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. The Ratio Method
3. Corrections to the Ratio
4. NDE
5. Luminosity Corrections
6. Status

Some Background

- 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. Broad, PAC-approved effort to measure all four form factors.
- 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 $\sigma_{mott}^{p,n}$, $\tau_{p,n}$, $\epsilon_{p,n}$, and $a(Q^2)$ are all known kinematic factors.

- Ratio (R) data on deuterium were collected in Run Group B.
- Corrections to the Ratio $R_{Cor} = f_{NDE} f_{PDE} f_{nuc} f_{fermi} f_{rad} R$

f_{rad}	Radiative Correction	✓	f_{fermi}	Fermi Correction	✓
f_{PDE}	Proton Detection Efficiency	✓	f_{NDE}	Neutron Detection Efficiency	✓
f_{nuc}	Nuclear correction	✓	f_{lumi}	Luminosity Correction	ongoing

Neutron Detection Efficiency - Method

- To measure Neutron Detection Efficiency (NDE) use the $ep \rightarrow e'\pi^+ n$ reaction from Run Group A as a source of tagged neutrons during three run periods.
- Detect $ep \rightarrow e'\pi^+$ and predict if neutron strikes CLAS12 (expected neutrons). Search for neutron and, if found, this is a detected neutron. Ratio of detected to expected is NDE.
- Get the yield by fitting the missing mass (MM) distributions in the neutron momentum bins in the range $P_{MM} = 0.4125 - 6.750$ GeV.
    1. Fit each MM distribution with a gaussian plus fourth-order polynomial across most of the kinematic range - same starting point, all parameters vary.
    2. Fix the mean (μ) and width (σ) of expected and detected neutrons at their average values. Refit.
    3. Vary the μ and σ values over their ranges and minimize the summed χ^2 of the detected and expected neutron distributions.
- Repeat steps 1-3 with a Crystal Ball (CB) function - gaussian with a power law tail.
- Calculate the integrals of the gaussian and CB functions and use them to obtain the ratio of detected to expected, the NDE.

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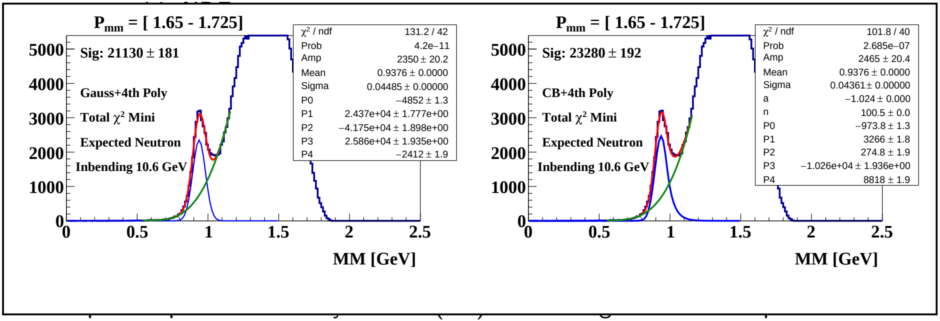

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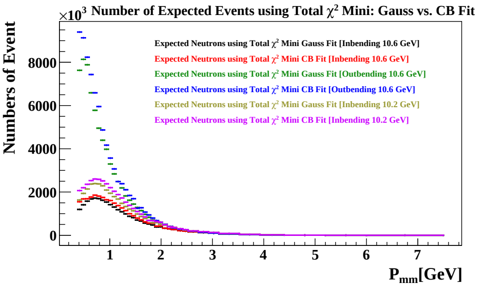
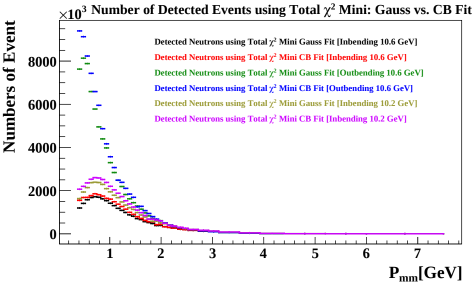
Neutron Detection Efficiency - Integrated Counts

