4-28-2023

Study of Missing Mass Background in the CLAS12 Detector

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Recommended Citation

Hess, Jessie; Gilfoyle, Gerard P.; and Baashen, Lamya, "Study of Missing Mass Background in the CLAS12 Detector" (2023). *Honors Theses*. 1705.
https://scholarship.richmond.edu/honors-theses/1705

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by

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Honors Thesis

Submitted to:

Physics Department

University of Richmond

Richmond, VA

April 28, 2023

Advisor: Dr. Gerard Gilfoyle

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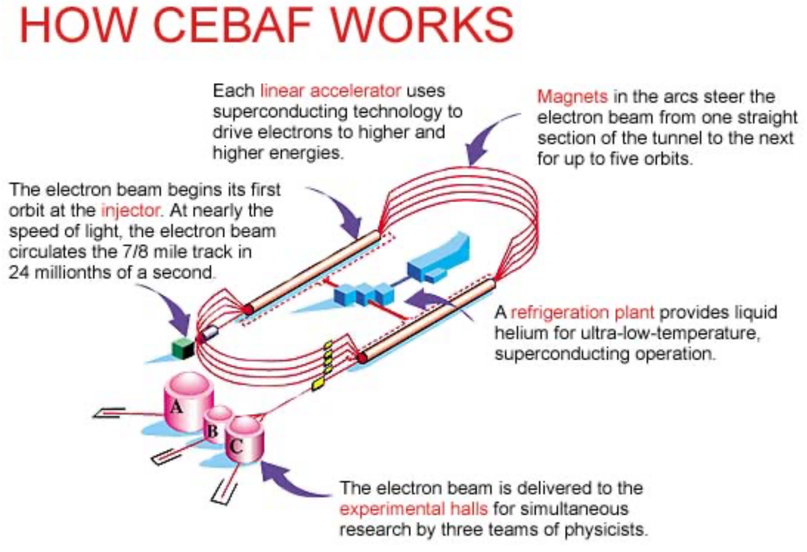
Abstract

At Jefferson Lab we use the CLAS12 detector to measure the neutron magnetic form factor. An accurate measurement of the CLAS12 neutron detection efficiency (NDE) is required. We use the nuclear reaction $ep \rightarrow e'\pi^+n$ as a source of tagged neutrons and obtain the NDE from the ratio of expected neutrons to detected ones. We assume the final state consists of $e'\pi^+n$ only, use the $e'\pi^+$ information to predict the neutron's position(expected) and then search for that neutron(detected). We select neutrons with the missing mass (MM) technique. We use simulation to validate our methods. We simulated events with the Monte-Carlo code *GEMC* and included background events. Even with background, the resolution of the simulated data is too small, so we used an existing smearing function and increased the resolution of the magnitude of the momentum and the angles of the electron and pion by a Resolution Scale Factor (RSF) to make the neutron MM resolution more realistic. We compared the simulated results with the run data distributions for several quantities like MM, energy, angles, etc. We selected the RSF that produced the best match. We then studied the composition of the low-MM background to understand its source.

Background

Jefferson Laboratory

The Thomas Jefferson National Accelerator Laboratory (JLAB) is a community of scientists using the 12-GeV Continuous Electron Beam Accelerator Facility (CEBAF). CEBAF works by shooting an electron beam that circulates the underground track with a linear accelerator in the straight section to drive electrons to higher energies, magnets that steer the electrons across the


HOW CEBAF WORKS

Each linear accelerator uses superconducting technology to drive electrons to higher and higher energies.

Magnets in the arcs steer the electron beam from one straight section of the tunnel to the next for up to five orbits.

The electron beam begins its first orbit at the injector. At nearly the speed of light, the electron beam circulates the 7/8 mile track in 24 millionths of a second.

A refrigeration plant provides liquid helium for ultra-low-temperature, superconducting operation.

The electron beam is delivered to the experimental halls for simultaneous research by three teams of physicists.

