Neutron Magnetic Form Factor G_M^n Measurement at High Q^2 with CLAS12

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Overview

- Scientific Motivation
- Previous Measurements of G_M^n
- The Ratio Method
- $\mathrm{D}(e,e'p)$& $\mathrm{D}(e,e'n)$ Selections
- Preliminary Ratio Result
- Corrections to the Ratio

Data Set used:

Run Group B, inbending with beam energies 10.2, 10.4 and 10.6 GeV

Why we need to measure elastic electromagnetic form factors EEFF

G_E, G_M: Fundamental quantity related to the electric charge and magnetic moment within the neutron.

- **provide important constraints for GPDs.**
- **EEFF's are a fundamental challenge for lattice QCD**
- **Measuring G_M^n with the other three form factors (G_E^p, G_M^p and G_E^n) allows extraction of the individual up and down quarks contributions.**
- **Early testing ground for lattice QCD**

There are 6 experiments in Hall A to measure all four elastic electric, G_E, and magnetic, G_M , form factors for the proton and neutron at high Q^2 and one experiment in Hall B.

The Worlds Data on G_M^n

Most experiments measured G_M^n at $Q^2 < 5$ GeV^2

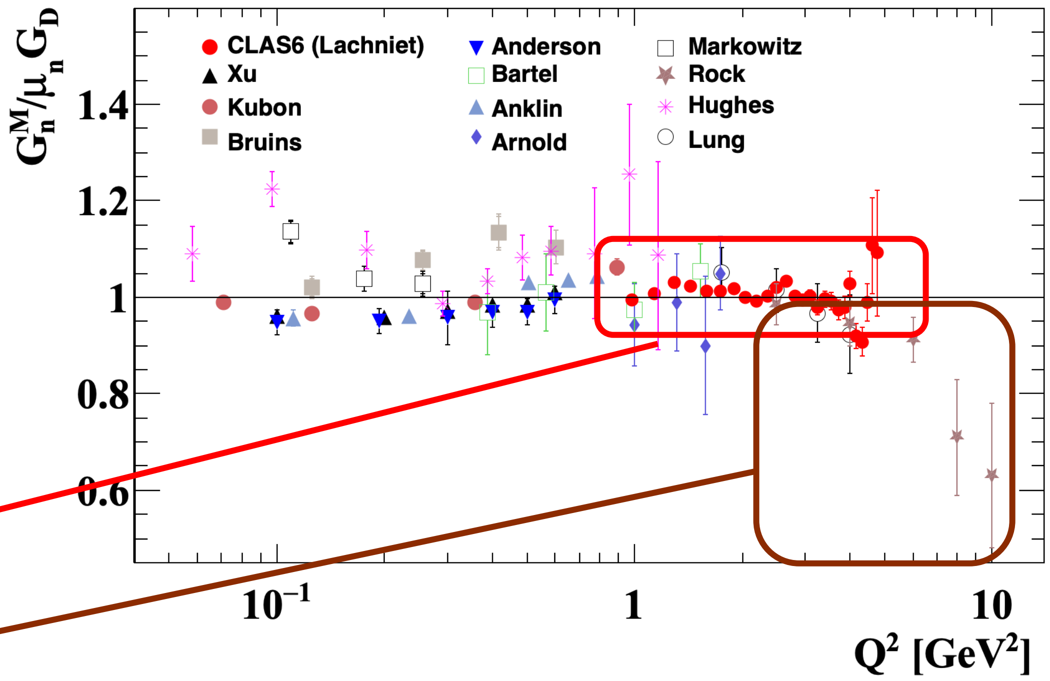
The measurement at $Q^2 < 5$ GeV^2 CLAS in Hall B at Jlab:

- ✓ Extract G_M^n at $Q^2 < 5$ GeV^2
- ✓ Using ratio of quasi-elastic $\frac{D(e,e'n)}{D(e,e'p)}$ from deuterium

ROCK experiment measured G_M^n at high Q^2 :

- ✓ Extract G_M^n at $Q^2 < 10$ GeV^2
- ✓ Using inclusive quasi-elastic scattering cross section data $d(e,e')X$
- ✓ Large systematic errors due to subtraction of proton contribution

CLAS shows a flat behavior at high Q^2 while
ROCK shows the data fall-off at high Q^2 with large uncertainties !!!



Measuring G_M^n at high Q^2 will extend our knowledge into these regions

How Do We Measure G_M^n on a Neutron? Ratio Method on Deuterium

The ratio of the free nucleon e-n to e-p cross sections in terms of the free nucleon form factors:

The numerator Requires a Precise Measurement of the Neutron Detection Efficiency (NDE)
$e\,p \rightarrow e'\,\pi^{+}(n)$

$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = \frac{\sigma_{mott}^{n}\left(G_E^{n\,2} + \frac{\tau_n}{\varepsilon_n} G_M^{n\,2}\right)\left(\frac{1}{1+\tau_n}\right)}{\sigma_{mott}^{p}\left(G_E^{p\,2} + \frac{\tau_p}{\varepsilon_p} G_M^{p\,2}\right)\left(\frac{1}{1+\tau_p}\right)}$$

the denominator is the precisely-known proton cross section.

Where:

$$\sigma_{Mott} = \frac{\alpha^2 E' \cos^2(\frac{\theta_e}{2})}{4E^3 \sin^4(\frac{\theta_e}{2})}\ ,\quad \tau = \frac{Q^2}{4\,M_{p,n}^2}\ ,\quad Q^2 = 4EE'\sin^2\left(\frac{\theta_e}{2}\right)\ ,\ \epsilon = \left[1 + 2(1+\tau)\tan^2(\frac{\theta_e}{2})\right]^{-1}$$

Solving for G_M^n:

$$G_M^n = \sqrt{\left[R_{Cor}\left(\frac{\sigma_{mott}^{p}}{\sigma_{mott}^{n}}\right)\left(\frac{1+\tau_n}{1+\tau_p}\right)\left(G_E^{p\,2} + \frac{\tau_p}{\varepsilon_p} G_M^{p\,2}\right) - G_E^{n\,2}\right]\frac{\epsilon_n}{\tau_n}}$$

-Extracting G_M^n requires knowledge of other EEFFs
-All four EEFFs will be measured at high Q^2 in Hall A

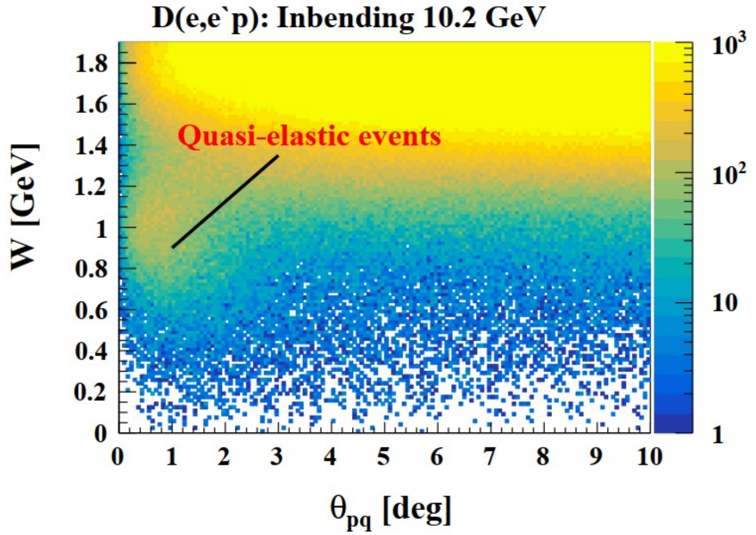
$$R_{Cor} = f_{\text{NDE}}\, f_{\text{PDE}}\, f_{\text{nuclear}}\, f_{\text{radiative}}\, f_{\text{fermi}}\, R$$

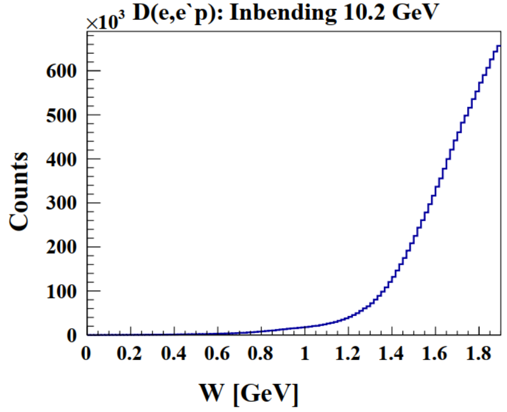
Quasi-elastic Selection

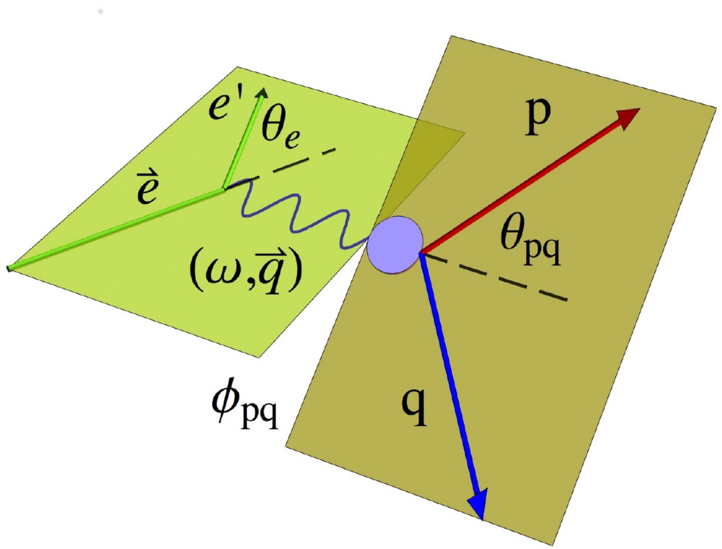
$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))}$$

$D(e,e'p)$ Selection

- Select electron in FD and positive charge particle hit PCAL/ECAL



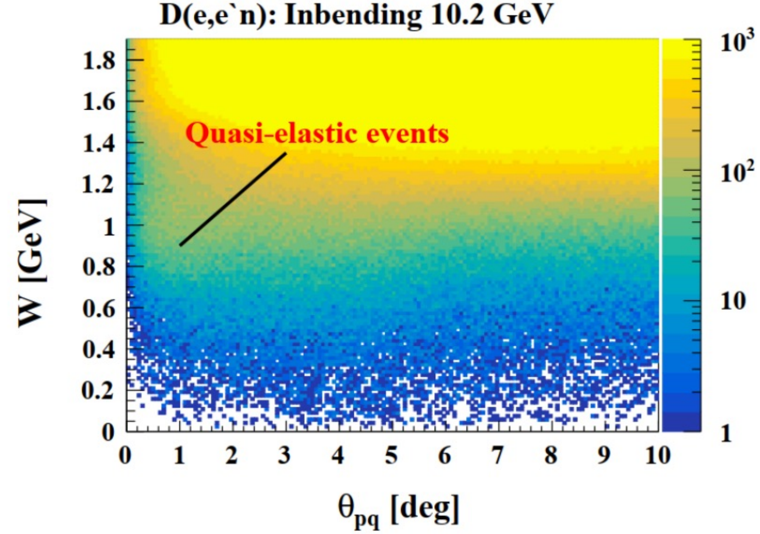


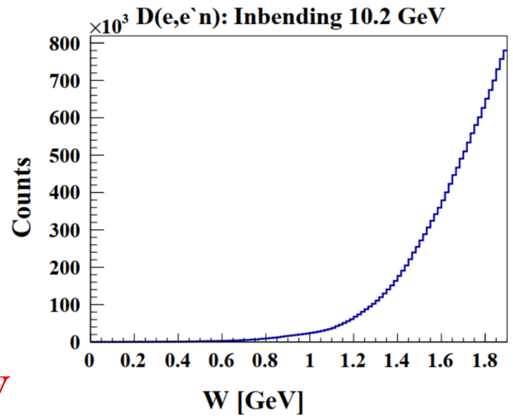


θ_{pq}: The angle between the transferred 3-momentum $\vec{q}$ and the momentum $\vec{P}_N$ of the detected nucleon.

$D(e,e'n)$ Selection

- Select electron in FD and neutral particle hit PCAL/ECAL





Data set shown is Pass1: RG-B spring19 at 10.2 GeV

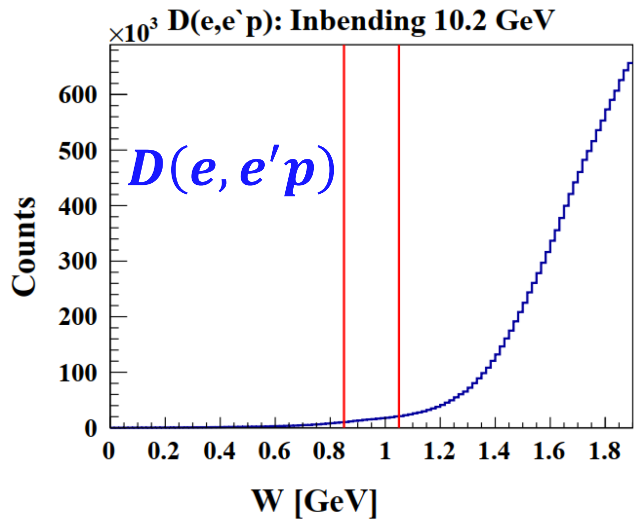
Quasi-elastic Selection

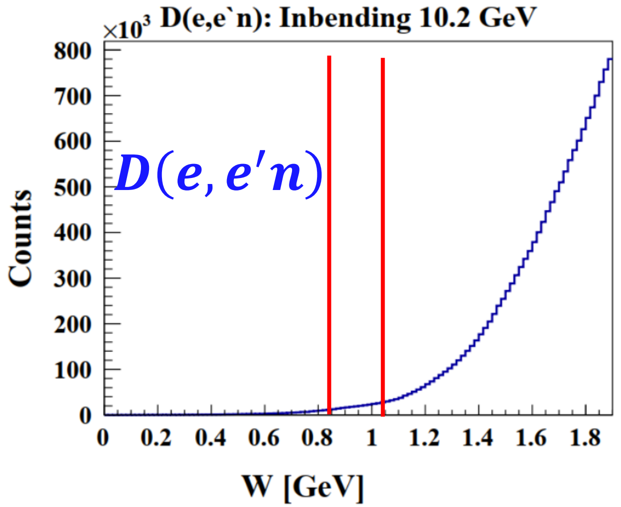
Cut applied

0.85 < W < 1.05

List of the cuts applied to select quasi-elastic events:

- *Incident electron beam energy* $E_{\text{beam}}^{\text{angles}}$ *Cut*
- $\Delta\phi = \phi_N - \phi_e$ *Cut*
- θ_{pq} *Cut*
- *Missing Energy Cut*



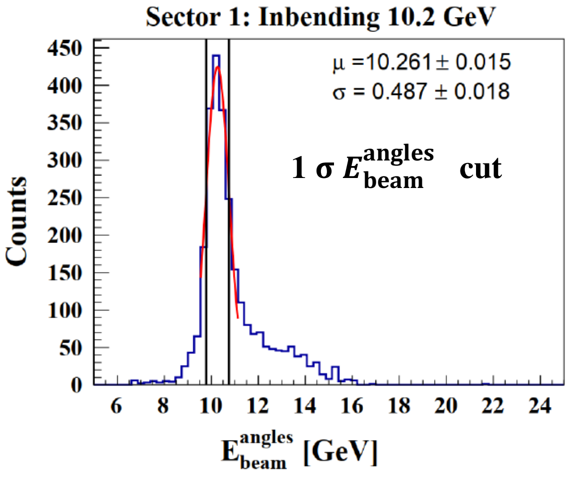


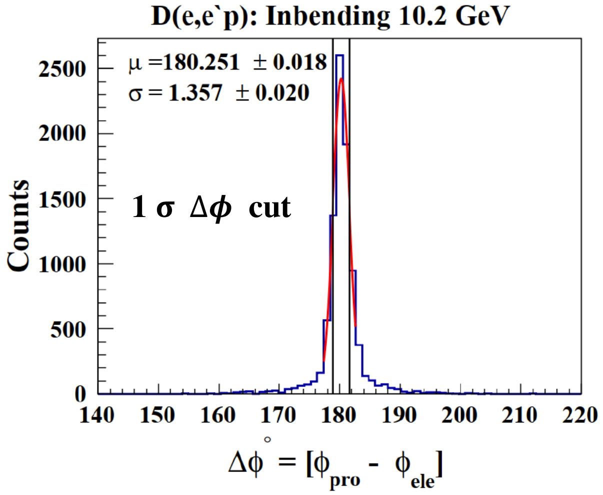
Quasi-elastic Selection

Cut applied

0.85 < W < 1.05

$D(e,e'p)$ Selection





1- Incident electron beam energy cut

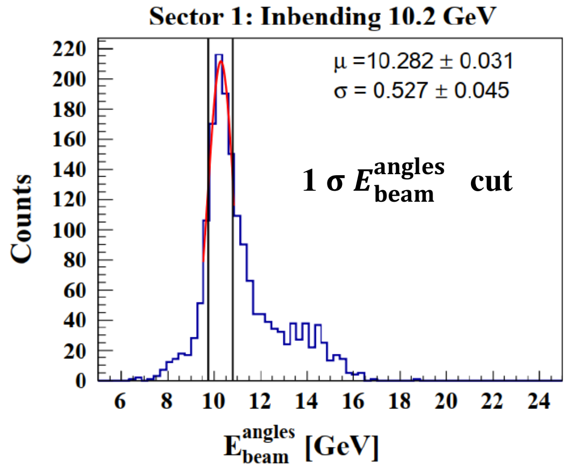
Calculated the incoming beam energy E_{beam}^{angles} using θ_e , θ_N:

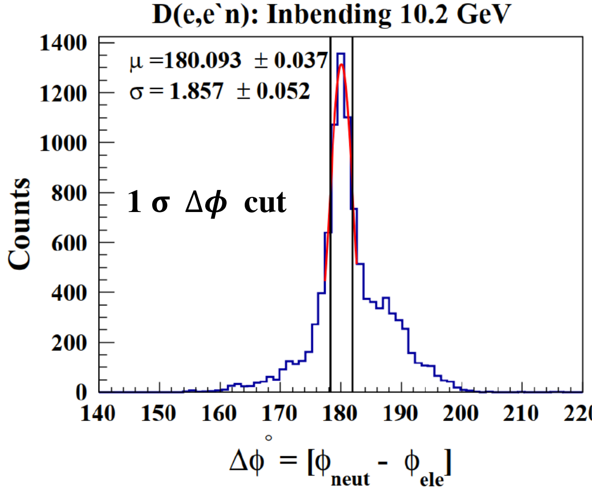
$$E_{beam}^{angles} = M_N \left(\frac{1}{tan\left(\frac{\theta_e}{2}\right) \tan(\theta_N)} - 1 \right)$$

2- $\Delta\phi = \phi_N - \phi_e$ *cut*

The difference in the lab azimuthal angle between the nucleon and the scattered electron

$D(e,e'n)$ Selection





Data set shown is Pass1: RG-B spring19 at 10.2 GeV

Quasi-elastic Selection

Cuts applied

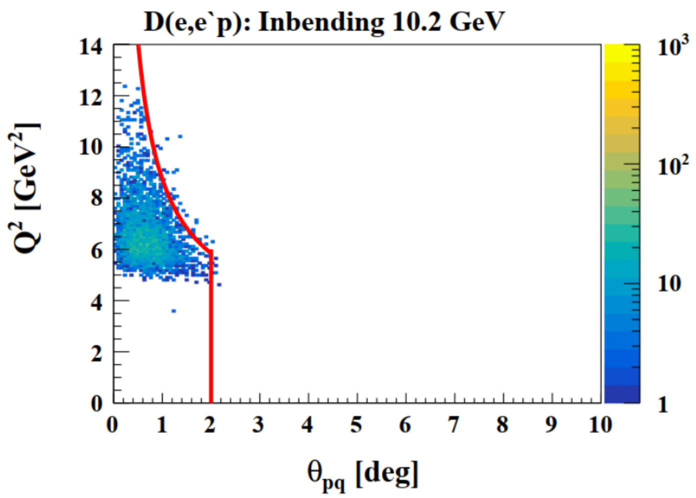
$0.85 < W < 1.05$

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

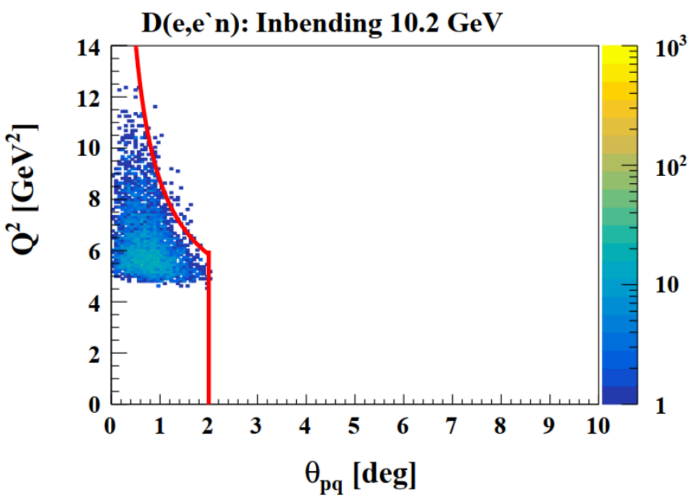
$1\ \sigma\ \Delta\phi$ cut

3- θ_{pq} cut

$D(e,e'p)$ Selection



$D(e,e'n)$ Selection



Quasi-elastic events depend on Q^2 value:

high Q^2 ⟶ Quasi-elastic events narrow

small Q^2 ⟶ Quasi-elastic events broader

To select quasi-elastic events while minimizing background contamination in the absence of the W cut, the function is introduced as follows:

$$f(\theta_{pq}) = 2.5204 + \frac{6.2127}{\theta_{pq}^{0.9003}}$$

Cuts Used

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

$\theta_{pq} < 2$

Data set shown is Pass1: RG-B spring19 at 10.2 GeV

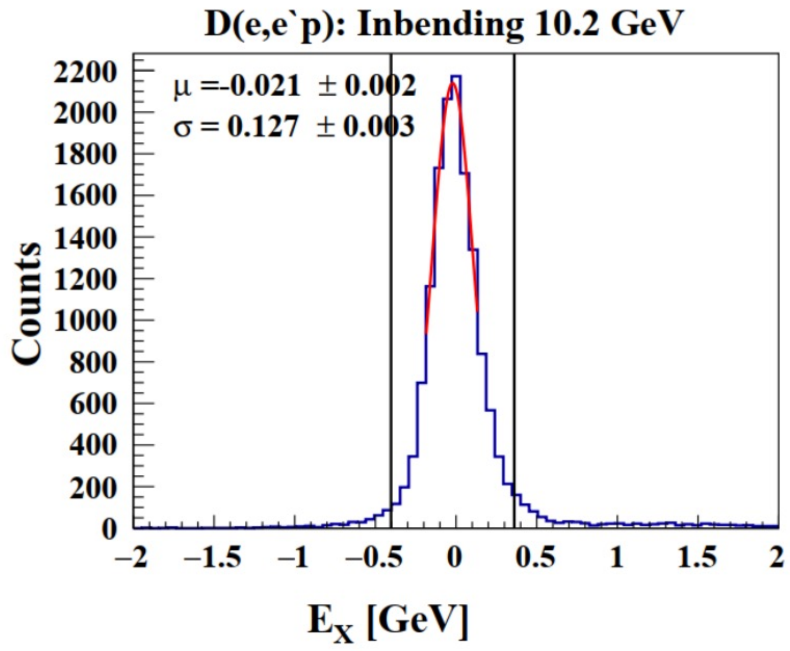
Quasi-elastic Selection

4- Missing Energy Cut

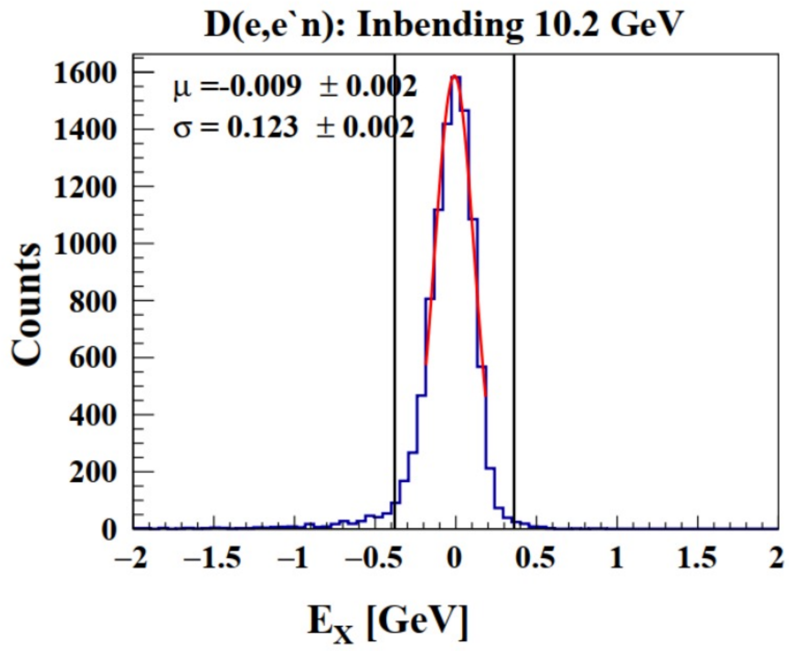
From the 4-momentum conservation law the missing energy for quasi-elastic events is expected to be zero.

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

$D(e, e'p)$ Selection



$D(e, e'n)$ Selection



Cut applied

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

$1\ \sigma\ \Delta\phi$ cut

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

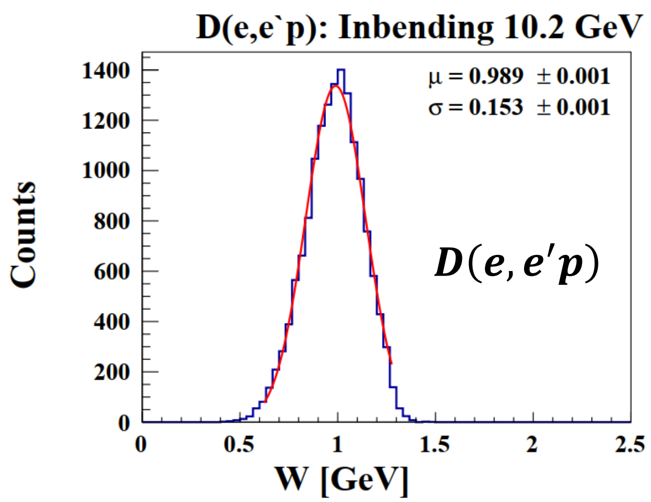
$\theta_{pq} < 2$

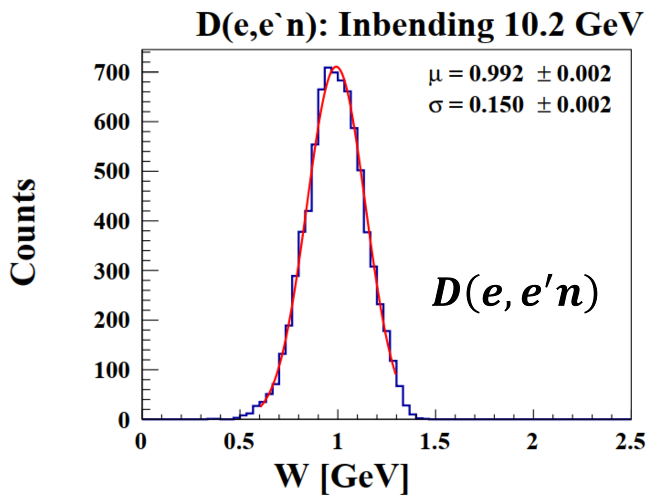
$3\ \sigma\ E_x$

Applied neutron momentum correction to $D(e, e'n)$ channel

Data set shown is Pass1: RG-B spring19 at 10.2 GeV

Quasi-elastic Selection

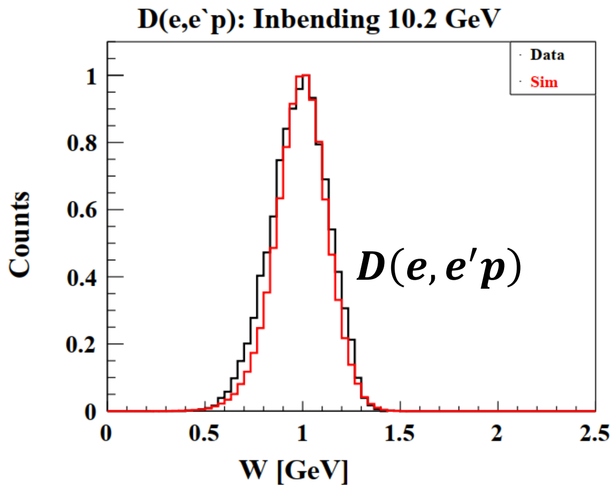


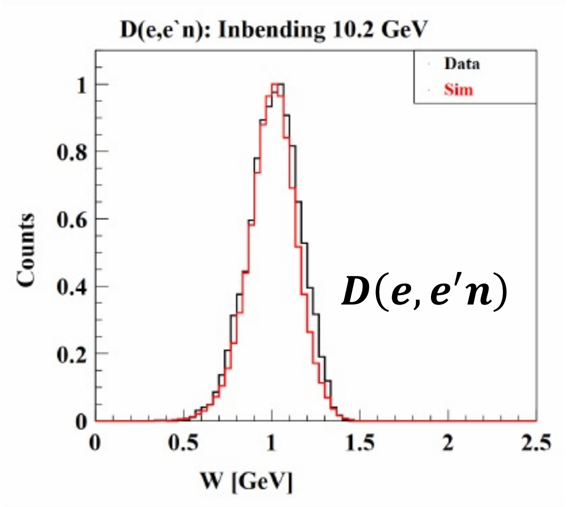


The W distribution of $D(e, e'p)$ and $D(e, e'n)$ that satisfied:

- **1 σ E_{beam}^{angles} cut**
- **1 σ $\Delta\phi$ cut**
- **$Q^2 < f(\theta_{pq})$**
- **$\theta_{pq} < 2$**
- **3 σ E_x**

Comparison of MC and Data to investigate quasi-elastic peaks





Simulated and reconstructed events with the same COATJAVA version as the data

QUEEG: A Monte Carlo Event Generator for Quasielastic Scattering on Deuterium, G.P. Gilfoyle , J.D. Lachniet , and O. Alam, CLAS-NOTE 2014-007, Sep 5, 2014.

Acceptance Matching for nucleon

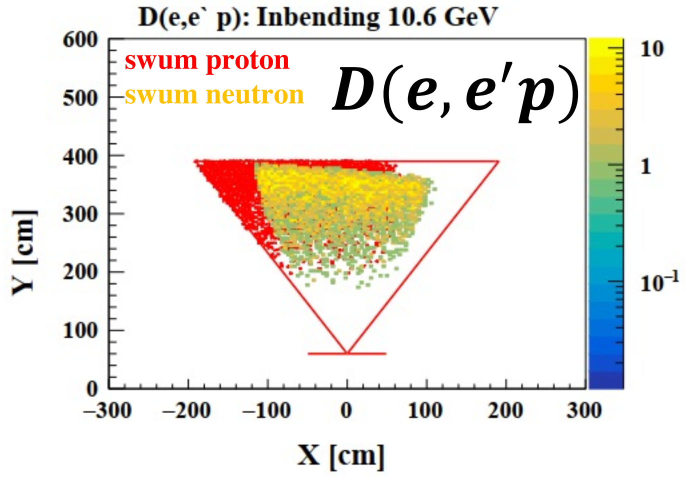
Using only the electron information, assume elastic scattering and stationary target, predict the proton momentum, and swim it through CLAS12.

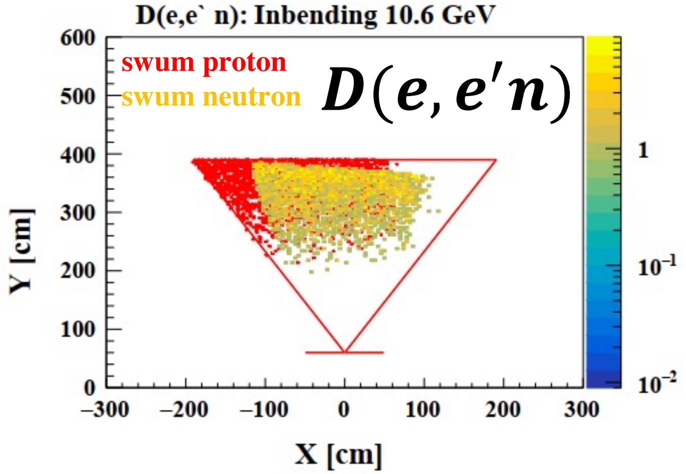
If the 'swum' proton track strikes the CLAS12 fiducial volume, continue. If it does not, then drop the event.

