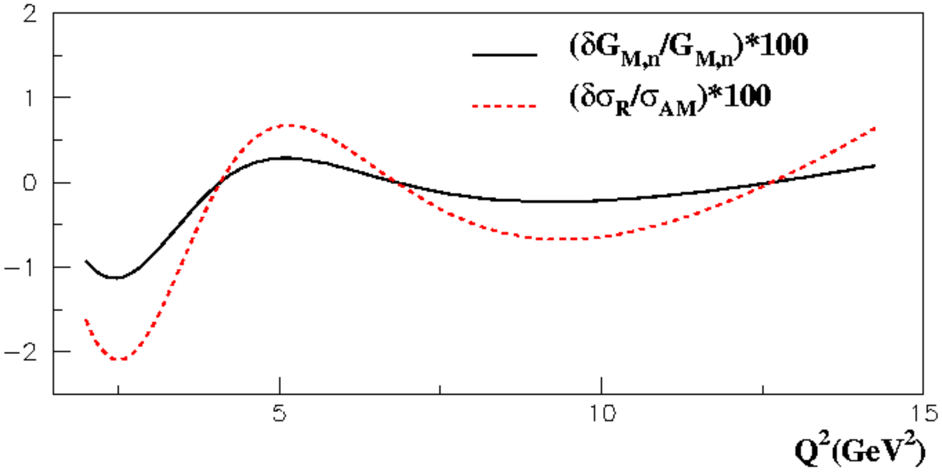
- Upper limits on systematic error from the CLAS measurement ($\Delta G_M^n/G_M^n = 2.7\%$).

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		

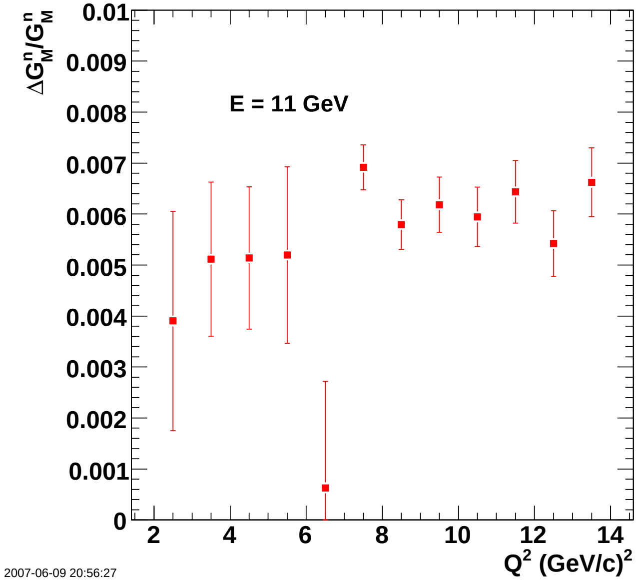
- Investigate the largest contributors (the top two rows in the table) and assume the other maximum values stay the same. **Goal: 3% systematic uncertainty**

Systematic Uncertainty Studies

- 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.



- Neutron Detection Efficiency - Simulate the uncertainty associated with fitting the shape of the measured neutron detection curves.



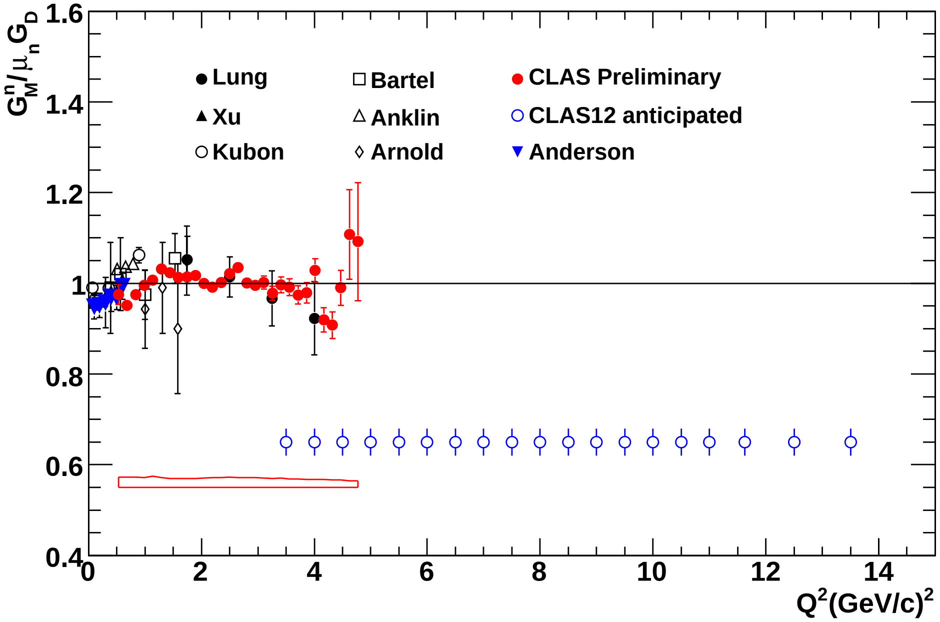
Systematic Uncertainties - Summary

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 ($\Delta G_M^n/G_M^n = 2.4\%$(2.7)). Red numbers represent the previous upper limits from the CLAS measurement.

Anticipated Results and Beam Request

- Expected Q^2 range and systematic uncertainty of 3% and world data for G_M^n.
- Will almost triple the current Q^2 range.
- Need to obtain statistical precision as good as the anticipated systematic uncertainty.



- We request 56 PAC days of beam time at 11 GeV at a luminosity per nucleon of $0.5 \times 10^{35}\ cm^{-2}s^{-1}$.

