Dual Target Design for CLAS12

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March 22, 2017

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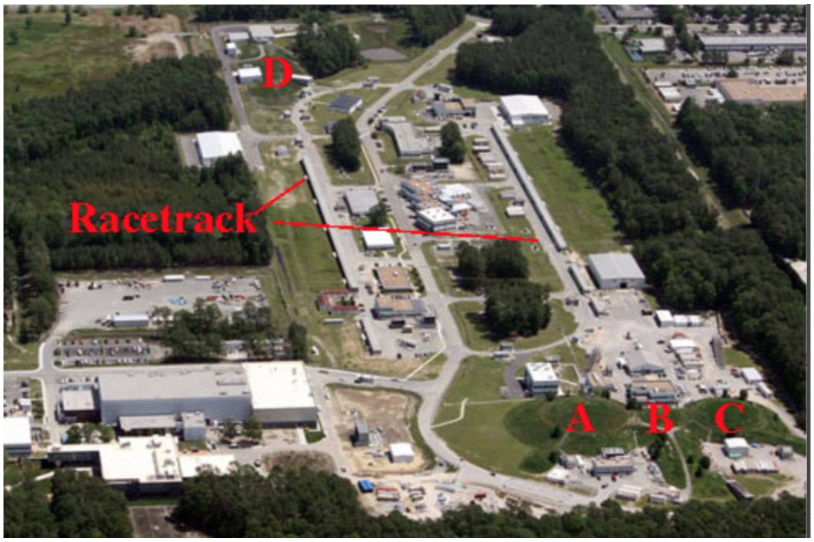


Figure 1: Aerial photo of JLab showing the racetrack shaped particle accelerator that the electrons are accelerated around and the four halls.

1 Abstract

One of the fundamental physics goals of Jefferson Lab (JLab) is to understand the structure and behavior of strongly interacting nuclei in terms of their basic constituents, quarks and gluons. 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). This form factor will be extracted from the ratio of the quasi-elastic electron-neutron to electron-proton scattering off a liquid deuterium (LD_2) target. A collinear liquid hydrogen (LH_2) target will be used to measure efficiencies at the same time as production data is collected from the LD_2 target. To test target designs we have simulated CLAS12 and the target geometry. Electron-nucleon events are produced first with the QUasiElastic Event Generator (QUEEG) which models the internal motion of the nucleons in deuterium.[1] The results are used as input to the CLAS12 Monte Caro code *gemc*: a Geant4-based program that simulates the particle's interactions with each component of CLAS12 including the target material. The dual target geometry added to *gemc* including support structures and cryogenic transport systems. A Perl script was written to define the target materials and geometries. The output of the script is a set of database entries read by *gemc* at runtime. An initial study of the impact of this dual-target structure revealed limited effects on the electron momentum and angular resolutions.

2 Introduction

2.1 Jefferson Lab and CLAS12

Jefferson Lab (JLab), a US National Laboratory located in Newport News Virginia, focuses on understanding the nature of the quark-gluon interaction that binds protons, neutrons, and nuclei together.
This goal is accomplished by using a mile long, racetrack-shaped, linear accelerator to produce an electron beam that gets deposited into 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:

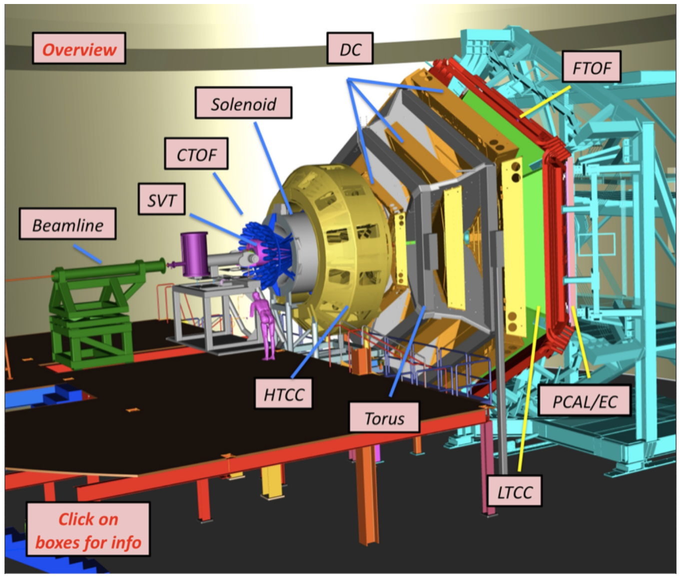


Figure 2: Computer generated image of CLAS12. Notice that CLAS12 is about 3 stories tall as shown by the purple man standing next to it.

