Study of the Neutron Detection Efficiency of the CLAS12 Detector
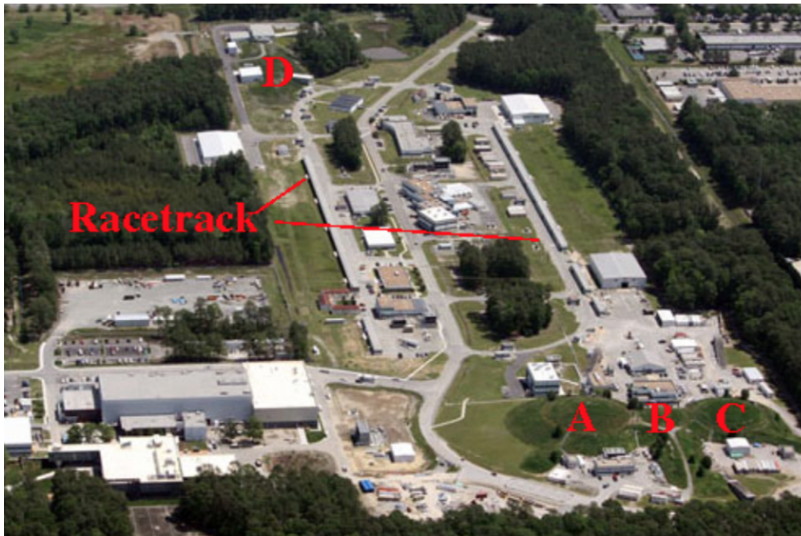
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Figure 1: Aerial photo of JLab showing the racetrack that the electrons are accelerated around and the four halls.

1 Abstract

One of the central physics goals of Jefferson Lab is to understand how quarks and gluons form nuclei. The 12 GeV upgrade is nearing completion and a new detector, CLAS12, is being built in Hall B. One of the approved experiments will measure the magnetic form factor of the neutron (G_M^n). To make this measurement, the ratio of electron-neutron (e-n) to electron-proton (e-p) scattering events will be extracted from deuterium in quasi-elastic kinematics. A major source of systematic uncertainty is the neutron detection efficiency (NDE) of CLAS12. To better understand the NDE I used the Monte Carlo code *gemc* to simulate quasi-elastic e-n events like those expected in the G_M^n experiment. I then analyzed the simulated e-n events by using the measured, scattered electron information to predict the neutron's path. The neutron is detected in CLAS12's electromagnetic calorimeter (EC). If the predicted neutron path intersected the fiducial volume of the EC, then I searched for a hit near that point. The NDE is the ratio of the number of neutrons found in the EC to the number of neutrons predicted to hit the EC. The analysis was done using the newly released CLAS12 reconstruction tools. I observe a rapid rise in the NDE at low neutron momentum and a plateau around 70% at 3GeV with the pre-shower calorimeter (PCAL). This plateau falls to 60% without PCAL.

2 Introduction

2.1 Jefferson Lab and CLAS12

Jefferson Lab (JLab), also called the Continuous Electron Beam Accelerator Facility (CEBAF), is a national lab located in Newport News, Virginia. The main goal of JLab is to understand how quarks and gluons come together to form nuclei.

This goal is accomplished by using a mile long, racetrack-shaped, linear accelerator to produce an electron beam that can be directed into any of the four halls A, B, C, or D (Figure 1). Each of these halls contains its own detector. JLab is just finishing an upgrade in which the beam energy was doubled to 12GeV, a new detector was built in Hall B, and Hall D was built. The new detector
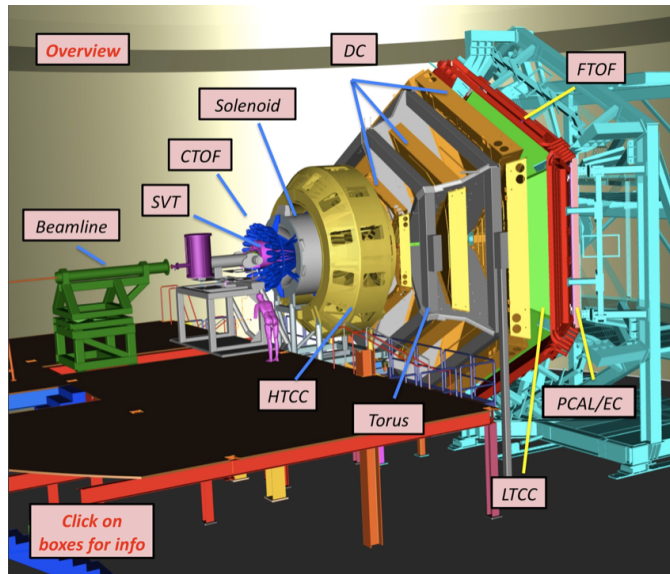
Figure 2: Computer generated image of CLAS12. Notice that CLAS12 is about 3 stories tall as shown by the purple man standing next to it.

in Hall B is called the CEBAF Large Acceptance Spectrometer (CLAS12) and is the one I will be focused on for my research.

