Measuring the Neutron Magnetic Form Factor in CLAS12

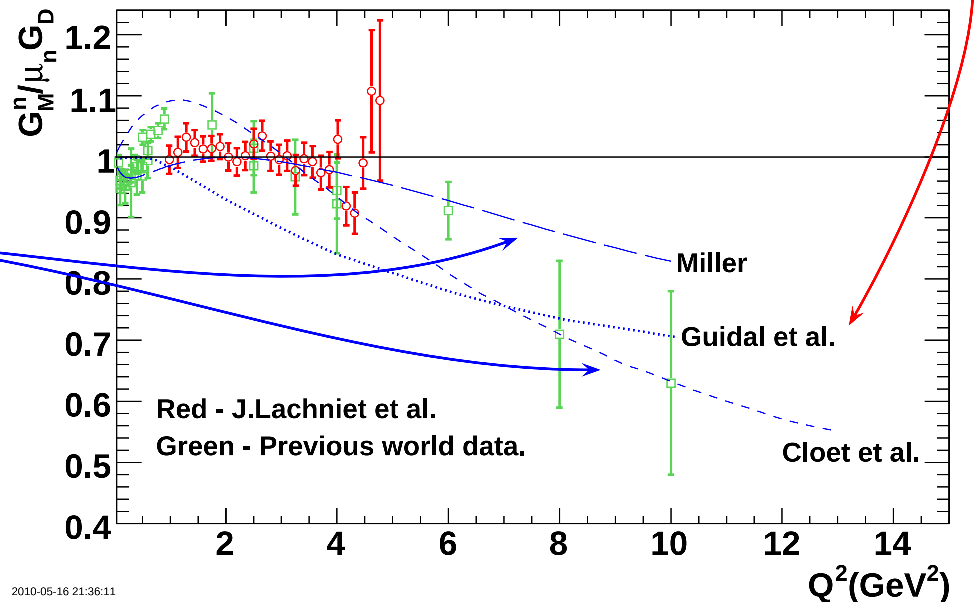
G.P. Gilfoyle, W.K.Brooks, and K.Hafidi (for the CLAS Collaboration)

Outline

1. Scientific Motivation
2. Necessary Background
3. Current Status
4. The Ratio Method (E12-07-104).
5. Conclusions

Scientific Motivation

- The neutron magnetic form factor (G_M^n) is a fundamental quantity.
- Describes the neutron magnetization at low Q^2 and the quark structure at higher Q^2 (DOE Milestone HP4).
- Constraint on generalized parton distributions (GPDs), Guidal *et al.*
- Testing ground for calculations built on QCD: Miller (light-cone), Cloët *et al* (Dyson-Schwinger).
- Early challenge for lattice QCD at high Q^2 (DOE Milestone HP9).
- Wide Q^2 range needed to separate u and d spatial distributions.



Part of NSAC Long Range Plan

Some Necessary Background

- Express the elastic cross section in terms of the elastic electromagnetic form factors (EEFFs): Dirac (F_1) and Pauli (F_2)

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\left[\left(F_1^2 + \kappa^2\tau F_2^2\right) + 2\tau\left(F_1 + \kappa F_2\right)^2 \tan^2\left(\frac{\theta}{2}\right)\right]$$

where κ is the anomalous magnetic moment, E (E') is the incoming (outgoing) electron energy, θ is the scattered electron angle, $\tau = \frac{Q^2}{4M^2}$, and $\sigma_{Mott} = \frac{\alpha^2 E' \cos^2(\frac{\theta}{2})}{4E^3 \sin^4(\frac{\theta}{2})}$.

- For convenience use the Sachs form factors.

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

where $G_E = F_1 - \tau F_2$, $G_M = F_1 + F_2$.

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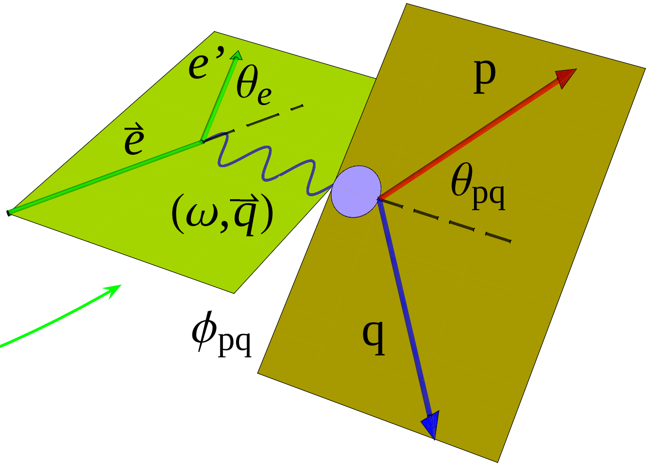
where $G_E = F_1 - \tau F_2$, $G_M = F_1 + F_2$.

- An important kinematic quantity θ_{pq} for quasielastic (QE) scattering from deuterium.



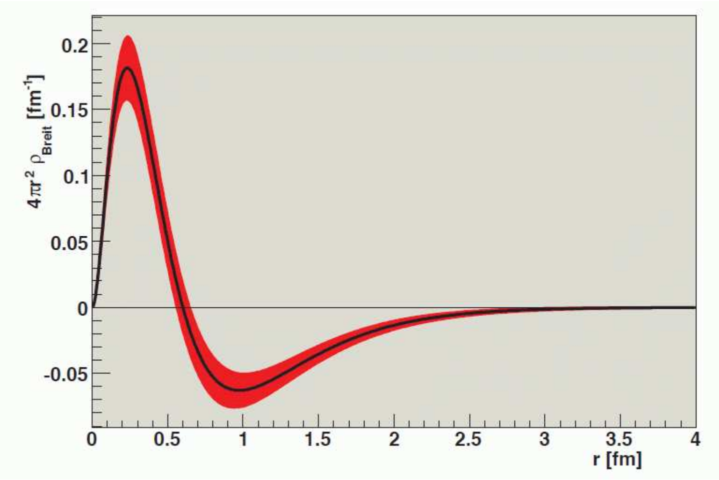
More Background - Interpreting the EEFFs

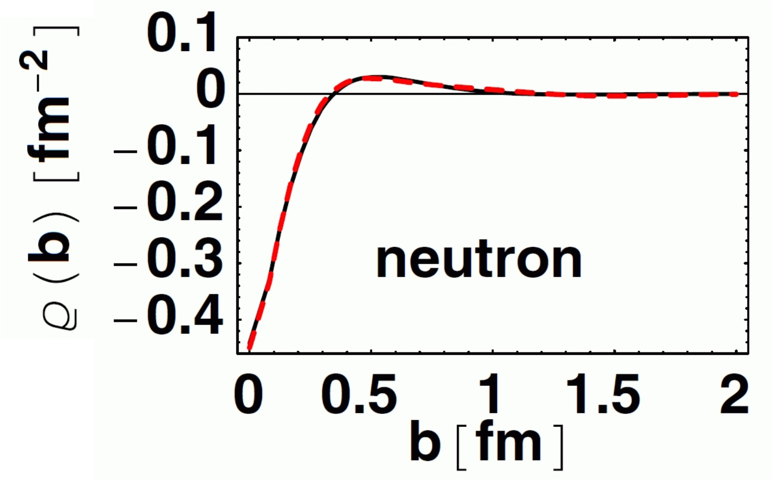
- At low momentum transfer ($Q^2 \ll M_N^2$) G_E and G_M are the Fourier transforms of the densities of charge and magnetization.

$$G_E(Q^2) = \int \rho(r) e^{-i\vec{q}\cdot\vec{r}} d^3r$$

where $\vec{q}$ is the 3-momentum transferred by the electron.

- At high Q^2 relativistic effects make the interpretation more interesting!

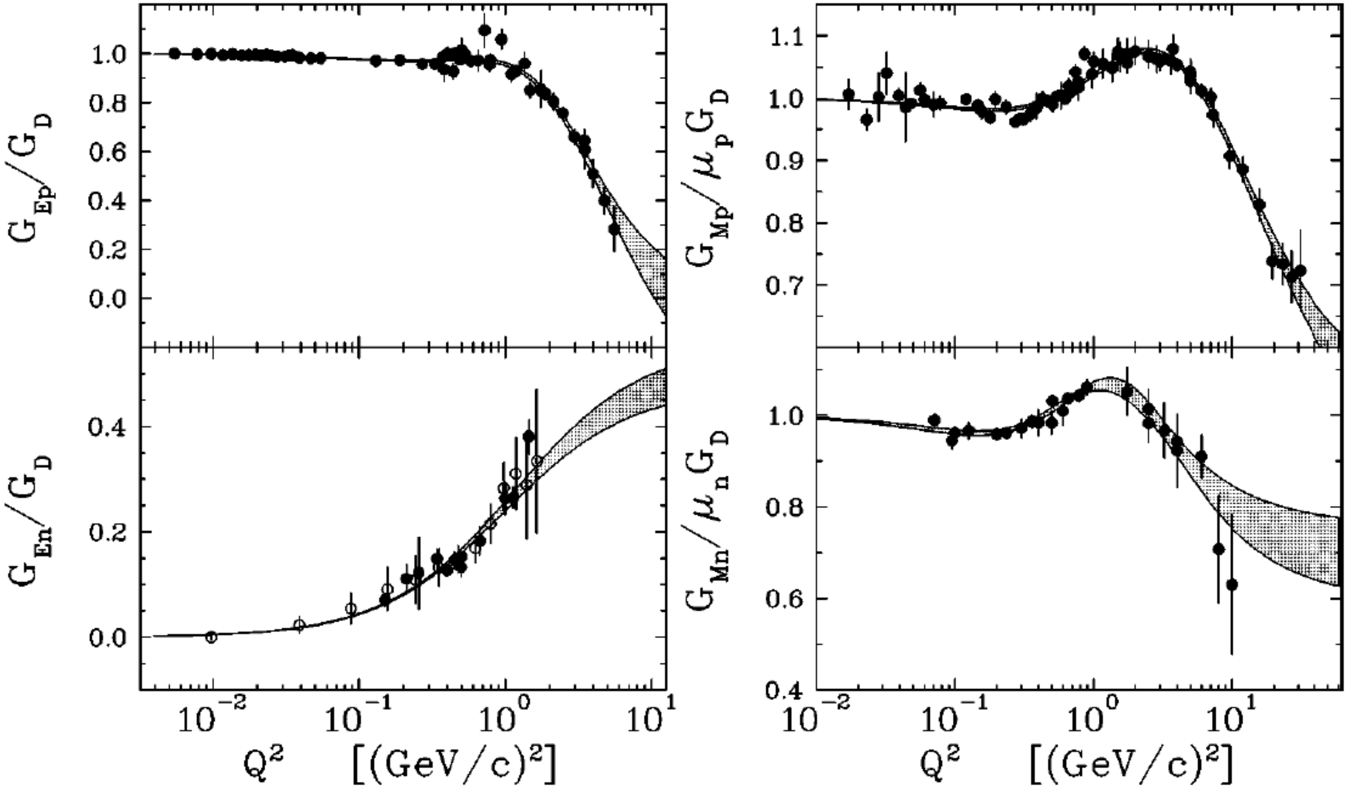




NSAC Long Range Plan

G.A.Miller, Phys.Rev.Lett.99:112001,2007

Current World Data on EEFFs



J.J.Kelly, Phys. Rev.C, 068202, 2004.

- Proton form factors have small uncertainties and reach higher Q^2.
- Neutron form factors are sparse and have large uncertainties.
- Significant deviations from the dipole form factor.