Figure 1: Graphic demonstration of how CEBAF works [7]

curved section, and a refrigeration plant that provides low temperatures for superconducting operation as shown in Figure 1. The ultra-low temperatures allow for continuous beam buckets since time to cool down is not required. The electrons travel a mile along an underground racetrack for up to five laps before hitting a nuclear target. [1] Jefferson National Laboratory is located in Newport News, VA as shown in figures 2 and 3. The JLAB mission is to investigate the sub-atomic nature of matter, quarks and gluons, test the theory of Quantum Chromodynamics (QCD), and explore quark confinement. Quarks are sub-atomic particles confined inside neutrons and protons.

Figure 2: Experimental Halls A, B, C at JLAB

Figure 3: Above view of the electron racetrack at JLAB

CLAS12 Detector

The CEBAF Large Acceptance Spectrometer (CLAS12) detector shown in figure 4 uses drift chambers to measure the trajectory of charged particles, a toroidal magnetic field to bend the particles to measure momentum, Cherenkov light to identify electrons, calorimeters to measure electron energy and detect neutrons, and scintillators that measure time of flight. Drift chambers are wire chambers that are filled with Argon and Carbon Dioxide. The wires inside are held at positive high voltages. When a charged particle passes by gas molecules, they knock electrons loose in the gas mixture (Argon and Carbon Dioxide) and these electrons are attracted to the positive charge in the wire [8]. This creates signals that can be read by a computer and used to discover the trajectory by reconstructing the path based upon the lowest rms value between the path and the known hits [9]. CLAS12 consists of a Forward Detector (FD) and a Central Detector (CD). We are focused on events in the FD. Figure 5 shows an example of a CLAS12 event.[1]

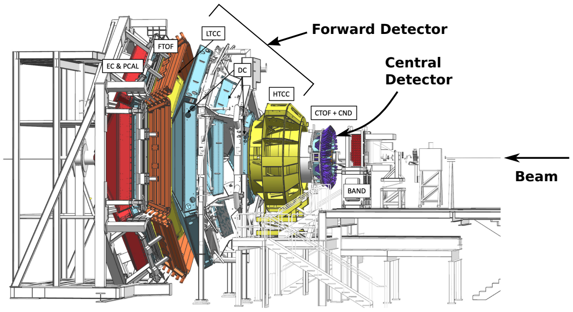


Figure 4: CLAS12 Detector

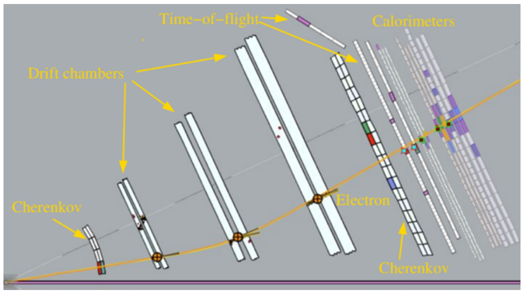


Figure 5: CLAS12 Event

Neutron Detection Efficiency

We are focused on measuring the Magnetic Form Factor of the Neutron (G_m^n) which is a fundamental quantity related to the distribution of magnetization or electric currents within the neutron. This quantity is the vector analog to charge distribution. The relationship between current or charge distribution and the form factor comes from the Fourier Transform of the form factor. There are three other form factors: the Magnetic Form Factor of the Proton, the Electric Form Factor of the Proton, and the Electric Form Factor of the Neutron. This form factor, along with the others, will test the accuracy of Quantum Chromodynamics (QCD) and the charge and electric current distributions within the neutron. QCD is the theory describing strong interactions between gluons and quarks and contains the feature that quarks and gluons cannot be observed in isolation which is called confinement and why studying their behavior inside protons and neutrons is crucial to understanding QCD [10]. The Magnetic Form Factor of the Neutron is also needed for flavor decomposition of quarks with the six flavors being up, down, charm, strange, top, and bottom. The Magnetic Form Factor of the Neutron, along with the other form factors, is needed to understand the contributions of up and down quarks. Up and down quarks are the most common quarks and understanding their contribution may provide evidence for di-quarks. The low Q^2 region is mapped out relatively well, so research is focused on the high Q^2 region which will provide us a better understanding of flavor decomposition. We extract the G_m^n from the ratio of e-n/e-p scattering from deuterium. Neutrons are harder to detect than protons, so we need to measure the neutron detection efficiency (NDE) to determine the numerator accurately. We extract the NDE from electron scattering events of the nuclear reaction (ep→e'n π^+). We determine the NDE by measuring the ratio of neutrons detected versus how many neutrons are expected. We assume the final state consists of $e'\pi^+n$ only and use the $e'\pi^+$ information to predict the neutron's position(expected) where it strikes the CLAS12 Calorimeter and then search for that neutron(detected) near the predicted hit. [2,3,4,5]

