

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 ₂	unpolarized LD ₂	unpolarized LD ₂
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

$$R = \frac{\frac{d\sigma}{d\Omega} (^2\text{H}(e, e'n)p)_{QE}}{\frac{d\sigma}{d\Omega} (^2\text{H}(e, e'p)n)_{QE}} = a(Q^2) \frac{\sigma_{mott}^n \left(G_E^{n2} + \frac{\tau_n}{\epsilon_n} G_M^{n2} \right) \left(\frac{1}{1+\tau_n} \right)}{\sigma_{mott}^p \left(G_E^{p2} + \frac{\tau_p}{\epsilon_p} G_M^{p2} \right) \left(\frac{1}{1+\tau_p} \right)}$$

Deuteron target Nuclear correction Well-known proton cross section.

where

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

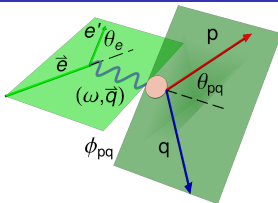
Solving for G_M^n

$$G_M^n = \sqrt{\left[\frac{R}{a(Q^2)} \left(\frac{\sigma_{mott}^p}{\sigma_{mott}^n} \right) \left(\frac{1 + \tau_n}{1 + \tau_p} \right) \left(G_E^{p2} + \frac{\tau_p}{\epsilon_p} G_M^{p2} \right) - G_E^{n2} \right] \frac{\epsilon_n}{\tau_n}}$$

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



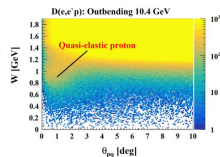
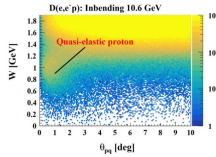
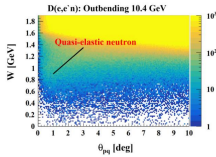
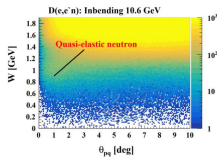
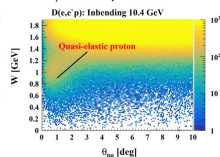
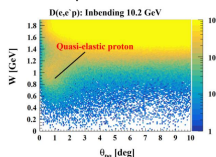
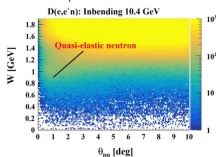
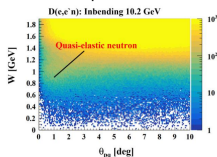
θ_{pq} is the angle the 3-momentum transfer $\Delta \vec{p}$ and the detected nucleon momentum $\vec{p}_N$

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

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

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 θ_e, θ_N .

Cuts Applied:
 $0.85 \text{ GeV} < W < 1.05 \text{ GeV}$

*S.Stepanyan, CLAS-NOTE
2002-008

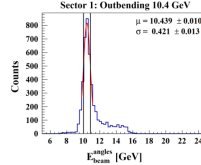
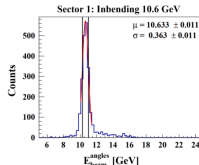
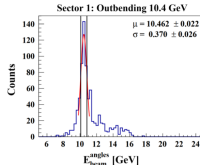
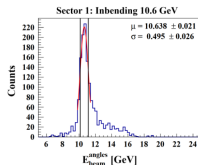
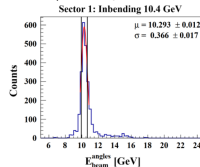
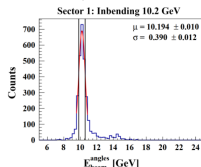
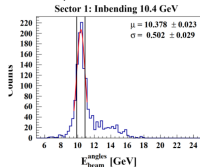
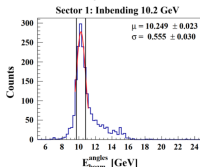
$$E_{beam}^{angles} = M_N \left(\frac{1}{\tan \frac{\theta_e}{2} \tan \theta_N} - 1 \right)$$