CLAS12 is actually built out of two smaller detectors, a central detector and a forward detector, each of which are comprised of several smaller components (Figure 2). By putting the two together CLAS12 is able to take data over a wide angle relative to the target.

2.1.1 Central Detector

The central detector has three main components to it: the silicon vertex tracker (SVT), the central time of flights (CTOF), and the solenoid.

The SVT is built out of strips of silicon and positioned close to the target. As charged particles pass through the silicon, the strips produce an electrical signal that can be measured and recorded to determine the position of the particle. Its very important that the SVT is close to the target because the position information it produces allows for a very accurate extrapolation of the vertex for a collision.

The CTOF do exactly what the name implies, they measure the time at which a particle goes by. By combining the time the CTOF measures with other measurements we can extract information such as a particles velocity.

The solenoid is the component that provides a magnetic field for the central part of the detector. When a charged particle enters a magnetic field its path through the magnetic field bends according to the Lorentz force law where the charge determines whether it bends inward or outward. The direction of the magnetic field produced by the solenoid makes negatively charged particles bend outward away from the beamline. Thus, by knowing which way a particle bends in the solenoid field, we can tell what its charge is which narrows down the particle for identification.

2.1.2 Forward Detector

The forward detector is comprised of a few more components than the central detector as discussed below.

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First are the drift chambers (DC) which are used to track a charged particles position through the detector. Each DC is filled with a gas and has bare wires placed in a tight hexagonal pattern with a voltage placed along the wire. When a charged particle enters, it ionizes the gas. The newly ionized gas particles are attracted to the wires, and when they hit the wire they produce an electrical signal. This signal is measured at each end of the wire and based on the difference between when the signal hits either end the position along the wire can be determined. Therefore, the drift chambers give us an accurate path in 3D space that a particle took through the detector.

Next are the forward time of flights (FTOF) which again do what the name implies except this time in the forward detector. By combining the timing information these give with the CTOF we can determine the velocity of the particle.

The forward detector also has a magnetic field, but here it is produced by the torus. The torus is a giant, supercooled magnet that produces a magnetic field a little more complicated than the solenoid, but it is still used for the same purpose. By watching how a particle bends in the magnetic field the sign of its charge can be determined which helps with particle identification. The magnetic field produced by the torus also bends negatively charged particles away from the beamline.

The next part of the detector are the low-thresh hold and high-thresh hold Cherenkov counters, LTCC and HTCC respectively. Each of these components are filled with a special gas and lots of photo multiplier tubes (PMT). They are used to help distinguish similar particles from one another for example, a π^- and an electron. The problem is both particles have a negative charge so both bend outward in the magnetic field; however, the π^- is a more massive particle so it moves slower than the electron. When the electron enters the Cherenkov counter it will be moving faster than the speed of light in the gas, thus it will start slowing down by giving off energy. It accomplishes this by producing Cherenkov radiation, which are really just photons. Using a complex set of mirrors, these photons are redirected into the PMTs which will amplify the signal for recording purposes. When the π^- enters the Cherenkov counter on the other hand, it will not be moving faster than the speed of light in the gas due to its greater mass. This means it won't produce any Cherenkov radiation which means there won't be any signals coming from the LTCC or the HTCC. Therefore, if a negatively charged particles track is being traced through the detector and there are signals coming from the Cherenkov counters along the track, then it is probably an electron; where as if there are no signals from the Cherenkov counters, then its probably a π^-.

The last parts of the forward detector are the pre-shower calorimeter (PCAL) and the EC. These two components are built out of alternating layers of lead and scintillator. A scintillator is a plastic that, when hit by a charged particle, creates light. The scintillator layers in each component are divided up into strips that have a PMT on the end. When a charged particle passes through a strip, the created light will travel down the strip into the PMT where the light will be amplified and turned into an electrical signal that can be recorded. The amount of light produced in the strip is related to the energy of the particle, so these components help measure energy. It is also possible to get some idea of the position a particle hit in the EC due to the orientation of the strips in each layer of scintillator. By alternating the layers of scintillator (Figure 3) in the EC as it projects back, one can simply look at the intersection of the hit strips within each layer to see about where a particle hit. The last purpose for PCAL and the EC are to stop particles from going out the back of the detector. The EC used to be enough to accomplish this goal when CLAS12's predecessor, CLAS6, was in Hall B, but with the beam energy being doubled to 12 GeV, PCAL was added to help in stopping stuff.