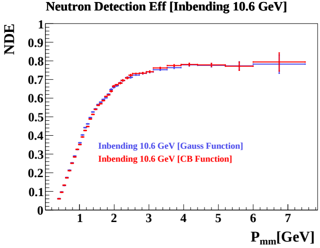


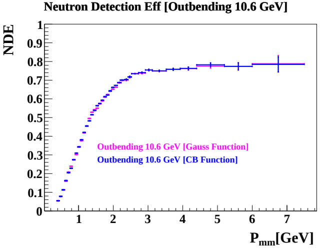


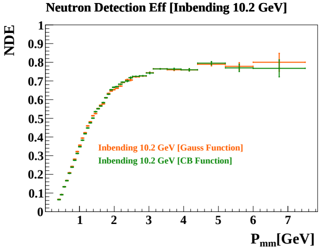
Comparison of integrated counts with Gaussian and Crystal Ball functions.

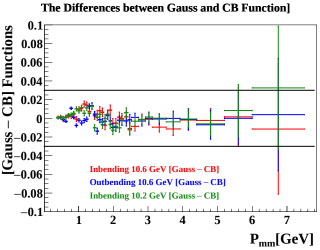
Neutron Detection Efficiency - Results

- NDE is the ratio of detected to expected.







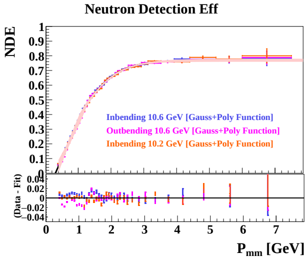


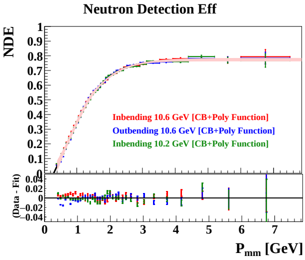
Neutron Detection Efficiency - Parameterization

- Generate a function to characterize the NDE.

$$\begin{aligned} \eta(P_{mm}) =& a_0 + a_1 P_{mm} + a_2 {P_{mm}}^2 + a_3 {P_{mm}}^3 && \text{for} \quad P_{mm} < p_t \\ =& a_4 \left(1 - \frac{1}{1 + \exp{\frac{P_{mm} - a_5}{a_6}}}\right) && \text{for} \quad P_{mm} \geq p_t, \end{aligned} \tag{1}$$

- Compare parameterization with data and between the two peak functions.





Neutron Detection Efficiency - Parameterization

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$$\eta(P_{mm}) = \begin{cases} a_0 + a_1 P_{mm} + a_2 {P_{mm}}^2 + a_3 {P_{mm}}^3 & \text{for} \quad P_{mm} < p_t \\ a_4 \left(1 - \dfrac{1}{1 + \exp\frac{P_{mm} - a_5}{a_6}}\right) & \text{for} \quad P_{mm} \geq p_t, \end{cases} \tag{1}$$

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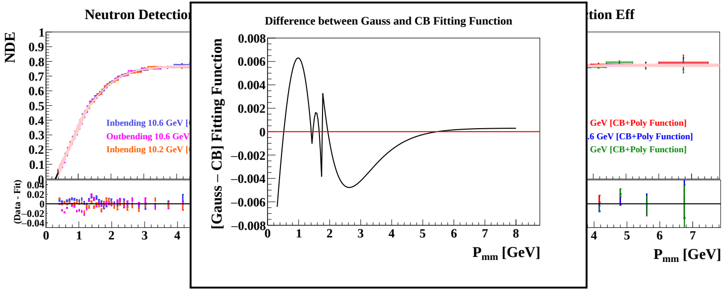

Neutron Detection Efficiency - Parameterization

- Generate a function to characterize the NDE.