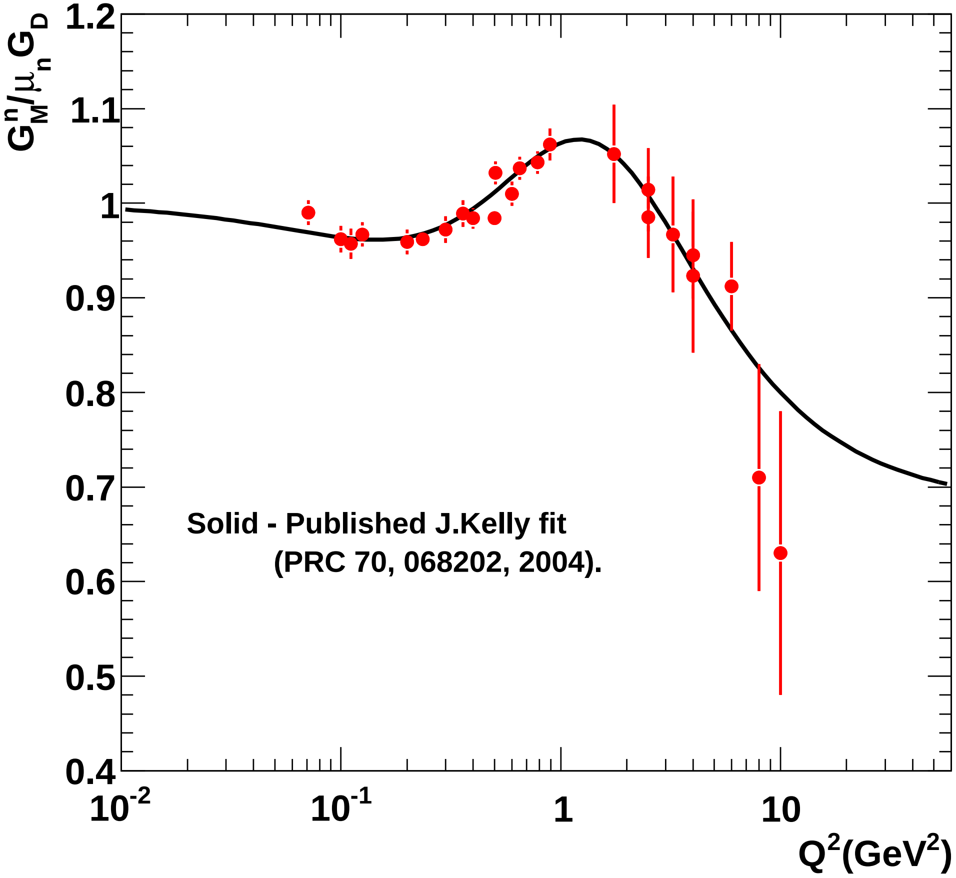
World’s Data for G_M^n

- Parameterization of world’s data on G_M^n done by J.Kelly (PRC, 70, 068202, 2004) using the following function.

$$\frac{G_M^n}{\mu_n G_D} = \frac{\sum_{k=0}^{n} a_k \tau^k}{1 + \sum_{k=1}^{n+2} b_k \tau^k}$$

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

- CLAS6 data in blue (Lachniet *et al.* PRL 102, 192001 (2009)).
- CLAS6 measurement used same ratio method.



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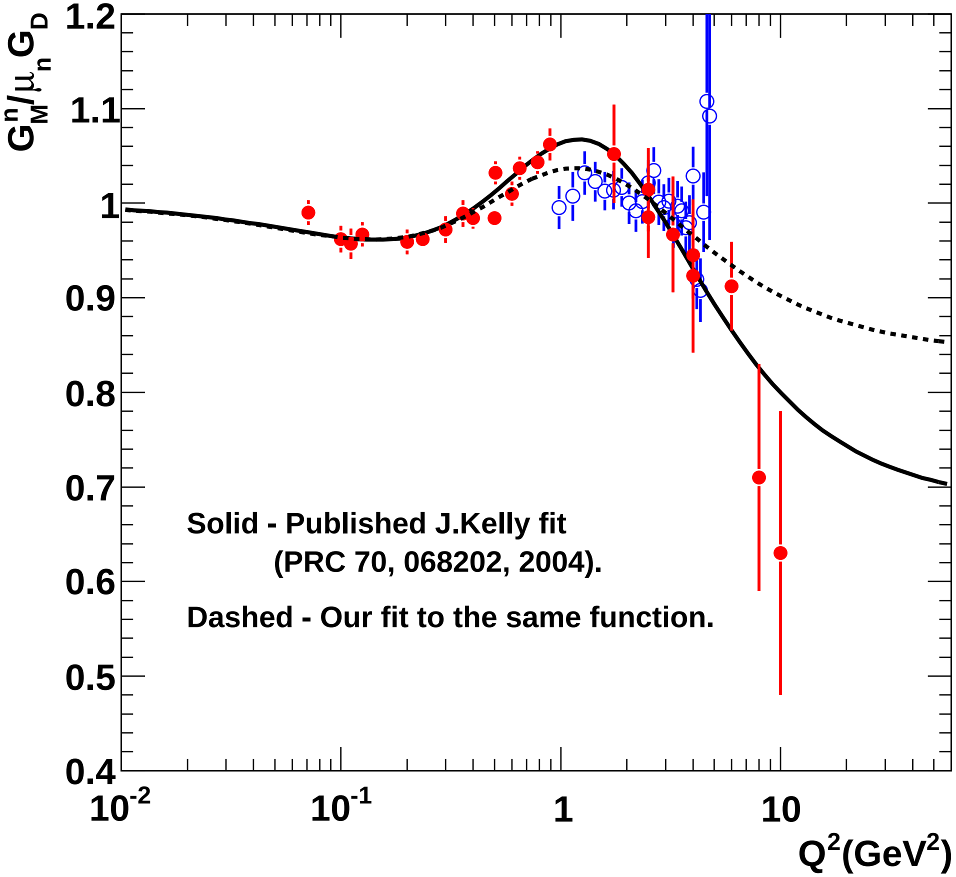


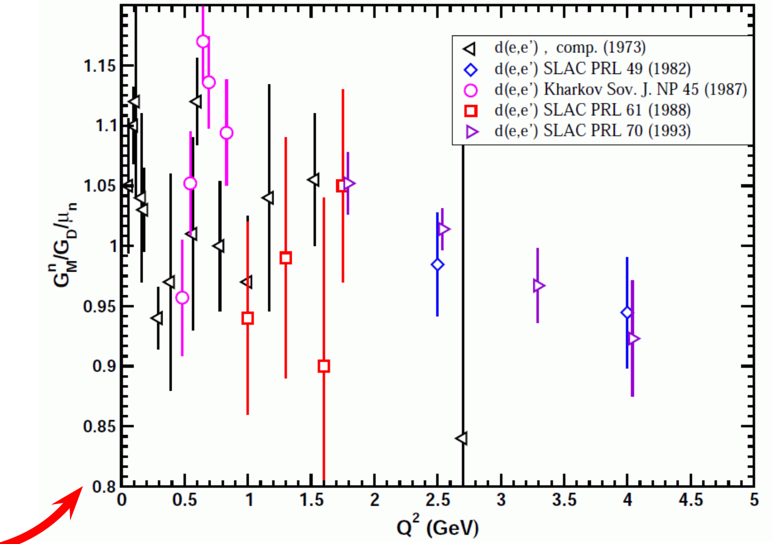
Solid - Published J.Kelly fit
(PRC 70, 068202, 2004).

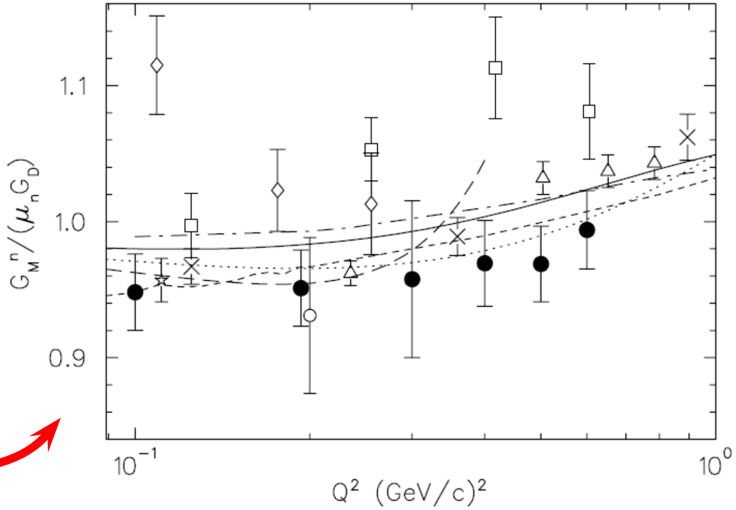
Dashed - Our fit to the same function.

Measuring G_M^n

- Early methods:
  - Neutrons on atomic electrons (V.E. Krohn and G.R. Ringo, Phys. Rev. 148 (1966) 1303).
  - Quasielastic $D(e,e')D$ and $D(e,e'n)p$: Use models to extract G_M^n; uncertainties $\approx 5\% - 20\%$.
- Modern methods:
  - Ratio of $e-n/e-p$ scattering from deuterium; more below.
  - Quasielastic $^3\vec{\mathrm{He}}(\vec{e},e')^3\mathrm{He}$: Constrain calculations of nuclear effects with other measurements ($A_{T'}$) for $Q^2 < 1\ \mathrm{GeV}^2$.

M. Jones, 2005 Hall C Workshop.





Anderson et al., PRC, 75, 034003, 2007.

Measuring G_M^n - The Ratio Method

- Without a free neutron target we use deuterium and measure R

$$R = \frac{\frac{d\sigma}{d\Omega}[{}^2\mathrm{H}(e,e'n)_{QE}]}{\frac{d\sigma}{d\Omega}[{}^2\mathrm{H}(e,e'p)_{QE}]}$$

$$= a(E,Q^2,\theta_{pq}^{max},W^2_{max}) \times \frac{\sigma_{Mott}\left(\frac{(G_E^n)^2+\tau(G_M^n)^2}{1+\tau} + 2\tau\tan^2\frac{\theta}{2}(G_M^n)^2\right)}{\frac{d\sigma}{d\Omega}[{}^1\mathrm{H}(e,e')p]}$$

  where $a(E,Q^2,\theta_{pq}^{max},W^2_{max})$ corrects for nuclear effects, θ_{pq}^{max} and W^2_{max} are kinematic cuts, and the numerator is the precisely-known proton cross section.

- Less vulnerable to nuclear structure (*e.g.*, deuteron model, *etc.*) and experimental effects (*e.g.*, electron acceptance, *etc.*).
- Must accurately measure the nucleon detection efficiencies and match the geometric solid angles.

