Measuring the Neutron Magnetic Form Factor G_M^n Using the Ratio Method with CLAS12

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Outline:

1. Motivation - Why Measure G_M^n?
2. Why two G_M^n experiments?
3. The Ratio Method
4. Neutron Detection Efficiency
5. Getting the ratio: particle selection, acceptance matching
6. Corrections, status.

Why Measure G_M^n?

- Campaign at JLab to measure all elastic electromagnetic form factors (magnetic and electric for proton and neutron).
- Reveal the internal landscape of the nucleon - i.e., the charge and magnetization distributions.
- Limiting case of General Parton Distributions - building a tomographic picture of the nucleon.
- Testing ground for lattice QCD.
- Crucial for flavor decomposition - angular momentum in the nucleon.
- Map the transition from the hadronic picture to a quark-gluon description.

Why Measure G_M^n twice?

- Both JLab G_M^n experiments use the ratio method first applied by H. Anklin *et al.* in the mid-90's (Phys. Lett., B336:313, 1994).
- Ratio method used by Lachniet *et al.* with CLAS6 in 2000.
- PAC32 approved PR12-07-104 (CLAS12 measurement) followed by PAC35 approval (PR12-09-019) (Hall A measurement).

From the PAC35 report:

"... although a large overlap in Q2 between the two proposals exist, the PAC is convinced that proposed measurement is very valuable to determine the magnetic form factor with high precision. Both experiments using different equipment, this will allow a better control for the systematic error on GM(n)."

Measure G_M^n with the Ratio Method

The elastic $e-n$ or $e-p$ cross section in terms of the Sachs form factors is

$$R = \frac{\frac{d\sigma}{d\Omega}\left({}^2\mathrm{H}(e,e'n)p\right)_{QE}}{\frac{d\sigma}{d\Omega}\left({}^2\mathrm{H}(e,e'p)n\right)_{QE}} = a(Q^2)\frac{\sigma^n_{mott}\left({G_E^n}^2 + \frac{\tau_n}{\epsilon_n}{G_M^n}^2\right)\left(\frac{1}{1+\tau_n}\right)}{\sigma^p_{mott}\left({G_E^p}^2 + \frac{\tau_p}{\epsilon_p}{G_M^p}^2\right)\left(\frac{1}{1+\tau_p}\right)}$$

Deuteron target

Nuclear correction

Well-known proton cross section.

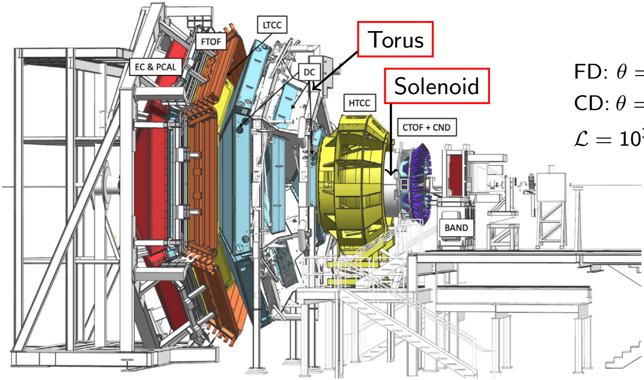
where

$$\tau_N = \frac{Q^2}{4M_N^2} \quad \epsilon = \left[1 + 2(1+\tau_N)\tan^2\frac{\theta}{2}\right]^{-1} \quad \sigma_{Mott} = \frac{\alpha^2 E' \cos^2\left(\frac{\theta}{2}\right)}{4E^3\sin^4\left(\frac{\theta}{2}\right)}$$

Solving for G_M^n

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

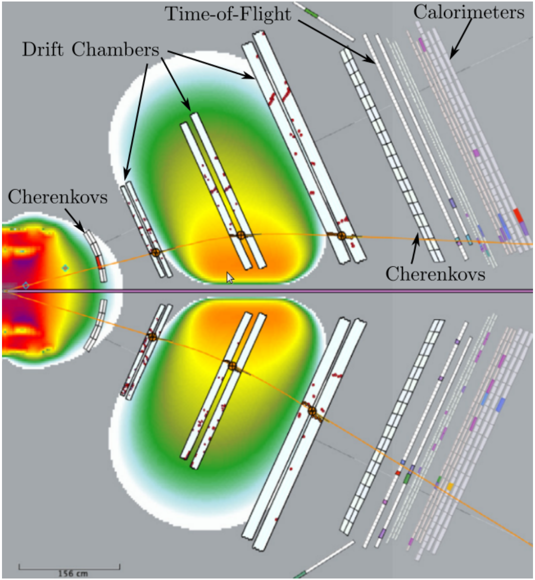
Measure G_M^n with the Ratio Method in CLAS12