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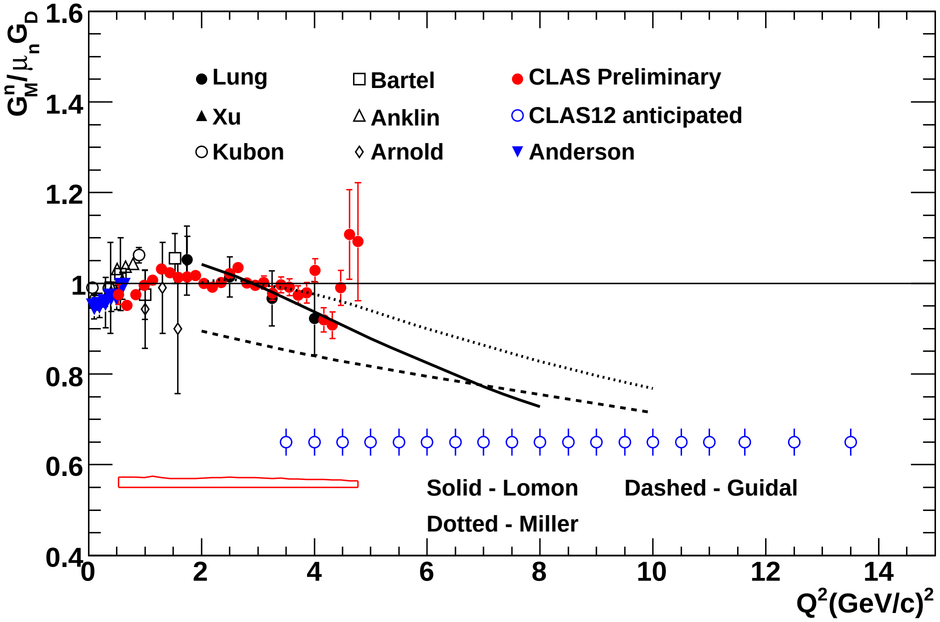


- We request 56 PAC days of beam time at 11 GeV at a luminosity per nucleon of $0.5 \times 10^{35}\ cm^{-2}s^{-1}$.

Lomon, Phys.Rev.C **66** 045501 (2002)

G. MIller, Phys. Rev. C **66**, 032201(R) (2002)

M.Guidal, M.K. Polyakov, A.Radyushkin, and M. Vanderhaeghen, Phys. Rev. D **72**, 054013 (2005).

Conclusions

- The neutron magnetic form factor is a fundamental quantity and extending the Q^2 range and coverage will probe deeper into hadronic structure, provide essential constraints on GPDs, and challenge lattice QCD.
- The CLAS12 detector will provide wide kinematic acceptance ($\mathrm{Q}^2 = 3 - 14(\mathrm{GeV/c})^2$) and independent measurements of neutrons with its calorimeters and TOF systems.
- We propose to use the ratio method on deuterium to reduce our sensitivity to a variety of sources of systematic uncertainty and limit systematic uncertainties to less than 3%.
- To keep systematic uncertainties small we will measure the detection efficiencies with a unique dual-cell target. Production and calibration data will be taken simultaneously.
- We request 56 PAC days of beam time at 11 GeV and a luminosity per nucleon of $0.5 \times 10^{35}\ cm^{-2}s^{-1}$ to obtain statistical precision in the highest Q^2 bin as good as the anticipated systematic uncertainty.

Run Statistics

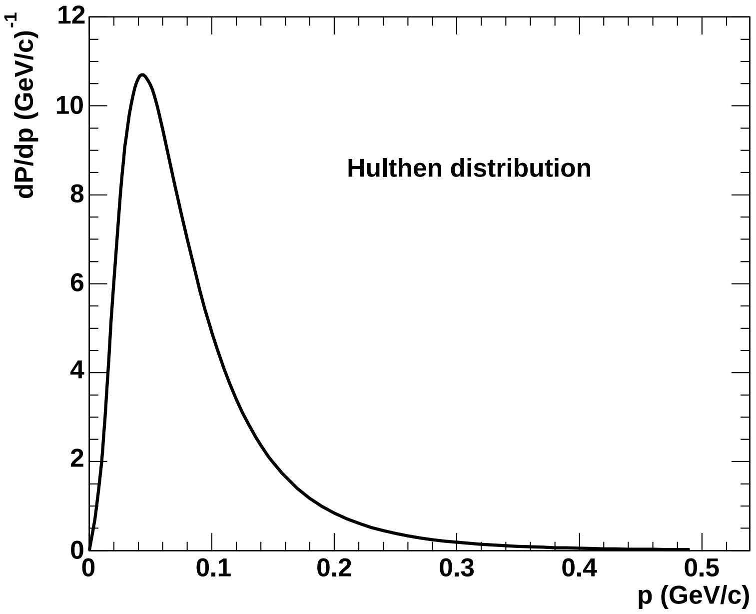
Q^2 $(GeV/c)^2$	Proton Rate (s^{-1})	Neutron Rate (s^{-1})	Proton Counts	Proton Error	Neutron Counts	Neutron Error	$\frac{\delta G^n_M}{G^n_M}$
2.5	0.016	0.081	3.0×10^4	0.0057	1.6×10^5	0.0025	0.0031
3.5	0.74	0.12	1.4×10^6	0.00083	2.3×10^5	0.0021	0.0011
4.5	0.34	0.098	6.6×10^5	0.0012	1.9×10^5	0.0023	0.0013
5.5	0.14	0.046	2.7×10^5	0.0019	8.9×10^4	0.0033	0.0019
6.5	0.061	0.018	1.2×10^5	0.0029	3.5×10^4	0.0053	0.0030
7.5	0.028	0.0081	5.5×10^4	0.0043	1.6×10^4	0.0080	0.0045
8.5	0.014	0.0040	2.8×10^4	0.00607	7.7×10^3	0.011	0.0064
9.5	0.0082	0.0021	1.6×10^4	0.0079	4.0×10^3	0.016	0.0088
10.5	0.0050	0.0012	9.7×10^3	0.010	2.2×10^3	0.021	0.012
11.5	0.0029	0.00068	5.7×10^3	0.013	1.3×10^3	0.028	0.015
12.5	0.0018	0.00041	3.4×10^3	0.017	8.0×10^2	0.035	0.020
13.5	0.0011	0.00026	2.2×10^3	0.021	5.0×10^2	0.044	0.025

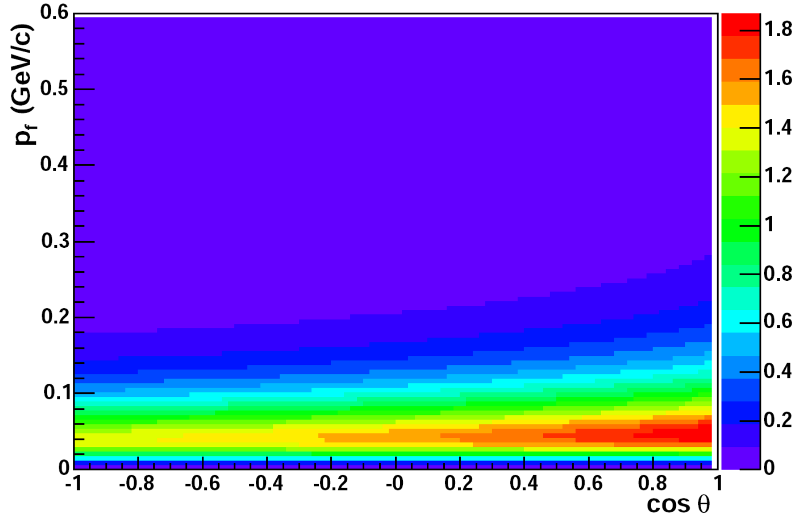
Rates and statistical uncertainties for quasielastic scattering. All bins are $\pm 0.5\ (GeV/c)^2$.