Measuring G_M^n - The Ratio Method

- Without a free neutron target we use deuterium and measure R

Extracting G_M^n requires knowledge of other EEFFs.

$$R = \frac{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'n)_{QE}]}{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'p)_{QE}]}$$

$$= a(E, Q^2, \theta_{pq}^{max}, W_{max}^2) \times \frac{\sigma_{Mott}\left(\frac{(G_E^n)^2+\tau(G_M^n)^2}{1+\tau} + 2\tau\tan^2\frac{\theta}{2}(G_M^n)^2\right)}{\frac{d\sigma}{d\Omega}[^1\mathrm{H}(e,e')p]}$$

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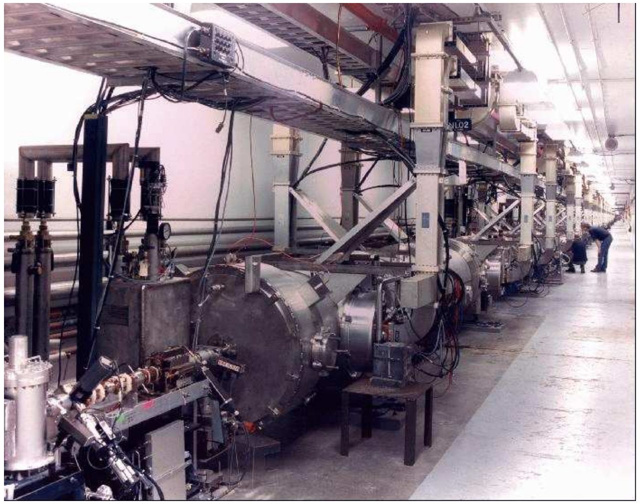
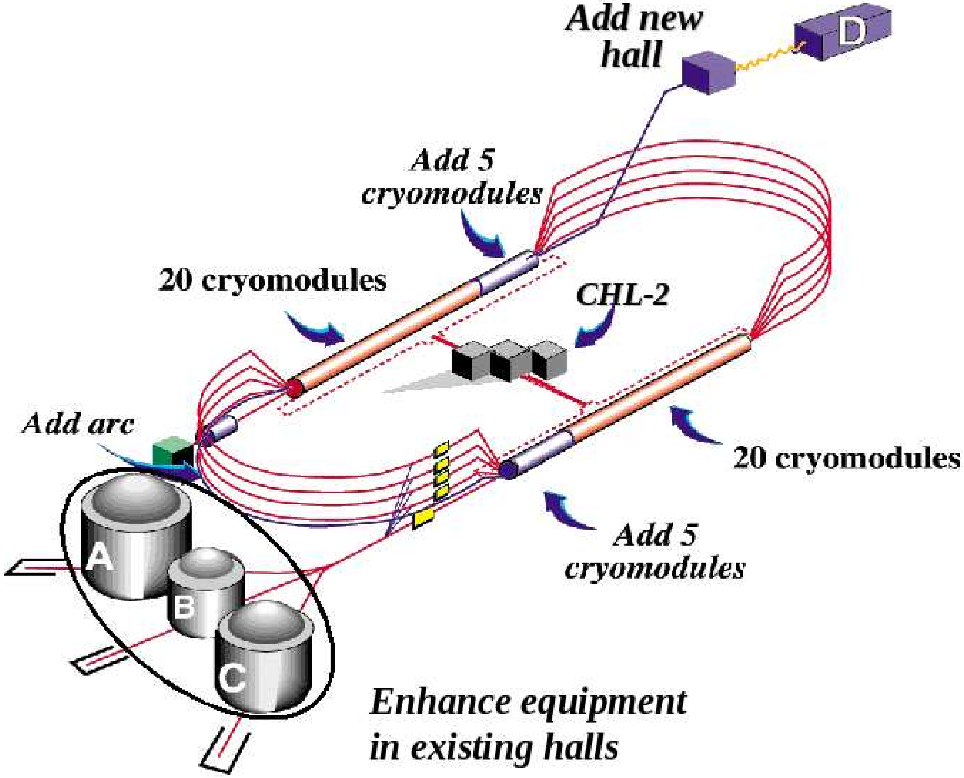
The Experiment - Jefferson Lab

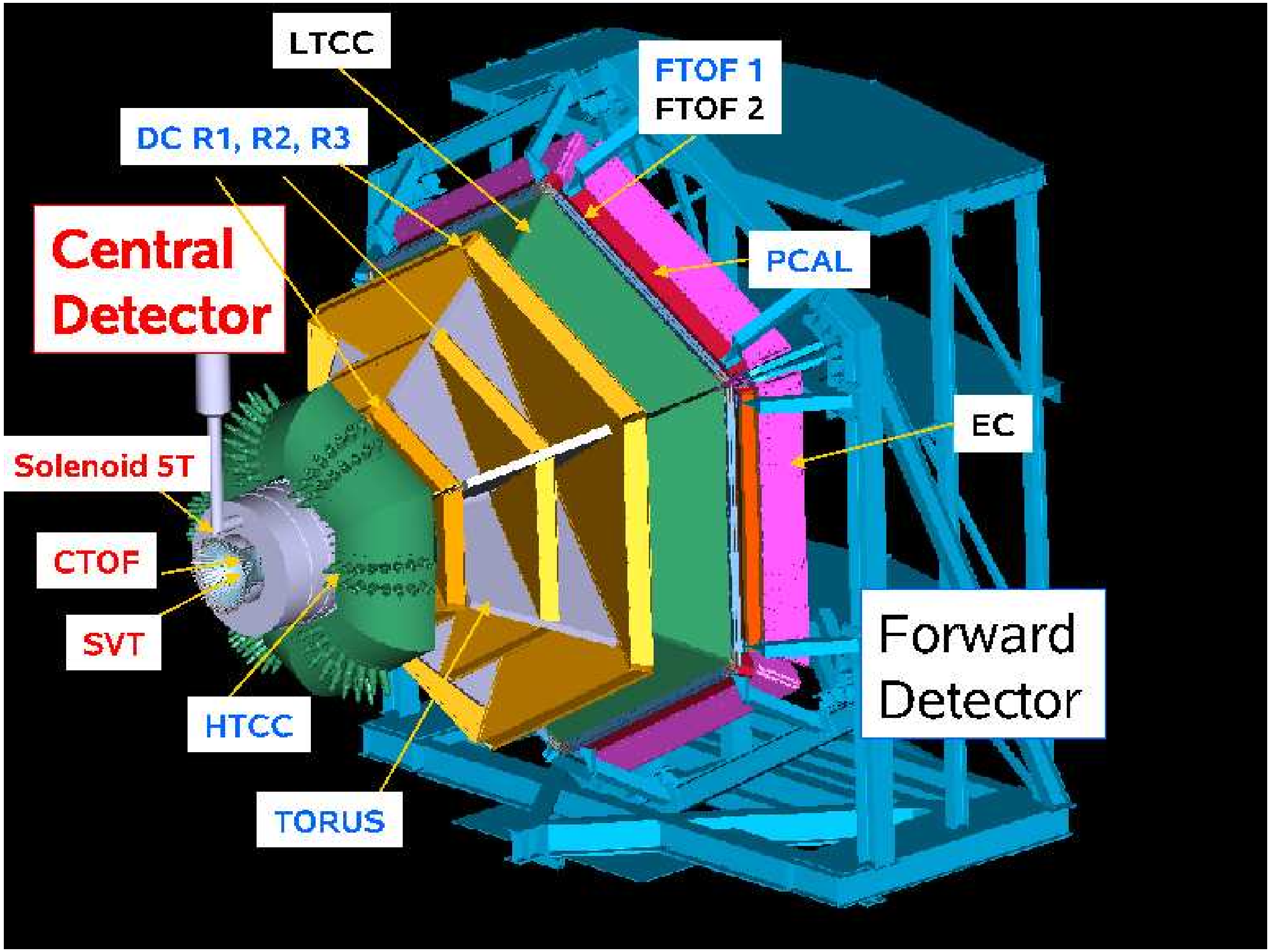




Continuous Electron Beam Accelerator Facility (CEBAF)

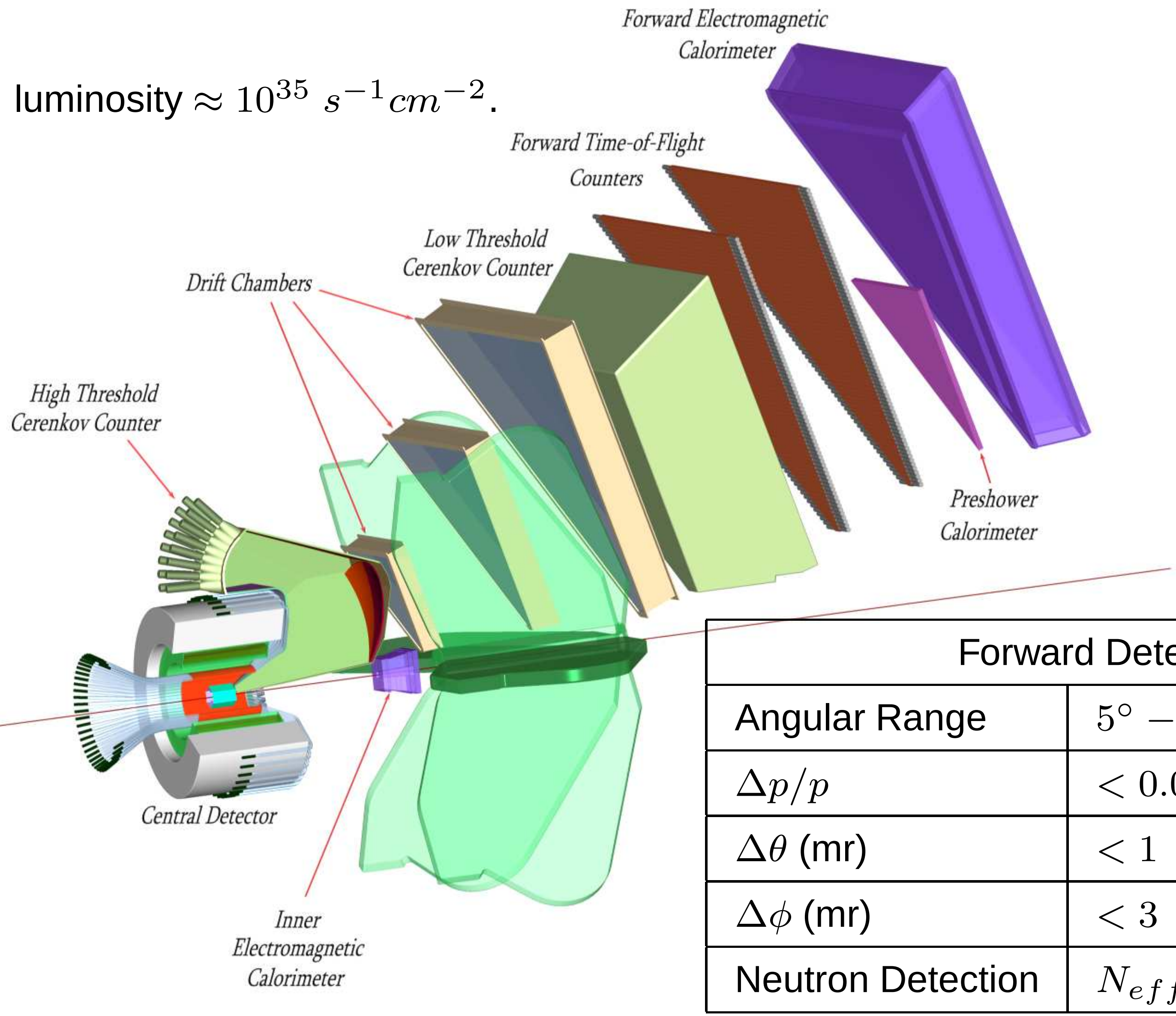
- Superconducting Electron Accelerator (currently 338 cavities), 100% duty cycle.
- $E_{max} = 11$ GeV in Hall B, $\Delta E/E \approx 2 \times 10^{-4}$, $I_{summed} \approx 90\ \mu A$, $P_e \geq 80\%$.

The CLAS12 Detector



CLAS12 Detector and G_M^n Target

luminosity $\approx 10^{35}\ s^{-1} cm^{-2}$.