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

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

Require FD electron and PCAL/ECAL neutral

Require FD electron and PCAL/ECAL proton



Quasi-Elastic Event Selection - 3

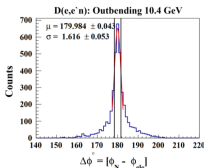
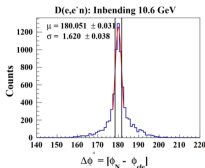
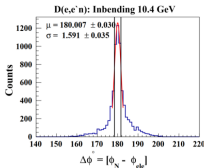
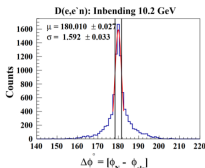
Data: Run Group B, Pass2
 Inbending energies: 10.2, 10.4, 10.6 GeV
 Outbending energies: 10.4 GeV

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

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

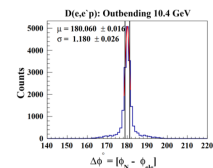
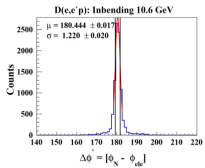
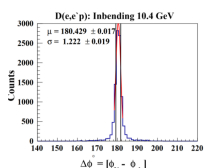
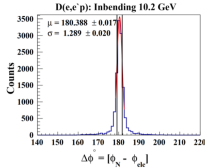
$^2\text{H}(e, e'n)$

Require FD electron and PCAL/ECAL neutral



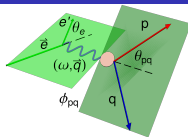
$^2\text{H}(e, e'p)$

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

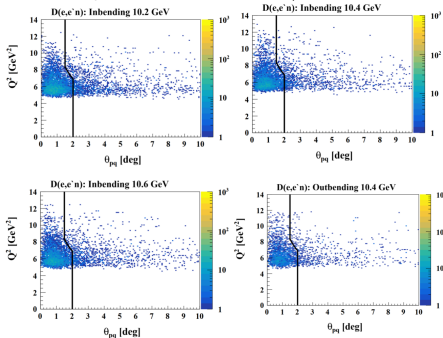


Cuts Applied:
 $0.85 \text{ GeV} < W < 1.05 \text{ GeV}$
 $1\sigma E_{beam}^{angles} \text{ cut}$
 $1\sigma \Delta\phi \text{ cut}$

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

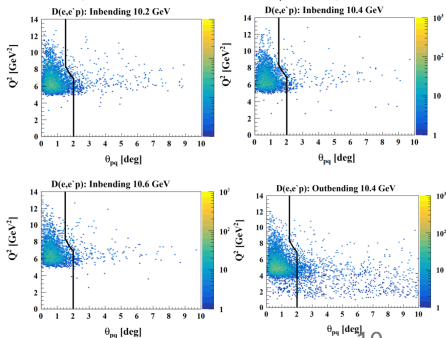
$^2\text{H}(e, e'n)$

Require FD electron and PCAL/ECAL neutral



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

Require FD electron and PCAL/ECAL proton



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

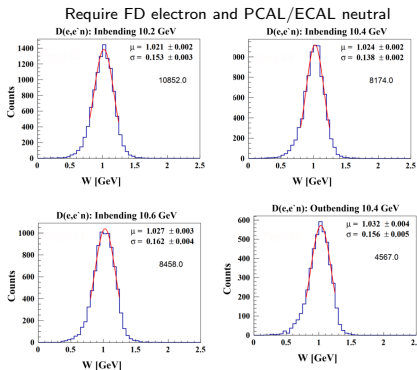
$1\sigma \Delta\phi$ cut

$Q^2 < f(\theta_{pq})$

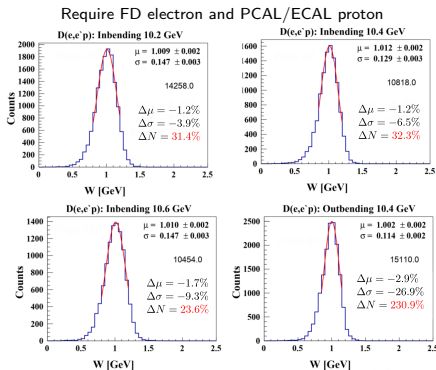
Inbending e' : $e - n$, $e - p$ distributions similar, $N_{ep} > N_{en}$ by $\approx 30\%$.

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.