Objective 1

Aim

The aim of this objective is to develop and run a simulation from start to finish that models the CLAS12 response. The pseudo-data that is created is used to compare the pseudo missing-mass spectra and the properties of events to the run-data. The simulated data contains more information than the run-data because it has the initial four vectors of the tracks and truth information that can be used to ascertain the initial particles that were generated and their trajectories. Using the simulated data, we can refine our calculations of the NDE and where we place missing-mass cuts. For this objective, we used the simulated data and the run data to extract initial NDE measurements at different momentum values and compare these results with one another.

Simulation

We use a sophisticated, physics-based simulation of CLAS12 (GEMC) to create pseudo-data to understand the CLAS12 response. We run batch jobs on the JLAB farm using a shell script to manage and execute the commands to:

1. Generate events (initial 4-vector of tracks) using Pythia [6]
2. Filter those events to get the desired ones
3. Run GEMC to simulate the CLAS12 response
4. Convert file format from evio to hipo
5. Merge background hits
6. Reconstruct the pseudo-data (i.e., extract the 4-vectors of each simulated track)
7. Use groovy scripts to select events and determine the NDE

We used the production versions of the CLAS12 Common Tools to update our past work and to add a new feature, background merging to the simulation. These background events come from actual CLAS12 data and make GEMC more realistic. Different backgrounds are used for different beam energies and currents. The low-Q^2 region is mapped out relatively well, so for our event simulation we attempted to generate more high-Q^2 events. Even with our attempts to purposely create more high-Q^2 events, there were still significantly more low-Q^2 events and thus as seen in the results section of Objective 1, there are still large error bars in the high-Q^2 region as compared to the low-Q^2 region.

Methods

We use the nuclear reaction ($ep \rightarrow e'n\,\pi^+$)-electron beam(e) on a proton target(p) producing a scattered electron(e'), neutron(n), and a pion(π^+). We then apply conservation of 3-momentum to get a missing 3-momentum vector and we get the missing mass from the missing 3-momentum. We use the missing mass to select the neutron peak. We assume that there are no other missing particles besides the neutron and use the 3-momentum to predict the neutron trajectory and swim the track to see if the neutron will hit CLAS12. If the track hits, the expected neutron histogram is incremented. Otherwise, if the track misses CLAS12, the event is thrown out. For good events (events where the track hits), we search for a neutron hit near the expected hit. We get the angle between the detected hit and the missing 3-momentum hit and place a cut on the angle. If the angle is less than 15 degrees, the NDE numerator at the neutron momentum value is incremented (detected neutron histogram). The value for the angle cut was chosen based upon knowledge of how far most detected neutron's tracks are from their expected neutron's trajectory. This can be seen in Figure 8 of the results section of Objective 1, where the difference in direction cosines for the x and y directions from the detected neutron's tracks are from their expected neutron's trajectory is centered at (0,0), but does contain significant hits outward from that point. We use that information to determine where to place the angle cuts. The ratio of the detected and expected histograms is the NDE.

Results

We have simulated twenty million events using the JLab farm, reconstructed those events, and selected the ones of interest. Our criteria for selecting events and the preliminary results for the NDE are discussed here. Figure 6 is a 2-D histogram of missing mass (MM) vs momentum for the missing neutral particle. We can see a concentration of events at the neutron MM^2, so we know our data set will include neutrons. Figure 7 is the MM^2 for the missing neutral particle ^{1}H(e ,e' $\pi^+ X_n$) and again shows a peak at the neutron MM^2 indicating a substantial amount of neutrons in our data set.