FD: $\theta = 5 - 35\ deg$, $\Delta p/p = 1\%$
CD: $\theta = 35{-}125\ deg$, $\Delta p/p = 3\%$
$\mathcal{L} = 10^{35} cm^{-2} s^{-1}$

- Large acceptance - covers most of 4π.
- Forward Detector (FD) - Torus magnet, Cherenkovs (HTCC, LTCC), drift chambers (DC), time-of-flight counters (FTOF), EM calorimeters (PCAL/EC)
- Central detector (CD) - Solenoid magnet, silicon vertex tracker, time-of-flight (CTOF), neutron detector (CND)
- Back-Angle Neutron Detector (BAND) - scintillator-based neutron detector.

A CLAS12 Event

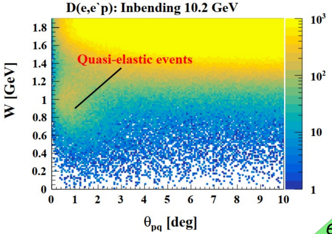


Quasielastic Event Selection to Measure G_M^n

Data: Run Group B, inbending electrons   Beam Energies: 10.2, 10.4, 10.6 GeV.

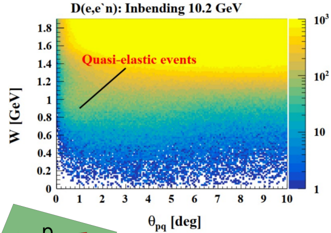
$^2\mathrm{H}(e, e'p)n$ selection

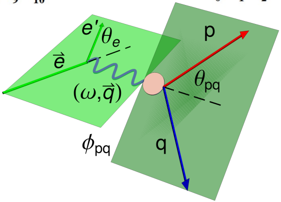
Select e' in FD and a single positive track in PCAL/ECAL



$^2\mathrm{H}(e, e'n)p$ selection

Select e' in FD and neutral track in PCAL/ECAL





The angle θ_{pq} lies between the 3-momentum transfer $\vec{q}$ and the 3-momentum $\vec{P}_N$ of the detected nucleon.

Beam Energy Cut

Calculate the beam energy E_{beam}^{angles} from the measured electron and nucleon angles θ_e, θ_N .*

$$E_{beam}^{angles} = M_N \left[\frac{1}{\tan\left(\frac{\theta_e}{2}\right) \tan\theta_N} - 1 \right]$$

$^2\mathrm{H}(e, e'p)n$ selection

$^2\mathrm{H}(e, e'n)p$ selection

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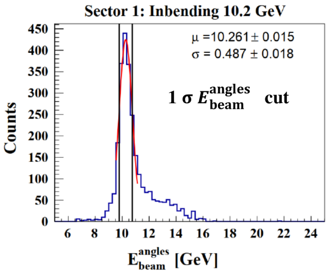

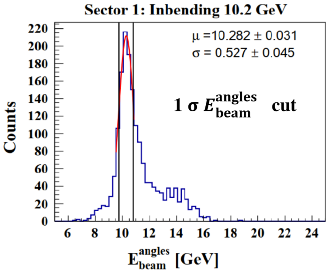

*Beam Energy Measurement with $ep \to ep$ elastic scattering on CLAS, S.Stepanyan, CLAS-NOTE 2002-008.

Azimuthal Angle Cut

Require the scattered electron and nucleon to lie in the same plane.
Restrict the recoil mass to $0.85 < W < 1.05$ GeV.

