

# Update on Neutron Magnetic Form Factor ( $G_M^n$ ) Measurement at High $Q^2$ with CLAS12

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## Outline:

- 1 Some Background
- 2 Datasets
- 3 Ratio Method
- 4 Selecting Quasi-elastic (QE)  $^2\text{H}(e, e'p)$  and  $^2\text{H}(e, e'n)$  reactions
- 5 Corrections to the Ratio
- 6 Preliminary Results
- 7 Remaining work

# The Magnetic Form Factor of the Neutron ( $G_M^n$ )

- The elastic, electromagnetic form factors ( $G_M^n$ ,  $G_E^n$ ,  $G_M^p$ , and  $G_E^p$ ) are fundamental quantities related to the distribution of charge and magnetization/currents in the neutron.
- Needed to extract the contribution of  $u$  and  $d$  quarks in the nucleon.
- Provide key constraints on generalized parton distribution (GPDs) and the structure of hadrons.
- Early test of lattice QCD because isovector form does not have disconnected diagrams.
- Broad, PAC-approved effort to measure all four form factors.

# Datasets - Run Group B

Exp. Detail	In-bending	Out-bending	In-bending
Run Period	Spring, 2019	Fall, 2019	Spring, 2020
Run Range	6156-6603	11093-11300	11323-11571
Beam	10.6 10.2	10.4	10.4
Number of Runs	117 106	97	171
Target	unpolarized LD <sub>2</sub>	unpolarized LD <sub>2</sub>	unpolarized LD <sub>2</sub>
Current	35-50 nA	40 nA	35-50 nA
Torus Field	-1	+1/+1.008	-1
Solenoid Field	-1	-1	-1

- Liquid deuterium target.
- Each dataset analyzed separately.
- Originally used Pass 1 - completed last November.
- Redoing analysis with Pass 2 data - ratio extraction complete, neutron detection efficiency and some other corrections ongoing.

# The Ratio Method to Measure $G_M^n$

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

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

Deuteron target ↙ ↘ Well-known proton cross section.

Nuclear correction

where

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

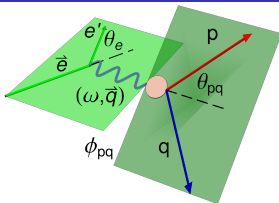
Solving for  $G_M^n$

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

Requires knowledge of other elastic, electromagnetic form factors

# Quasi-Elastic Event Selection - 1

Data: Run Group B, Pass 2  
 Inbending energies: 10.2, 10.4, 10.6 GeV  
 Outbending energies: 10.4 GeV



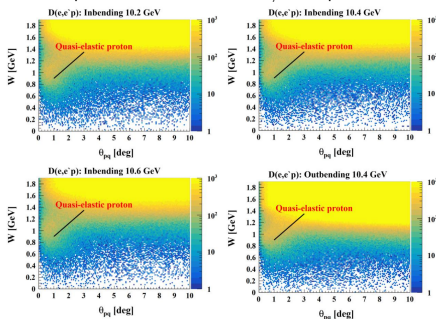
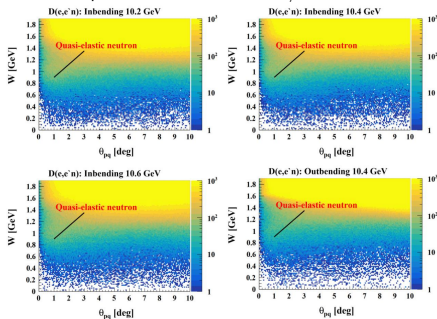
$\theta_{pq}$  is the angle the 3-momentum transfer  $\Delta\vec{p}$  and the detected nucleon momentum  $\vec{P}_N$

${}^2\text{H}(e, e'n)$

${}^2\text{H}(e, e'p)$

Require FD electron and PCAL/ECAL neutral

Require FD electron and PCAL/ECAL proton



# Quasi-Elastic Event Selection - 2

Data: Run Group B, Pass2

Inbending energies: 10.2, 10.4, 10.6 GeV

Outbending energies: 10.4 GeV

Electron beam energy cut\*

Calculate beam energy  $E_{beam}^{angles}$  using  $\theta_e, \theta_N$ .

Cuts Applied:  
0.85 GeV <  $W$  < 1.05 GeV

\*S.Stepanyan, CLAS-NOTE  
2002-008

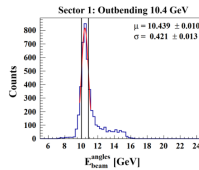
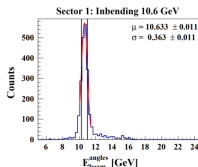
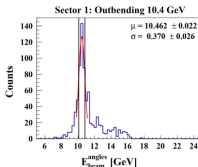
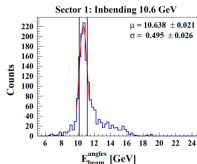
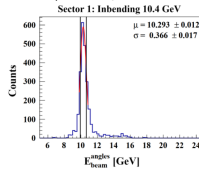
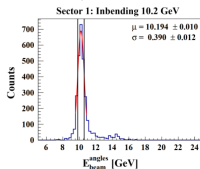
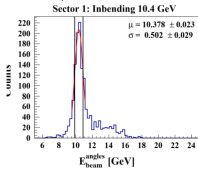
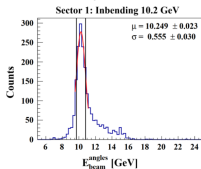
$$E_{beam}^{angles} = M_N \left( \frac{1}{\tan \frac{\theta_e}{2} \tan \theta_N} - 1 \right)$$