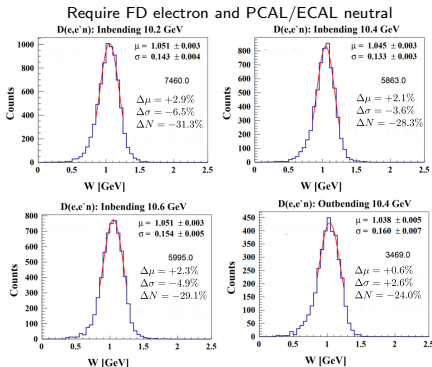
Impact of Acceptance Matching

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

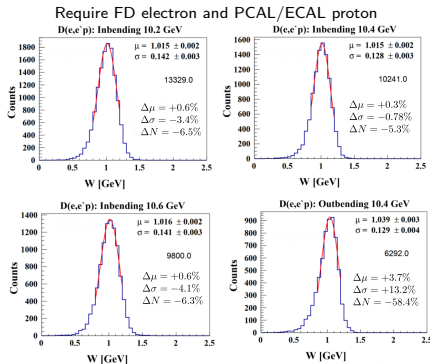
Cuts Applied:
 $1\sigma E_{beam}^{angles}$ cut
 $1\sigma \Delta\phi$ cut
 $Q^2 < f(\theta_{pq})$
 Acceptance Matching

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

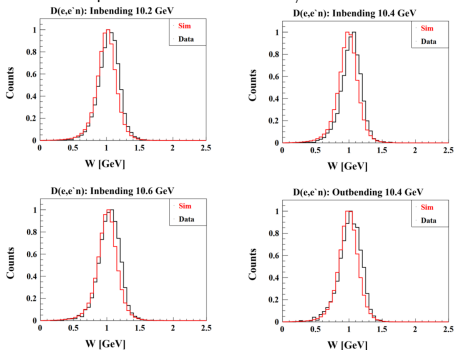
Data: Run Group B, Pass2
 Inbending energies: 10.2, 10.4, 10.6 GeV
 Outbending energies: 10.4 GeV

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

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

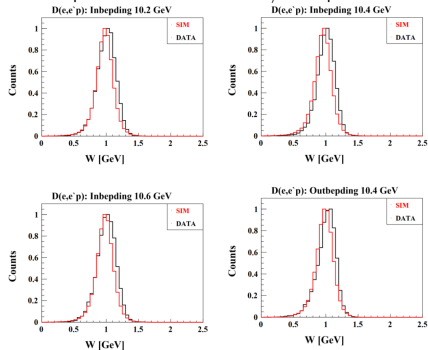
$^2\text{H}(e, e'n)$

Require FD electron and PCAL/ECAL neutral



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

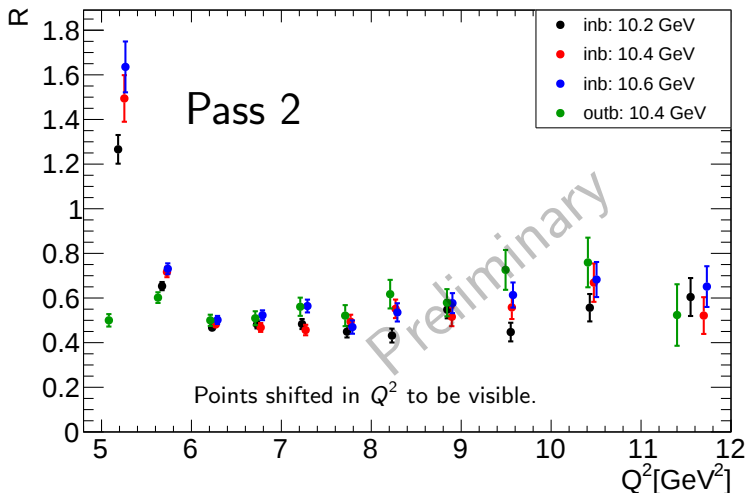
Require FD electron and PCAL/ECAL proton



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



Corrections to the Ratio

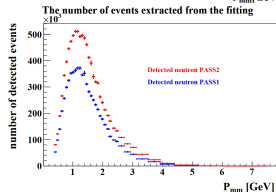
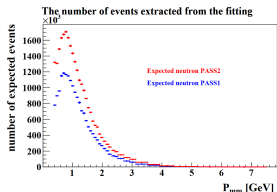
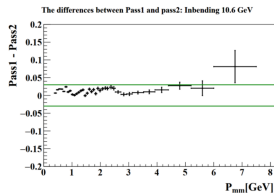
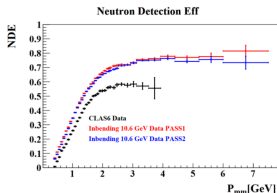
$$R_{Cor} = f_{NDE} f_{PDE} f_{nuc} f_{fermi} f_{rad} R$$

- 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 $\approx 1.5\%$.