Based on 56 PAC days of beam time and a luminosity per nucleon of $0.5 \times 10^{35}\ cm^{-2}s^{-1}$.

Procedure for Quasielastic Simulation

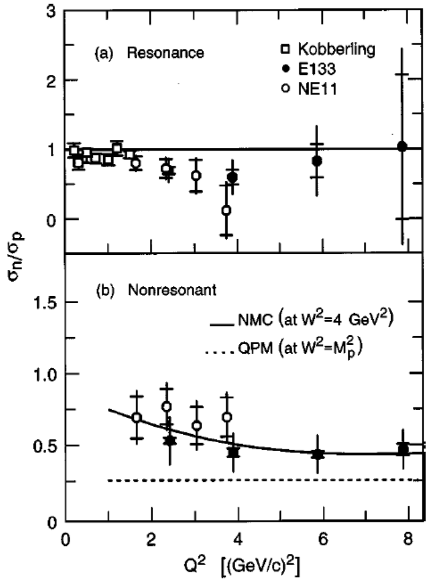
- Pick a Q^2 weighted by the elastic cross section.
- Pick p_f and $\cos\theta$ of the target nucleon weighting it by the combination of the Hulthen distribution and the effective-beam-energy effect.
- Boost to the rest frame of the nucleon and rotate coordinates so the beam direction is along the z 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.

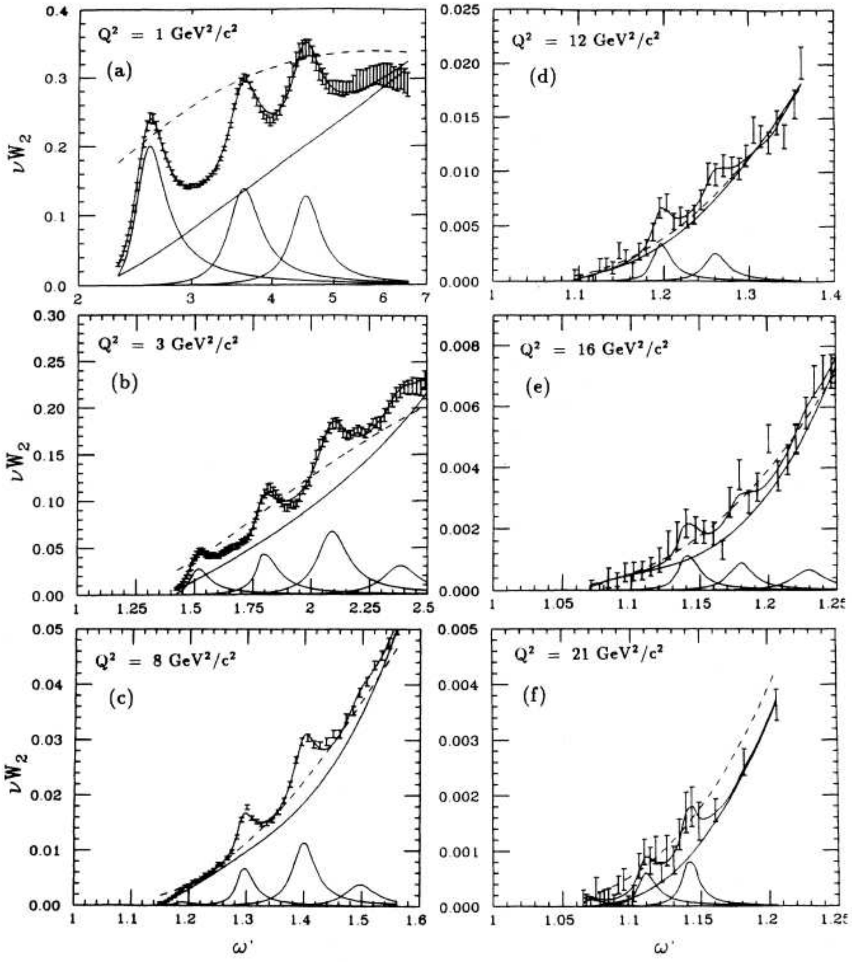




Procedure for Inelastic Simulation - 1

- 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.