${}^2\text{H}(e, e'n)$

${}^2\text{H}(e, e'p)$

Require FD electron and PCAL/ECAL neutral

Require FD electron and PCAL/ECAL proton



# Quasi-Elastic Event Selection - 3

Data: Run Group B, Pass2  
 Inbending energies: 10.2, 10.4, 10.6 GeV  
 Outbending energies: 10.4 GeV

Cuts Applied:  
 $0.85 \text{ GeV} < W < 1.05 \text{ GeV}$   
 $1\sigma E_{beam}^{angles}$  cut

$\Delta\phi$  cut

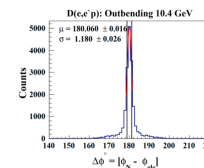
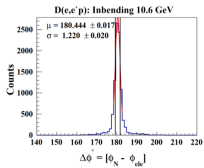
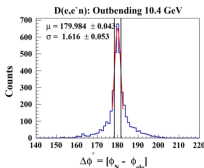
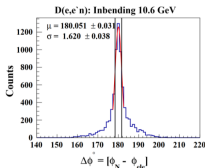
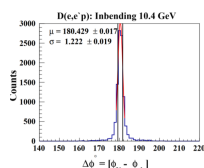
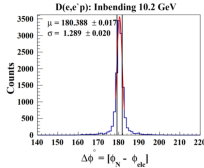
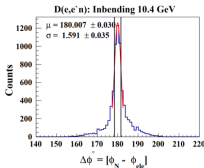
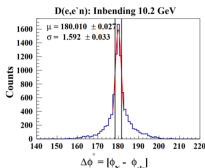
$\Delta\phi = \phi_N - \phi_e$  where  $\phi_N$  and  $\phi_e$  are the azimuthal angles of the nucleon and electron.

${}^2\text{H}(e, e'n)$

${}^2\text{H}(e, e'p)$

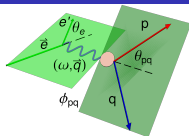
Require FD electron and PCAL/ECAL neutral

Require FD electron and PCAL/ECAL proton



# Quasi-Elastic Event Selection - 4

Data: Run Group B, Pass2  
 Inbending energies: 10.2, 10.4, 10.6 GeV  
 Outbending energies: 10.4 GeV

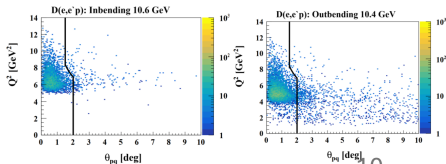
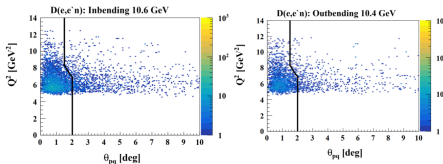
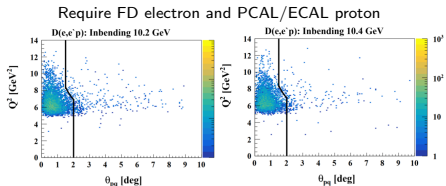
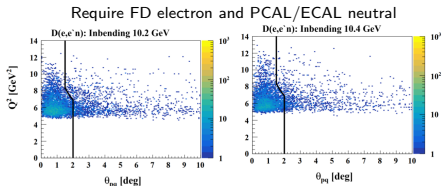


Cuts Applied:  
 $0.85 \text{ GeV} < W < 1.05 \text{ GeV}$   
 $1\sigma E_{beam}^{angles}$  cut  
 $1\sigma \Delta\phi$  cut

$\theta_{pq}$  cut on QE events  
 Range of  $\theta_{pq}$  distribution shrinks with increasing  $Q^2$ .  
 $Q^2 < f(\theta_{pq})$

${}^2\text{H}(e, e'n)$

${}^2\text{H}(e, e'p)$





# Comparing QE $e - p$ and $e - n$ Distributions

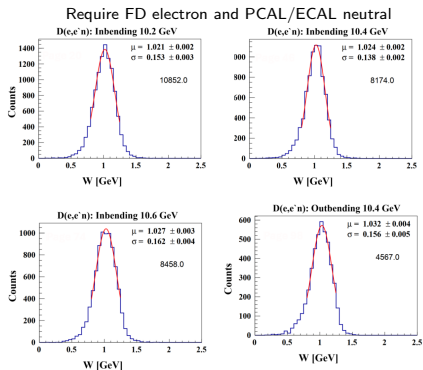
Data: Run Group B, Pass2  
 Inbending energies: 10.2, 10.4, 10.6 GeV  
 Outbending energies: 10.4 GeV

Cuts Applied:  
 $1\sigma E_{beam}^{angles}$  cut  
 $1\sigma \Delta\phi$  cut  
 $Q^2 < f(\theta_{pq})$

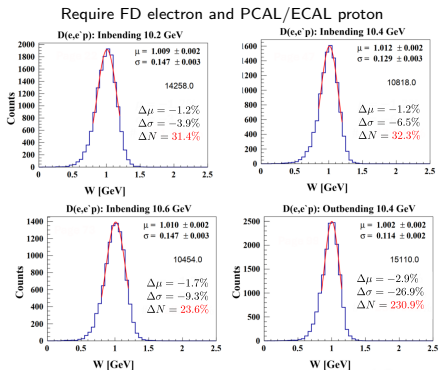
Inbending  $e'$ :  $e - n$ ,  $e - p$  distributions similar,  $N_{ep} > N_{en}$  by  $\approx 30\%$ .

