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

Deuteron target

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

Nuclear correction

Well-known proton cross section.

where

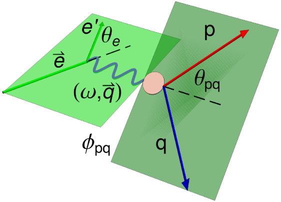
$$\tau_N = \frac{Q^2}{4M_N^2} \quad \epsilon = \left[1 + 2(1+\tau_N)\tan^2\frac{\theta}{2}\right]^{-1} \quad \sigma_{Mott} = \frac{\alpha^2 E' \cos^2\left(\frac{\theta}{2}\right)}{4E^3\sin^4\left(\frac{\theta}{2}\right)}$$

Solving for G_M^n

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

Requires knowledge of other elastic, electronmagnetic form factors

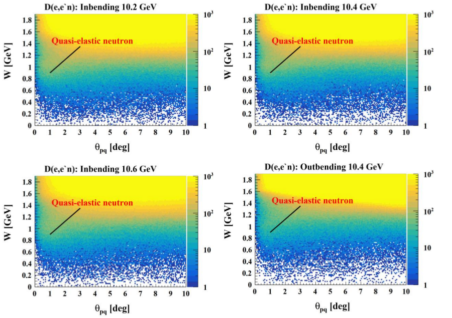
Data: Run Group B, Pass 2
Inbending energies: 10.2, 10.4, 10.6 GeV
Outbending energies: 10.4 GeV



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

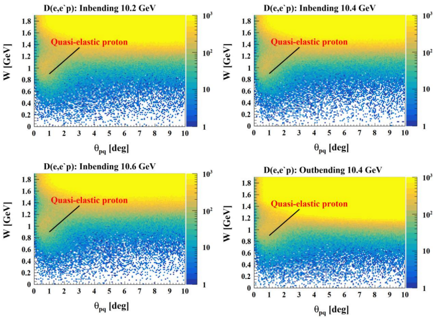
$^2\mathrm{H}(e,e'n)$

Require FD electron and PCAL/ECAL neutral



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

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

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

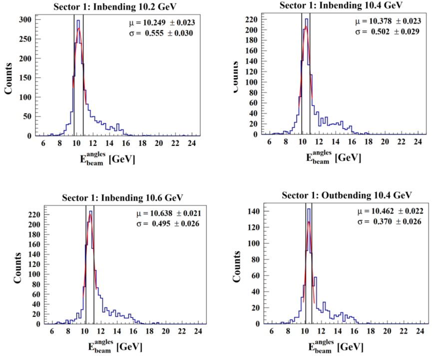
Electron beam energy cut*
Calculate beam energy E^{angles}_{beam} using θ_e, θ_N.

*S.Stepanyan, CLAS-NOTE 2002-008

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

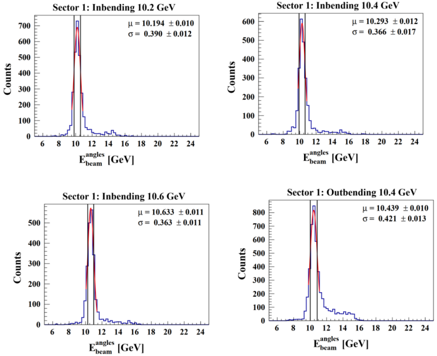
$^2\mathrm{H}(e, e'n)$

Require FD electron and PCAL/ECAL neutral



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

Require FD electron and PCAL/ECAL proton



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

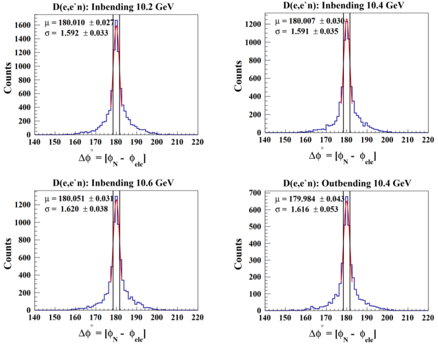
Cuts Applied:
$0.85 \text{ GeV} < W < 1.05 \text{ GeV}$
$1\sigma \ E_{beam}^{angles}$ cut