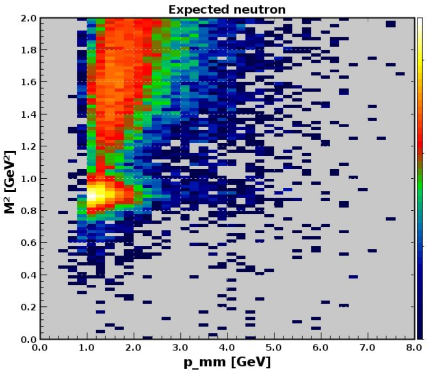


Figure 6: Histogram of MM^2 vs momentum for expected neutrons

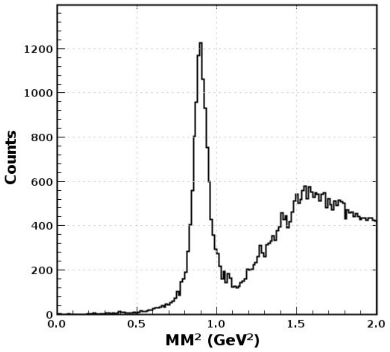


Figure 7: MM^2 for the missing particle ^{1}H(e ,e'$\pi^+\chi_n$)

Figure 8 shows a 2-D histogram of the difference in x and y direction cosines between the path of the expected particle and the trajectory of a detected neutron. Events are concentrated at (0,0) and decrease as we move radially outwards. A cut is placed around the center of the distribution to select neutrons. Figure 9 shows MM^2 for the missing particle after that selection cut is placed on the data. Figure 10 is a histogram of the momentum of expected neutrons and the detected neutrons. Their ratio constitutes NDE. Figure 11 shows the preliminary NDE results for simulation(blue) compared to measured NDE results from Spring, 2018 run (green). The simulation, within uncertainties, agrees with the data for the high momentum plateau. This region is important to reach high Q^2 with the e-n part of the neutron magnetic form factor measurement. [2,3]

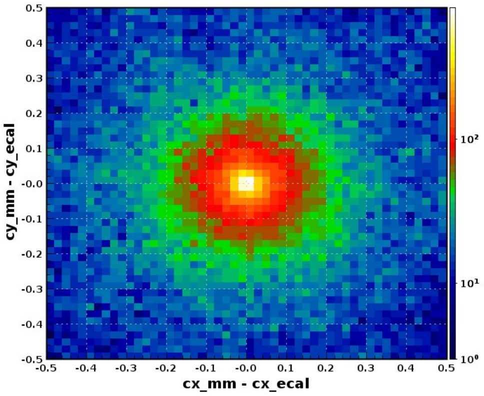


Figure 8: Selection cut for cx vs cy

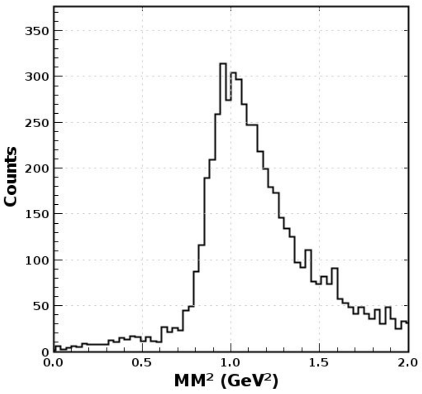


Figure 9: MM^2 for the missing particle ^{1}H(e ,e'$\pi^+\chi_n$) after cx vs cy selection cut

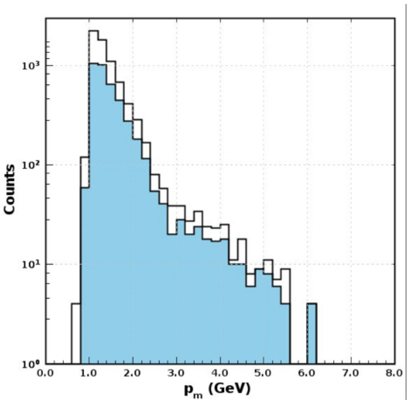


Figure 10: Histogram of momentum of expected neutrons(white) compared to detected neutrons (blue)