Outbending  $e'$ : Many more  $e - p$  than  $e - n$  events.

${}^2\text{H}(e, e'n)$



${}^2\text{H}(e, e'p)$



Changes in values are relative to  $e - n$  events.

# Impact of Acceptance Matching

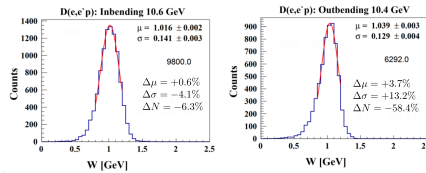
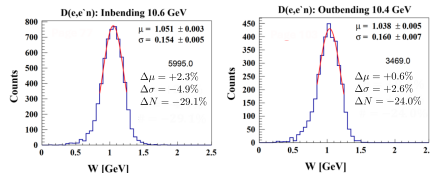
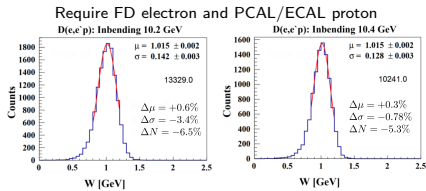
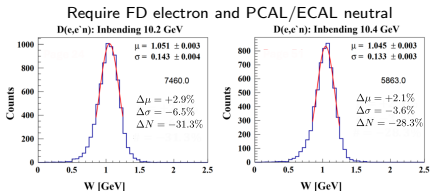
Data: Run Group B, Pass2  
 Inbending energies: 10.2, 10.4, 10.6 GeV  
 Outbending energies: 10.4 GeV

Cuts Applied:  
 $1\sigma E_{beam}^{angles}$  cut  
 $1\sigma \Delta\phi$  cut  
 $Q^2 < f(\theta_{pq})$   
 Acceptance Matching

Lose  $\approx 30\%$  of  $e - n$  events,  $\approx 5\%$   
 for inbending  $e - p$  and over half for  
 outbending.

${}^2\text{H}(e, e'n)$

${}^2\text{H}(e, e'p)$



Changes due to acceptance matching.

# Comparison with Simulation

Data: Run Group B, Pass2  
Inbending energies: 10.2, 10.4, 10.6 GeV  
Outbending energies: 10.4 GeV

Cuts Applied:  
 $1\sigma E_{beam}^{angles}$  cut  
 $1\sigma \Delta\phi$  cut  
 $Q^2 < f(\theta_{pq})$   
Acceptance Matching

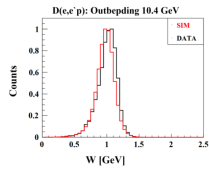
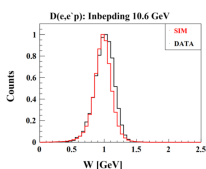
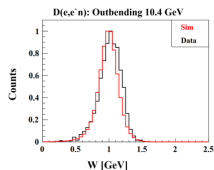
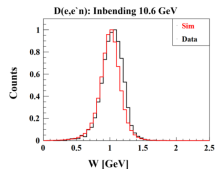
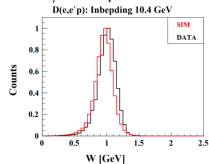
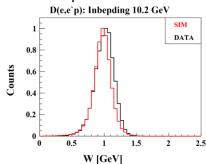
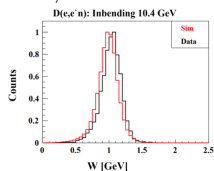
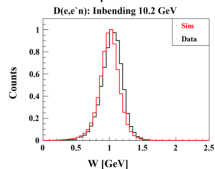
Used QUEEG event generator (CLAS-NOTE 2014-007) to simulate QE scattering from deuterium.

${}^2\text{H}(e, e'n)$

${}^2\text{H}(e, e'p)$

Require FD electron and PCAL/ECAL neutral

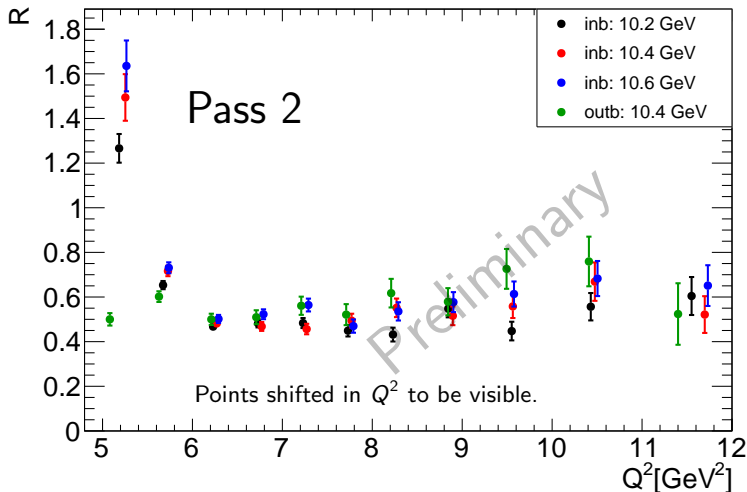
Require FD electron and PCAL/ECAL proton



# Preliminary Ratio Result Uncorrected

$$R = \frac{2H(e,e'n)}{2H(e,e'p)}$$

Cuts Applied:  
 $1\sigma E_{beam}^{angles}$  cut  
 $1\sigma \Delta\phi$  cut  
 $Q^2 < f(\theta_{pq})$   
Acceptance Matching