Forward Detector	
Angular Range	$5^\circ - 40^\circ$ (outbenders)
$\Delta p/p$	< 0.01 @ 5 GeV/c
$\Delta\theta$ (mr)	$< 1 \quad p > 2.5\ \mathrm{GeV/c}$
$\Delta\phi$ (mr)	$< 3 \quad p > 2.5\ \mathrm{GeV/c}$
Neutron Detection	$N_{eff} = 0.1 - 0.6$

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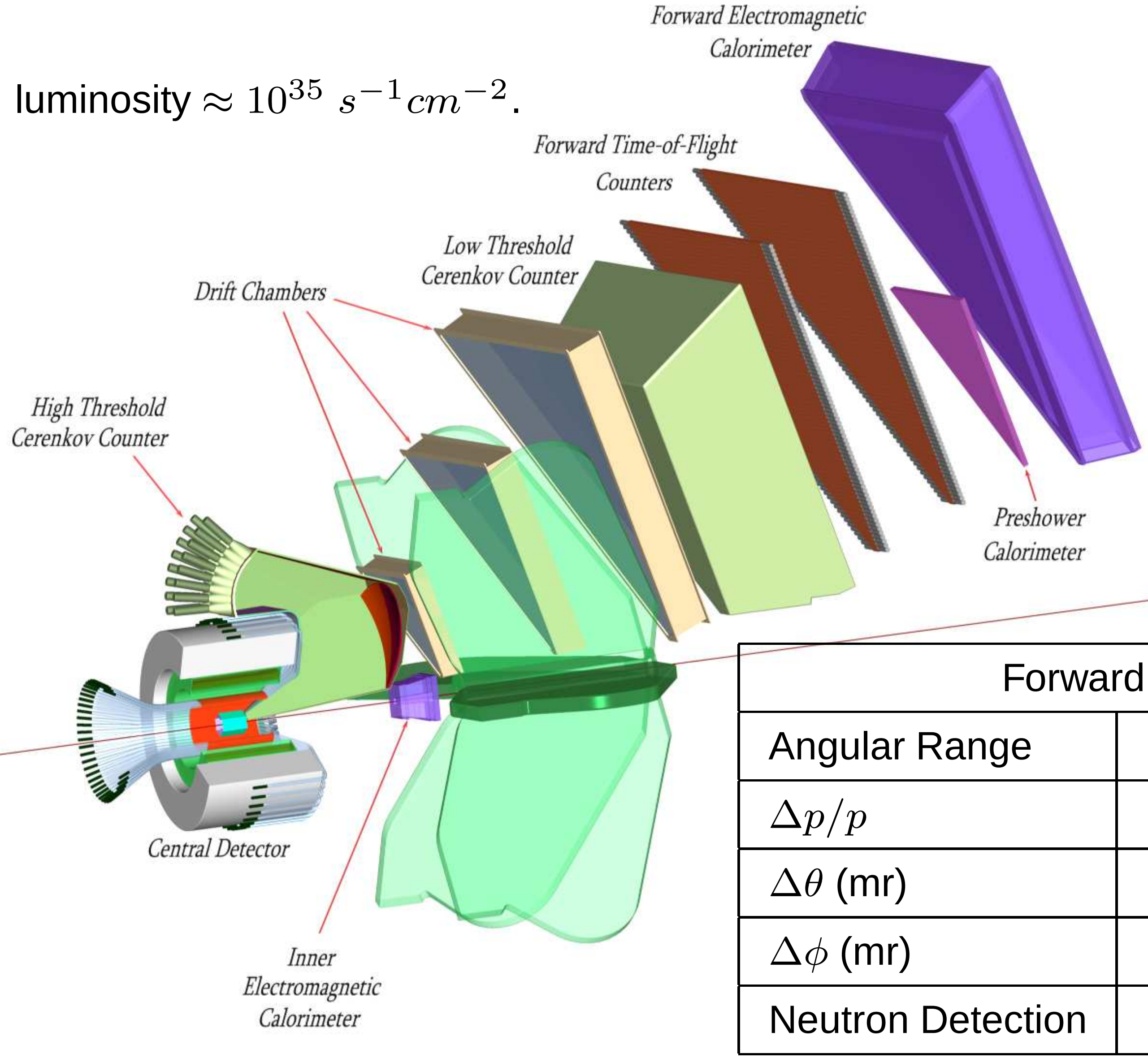

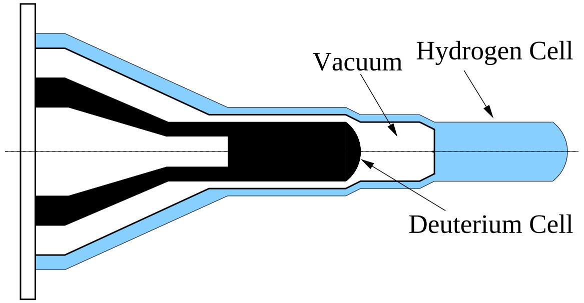

The collinear, dual, hydrogen-deuterium target enables us to collect high-precision, *in situ* calibration data so systematic uncertainties $\leq 3\%$.

Forward Detector	
Angular Range	$5^\circ - 40^\circ$ (outbenders)
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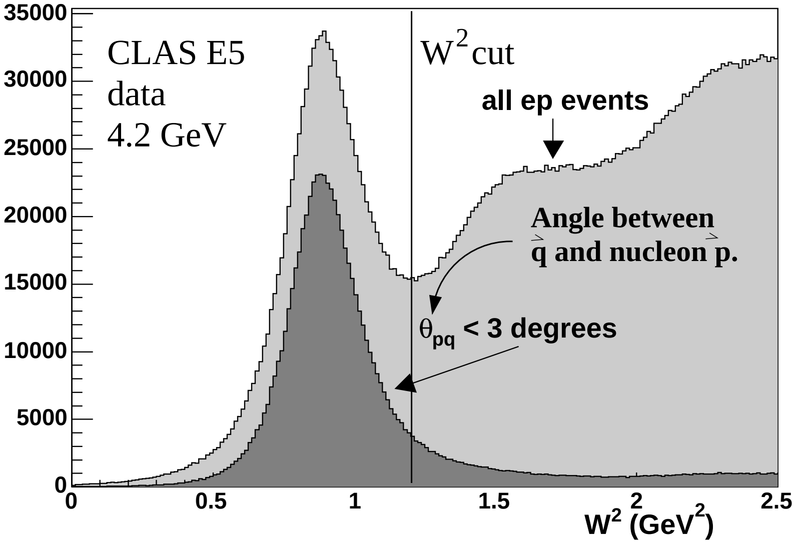
Selecting Quasielastic Events

- Select $e-p$ events using the CLAS12 tracking system for electrons and protons.
- Select $e-n$ events with either the TOF or electromagnetic calorimeters; semi-independent measurements of the neutron production.
- Apply a θ_{pq} cut to isolate 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.



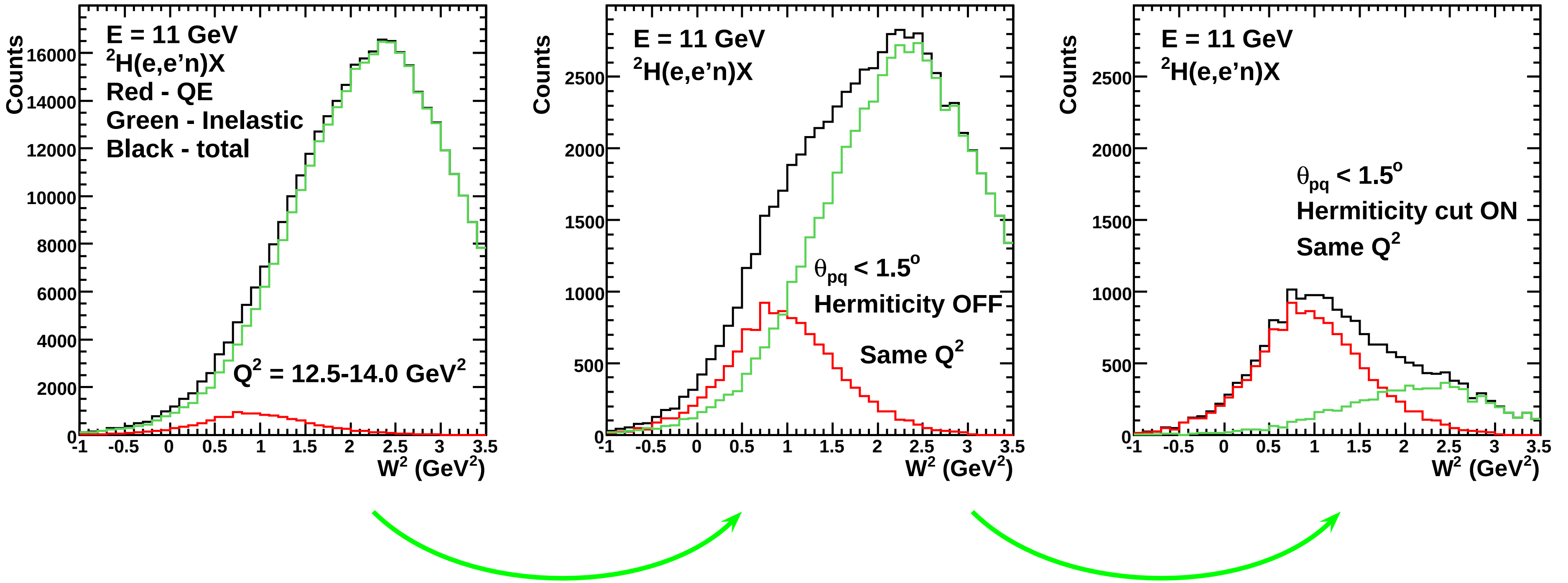
- Measure the neutron production in both electromagnetic calorimeters and TOF scintillators; providing an internal consistency check.

Impact of inelastic background will be greater at large Q^2 due to increasing width of W^2.

Hermiticity Cut

Challenge: Separate QE events from high-Q^2, inelastic background.

1. θ_{pq} **cut:** QE neutrons/protons emitted in a narrow cone along $\vec{q}$.
2. **Hermiticity cut:** No additional particles in the event.

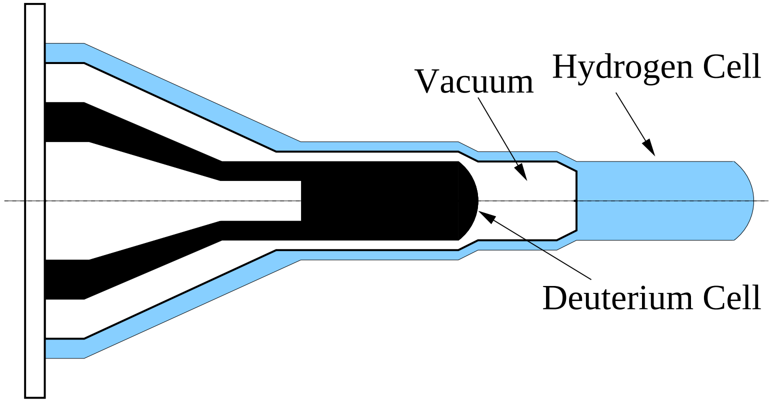


Apply θ_{pq} cut.

Apply hermiticity cut.

