# $G_M^n$ Results From Hall B

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Outline:

1. Motivation - Why Measure $G_M^n$?
2. Why two $G_M^n$ experiments?
3. The Ratio Method
4. Getting the ratio: particle selection, acceptance matching
5. Corrections, neutron detection efficiency, status.

# Why Measure $G_M^n$?

- Part of a JLab campaign to measure all elastic electromagnetic form factors (magnetic and electric for proton and neutron).
- Goal is to reveal the internal landscape of the nucleon - i.e., the charge and magnetization distributions.
- Connections to a range of physics topics
  - 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 on deuterium first applied by H. Anklin *et al*. (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 the 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

Deuteron target

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

Nuclear correction

Well-known proton cross section.

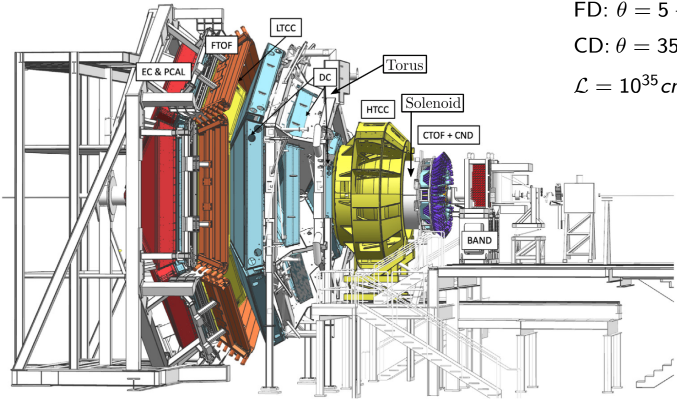
where

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

Solving for $G_M^n$

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

# The CLAS12 Detector in Hall B




FD: $\theta = 5 - 35\ deg$, $\Delta p/p = 1\%$

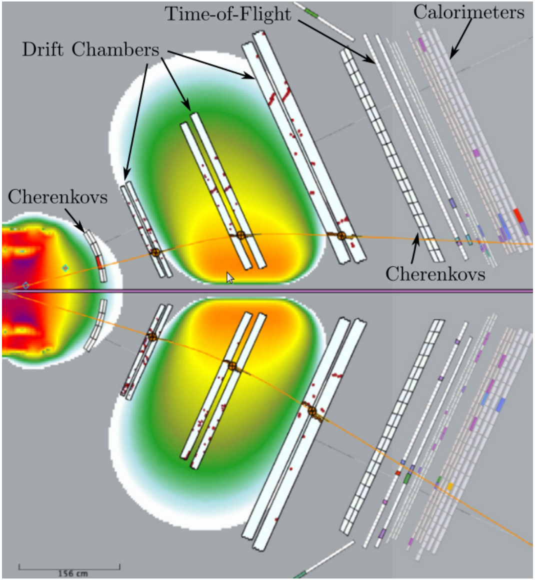
CD: $\theta = 35 - 125\ deg$, $\Delta p/p = 3\%$

$\mathcal{L} = 10^{35} cm^{-2} s^{-1}$

The $e - n$ and $e - p$ data are taken simultaneously with the same detector so many quantities (deadtime, integrated charge) cancel in the ratio.

- Large acceptance - covers most of $4\pi$.
- 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, barrel micromesh tracker, time-of-flight (CTOF), neutron detector (CND)
- Back-Angle Neutron Detector (BAND) - scintillator-based neutron detector.

# A CLAS12 Event

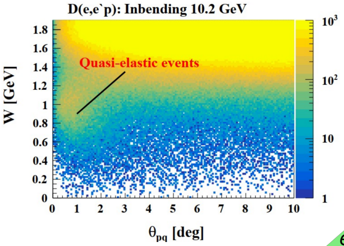


# Quasielastic Event Selection to Measure $G_M^n$

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

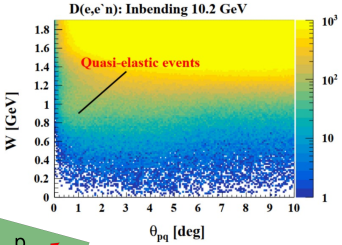
**$^2\mathrm{H}(e, e'p)n$ selection**

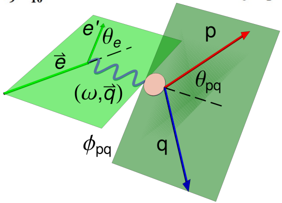
Select $e'$ in FD and a single positive track in PCAL/ECAL.




