Update on the High-Precision Measurement of G_M^n With CLAS

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and the CLAS Collaboration

Outline:
1. Motivation.
2. Previous Measurements.
3. Necessary Background.
4. The Ratio Method.
5. Results.
6. Current Status and the Future.
7. Conclusions.

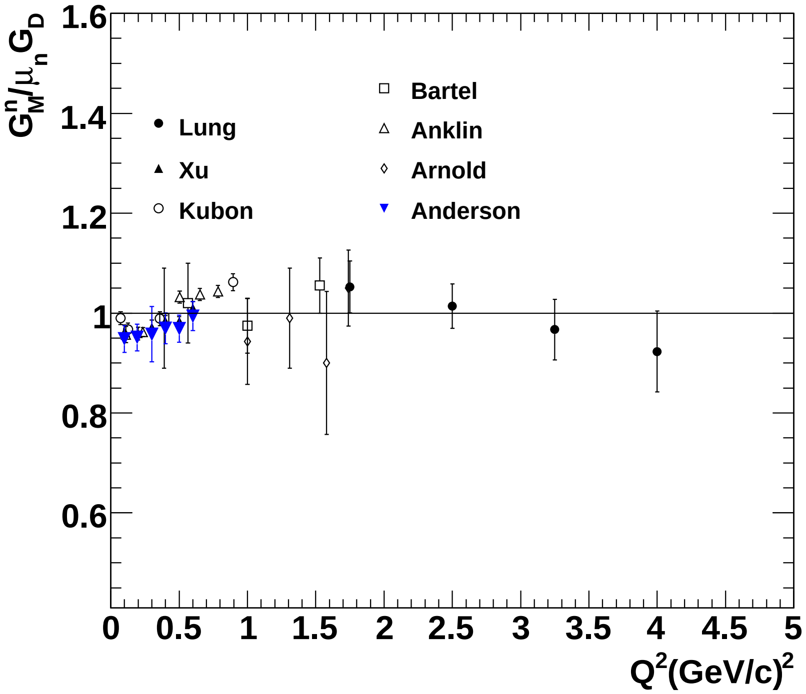
Scientific Motivation

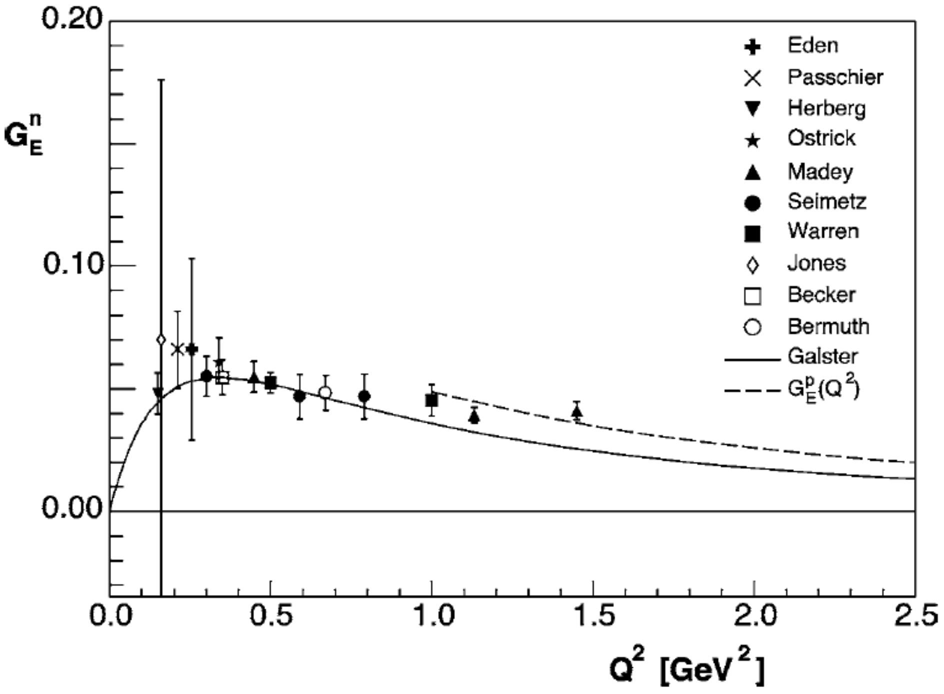
- To explore the ground state structure of the proton and neutron.
- $G_M^n(Q^2)$ is a fundamental observable related to the spatial distribution of the magnetization in the neutron.
- Elastic form factors (G_M^n, G_E^n, G_M^p, and G_E^p) provide key constraints on generalized parton distributions (GPDs) 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.

