# NEUTRON DETECTION EFFICIENCY OF THE CLAS12 DETECTOR

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# ABSTRACT

I simulated CLAS12, a detector which is part of the Jefferson Lab 12 GeV upgrade, to obtain a preliminary estimate of it's neutron detection efficiency (NDE). Knowledge of the NDE of a detector is important for calculating systematic uncertainty of neutron measurements made with the detector. Many experiments planned for the CLAS12 detector require neutron measurements, so knowledge of NDE is essential. An important experiment requiring knowledge of NDE is measuring the magnetic form factor of the neutron (experiment E12-07-104).

# INTRODUCTION

## Jefferson Lab and CLAS12

Jefferson Lab (JLab) is located in Newport News Virginia, and is focused on understanding the nature of the quark-gluon interaction that binds proton, neutron, and nuclei together. The central scientific instrument at JLab is the Continuous Electron Beam Accelerating Facility (CEBAF). CEBAF creates a precise continuous beam of electrons and allows up to three targets to receive beam simultaneously, one each in Hall A, B, and C. Currently CEBAF runs at 6 GeV, but soon will be upgraded to 12 GeV.

The 12-GeV Upgrade is important for multiple reasons including mapping of the transition to the quark-gluon degrees of freedom, and probing new and exciting features of the fundamental constituents of matter. The current detector housed in Hall B is CLAS. This detector will be replaced by CLAS12 (see figure 1) as part of the Upgrade[1]. The new CLAS12 will rely on layers of drift chambers, Cherenkov counters, time-of-flight scintillators (TOF), and electromagnetic calorimeters to identify particles and reconstruct events.

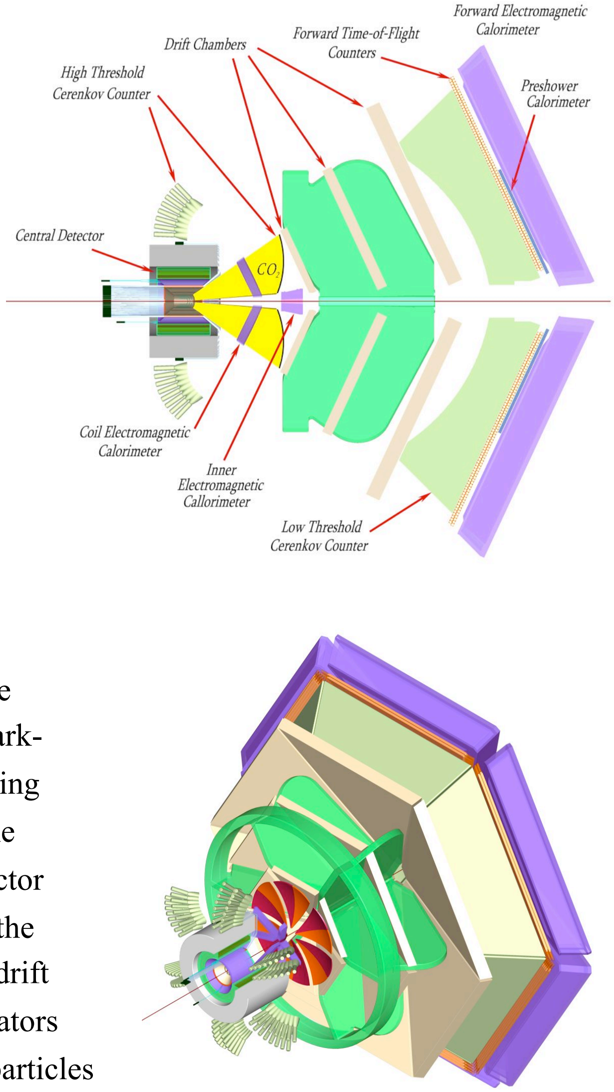

Figure 1: CLAS12

The drift chambers consist of large gas filled chambers in a magnetic field with hundreds of wires placed at regular intervals. When a charged particle travels through the gas it ionizes gas particles, which are then attracted to the nearest wire. When the ionized particles hit the wire we receive a signal. By observing which wires were "hit" we can reconstruct the path that the particle took[1]. The path of a charged particle will bend due to the magnetic field, and the amount of curvature is determined by the mass of the particle. Thus the drift chamber can be used to determine the charge (direction of curvature) and mass (amount of curvature) of the particle.