1. The beam energy was doubled to 12GeV
2. A new detector was built in Hall B (CLAS12)
3. Hall D was built

Hall B currently houses the CEBAF Large Acceptance Spectrometer (CLAS12) (Figure 2).

CLAS12 has two major parts, the forward detector and the central detector which detect and measure the properties of charged and neutral particles produced by bombarding nuclei with electron beams.

2.1.1 Central Detector

The central detector sits physically close to, and is centered on, the target. It is cylindrical in shape and its purpose is to detect particles with polar scattering angles greater than 35 degrees. It has three main components: the central time of flights (CTOF), the solenoid and the silicon vertex tracker (SVT).

The Central Time of Flight (CTOF) detector consists of 48 trapezoidal scintillation paddles. When an ionizing particle passes through a paddle, some of its energy is converted to light. This light is transferred along light guides to both ends of the paddle. At the end of each light guide exists a photo multiplier tube (PMT). The PMT converts the light into an electrical signal which is read out using an Analog to Digital Converter (ADC) and a Time to Digital Converter (TDC) to give energy and timing output. The CTOF, therefore, measures the time at which a particle goes by.

The solenoid 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 the particle bends inward or outward. The direction in which a charged particle bends therefore can help us with particle identification.

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 to determine the position of the particle. Its very important that the SVT be close to the target because the position information it produces allows for a very accurate extrapolation of collision vertex.

2.1.2 Forward Detector

The forward detector is located downstream from the target (where downstream means farther from the entry point of the beamline). Its purpose is to detect particles at smaller polar angles than the central detector -approximately 5-45 degrees. Its consists of multiple components as described below.

The Forward Time-of-Flight System (FTOF) is a major component of the CLAS12 forward detector used to measure the time-of-flight of charged particles emerging from interactions in the target. It consist of 3 sets of scintillation paddles at the ends of which are PMT's and functions in a similar fashion to the CTOF.

The forward detector also has a magnetic field produced by the torus. The torus is a giant, supercooled magnet that produces a magnetic field that is used for the same purpose as the solenoid. By observing how a particle bends in the magnetic field, the sign of its charge can be determined which helps with particle identification.

The drift chambers (DC) which are used to track the position of a charged particle as it passes through the detector. It consists of large gas filled chambers containing thin, high voltage wires placed at regular intervals in a hexagonal pattern. Passage of particles through the chambers frees electrons from the gas, which are attracted to the nearest positive wires, thus creating an electrical signal that can be used to track the trajectory of the particle.

The detector also contains low-thresh hold and high-thresh hold Cherenkov counters, the LTCC and HTCC respectively. Each of these components are filled with a special gas and many PMT's. They help distinguish particles with the same charge but a different mass, for example, a π^- and an electron. Since both particles have a the same magnitude negative charge, both bend in the same direction in the magnetic field; however, the π^- particle 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, comprised mostly of photons. These photons are redirected into the PMTs which 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 hits in the Cherenkov counters along the track, then it is probably an electron; whereas if there are no such hits from the Cherenkov counters, then its probably a π^-.

The forward detector contains the Pre-shower Calorimeter (PCAL) and the Electromagnetic Calorimeter (EC), both consisting 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 their ends. 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. Since the PCAL and the EC are the last components of CLAS12, their purpose is also to stop particles from going out the back of the detector. CLAS6 contained the EC which

