Simulation of the CLAS12 Neutron Detection Efficiency

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The Thomas Jefferson National Accelerator Facility, JLab *(Figure 1)*, is a premier research center focused on studying the subatomic components of matter that form atomic nuclei, particularly quarks and gluons. It operates a unique continuous-wave superconducting electron accelerator called CEBAF Shown in Figure 1. Electrons are accelerated within cryogenic superconducting cavities, achieving energies up to 12 GeV after five revolutions around the racetrack. Four end stations hold stationary targets. Researchers deepen our understanding of the strong force. Our focus is on the CLAS12 Detector in Hall B (*Figure 2*).

Figure 1 Jefferson Lab

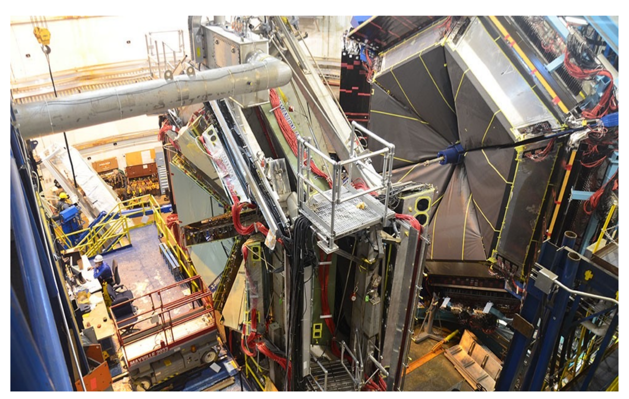


Figure 2 CLAS12

CEBAF Large Acceptance Spectrometer (CLAS 12)

CLAS12 is the newest generation of the CEBAF Large Acceptance Spectrometer at Jefferson Lab, designed to take full advantage of the facility's upgraded 12 GeV electron beam. The CLAS12 detector at Jefferson Lab has wide geometric acceptance *(Figure 3)* meaning it can detect particles over a broad range of angles, allowing for efficient event reconstruction. (1) Cherenkov Detectors identify electrons, pions, and kaons. (2) Drift Chambers track the path of particles deflected by the toroidal magnetic field to measure their momentum. (3) The Time-of-Flight system determines particle types by measuring their velocity and extracting their mass. (4) The Calorimeters measure the energy of both charged and neutral particles.

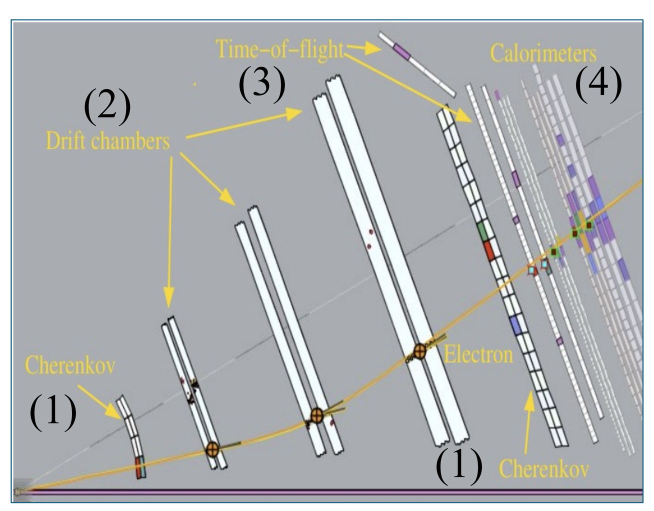


Figure 3 A CLAS12 Event Display

Neutron Detection Efficiency(NDE)

We are interested in the neutron's magnetic form factor, G_M^n, which describes how electric currents are distributed inside the neutron. Determining G_M^n requires accurate neutron efficiencies, because the neutron is electrically neutral, and not all scattered neutrons are detected. We measure the NDE by taking the ratio of the number of neutrons that are actually detected to the total neutrons expected from the $^1H(e, e', \pi^+)\,X_n$ reaction. We use the $^1H(e, e', \pi^+)\,X_n$ reaction as a source of tagged neutrons, where X_n represents neutral particles.

Method to Extract NDE

Our goal is to extract the neutron detection efficiency (NDE) from the simulated data to test our method for fitting the neutron peak. An event generator produces initial 4-vectors and the passage of particles through CLAS12 is simulated with the geant-based program *gemc*. These pseudo-data are reconstructed with the same tools used for production data. Given that we have the simulated momentum and energy of the electron and pion, we apply four-momentum conservation to determine the missing mass (MM) of the neutron as a function of neutron momentum, in six different momentum bins. The MM distribution is then fitted using Gaussian functions and Crystal Ball (See Eq.1) functions, each combined with a polynomial background. Since we have simulated data, we also know the truth information from the event generator. Hence, we can judge the accuracy of our analysis. We require an electron e^-, pion π^+, and neutral particle in the final simulated state. Then, we conducted the following analysis:

1. We applied the Gaussian function and Crystal Ball (CB) function with fourth-order polynomials to fit the missing mass distribution.
2. We extracted the neutron distributions using truth information from the simulated data.
3. We compared the integrated values from different fit functions with the neutron event counts from truth information to assess consistency and accuracy.