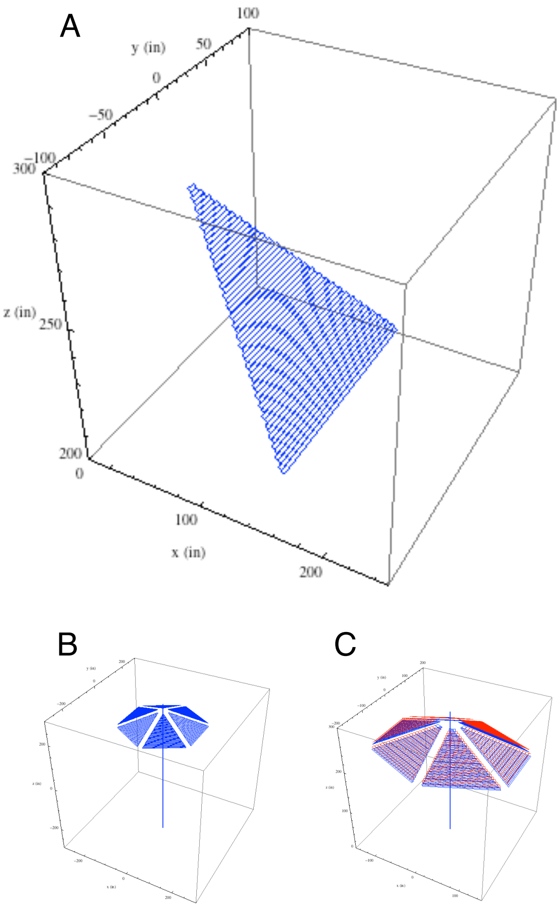

Figure 2
A: one section of a panel
B: one panel
C: panels P1A (blue) and P1B (red)

The Cherenkov counters work using a phenomenon called Cherenkov radiation. When a charged particle travels through a material its electric and magnetic fields displace electrons in molecules close to its path[2]. After the particle passes by, these electrons return to their ground states and release photons. Usually these photons undergo destructive interference and no radiation can be detected. However if the particle is traveling faster than the speed of light in the material the photons interfere constructively and can be detected. This is called Cherenkov radiation, and a Cherenkov counter works by detecting this. By choosing to make a Cherenkov counter out of a materiel with a low index of refraction, we make sure that a particle must be traveling close to the speed of light to emit Cherenkov radiation. Only light particles will be able to travel fast enough to create Cherenkov radiation. We use this to distinguish between similar particles.

Scintillators are a layer of material that release light when a particle travels through it. A charged particle traveling through the scintillator will create ionizing radiation and cause a nearby molecule to enter an excited state. This molecule will quickly fall into a lower energy state and release light. Each layer of the TOFs in CLAS12 are made with a series of scintillating strips in a triangle shape (figure 2A). Each layer of scintillator is made of six sections arranged circularly (figure 2B). There are three

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[1] Unfortunately neutral particles won't ionize gas, so this cannot be used to track their path

[2] Again, this part of the detector will not detect neutral particles

layers of scintillators, but we will focus on layers P1A and P1B (figure 2C), which are most important for neutron detection These scintillators release light within nanoseconds of being excited, and are used to measure the time at which a particle reaches the scintillator. Since there are many scintillators in parallel and we know which scintillator a particle travels though we can extract the particle's position as well.

Electromagnetic calorimeters measures the energy of a particle. The calorimeter in CLAS12 consists of alternating layers of lead and scintillators. The lead causes the particle entering the calorimeter to create a particle shower, and the energy of the particles in this shower are measured with the scintillators. This allows us to measure a fraction, or sample, of the initial particles energy which we can use to calculate the particles total energy. Using the information from each component of the detector we are able to identify particles and determine their path through the detector, allowing us to reconstruct the event and extract information such as initial scattering angles and momenta.

## Magnetic Form Factor of the Neutron

One of four elastic form factors which describe the internal structure of hadrons, the magnetic form factor of the neutron ($G_m^n$) describes the distribution of electric current within the neutron. Although the neutron has a net neutral charge, the quarks which make up the neutron each have non-zero electric charge. Since $G_m^n$ describes the electric current within the neutron, it describes the motion of the neutron's constituent quarks. This makes $G_m^n$ a very interesting and fundamental quantity. Compared to the other form factors, we have little knowledge of $G_m^n$.