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

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



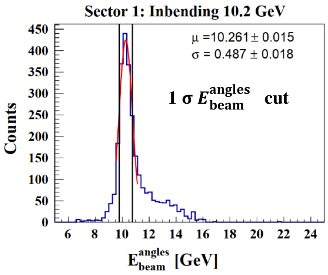




The angle $\theta_{pq}$ lies between the 3-momentum transfer $\vec{q}$ and the 3-momentum $\vec{P}_N$ of the detected nucleon.

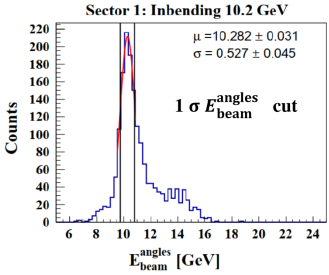
Calculate the beam energy $E_{beam}^{angles}$ from the measured electron and nucleon angles $\theta_e$, $\theta_N$ .* Restrict the recoil mass to $0.85 < W < 1.05$ GeV.

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

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




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



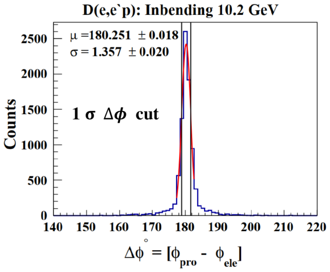

$*$ Beam Energy Measurement with $ep \to ep$ elastic scattering on CLAS, S.Stepanyan, CLAS-NOTE 2002-008.

# Azimuthal Angle Cut

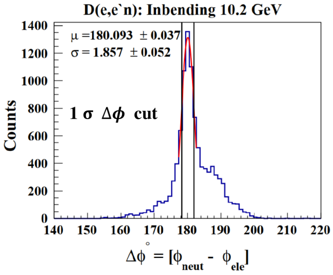
Require the scattered electron and nucleon to lie in the same plane.
Restrict the recoil mass to $0.85 < W < 1.05$ GeV.

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

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




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

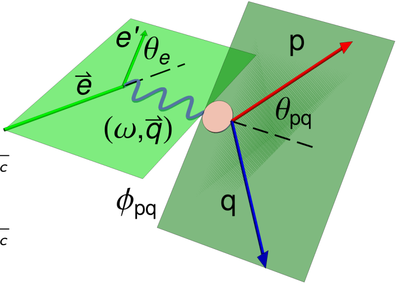


# $\theta_{pq}$ Cut

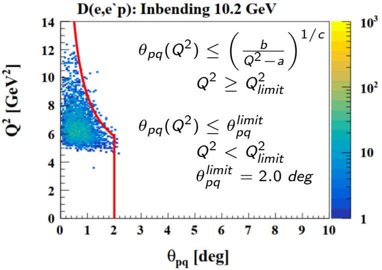
Quasielastic events have a small angle $\theta_{pq}$ relative to the 3-momentum transfer $\vec{q}$.

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

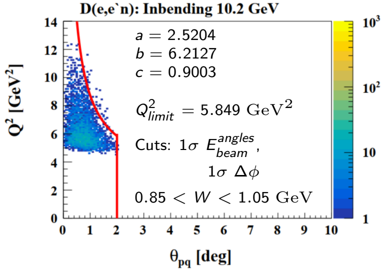
$$\leq \left(\frac{b}{Q^2 - a}\right)^{1/c}, Q^2 > a + \frac{b}{(\theta_{pq}^{limit})^c}$$




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




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

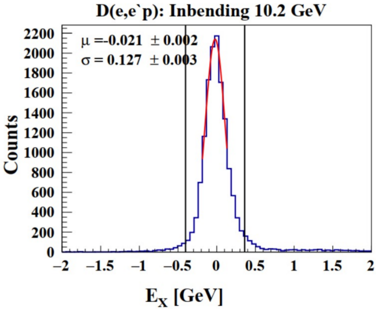


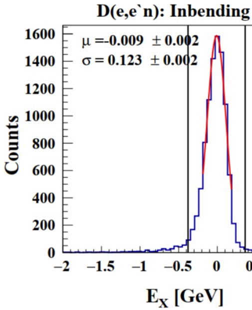
# Missing Energy Cut

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: $1\sigma$ $E_{beam}^{angles}$, $1\sigma$ $\Delta\phi$, $\theta_{pq}$ cut, $3\sigma$ $E_x$.