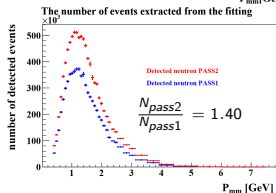
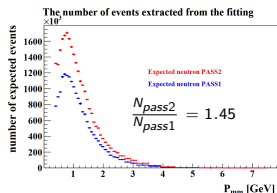
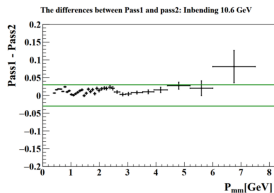
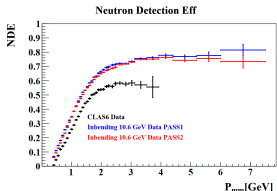
$$R_{Cor} = f_{NDE} f_{PDE} f_{nuc} f_{fermi} f_{rad} R$$

- $f_{NDE}$ : Neutron Detection Efficiency - ✓ ✓
- $f_{PDE}$ : Proton Detection Efficiency - ✓
- $f_{nuc}$ : Nuclear correction - in progress
- $f_{fermi}$ : Fermi Correction - ✓ ✓
- $f_{rad}$ : Radiative Correction - ✓ ✓

✓ - Done.      ✓ ✓ - Done and presented.

# Neutron Detection Efficiency - Pass 1 vs Pass 2

- To measure Neutron Detection Efficiency (NDE) use the  $ep \rightarrow e'\pi^+n$  reaction from RGA as a source of tagged neutrons.
- Detect  $ep \rightarrow e'\pi^+$ , predict location of neutron and if it strikes CLAS12 (expected neutrons) and then search for it. If found, this is a detected neutron. Ratio of detected to expected is NDE.
- Results - significant increase in the number of expected and detected neutrons. The average residual is  $\approx 1.5\%$ .

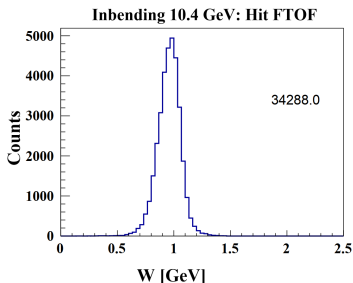


# Proton Detection Efficiency

- Use the  ${}^2\text{H}(e, e'p)n$  reaction in QE kinematics and pass 2 data.

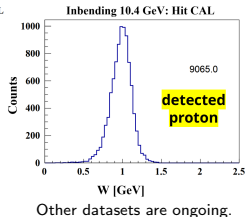
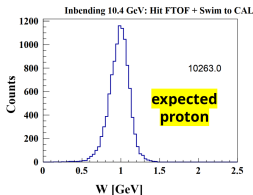
- Expected Proton

- Select  $e'$  in FD and require proton hit FTOF.
- Apply QE cuts.
  - $1\sigma E_{beam}^{angles}$  cut
  - $1\sigma \Delta\phi$  cut
  - $Q^2 < f(\theta_{pq})$
- Use the  $e'$  information, assume elastic scattering and a stationary target, predict the proton 3-momentum. Swim it to PCAL/ECAL. If it strikes the front face it is an expected proton. Otherwise drop the event.



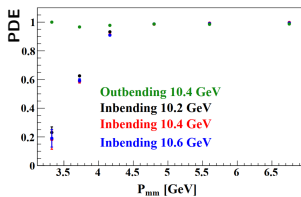
- Detected Proton

- Electron in FD, proton in PCAL/ECAL.
- QE cuts:  $E_{beam}^{angles}$ ,  $\Delta\phi$ ,  $Q^2 < f(\theta_{pq})$
- Extract yields - ratio of detected to expected is the PDE.

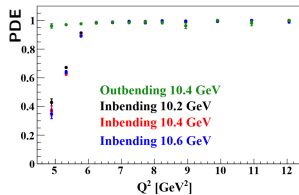


# Proton Detection Efficiency Results

Momentum  
Dependence

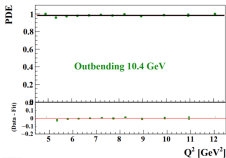
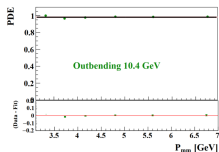
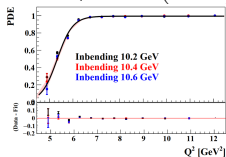
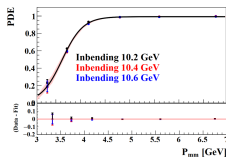


$Q^2$  Dependence



$$\eta(P_{mm}) = a_0 \left( 1 - \frac{1}{1 + \exp\left(\frac{P_{mm} - a_1}{a_2}\right)} \right)$$

$$\eta(Q^2) = b_0 \left( 1 - \frac{1}{1 + \exp\left(\frac{Q^2 - b_1}{b_2}\right)} \right)$$