It is important to note that the EC and PCAL are very important to my research due to their ability to detect neutrons. While most of the components in CLAS12 can't detect neutral particles, the EC and PCAL can, albeit indirectly. When a neutron comes in and hits one of the layers of

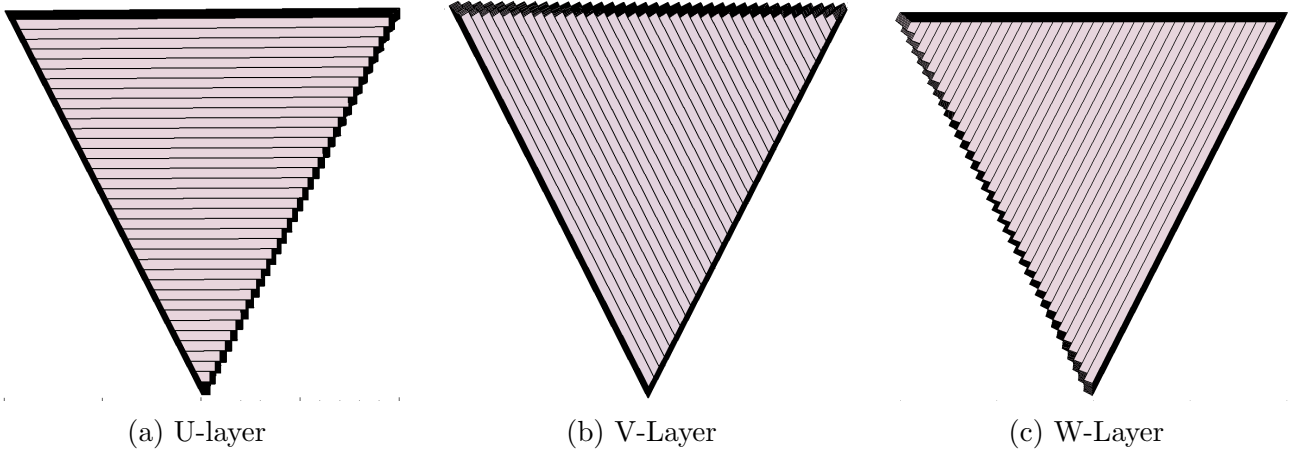(a) U-layer   (b) V-Layer   (c) W-Layer

Figure 3: These are the three different layers of scintillator used in the EC.

lead between the scintillators, it will cause a shower of mostly charged particles. These charged particles can be detected by PCAL and the EC. Therefore, by working backward, it is possible to reconstruct where the shower started and how much energy the particle that created the shower had. By doing this, PCAL and the EC can tell us if a neutron hit or not.

2.2 Neutron Magnetic Form Factor

When the upgrade at JLab is completed, one of the approved experiments for CLAS12 is the measurement of G_M^n. G_M^n is one of four elastic form factors. The neutron also an electric form factor (G_E^n) and the proton has a magnetic form factor (G_M^p) and an electric form factor (G_E^p) as well. The form factors are important because they provide a meeting ground between experiment and theory. By comparing a value measured in the lab for these quantities to one calculated from a theory we get an idea of how well that theory seems to work. We are now also able to use the form factors to map out the position and momentum of quarks in the neutron due to new technologies at JLab through a process called flavor decomposition.

G_M^n is the form factor my research is focused around. It gives us information about the distribution of currents in the neutron. While the neutron is itself an electrically neutral particle, the quarks inside are not. When these quarks start moving they will produce a current due to the fact they are electrically charged. If there is a current, then there is a magnetic field which is thus why it is called the magnetic form factor of the neutron.

The reason we are interested in measuring G_M^n is because not much is known about it. Figure 4 shows the world's current knowledge of G_M^n along with predictions of what CLAS12 should measure when we start running.