$$\Delta\phi = \phi_N - \phi_e$$

$^2\mathrm{H}(e, e'p)n$ selection

$^2\mathrm{H}(e, e'n)p$ selection

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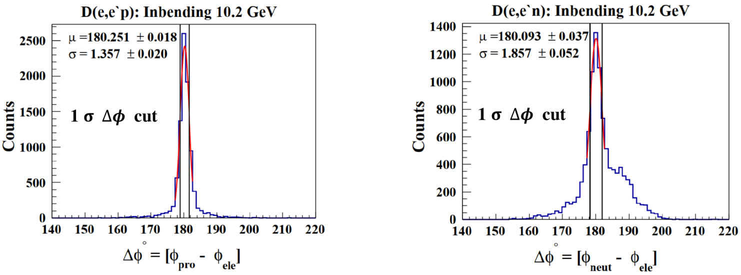
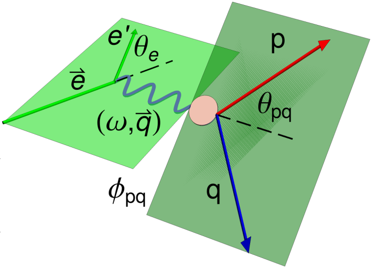


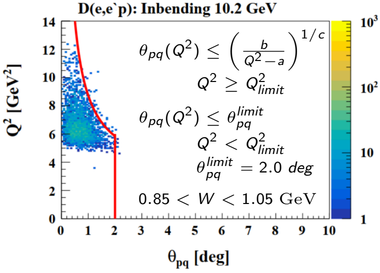
Quasielastic events have a small angle θ_{pq} relative to the 3-momentum transfer $\vec{q}$.



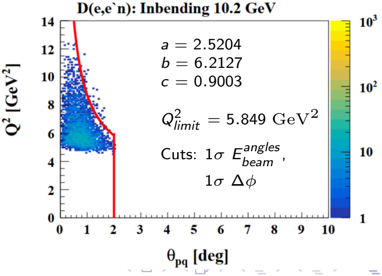
$$\theta_{pq} \le \quad \theta_{pq}^{limit} = 2\ deg, \qquad Q^2 < a + \frac{b}{(\theta_{pq}^{limit})^c}$$

$$\le \quad \left(\frac{b}{Q^2 - a}\right)^{1/c} \qquad Q^2 > a + \frac{b}{(\theta_{pq}^{limit})^c}$$

$^2\mathrm{H}(e,e'p)n$ selection



$^2\mathrm{H}(e,e'n)p$ selection

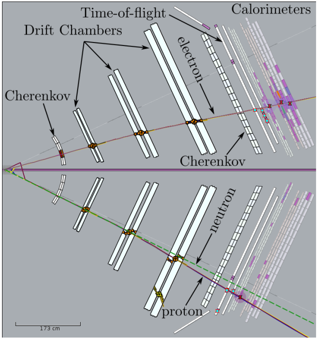


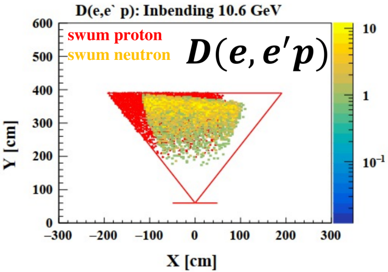
Acceptance Matching

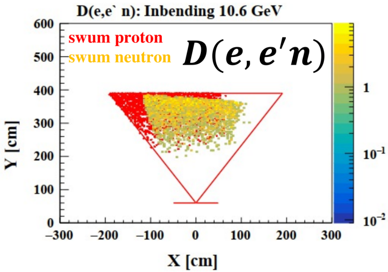
To insure the $e - n$ and $e - p$ acceptances are equal (1) start with the electron information, (2) assume elastic scattering, (3) assume a stationary proton target, (4) calculate its momentum, and (5) swim the track through CLAS12.

If the track strikes the CLAS12 fiducial volume keep the event, otherwise drop it.

Repeat 1-5 for the neutron and if the track hits CLAS12 keep the event, otherwise drop it.







Missing Energy Cut

The conservation of 4-momentum conservation implies the missing energy for quasi-elastic events should be zero.

$$E_x = E_{beam} + E_N - E_{e'} - E_{N'} \quad \text{where} \quad E = \sqrt{P^2 + m^2}$$

Cuts applied: 1σ E_{beam}^{angles}, 1σ $\Delta\phi$, θ_{pq} cut, 3σ E_x.