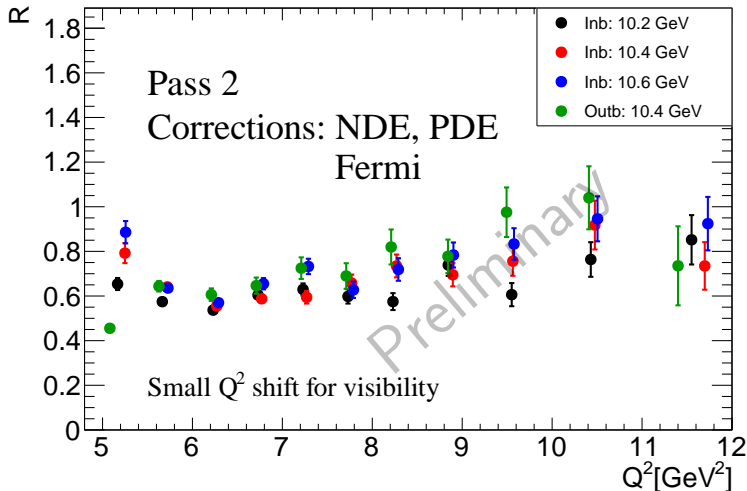




# Preliminary Ratio Result corrected

$$R = \frac{2H(e,e'n)}{2H(e,e'p)}$$

Cuts Applied:  
 $1\sigma E_{beam}^{angles}$  cut  
 $1\sigma \Delta\phi$  cut  
 $Q^2 < f(\theta_{pq})$   
Acceptance Matching



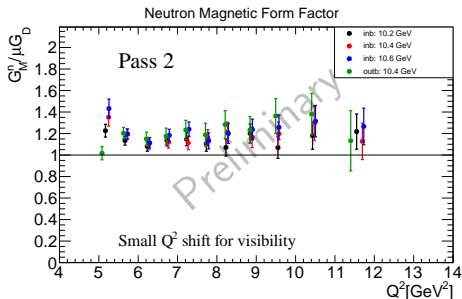
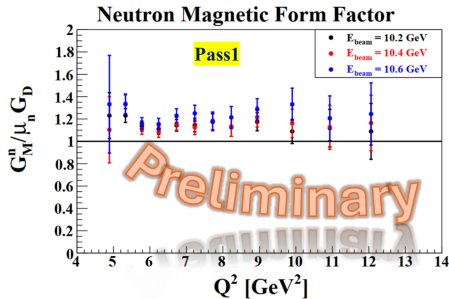
# Preliminary $G_M^n$ Result - 1

Recall Slide 4.

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

Use Arrington et al. parameterization of form factors (Physics Letters B 777 (2018) 8–15)

Leads to



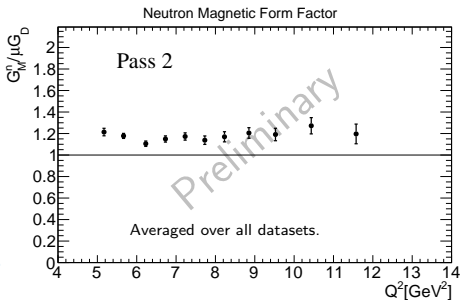
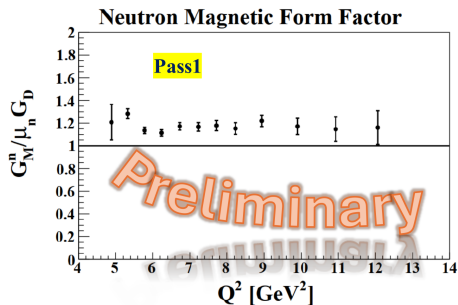
# Preliminary $G_M^n$ Result - 2

Recall

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

Use Arrington et al. parameterization of form factors (arXiv:1707.09063v2 [nucl-ex])

Leads to



- NDE for remaining RGA, Pass 2 data sets. Inbending, 10.6-GeV finished, outbending 10.6 GeV and inbending 10.2 GeV ongoing.
- Study differences between pass1 and pass 2  $W$  distribution.
- Nuclear correction - collaborating with two theorists .
- Systematic uncertainties for Pass 2  $G_M^n$  results - follow same procedure as Pass 1.
- Study luminosity effects.

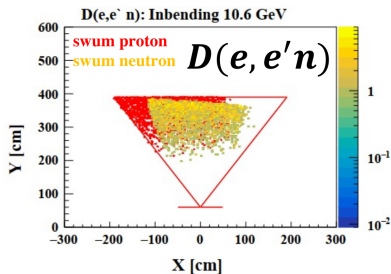
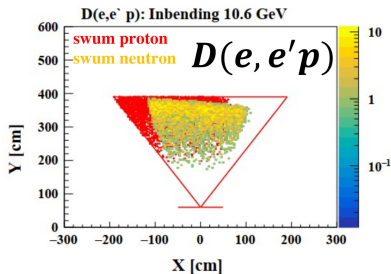
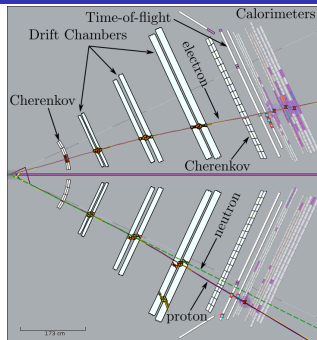
# Backup Slides

# 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.

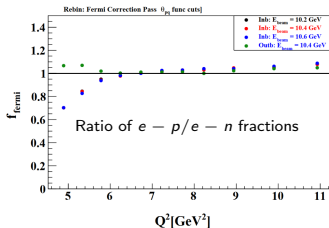
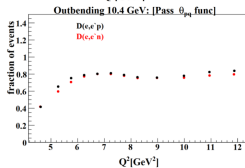
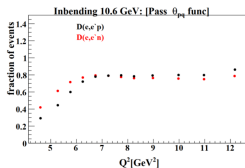
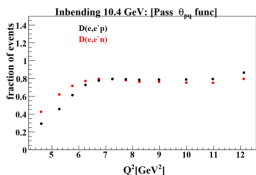
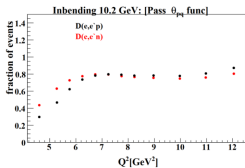
If the track strikes the CLAS12 fiducial volume keep the event, otherwise drop it.

