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GEANT SIMULATIONS OF PRESHOWER CALORIMETER FOR CLAS12 UPGRADE OF THE FORWARD ELECTROMAGNETIC CALORIMETER

Kristin Whitlow and Stepan Stepanyan

ABSTRACT

Hall B at the Thomas Jefferson National Accelerator Facility uses the CEBAF (Continuous Electron Beam Accelerator Facility) Large Acceptance Spectrometer (CLAS) to study the structure of the nucleon. An upgrade from a 6 GeV beam to a 12GeV beam is currently planned. With the beam energy upgrade, more high-energy pions will be created from the interaction of the beam and the target. Above 6GeV, the angle between the two-decay photons of high-energy pions becomes too small for the current electromagnetic calorimeter (EC) of CLAS to differentiate between two photon clusters and single photon events. Thus, a preshower calorimeter will be added in front of the EC to enable finer granularity and ensure better cluster separation for all CLAS experiments at higher energies. In order to optimize cost without compromising the calorimeter's performance, three versions of the preshower, varying in number of scintillator and lead layers, were compared by their resolution and efficiency. Using GSIM, a GEANT detector simulation program for CLAS, the passage of neutral pions and single photons through CLAS and the new preshower calorimeter (CLAS12 EC) was studied. The resolution of the CLAS12 EC was calculated from the Gaussian fit of the sampling fraction, the energy CLAS12 EC detected over the Monte Carlo simulated energy. The single photon detection efficiency was determined from the energy and position of the photon hits. The fractional energy resolution measured was $\Delta E/E$ = 0.0972 in the five-module version, 0.111 in the four-module version, and 0.149 in the three-module version. Both the five- and four-module versions had 99% single photon detection efficiency above 0.5GeV while the 3 module version had 99% efficiency above 1.5GeV. Based on these results, the suggested preshower configuration is the four-module version containing twelve layers of scintillator and fifteen layers of lead. This version provides a reasonable balance of resolution, efficiency, and cost. Additional GSIM simulations will be undertaken to verify that the four-module version has acceptable π° mass reconstruction and to continue Research and Development (R&D) analysis on the preshower calorimeter.

INTRODUCTION

The Thomas Jefferson National Accelerator Facility (Jefferson Lab) in Newport News, Virginia currently uses the Continuous Beam Electron Accelerator Facility (CEBAF) to send a 6GeV beam of electrons to three experimental halls. Hall B uses the CEBAF Large Acceptance Spectrometer (CLAS) to study nucleon structure in multi-particle reactions. CLAS detects and measures almost all final-state particles created in collisions using multi-wire drift chambers (DC), time-of-flight scintillation counters (SC), a gas-filled threshold Cherenkov counter (CC), and an electromagnetic calorimeter (EC) [1]. A beam upgrade from 6GeV to 12GeV is currently in the planning stages for CEBAF. With the doubling of the beam energy, each of the three halls must also upgrade its detectors. While the upgraded CLAS detector (CLAS12) will utilize many of the existing detector components, major new components include superconducting torus coils, a new gas Cherenkov counter, a new vertex detector, a new DC, an upgraded SC, and a preshower calorimeter [2, 3].

The main purposes of the electromagnetic calorimeter are to measure the energy of high-energy showering particles [4], to differentiate between electrons and π^-, and between photons and neutrons [1]. Detection of photons is primarily used for π° and η reconstruction via their two photon decays. Background pions are a recurrent problem for the analysis of single photon reactions (DVCS) and must be accurately detected so that the appropriate cuts can be made to exclude them [3]. Since pions themselves cannot be detected due to their short lifetimes, their two-photon decay is used to determine their presence [3]. With the beam energy upgrade, more high-energy pions will be created from the interaction of the beam and the target. Above 6GeV, the angle between the two photons from a $\pi°$ decay becomes too small for the existing electromagnetic calorimeter to distinguish between two photon clusters and single photon events (Figure 1). Thus, an additional preshower calorimeter with finer granularity to resolve photon clusters from high-energy $\pi°$-decay is needed.