Some Necessary Background

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

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

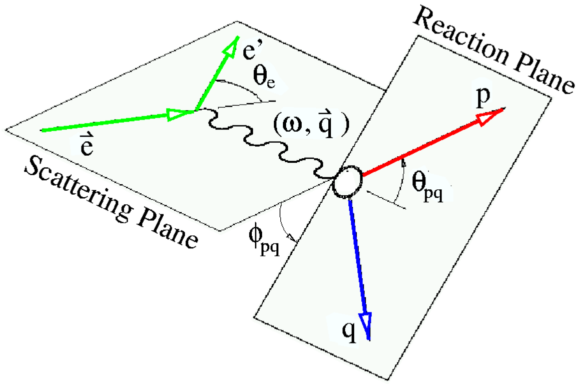
where

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

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

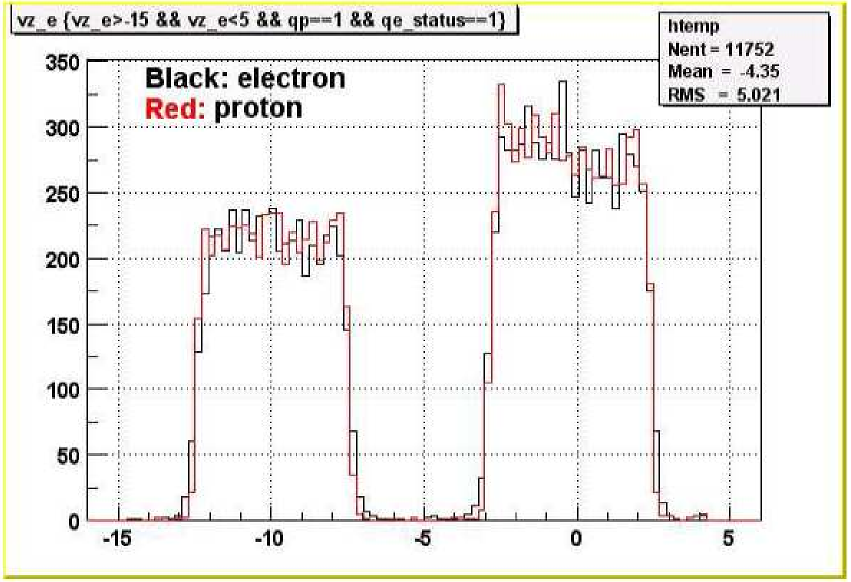
$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = a(Q^2)\frac{\frac{G_E^n{}^2+\tau G_M^n{}^2}{1+\tau} + 2\tau G_M^n{}^2\tan^2(\frac{\theta}{2})}{\frac{G_E^p{}^2+\tau G_M^p{}^2}{1+\tau} + 2\tau G_M^p{}^2\tan^2(\frac{\theta}{2})}$$

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



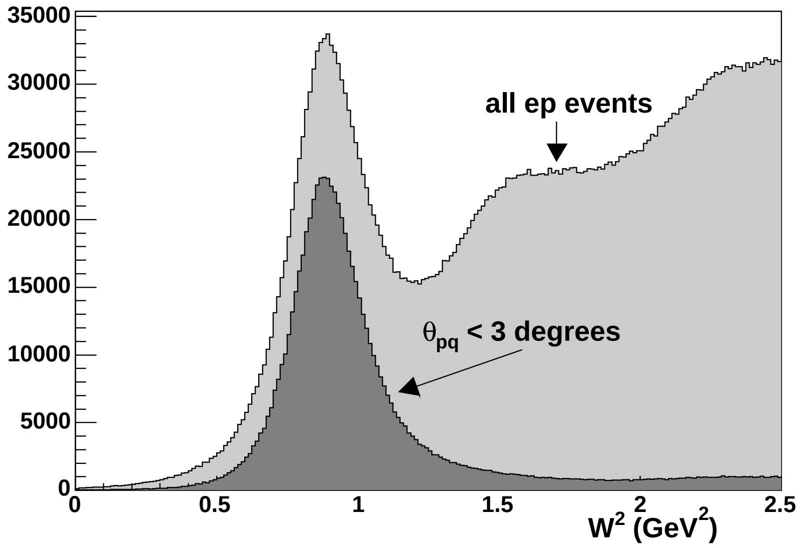
Experimental Details

- Data Set: 2.3 billion triggers at three sets of running conditions. Two sets at beam energies $4.2\ \mathrm{GeV}$ and $2.6\ \mathrm{GeV}$ with positive torus polarity (electrons in-bending).
- Another data set was collected at $2.6\ \mathrm{GeV}$ with reversed torus polarity (electrons outbending) to reach lower Q^2.
- Dual target cell with liquid hydrogen and deuterium separated by 4.7-cm. Perform *in situ* calibrations during data collection.
- Targets are well separated in tracking.



The Ratio Method - Event Selection

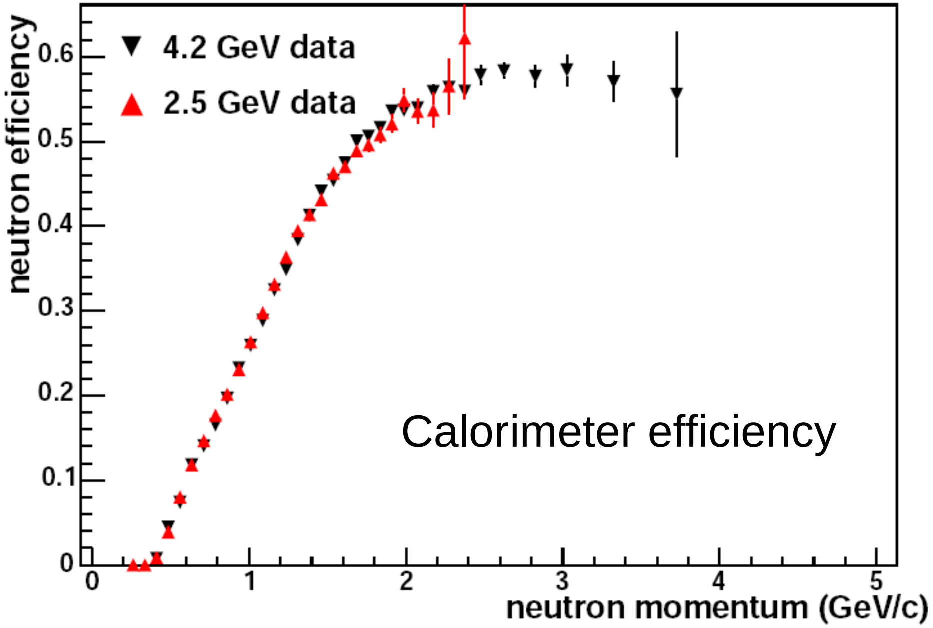
- Use $e-n/e-p$ ratio to reduce systematic uncertainties.
- $e-p$ selection: ‘standard’ CLAS analysis cuts for electrons and protons .
- $e-n$ selection: same criteria for electrons; use TOF and calorimeter as independent measurements of the neutron with cuts to reject photons.
- Quasi-elastic event selection: Apply a maximum θ_{pq} cut to eliminate inelastic events plus a cut on W^2.
- 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.