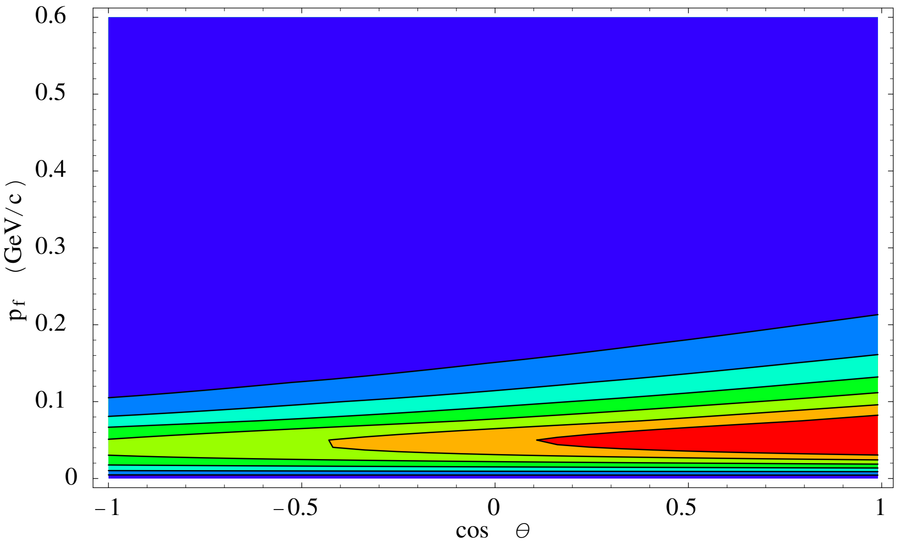




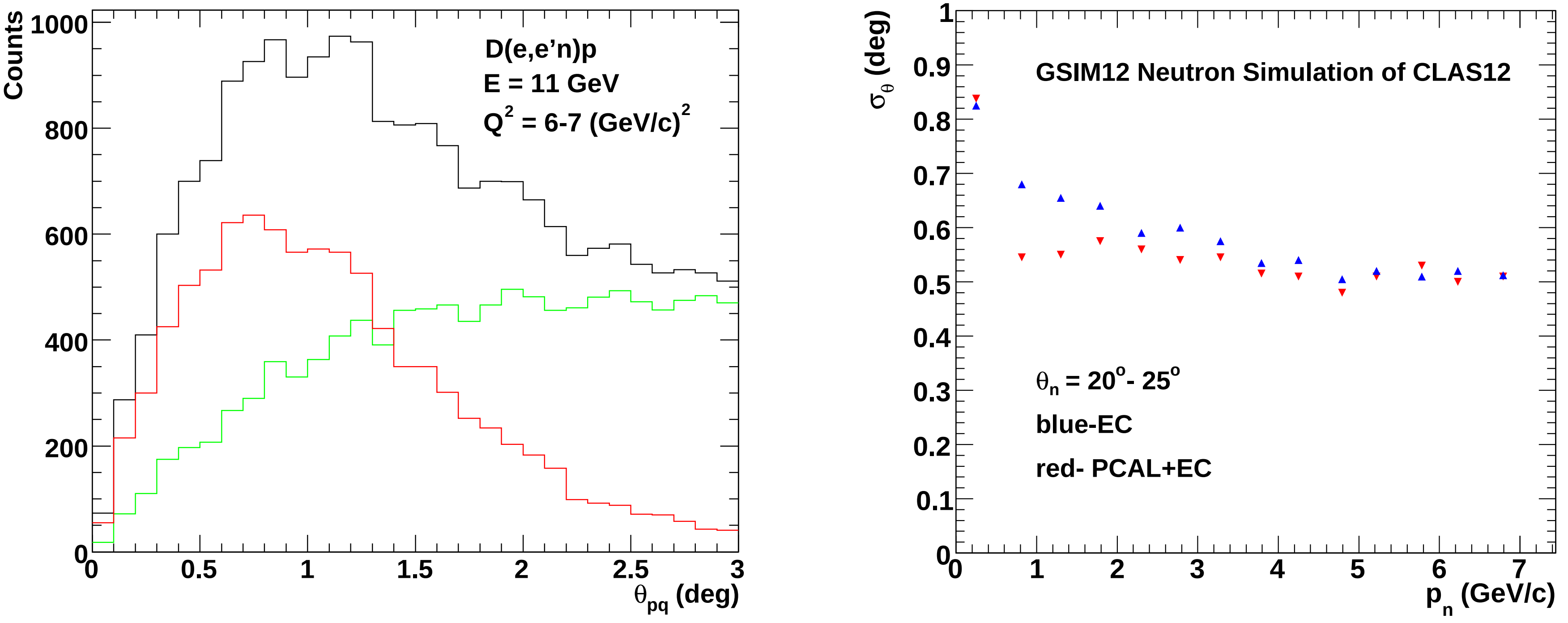
Inelastic cross sections as a function of $\omega' = 1 + W^2/Q^2$.

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.



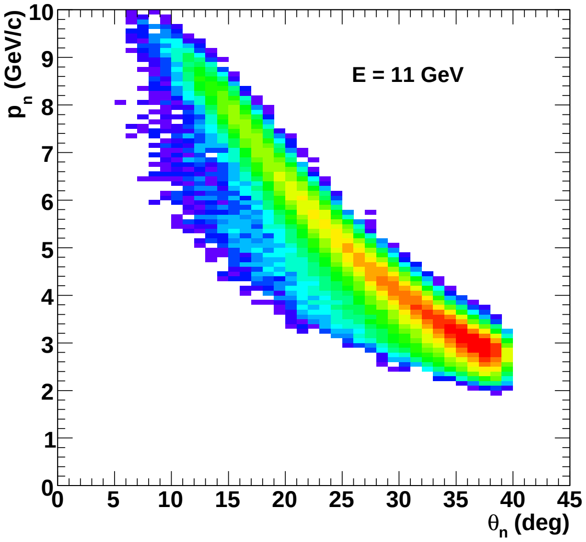
Selecting Quasielastic Neutrons - Angular Distributions



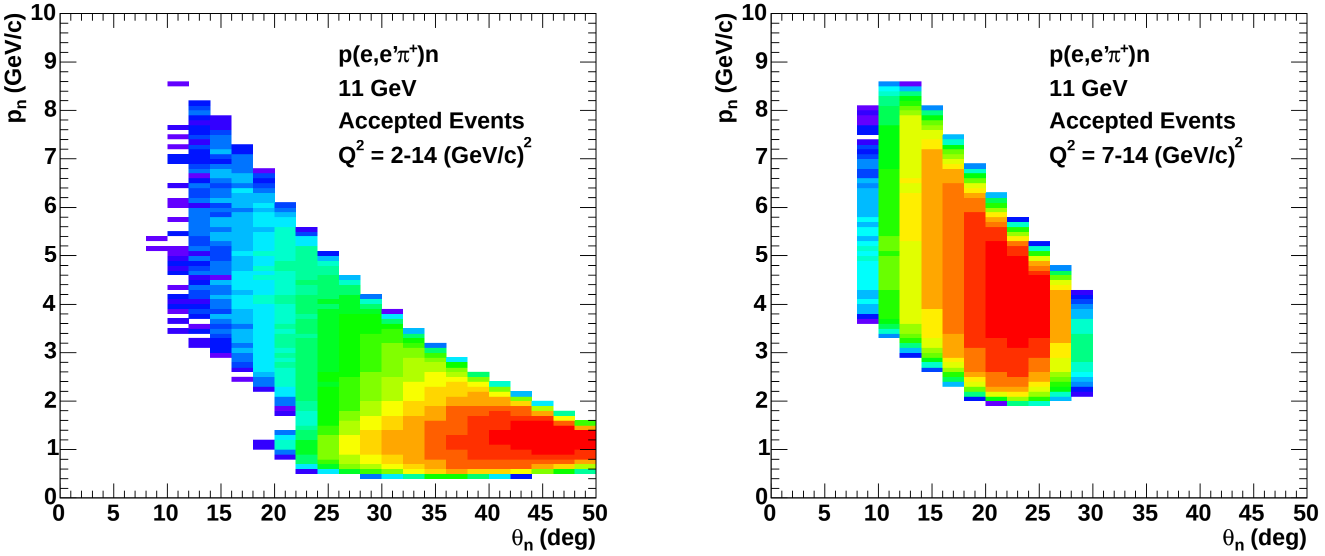
Angular distribution of θ_{pq} for the quasielastic (red), inelastic (green), and total (black) contributions (left-hand panel) and a GSIM12 simulation of the angular resolution of CLAS12 for neutrons in the forward tracking system (right-hand panel).