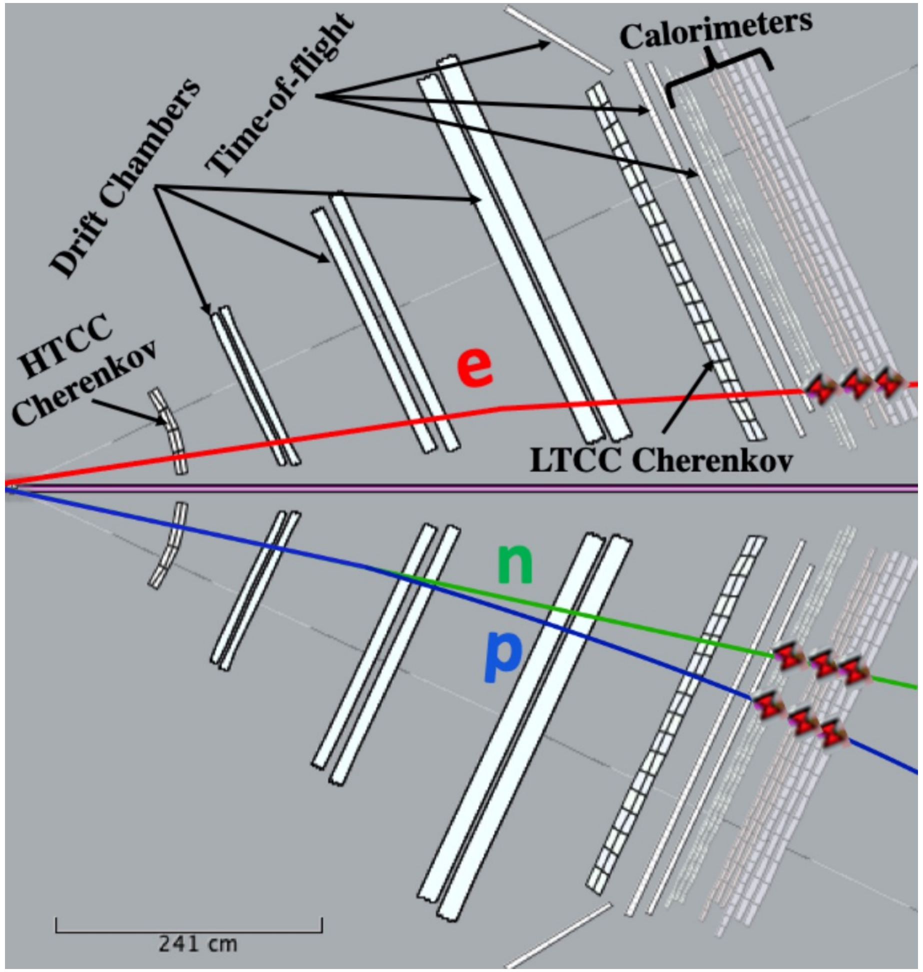
For the same event using only the electron information, assume elastic scattering and stationary target, predict the neutron momentum, and swim the neutron track through CLAS12.

If the 'swum' neutron track strikes the CLAS12 fiducial volume, continue. If it does not, then drop the event.

If both 'swum' tracks hit CLAS12, begin the nucleon analysis

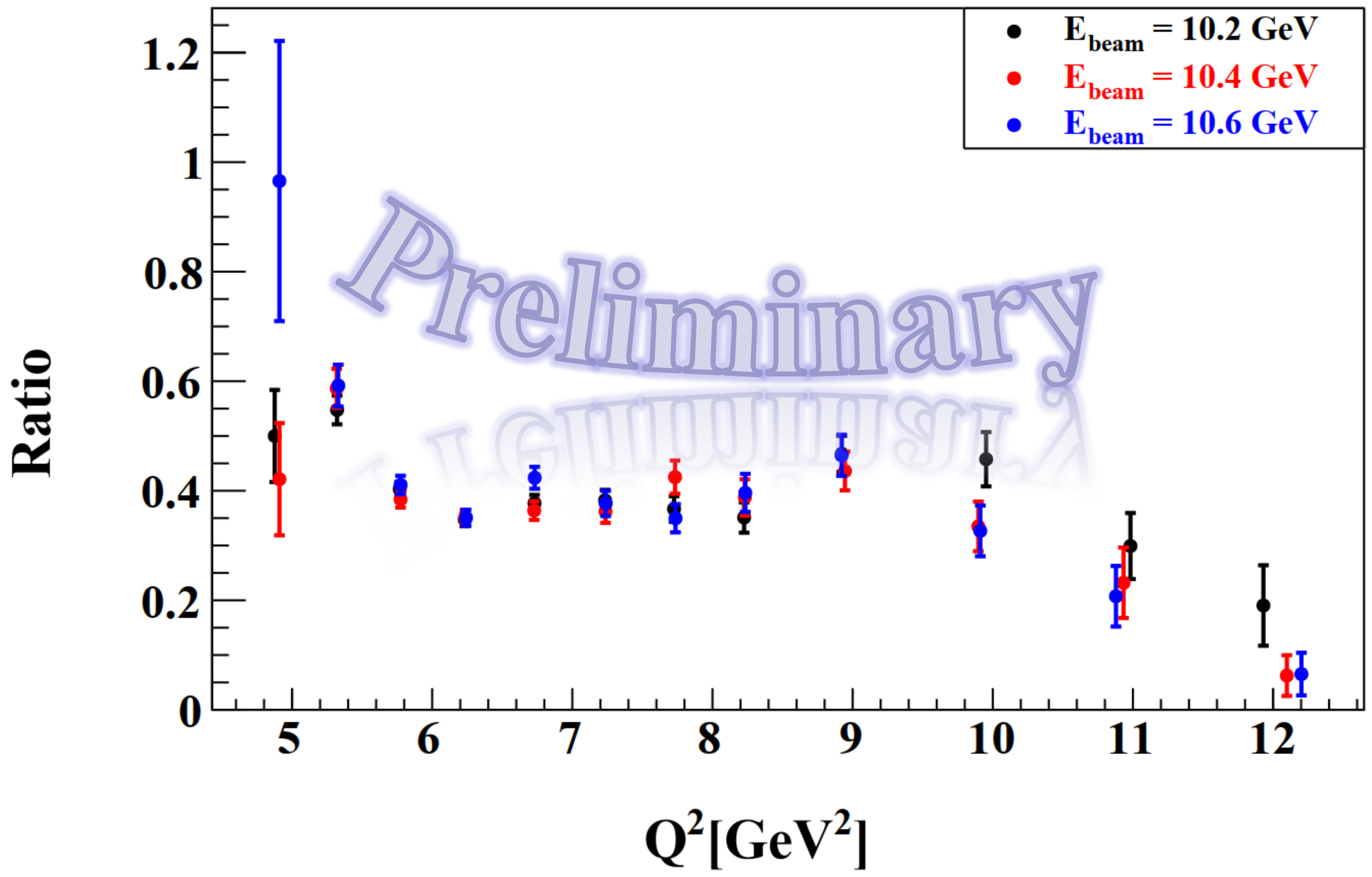






Ratio Result

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



The W distribution of $D(e,e'p)$ and $D(e,e'n)$ that satisfied:

- 1 σ E_{beam}^{angles} cut
- 1 σ $\Delta\phi$ cut
- $Q^2 < f(\theta_{pq})$
- $\theta_{pq} < 2$
- 3 σ E_x
- Apply Acceptance Matching

Corrections to the Ratio

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

- f_{NDE}: **Neutron Detection Efficiency Correction** ✓ ***done***
- f_{PDE}: **Proton Detection Efficiency Correction**
- f_{nuclear}: **Nuclear Correction**
- f_{fermi}: **Fermi Correction** ✓ ***done***
- $f_{\mathrm{radiative}}$: **Radiative Correction** ✓ ***done***

NDE Corrections to the Ratio

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

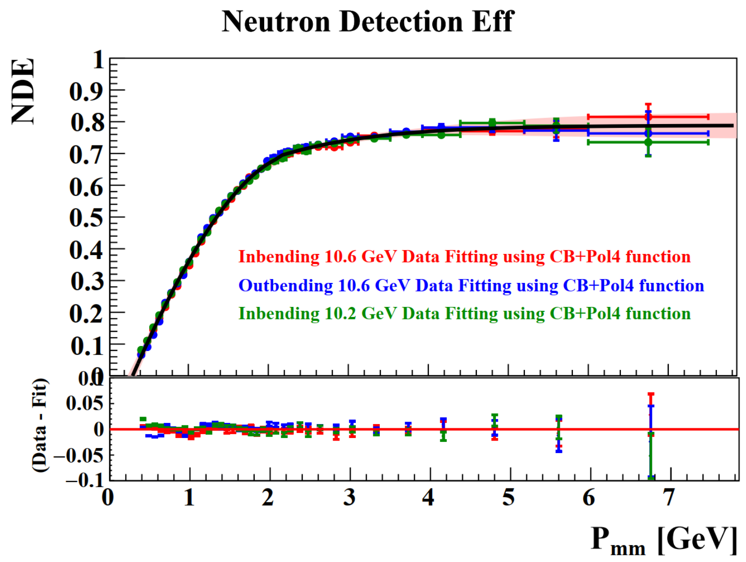
The NDE is the largest correction to the Ratio

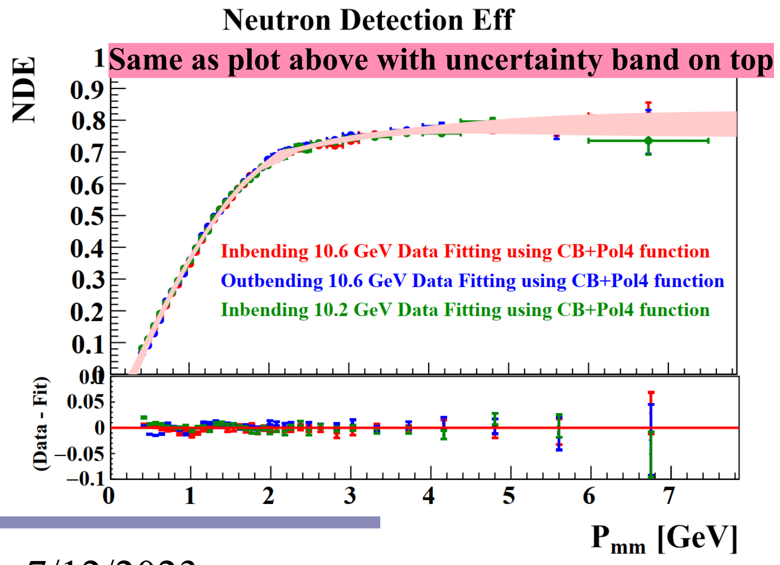
Determine the neutron detection efficiency (NDE) by using: $e\,p \rightarrow e'\,\pi^+(n)$

Fit the neutron detection efficiency (NDE) with:

$$\eta(P_{mm}) = a_0 + a_1 P_{mm} + a_2 P_{mm}^2 + a_3 P_{mm}^3 \quad \text{for} \quad P_{mm} < 2.15\ GeV$$

$$= a_4\left(1 - \frac{1}{1 + e^{\frac{P_{mm}-a_5}{a_6}}}\right) \quad \text{for} \quad P_{mm} > 2.15\ GeV$$





See talk in plenary session on Friday.

NDE Corrections to the Ratio

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

Determine the neutron detection efficiency (NDE) by using: $e\,p \rightarrow e'\,\pi^+(n)$

The NDE is the largest correction to the Ratio

Fit the neutron detection efficiency (NDE) with:

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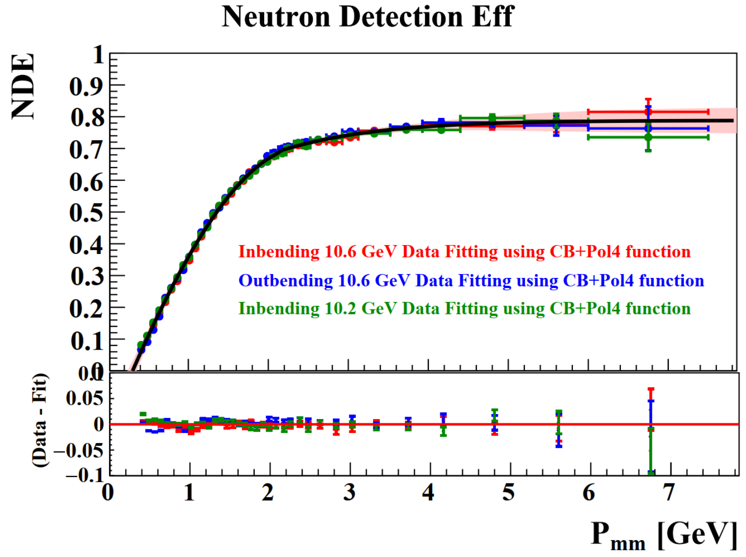
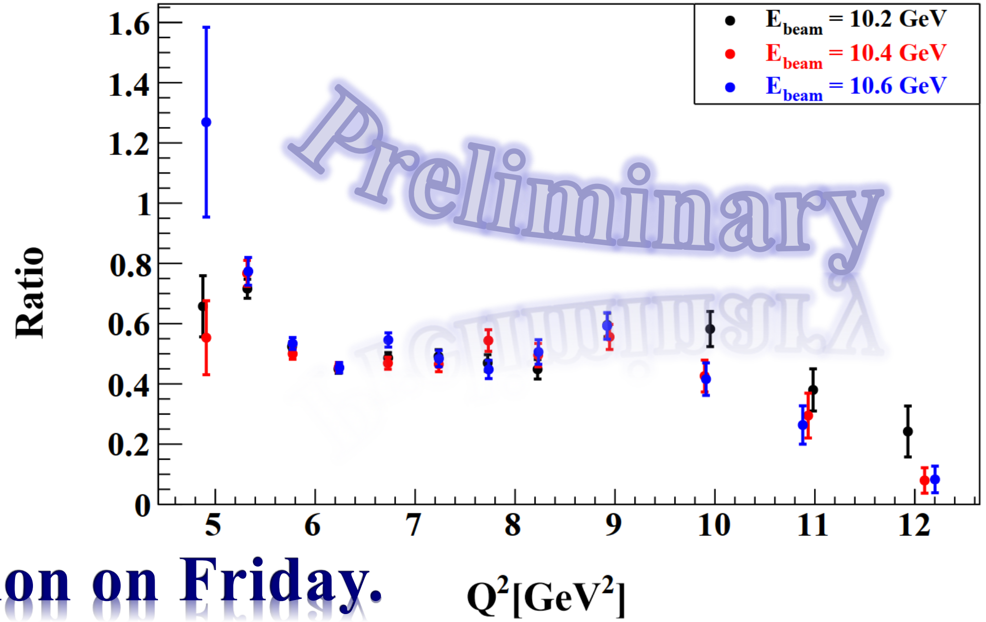
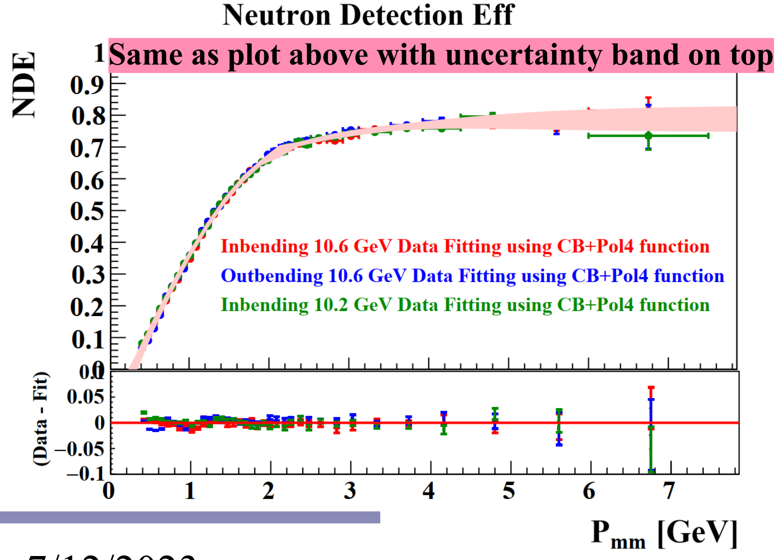