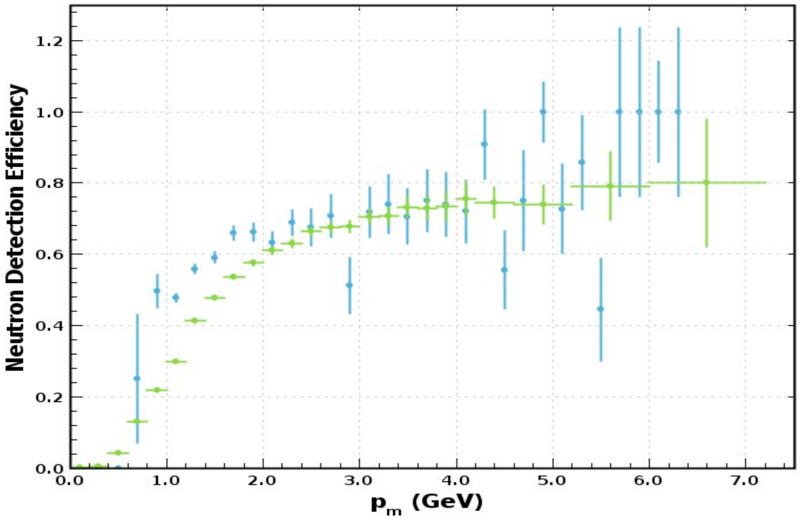


Figure 11: Preliminary NDE results for simulation(blue) compared to measured NDE results for Spring, 2018 run (green)

Conclusions

1. We have developed a full simulation from event generation to post-reconstruction analysis.
2. The event generator is Pythia.[6]
3. We have included background in our simulation to make it more realistic.
4. We are using the production version of GEMC which includes recent efforts at resolution matching of the CLAS12 components.
5. In our initial efforts to study the ^{1}H(e, e' π^+n) reaction we extract the NDE and compare with a similar effort to extract the NDE from the data. This simulation is consistent with the data.[5]

Objective 2

Aim

To extract the NDE we need to determine the yield of expected and detected neutrons from the ep→e'n π^+ reaction. Figure 12 shows the missing mass distribution for one of the bins in missing momentum for detected neutrons. Note the significant background from higher mass events. The red curve is a fit to the central neutron peak with a low-mass tail. This low-mass tail can come from the neutron peak itself or the higher-mass contribution above 1.0 GeV/c^2. Our motivation here is to develop a realistic simulation of the NDE reaction and then use the truth information from that simulation to study the source of the events in the low-mass tail. To that end, we assume the missing mass resolution of the simulation is smaller than the data, so we must increase the resolution effect in the simulated data.

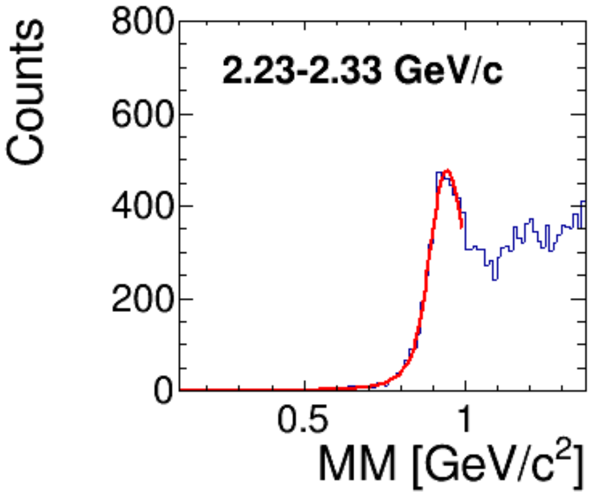


Figure 12: Missing mass distribution for one of the bins in missing momentum for detected neutrons

Methods

We use the same simulated data as in objective 1 and use the same methodology to produce a histogram of missing mass. Even with the additional background, we hypothesized the resolution of the simulated data would be too small relative to the run data because historically this has been the case. We increased the neutron peak resolution by using a smearing function that widened the pion and electron θ, φ, and momenta values which widened the missing-mass (MM) peak. We developed a series of Resolution Scale Factors (RSF) that altered the smearing function to give smear the neutron peak resolution by different magnitudes in order to fit the slope of the low-MM^2 tail of the simulated data to the run data.