Crystal Ball Function

Crystal Ball function:

$$f(x) = N \cdot \begin{cases} e^{-\frac{(x-\bar{x})^2}{2\sigma}}, \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot \left(B - \frac{x-\bar{x}}{\sigma}\right)^{-n}, \text{for } \frac{x-\bar{x}}{\sigma} \le -\alpha \end{cases} \qquad \text{Eq. 1}$$

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

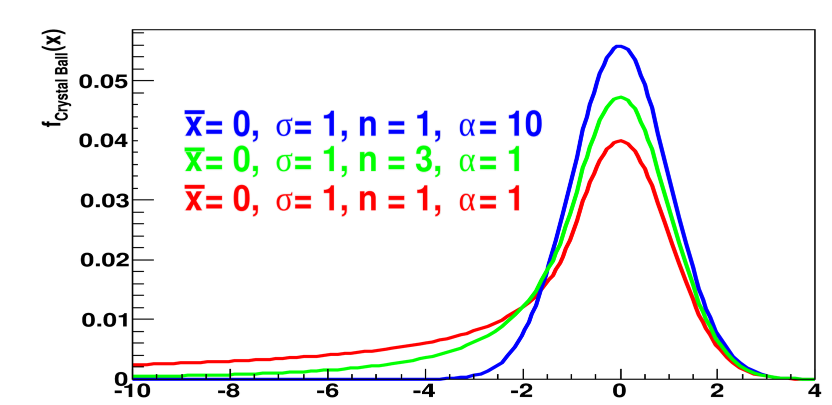
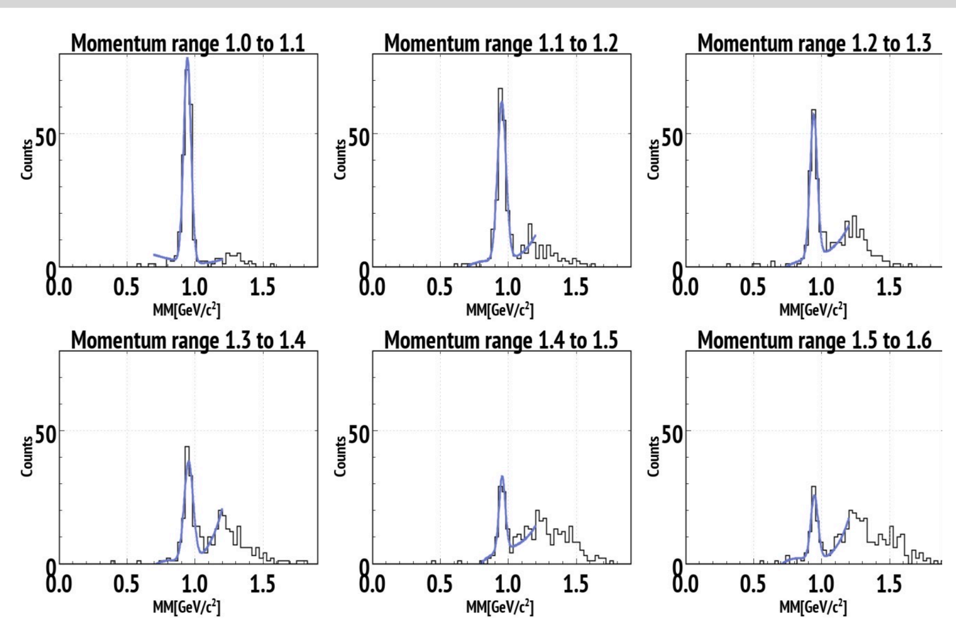