We have prepared a draft of a CLAS12 NOTE that we expect to complete in the next month.

$$\eta(P_{mm}) = a_0 + a_1 P_{mm} + a_2 {P_{mm}}^2 + a_3 {P_{mm}}^3$$
$$= a_4 \left(1 - \frac{1}{1 + \exp\frac{P_{mm} - a_5}{a_6}}\right) \quad \text{for} \quad P_{mm} \geq p_t, \tag{1}$$

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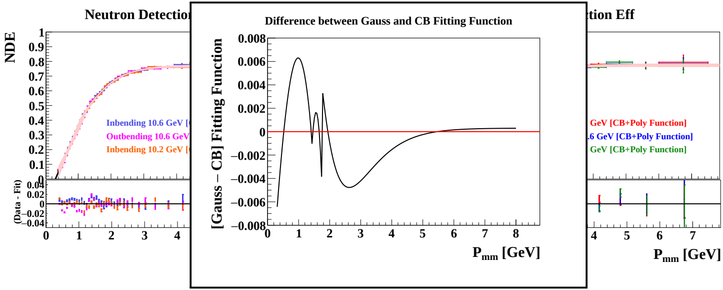
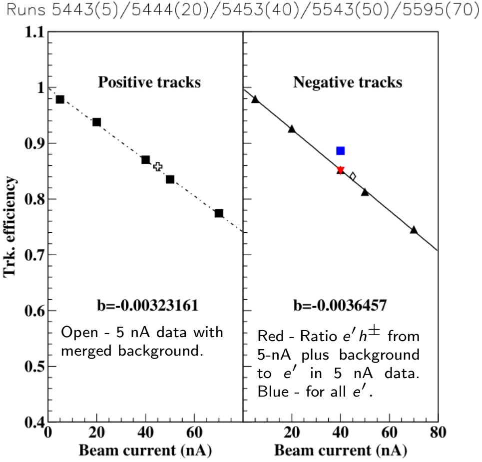


Luminosity Correction - Background

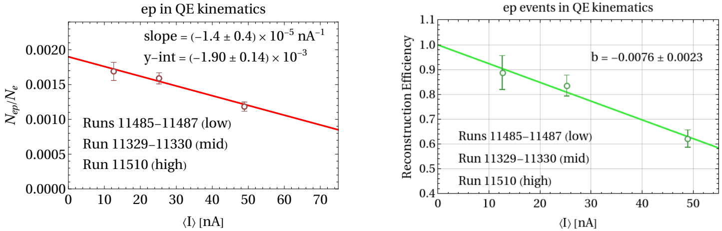
1. Analysis of CLAS12 data has shown a significant inefficiency in the Forward Detector charged particle reconstruction. See figure.
2. This inefficiency is associated with high occupancies in detectors, especially in the region-1 drift chambers.
3. This effect can limit the production luminosity (beam current) below the expected value.
4. Slope of the line ("b") factor can be used as a correction factor.



CLAS12 FD charge particle reconstruction efficiency and the beam background merging, S.Stepanyan *et al.*, CLAS12 NOTE 2020-005.

Luminosity Correction - Method

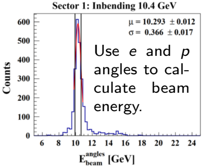
1. Used the code written for the G_M^n analysis by Lamya Baashen for her thesis.
2. For a given topology (*e.g.* $ep \rightarrow e'p$ for the G_M^n analysis) extract the ratio of the final state to the number of inclusive electrons as a function of the incident beam current - N_{ep}/N_e in quasi-elastic (QE) kinematics here.
3. Fit the luminosity dependence. See the left-hand plot below.
4. To extract the reconstruction or tracking efficiency divide the data points by the intercept from the previous step to normalize the data. Use this fit to determine the tracking or reconstruction efficiency. See the right-hand plot below.

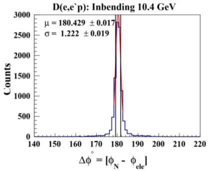


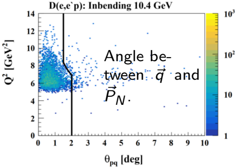
5. The reconstruction efficiency in the right-hand plot clearly shows a downward slope, but the data points have significant uncertainties and the magnitude of the slope is considerably larger than others we have seen.