$\Delta\phi$ cut

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

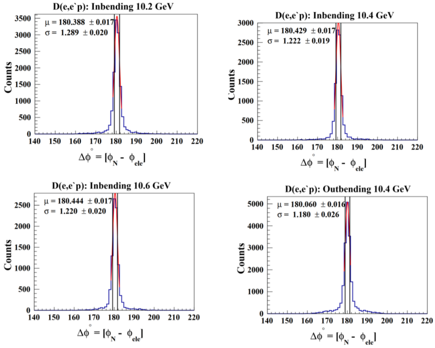
$^2\mathrm{H}(e, e'n)$

Require FD electron and PCAL/ECAL neutral

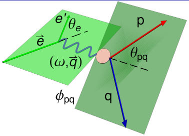


$^2\mathrm{H}(e, e'p)$

Require FD electron and PCAL/ECAL proton



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

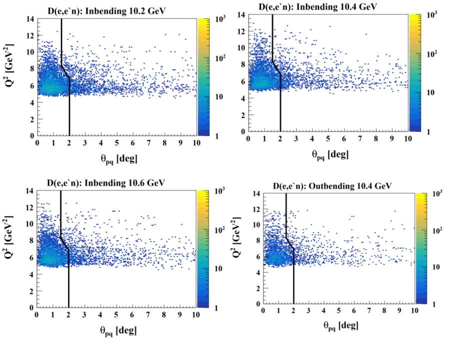


Cuts Applied:
$0.85 \text{ GeV} < W < 1.05 \text{ GeV}$
$1\sigma\ E_{beam}^{angles}$ cut
$1\sigma\ \Delta\phi$ cut

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

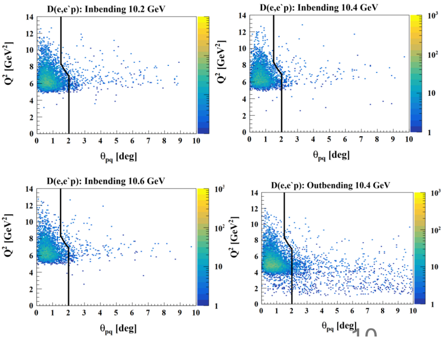
$^2\text{H}(e, e'n)$

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

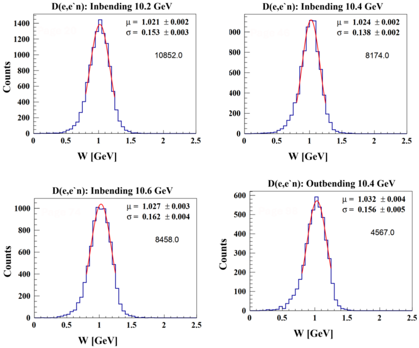
Cuts Applied:
1σ E_{beam}^{angles} cut
1σ $\Delta\phi$ cut
$Q^2 < f(\theta_{pq})$

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.

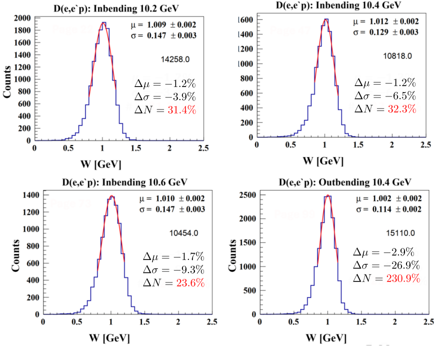
$^2\mathrm{H}(e,e'n)$

Require FD electron and PCAL/ECAL neutral



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

Require FD electron and PCAL/ECAL proton



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

Impact of Acceptance Matching

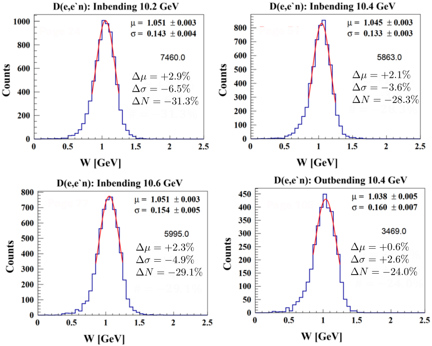
Data: Run Group B, Pass2
Inbending energies: 10.2, 10.4, 10.6 GeV
Outbending energies: 10.4 GeV

Cuts Applied:
1σ E_{beam}^{angles} cut
1σ $\Delta\phi$ 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.