The Ratio Method - Corrections

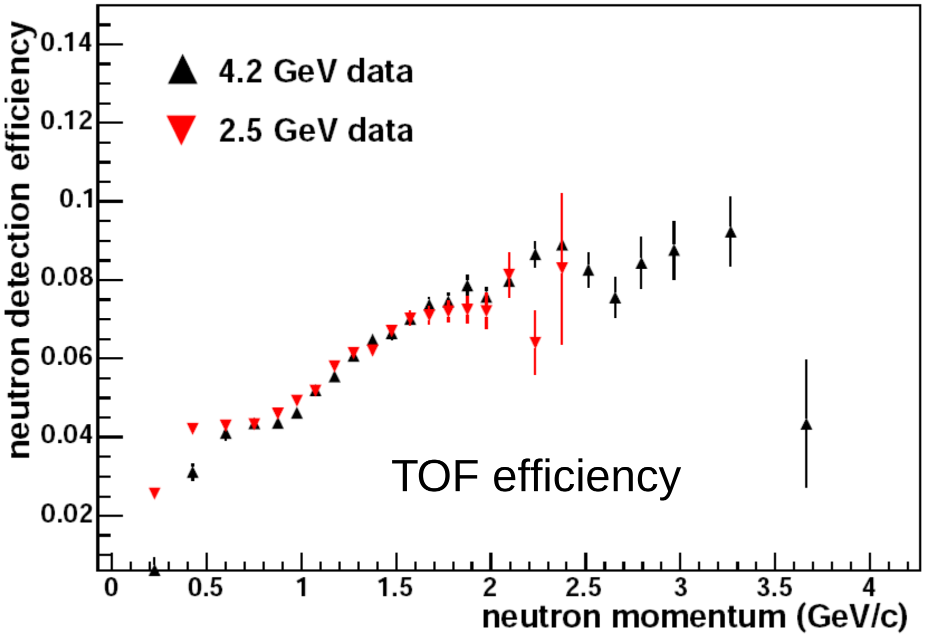
Neutron detection efficiency:

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. Standard CLAS cuts for electron selection.
3. For π^+, use positive tracks, cut on the difference between β measured from tracking and from time-of-flight.
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).



6. In the TOF use the neutron momentum $\vec{p}_n$ to predict which TOF paddle is hit (reconstructed event) and then search in that paddle (a found event if it's there). Reduce photon background by requiring a minimum energy deposited.

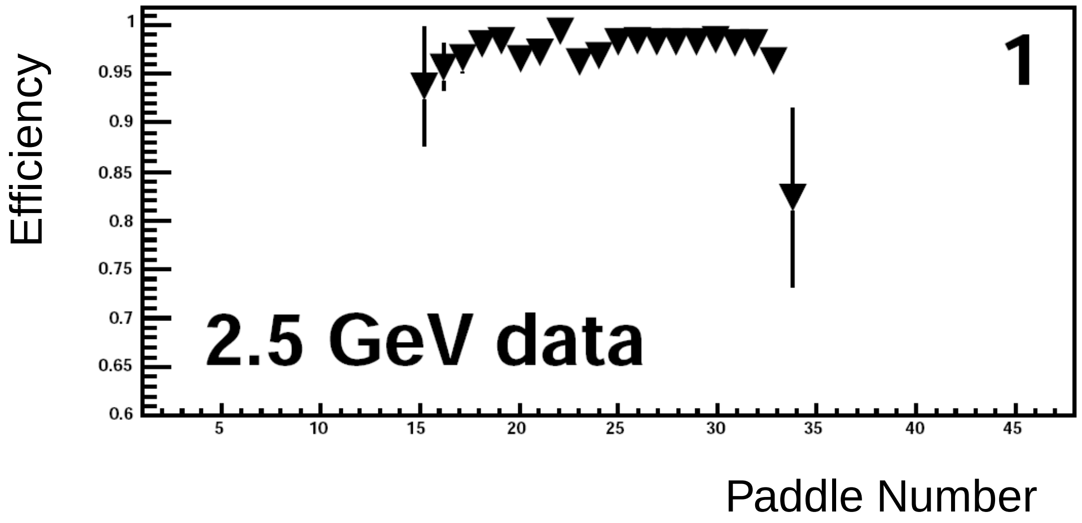
7. We have made two measurements of the neutron detection efficiency (calorimeter and TOF) for each set of running conditions.