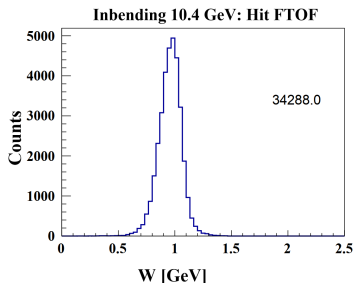


Proton Detection Efficiency

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

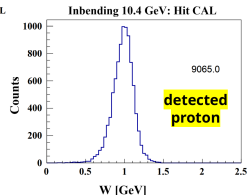
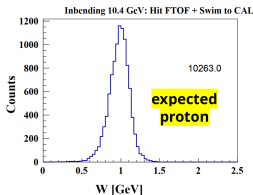
Expected Proton

- 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

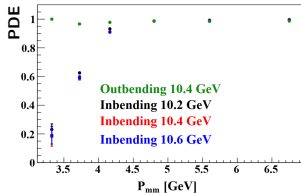
- Electron in FD, proton in PCAL/ECAL.
- QE cuts: $E_{beam}^{angles}, \Delta\phi, Q^2 < f(\theta_{pq})$
- Extract yields - ratio of detected to expected is the PDE.



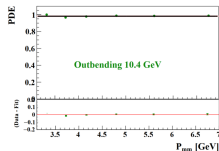
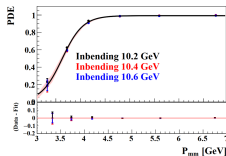
Other datasets are ongoing.

Proton Detection Efficiency Results

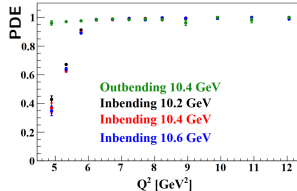
Momentum
Dependence



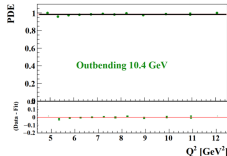
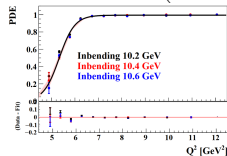
$$\eta(P_{mm}) = a_0 \left(1 - \frac{1}{1 + \exp\left(\frac{P_{mm} - a_1}{a_2}\right)} \right)$$



Q^2 Dependence

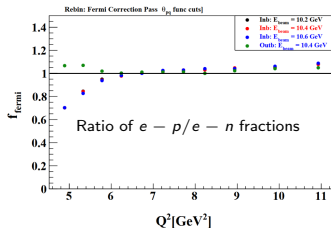
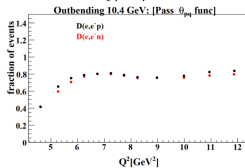
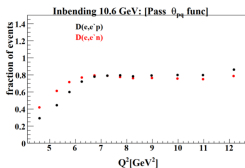
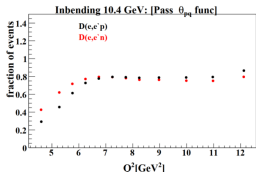
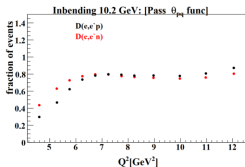


$$\eta(Q^2) = b_0 \left(1 - \frac{1}{1 + \exp\left(\frac{Q^2 - b_1}{b_2}\right)} \right)$$



Fermi Corrections

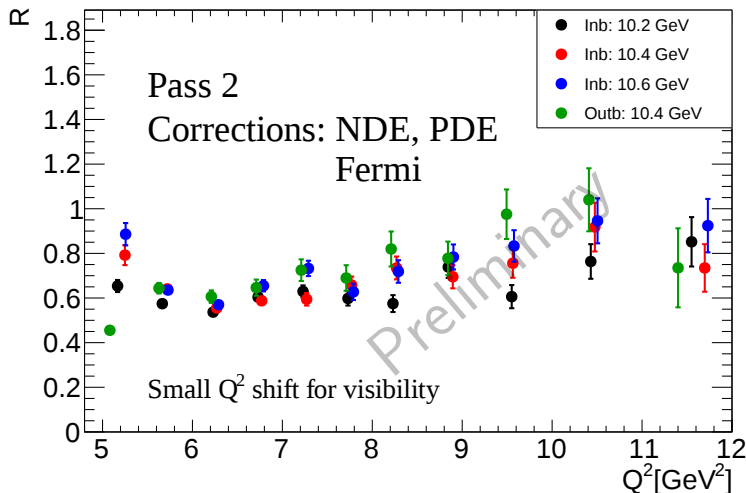
- Fermi motion in the target causes scattered nucleons to migrate out of the CLAS12 acceptance.
- Effect was simulated using the QUEEG generator.
- Fraction of correction (f_{pro} , f_{neut}) is the ratio of the number of actual hits in the acceptance that satisfy the θ_{pq} cut to the number of expected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