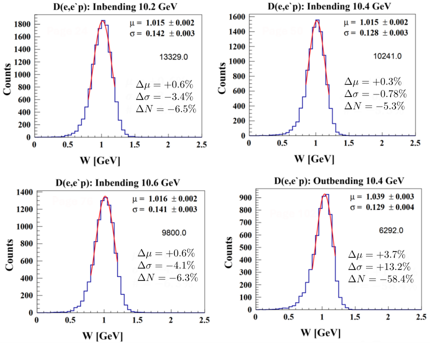
$^2\mathrm{H}(\mathrm{e},\mathrm{e}'\mathrm{n})$

Require FD electron and PCAL/ECAL neutral



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

Require FD electron and PCAL/ECAL proton



Changes due to acceptance matching.

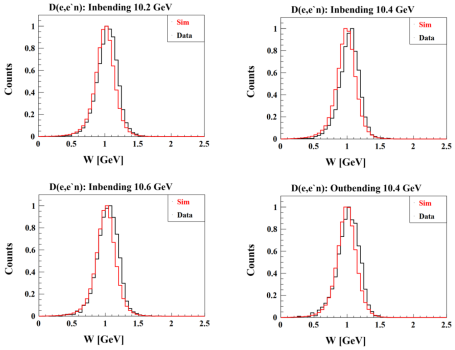
Comparison with Simulation

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

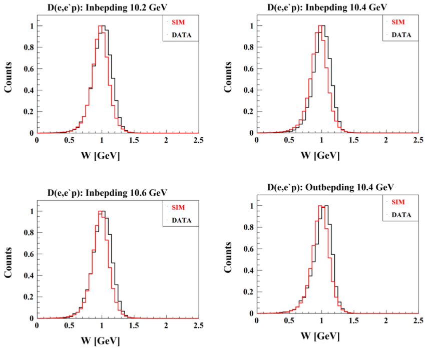
$^2\mathrm{H}(\mathrm{e},\mathrm{e'n})$

Require FD electron and PCAL/ECAL neutral



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

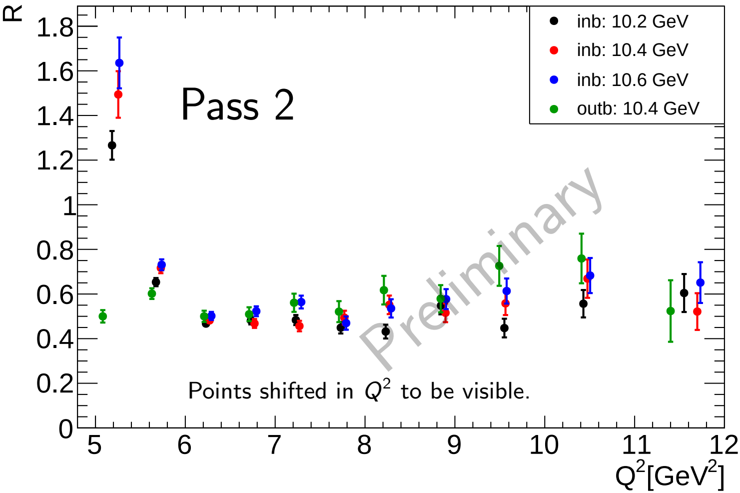
Require FD electron and PCAL/ECAL proton



Preliminary Ratio Result Uncorrected

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

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



Corrections to the Ratio

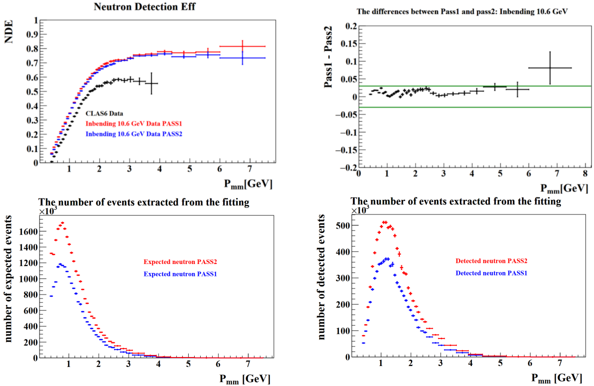
$R_{Cor} = f_{NDE} f_{PDE} f_{nuc} f_{fermi} f_{rad} R$

- 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.