Ratio Method Calibrations - Neutron Detection Efficiency - 2

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



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

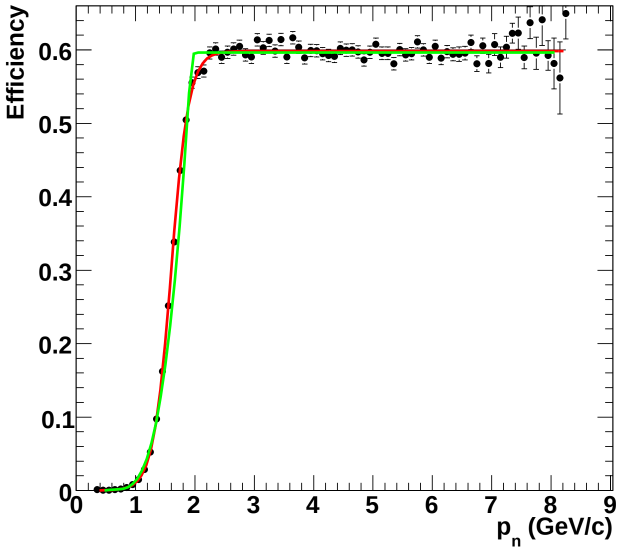


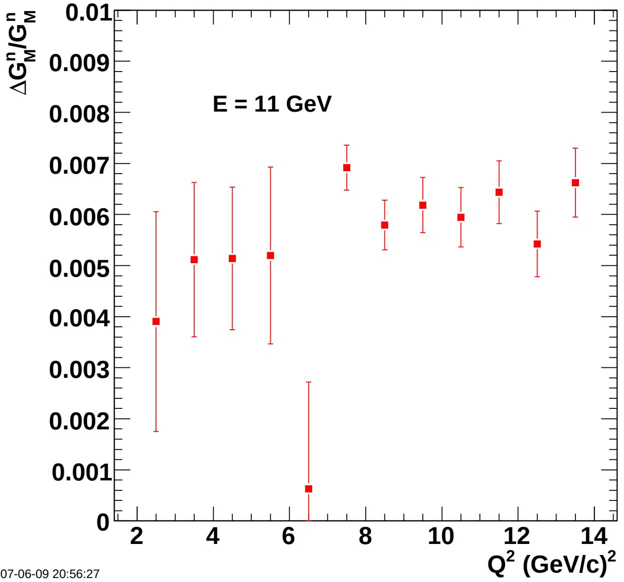
Systematic Uncertainties - Neutron Detection Efficiency

- 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.





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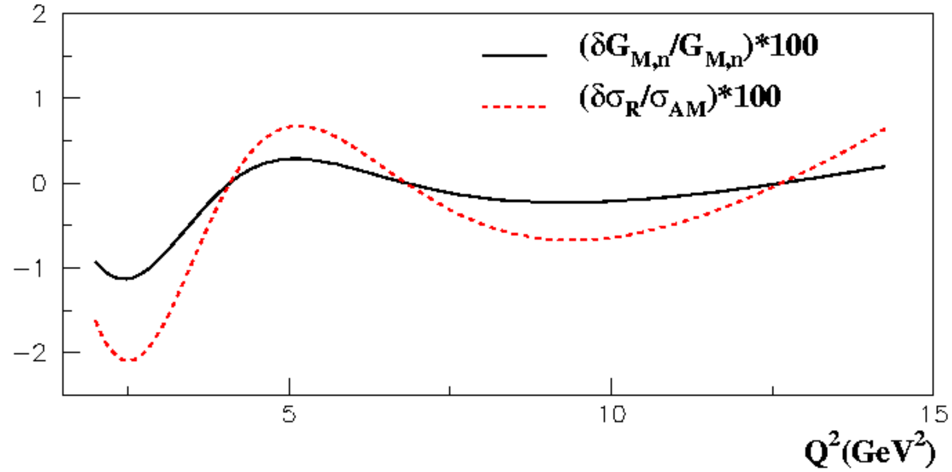
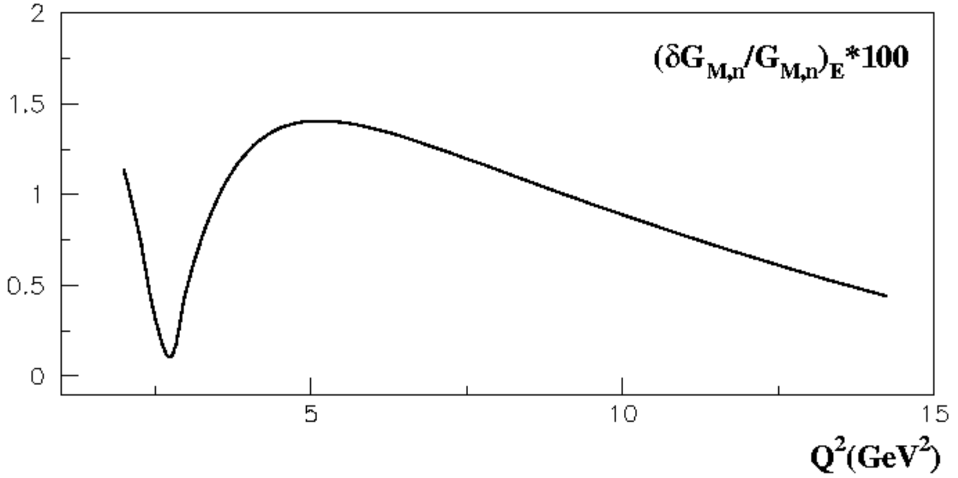
Systematic Uncertainties - Other Elastic Form Factors