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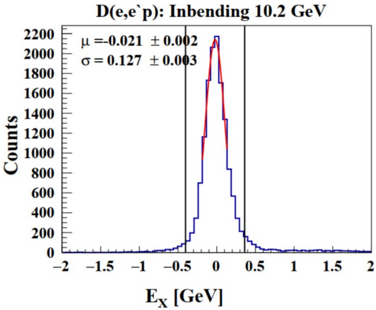
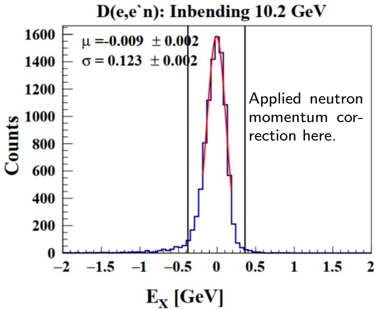
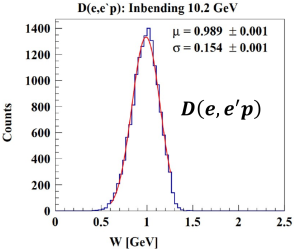
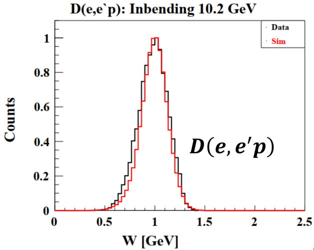




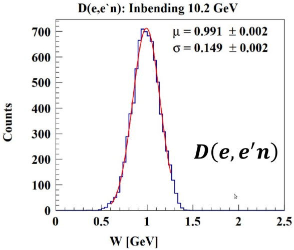
Validate the Quasielastic Event Selection

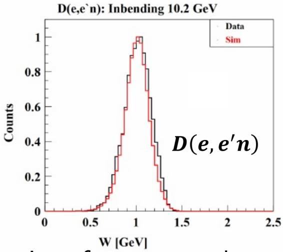
$^{2}\mathrm{H}(e, e'p)n$ selection





$^{2}\mathrm{H}(e, e'n)p$ selection





Used QE scattering on deuterium event generator QUEEG (CLAS12-NOTE 2014-007).

Measured and simulated W distributions for $e - n$ and $e - p$ are similar.

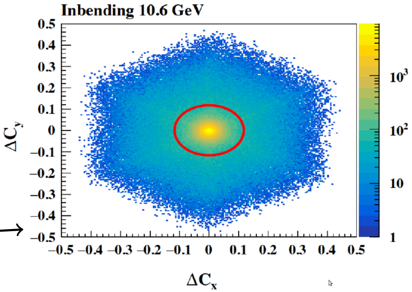
Corrections to the Ratio

$$R_{Cor} = f_{NDE} f_{PDE} f_{nuclear} f_{fermi} f_{radiative} R$$

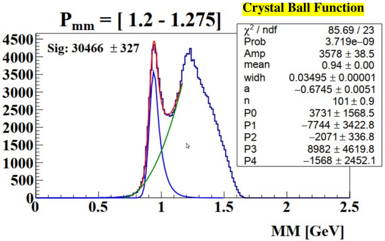
- f_{NDE}: Neutron Detection Efficiency
- f_{PDE}: Proton Detection Efficiency
- $f_{nuclear}$: Nuclear Correction
- f_{fermi}: Fermi motion correction
- $f_{radiative}$: Radiative corrections

Neutron Detection Efficiency (NDE)

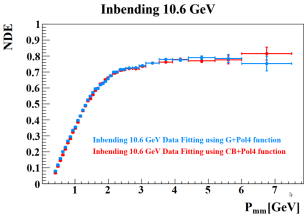
- Use the $^{1}\mathrm{H}(e, e'\pi^{+}n)$ reaction from Run Group A as a source of tagged neutrons.
- Select single-π^{+} events (no other charged particles) and predict where the missing neutron hits the ECAL. If it hits the fiducial volume, it is an expected neutron.
- Search over all neutral hits near the predicted neutron hit. If one hit is near, this is a detected event.

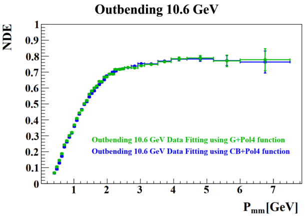


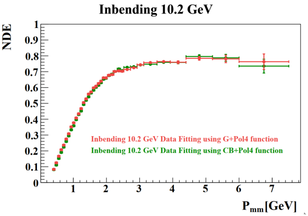
- Assume the missing momentum is equal to the neutron momentum, $P_{mm} = P_n$ and fit the missing mass distribution in each missing momentum bin (36 missing momentum bins).
- Extract the yield of expected and detected neutrons.
- Ratio of detected to expected is the NDE.