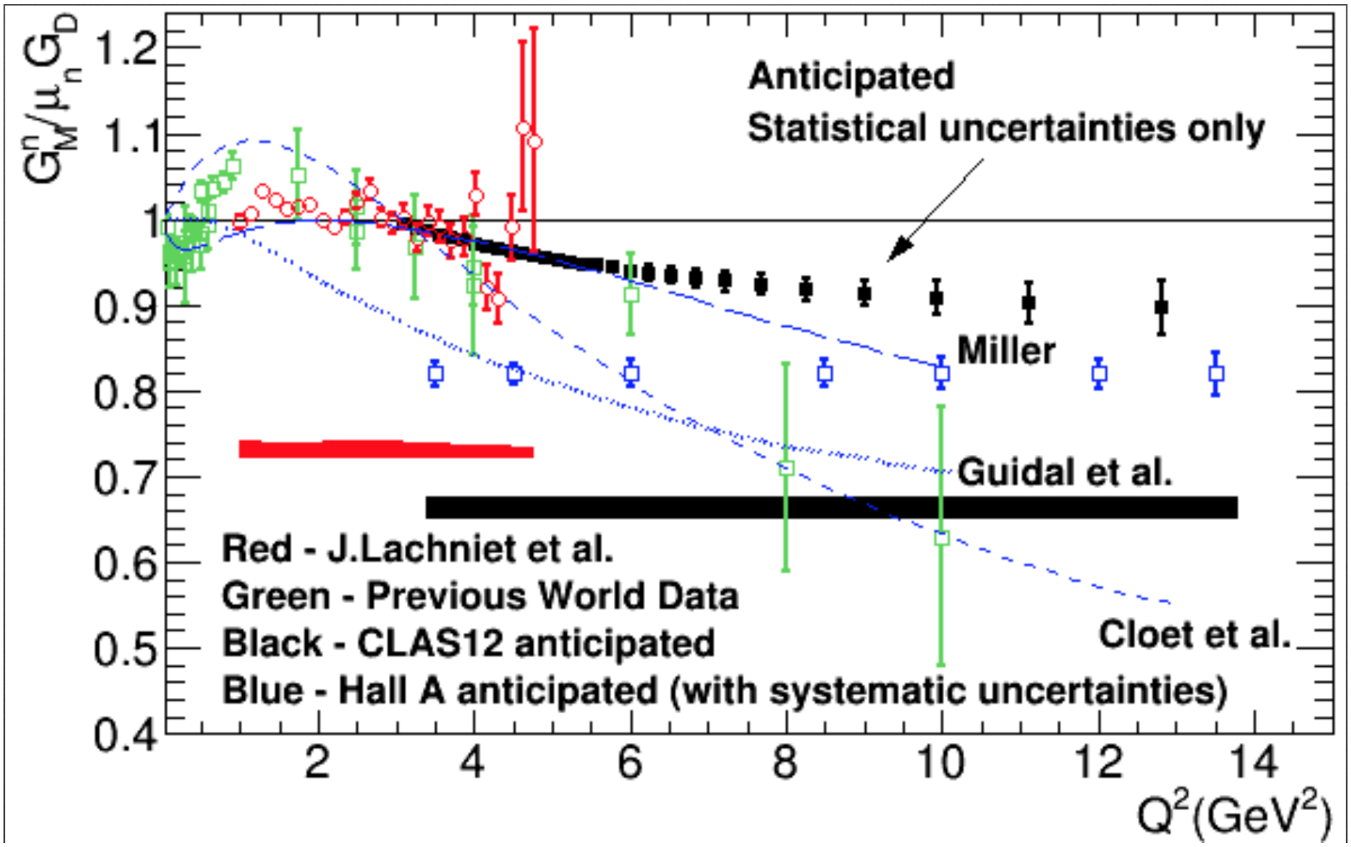


Figure 3: Worlds Data on G_M^n

was enough to stop particles at 6 GeV, but with the doubling of energies for CLAS12, the PCAL was also added to ensure that the more energetic particles don't exit out the back.

2.2 Neutron Magnetic Form Factor

One of the approved experiments for CLAS12 is the measurement of G_M^n, one of four elastic form factors. The neutron also has 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 help validating or invalidating 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.

My research is centered around the G_M^n. 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 them being 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. Therefore, G_M^n gives us an idea of the magnetization of neutrons.

We are interested in measuring G_M^n is because not much is known about it. Figure 3 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 (also known as the kick we give) during electron elastic scattering (Q^2) and the y-axis shows a normalized measurement of G_M^n.