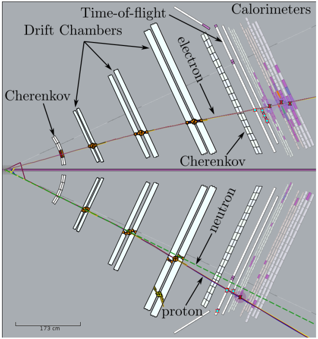

Applied neutron momentum correction here.

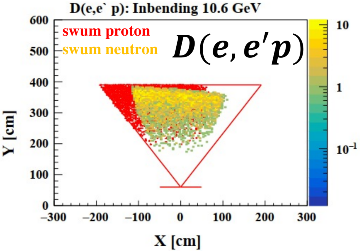
# Acceptance Matching

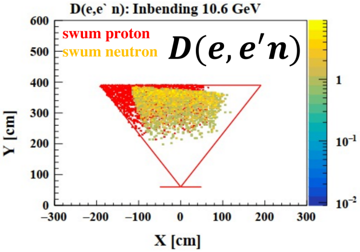
To insure the $e-n$ and $e-p$ acceptances are equal (1) start with the electron information, (2) assume elastic scattering, (3) assume a stationary proton target, (4) calculate its momentum, and (5) swim the track through CLAS12.

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.




Cuts:

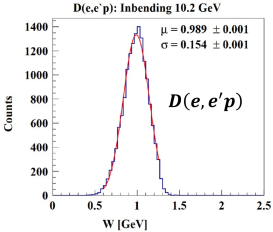
$1\sigma\ E_{beam}^{angles}$
$1\sigma\ \Delta\phi$
$\theta_{pq}$
$3\sigma\ E_x$

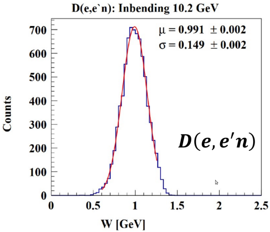
No $W$ cut

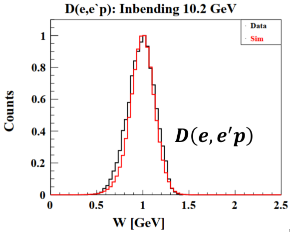
# Validate the Quasielastic Event Selection

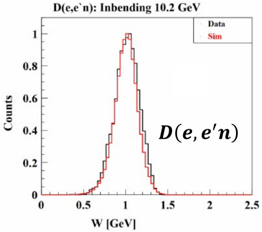
$^2\mathrm{H}(e, e'p)n$ selection

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

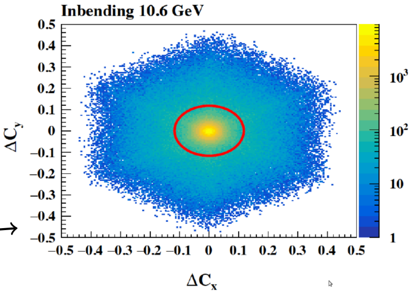
# Corrections to the Ratio

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

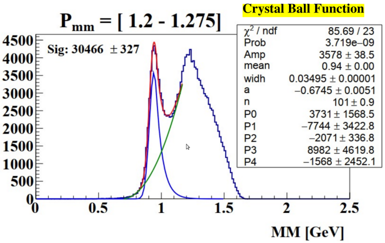
- $f_{NDE}$: Neutron Detection Efficiency
- $f_{PDE}$: Proton Detection Efficiency
- $f_{nuclear}$: Nuclear Correction
- $f_{fermi}$: Fermi motion correction
- $f_{radiative}$: Radiative corrections