The Ratio Method - Corrections

Proton detection efficiency:

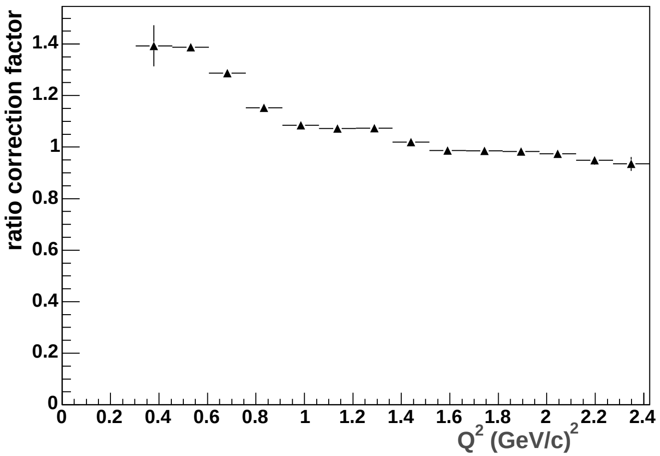
1. Use $ep \rightarrow e'p$ elastic scattering from hydrogen target as a source of tagged protons.
2. Standard CLAS cuts for electron selection with a W^2 cut to select ep elastic events.
3. Protons were identified as positive tracks with a coplanarity cut applied.
4. In the TOF use the missing momentum from $ep \rightarrow e'X$ to predict the TOF paddle that will be struck by the proton (a reconstructed event). Search that paddle or an adjacent one for a positively-charged particle (a found event if it's there). Results below are for sector 1 in CLAS.



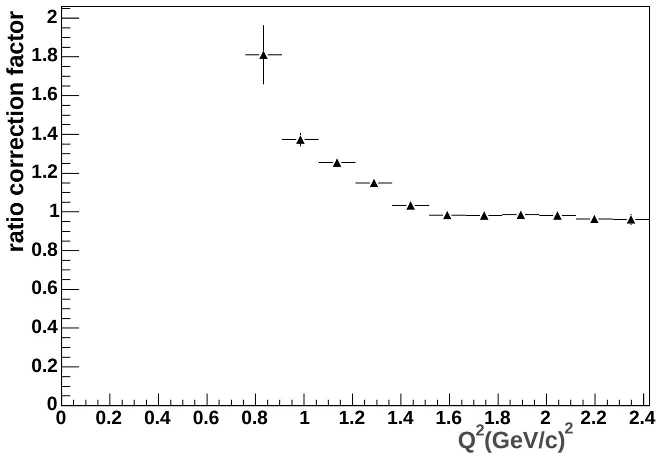
The Ratio Method - Corrections

- Nuclear effects: The $e-n/e-p$ ratio for free nucleons differs from the one for bound nucleons. Two calculations of the correction $a(Q^2)$ to R (Jeschonnek and Arenhoevel) averaged to 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 (CLAS-Note 2005-022) and close to unity.
- Fermi motion in the target: Causes nucleons to migrate out of the CLAS acceptance. This effect was simulated and the 2.6-GeV results for R are shown here.

TOF (2.6 GeV)



Calorimeter (2.6 GeV)