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



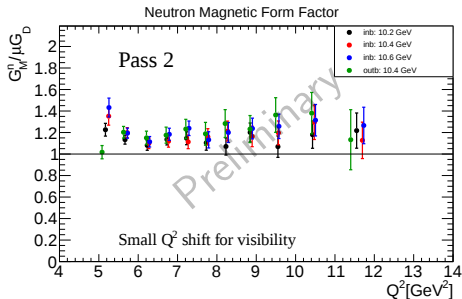
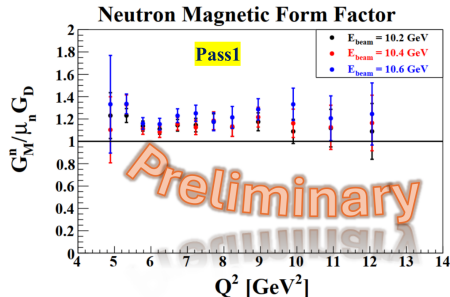
Preliminary G_M^n Result - 1

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



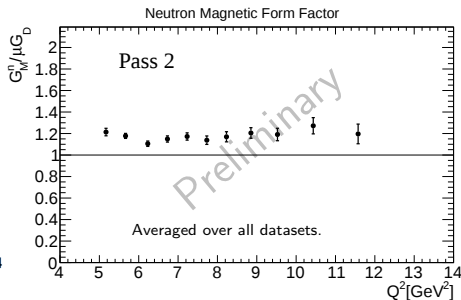
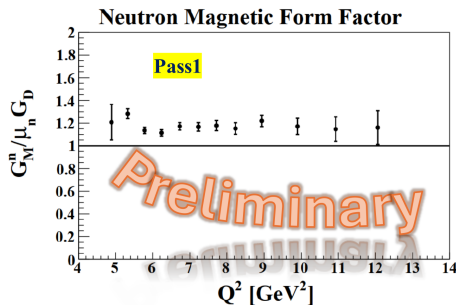
Preliminary G_M^n Result - 2

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, others 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.

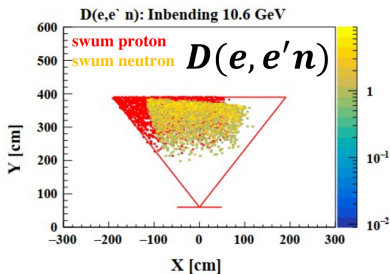
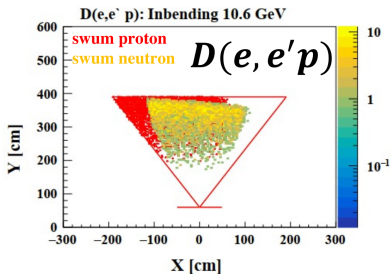
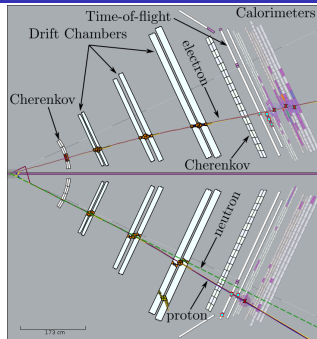
Backup Slides

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.