Figure 3 compares our current knowledge of $G_m^n$ with the other form factors. $G_m^n$ is on the bottom right. Notice the larger error bars and fewer data points for $G_m^n$, especially towards higher $Q^2$ (four-momentum transfer during elastic electron scattering). We will be able to accurately measure $G_m^n$ at higher energies with the Upgrade and CLAS12. Figure 4 shows our current knowledge of $G_m^n$, along with theory curves. The red data points were measured using CLAS and the ratio method[3], while the green points are all other existing data. Notice that the theory curves diverge at large $Q^2$. By measuring $G_m^n$ at these higher energies[4] we will be able to test these theories and eliminate incorrect ones.

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[3] This method was also used in the CLAS measurement of Gmn at lower energies

[4] CLAS12 measurements will be from about 4-14 Q2

Figure 3: Comparison of the four form factors [2]

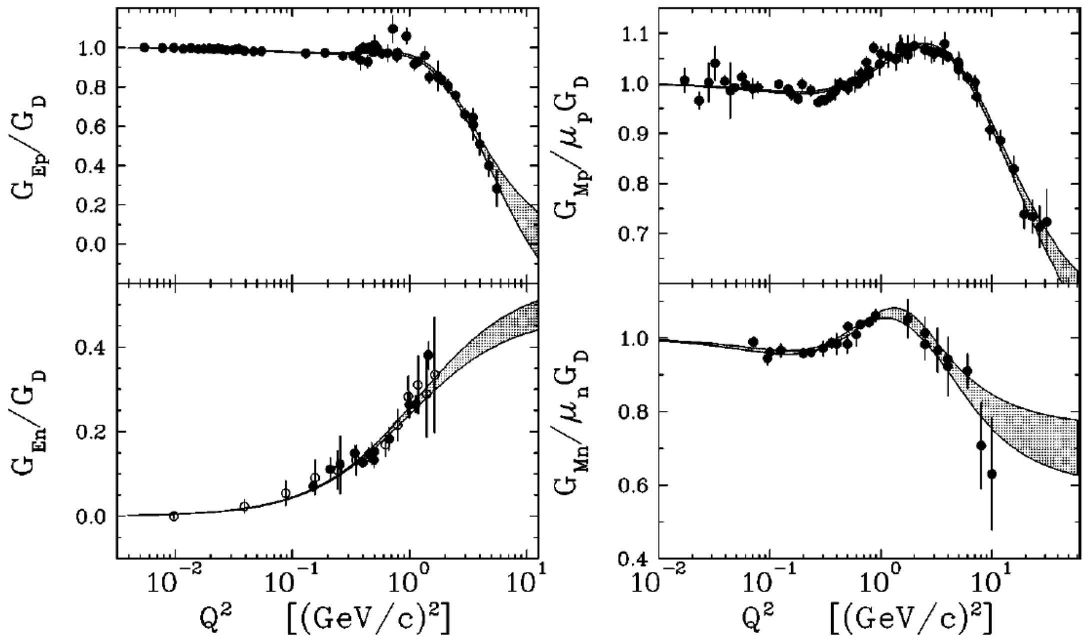
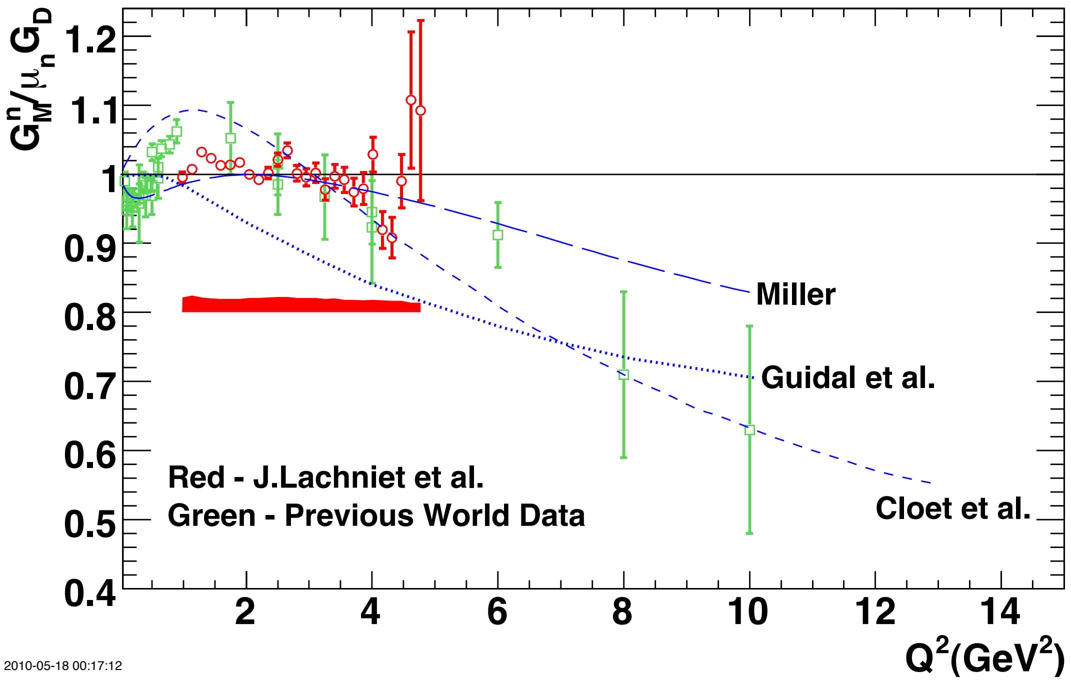