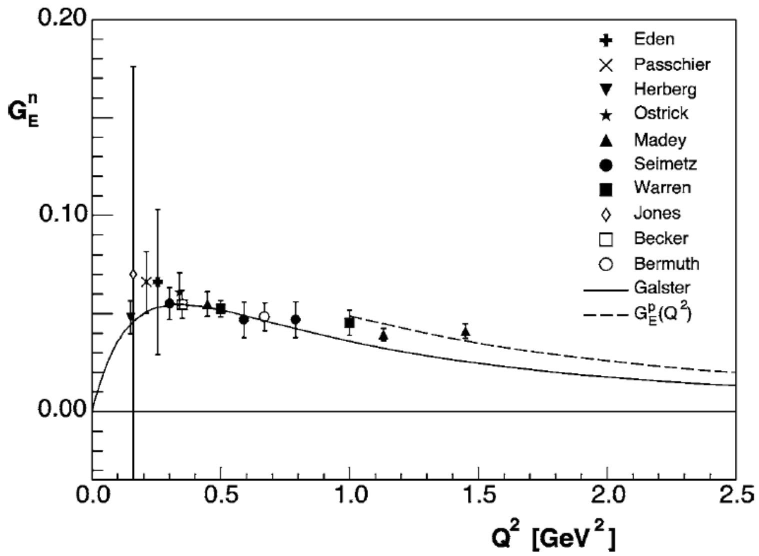
- Systematic uncertainty ($\Delta G_M^n / G_M^n \times 100$) based on differences in the proton reduced cross section parameterizations of Bosted and Arrington-Melnitchouk.

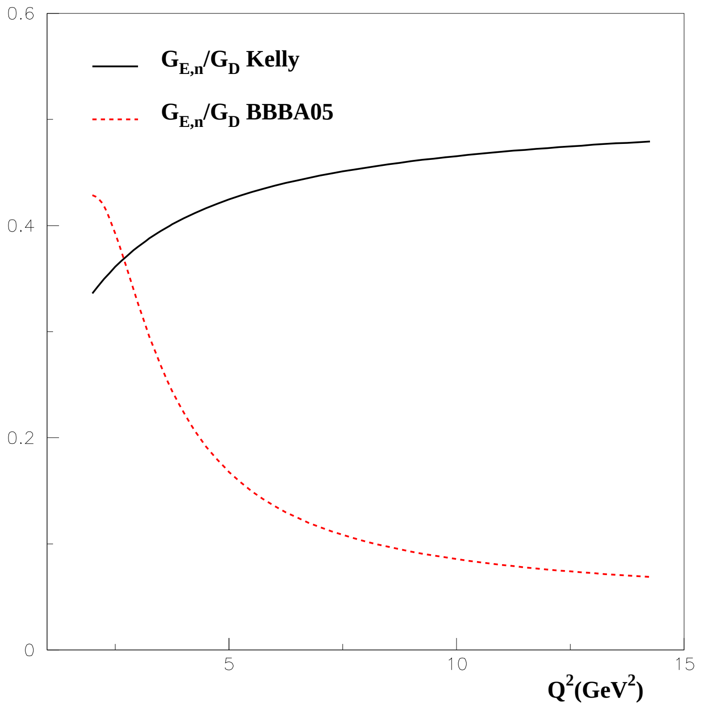


- Systematic uncertainty ($\Delta G_M^n / G_M^n \times 100$) based on differences in G_E^n parameterizations of Kelly and BBBA05.



Neutron Electric Form Factor G_E^n





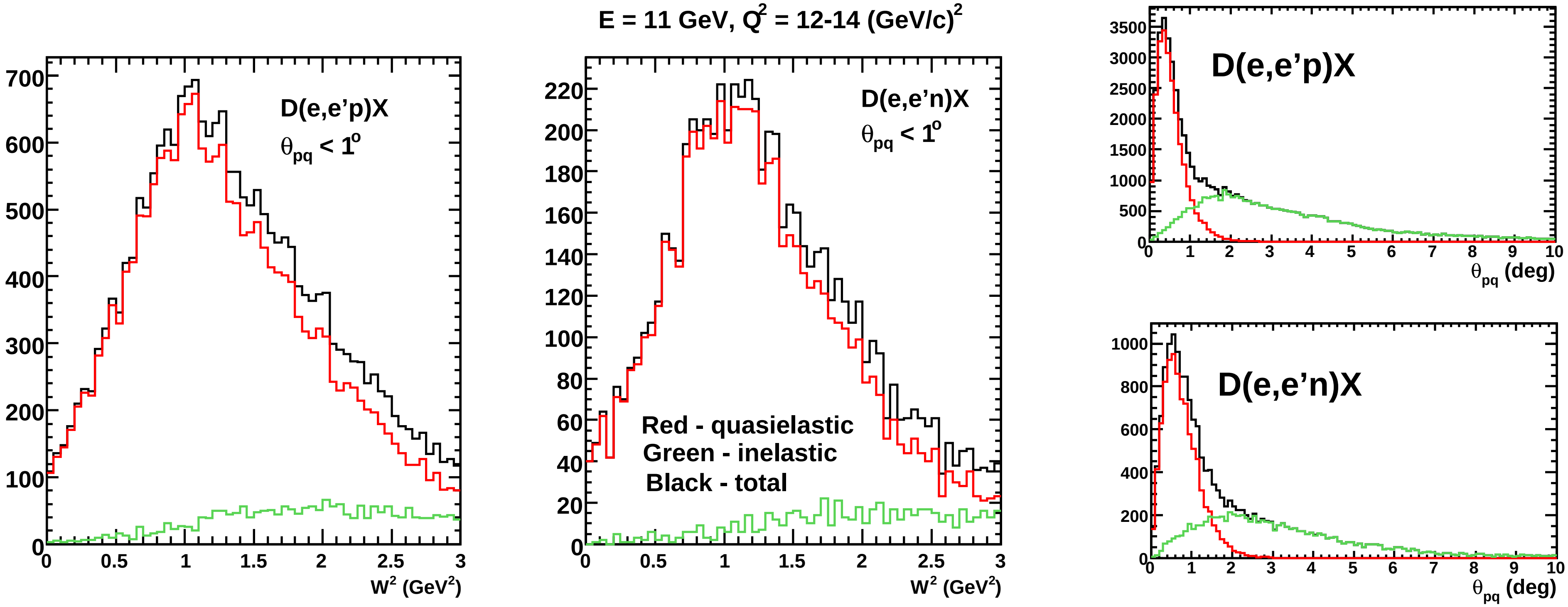
World data on G_E^n. (C.E. Hyde-Wright and K.deJager, Ann. Rev. Nucl. Part. Sci. **54** (2004) 54 and references therein.)