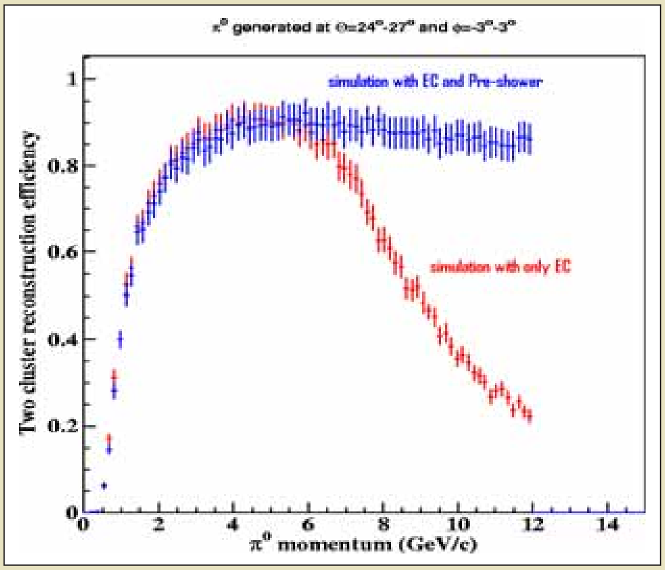

Figure 1. Two cluster reconstruction efficiency of EC with and without preshower for $\pi° \rightarrow \gamma\gamma$ for momentum up to 12GeV.

The preshower calorimeter will be positioned in front of the existing electromagnetic calorimeter, creating the CLAS12 electromagnetic calorimeter. It will have a geometry similar to the current EC: a lead-scintillator sandwich in a truncated triangular pyramid utilizing a three stereo readout system [1] (Figure 2). Each scintillator layer is sliced into a number of strips which are rotated by 120° in each successive layer [1]. The pattern is repeated every three scintillator layers, creating a module [1].

After evaluating $\pi°$ mass reconstruction and fiducial acceptance, the five-module version with fifteen layers of lead and scintillator and 108 scintillator strips per layer (Figure 3) was taken as a standard for comparison since it showed the best detection efficiency and resolution. The focus of this project was to optimize cost without compromising the calorimeter's performance by comparing the energy resolution and single photon detection efficiency of three different versions of the preshower varying in the number of scintillator and lead layers. The three-module version contained fifteen layers of lead and nine layers of scintillators with the first six layers having double lead thickness (Figure 4). The four-module version contained fifteen layers of lead and twelve layers of scintillators but with the first three layers having double lead thickness (Figure 5).