NDE Results and Parameterization





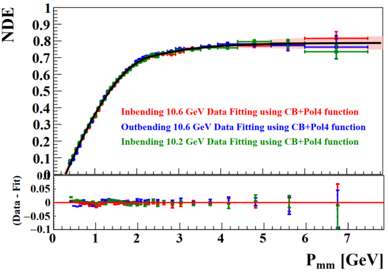


$$\epsilon_{NDE}(P_{mm}) = a_0 + a_1 P_{mm} + a_2 P_{mm}^2 + a_3 P_{mm}^3 \qquad P_{mm} < P_t$$

$$= a_4 \left(1 - \frac{1}{1 + \exp\left(\frac{P_{mm} - a_5}{a_6}\right)}\right) \qquad P_{mm} < P_t$$

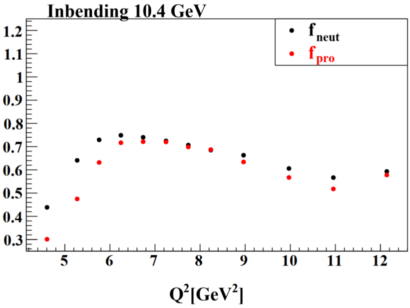
where P_t is the point where the two functions meet and the a_i are the fit coefficients.

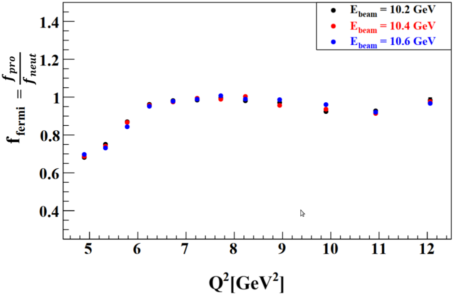
The plateau is at $\epsilon_{NDE} \approx 0.79$.



Fermi Corrections to the Ratio

- Fermi motion in the target causes nucleons to migrate out of the CLAS12 acceptance.
- This effect was simulated using QUEEG generator.†
- Take the ratio of the actual hit within the acceptance and satisfy the θ_{pq} cut to the expected hit that is calculated using electron information. Do this for both nucleons and take the super ratio.

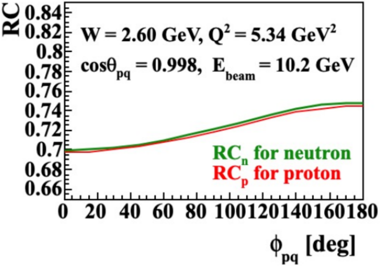


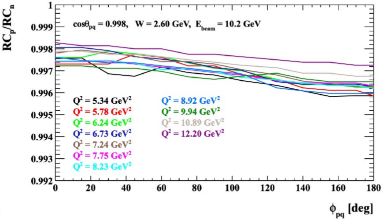


† CLAS-NOTE 2014-007.

Radiative Corrections to the Ratio

- Photons can be emitted before or after the collisions and alter the final, detected electron energy.
- The radiative corrections (RC) for G_M^n were calculated with the program EXCLURAD.
- The EXCLURAD program is written by A. Afanasev for exclusive $^1\mathrm{H}(e,e'\pi^+)n$ and modified to include the $^2\mathrm{H}(e,e'p)$ and $^2\mathrm{H}(e,e'n)$ channels.
- The EXCLURAD code contains the radiative correction for the electron.
- The radiated cross section is
  $$\frac{d\sigma}{d\Omega} = (1+\delta)\frac{d\sigma}{d\Omega}_{Born}.$$
- The calculation is performed twice, once for $^2\mathrm{H}(e,e'p)$ and then for $^2\mathrm{H}(e,e'n)$.
- Significant correction, but close to 1.0 in the ratio.





Status of CLAS12 Measurement

- The neutron magnetic form factor G_M^n is a fundamental quantity related to the magnetization in the nucleon.
- We are extracting G_M^n in the range $Q^2 = 5 - 12\ \mathrm{GeV}^2$ using the ratio method $R = \frac{e-n}{e-p}$ in quasielastic kinematics.
- Precise measurement of Neutron Detection Efficiency is essential. We found $\epsilon_{NDE} = 0.788 \pm 0.009$ in the region of the plateau.
- Some corrections to the ratio remain (nuclear, proton detection efficiency), determination of the systematic uncertainty, validation of some steps in the analysis.

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Thank You!