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



# Fermi Corrections

- Fermi motion in the target causes scattered nucleons to migrate out of the CLAS12 acceptance.
- Effect was simulated using the QUEEG generator.
- Fraction of correction ( $f_{pro}$ ,  $f_{neut}$ ) is the ratio of the number of actual hits in the acceptance that satisfy the  $\theta_{pq}$  cut to the number of expected hits calculated using the electron information and assuming no Fermi motion.



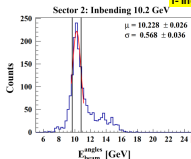
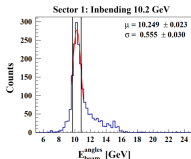
# Electron Beam Energy Cut - Inbending, 10.2 GeV

$D(e, e'n)$  Selection

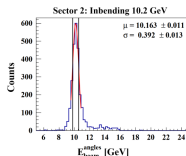
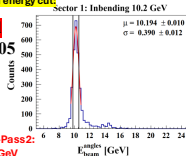
Quasi-elastic Selection

$D(e, e'p)$  Selection

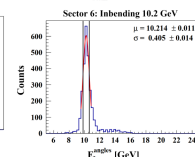
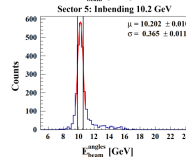
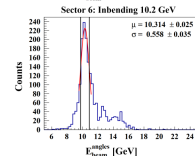
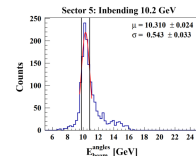
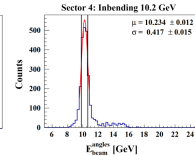
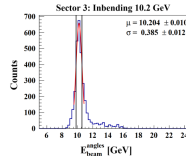
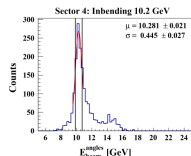
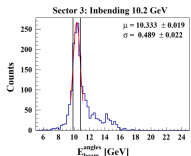
1- Incident electron beam energy cut



Cut applied  
 $0.85 < W < 1.05$



Data: Run Group B -Pass2:  
inbending 10.2 GeV





# Electron Beam Energy Cut - Inbending, 10.4 GeV

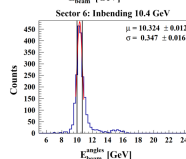
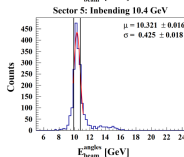
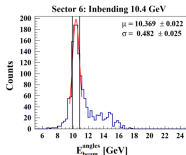
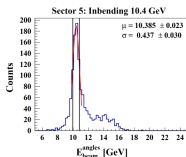
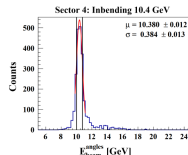
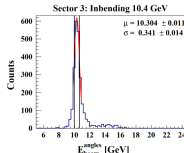
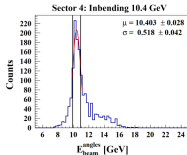
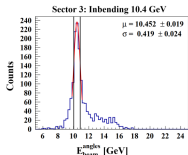
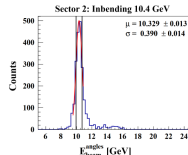
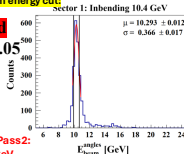
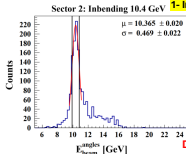
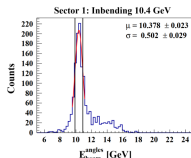
## $D(e, e'n)$ Selection Quasi-elastic Selection

## $D(e, e'p)$ Selection

1- Incident electron beam energy cut

**Cut applied**  
 $0.85 < W < 1.05$

Data: Run Group B - Pass2:  
 inbending 10.4 GeV



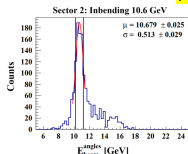
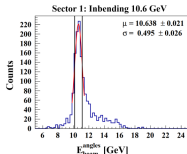
# Electron Beam Energy Cut - Inbending, 10.6 GeV

$D(e, e'n)$  Selection

Quasi-elastic Selection

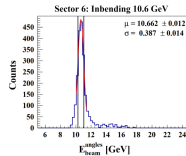
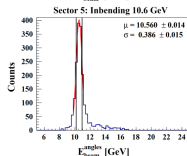
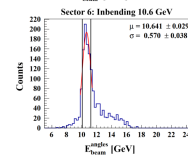
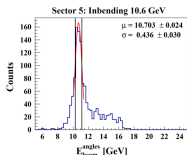
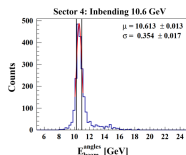
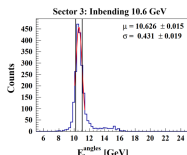
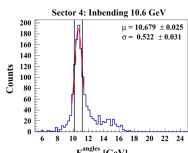
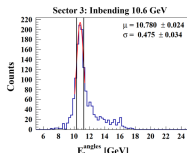
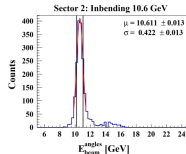
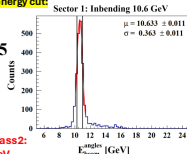
$D(e, e'p)$  Selection