Luminosity Correction - Increasing the Number of Events

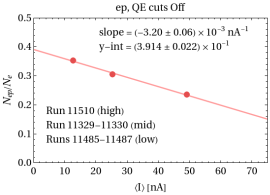
1. The data in the previous slide had large statistical uncertainties because the cross section for quasielastic events is small.
2. The QE selection on three essential cuts - (1) beam energy cut, (2) ϕ_{ep} cut, and θ_{pq} cut.

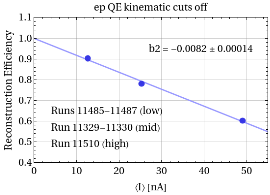






3. Turn these three cuts off in the analysis to obtain more events.



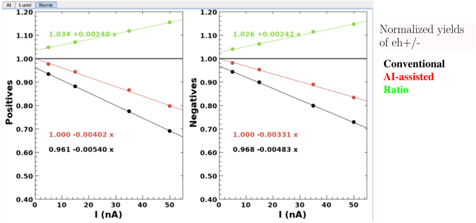


The slope of the reconstruction efficiency is consistent with the QE cuts turned on with much smaller uncertainty.

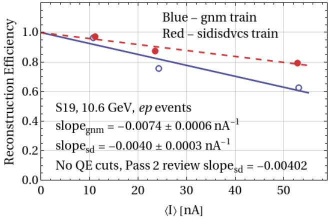
4. Slopes with QE cuts on and off are the same within uncertainties.

Luminosity Correction - Compare with other trains

1. Steeper slope of reconstruction efficiency with luminosity observed for *ep* events from gnm train compared with eh_+ slope for pass 2 review.
2. Data from the sidisdvcs train was analyzed to check for luminosity effects. That group obtained a slope of $b = 0.00402\ nA^{-1}$ for eh^+ events during the preparation of the Run-Group B Pass 2 analysis review. See figure.

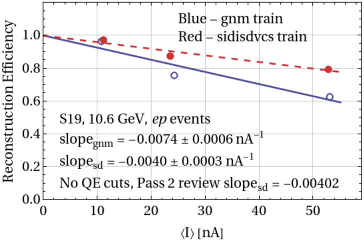


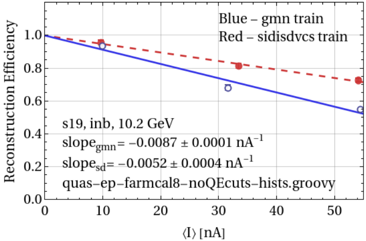
3. Compare luminosity effect for final state from gnm train (*ep*, no pions) and sidisdvcs train (has protons, pions) using the same G_M^N analysis code.
4. Plot is a comparison of *ep* events from different trains, spring 2019, 10.6 GeV, runs 6157, 6371, 6378.
5. The G_M^n analysis code gets the same slope as seen above.

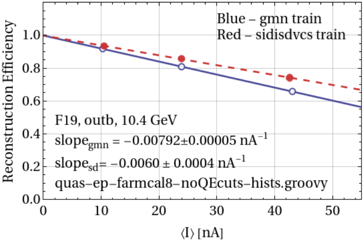


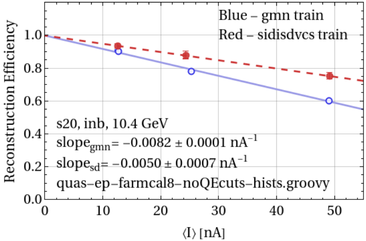
Luminosity Correction - Check all the run periods

Used the same gnm code on all the data sets and get results consistent with the previous slides.









Status

Luminosity Correction (last correction?)