The neutron electric form factor from Kelly and BBBA05 parameterizations as a function of Q^2 (J. J. Kelly, Phys. Rev, C 70, 068202 (2004) and R. Bradford, A. Bodek, H. Budd and J. Arrington, hep-ph/0602017.)

Suppressing the Inelastic Background

- Additional analysis to improve the neutron angular resolution: different EC fitting algorithm, use pCAL which has greater segmentation.
- Calculate the inelastic background.
  - ‘Calibrate’ the calculation with other information from CLAS12.
  - $D(e, e')X$ (L.M.Stuart, *et al.*, Phys. Rev. D **58**, 032003 (1998)).
  - Use $D(e, e'p)X$ and $D(e, e'n)X$ and study dependence of maximum θ_{pq}, multiplicity veto (recall previous plot), and ϕ_{pq} dependence.
  - Use missing mass to study $D(e, e'p)n$.
- Calculate the quasielastic lineshape.
  - ‘Calibrate’ the reaction with other information using other reactions as mentioned above.
  - Inelastic background is small for $W^2 \leq 0.9\ GeV^2$.
  - Calculate lineshape with Sim12 and fit the low W^2 portion of the W^2 spectrum.

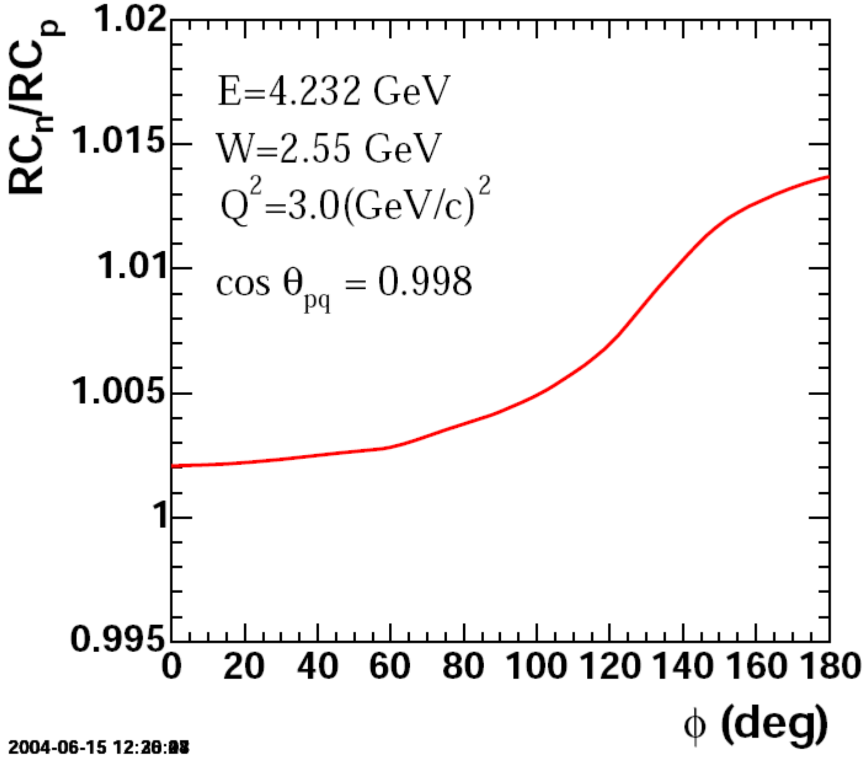
W^2 Spectra at the Acceptance Edge



W^2 spectra at the edge of the acceptance $\mathrm{Q}^2 = 12 - 14(\mathrm{GeV}/\mathrm{c})^2$ for protons (left-hand panel) and neutrons (right-hand panel). Both reactions include the multi-particle veto.