Results

We used an exponential to fit the slope of the low-MM^2 tail and extracted λ, the slope parameter shown in figure 13 for one RSF value. We expected to select an RSF by interpolating over a graph of λ vs RSF as shown in figure 14 and selecting the value that best matched the run data. We were unable to do so because the dependence of λ on RSF did not overlap the measured data.

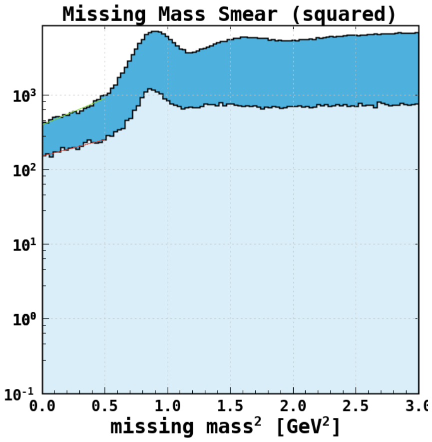


Figure 13: MM^2 on Log Scale for RSF=1.3, simulated data is dark blue and run data is light blue

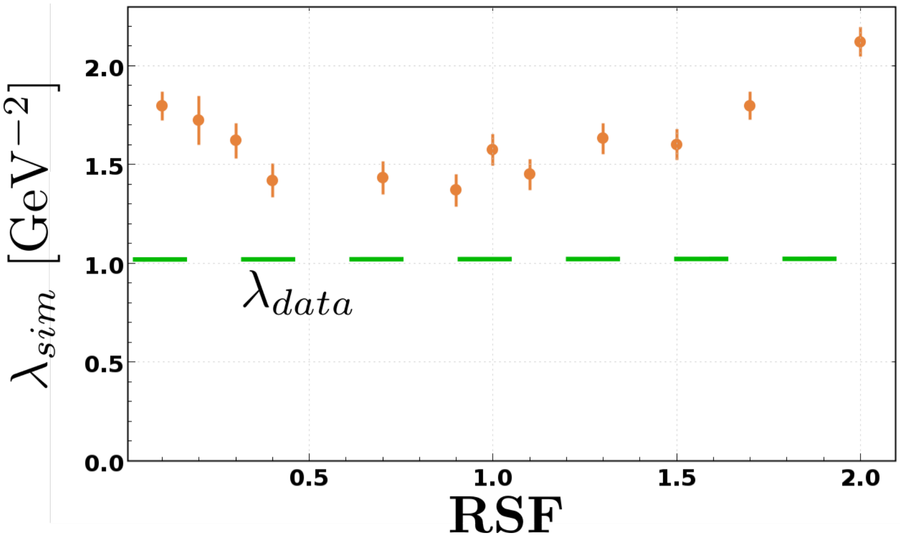


Figure 14: Graph of RSF vs Lambda (slope) with line representing run data value

We decided to use the neutron peak in the simulated and measured distributions to investigate the resolution. We fit the central region of the neutron peak with a gaussian over the range from one sigma below the fitted peak value to one sigma above. We found the width/sigma of the simulated data with no smearing applied was actually larger than the data width. For the data we have a width of 0.034 GeV^2 while the simulation has a width of 0.050 GeV^2 as shown in figures 15 and 16. This explains the behavior seen in figure 14 with the slope of the distributions in the low-mass region. This is likely due to the additional background that was added to the simulation in order to reduce the resolution of the simulation.