NDE correction increases the ratio values by ≈ 20%





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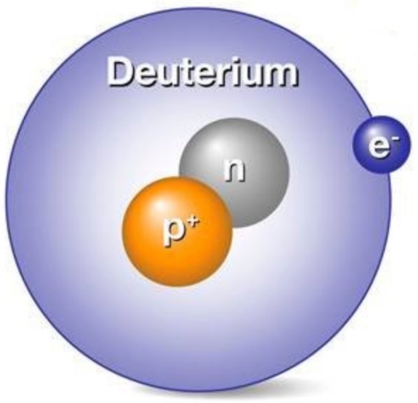
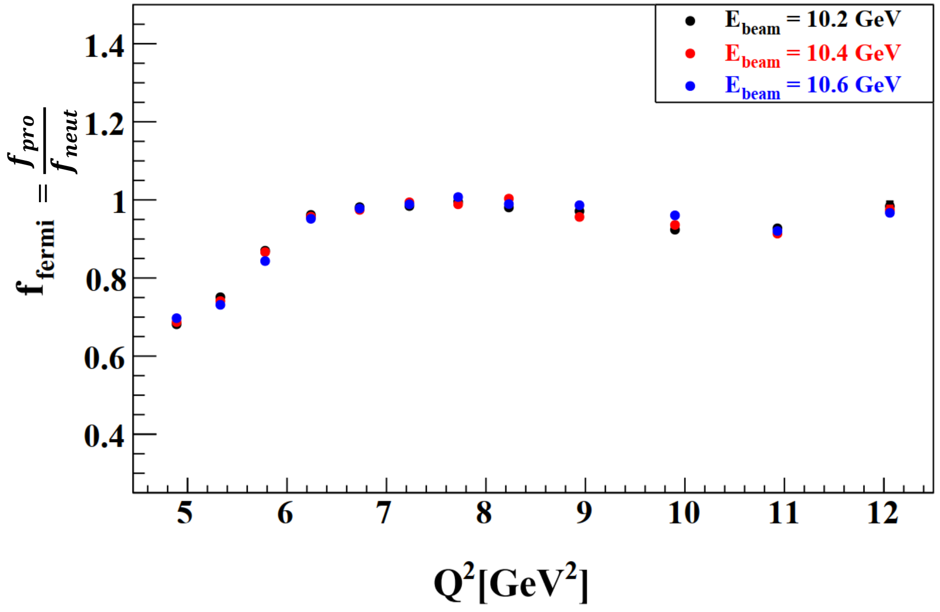
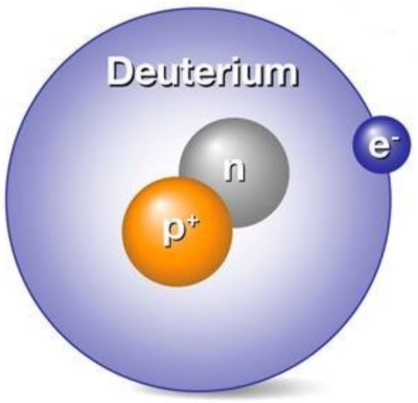
Fermi Corrections to the Ratio



- **Fermi motion in the target: Causes nucleons to migrate out of the CLAS12 acceptance.**
- **This effect was simulated using QUEEG generator.**
- **Fraction of correction (f_{pro} , f_{neut}): 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.**



Fermi Corrections to the Ratio



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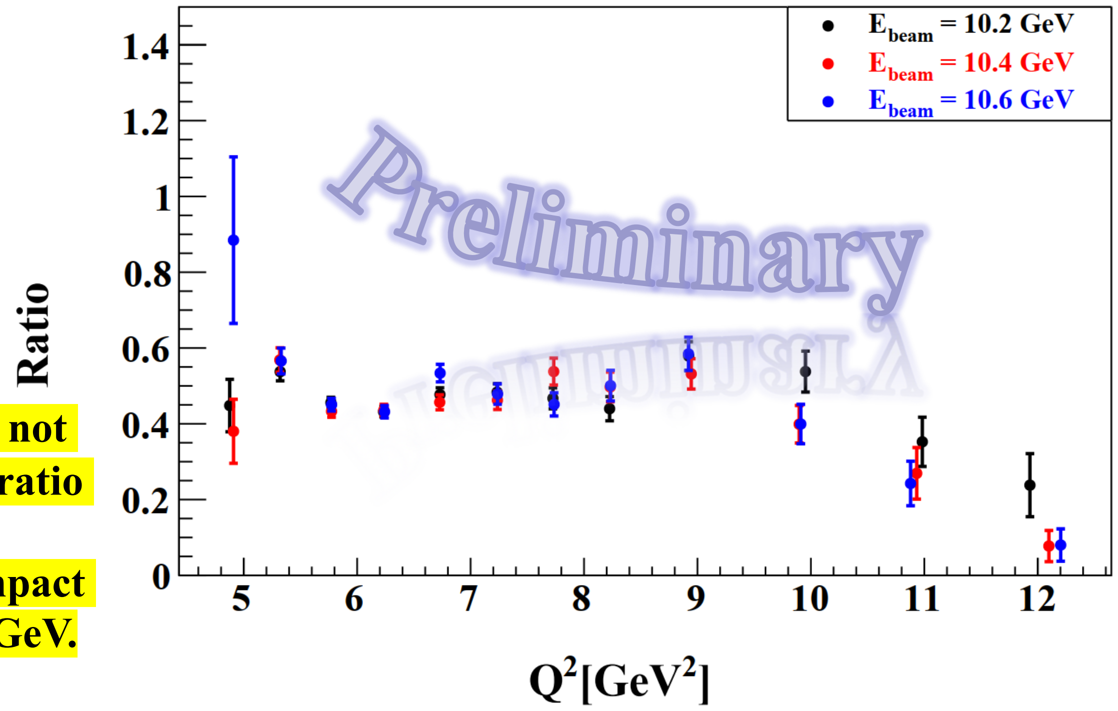
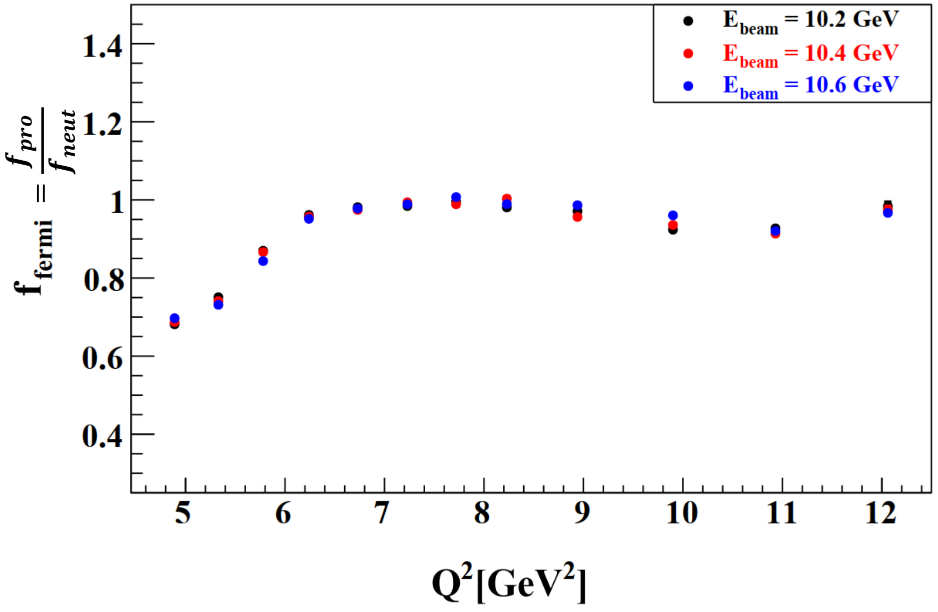
- This effect was simulated using QUEEG generator.
- Fraction of correction (f_{pro} , f_{neut}): the ratio of the number of actual hits in the acceptance that satisfy the θ_{pq} cut to the number of expected hits calculated using the electron information and assuming no Fermi motion.



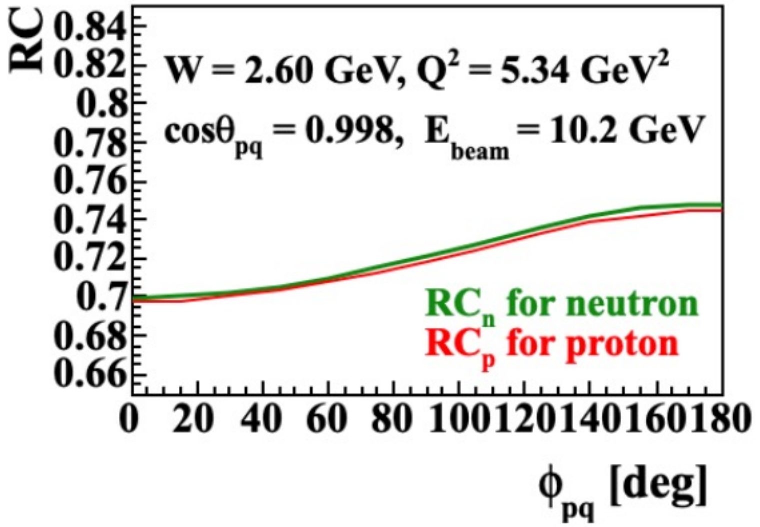


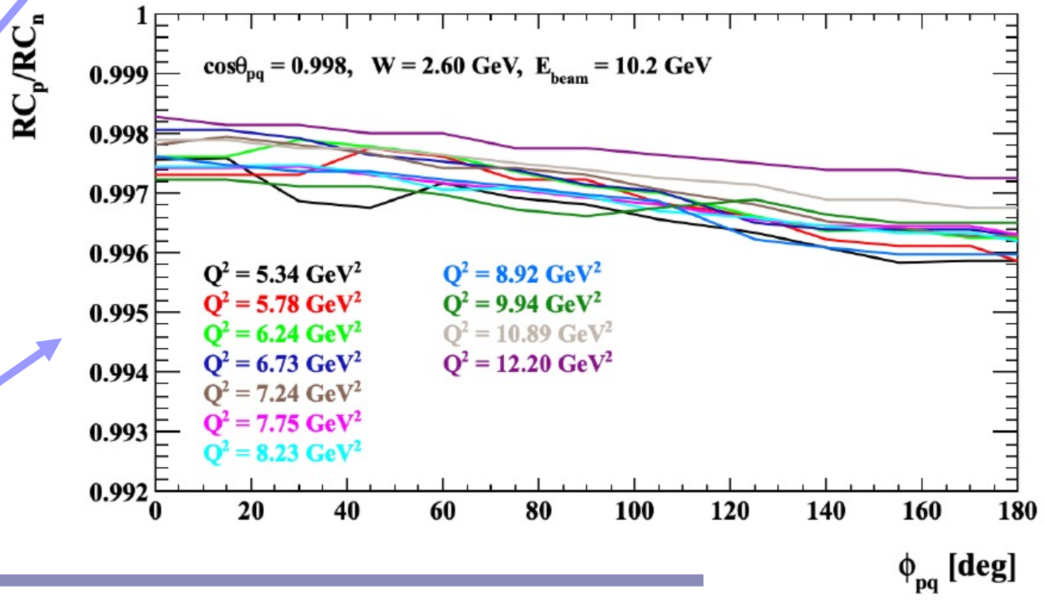
Fermi correction does not significantly affect the ratio for $Q^2 > 6.5$ GeV. However, there is an impact on the ratio below 6.5 GeV.

Radiative Corrections to the Ratio

- Photons can be emitted before or after the collisions and alter the final, detected electron energy.
- The radiative corrections (RC) for G_M^n calculated used program EXCLURAD.
- The EXCLURAD program is written by A. Afanasev for exclusive $p(e, e'\pi^+)n$.
- Modified by G. Gilfoyle to include the $D(e, e'p)n$ and $D(e, e'n)p$ channels.
- The radiative corrections were calculated with EXCLURAD.
- The radiated cross section: $\left(\frac{d\sigma}{d\Omega}\right) = (1+\delta)\left(\frac{d\sigma}{d\Omega}\right)_{Born}$
- The calculation is performed twice, once for $D(e, e'p)n$ and once for $D(e, e'n)p$ channel.

The ratio of RC_p to RC_n radiative corrections differs by about 0.3% and does not significantly impact the ratio values.

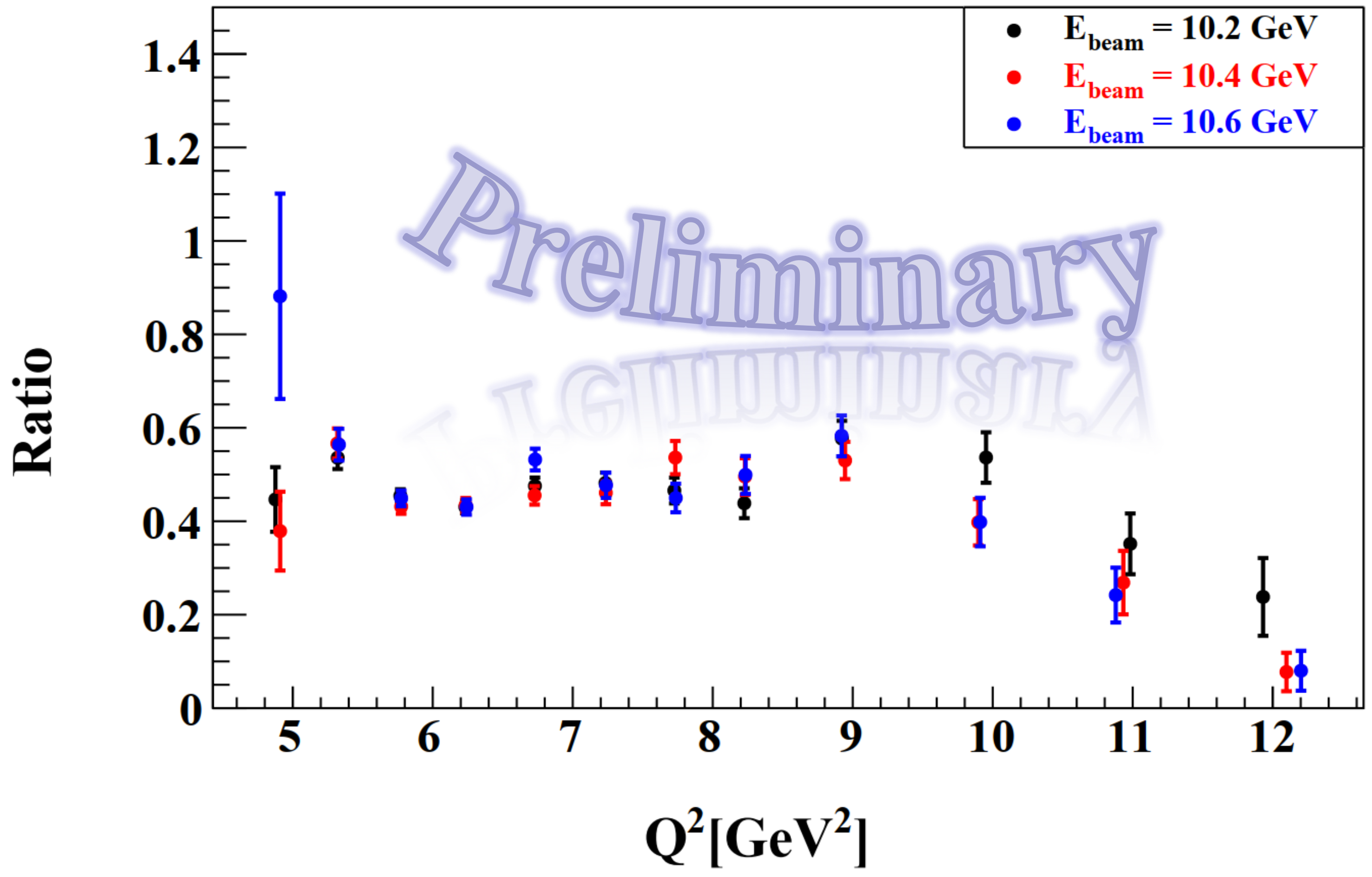




Corrections to the Ratio

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

✓ ✓ ✓



Conclusion and Outlook

- The neutron magnetic form factor G_M^n is a fundamental quantity related to the magnetization in the neutron.
- Extract G_M^n at $Q^2 \simeq 5$ -12 GeV^2 using the ratio method $R = \frac{d(e,e'n)}{d(e,e'p)}$.
- Precise measurement of the Neutron Detection Efficiency is here.
- NDE ~ 0.7884 ± 0.0087 at the plateau ($p_{mm} > 3.5$ GeV) for two different magnetic field configurations with two different beam energies.