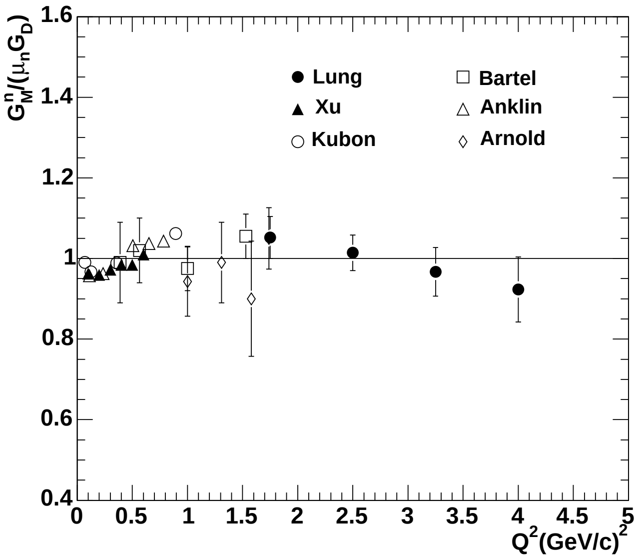
The Ratio Method - Corrections

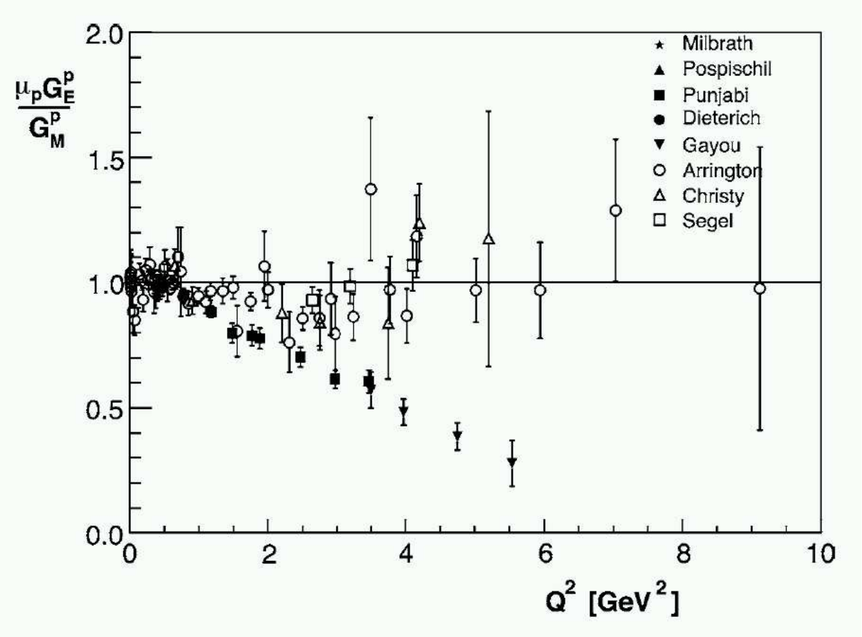
- Nuclear effects: The $e-n/e-p$ ratio for free nucleons can be altered here because we measure the quasielastic scattering from bound nucleons. This factor $a(Q^2)$ was calculated and we compared results from Jeschonnek and Arenhoevel. Where the calculations overlap in Q^2, the average correction to 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.

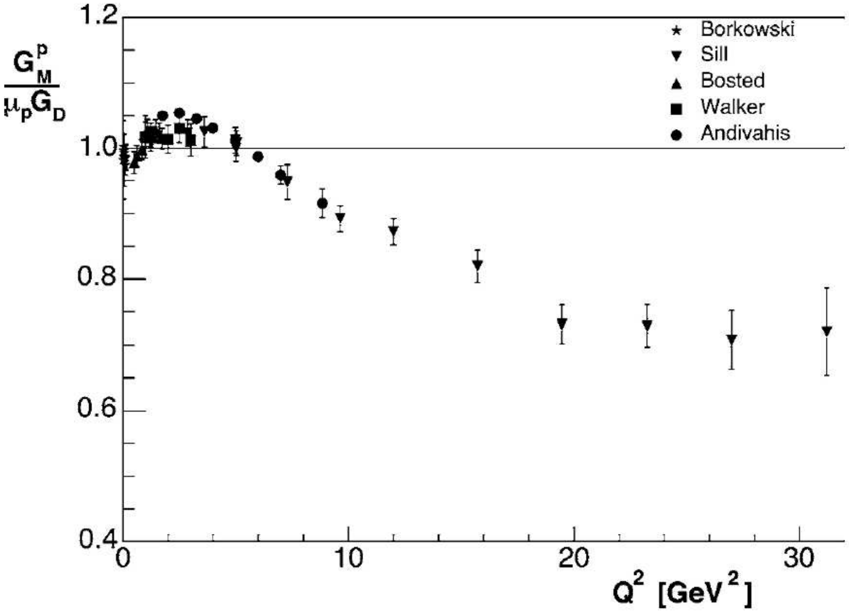


Published Measurements of Elastic Form Factors

- 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.

G_M^n and GPDs

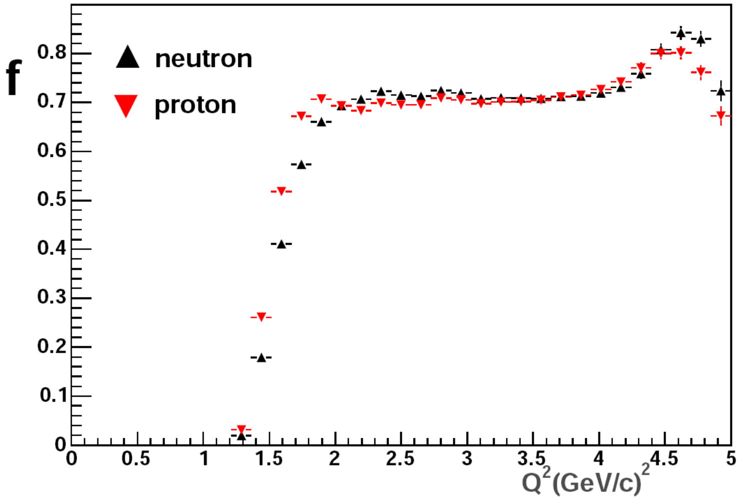
Elastic form factors (G_M^n, G_E^n, G_M^p, and G_E^p) provide key constraints to 'stabilize the parameterizations' of generalized parton distributions (GPDs) which hold the promise of a three-dimensional picture of the nucleon.

$$G_M^n(t) = \int_{-1}^{+1} dx \sum_q (e_q H^q(x,\zeta;t) + \kappa e_q E^q(x,\zeta;t))$$

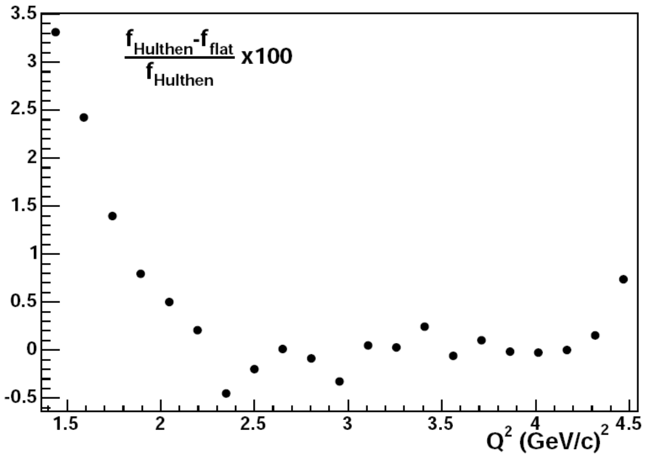
> 'High-quality data on the neutron form factors in a wide t range would be highly valuable for pinning down the differences in the spatial distribution of u and d quarks ... drastic differences in the behavior of u and d contributions to the form factors'
>
> (M.Diehl, Th. Feldmann, R. Jakob, and P.Kroll, hep-ph/0408173v2).

Effect of Fermi Motion

- The Fermi motion in the target can drive some of the nucleons out of the CLAS acceptance. This effect turns out to be small in the ratio and decreases as Q^2 increases.



Fraction of nucleons scattered into the EC acceptance at 4.2 GeV



Fractional difference in the ratio correction factor between the Hulthen distribution and a flat distribution.