Calibrations - Proton Detection Efficiency

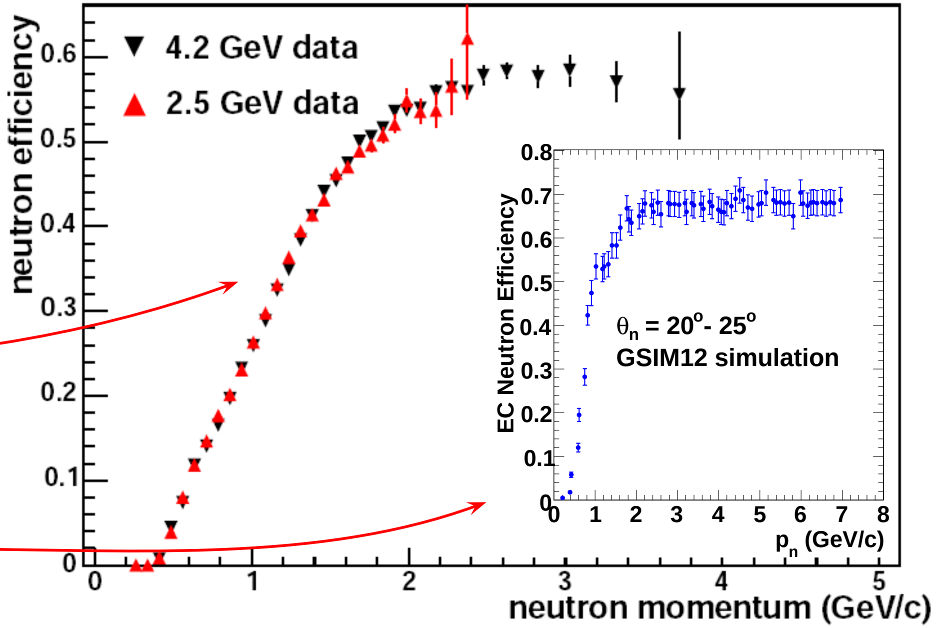
1. Use $ep \rightarrow e'p$ elastic scattering from hydrogen target as a source of tagged protons.
2. Select elastic $e - p$ events with a W^2 cut.
3. Identify protons as positive tracks with a coplanarity cut applied.
4. Use the missing momentum from $ep \rightarrow e'X$ to predict the location of the proton 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.



Calibrations - 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. 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, $ep \to e'\pi^+ X$ 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 CLAS6 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



Simultaneous, *in situ* calibrations with dual hydrogen-deuterium target.

The Ratio Method - Systematic Errors

- G_M^n is related to the $e-n/e-p$ by the following (neutron (n) and proton (p)).

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

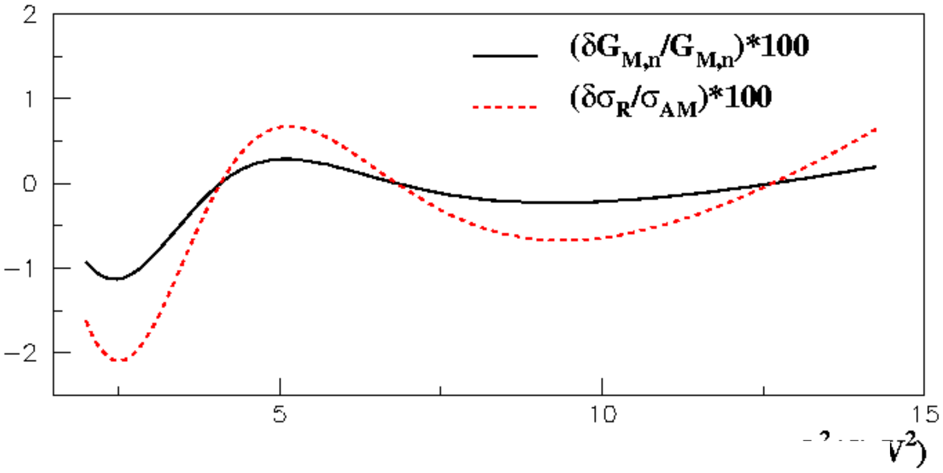
- Upper limits on systematic error from the CLAS6 measurement ($\Delta G_M^n/G_M^n = 2.7\%$).

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		

- CLAS12 Goal: **$\leq$3% systematic uncertainty**

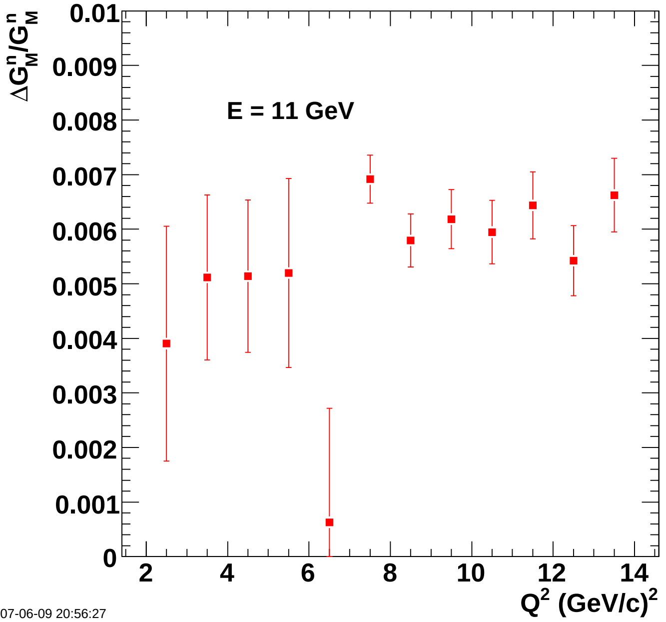
Systematic Uncertainty Studies

- Systematic uncertainty for proton cross section ($\Delta G_M^n/G_M^n \times 100$) based on differences in the proton reduced cross section parameterizations of Bosted (PRC 51, 409 (1995)) and Arrington-Melnitchouk.



- Similar approach to systematic uncertainty ($\Delta G_M^n/G_M^n \times 100$) for G_E^n based on differences in G_E^n parameterizations of Kelly (PRC 70, 068202 (2004))and BBBA05 (hep-ph/0602017).

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



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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)
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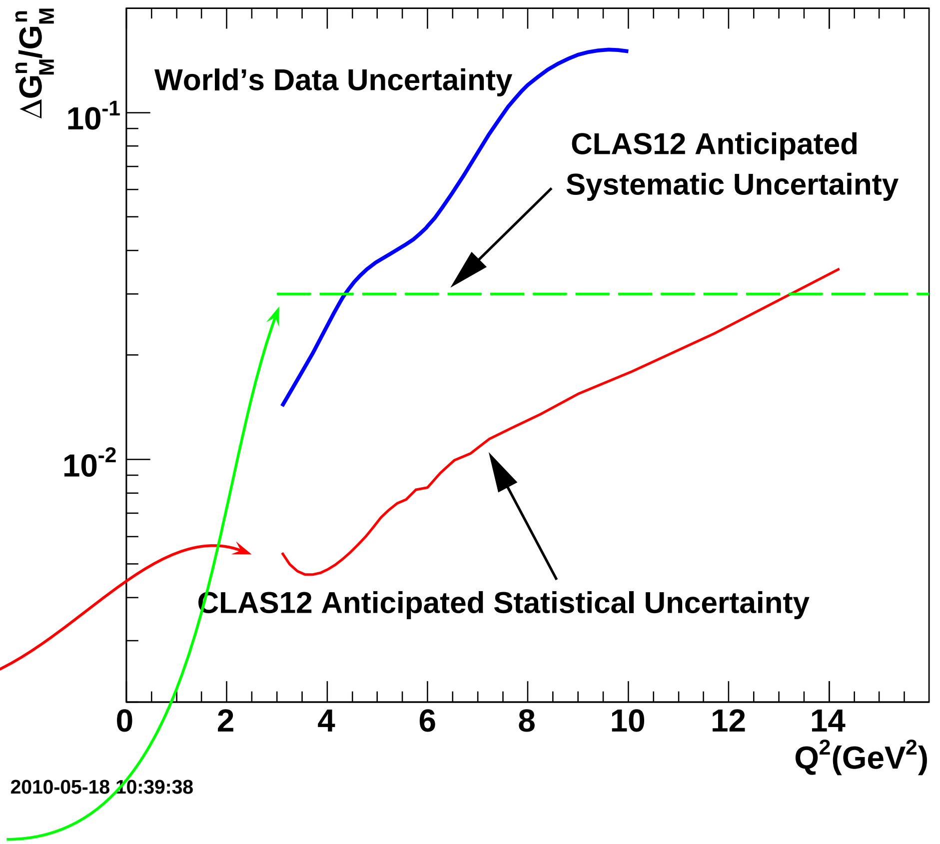
Nuclear Corrections	< 0.2		

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 CLAS6 measurement.

Statistical Uncertainties

- Use Alberico *et al.* (PRC 79, 065204 (2009)) to estimate G_M^n.
- $Q^2 = 3.5 - 15.0\ \mathrm{GeV}^2$, but statistical uncertainty exceeds systematic uncertainty at highest Q^2.
- Statistical Uncertainty: less than 3% for $Q^2 \approx 11.5\ \mathrm{GeV}^2$; much better at lower Q^2.
- Systematic Uncertainty: less than 3% across the full Q^2 range.