1. Short-term goal is to understand/validate the steep slope in the reconstruction efficiency.
2. Study the G_M^n luminosity dependence in simulation.
3. Study the effect of adding background to the low-luminosity G_M^n runs.
4. Created another train to look at a wider range of topologies.

Neutron detection efficiency

1. Study any sector dependence on the NDE.
2. Complete the draft of the existing CLAS12 NOTE.

Backup Slides

Fit Parameters	Gaussian Function	Crystal Ball Function
χ^2	0.5543	0.5708
a_0	-0.1464 $\pm$ 0.0175	-0.1276 $\pm$ 0.0296
a_1	0.4341 $\pm$ 0.0430	0.3896 $\pm$ 0.0932
a_2	0.1515 $\pm$ 0.0362	0.1642 $\pm$ 0.1013
a_3	-0.0884 $\pm$ 0.0105	-0.0817 $\pm$ 0.0384
a_4	0.7741 $\pm$ 0.0032	0.7738 $\pm$ 0.0024
a_5	0.8836 $\pm$ 0.0580	0.9834 $\pm$ 0.0223
a_6	0.6524 $\pm$ 0.0394	0.5900 $\pm$ 0.0194
p_t	1.7695 $\pm$ 0.0052	1.4221 $\pm$ 0.0683

Table: The fit parameters of the neutron detection efficiency.

The Crystal Ball function is given by

$$f(x;\alpha,n,\bar{x},\sigma) = N\exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right), \quad \text{for}\ \frac{x-\bar{x}}{\sigma} > -\alpha$$

$$= N\cdot A\cdot\left(B-\frac{x-\bar{x}}{\sigma}\right)^{-n}, \quad \text{for}\ \frac{x-\bar{x}}{\sigma} < -\alpha$$

where

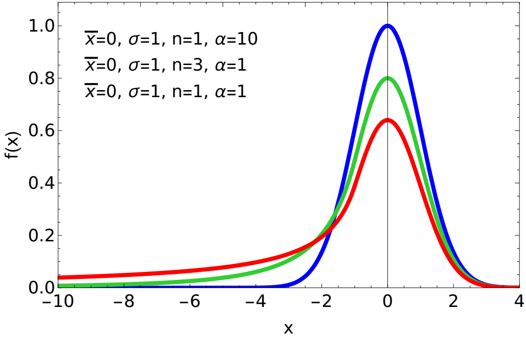
$$A = \left(\frac{n}{|\alpha|}\right)^n\cdot\exp\left(-\frac{|\alpha|^2}{2}\right),$$

$$B = \frac{n}{|\alpha|} - |\alpha|,$$

$$N = \frac{1}{\sigma(C+D)},$$

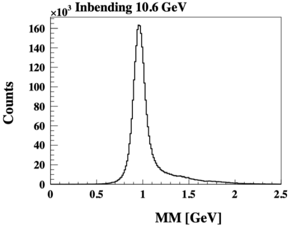
$$C = \frac{n}{|\alpha|}\cdot\frac{1}{n-1}\cdot\exp\left(-\frac{|\alpha|^2}{2}\right),$$

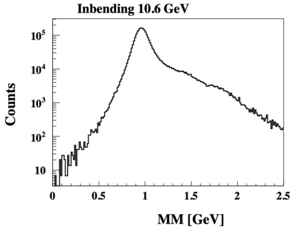
$$D = \sqrt{\frac{\pi}{2}}\left(1+\operatorname{erf}\left(\frac{|\alpha|^2}{2}\right)\right)$$



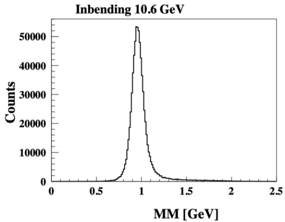
QE neutron missing mass distributions 19

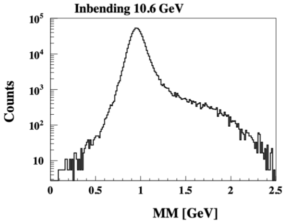
Expected neutrons





Detected Neutrons





QE neutron missing mass distributions