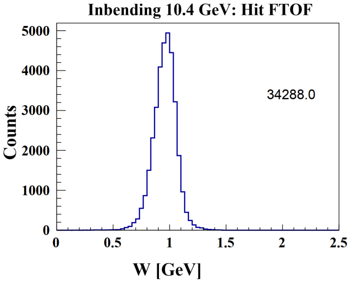
Neutron Detection Efficiency - Pass 1 vs Pass 2

- 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 or expected and detected neutrons. The average residual is $\approx 1.5\%$.

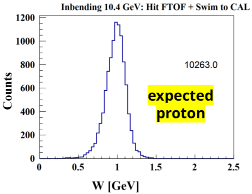


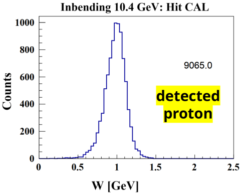
Proton Detection Efficiency

- Use the $^{2}\mathrm{H}(e, e'p)n$ reaction in QE kinematics and pass 2 data.
- Expected Proton
  - Select e' in FD and require proton hit FTOF.
  - Apply QE cuts.
    - 1σ E_{beam}^{angles} cut
    - 1σ $\Delta\phi$ 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.

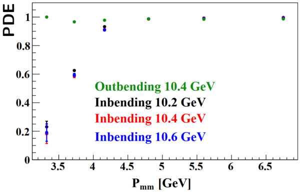


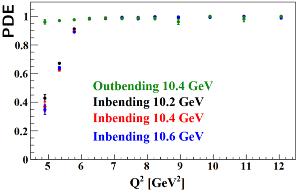


Other datasets are ongoing.

Proton Detection Efficiency Results

Momentum Dependence

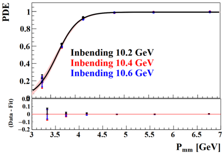


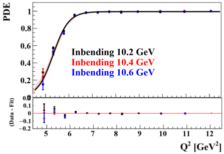


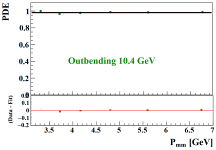
Q^2 Dependence

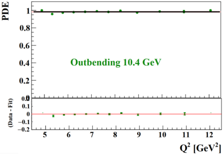
$$\eta(P_{mm}) = a_0\left(1 - \frac{1}{1+\exp\left(\frac{P_{mm}-a_1}{a_2}\right)}\right)$$

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



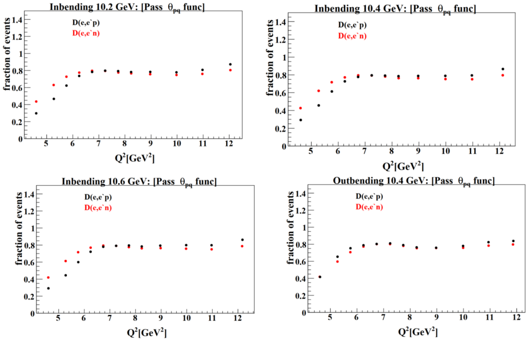


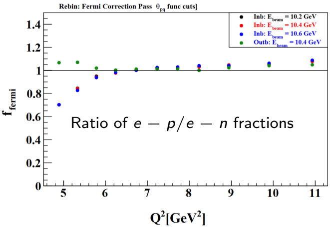




Fermi Corrections

- 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.