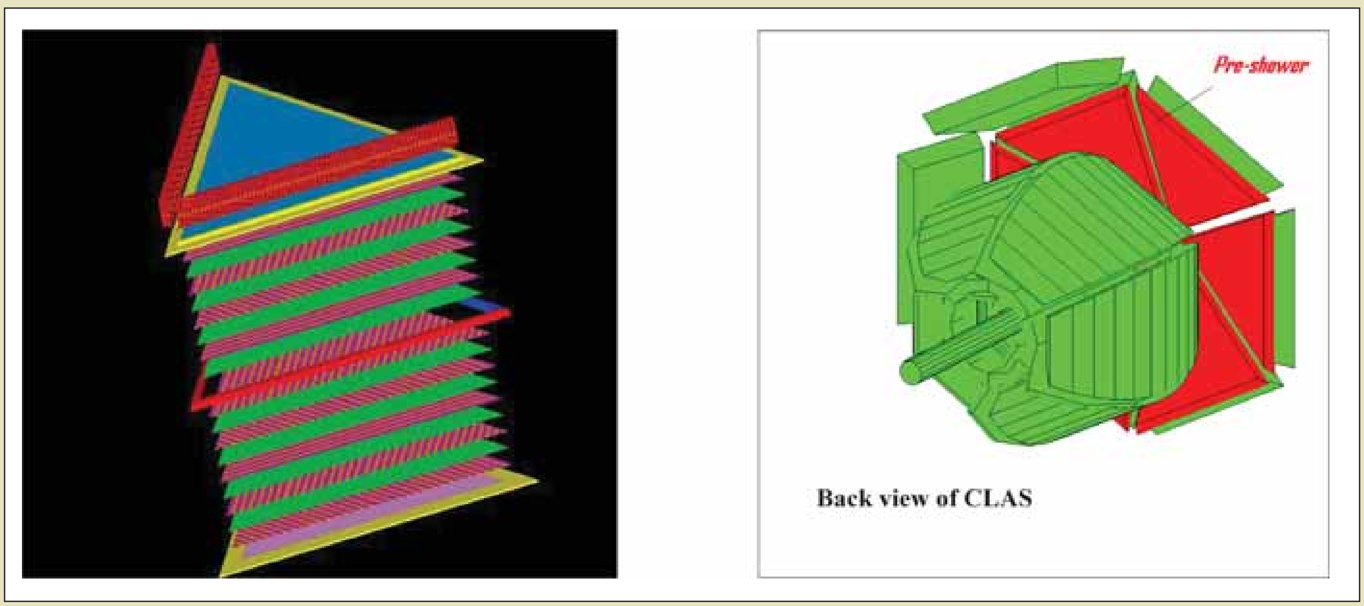

Figure 2. Preshower geometry: scintillator layers are highlighted in pink and lead layers are in green. Photomultiplier tubes will be attached to the scintillator strips by optic fibers and located behind the detector allowing the preshower and EC modules to be placed as close as possible. [1] The preshower will have the same truncated triangular pyramid design and orientation in CLAS12 as the current EC have in CLAS, positioned about 5m away from the CLAS target point.

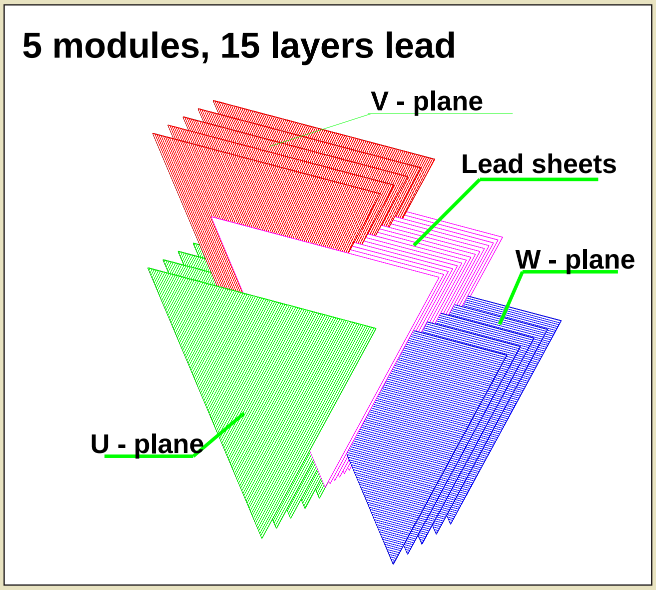

Figure 3. Five-module version with 15 layers of scintillator and 15 layers of lead.

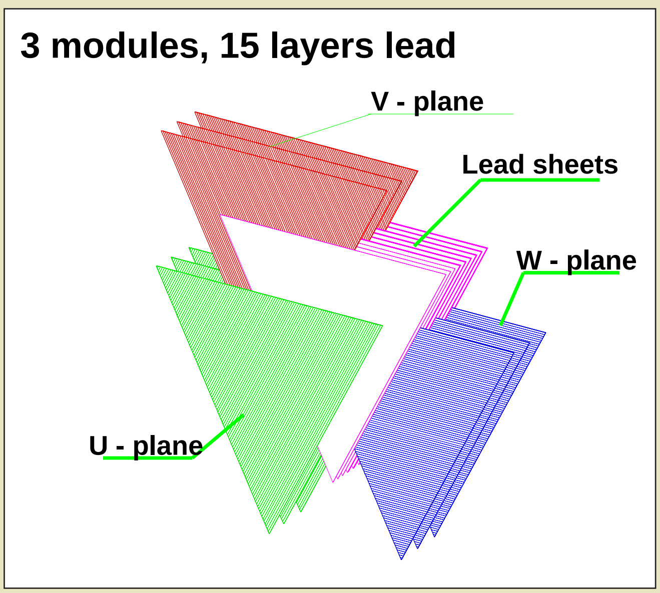

Figure 4. Three-module version with 9 layers of scintillator and 15 layers of lead. The first 6 layers of lead are doubled in thickness.