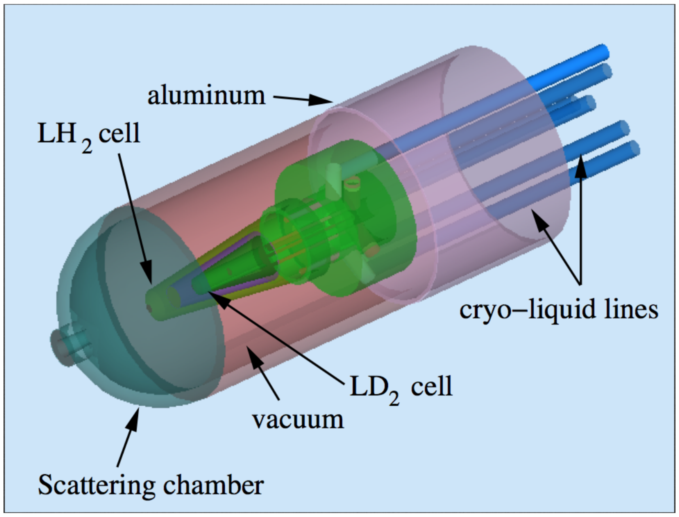


Figure 4: Dual Target with Support Structures and Cryogenic transport

The green points are data taken before CLAS6 and the red points show data taken with CLAS6. The error bars are especially large, especially at larger Q^2. The black points in this plot show what the predicted measurements using CLAS12 are, with sufficiently small error bars. The blue points are showing the predicted values for an experiment to measure G_M^n in Hall A. JLab, therefore, has two experiments in different halls aimed at measuring the Neutron Magnetic Form factor, a fact that should elucidate the importance of this measurement.

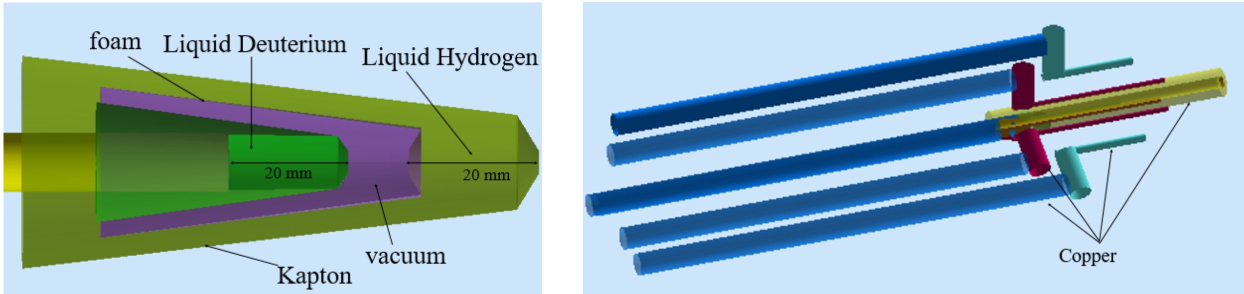
In order to measure G_M^n we will be using the Ratio Method by taking a ratio of electron-neutron (e-n) to electron-proton (e-p) events from quasi-elastic scattering off Deuterium. Mathematically, this is shown in equation (1).

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

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. The cross section is the effective area of the detector being used to detect the events. The ratio allows us to cancel out many factors and it makes our measurement less susceptible to sources of error such as acceptances and efficiencies. When this ratio is expanded, we get everything on the 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. Therefore, for the purposes of this calculation, we can ignore it. Thus, the only significant unknown in equation (1) is G_M^n. We can, thus, solve for G_M^n to get our measurement of it from the ratio of the effective areas/cross sections.

2.3 The Dual Target

We will be using a uniquely designed dual-cell target when we start using CLAS12 to take measurements of G_M^n. This dual-cell target allows for a different reactions to occur from each cell. A computer generated image of the target is shown in Figure 4.



(a) Dual Target

(b) Cryogenic Transport System

Figure 5: These are the two big chunks of the target.

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

Historically, the NDE has been the limiting factor in the precise measurement of G_M^n. 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. Since the electronics that are used to collect this data are very sensitive to environmental effects, moving the detector to a different room could have drastic effects on what the calibration of the detector is. Thus, the data collected in this manner will have a higher systematic uncertainty. This problem plagued previous measurements of G_M^n in CLAS6, for instance.

The neutron produced by the calibration reaction is referred to as a tagged neutron because both the scattered electron and the π^+ are charged particles so when they pass through the components of CLAS12, they should be detected, fairly easily, by its various components. Since we know the momentum of the electron before the collision (because we can control that), and we will know the momentum of the scattered electron and π^+ after the collision from our measurements (because they are charged and easy to detect), we should be able to determine the momentum of the tagged neutron. Since the neutron is neutral, its path shouldn't bend in the magnetic field. Thus, once we know its momentum, we'll know its trajectory a straight line through the detector in the direction of its momentum. Using this knowledge of where the neutron should go, we can cross-check 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 tagged neutrons we actually detect, we can calculate the NDE. By performing this calibration simultaneously with the production run we are able to reduce our systematic uncertainty to less than 3% which is lower than any other experiment that has attempted to measure G_M^n.