Future works :

- Study the proton detection efficiency in the Forward Detector.
- Apply nuclear correction.
- Calculate G_M^n.
- Study the uncertainties.

Thank You!!

Why we need to measure elastic electromagnetic form factors EEFF

G_p, G_M: Fundamental quantity related to the electric and magnetic properties of the nucleon.

provide important constraints for GPDs.

Listing of the electromagnetic form factors of the nucleons experiments

Quantity	Exp.	Method	Target	Q^2 [GeV^2]	Hall	Status
G_M^p	E12-07-108	Elastic Scattering	LH_2	2.0 – 15.7	A	Phys. Rev. Lett., 128, 102002 (2022).
G_E^p/G_M^p	E12-07-109	Polarization transfer	LH_2	5 – 12	A	Fall 2024
G_M^n	E12-07-104	$e-n$ / $e-p$ ratio	LD_2 , LH_2	5 - 12.0	B	Data collection complete
G_M^n	E12-09-019	$e-n$ / $e-p$ ratio	LD_2 , LH_2	1.9 – 9.9	A	Data collection complete
G_E^n/G_M^n	E12-09-016	Double polarization asymmetry	Polarized ^3He	3.8 – 10	A	Data collection complete
G_E^n/G_M^n	E12-17-004	Polarization transfer	LD_2	4.3	A	Summer 2023
G_E^n/G_M^n	E12-11-009	Polarization transfer	LD_2	Up to 6.9	A	To be scheduled

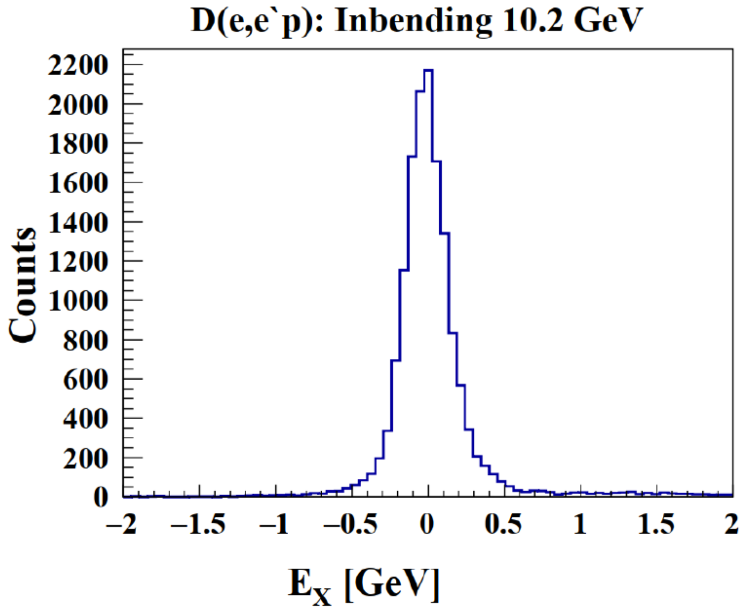
Quasi-elastic Selection

4-Missing Energy Cut

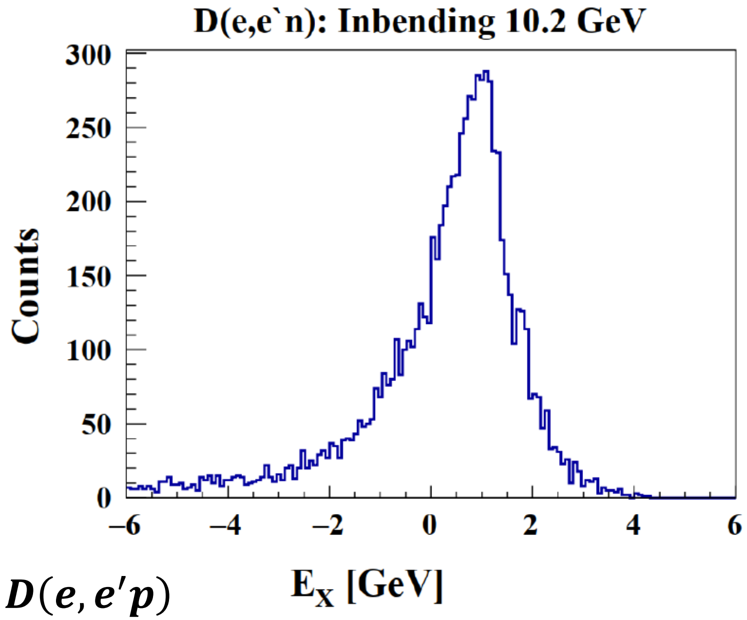
From the momentum conservation law the transverse momentum for quasi-elastic events are expected to be zero.

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

$D(e,e'p)$ Selection



$D(e,e'n)$ Selection



Cut applied

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

$1\ \sigma\ \Delta\phi$ cut

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

$\theta_{pq} < 2$

There is offset from zero and distorted
$D(e,e'n)$ has a wider peak compare to $D(e,e'p)$

Neutron Momentum Correction

$$\Delta P_{neut} = p_{calc} - p_{meas}$$

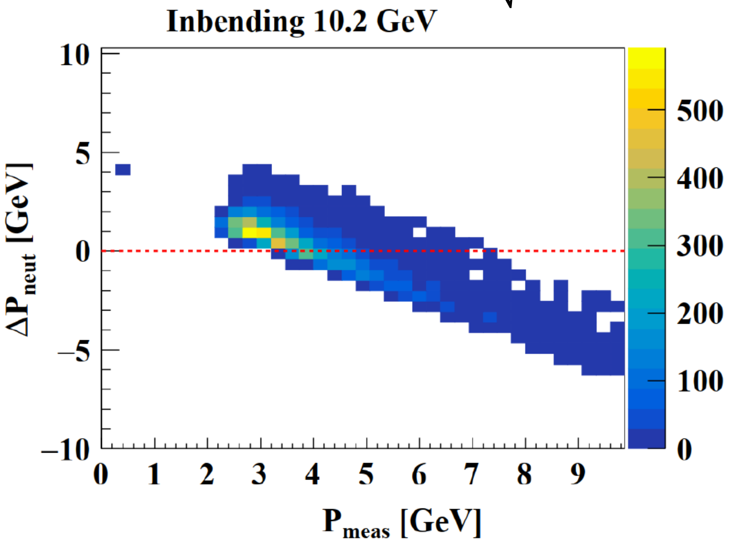
In order to correct the measured neutron momentum (P_{meas}) a calculated neutron momentum (P_{calc}) is used as a reference (accurate value)

The calculated neutron momentum is determined based on the known E_{beam} and the measured electron polar angle, assuming elastic scattering

$$P_{calc} = \sqrt{E_0^2 - 2\,E_0 * p_{ecal} * \cos\theta_e + p_{ecal}^2}\ , \qquad \text{where} \quad P_{ecal} = \frac{E_0}{1 + 2E_0 \sin^2(\frac{\theta_e}{2})/M_N}$$

The measured neutron momentum (P_{meas}) is determined using

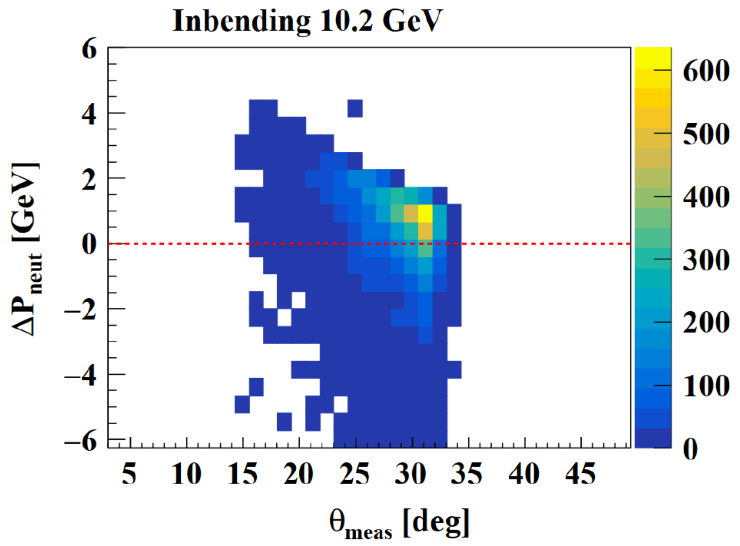
$$P_{meas} = \frac{m_n\,\beta_{neutral}}{\sqrt{1 - \beta_{neutral}^2}}\ , \qquad \text{where} \quad \beta_{neutral} = \frac{l_{n(REC)}}{c.(t_{n(REC)} - t_{st})}$$



The neutron momentum correction is made in two steps:

1- $\Delta P_{neut}\ vs.\ P_{meas}$

2- $\Delta P_{neut}\ vs.\ \theta_{meas}$



Neutron Momentum Correction

1- ΔP_{neut} vs. P_{meas}

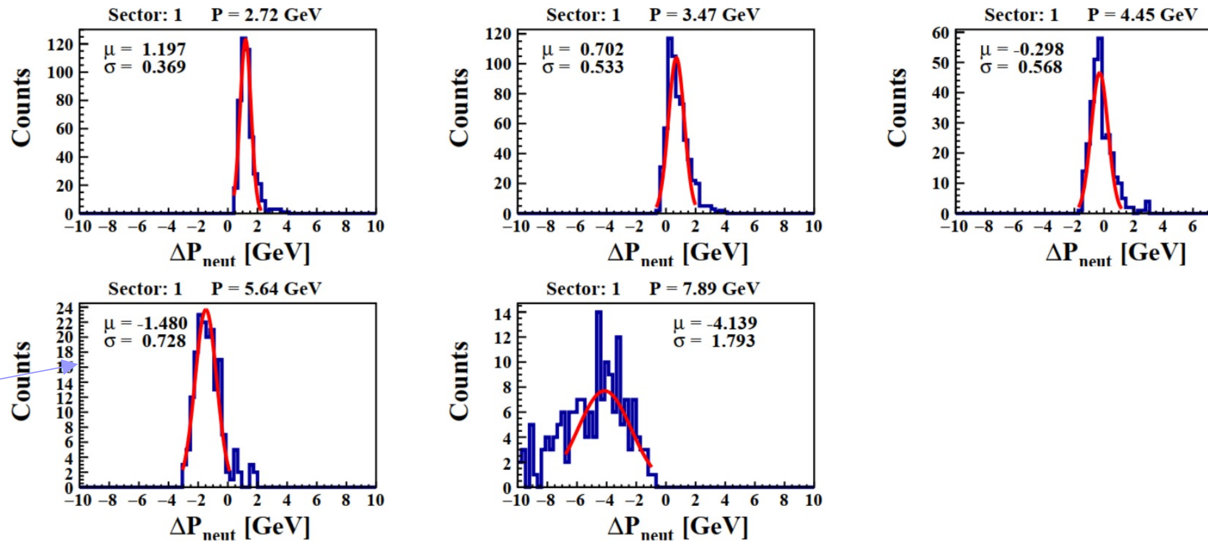
1- Correction done for each sector
2- Binning ΔP_{neut} in P_{meas}
3- Fitting ΔP_{neut} using Gauss
4- The mean of the Gauss is then fit by 1st order Poly:

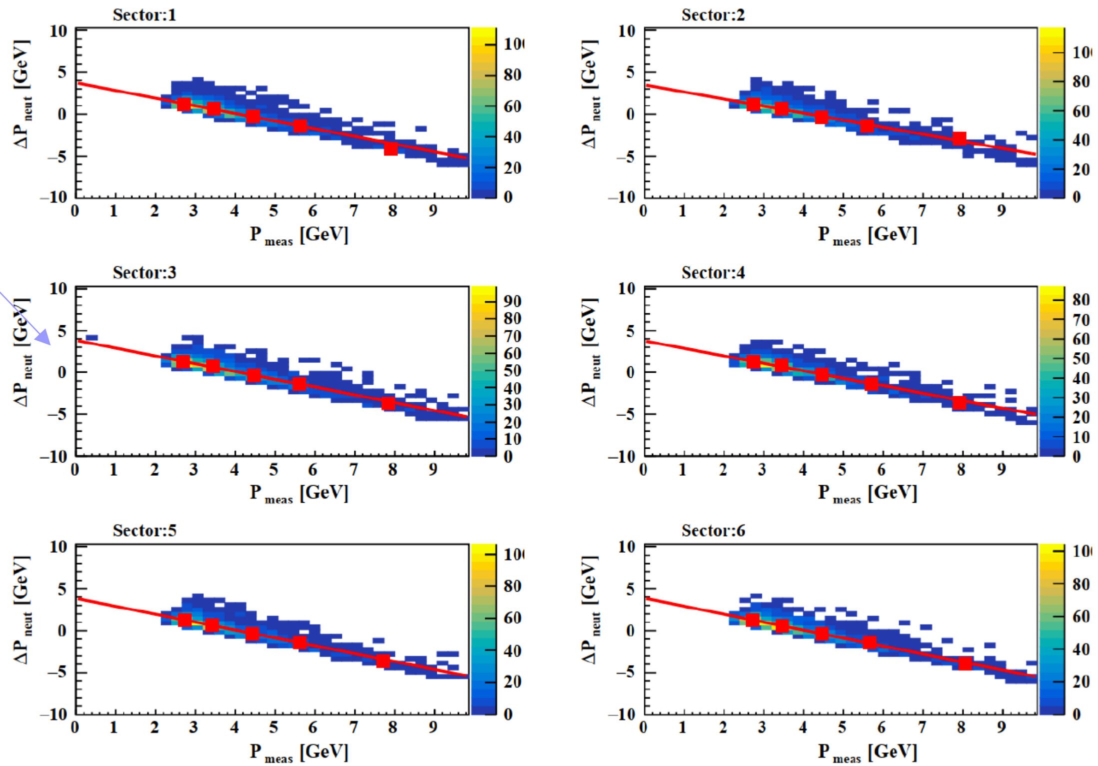
$$\mu_p = a_p + b_p\, P_{meas}$$

5- the momentum correction function

$$P_{Pcorr} = P_{meas} + \mu_p$$

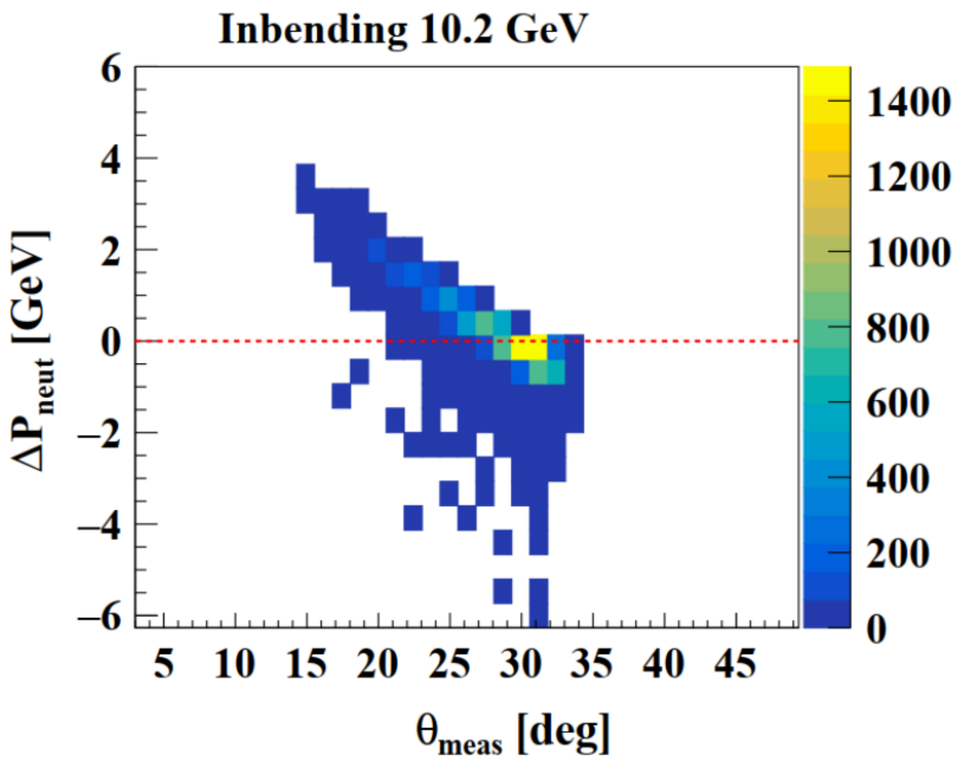
is then implemented with the parameters coming from fits.