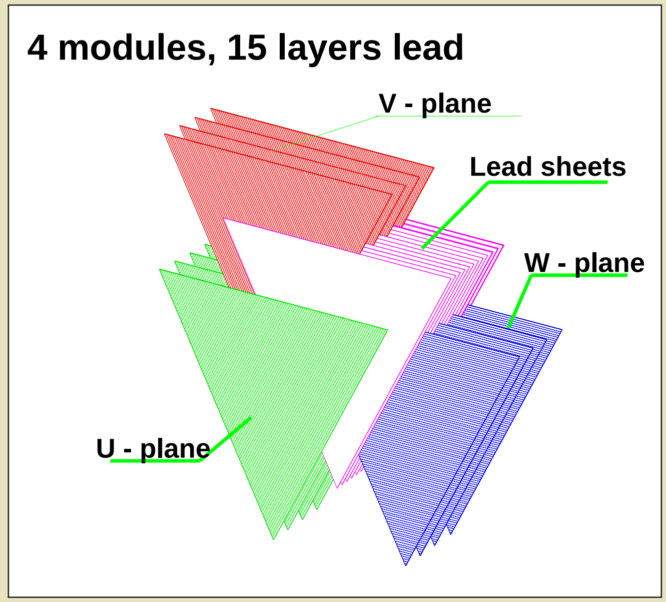

Figure 5. Four-module version with 12 layers of scintillator and 15 layers of lead. The first 3 layers of lead are doubled in thickness.

METHODS AND MATERIALS

The first task was to simulate the single gammas and π°s using a single particle generator, SPGEN. Two sets of photon events were generated, one for evaluating the fiducial acceptance and the other for efficiency and energy resolution. The single photons used to calculate the detection efficiency and resolution had a momentum range from 0 to 9GeV, a distribution azimuthal angle (ϕ) of 0°, and a polar angle (θ) of 25°. The single gammas generated for the fiducial acceptance had the same momentum range but ϕ angles from 0° to 360° and θ angles 5° to 48°. The generated π°s had a momentum range from 0 to 9GeV, ϕ range of -3° to 3°and θ angle range of 24°–27°.

GSIM code was modified to simulate the particles' passage through the CLAS detector. The files were then processed through the CLAS event reconstruction program, RECSIS, and the resulting ntuples were used to analyze the different models. Data analysis was performed using the physics analysis workstation, PAW++, FORTRAN functions, and kumac files. The same histograms were filled for each model, so comparisons between the various versions could be made easily.

π° Mass Reconstruction

The π° mass was calculated only on the five-module version because it was necessary to verify that the photon energy calibrations were correct. This was critical for comparing the energy resolutions of various models, the focus of this study. In order to determine the ability of the five-module version to reconstruct π° masses accurately, the π° mass had to be evaluated and compared with its known value. The mass was calculated from the following equation:

$$M_{\gamma\gamma} = 2E_{\gamma1}E_{\gamma2}(1-\cos\theta_{\gamma1\gamma2})$$

Where $E_{\gamma 1}$ and $E_{\gamma 2}$ are energies of decay photons and $\theta_{\gamma 1 \gamma 2}$ is the angle between the photons' momentum vectors. The only events used to reconstruct the π° mass in this study were those that contained two cluster hits that have energy in both the preshower and EC. The energies of the photons were found by adding the hit energies of each photon in the preshower and the EC and then correcting with the sampling fraction. The sampling fraction was determined from the average ratio of the detected energy and the Monte Carlo simulated energy of a photon. In principle, the sampling fraction has some energy dependence but within this study's energy range and calorimeter resolution that dependence can be ignored [3]. It is important to stress that the sampling fraction only has meaning for a single showering particle like a photon or electron. Therefore with correctly calibrated photon readings, such as an accurate sampling fraction and correctly reconstructed angles, the π° mass should be correct. The positions of the photon events were then used to calculate the angle of separation between the decay photons. From the Gaussian fit to the mass distribution, the mean was compared with the known value and checked for accuracy.

While both the angular and energy resolution of the preshower are critical in evaluating the reconstructed π° mass, the focus of this project was to evaluate the energy resolution of different models. This study is one of many that are responsible for deciding the final geometry of the preshower calorimeter and primarily focuses on comparing the energy resolution and single photon detection efficiency of different calorimeter models.

Fiducial Acceptance

The maximum acceptance range of the preshower was determined by using the five-module version and turning off the geometry of all other detectors in CLAS. The θ and ϕ angles of the photons were calculated using the positions of the hits in the lab coordinate system. Plotting the θ vs. ϕ graph revealed the range at which the photons had been detected. Then, a function that followed the edge of the distribution was found so it could be used as a fiducial cut in later analysis programs.