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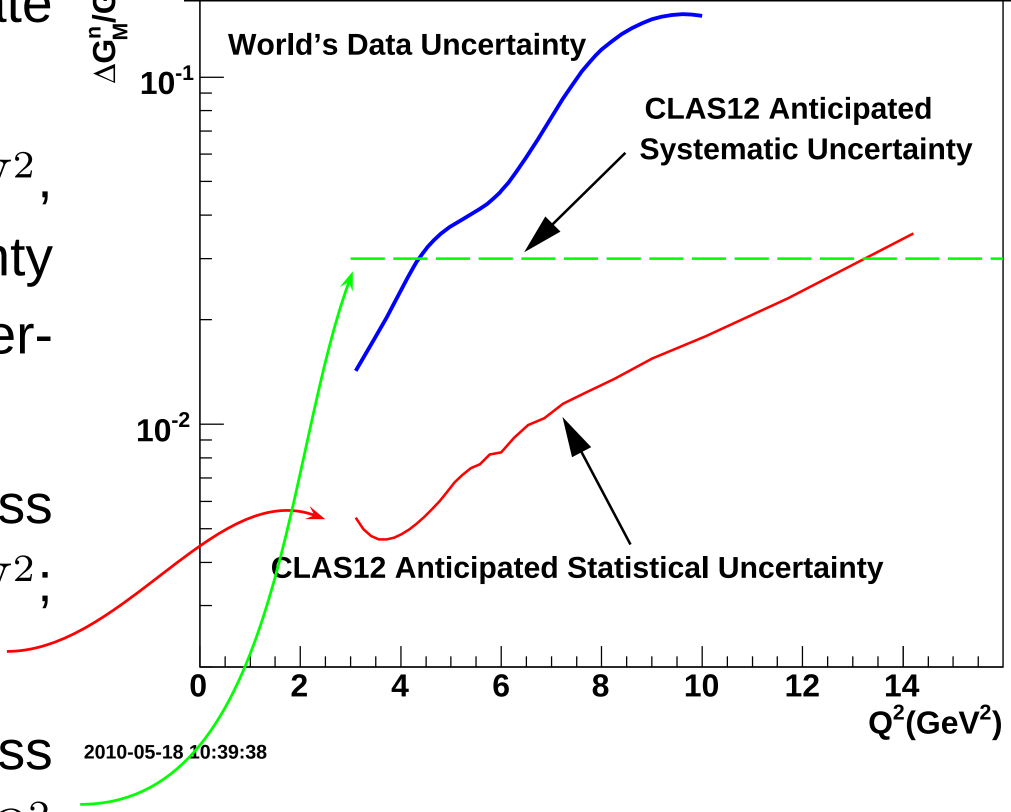
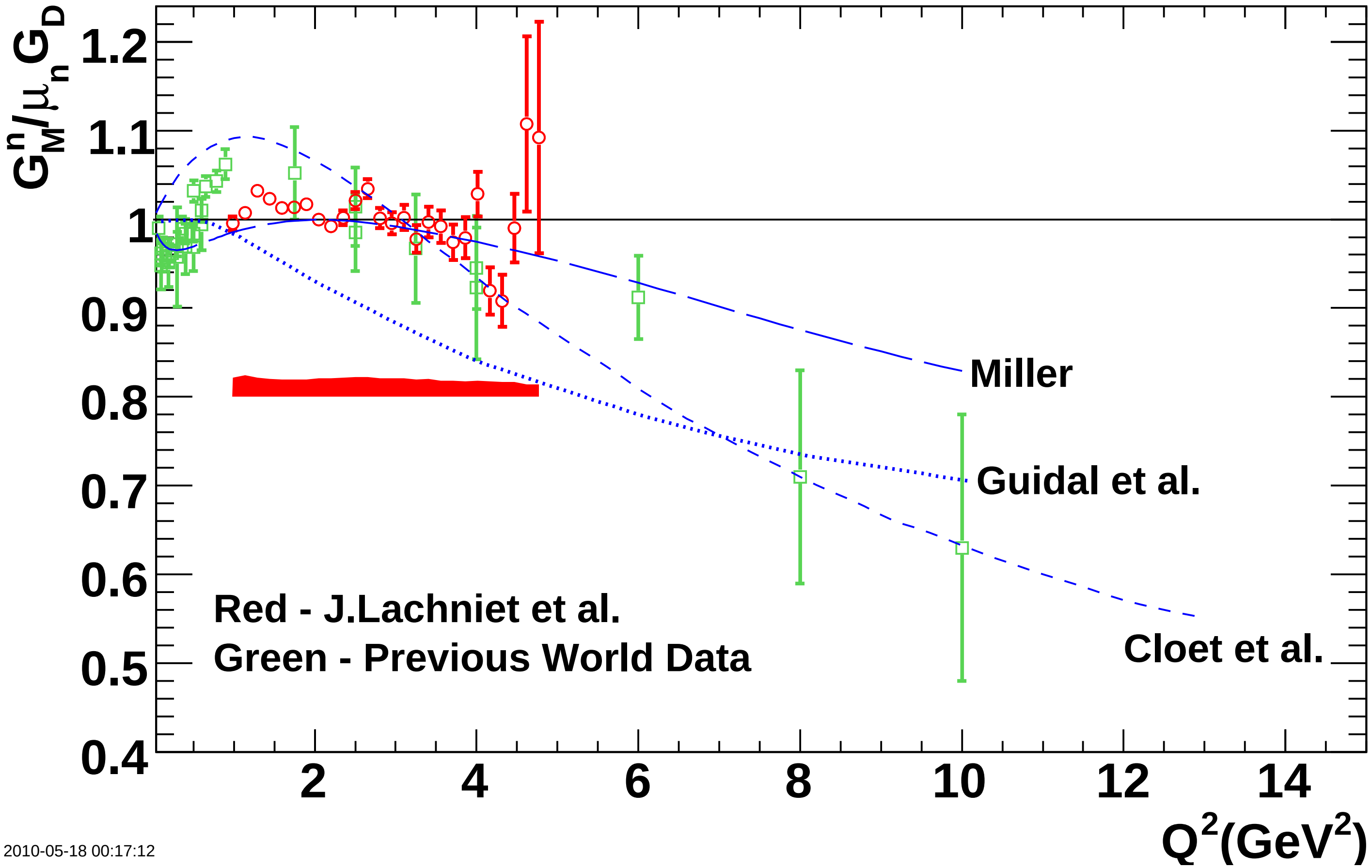
Will extend the Q^2 range of G_M^n with higher precision.



Approved for 30 days of running, A$^-$ rating.

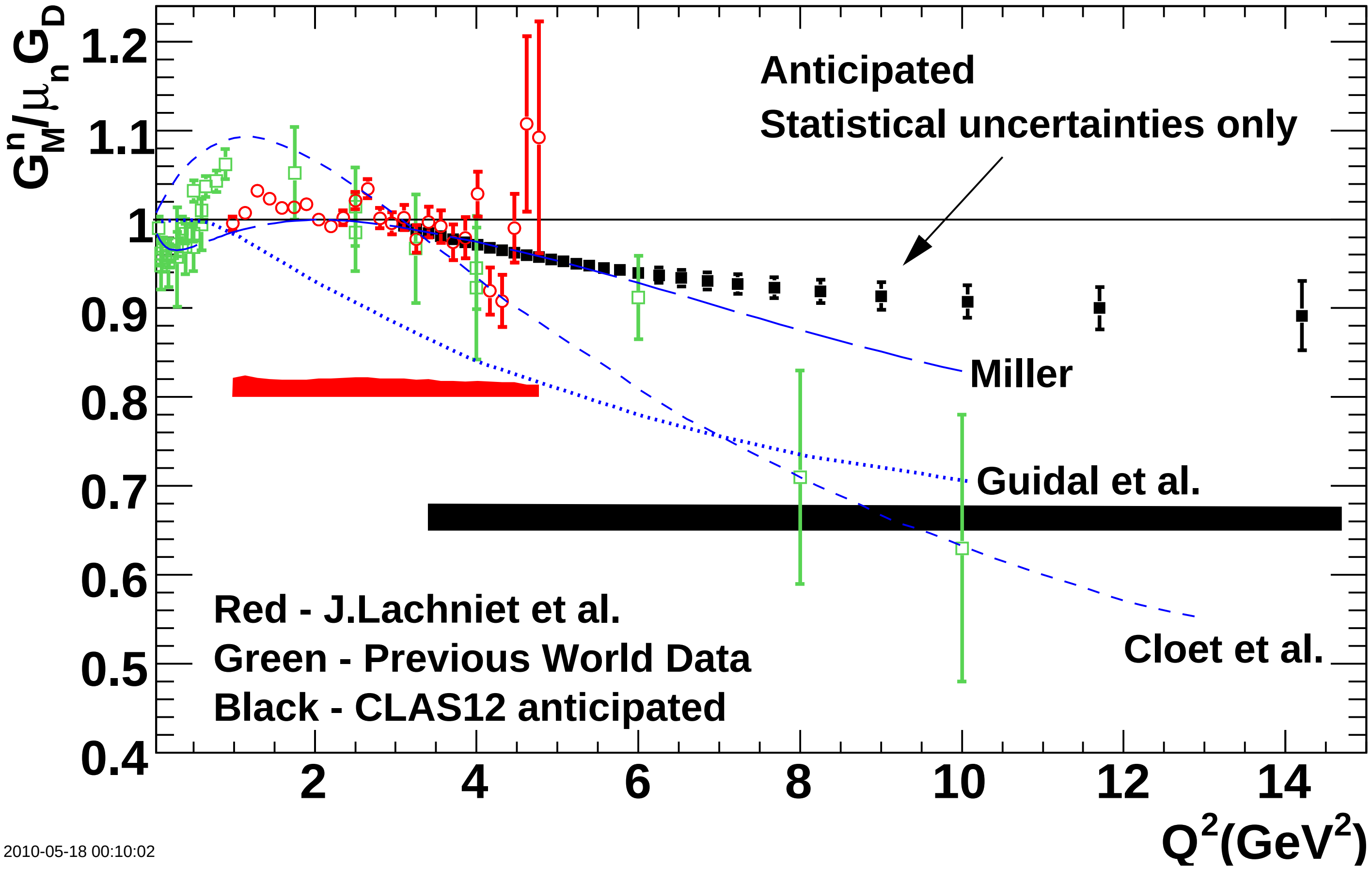
CLAS12 Anticipated Results



Uncertainty bands are for CLAS6 (Lachniet *et al.*) (red) and CLAS12 anticipated (black).

Miller - PRC 66, 032201(R) (2002); Guidal - PRD 72, 054013 (2005); Cloët - Few Body Syst., 46:1-36 (2009).

CLAS12 Anticipated Results



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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.
- With a tested method used in CLAS6, we will significantly expand our understanding of nucleon structure and challenge theory.
- The CLAS12 detector will provide wide kinematic acceptance ($\mathrm{Q}^2 = 3 - 15(\mathrm{GeV/c})^2$) 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 have been approved for 30 PAC days of beam time at 11 GeV (A^- rating).

Part of a broad effort to measure the EEFFs at JLab and includes E12-09-019 in Hall A to also measure G_M^n.

Update for E12-07-104: CLAS12 G_M^n - Additional Slides

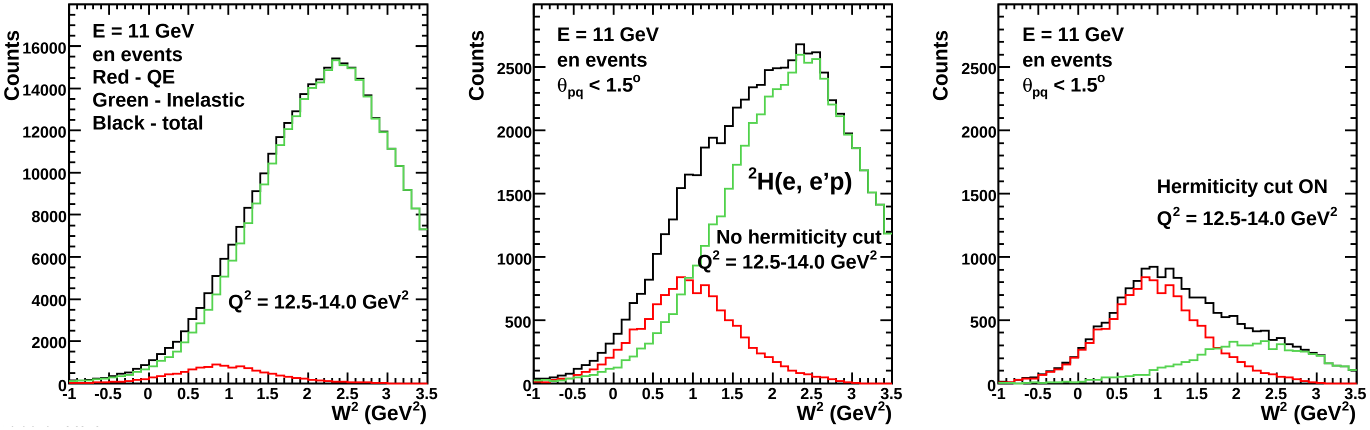
More on the CLAS12 Detector

	Forward Detector	Central Detector
Angular Range		
Charged Particles	$5^\circ - 40^\circ$	$40^\circ - 135^\circ$
Photons	$2^\circ - 40^\circ$	N/A
Resolution		
$\Delta p/p$	< 0.01 @ 5 GeV/c	< 0.03 @ 0.5 GeV/c
$\Delta\theta$ (mr)	< 0.5	< 10
$\Delta\phi$ (mr)	< 0.5	< 6
Neutron Detection		
N_{eff}	0.1-0.6	0.1

Update for E12-07-104: CLAS12 G_M^n - Optimizing θ_{pq} Cut

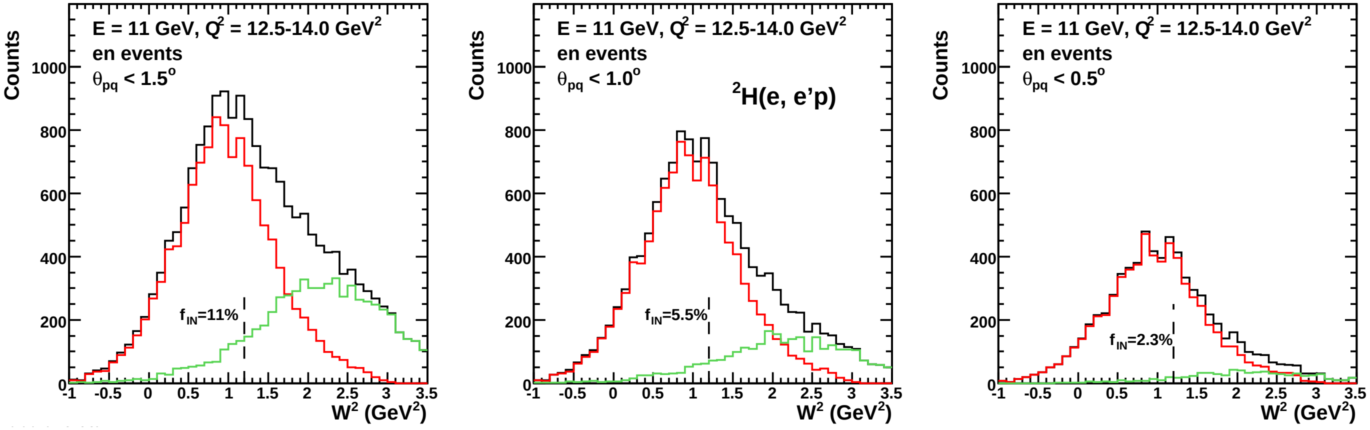
1. Recall effect of requiring $\theta_{pq} < 1.5°$ and hermiticity cut to reduce inelastic background.