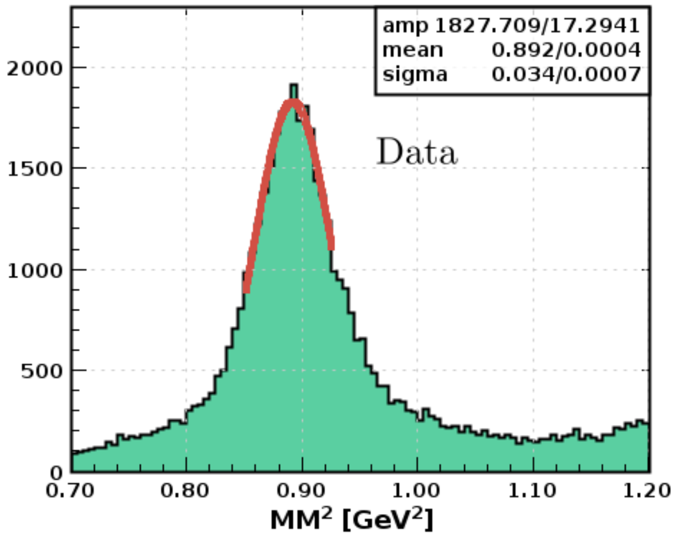


Figure 15: Graph of core fit of MM^2 peak with Gaussian on run data

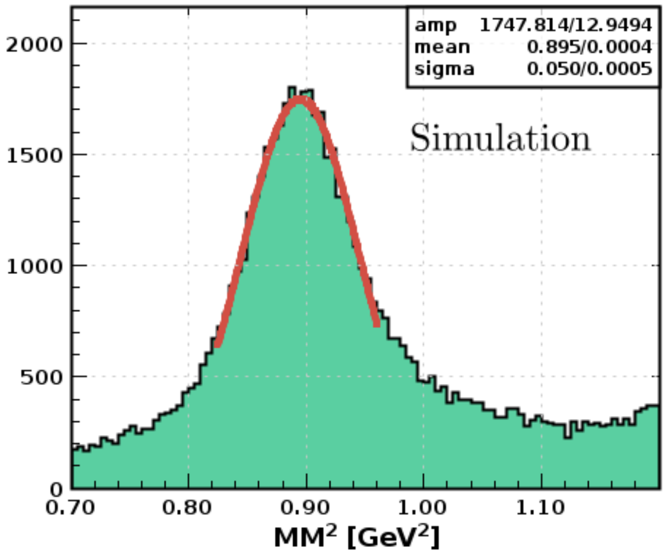


Figure 16: Graph of core fit of MM^2 peak with Gaussian on simulated data

Figure 17 shows MM^2 distribution from the simulation. We used the truth information to separate $e'\pi^+n$ events (blue-green histogram) from background ones that had additional neutral particles, usually photons, in the final state (green histogram). There is a long, low-MM^2 tail from the neutron peak and one from the background events. In this calculation the high-MM^2 background in the region of the neutron peak is small.