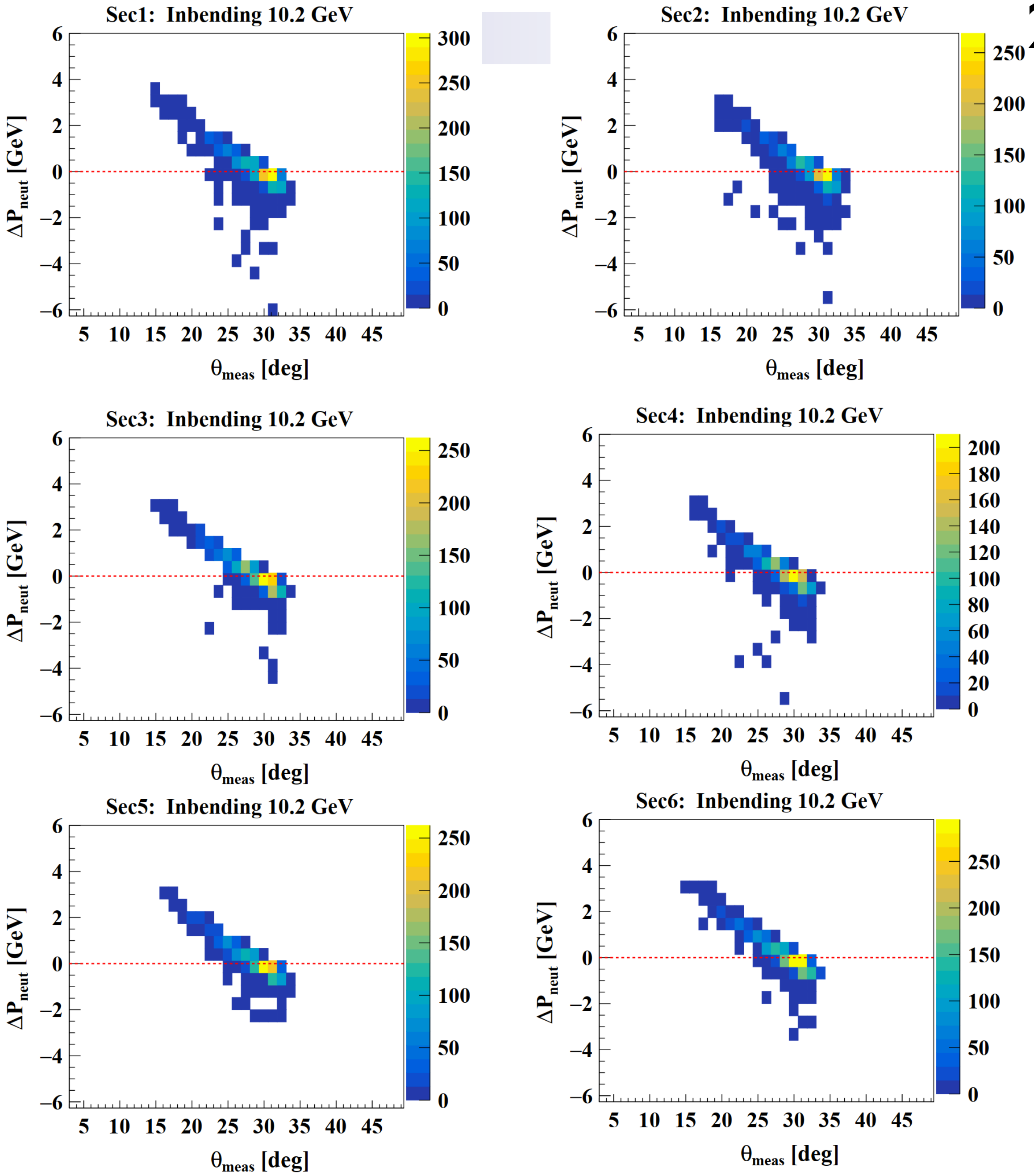




Neutron Momentum Correction

$2 - \Delta P_{neut}$ vs. θ_{meas}





Neutron Momentum Correction

$2 - \Delta P_{neut}\ vs.\ \theta_{meas}$

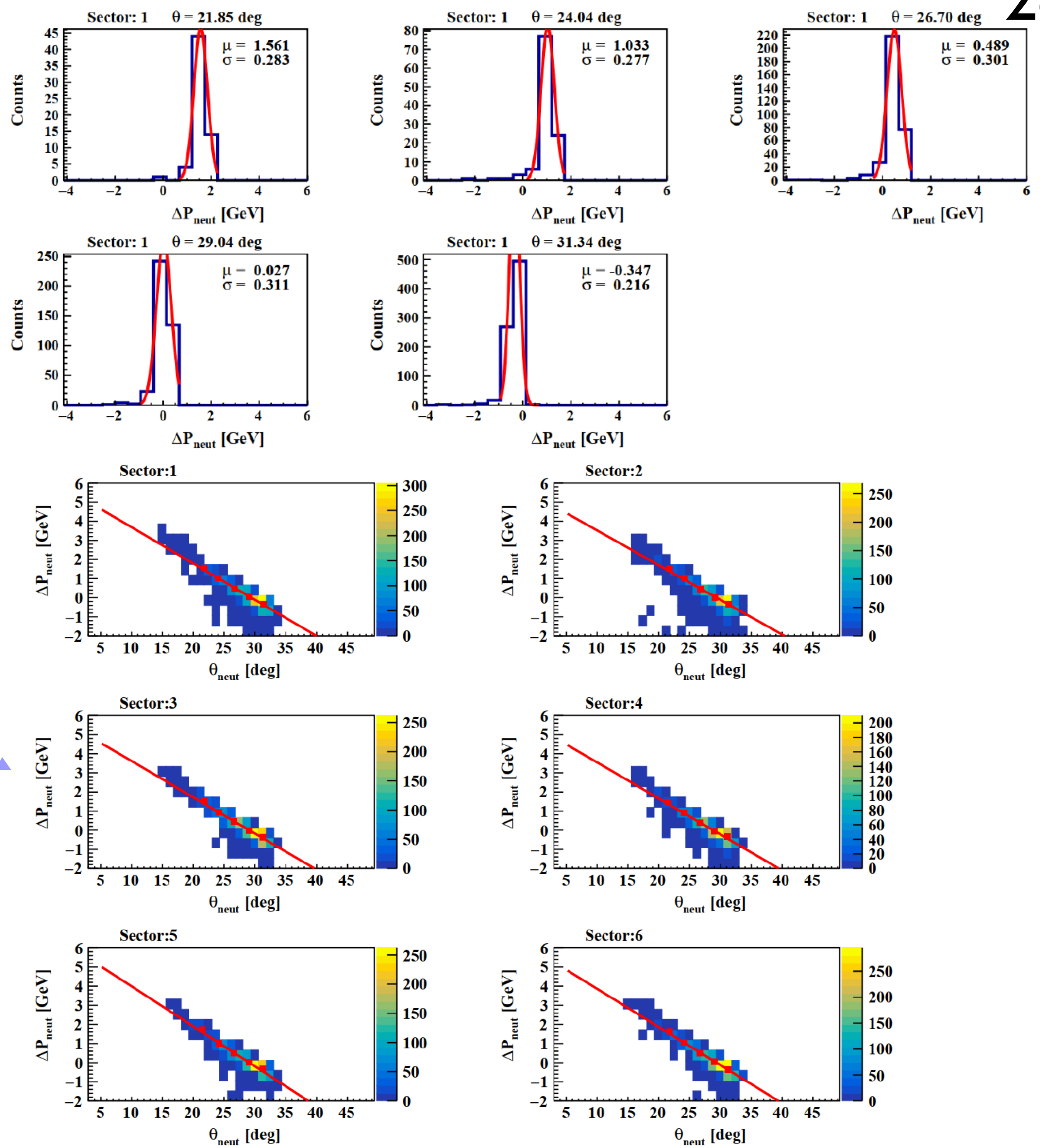
1- Correction done for each sector
2- Binning ΔP_{neut} in θ_{meas}
3- Fitting ΔP_{neut} using Gauss
4- The mean of the Gauss is then fit by 1st order Poly

$$\mu_\theta = a_\theta + b_\theta\, \theta_{meas}$$

5- the momentum correction function

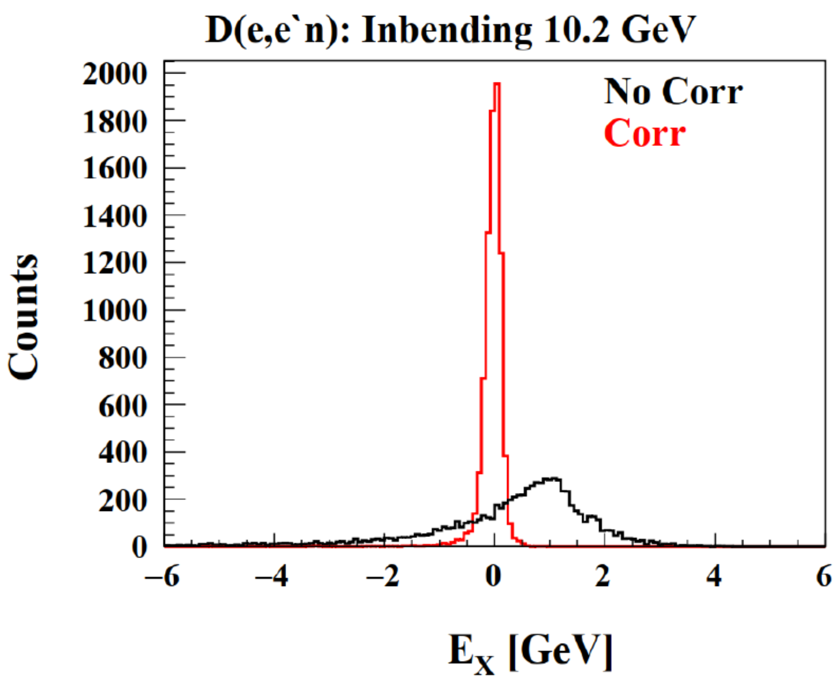
$$P_{\theta corr} = P_{meas} + \mu_\theta$$

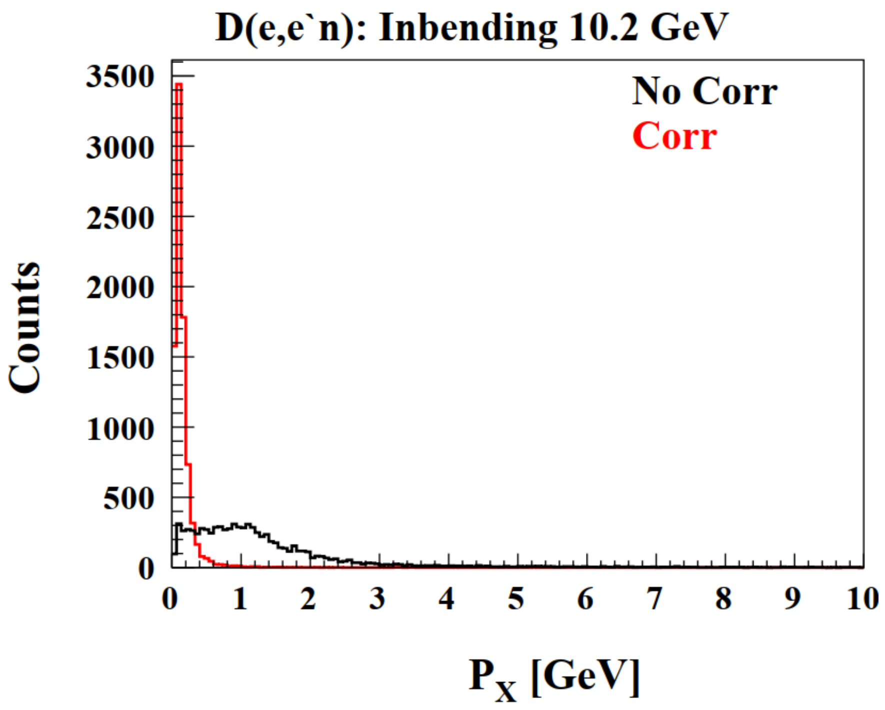
is then implemented With the parameters coming from fits.



Applied Neutron Momentum Correction

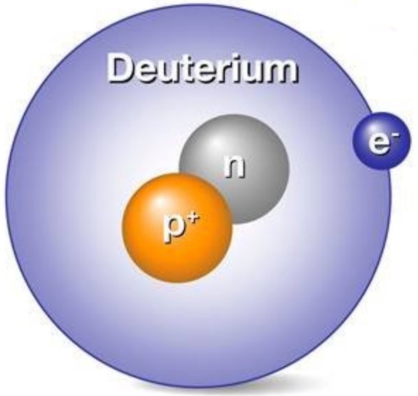
In order to correct the measured neutron momentum (P_{meas}) a calculated neutron momentum (P_{calc}) is used as a reference (accurate value)



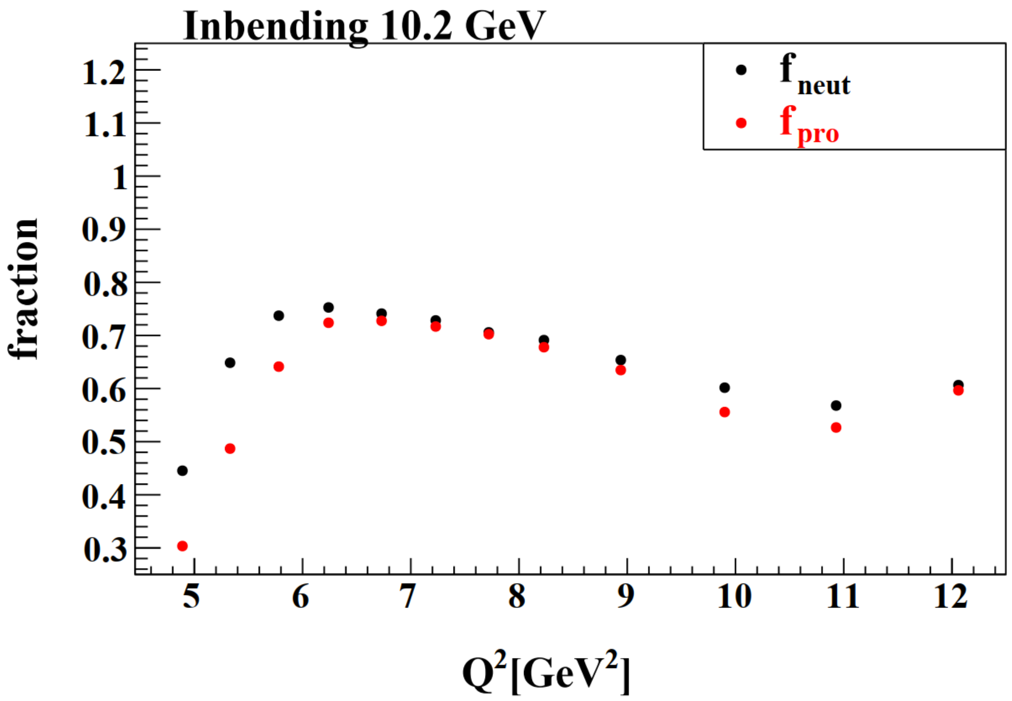


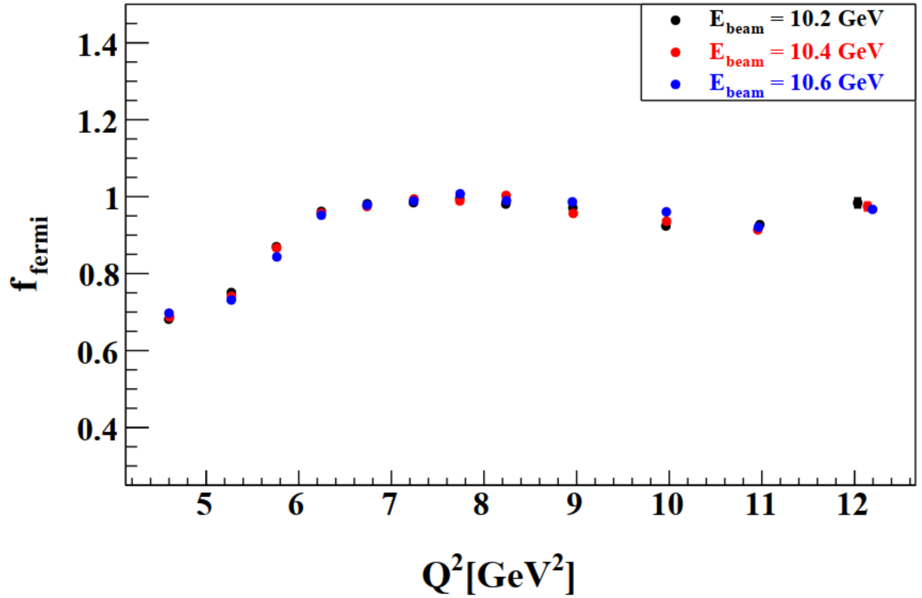
The corrections have led to clear improvements in both the resolutions and peak position of the missing energy distribution.