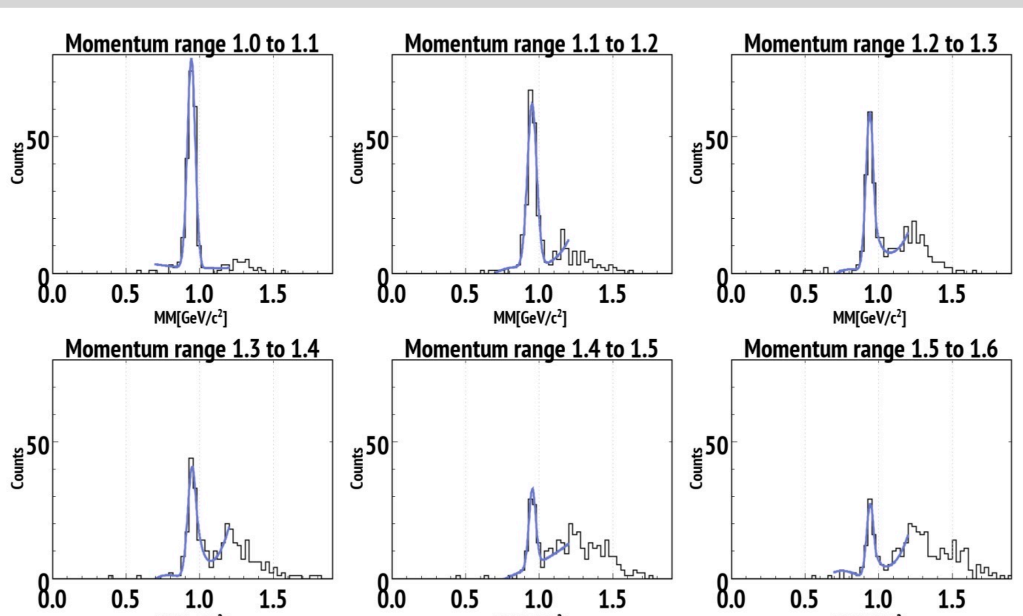
Figure 4 Crystal Ball Function

Results



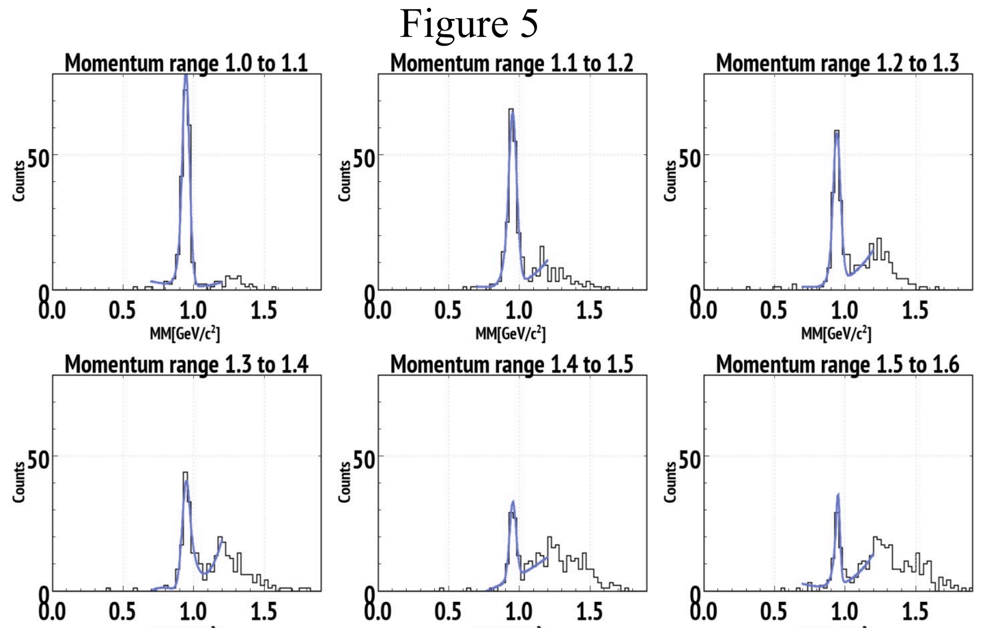
MM(GeV/c^2)

Figure 5



MM(GeV/c^2)

Figure 6



MM(GeV/c^2)

Figure 7

Figure 5 : Gaussian + Polynomial Background

Figure 6 : Crystal Ball with high-MM Tail + Polynomial Background

Figure 7: Crystal Ball with Low-MM Tail + Polynomial Background

Results (Cont.)

P(GeV/c)	N	N′	N^1_{Fit}	N^2_{Fit}	N^3_{Fit}
1.0-1.1	177 ± 13	175 ± 13	130 ± 11	130 ± 11	130 ± 11
1.1-1.2	180 ± 13	168 ± 13	116 ± 11	116 ± 11	113 ± 11
1.2-1.3	154 ± 12	151 ± 12	91 ± 10	94 ± 10	86 ± 9
1.3-1.4	122 ± 11	120 ± 11	77 ± 9	77 ± 9	81 ± 9
1.4-1.5	83 ± 9	72 ± 8	40 ± 6	41 ± 6	41 ± 6
1.5-1.6	73 ± 9	65 ± 8	41 ± 6	32 ± 6	43 ± 7