In this plot the x-axis is the square of the four momentum transfer during electron elastic scattering (Q^2) and the y-axis shows a normalized measurement of G_M^n. The green points are data taken before CLAS6 and the red points show data taken with CLAS6. Notice how large the error bars are, especially as they approach larger Q^2. The black points in this plot show what the predicted measurements using CLAS12 are and, as can be seen, the error bars are much smaller for those points. Also notice the blue points are showing the predicted values for an experiment to measure G_M^n in Hall A. First, the fact that there are two experiments at the same lab to measure the same quantity in different halls shows just how important this measurement is. Second, the y-value for the blue points has no meaning, they are simply there to show what value of Q^2 Hall A
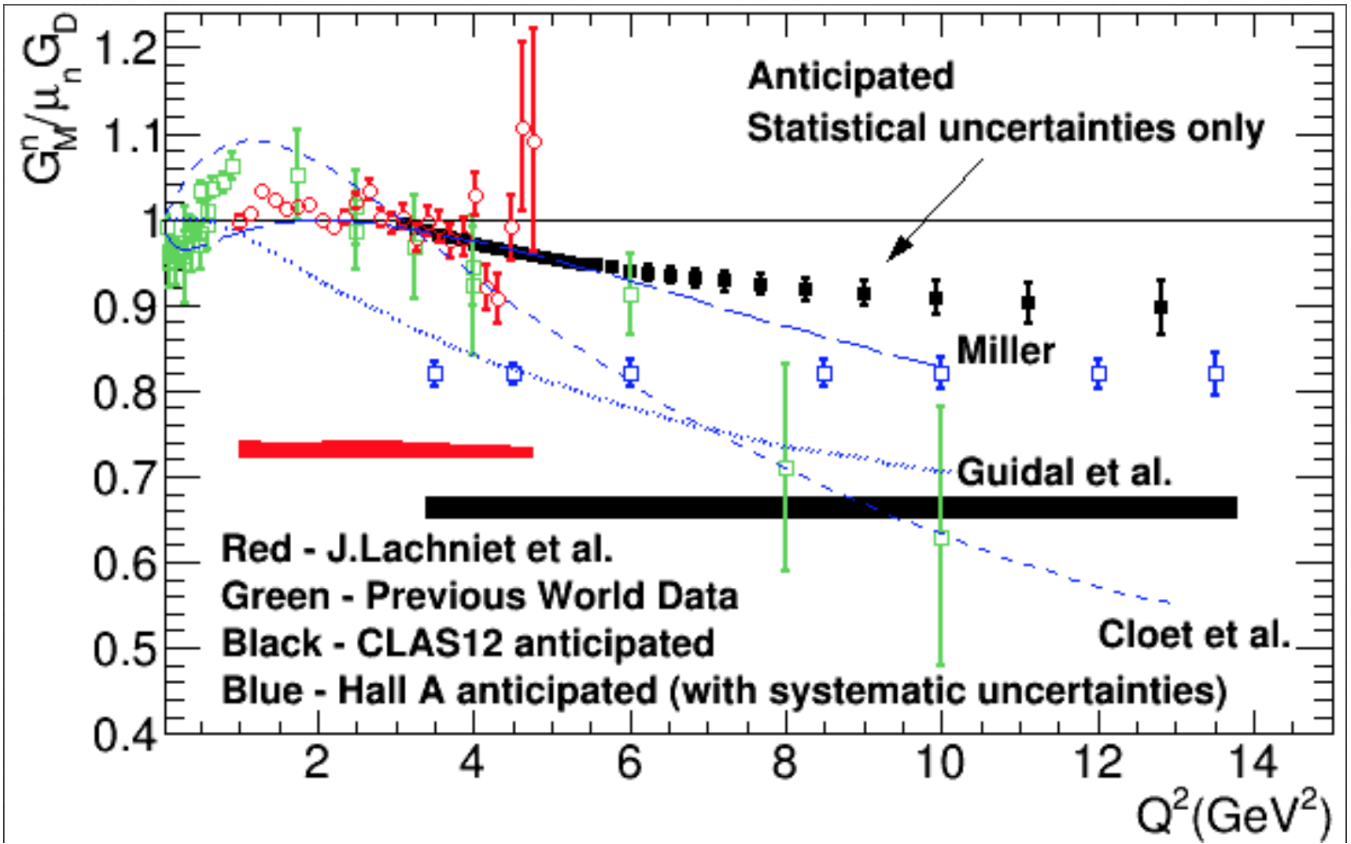
Figure 4: Worlds Data on G_M^n

will be taking data at.