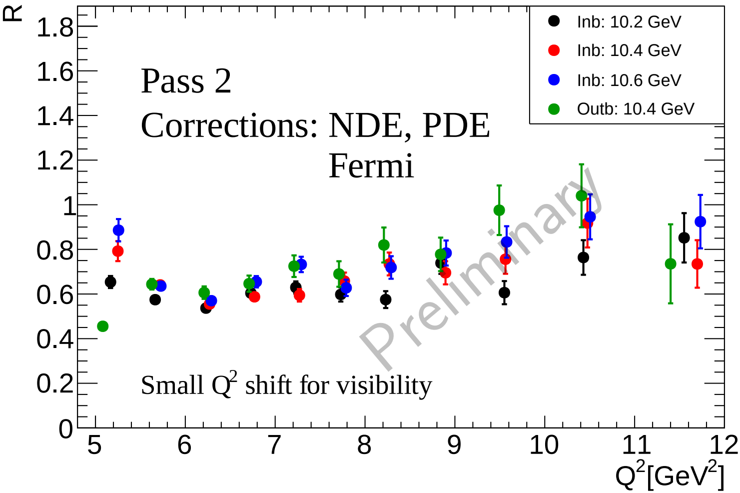




Preliminary Ratio Result corrected

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

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

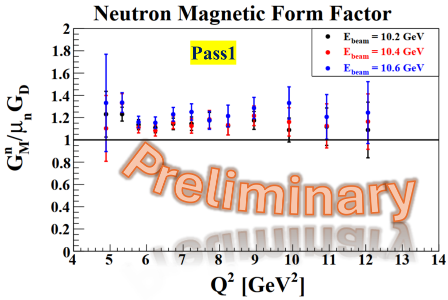


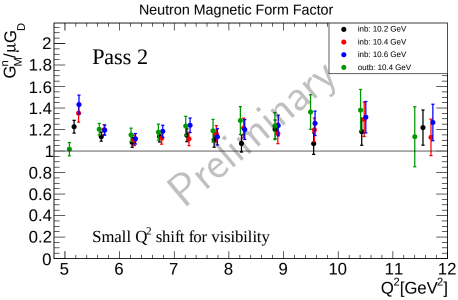
Recall Slide 4.

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

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

Leads to





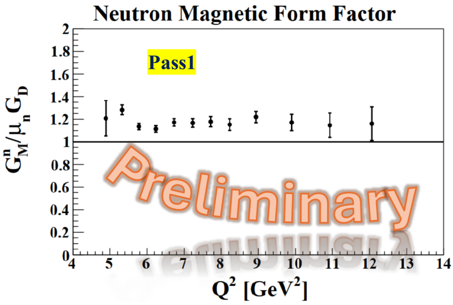
Preliminary G_M^n Result - 2

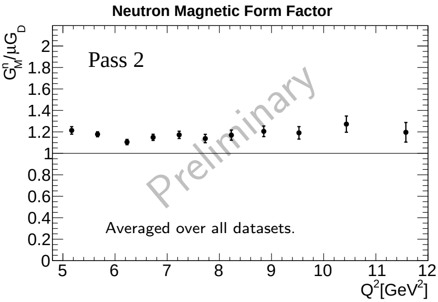
Recall

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

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

Leads to





Remaining Work

- 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.

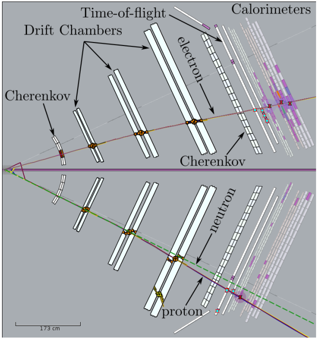
Backup Slides

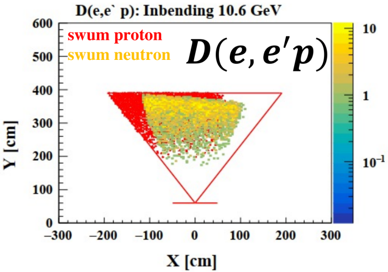
Acceptance Matching

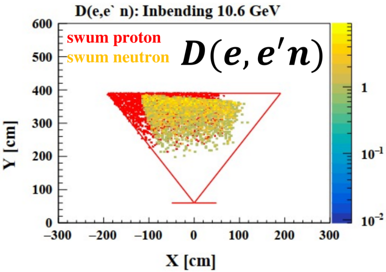
To insure the $e - n$ and $e - p$ acceptances are equal (1) start with the electron information, (2) assume elastic scattering, (3) assume a stationary proton target, (4) calculate its momentum, and (5) swim the track through CLAS12.

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

Quasi-elastic Selection

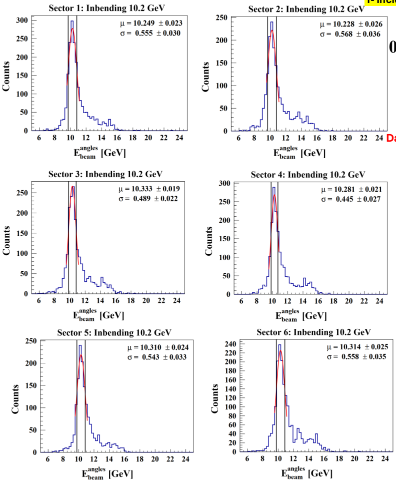
1- Incident electron beam energy cut:

Cut applied

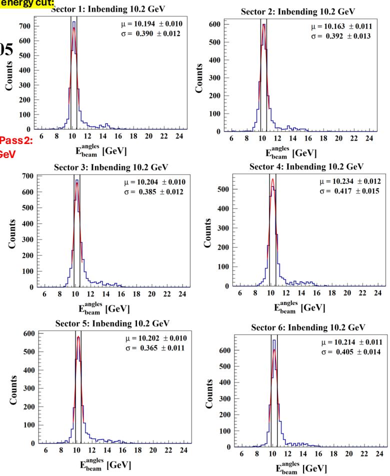
0.85 < W < 1.05

Data: Run Group B -Pass2: inbending 10.2 GeV

$D(e,e'n)$ Selection



$D(e,e'p)$ Selection

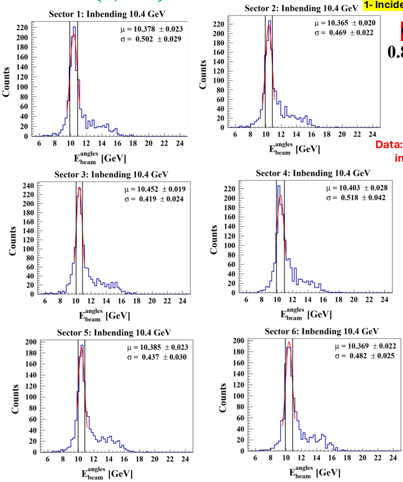


Electron Beam Energy Cut - Inbending, 10.4 GeV

Quasi-elastic Selection

1- Incident electron beam energy cut:

$D(e,e'n)$ Selection

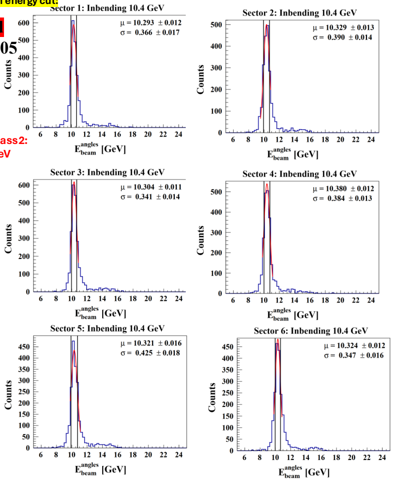


Cut applied

0.85 < W < 1.05

Data: Run Group B -Pass2: inbending 10.4 GeV

$D(e,e'p)$ Selection



Electron Beam Energy Cut - Inbending, 10.6 GeV

Quasi-elastic Selection

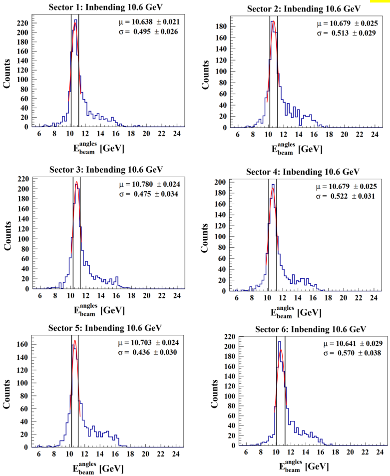
1- Incident electron beam energy cut:

Cut applied

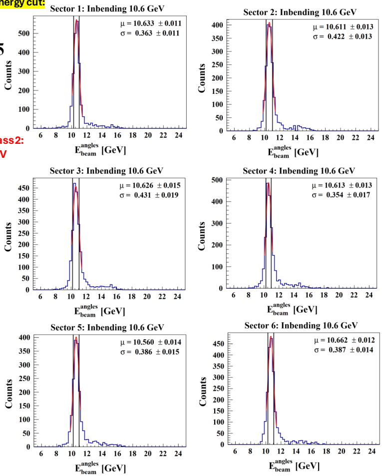
$0.85 < W < 1.05$

Data: Run Group B -Pass2: inbending 10.6 GeV

$D(e,e'n)$ Selection



$D(e,e'p)$ Selection



Quasi-elastic Selection

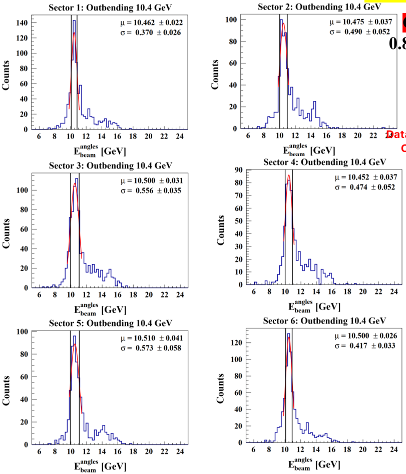
1- Incident electron beam energy cut:

Cut applied

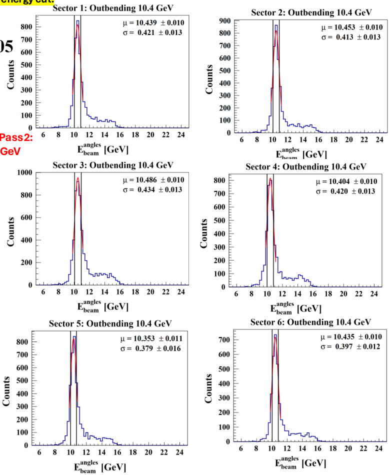
$0.85 < W < 1.05$

Data: Run Group B -Pass2: Outbending 10.4 GeV

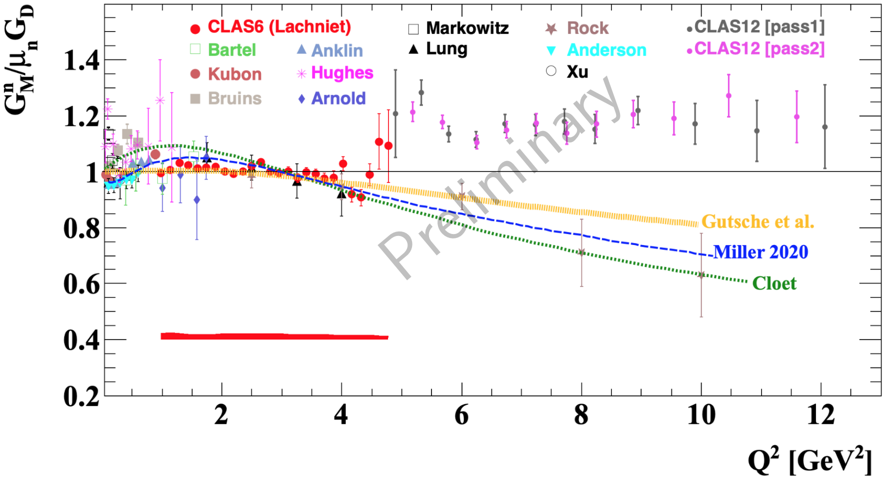
$D(e,e'n)$ Selection



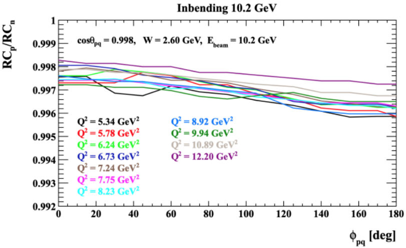
$D(e,e'p)$ Selection

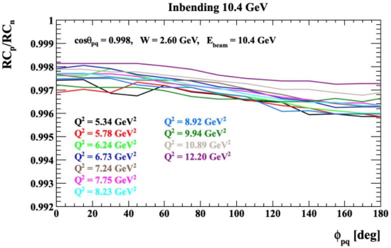


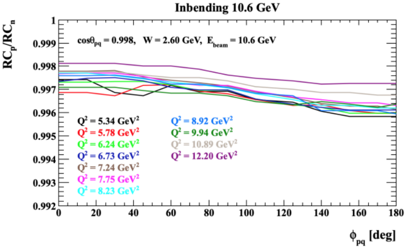
Preliminary G_M^n



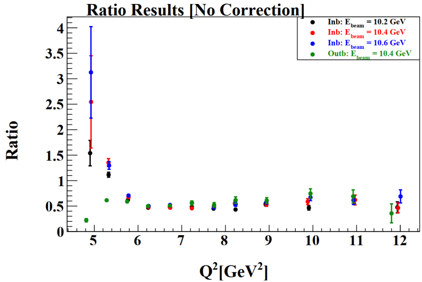
Corrections to the Ratio - Fermi

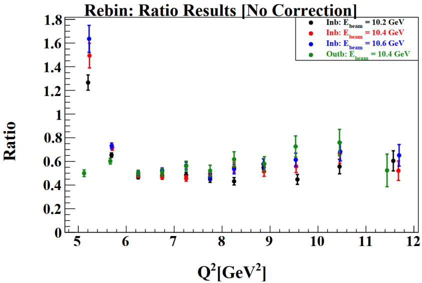






Ratio Result $R = \frac{D(e,e'n)}{D(e,e'p)}$





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Cut applied

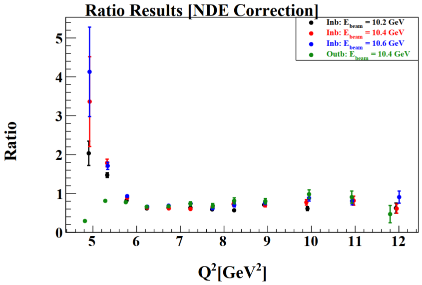
1 σ $E_{\text{beam}}^{\text{angles}}$ cut

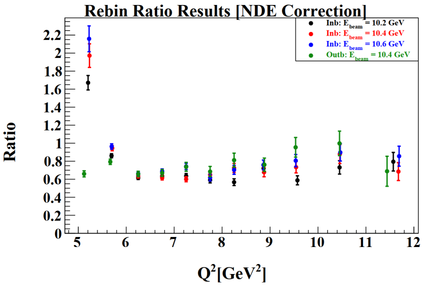
1 σ $\Delta\phi$ cut and $Q^2 < f(\theta_{pq})$

Apply Acceptance Matching

Ratio Result

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





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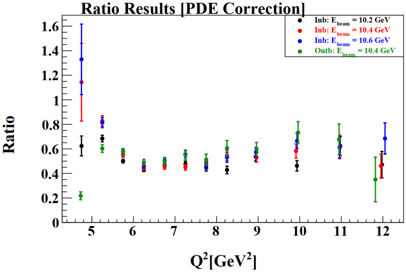