Figure 4: Current knowledge of $G_m^n$ [2]



EQUATION 1: RATIO METHOD [2]

Cross section of elastic electron-neutron scattering in deuterium

4 momentum transfer from electron to neutron

Factor correcting for cuts on the data

Neutron scattering angle

$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = a(Q^2)\frac{\frac{{G_E^n}^2+\tau {G_M^n}^2}{1+\tau} + 2\tau {G_M^n}^2\tan^2(\frac{\theta}{2})}{\frac{{G_E^p}^2+\tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2\tan^2(\frac{\theta}{2})} \qquad \tau = \frac{Q^2}{4M^2}$$

Cross section of elastic electron-proton scattering in deuterium

Proton scattering angle

Neutron mass

## Ratio Method

Free neutrons don't exist naturally, they decay. Thus we cannot create a target of pure neutrons, we have to use targets of atomic nuclei where neutrons are stable, and then scatter electrons off them to probe their internal structure. We use a deuterium target, which has nuclei of one proton and one neutron. Our technique for measuring $G_m^n$ involves taking the ratio of elastic[5] neutron and elastic proton cross sections of deuterium. Using this ratio and our knowledge of the other form factors we are able to extract $G_m^n$ (see equation 1). To detect elastic neutron and proton events we will use the CLAS12 detector which will be built at Jefferson Lab.

The higher beam energies of CLAS12 will result in a higher proportion of inelastic events. Since the measurement of $G_m^n$ depends on elastic scattering cross-sections, this increase in inelastic scattering causes an immense background. To reduce the inelastic background in our measurements we will use a variety of cuts on the data. The factor $a(Q^2)$ is a correcting factor taking these cuts into account.

The proton cross section is well known, and, as seen in Figure 1, the other form factors are also well understood. Thus we can rearrange equation 1 to obtain a formula that gives $G_m^n$ as a function of neutron elastic cross section at a specified $Q^2$. The more accurately we can measure

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[5] Elastic here means no kinetic energy is lost in the collision.

the neutron cross section, the more accurately we can understand $G_m^n$. The largest contributor to the systematic uncertainty of the neutron cross section measurement is uncertainty in NDE. By increasing our understanding of NDE in CLAS12 we can reduce error in the $G_m^n$ measurement.

# METHODS

## Introduction

Simulating CLAS12 was done on a supercomputing cluster. The supercomputer consists of 20 nodes, each with 12 CPUs. Each CPUs is capable of running an instance of the simulation simultaneously, and theoretically up to 240 simulations in parallel[6]. After completing the simulation the results were sent back to a head node and merged for analysis. The simulation itself consisted of running a series of software packages.