In order to measure G_M^n we will be using the Ratio Method by taking a ratio of electron-neutron (e-n) to electron-proton (e-p) events from quasi-elastic scattering off Deuterium. Mathematically, this is shown in equation (1).

$$R = \frac{\frac{d\sigma}{d\Omega}\left(D\left(e, e'n\right)\right)}{\frac{d\sigma}{d\Omega}\left(D\left(e, e'p\right)\right)} = a(Q^2)\frac{\frac{G_E^{n\,2} + \tau G_M^{n\,2}}{1+\tau} + 2\tau G_M^{n\,2}\tan^2\left(\frac{\theta}{2}\right)}{\frac{G_E^{p\,2} + \tau G_M^{p\,2}}{1+\tau} + 2\tau G_M^{p\,2}\tan^2\left(\frac{\theta}{2}\right)} \tag{1}$$

$$\tau = \frac{Q^2}{4M^2} \tag{2}$$

The fraction just shows that we are using a ratio of the scattering cross sections of e-n to e-p event off of Deuterium. For the purposes of this equation, think of the cross section as the effective area of the detector being used to detect the events. The reason we take a ratio of the two is because this allows lots of things to cancel out and it makes our measurement less susceptible to sources of error such as acceptances and efficiencies. When this ratio is expanded out, we get everything on the far right side of the equation. The $a(Q^2)$ piece acts as a correction factor for any cuts placed on the data, τ is dependent on Q^2 and mass of the neutron, G_E^p and G_M^p are known quantities, and θ is just the scattering angle of the electron. This only leaves G_E^n and G_M^n. G_E^n is known to be small relative to G_M^n and squaring it will only make it smaller so that for our purposes we can essentially ignore it. This means the only significant unknown in equation (1) is G_M^n. Therefore, we can solve for it to get our measurement of it from the ratio of the cross sections.
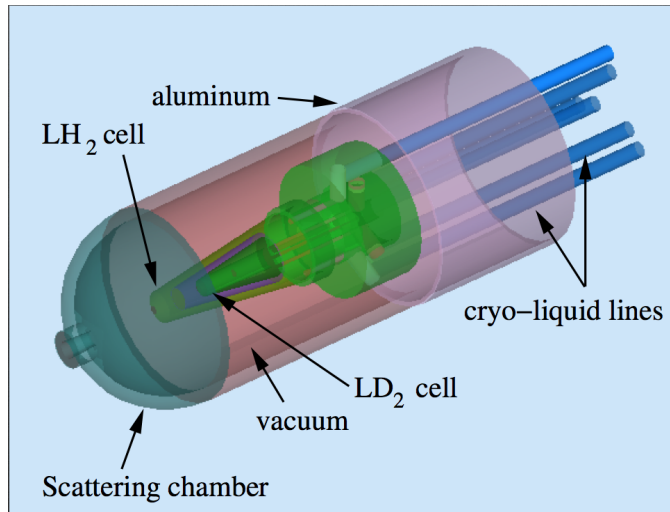
Figure 5: Computer generated image of the dual-cell target

2.3 The Target

When we start using CLAS12 to take measurements of G_M^n we will be using a target unique to our experiment. What makes the target unique is that it is a dual-cell target that allows for a different reactions to occur from each cell. A computer generated image of the target is shown in Figure 5.

One cell of the target will contain liquid Deuterium to produce the e-n and e-p events as described in section 2.2. The other cell will contain liquid Hydrogen and will be used to produce the calibration reaction $p\,(e, e'\pi^+ n)$. This notation says that we have a single proton nucleus (Hydrogen), an electron beam coming in, and we get a scattered electron, a π^+ particle, and a neutron out. This reaction will be used to calculate the neutron detection efficiency (NDE) of CLAS12.

Historically, the NDE has been the limiting factor in the precision of the G_M^n measurement. This is because, in the past, experiments would have been run to collect production data and then the calibration would have happened later on a separate run and sometimes even in a different room. The problem with this is that the electronics that are used to collect this data are very sensitive to environmental effects. This means moving the detector to a different room could have drastic effects on what the calibration of the detector is. Therefore, data collected in this manner will have a higher systematic uncertainty. This is the reason for the larger error bars on the green points shown in Figure 4.