Table 1 Number of counts in neutron peak for different conditions

Column **N** is the number of events within $\pm\sigma$ around the peak in the MM pseudodata with both neutron peak and background. Column **N′** is the neutron-only events selected using the generated data. Column $\mathbf{N^1_{Fit}}$ is calculated using the CB function with a low-MM tail:

$$\mathbf{N^1_{Fit}} = \frac{\int_{\mu-\sigma}^{\mu+\sigma} n(MM)dMM}{\Delta MM}, \qquad \text{Eq. 2}$$

where $n(MM)$ is a fit to the histogram of events as a function of missing mass, μ is the peak position, σ is the width, and ΔMM is the bin size in the histogram. Column $\mathbf{N^2_{Fit}}$ and Column $\mathbf{N^3_{Fit}}$ are the fitted results of the neutron peak using a Gaussian function and a CB function with a high-MM tail calculated by the same approach as Eq.2. Quantity **N″** is the number of neutron-only events with the range from 0.7 GeV/c^2 to 1.5 GeV/c^2. Quantity $\mathbf{N^4_{Fit}}$ is the integration value of the high-MM-tail CB function of the same range to consider the effect of the background to the function.

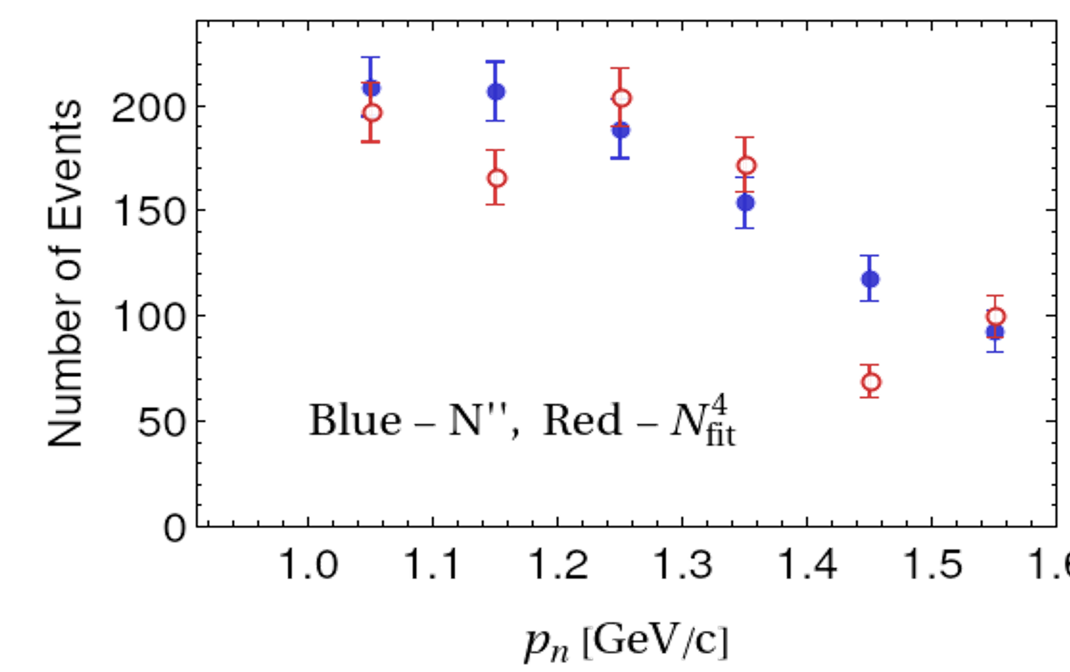


Figure 8 Comparison of N″ and N^4_{Fit}

Conclusions

(1) The three functions yield similar results across momentum ranges, showing the neutron peak is largely insensitive to the fit choice. (2) The similarity between functions N and N′ suggests that background contributions have minimal effect on the neutron peak. (3) The gap between N and the fits suggests a significant background. The difference between (2) and (3) needs further study. (4) Figure 8 shows that over a broader range, N″ closely follows N^4_{Fit}. The sharp increase in event counts for the CB function may result from background effects.

References

[1] "CLAS12." Jefferson Lab Experimental Hall B. N.p., n.d. Web. 27 Sept. 2016..

[2] "Crystal Ball Function." Wikipedia, Wikimedia Foundation, 27 Nov. 2020, https://en.wikipedia.org/wiki/Crystal_Ball_function.

[3] J. Lachniet, A. Afanasev, H. Arenhovel, W. K. Brooks, G. P. Gilfoyle, D. Higinbotham, S. Jeschonnek, B. Quinn, M. F. Vineyard, et al. Precise Measurement of the Neutron Magnetic Form Factor GMn in the FewGeV 2 Region. Phys. Rev. Lett., 102(19):192001, 2009.