When simulating CLAS12 we use a Cartesian coordinate system to identify positions within the simulation. The origin is in the deuterium target, which is located in the center of the front of the detector. The z-axis lies along the beam direction, which goes horizontally through the target and center of the detector. CLAS12 is radially symmetric about this z-axis. The x position is defined as the vertical distance from the z-axis and y position is horizontal distance from the z-axis. Two angles, theta and phi (see figure 5), are also commonly used in the

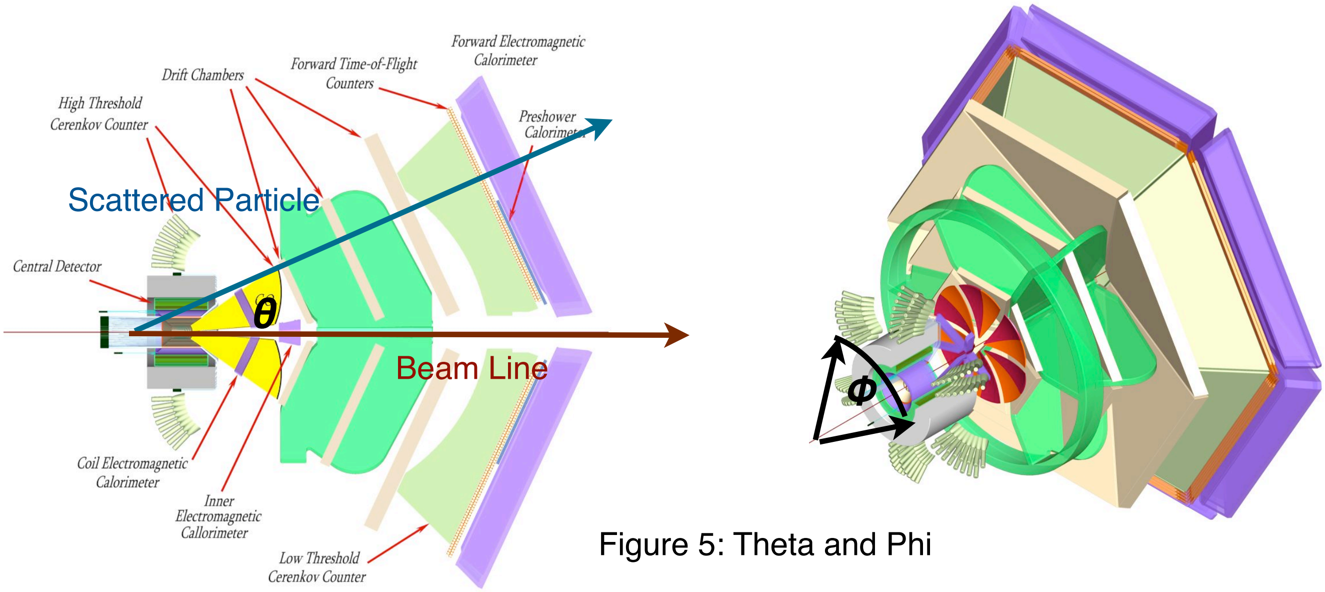

Figure 5: Theta and Phi

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[6] The actual number of simulations capable of running in parallel was 224, but this was due to having to connect to an external database which restricted the maximum number of connections from a single computer.

simulation to describe scattering angles. Theta is the angle between a vector and the z-axis, where phi is the angle between a vector's projection into the x-y plane and the x-axis.

## Software

### *NeutronElasticEventGen*

The first step of the simulating CLAS12 is running NeutronElasticEventGen. This code was written in C++ by me, and is used to create a file describing elastic electron-neutron scattering events. The code takes a range of angles and number of events to simulate as input. For each event the software calculates a random value using a uniform distribution within the given range and sets this as the electron's theta scattering angle. A random phi value is also chosen using a uniform distribution over 360 degrees. Next the value of various physical quantities that describe the event (neutron scattering angle, electron momentum, neutron momentum...) are calculated assuming an electron scattered off a neutron at the given theta and phi angles with the an 11GeV beam energy. The process is repeated until the desired number of events have been created, and the data from all these events is saved in an output file in the LUND format. Since we can specify the theta scattering angle we can test specific ranges of the detector's TOF panels.

While our simulated angular scattering distribution for phi is realistic, the theta distribution is not. We create a uniform distribution over an angle range in the simulation, while in reality the high beam energy will result in more electrons scattering at lower theta angles. However, since we are measuring efficiency the distribution of scattering angles is unimportant[7], and this unrealistic distribution speeds up the required simulation time by allowing a larger portion of the events to scatter at higher angles. This means we get larger statistics (more events) which translates to lower uncertainty.