Effect of θ_{pq} and hermiticity cuts.

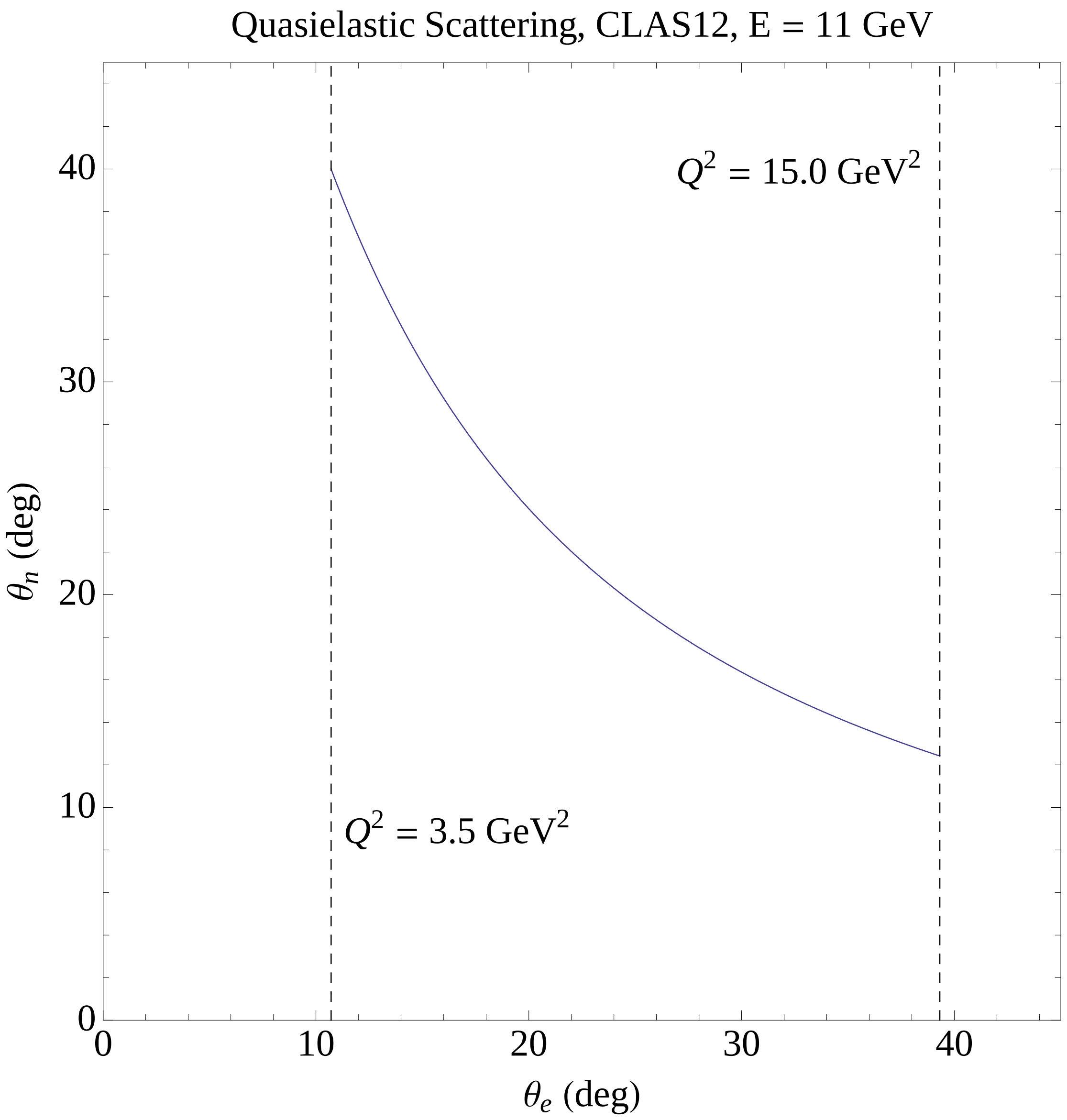


2. To reduce inelastic background further, reduce the maximum θ_{pq}.

$f_{IN} = \frac{inelastic}{total}$ for $W^2 < 1.2\ \mathrm{GeV}^2$.

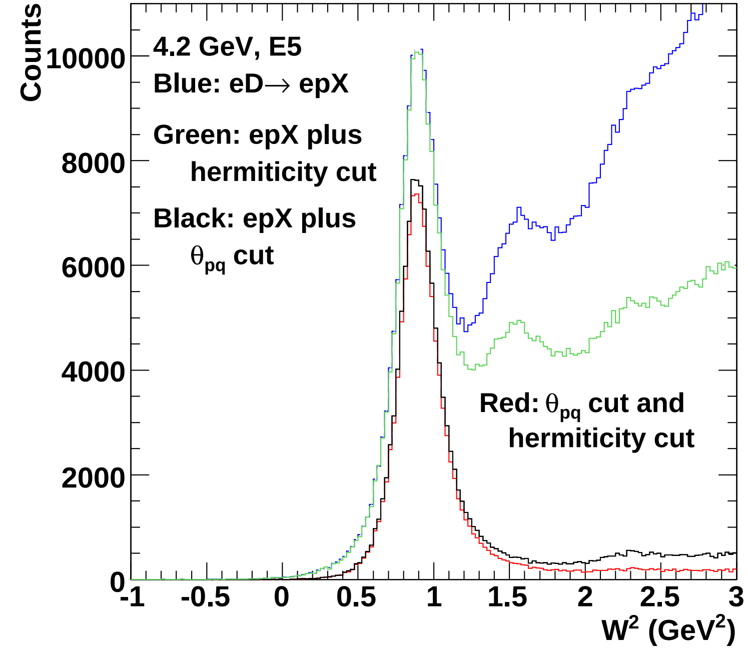


Update for E12-07-104: CLAS12 G_M^n - QE Scattering Angles



Update for E12-07-104: CLAS12 G_M^n - Hermiticity Cut

1. For the CLAS6 data, the hermiticity cut is not needed. Applying it just reduces the already small inelastic background (compare black and red histograms).
2. Without requiring $\theta_{pq} < 3^\circ$, the hermiticity cut still reduces the inelastic background (compare blue and green histograms).



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3. Hermiticity cut here includes ep events with additional out-of-time tracks or ones that fall outside the vertex cut (1.5 cm).
4. Effect of hermiticity cut in CLAS12 simulation is qualitatively consistent with CLAS6, E5 data.

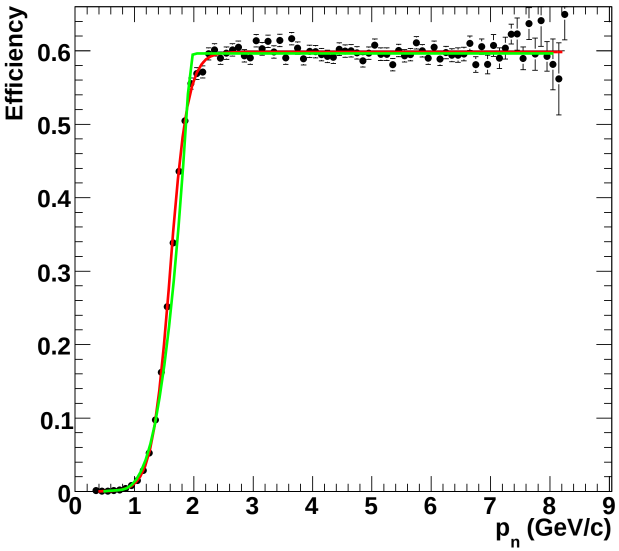
Update for E12-07-104: Neutron Detection Efficiency Uncertainty

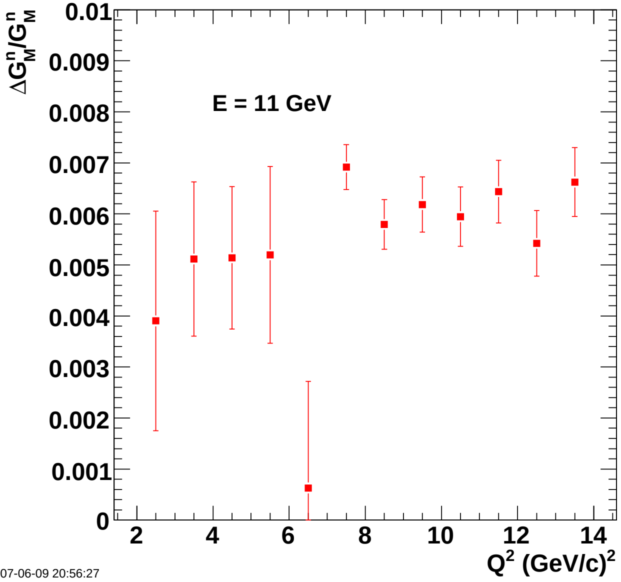
- Characterize the neutron detection efficiency ϵ_n with

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

where S is the height of the plateau for $p_n > 2\ GeV/c$, p_0 is the center of the rising part of ϵ_n, and a_0 controls the slope of ϵ_n in this 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 take the difference.