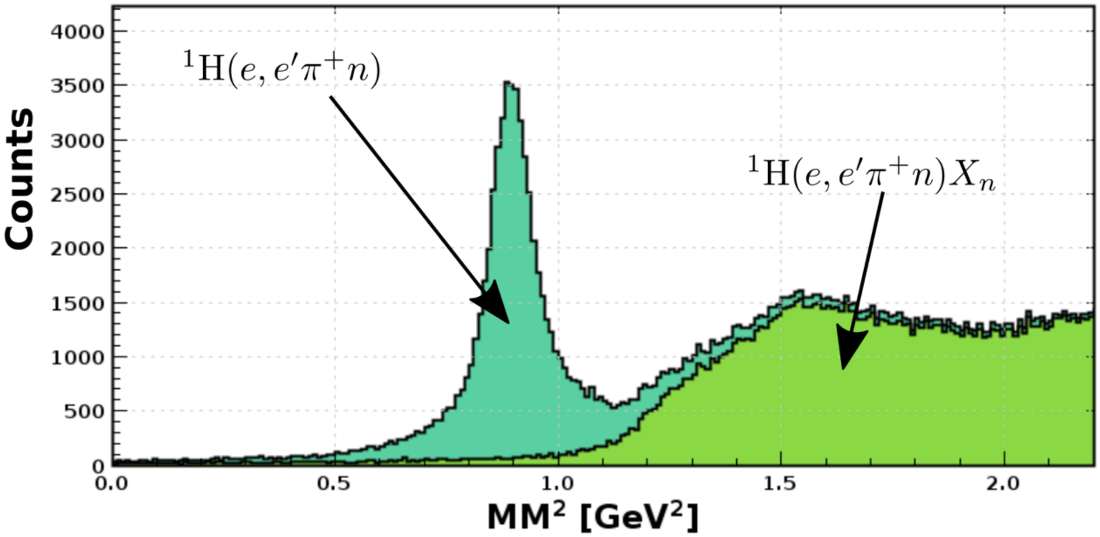


Figure 17: Graph of MM^2 with and without background

Conclusions

We have developed a full end-to-end simulation of the NDE reaction including background. For this reaction, the simulated MM^2 width exceeds the data width making the simulation a good testing ground for our background study. Using the truth information from the simulation we separated $e'\pi^+n$ signal events $e'\pi^+n\,\chi_n$ background events. The undetected neutral particle is typically a photon. We found long, low-MM^2 tails from both sets of events and the background in the region of the neutron mass was small. This indicates the peak primarily consists of neutrons, however in the region of low-MM^2 we must be careful when trying to select neutrons because the background is a more substantial portion of the total events.

Further Discussion

The results of the composition of the missing mass squared spectrum with and without background allow us to attempt to more accurately fit the region of neutron mass. This will allow us to place more precise cuts on which particles we tag as neutrons and obtain a more precise measurement for NDE. Further research could go into understanding how to account for the impact of the high energy background in the low missing mass region and whether this difference will produce a substantial difference in NDE particularly in the high Q^2 region. To do this we would need to simulate more events and focus simulation efforts on the high Q^2 region. As shown in Figure 11 of Objective 1, even with a large number of simulated events, there tend to be large error bars in the high Q^2 region which means we need a larger number of events and/or to increase the bin size in this region. We could then study the effect of the high missing mass background that partially comprises the low-MM tail and ascertain its significance. Further work could also go into connecting Objective 1 and Objective 2 and redoing the NDE calculation with the new information learned in Objective 2 as well as calculating to contributions of the higher mass background more precisely. This could be done by subtracting the $^{1}H(e,e'^{\pi^+}n)\chi_n$ histogram from the $^{1}H(e,e'^{\pi^+}n)$ and experimenting with different fits of the resultant histogram.

Acknowledgments

This work was supported by the Department of Energy, Jefferson National Laboratory, and the University of Richmond.

References

1. "CLAS12." Jefferson Lab Experimental Hall B. N.p., n.d. Web. 27 Sept. 2016..
2. G.P. Gilfoyle et al. Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium. E12-07-104, Jefferson Lab, Newport News, VA, 2007. https://www.jlab.org/exp_prog/proposals/07/PR12-07-104.pdf.
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 Few-GeV 2 Region. Phys. Rev. Lett., 102(19):192001, 2009.
4. K. Sherman and G.P. Gilfoyle. Measuring the Neutron Detection Efficiency in CLAS12. In Bull. Am. Phys. Soc., Fall DNP Meeting, 2016. EA.00047.
5. L. Baashen, B. Raue, C. Smith, and G.P. Gilfoyle. Measurement of the Neutron Magnetic Form Factor at High Q2 Using the Ratio Method on the Deuteron. In Bull. Am. Phys. Soc., Fall DNP Meeting, 2020. EL.00006.
6. Torbjorn Sjostrand, Stephen Mrenna, and Peter Z. Skands. PYTHIA 6.4 Physics and Manual. JHEP, 05:026, 2006.
7. Affairs, Public. “Did You Know?” *Jefferson Lab Visitor's Center - Do You Know How CEBAF Works?*, 20 Sept. 2013, https://www.jlab.org/visitors/science/works.html.
8. Carman, D. S. (2013, April 30). *Drift Chambers (DC)*. Clas12 Drift Chamber System. Retrieved April 9, 2023, from https://www.jlab.org/Hall-B/clas12-web/subsystems/dc-intro.html
9. Meyer, Mac. *Drift Chambers: The Science Behind Art.* July 2, 2009, https://clasweb.jlab.org/wiki/images/f/f3/How-works.pdf. PowerPoint Presentation.
10. Sterman, G. (2006). Quantum Chromodynamics. *Encyclopedia of Mathematical Physics*, 144–153. https://doi.org/10.1016/b0-12-512666-2/00293-5