### *gemc*

After NeutronElasticEventGen runs, its output is read into gemc (Geant4 Monte Carlo.) This program is based on Geant4, a software package used to simulate elementary particles moving through matter. We use it to simulate the interactions of particles with the detector after scattering has occurred. Using the data from the input file, gemc takes parameters such as a particle's momentum vector and simulates each particle traveling through the detector.  Every

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[7] All we care about is the proportion of thrown events to detected events, so the total number of events will only affect the error of this calculation.

time a particle interacts with part of the detector in the simulation gemc determines what signal, if any, the detector would send. Thus if Cherenkov radiation was created as the simulated particle stepped through the Cherenkov counter, gemc would create the same signal in our data as if a real particle had created Cherenkov radiation in the real Cherenkov counter.

Simulating the entire detector simultaneously can make each event take a very long time. Certain components, such as the electromagnetic calorimeter, add more time to the simulation than others, so being able to simulate just the components of the detector we are interested in is important. To achieve this we use a gcard. The gcard is a specifically formatted file describing the components of the detector gemc should include in the simulation. Before the simulation begins, gemc reads the gcard and downloads the geometries of the specified components from a database at jlab. Since gemc uses this central database, should the design of a component change, by redefining its geometry at the database everyone's simulations will use the new correct design.

After simulating each event gemc creates a data file containing all the signals the detector would output for each event. The output from gemc is in EVIO format, and must be converted before we can use our reconstruction software. We use evio2root to translate the data from EVIO banks into ROOT trees. ROOT is a software package developed by CERN and used for data analysis. It contains powerful tools for analyzing and graphing large quantities of data efficiently. This makes it perfectly suited for dealing with the large amount of events we simulate.

### *Socrat*

Next we must reconstruct each event using only the simulated signals from the detector. Event reconstruction means determining the initial angles and momenta of the scattered particles in the event. To reconstruct we use a piece of code called Socrat which runs within ROOT. Originally Socrat only reconstructed electrons, and so we modified it to reconstruct neutrons as well.

Taking the initial momentum vector of the reconstructed electron, we then determine the neutron's initial momentum after scattering. Since the neutron has no charge it is not affected by the magnetic field within the detector, and travels in a straight path until it collides with something. Thus after determining its initial momentum, we can trace the path of the neutron through the detector and predict where the neutron should interact with the TOFs.

The TOFs do not cover the full phi range, and are separated into 6 identical sections that each cover approximately one sixth of the range. This means that even if an electron is detected in the TOFs, the corresponding neutron might travel through a small section of the detector not covered by the TOFs (see figure 2B). I added a function to Socrat called NeutronTracking which checks if the neutron would hit the TOF based on the electron's scattering momentum using the line-plane intersection formula[8]. If the neutron would not hit the TOFs the event is thrown out. If the neutron would hit the TOFs we say we have a “found neutron,” and that neutron detection is possible for this event. If we have a found neutron, its momentum along with the electron’s momentum, any hits present in the TOF and other information is stored in a ROOT data tree and exported for final analysis.

The first detector component that neutrons may interact with is the TOFs. The neutron can’t ionize molecules in the scintillator (the main method of scintillator detection), but instead must hit an atomic nucleus in the scintillator to cause an excited state which will then decay. This means that the efficiency of detecting neutrons is much less than that of detecting charged particles such as protons and electrons. Using the ROOT tree output by Socrat, our next step is to look at all the hits in the TOF for the event and determine if one of them was the neutron. I wrote a routine that calculates the position vector of each hit and the momentum vector of the neutron. Using these vectors we can determine the angle between the neutron path and the hit using equation 2, which is a rearrangement of the definition of the vector dot product.

EQUATION 2: $$\frac{NuetronMomentum * HitPosition}{|NeutronMomentum||HistPosition|} = Cos[\gamma]$$

where gamma is the angle between the neutron momentum and the hit position vector. The smaller gamma is the closer the neutron path is to the path of a particle.