The neutron produced by the calibration reaction is referred to as a tagged neutron. This is because both the scattered electron and the π^+ are charged particles so when they pass through the detector they should be picked up by the various components. Therefore, since we know the momentum of the electron before the collision, and we will know the momentum of the scatter electron and π^+ after the collision from our measurements, we should be able to determine the momentum of the tagged neutron. Since the neutron is a neutral particle its path shouldn't bend in the magnetic field. Thus, once we know its momentum, we'll know its path is just a straight line through the detector in the direction of its momentum. Using this predictive knowledge of where the neutron should go, we can check for neutron hits in PCAL or the EC to see if a neutron was picked up around the predicted location. By determining how many of these neutrons we actually detect, we can calculate the NDE. Because we can perform this calibration simultaneously to the production run we are able to push our systematic uncertainty to less than 3% which is lower than
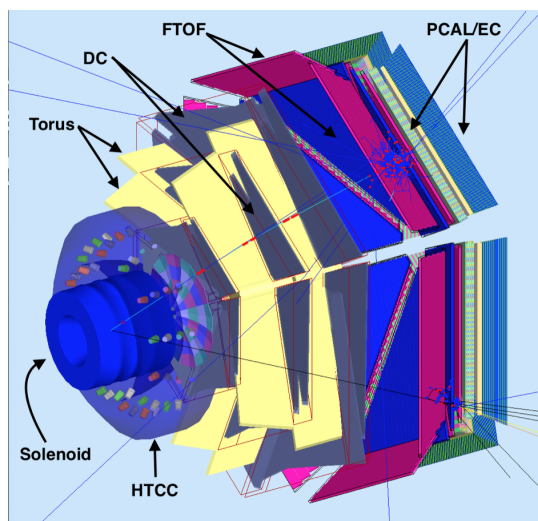
Figure 6: This shows what the simulation of an event in *gemc* looks like.

any other experiment that has attempted to measure G_M^n.

3   Methods

It is very important that an approximation of the NDE be known before we start actually running our experiment. If we have an approximation before hand, then when we start running we have something to compare to. This allows us to determine if we are getting expected results or if we should be examining something more closely. Since the detector is still in the process of being built we used a number of software packages to simulate CLAS12 and determine the NDE from there.

3.1   QUEEG

Before I can run any simulations I need to have events to simulate. To produce those events I used the JLab developed QUasi-Elastic Event Generator (QUEEG) written in C++. QUEEG takes as an argument the ratio of e-n to e-p events it should produce, the energy of the incoming electron, what the range of electron scattering angles it should produce are, and how many events it should produce. It then produces quasi-elastic events off of Deuterium and outputs them in a file. QUEEG can format the file in several ways but I had it format the events in the LUND format so that it can be easily read in by *gemc*. Since I am only worried about determining the NDE I only needed e-n events so I set the ratio of e-n to e-p events to 1. I then used QUEEG to produce about 150,000 e-n events ranging from 7-80 degrees using 11 GeV electrons.

3.2   *gemc*

Once QUEEG had generated the e-n events they were passed into the JLab produced CLAS12 simulation software GEant4 Monte Carlo (*gemc*). As the name implies, *gemc* is a C++, Geant 4 based software package that simulates CLAS12's response to physics events. Each of the components mentioned in sections 2.1.1 and 2.1.2 have been geometrically modeled with the correct materials