# Neutron Detection Efficiency (NDE)

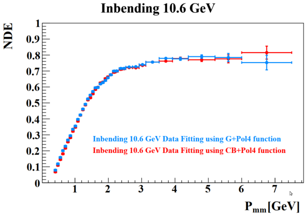
- Use the ${}^{1}\mathrm{H}(e, e'\pi^{+}n)$ reaction from Run Group A as a source of tagged neutrons.
- Select single-$\pi^{+}$ events (no other charged particles) and predict where the missing neutron hits the ECAL. If it hits the fiducial volume, it is an expected neutron.
- Search over all neutral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

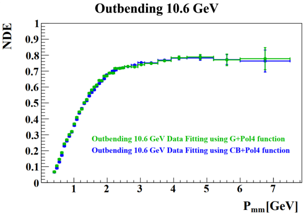


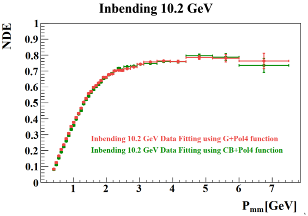

- Assume the missing momentum is equal to the neutron momentum, $P_{mm} = P_n$ and fit the missing mass distribution in each missing momentum bin (36 missing momentum bins).
- Extract the yield of expected and detected neutrons.
- Ratio of detected to expected is the NDE.



# NDE Results and Parameterization



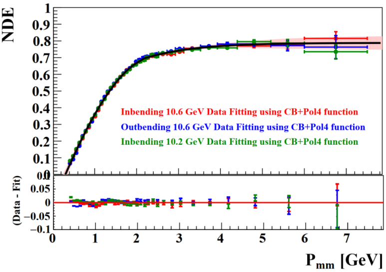




$$
\begin{aligned}
\epsilon_{NDE}(P_{mm}) &= a_0 + a_1 P_{mm} + a_2 P_{mm}^2 + a_3 P_{mm}^3 && P_{mm} < P_t \\
&= a_4 \left( 1 - \frac{1}{1 + \exp\left( \frac{P_{mm} - a_5}{a_6} \right)} \right) && P_{mm} < P_t
\end{aligned}
$$

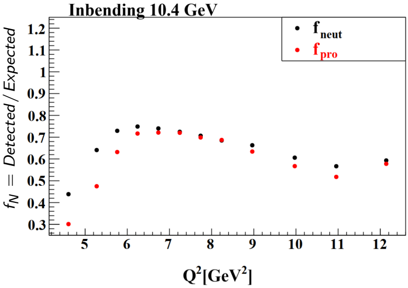
where $P_t$ is the point where the two functions meet and the $a_i$ are the fit coefficients.

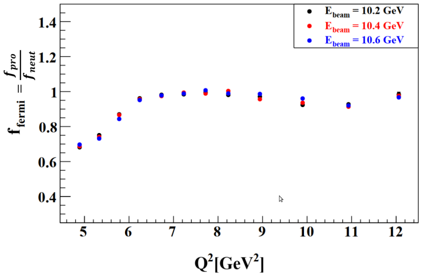
The plateau is at $\epsilon_{NDE} \approx 0.79$.



# Fermi Corrections to the Ratio

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

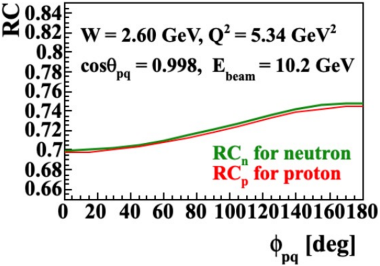


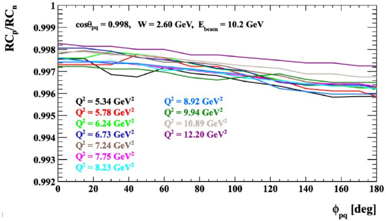




† CLAS-NOTE 2014-007.

# 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.
- Measurement of the Neutron Detection Efficiency is essential. We found $\epsilon_{NDE} \approx 0.8$ in the region of the plateau.
- Corrections to the ratio remain (nuclear, proton detection efficiency), determination of the systematic uncertainties, validation of steps in the analysis, comparison with simulation,...

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**Thank You!**

# Backup Slides

# World's data on $G_M^n$