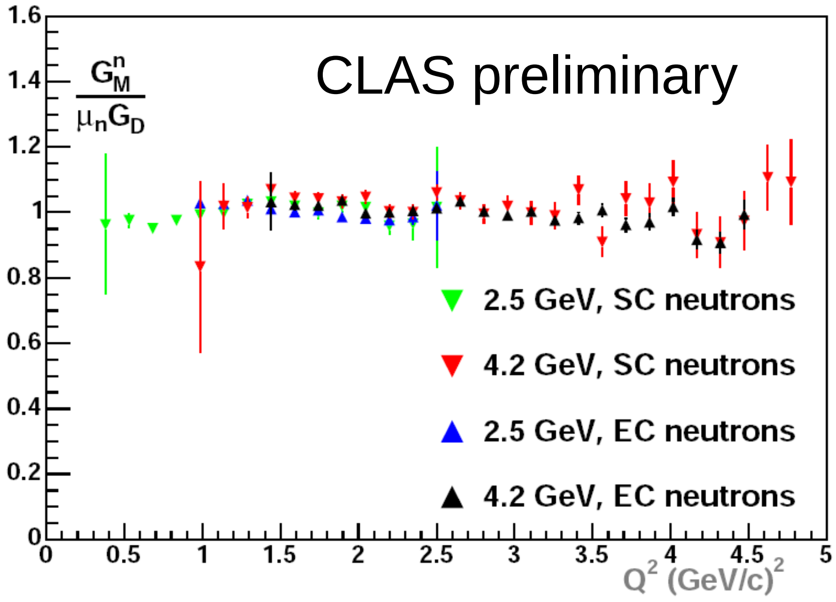
The Ratio Method - Systematic Errors

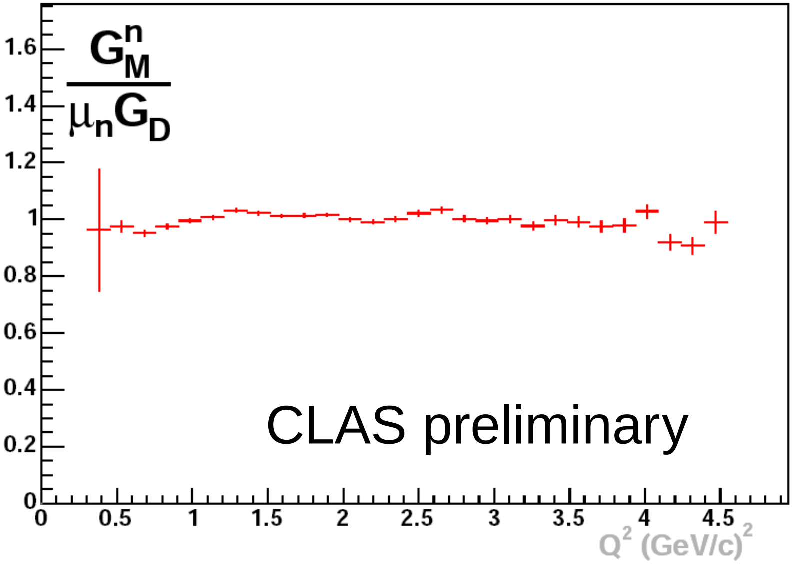
Quantity	2.6 GeV (%)	4.2 GeV (%)	Quantity	2.6 GeV (%)	4.2 GeV (%)
Calorimeter neutron efficiency parameterization	< 1.5	< 1.0	TOF neutron efficiency parameterization	< 2.0	< 3.2
proton σ	< 1.0	< 1.5	G_E^n	< 0.5	< 0.7
Fermi loss correction	< 0.8	< 0.9	θ_{pq} cut	< 0.4	< 1.0
neutron accidentals	< 0.07	< 0.3	neutron MM cut	< 0.5	< 0.07
neutron proximity cut	< 0.22	< 0.15	proton efficiency	< 0.3	< 0.35
Nuclear Corrections	< 0.17	< 0.2	Radiative corrections	< 0.05	< 0.06

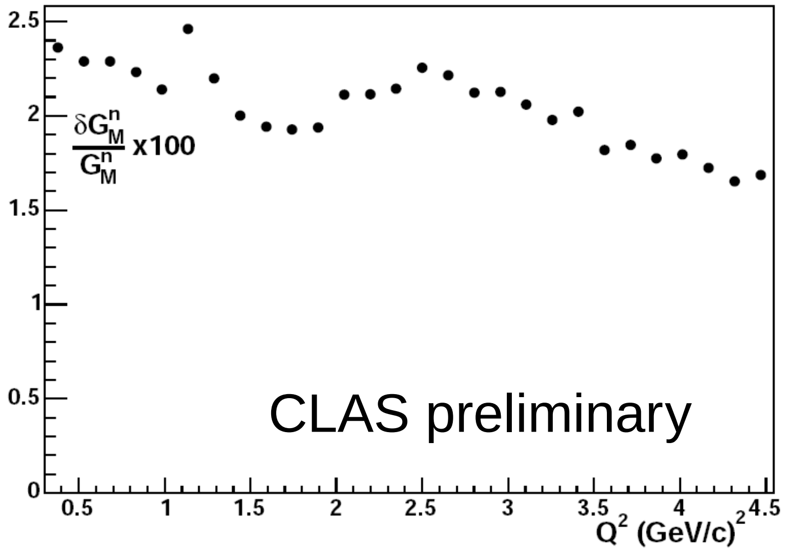
Upper limits on percent estimated systematic error for different contributions.

Results - Overlaps and Final Averages

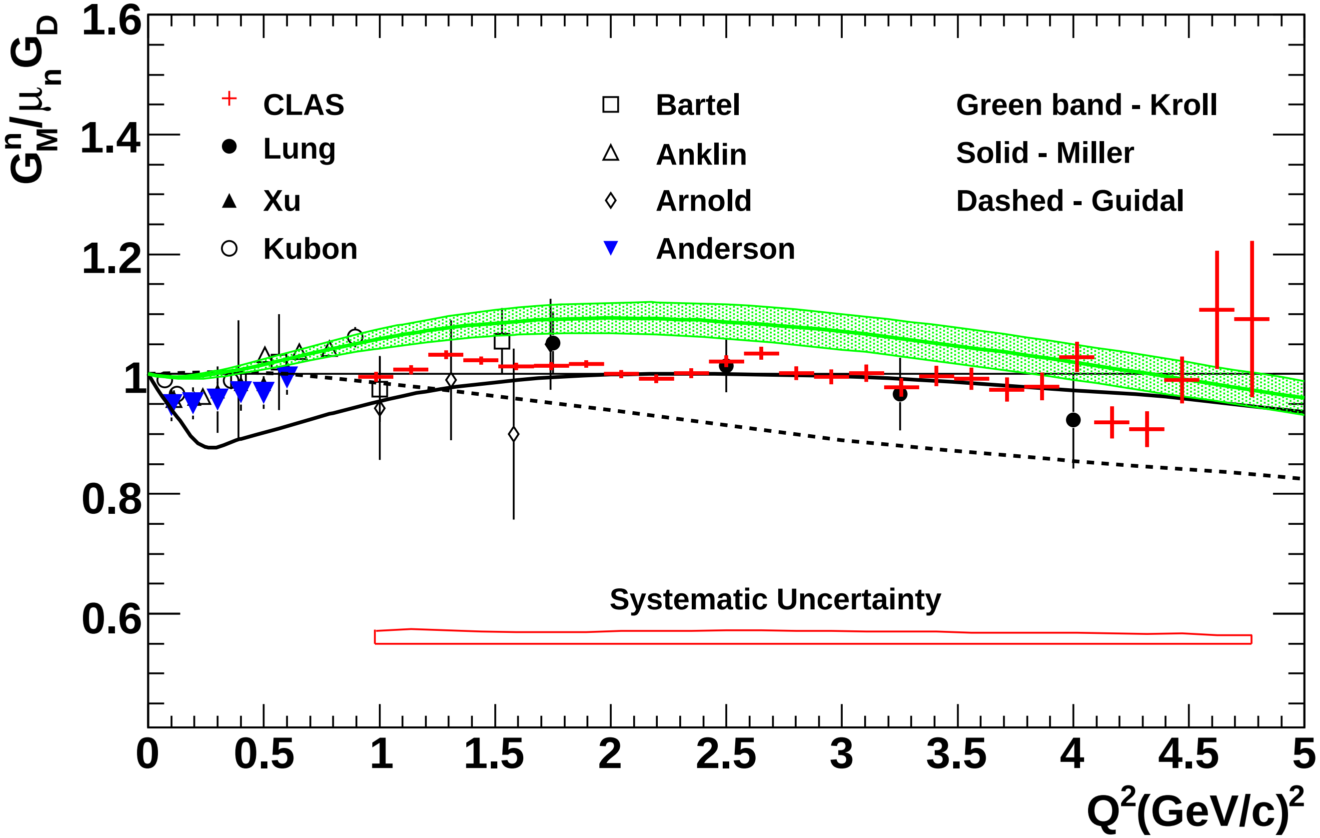
- Overlapping measurements of G_M^n scaled by the dipole are consistent.
- Weighted-average $G_M^n/\mu_n G_D$ and systematic uncertainty $\frac{\delta G_M^n}{G_M^n} \times 100$ ($< 2.5\%$).