We wrote a Perl script that utilized the CLAS12 Monte Carlo code *gemc* and Geant4 API (Application Program Interface) to define specific geometries and materials for the target. Figure 5a shows the positions and geometries of the two target cells as well as the structures holding them. We made the following design decisions in order to make the target structures easy to modify and the Perl script easy to reuse and read:

1. Made separate procedures for each target component to make replacement or modification of individual parts of the target easy.

2. Established proper dependencies between all the target components to ensure that changes made to any substructure would reflect across the whole target therefore making changes easy to implement. Some of the geometries such as hemispherical caps with conical craters were made using advanced features of Geant4 such as addition and subtraction of solids.

3. Extensively documented and commented the Perl script to increase code readability.

The target cells are surrounded by support structures and tubing for transporting cryogenic liquids for cooling the target system. There are three sets of two tubes arranged around the target cells at intervals of 120 degrees as shown in Figure 5b. We added these ancillary systems to the target definition script because:

1. These structures could potentially alter the properties of the particles scattered from the targets upon interaction.

2. They might produce background particles when the primary reaction products pass through them and we might need to identify and remove such particles during the analysis stage.

The output of the Perl script is a set of database entries read by *gemc* at runtime.

Figure 4 shows the complete target structure consisting of all the aforementioned components along with the scattering chamber and the aluminum outer casing.

3 Methods

We need to have an approximation of NDE before running the experiment because then when we start running, we have something to compare the measured value to. 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

In order to realistically simulate this experiment, we have developed the QUasiElastic Event Generator (QUEEG) which models the internal motion of the nucleons in deuterium. It extends a previous version used in Hall B to measure the form factor at lower energies.

To simulate the quasi-elastic production we treat the deuteron as composed of two, on-shell nucleons, one of which will act as a spectator in the interaction. The quasi-elastic interaction is then elastic scattering with the target nucleon. 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.

Options were added to the original QUEEG code to improve the simulation of the experiment to measure G_M^n :

1. Included a dependence on the azimuthal angle between the scattering plane (defined by the incoming and scattered electrons) and the reaction plane (defined by the detected nucleon momentum and the 3-momentum transfer for this experiment and others).

2. Simulated a realistic event vertex distribution for a cylindrical target.

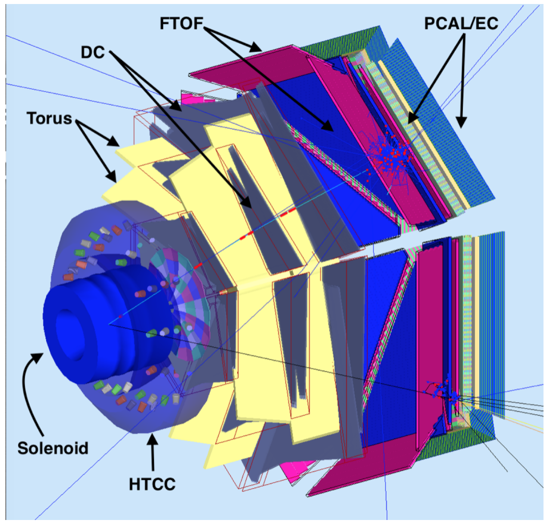


Figure 6: This shows what the simulation of an event in *gemc* looks like.

   (a) We randomly distributed the event vertex along the beamline in the target region. When the center of the target was at -15 and the target was 20 mm long, the plot we obtained was a uniform distribution spanning the range -25mm to -5 mm. This is shown in Figure 3.
   (b) We used von Neumann rejection to select random points in the plane traverse to the beamline within a fixed radius from the beam.

3. Added a threshold on the missing momentum, pm, i.e. the momentum of the spectator nucleon. This option enables us to obtain better Monte Carlo statistics at larger pm where the cross section is small.

4. Exported the simulated results in LUND format for use with Geant4 Monte Carlo Simulation(*gemc*).

5. Incorporated minimum and maximum limits on the electron scattering angle. This option enables us to simulate the kinematic region more efficiently.