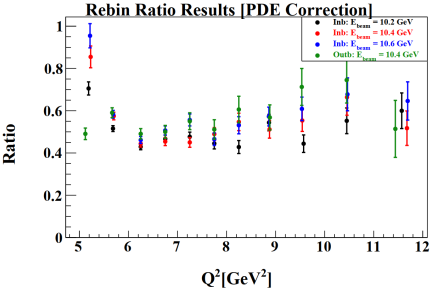
Corrections to the Ratio - PDE

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

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





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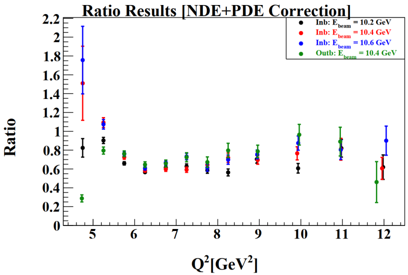
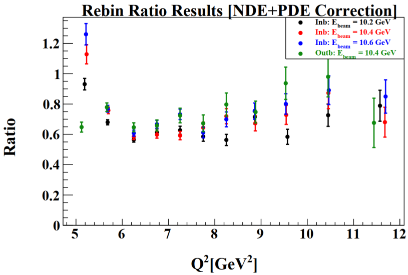
Corrections to the Ratio - NDE+PDE

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

Ratio Result

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





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Corrections to the Ratio - NDE+PDE+Fermi

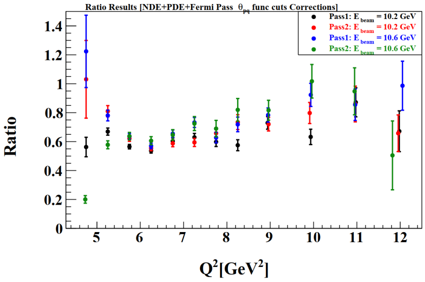
Cut applied

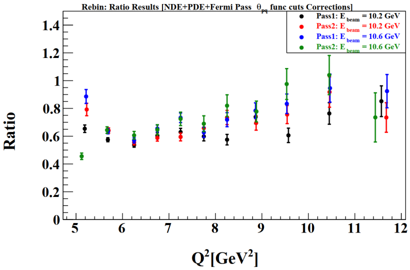
$1\ \sigma\ E_{beam}^{angles}$ cut

$1\ \sigma\ \Delta\phi$ cut and $Q^2 < f(\theta_{pq})$

Apply Acceptance Matching

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





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