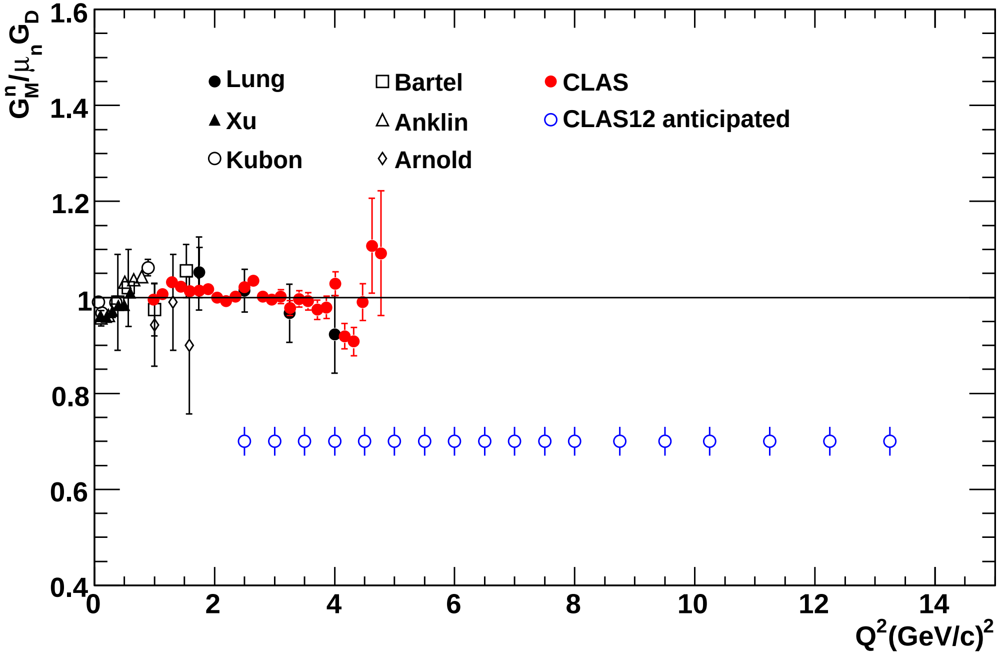


Results - Comparison with Existing Data



Current Status and the Future

- Analysis of the normal-torus-field data at 2.6 GeV and 4.2 GeV are under CLAS Collaboration review and have received verbal approval.
- The reversed-torus-polarity data set is still being analyzed.
- A draft of a Physical Review Letter is ready for Collaboration review.
- A proposal to measure G_M^n at 12 GeV was approved by the JLab PAC in June, 2007. The expected data range and uncertainties are shown below.