6. The original code was part of a suite of programs that used locally-developed libraries. We streamlined the libraries needed for QUEEG and modified the directory structure and build systems to make the program more robust and accessible.

3.2 *gemc*

Once QUEEG has generated the e-n events they are passed into the JLab produced CLAS12 simulation software GEant4 Monte Carlo (*gemc*). *gemc* is a C++ Geant 4 based software package that simulates CLAS12's response to physics events. Each component of CLAS12 has been geometrically modeled with the correct materials to realistically simulate physical reactions. Figure 6 shows what a simulation in *gemc* looks like.

This Geant4-based program simulates the particle's interaction with each component of CLAS12, including the target material, the supporting systems and the cryogenic transport systems and is used as a tool to study the response of the detector. We used straight tracks with no magnetic field

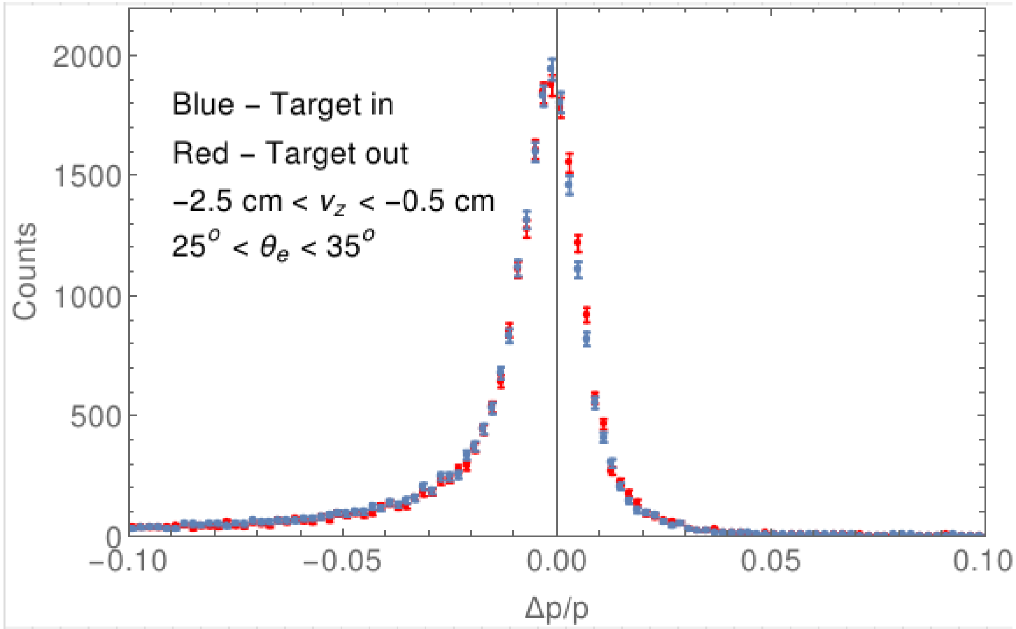


Figure 7: Momentum difference distribution with Target In and Out.

to match the *gemc* geometry with the assumed target geometry. For more complex analysis, Clara, a data analysis framework developed by Jefferson Lab scientists, was used for event reconstruction and to study the effect of the target material on large angle electron scattering in CLAS12.

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. Some of the energy is lost as low energy photons as shown by the dark blue lines as well. 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 and the PCAL. After *gemc* has simulated CLAS12's response to the read in events, it outputs its simulated data into an evio file which is then analyzed.

3.3 CLAS12 Reconstruction Software

Once *gemc* has created the evio file, the simulated data must be reconstructed and analyzed. To do this, we used the newly released, JLab developed, CLAS12-reconstruction 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. It determines things like how much energy was deposited in each hit, basically information that CLAS12 would actually report when it is in action.

4 Results

Figure 7 shows the distributions of the percent momentum difference, $\frac{\Delta p}{p} = \frac{p_{reconstrcuted} - p_{reconstrcuted}}{p_{reconstrcuted}}$, where $p_{reconstrcuted}$ is the reconstructed momentum and $p_{generated}$ is the generated momentum, for an electron scattering angle θ for $25° < \theta < 35°$and vertex position along the beam axis for $-2.5cm < v_z < -0.5cm$. There is little difference between the two distributions.