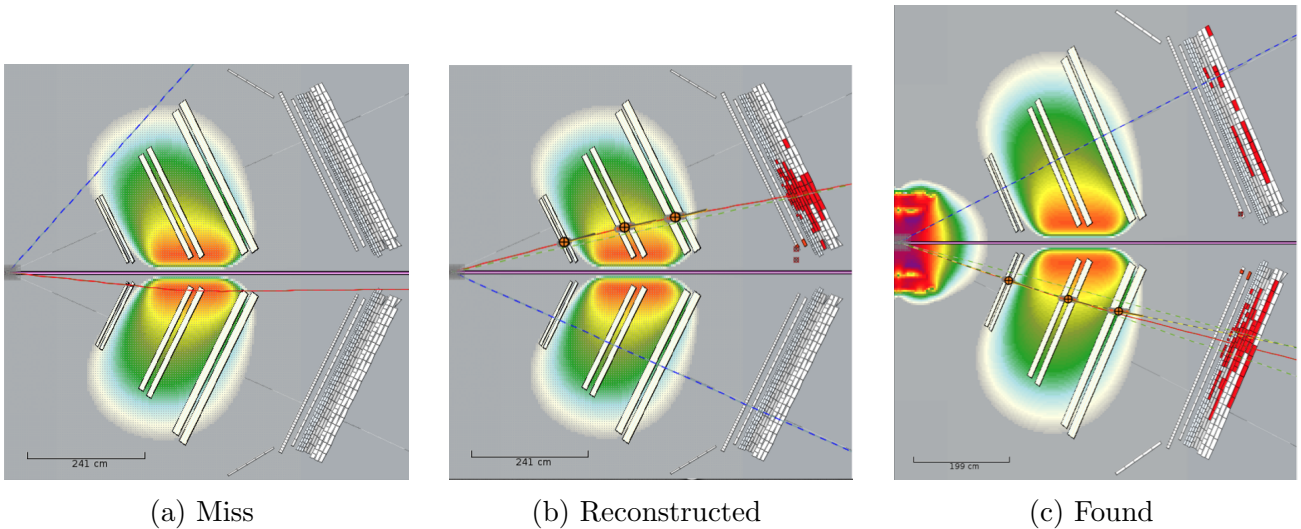(a) Miss   (b) Reconstructed   (c) Found

Figure 7: The dotted blue line shows the path the neutron takes while the red line shows the path of the electron.

so as to produce realistic physical reactions. Each of these components can be toggled on and off as needed for the simulation. Figure 6 shows what a simulation in *gemc* looks like.

The event being simulated in Figure 6 is an e-n event. The black line shows the path of the neutron and the light blue line shows the path of the scattered electron. Each of the red dots indicate a hit in the detector. While most of the energy of the particles goes into the detecting components of the detector, some of that energy is lost as low energy photons as shown by the dark blue lines. The brighter colored lines in the lower right corner indicate other particles such as a π^+ that are created in the shower the neutron creates when it hits the lead in the EC. After *gemc* has simulated CLAS12's response to the read in events, it outputs its simulated data into an evio file.

Due to the fact that the PCAL also contains layers of lead, it is understandable to think that the PCAL will contribute the the NDE since it is the neutrons interaction with lead that creates the shower, ultimately allowing the neutron to be detected. To account for this I ran all of the events through *gemc* once with PCAL and once without to see how the NDE changed.

3.3 CLAS12-Reconstruction

Once *gemc* has created the evio file, the simulated data must be reconstructed and analyzed. To do this I used the newly released, JLab developed, CLAS12-reconstuction package. First, the evio file must be passed through the program CLAS12-reconstruction. This program walks through each event that *gemc* puts in the evio file and reconstructs each event. This means it determines things like what hits happened where and how much energy was deposited in each hit, basically information that CLAS12 would actually report when it is up and running. It then takes the reconstructed data and fills a databank. With the databank full of the reconstructed data I was able to develop an analysis algorithm to determine what the NDE was. The algorithm was written in groovy and is called neutronEfficiency8.groovy. It uses the *coatjava* package included with the CLAS12-reconstruction.