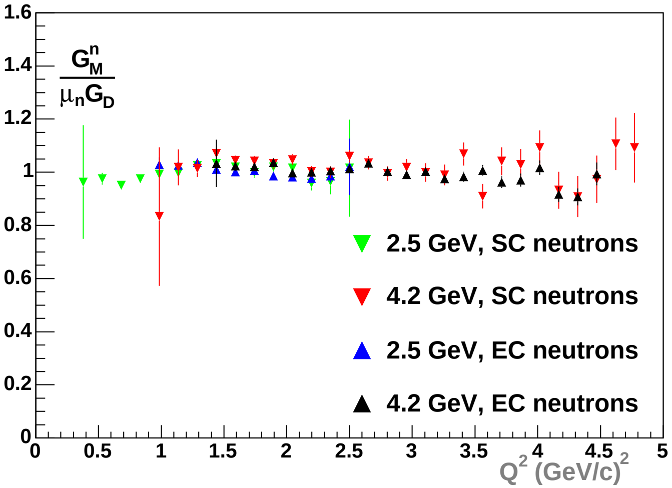


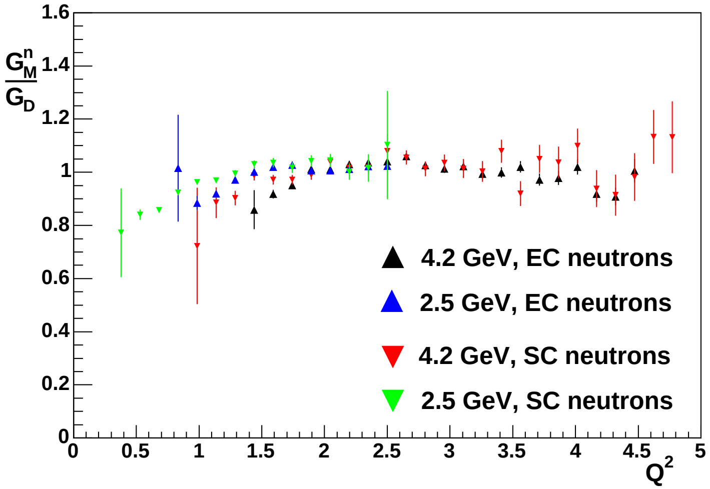
Conclusions

- We have measured the neutron magnetic form factor G_M^n over the range $\mathrm{Q}^2 = 1.0 - 4.5\ (\mathrm{GeV/c})^2$ to a precision better than 2.5%.
- The four different measurements of G_M^n at two beam energies with the calorimeter and the TOF system in CLAS are consistent.
- Some differences exist with previous measurements at $\mathrm{Q}^2 < 1(\mathrm{GeV/c})^2$.
- The results are consistent with the dipole approximation within 5% across almost the full range of Q^2.
- Analysis note has been approved and a well-developed draft of a Letter is ready for ad hoc review.

Additional Slides

Effect of Fermi Correction

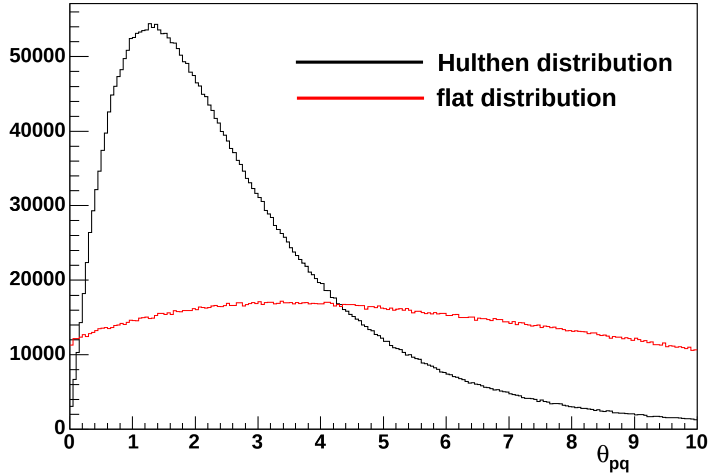




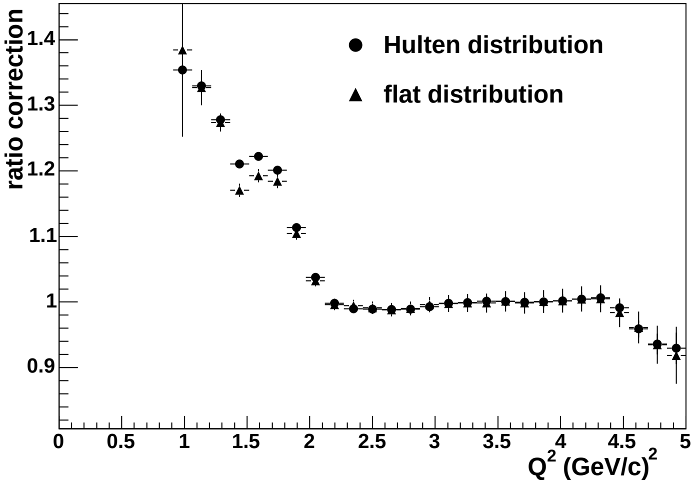
Reduced G_M^n for four different measurements.

Reduced G_M^n for four different measurements. The Fermi corrections have *not* been applied.

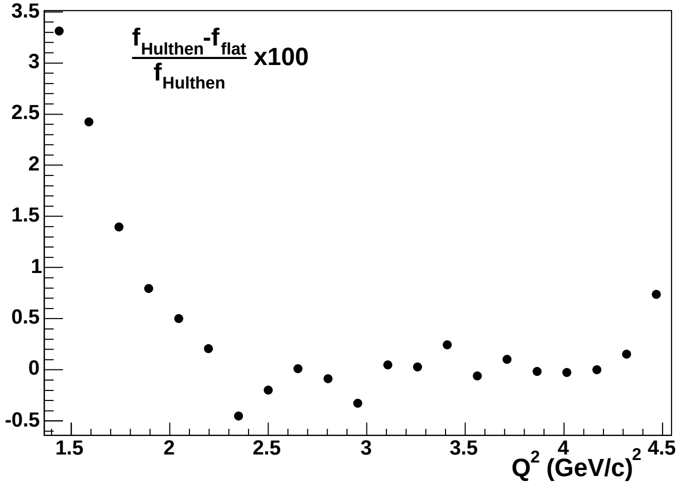
Uncertainty of the Fermi Correction



Nucleon momentum distributions.