Next I applied cuts to each hit detected in the TOFs to determine if the hit is a neutron. I looped through each hit and first check if gamma is less than 10 degrees. Then I checked the energy deposited in the TOFs for the hit. Low energy deposited corresponds to light background particles passing through the scintillator. By requiring the energy deposited to be 5.0 MeV most of this background can be removed. If the hit passes both of these cuts then the hit was the neutron. We call this a reconstructed neutron. The NDE is the ratio of reconstructed to found neutrons.

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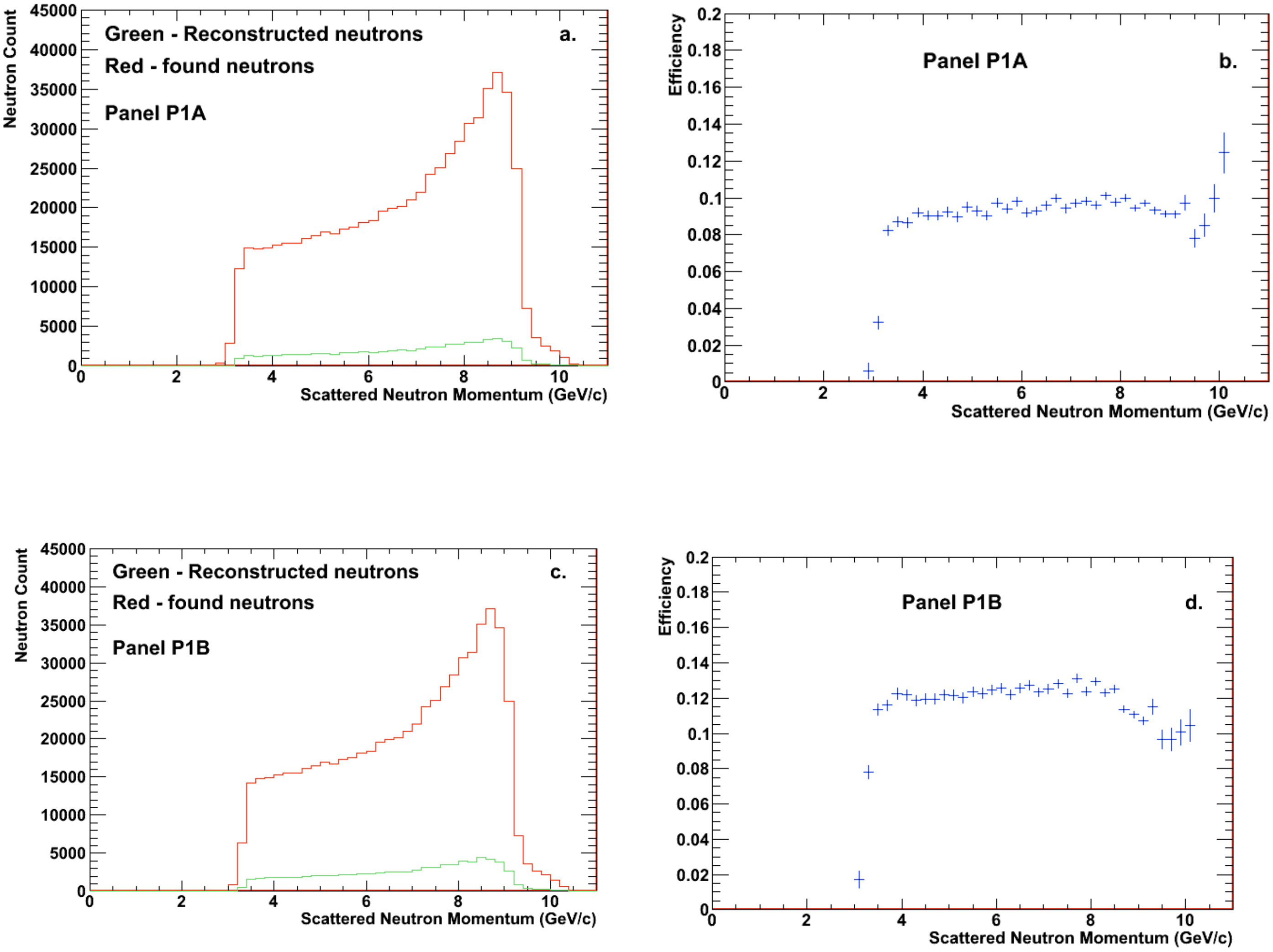
[8] http://en.wikipedia.org/wiki/Line-plane_intersection