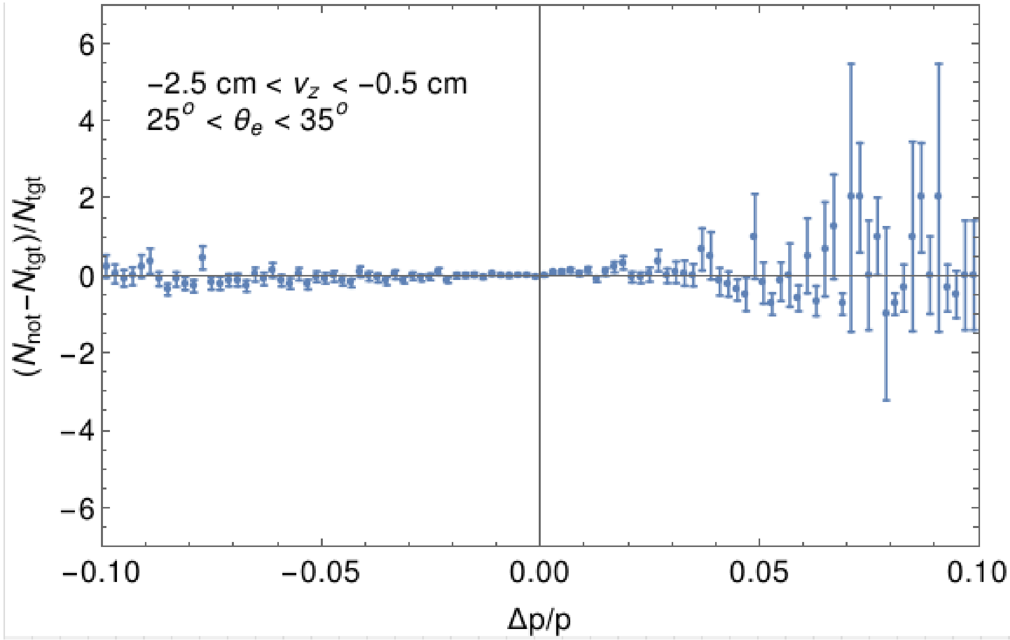


Figure 8: Difference in count between that for target in and target out.

Figure 8 represents the difference between the $\frac{\Delta p}{p}$ distributions for target in and target out. There is no statistically significant difference between the two distributions.

5 Discussion

The results seem very encouraging. The curve on Figure 7 tends to follow a Gaussian since the most commonly occurring events should be those for which there is no momentum gain or less as an electron is sent through CLAS12 and then is reconstructed back. Therefore, we peak at $\frac{\Delta p}{p} = 0$. This Gaussian however is not centered around the y axis and is rather skewed to the left. The tail towards the left shows that there were non-zero number of electrons with a negative $\frac{\Delta p}{p}$ ratio. Therefore, for these electrons, $p_{generated}$ was greater than $p_{reconstrcuted}$, an event which physically seems more plausible than the converse i.e. the electron gaining momentum after passing through all of the components of CLAS12. The loss in momentum corresponds to a loss in energy of the electron as it passes through all the components of CLAS12. Therefore, points to the left of the zero percent momentum-change line represent a loss in energy as a particle passed through various components of CLAS12. Points on the right of the zero percent momentum-change line represent a gain in energy as a particle passed through. Physically, it is correct to say that more events will have the former property as opposed to the latter one.

Please note that this skew would not be present if the above mentioned CLAS12 Reconstruction Software accounted for this anomaly and automatically corrected for the loss of energy in order to ensure that the total energy of the incoming electron is the same as that of the reconstructed electron. We will run this experiment again with the same parameters mentioned above with the reconstruction software also accounting for the energy losses in order to see if we get the exact same graph but with the skew absent.

Figure 8 is very interesting in terms of seeing the error bars of number of counts for various ratios of momenta. It is obvious that the error bars are the smallest for when the percentage momentum-change is 0, and that is because most of the events have this property. Areas where

$-0.05 < \frac{\Delta p}{p}$ and $\frac{\Delta p}{p} > 0.05$ have higher error bars because less reconstructed electrons have such properties and so we generate less hits for such events. After comparing the Figure 7 and 8 together, its also obvious that the error bars for $-0.05 < \frac{\Delta p}{p}$ points is smaller than that of $\frac{\Delta p}{p} > 0.05$. The reason is that reason is that we see more hits/events in the $-0.05 < \frac{\Delta p}{p}$ region because the Gaussian is skewed towards the left side.

6 Sources

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