The first thing the algorithm does is grab an event and check to makes sure that the event being analyzed has both a scattered electron and a neutron. If the event doesn't, then that event is thrown out and the algorithm moves on to the next one. If the event does have both required
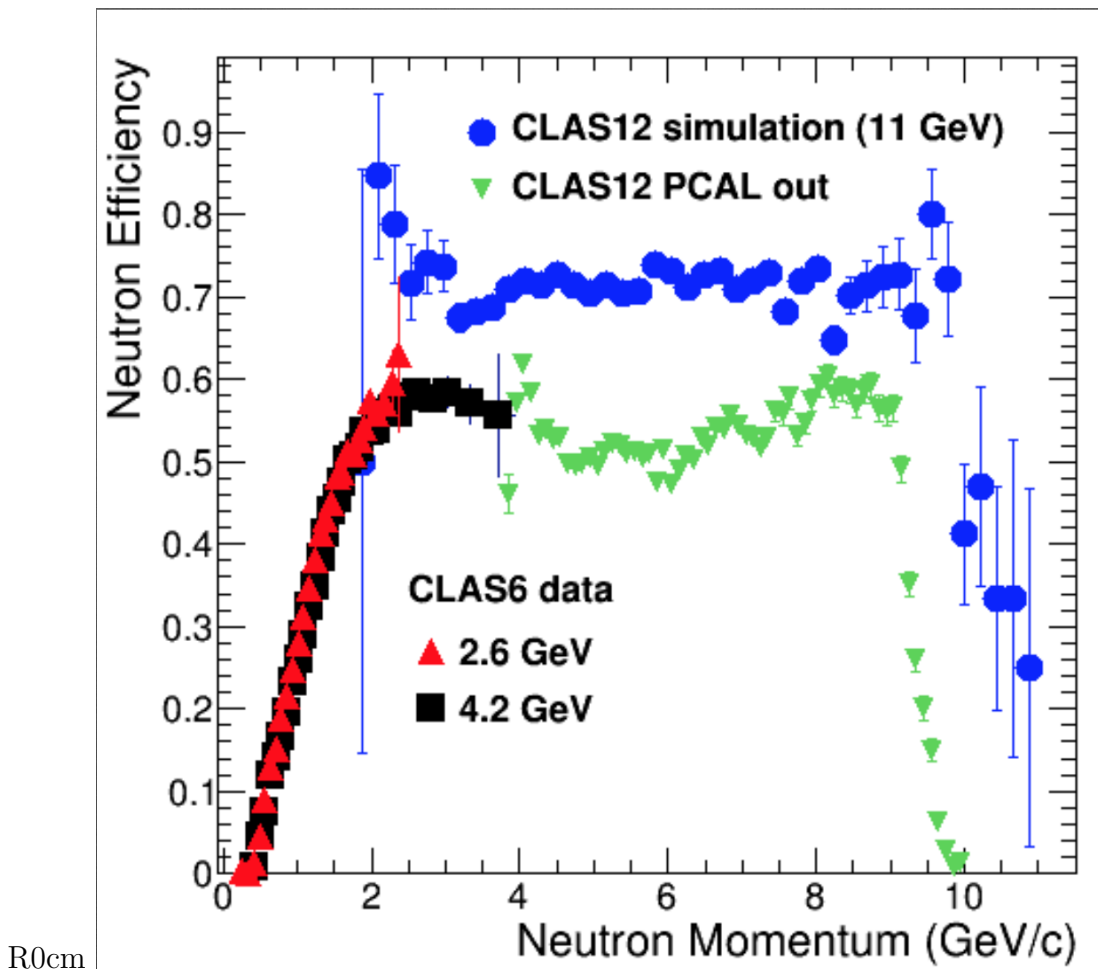
Figure 8: Plot showing the NDE I calculated (green and blue points) along with the known NDE from CLAS6.

particles, then it gets the known scattered electron momentum from what QUEEG produced. Next, the algorithm calculates the neutron momentum from the know scattered electron momentum and the fact that the electron beam is 11 GeV. With the neutron momentum calculated, the algorithm checks to see if the neutrons predicted path intersects the fiducial volume of the EC.

If the neutron misses the EC, then the event is thrown out and the algorithm moves on to the next event (Figure 7a). If it does intersect the EC, then the event is counted as reconstructed (Figure 7b). The next step is to check the databank from the reconstruction to see if any neutrons were detected around the predicted location. The algorithm considers any neutron hit within $1.5°$ of the predicted location to be close enough to possibly be the neutron it is looking for. Thus, if it finds a neutron hit within $1.5°$ of the prediction then it counts the neutron as found (Figure 7c); otherwise, it just moves on to the next event. The NDE is computed by taking the ratio of the reconstructed to found neutrons.

I ran about 140,000 e-n events through my analysis algorithm.

4 Results

Figure 8 shows what we got for the NDE of CLAS12.

The blue points represent the NDE while PCAL is in place and the green points show the

NDE without PCAL. The blue points plateau at 3 GeV around 70% and don't start to taper off till around 10 GeV. The green points on the other hand plateau between 50-60% and fall off around 9 GeV.

5   Discussion

The results I got are very exciting. From the CLAS6 data, we expect a plateau around 60% at 3 GeV which the green points do seem to agree with. This makes sense, because without PCAL all thats left to detect neutrons is the EC. Since its the same EC that was used in CLAS6, the NDE for it should be about the same. The reason there is a fall off around 9 GeV is because at higher energies the neutrons start to go straight down the beam tube so there are some acceptance issues. There is also one point right at 3 GeV that seems unreasonably high which is thought to be due to the geometry of the EC without PCAL but it is still be explored.

The blue points are also very exciting. These points represent what CLAS12 should be showing when it becomes fully operational. It does seem that the addition of PCAL has raised the NDE about 10% which again makes sense because the neutron now has more chances to create a shower that will allow for its detection. Also, the reason for the drops offs at the higher and lower energies are because at those energies the neutron is either going down the beam line or scattering at too large of a angle for CLAS12 to pick up, so again they are acceptance issues.

While these are exciting results it should be noted that all of our simulations were done with events off Deuterium, which is what we will be using for our production data, not our calibration data. This is because QUEEG was readily available and it only produces event off Deuterium. We are currently working on developing event generation code that will produce the calibration events off Hydrogen to make our simulation and analysis more accurate.

6 Sources

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