Fermi Corrections to the Ratio

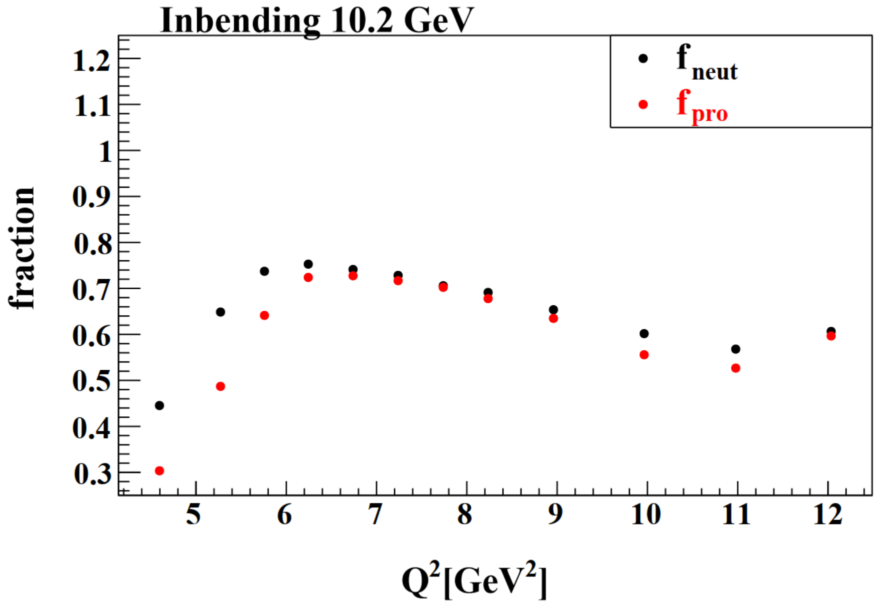


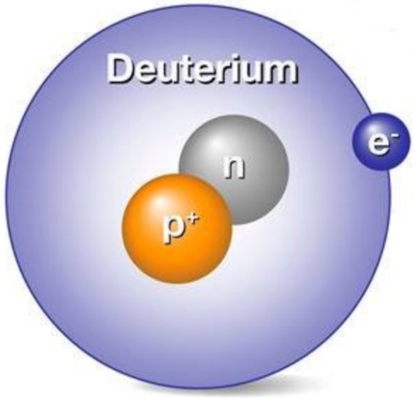
- Fermi motion in the target: Causes nucleons to migrate out of the CLAS12 acceptance.
- This effect was simulated using QUEEG generator.
- Fraction of correction: the ratio of the number of actual hits in the acceptance that satisfy the θ_{pq} cut to the number of expected hits calculated using the electron information and assuming no Fermi motion.





Fermi Corrections to the Ratio

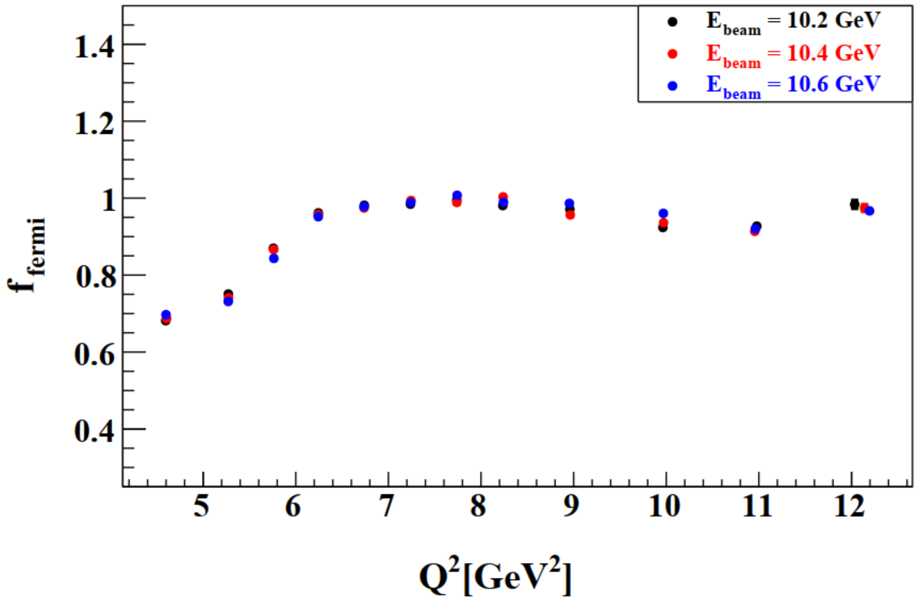


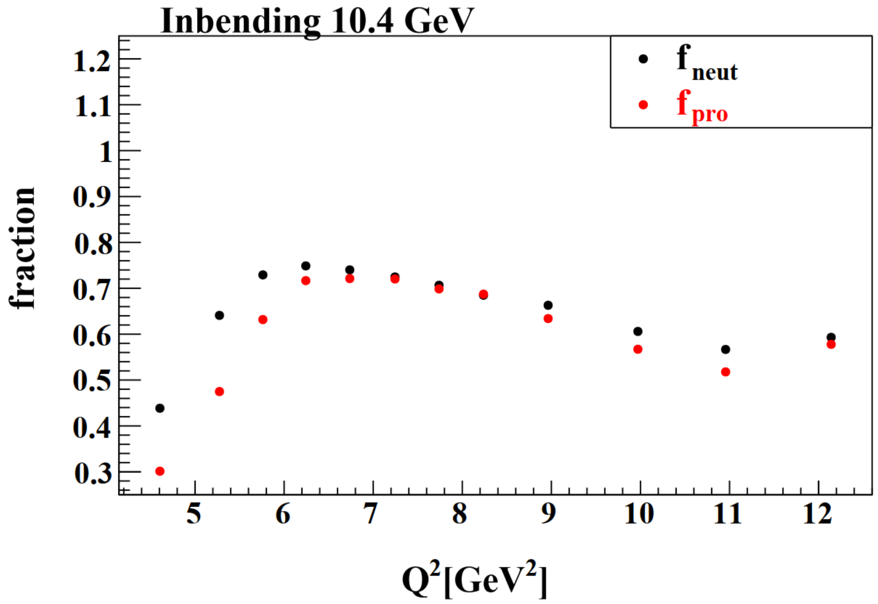


eons to migrate out of the CLAS12 acceptance.

generator.

umber of actual hits in the
e number of expected hits
n and assuming no Fermi





G_M^n Calculation

arXiv:1707.09063v2 [nucl-ex] 11 Dec 2017

$$G_M^n = \sqrt{\left[R_{Cor}\left(\frac{\sigma^p_{mott}}{\sigma^n_{mott}}\right)\left(\frac{1+\tau_n}{1+\tau_p}\right)\left(G_E^{p\,2} + \frac{\tau_p}{\varepsilon_p}\;G_M^{p\,2}\right) - G_E^{n\,2}\right]\frac{\epsilon_n}{\tau\;n}}$$

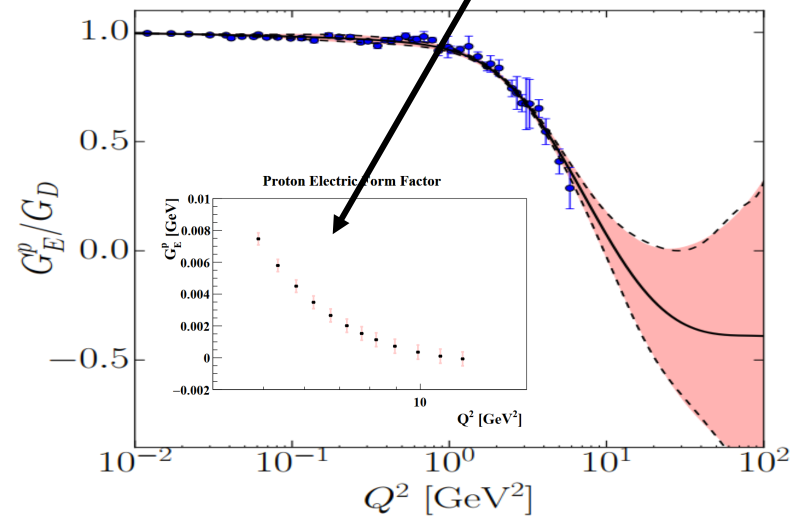
$$\frac{\sigma^p_{mott}}{\sigma^n_{mott}} \approx 1\,, \qquad \frac{1+\tau_n}{1+\tau_p} \approx 1$$

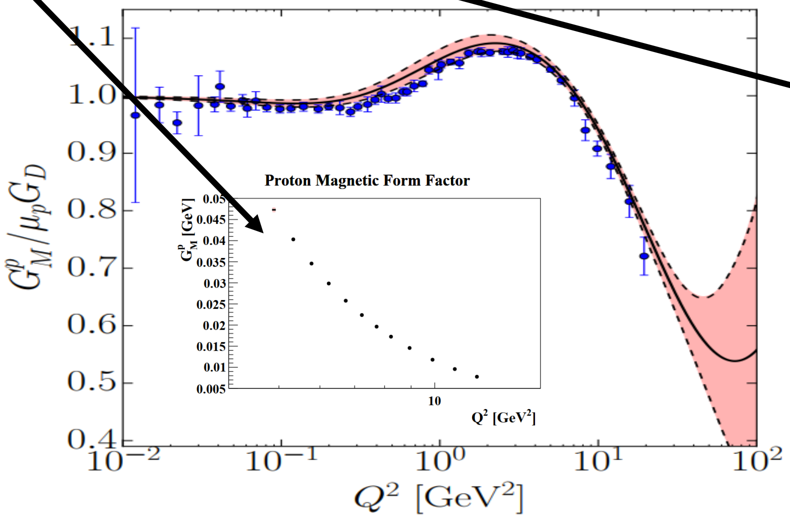
$$\sigma_{Mott} = \frac{\alpha^2 E' \cos^2(\frac{\theta_e}{2})}{4E^3 \sin^4(\frac{\theta_e}{2})}\,, \qquad \tau_{n,p} = \frac{Q^2}{4\,M^2_{p,n}}$$

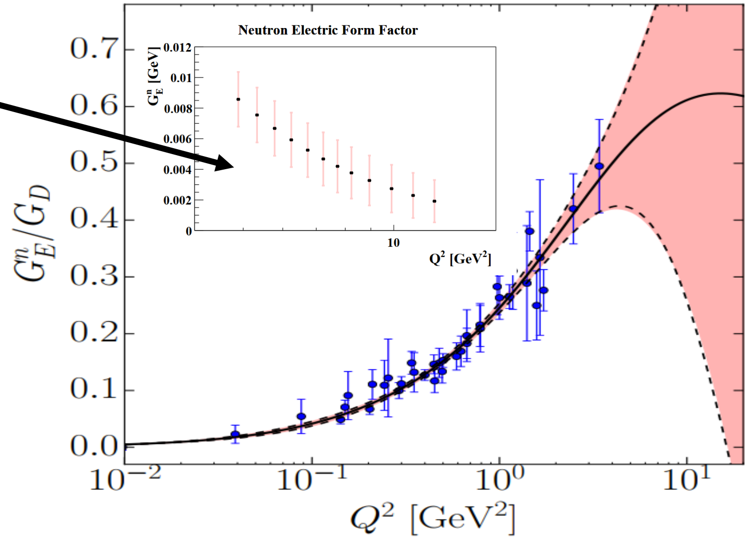
$$\epsilon = \left[1 + 2(1+\tau)\tan^2(\frac{\theta_e}{2})\right]^{-1}$$

$$G_M^n = \sqrt{\left[R_{Cor}\left(G_E^{p\,2} + \frac{\tau_p}{\varepsilon_p}\;G_M^{p\,2}\right) - G_E^{n\,2}\right]\frac{\epsilon_n}{\tau\;n}}$$

Using Arrington Parameterizations







G_M^n Calculation

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$$G_M^n = \sqrt{\left[R_{Cor}\left(\frac{\sigma^p_{mott}}{\sigma^n_{mott}}\right)\left(\frac{1+\tau_n}{1+\tau_p}\right)\left(G_E^{p\,2} + \frac{\tau_p}{\varepsilon_p}\ G_M^{p\,2}\right) - G_E^{n\,2}\right]\frac{\epsilon_n}{\tau\ n}}$$

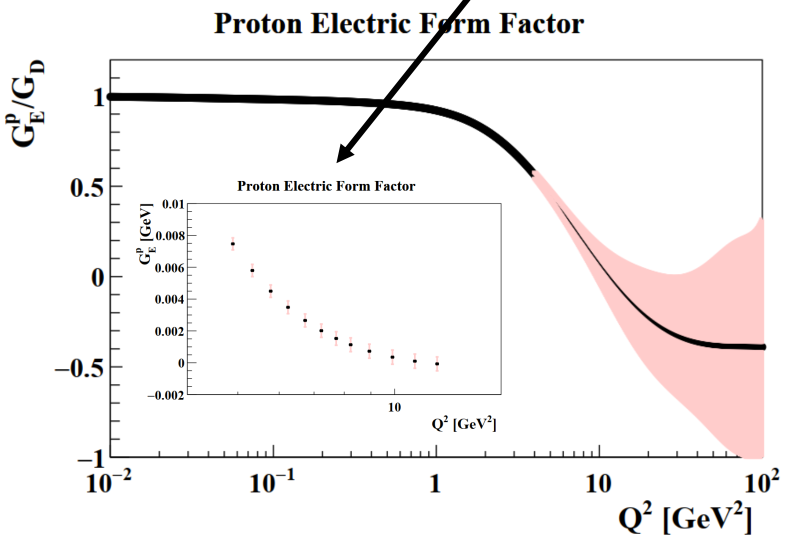
$$\sigma_{Mott} = \frac{\alpha^2 E' \cos^2(\frac{\theta_e}{2})}{4E^3 \sin^4(\frac{\theta_e}{2})}, \qquad \tau_{n,p} = \frac{Q^2}{4\,M^2_{p,n}}$$

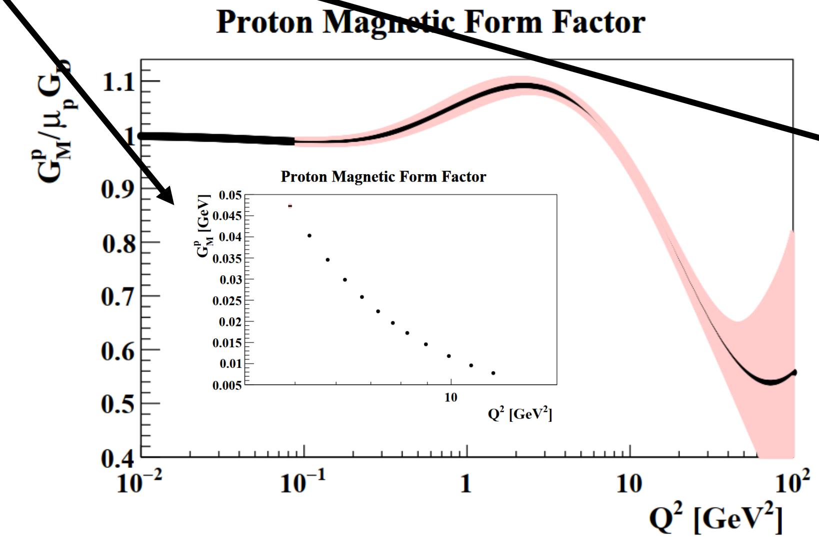
$$\frac{\sigma^p_{mott}}{\sigma^n_{mott}} \approx 1, \qquad \frac{1+\tau_n}{1+\tau_p} \approx 1$$