1- Incident electron beam energy cut



Cut applied  
 $0.85 < W < 1.05$

Data: Run Group B -Pass2:  
inbending 10.6 GeV



# Electron Beam Energy Cut - Outbending, 10.4 GeV

$D(e, e'n)$  Selection

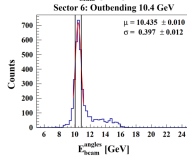
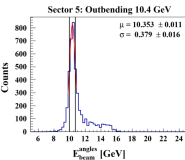
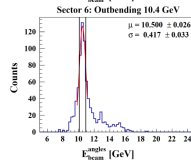
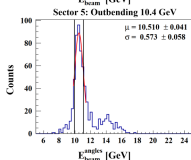
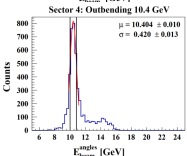
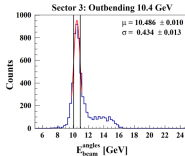
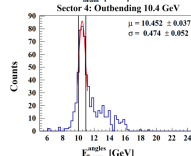
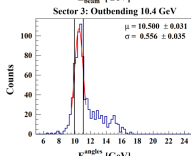
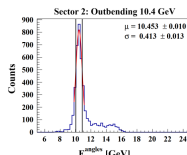
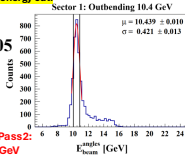
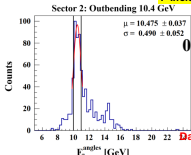
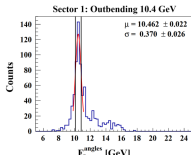
## Quasi-elastic Selection

$D(e, e'p)$  Selection

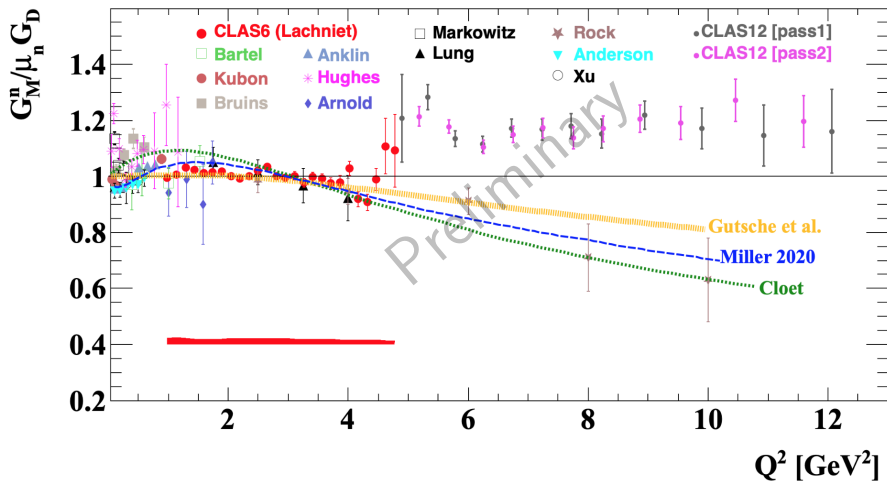
1- Incident electron beam energy cut

**Cut applied**  
 $0.85 < W < 1.05$

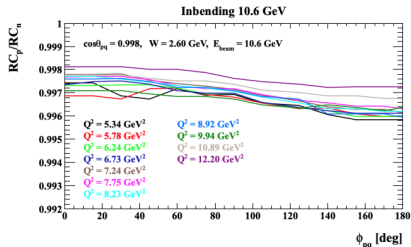
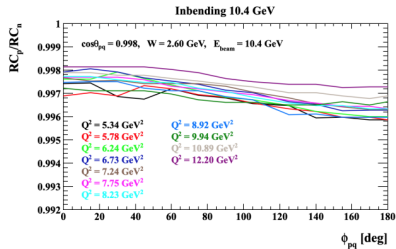
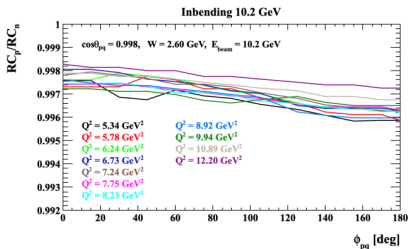
Data: Run Group B - Pass2:  
 Outbending 10.4 GeV



# Preliminary $G_M^n$



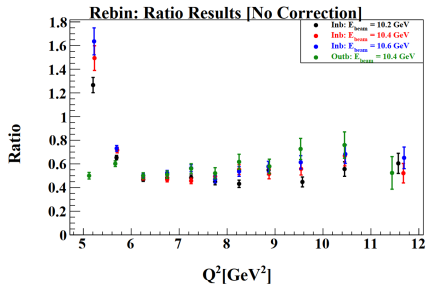
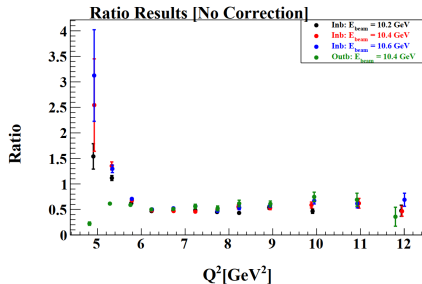
# Corrections to the Ratio - Fermi