Electron Beam Energy Cut - Inbending, 10.2 GeV

D(e, e'n) Selection

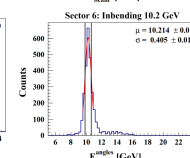
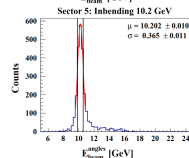
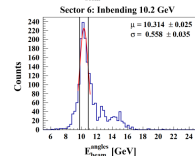
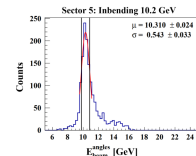
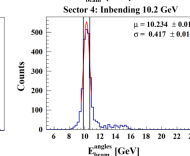
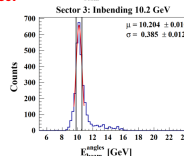
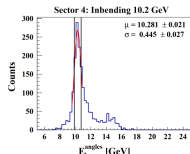
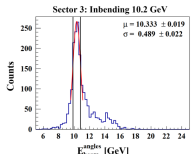
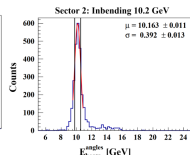
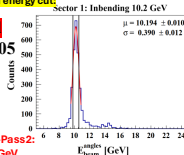
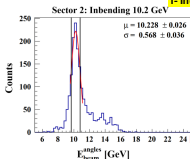
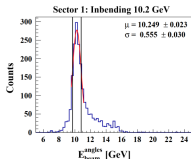
Quasi-elastic Selection

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

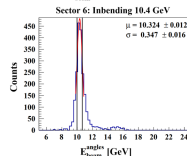
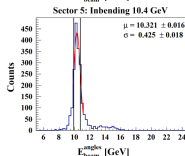
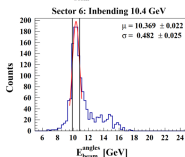
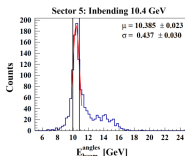
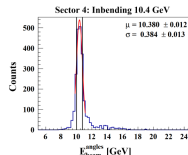
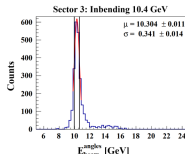
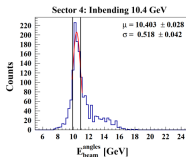
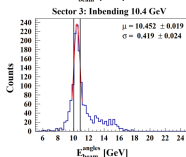
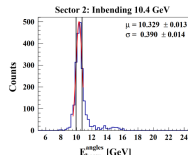
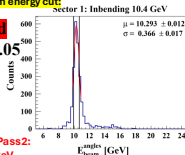
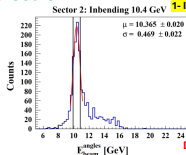
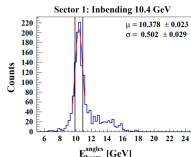
Quasi-elastic Selection

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

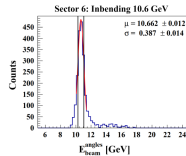
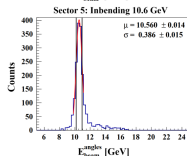
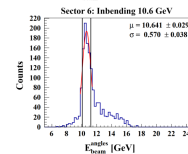
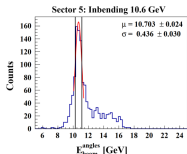
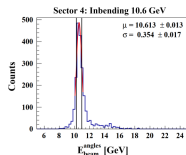
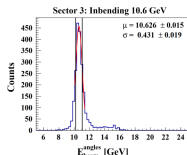
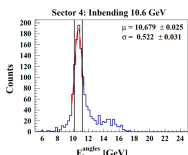
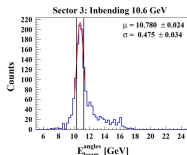
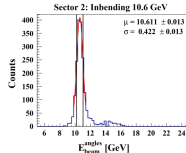
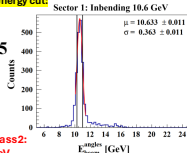
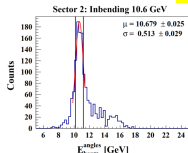
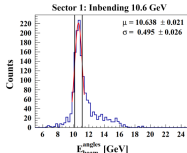
Quasi-elastic Selection