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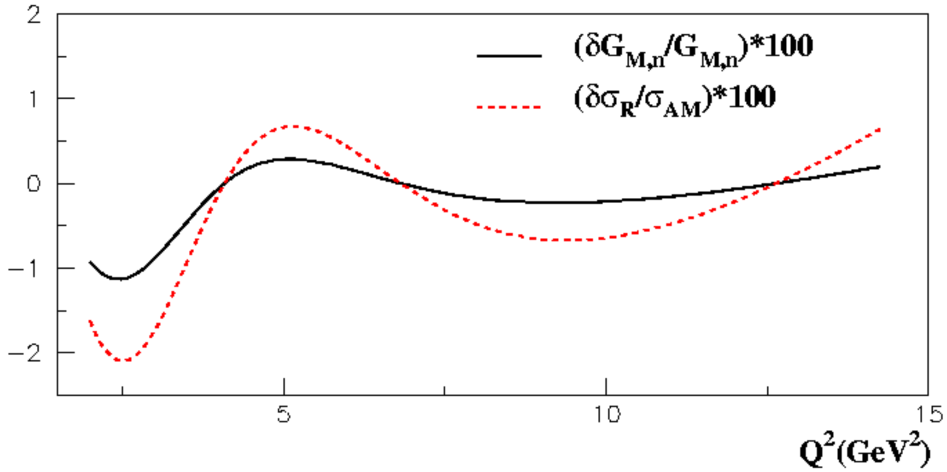
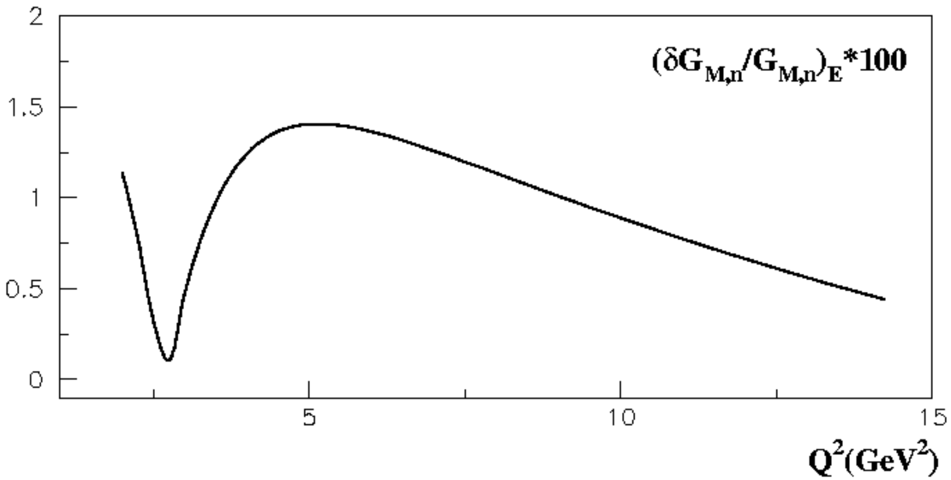
Update for E12-07-104: Other Elastic Form Factors Uncertainties

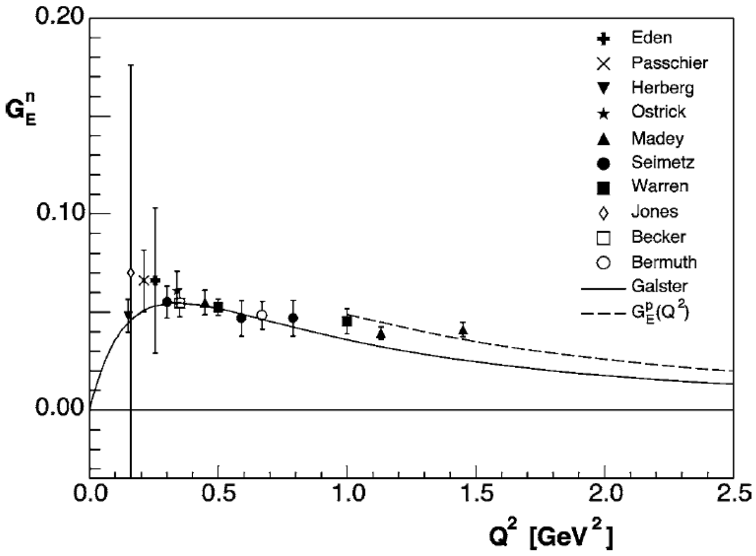
- Systematic uncertainty ($\Delta G_M^n/G_M^n \times 100$) based on differences in the proton reduced cross section parameterizations of Bosted and Arrington-Melnitchouk.



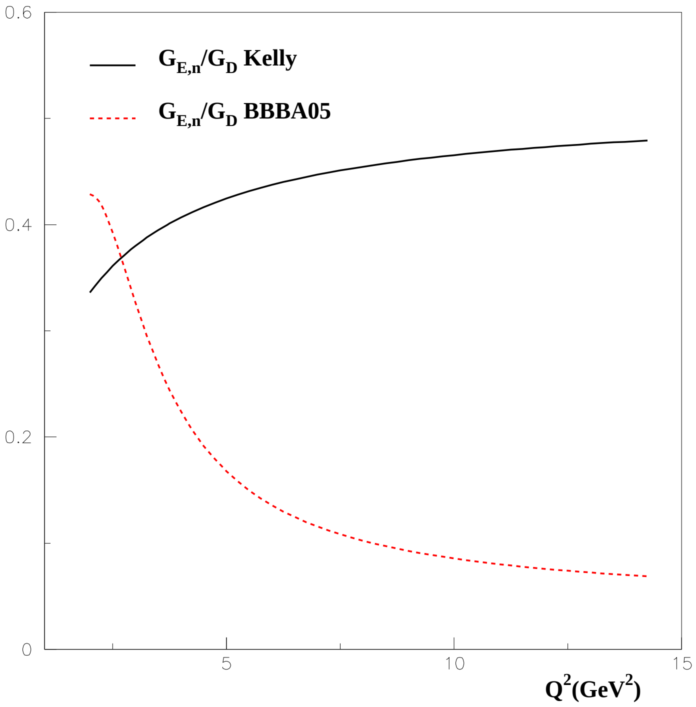
- Systematic uncertainty ($\Delta G_M^n/G_M^n \times 100$) based on differences in G_E^n parameterizations of Kelly and BBBA05. Future measurements will reduce the uncertainty for $Q^2 < 7.5\ \mathrm{GeV}^2$.



Update for E12-07-104: G_E^n Uncertainty



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



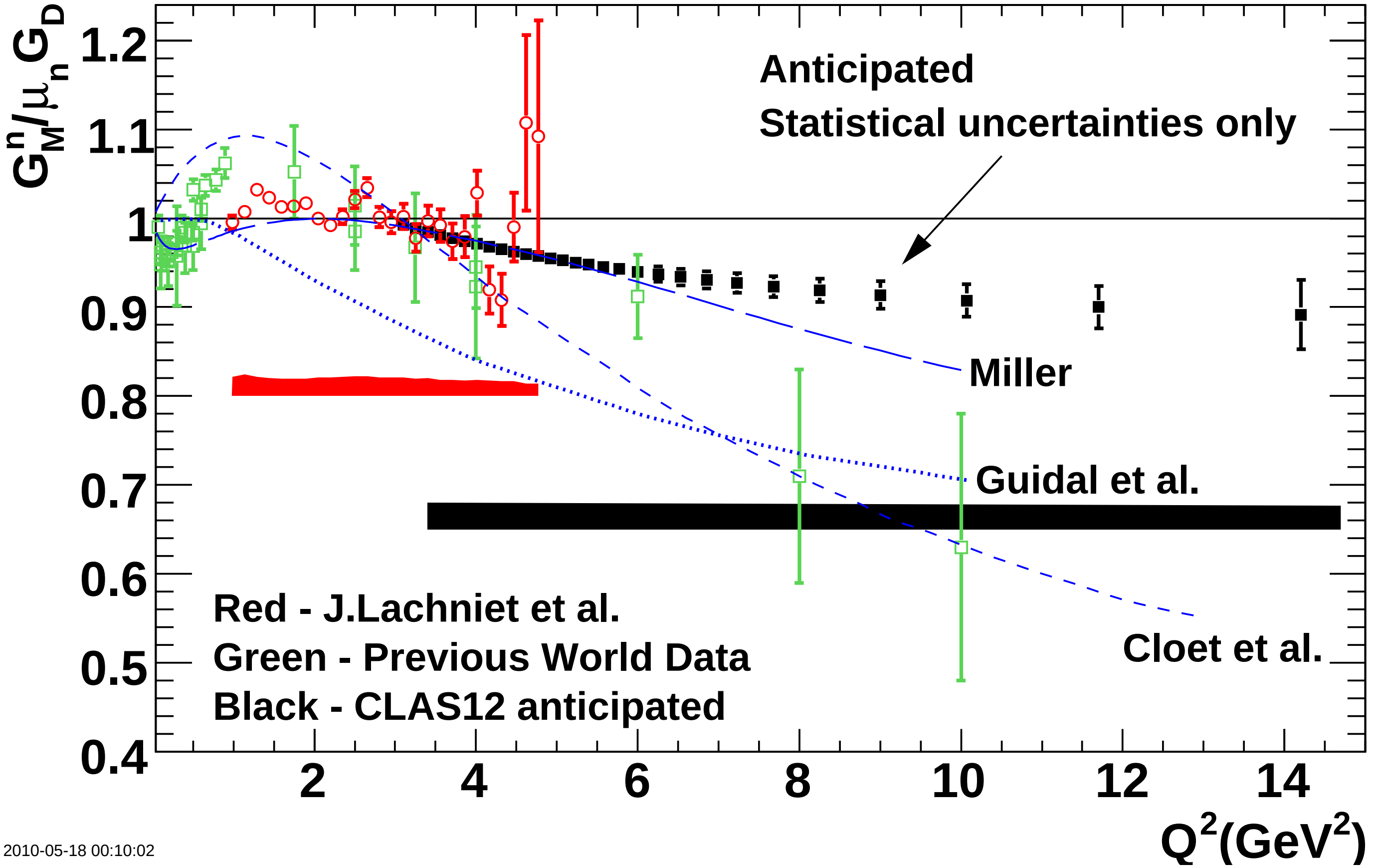
The neutron electric form factor from Kelly and BBBA05 parameterizations as a function of Q^2 (J. J. Kelly, PRC 70, 068202 (2004) and R. Bradford *et al.*, hep-ph/0602017.)

Update for E12-07-104: Systematic Uncertainties

Summary of expected systematic uncertainties for CLAS12 G_M^n measurement in percentages ($100 \times \Delta G_M^n / G_M^n = 2.5\%$(2.7)). Red numbers represent the previous upper limits from the CLAS6 measurement.

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

Update for E12-07-104: Comparison of CLAS6 and CLAS12 measurements



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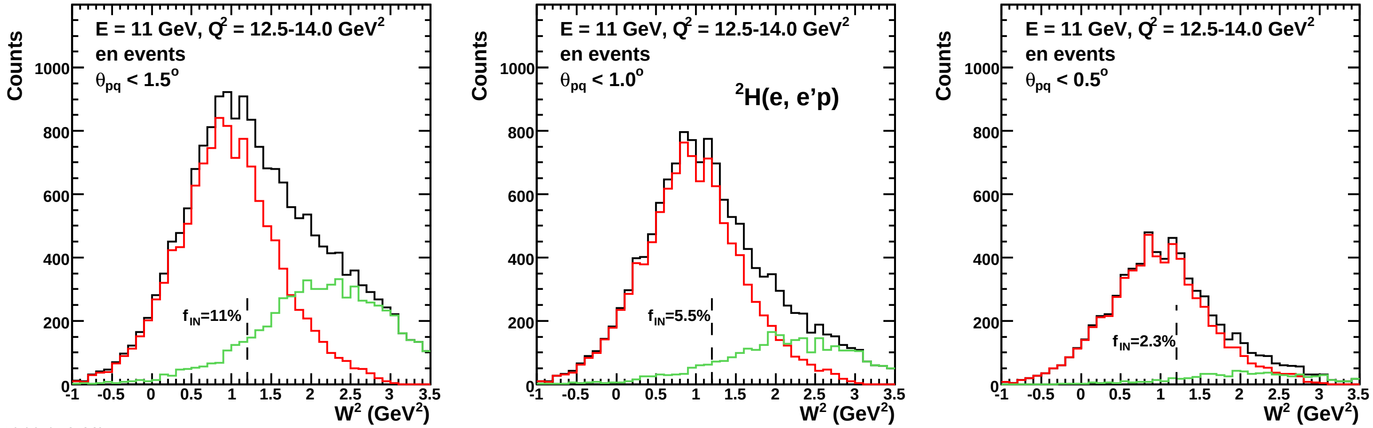
Update for E12-07-104: Comparison of CLAS12 and E12-09-019 methods

1. To reduce inelastic background further, reduce the maximum θ_{pq}.

$f_{IN} = \frac{inelastic}{total}$ for $W^2 < 1.2\ \mathrm{GeV}^2$.



2. In a similar Q^2 range, in E12-09-019 only the θ_{pq} cut will be used leaving more inelastic background contaminating the the QE peak.
3. At higher Q^2 (*i.e.* in PR10-005), the width of the inelastic component will continue to increase.