# Corrections to the Ratio - None

$$\text{Ratio Result } R = \frac{D(e, e'n)}{D(e, e'p)}$$

**Cut applied**  
 $1 \sigma E_{\text{beam}}^{\text{angles}} \text{ cut}$   
 $1 \sigma \Delta\phi \text{ cut and } Q^2 < f(\theta_{pq})$   
Apply Acceptance Matching

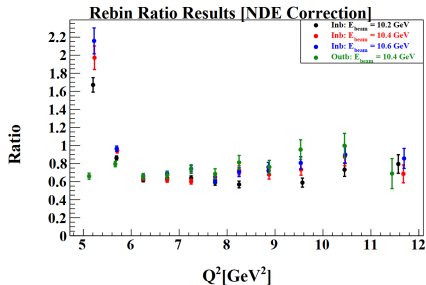
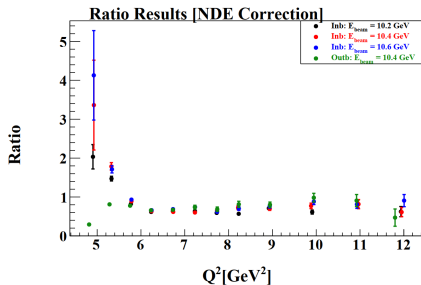


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# Corrections to the Ratio - NDE

**Ratio Result**  $R = \frac{D(e, e'n)}{D(e, e'p)}$

**Cut applied**  
 $1 \sigma E_{\text{beam}}^{\text{angles}}$  cut  
 $1 \sigma \Delta\phi$  cut and  $Q^2 < f(\theta_{pq})$   
Apply Acceptance Matching

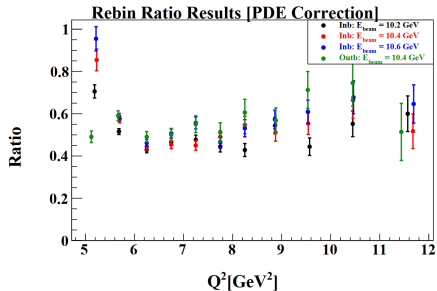
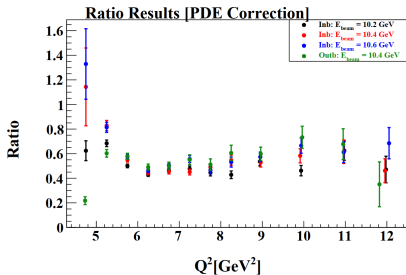


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# Corrections to the Ratio - PDE

$$\text{Ratio Result } R = \frac{D(e, e'n)}{D(e, e'p)}$$

**Cut applied**  
 $1 \sigma E_{\text{beam}}^{\text{angles}} \text{ cut}$   
 $1 \sigma \Delta\phi \text{ cut and } Q^2 < f(\theta_{pq})$   
Apply Acceptance Matching



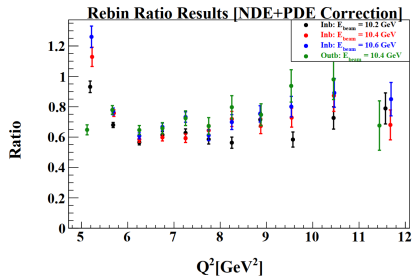
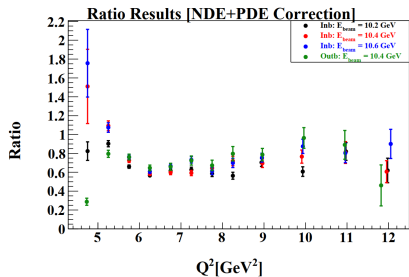
26



# Corrections to the Ratio - NDE+PDE

**Ratio Result**  $R = \frac{D(e, e'n)}{D(e, e'p)}$

**Cut applied**  
 $1 \sigma E_{\text{beam}}^{\text{angles}} \text{ cut}$   
 $1 \sigma \Delta\phi \text{ cut and } Q^2 < f(\theta_{pq})$   
 Apply Acceptance Matching

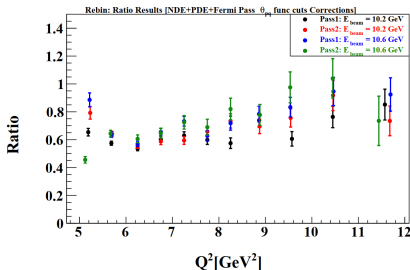
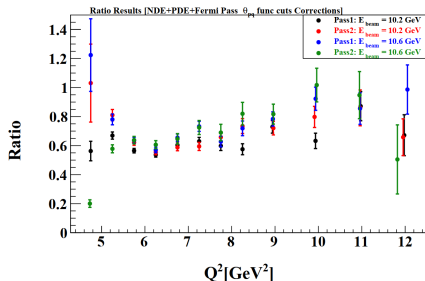


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# Corrections to the Ratio - NDE+PDE+Fermi

**Ratio Result**  $R = \frac{D(e, e'n)}{D(e, e'p)}$

**Cut applied**  
 $1 \sigma E_{\text{beam}}^{\text{angles}} \text{ cut}$   
 $1 \sigma \Delta\phi \text{ cut and } Q^2 < f(\theta_{pq})$   
 Apply Acceptance Matching



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