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

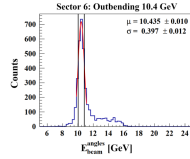
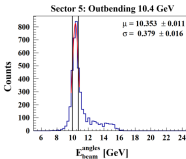
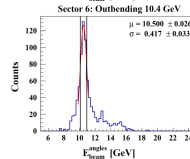
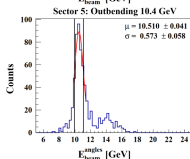
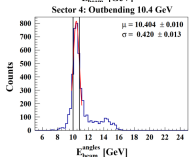
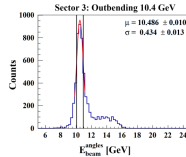
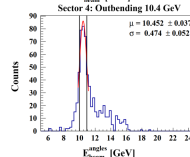
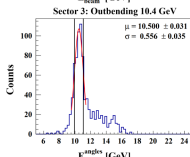
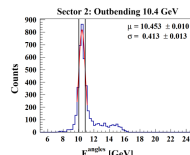
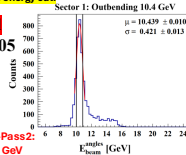
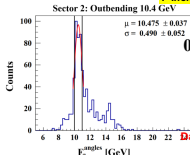
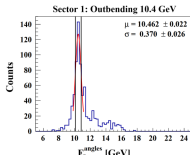
Quasi-elastic Selection

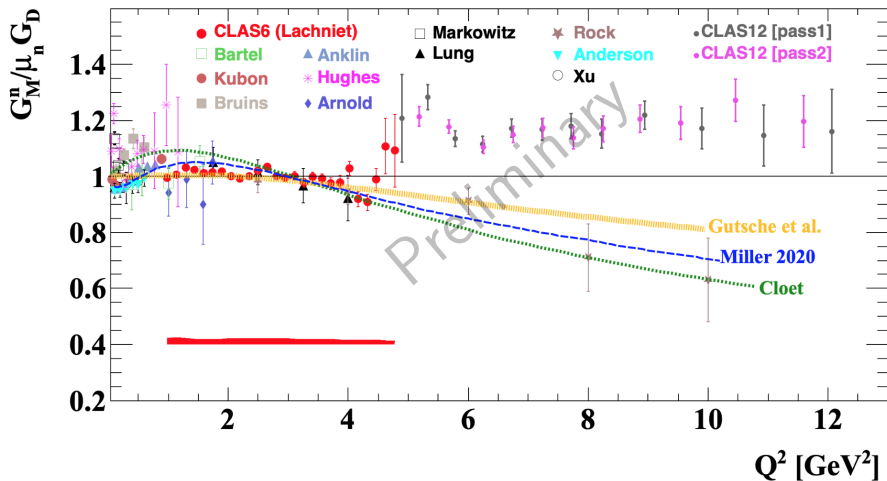
D(e, e'p) Selection

1- Incident electron beam energy cut:

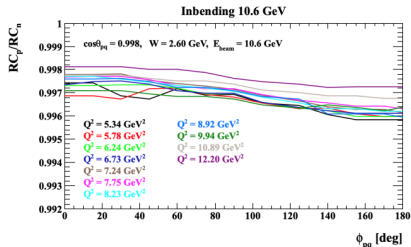
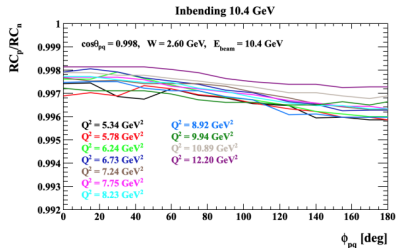
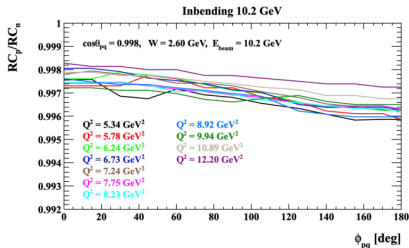
Cut applied
 $0.85 < W < 1.05$

Data: Run Group B - Pass2:
Outbending 10.4 GeV





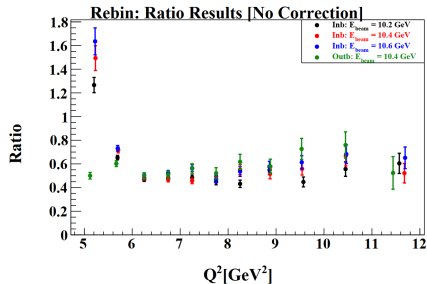
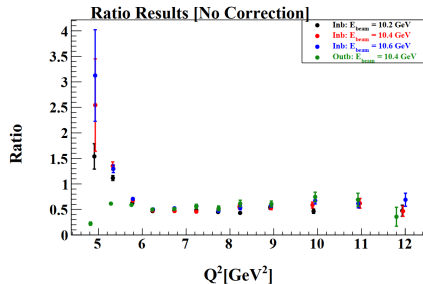
Corrections to the Ratio - Fermi