# RESULTS

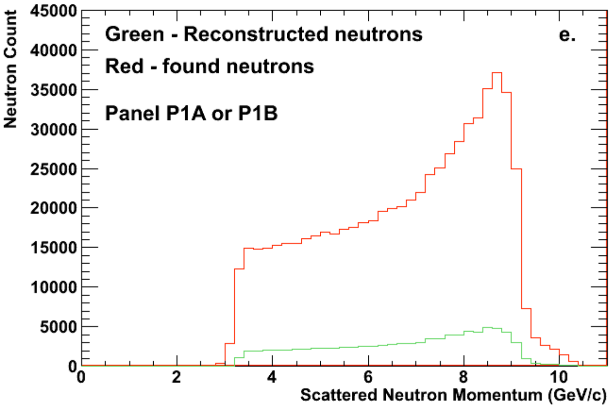
Below are the results for the NDE for panel P1A. Plot a shows a comparison of found and reconstructed neutrons compared to scattered neutron momentum, which is dependent on scattering angle. Plot b shows NDE compared to scattered neutron momentum. This was obtained by dividing the number of reconstructed neutrons by the number of found neutrons for each bin. We obtained an average efficiency of 10% across all momenta. The lack of data at low scattering momentum is due to the scattered electron having a large momentum and low scattering angle. The electron scattering angle is too small to hit the detector, which can detect particles down to a theta of 5 degrees, so these events are discarded.

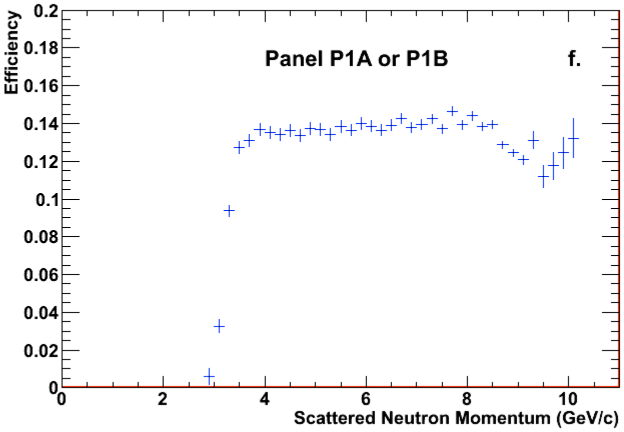
Figure 6: CLAS12 NDE



Similarly, plots c and d are for panel P1B. Notice that the efficiency is higher than P1A. This is due to the way neutrons are detected in the scintillator. For a neutron to be detected it must collide with a molecule in the scintillator, and this creates a spray of particles. This spray contains charged particles which can be easily detected. Since P1B is behind P1A, the spray created by the neutron in P1A is detected by P1B. Indeed, almost all neutrons detected in P1A are also detected in P1B.

Plots e and f show data where a neutron was reconstructed in either P1A or P1B. This is the actual NDE of the TOFs. We have found that the efficiency is about 13.5% over all momentum ranges. This value is dependent on values such as the gamma cut and energy deposited cut. We are confident in our gamma cut, and will use the same energy deposited cut as CLAS, which used some of the same panels.

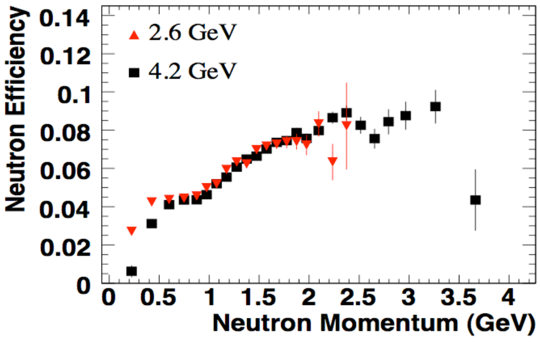




# CONCLUSION

Our simulated value of NDE is a preliminary estimate, and it agrees with our prediction and with CLAS data. Below is a plot showing the measured NDE of CLAS' TOF with 2.6 and 4.2 GeV beam energies. Our simulated beam energy was 11 GeV, but the efficiency is similar to ours at 3-4 GeV neutron momentum for panel P1A, which was used in CLAS. Thus we are confident in our simulated values for CLAS12 neutron detection efficiency.

Figure 7: CLAS NDE [3]



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