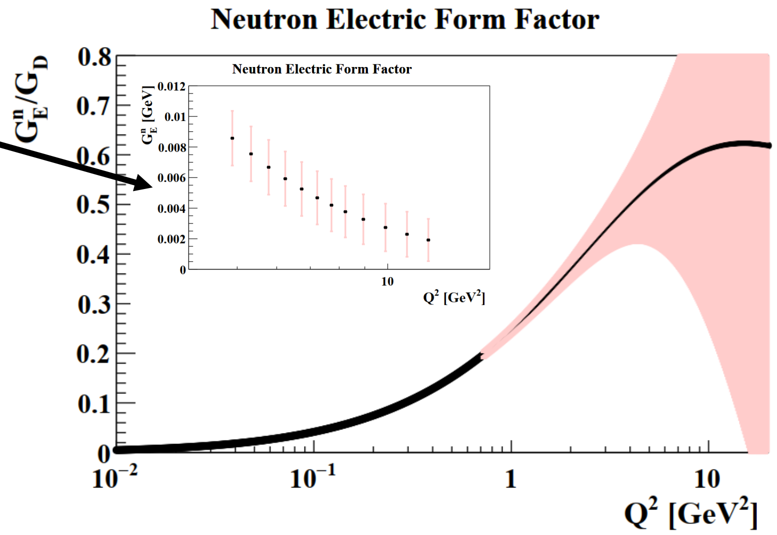
$$\epsilon = \left[1 + 2(1+\tau)\tan^2(\frac{\theta_e}{2})\right]^{-1}$$

$$G_M^n = \sqrt{\left[R_{Cor}\left(G_E^{p\,2} + \frac{\tau_p}{\varepsilon_p}\ G_M^{p\,2}\right) - G_E^{n\,2}\right]\frac{\epsilon_n}{\tau\ n}}$$

Using Arrington Parameterizations







Using Arrington Parameterizations

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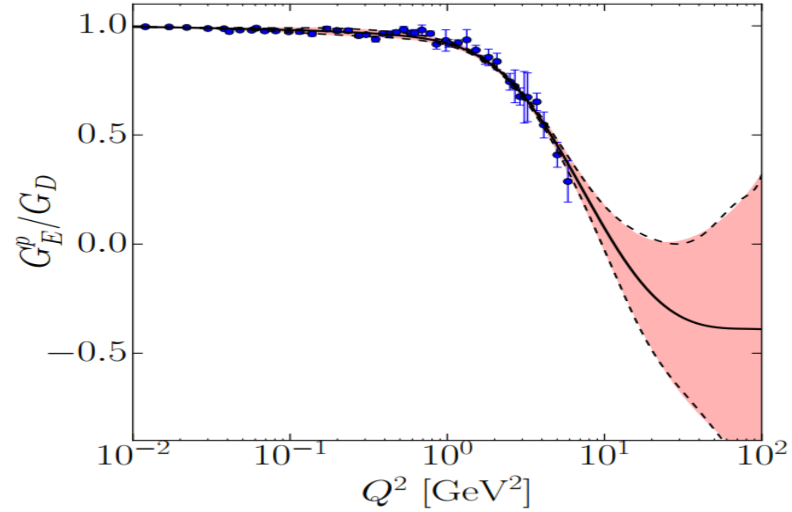
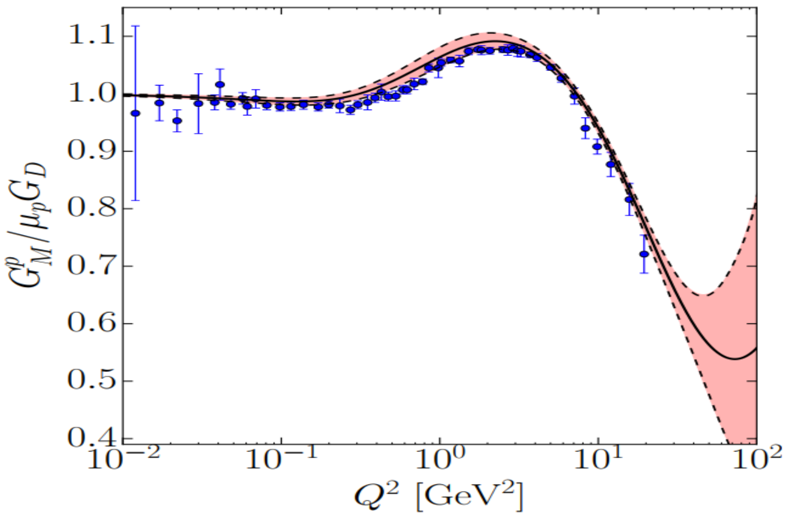
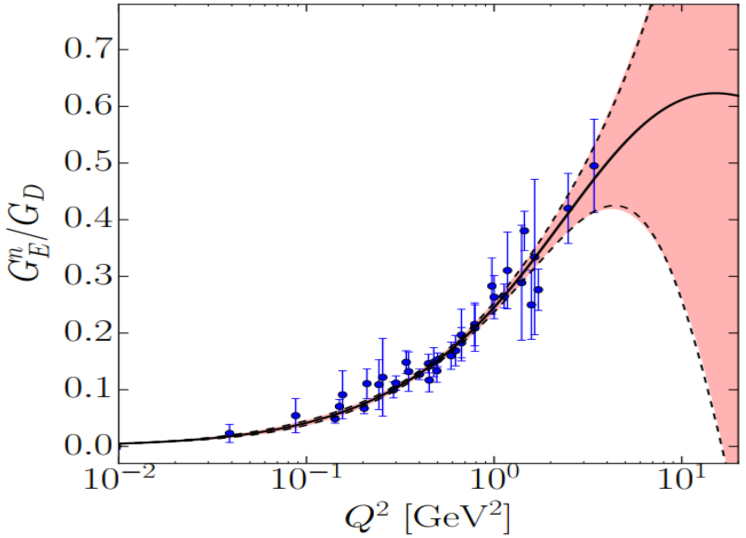


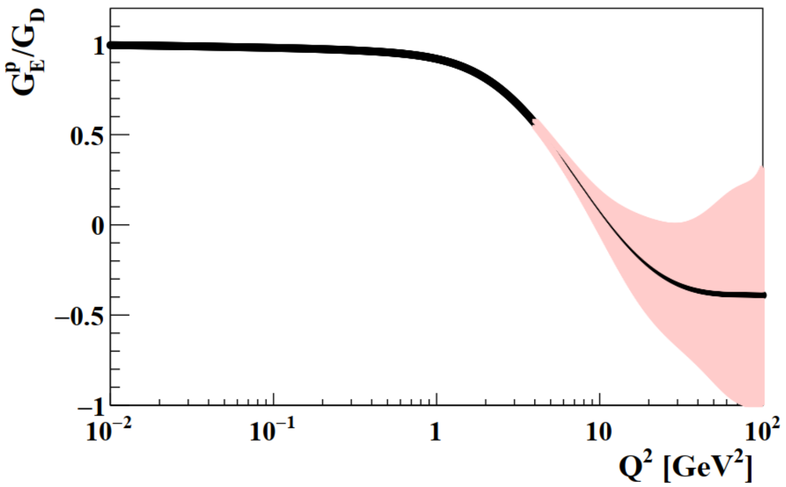


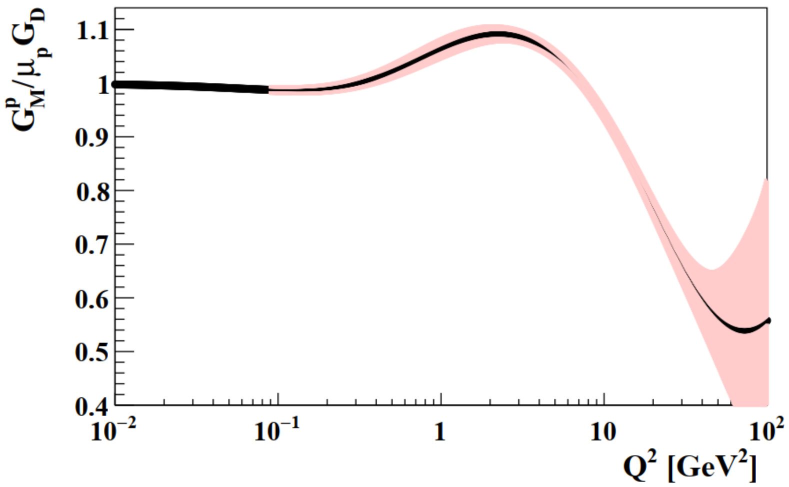


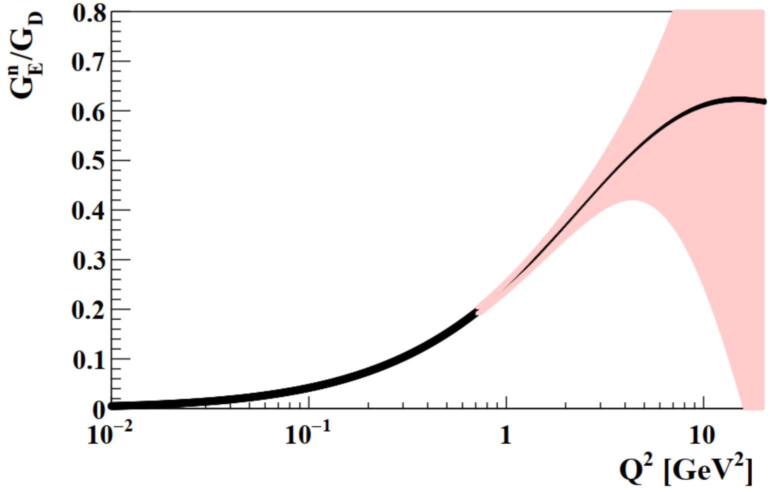
Proton Electric Form Factor

Proton Magnetic Form Factor

Neutron Electric Form Factor

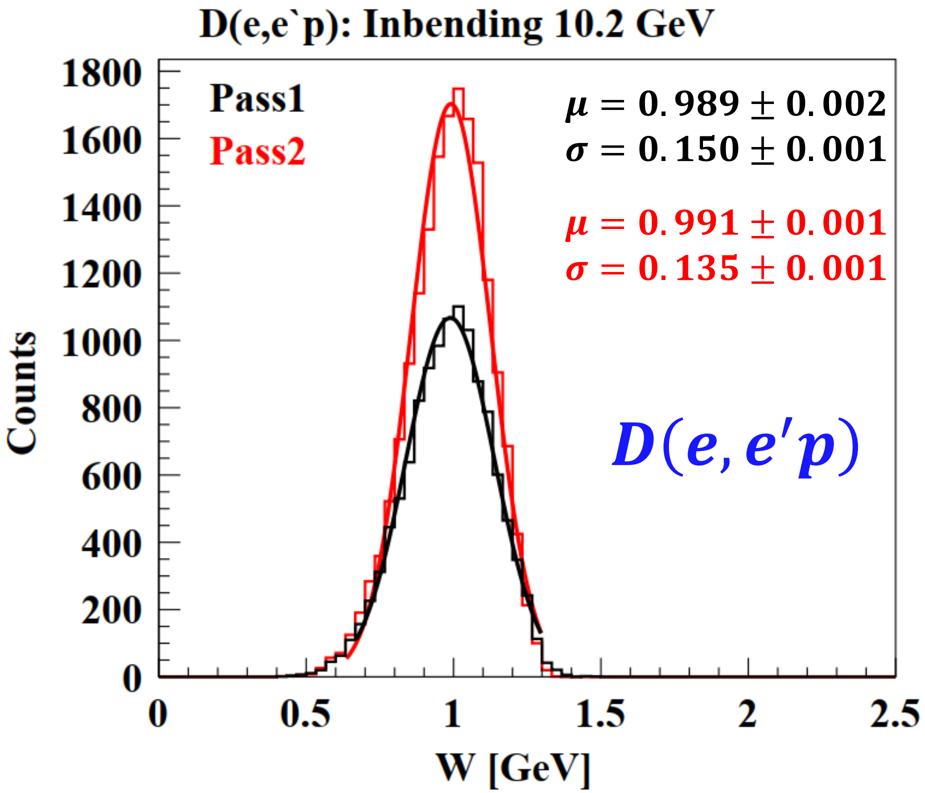






Comparing Pass2 and Pass1 RG-B for 10.2 GeV

The W distribution of $D(e,e'p)$ and $D(e,e'n)$ satisfied:



✓Improved the resolution by ~ 10%

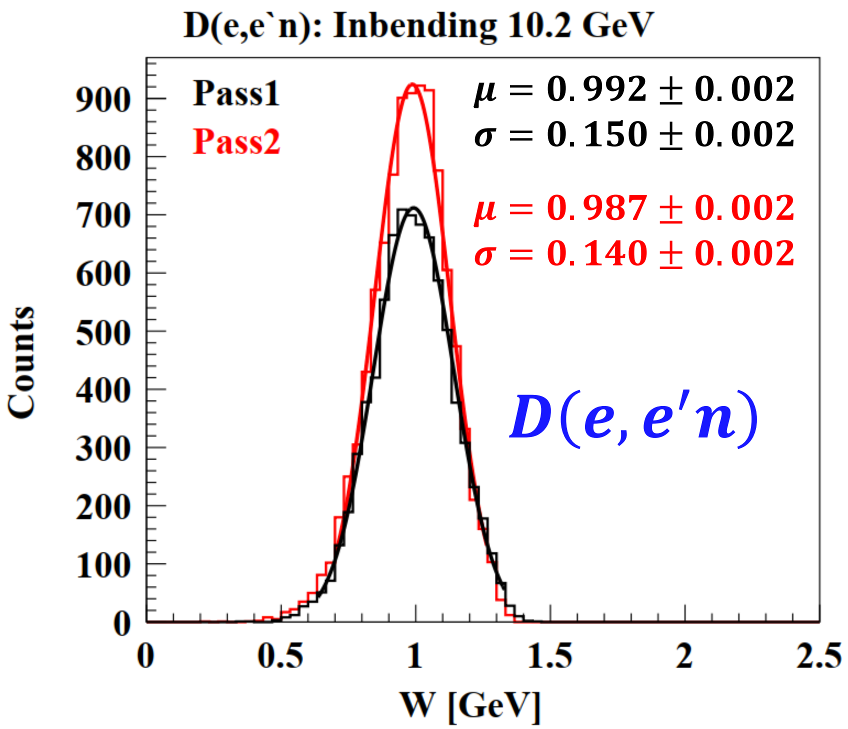
✓Increase the number of events in W from pass1 to pass2 by ~ 45%

- 1 σ E_{beam}^{angles} cut
- 1 σ $\Delta\phi$ cut
- $Q^2 < f(\theta_{pq})$
- $\theta_{pq} < 2$
- 3 σ E_x (miss energy cut)

Where:

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

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



✓Improved the resolution by ~ 7%

✓Increase the number of events in W from pass1 to pass2 by ~ 18.7%

$$P_e = \frac{E_{beam}}{1+\frac{2E_{beam}}{M}sin^2(\frac{\theta_e}{2})} \quad (1)$$

$$Q^2 = 4E_{beam}P_e sin^2(\frac{\theta_e}{2}) \quad (2)$$

$$E_e = \sqrt{P_e^2 + m_e^2} \;, \quad m_e^2 \sim 0 \quad \rightarrow E_e = P_e \quad (3)$$

Solve (1) & (2) for θ_e:

$$sin^2(\frac{\theta_e}{2}) = \frac{Q^2}{4E_{beam}^2 - \frac{2E_{beam}^2 Q^2}{M}}$$

$$\alpha = \frac{Q^2}{4E_{beam}^2 - \frac{2E_{beam}^2 Q^2}{M}}$$

$$1 - sin^2(\frac{\theta_e}{2}) = cos^2(\frac{\theta_e}{2}) = 1 - \alpha$$

$$\frac{sin^2(\frac{\theta_e}{2})}{cos^2(\frac{\theta_e}{2})} = tan^2(\frac{\theta_e}{2}) = \frac{\alpha}{1-\alpha}$$