Corrections to the Ratio - None

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

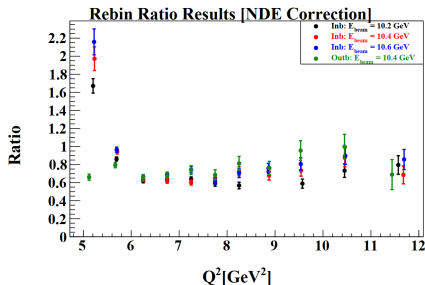
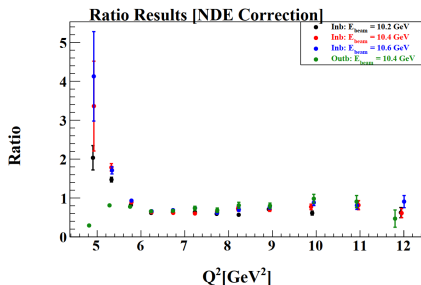
Cut applied
 $1 \sigma E_{\text{beam}}^{\text{angles}} \text{ cut}$
 $1 \sigma \Delta\phi \text{ cut and } Q^2 < f(\theta_{pq})$
 Apply Acceptance Matching



Corrections to the Ratio - NDE

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

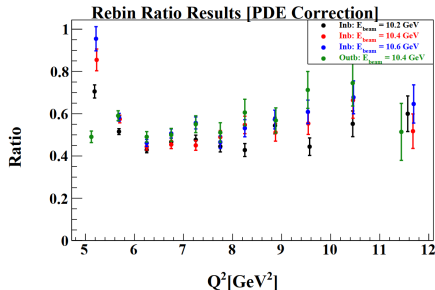
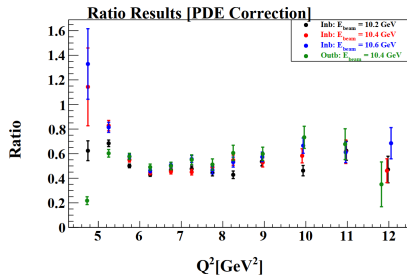
Cut applied
 $1 \sigma E_{\text{beam}}^{\text{angles}} \text{ cut}$
 $1 \sigma \Delta\phi \text{ cut and } Q^2 < f(\theta_{pq})$
 Apply Acceptance Matching



Corrections to the Ratio - PDE

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

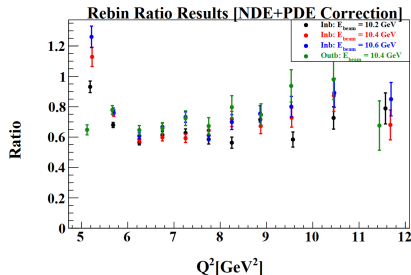
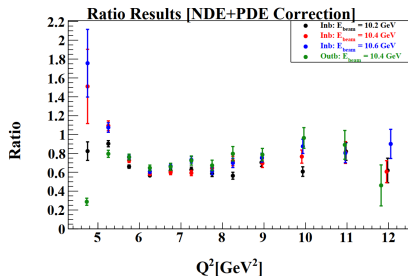
Cut applied
 $1 \sigma E_{\text{beam}}^{\text{angles}} \text{ cut}$
 $1 \sigma \Delta\phi \text{ cut and } Q^2 < f(\theta_{pq})$
 Apply Acceptance Matching



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

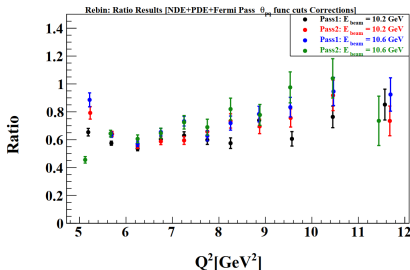
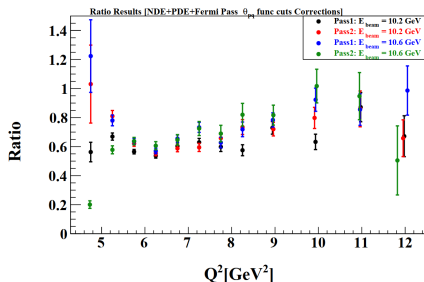


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Corrections to the Ratio - NDE+PDE+Fermi

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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