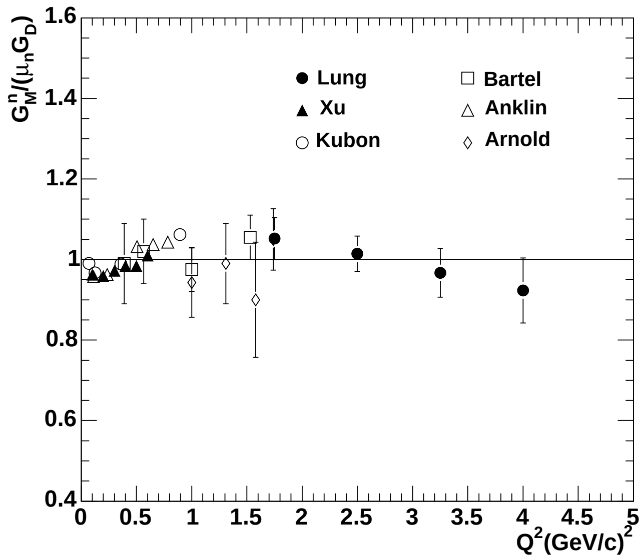
Ratio correction factors at 4.2 GeV.

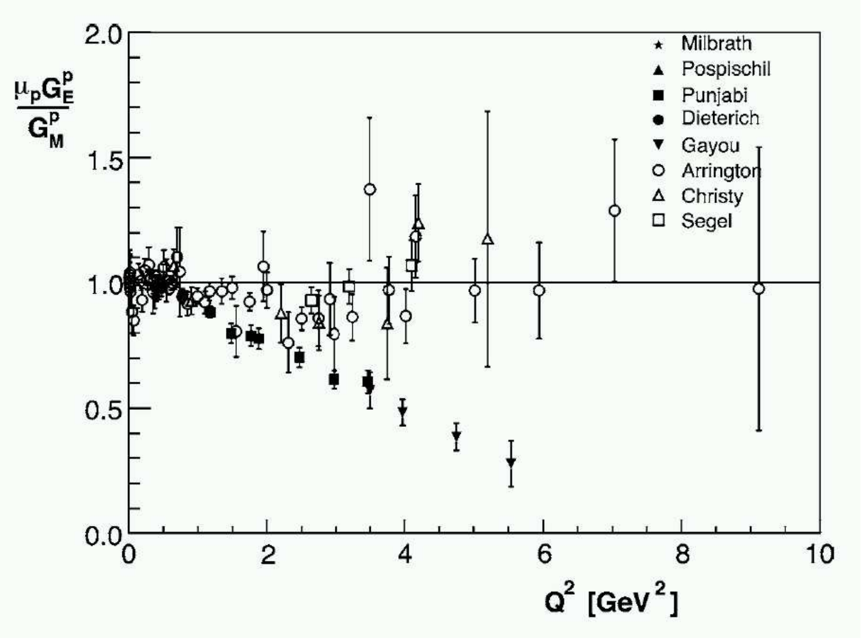


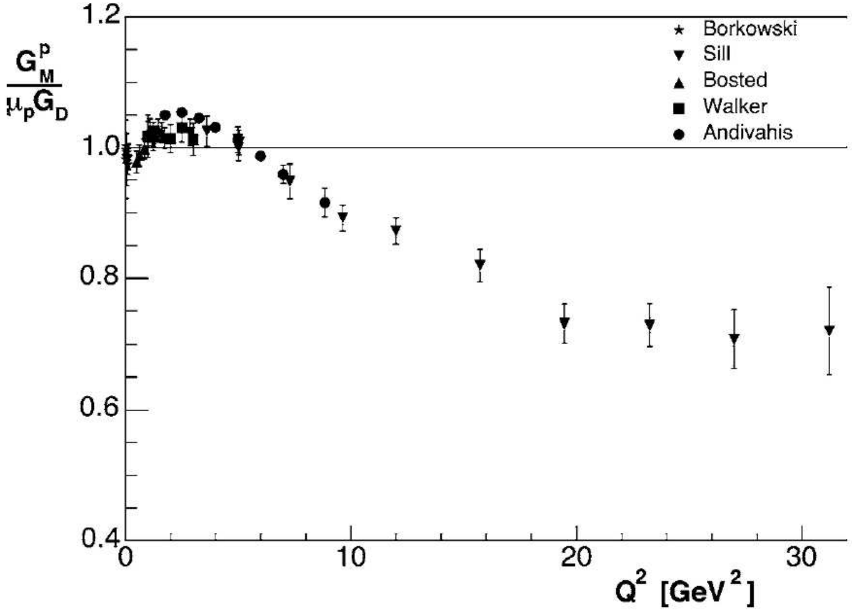
Fractional difference in the ratio correction factor obtained from the Hulthen and flat nucleon momentum distributions.

Published Measurements of Elastic Form Factors

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







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The Ratio Method - Systematic Errors

- Calorimeter neutron detection efficiency parameterization: The neutron efficiency was fitted with a third order polynomial plus a flat region at higher momentum. To study systematic uncertainties the highest order term was dropped and the ratio R regenerated. The upper limit on the range of differences for the different extractions of R was assigned the systematic uncertainty.
- TOF neutron detection efficiency parameterization: Similar to calorimeter extraction except the second and third order terms in the polynomial were dropped.

Detector	2.6 GeV	4.2 GeV
Calorimeter	1.5	1.0
TOF	2.0	2.0

Percentage systematic uncertainties in neutron efficiency parameterization.

- These are the largest contributions from this measurement.

Reducing SC Background

1. Cut on the time difference between the measured TOF and the predicted TOF using the neutron momentum extracted from the missing momentum.

2. Require a minimum of 5 MeV (electron equivalent) in the SC to reject low-energy photons.