Energy Resolution

The energy resolution of a calorimeter is a measure of how accurately it determines the energy of a particle. Experimentally, resolution reflects fluctuations in the amount of energy the scintillators absorb. The EC used in CLAS is a sampling calorimeter; it detects or "samples" a fraction of the energy of the showering particles that pass through it [4]. The sampling fraction is the intrinsic fraction of energy the calorimeter samples. Due to the effects of electromagnetic showering, the resolution of a sampling calorimeter obeys the following equation [3]:

$$\frac{\Delta E}{E} = \frac{Const}{\sqrt{E}} \oplus \frac{a}{E} \oplus b$$

Term ***a*** is important at low energies, term ***b*** is important at high energies. In the range of energies we are interested, 1 to 10GeV, the resolution can be approximated with the following expression:

$$\frac{\Delta E}{E} \approx \frac{Const}{\sqrt{E}}$$

The energy of the photon was calculated by adding the energy of the clusters in both the preshower and the EC. Then the sampling fraction was calculated by dividing the total energy of the photon by its Monte Carlo simulated momentum. CLAS12 calorimeter's resolution was obtained by fitting a Gaussian curve to the sampling fraction distribution over several energy bins and using the corresponding sigma (peak width) and mean values according to the following equations:

$$\frac{\Delta E}{E} = \frac{\sigma}{Mean} \Rightarrow Const = \frac{\sigma}{Mean}\sqrt{E}$$

Single Photon Detection Efficiency

The single photon detection efficiency of the preshower and electromagnetic calorimeter specifies the percentage of photons the calorimeters detect at the appropriate energy deposition. For each model, this efficiency was determined by comparing the Monte Carlo momentum distribution after a cut was performed on the sampling fraction to that of the Monte Carlo momentum distribution without any cuts. The sampling fraction cut was determined by plotting the sampling fraction vs. the number of events and placing a cut at the beginning of the sampling fraction distribution.

RESULTS

π° Mass Reconstruction

In Figure 6, the reconstructed π° mass, $M_{\gamma\gamma}$, of the five-module version is shown. The Gaussian fit to the distribution had a mean of 0.131GeV and a width of 0.01340GeV.

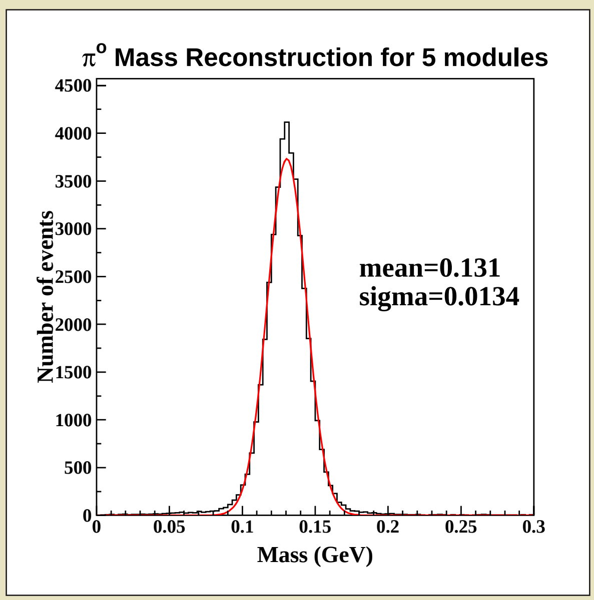

Figure 6. π° mass reconstruction from its two photon decay. The mean is the π° mass. π° momentum range from 0 to 9GeV.

Fiducial Acceptance

In Figure 7, the distribution azimuthal angle (ϕ) vs. polar angle (θ) of detected photons is shown. The proposed equation for a fiducial cut of the acceptance range is:

$$\varphi = 8.6(\theta - 6.5)^{0.27} + 4$$

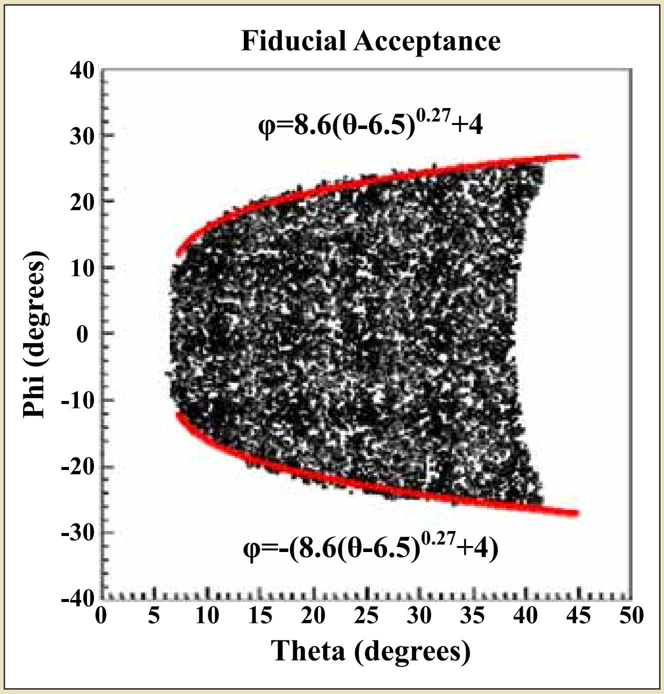

Figure 7. Fiducial acceptance range for photons detected in the pre-shower. The geometry of all other CLAS detectors is turned off. The proposed fiducial cut is the equation.

Energy Resolution

The graphs were created by plotting $\frac{\sigma}{Mean}$ *vs* $\frac{1}{\sqrt{E}}$ and the slope of the linear fit was taken as the energy resolution constant. As shown in Figure 8, the resolution measured in the five-module version was 0.972E-01+/-0.108E-02. As shown in Figure 9, the resolution of four-module was 0.111+/-0.117E-02. The resolution of the three-module was 0.149+/-0.152E-02, Figure 10.

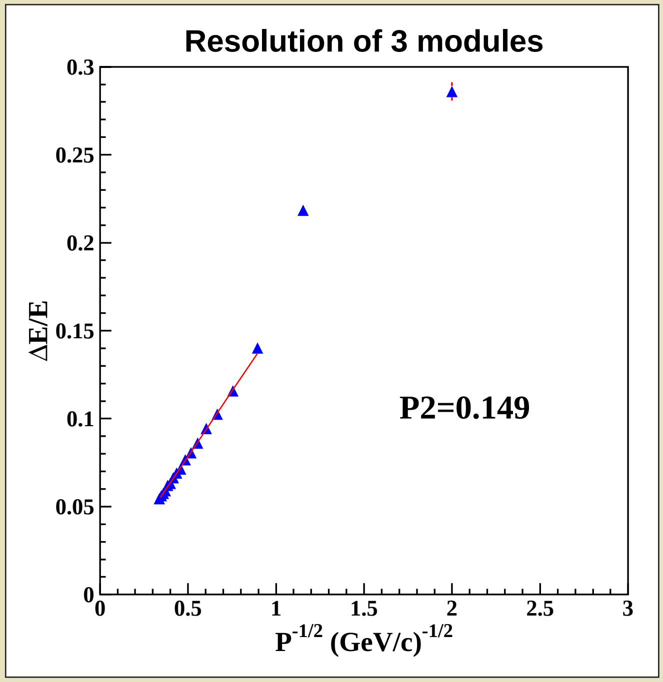

Figure 8. Energy resolution of three-module calorimeter. The slope, P2, is constant term.

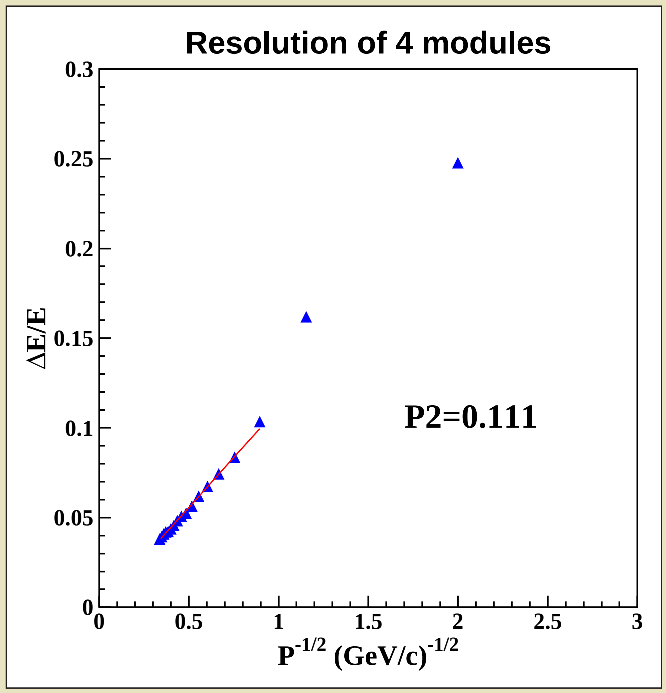

Figure 9. Energy resolution of four-module calorimeter. The slope, P2, is constant term.

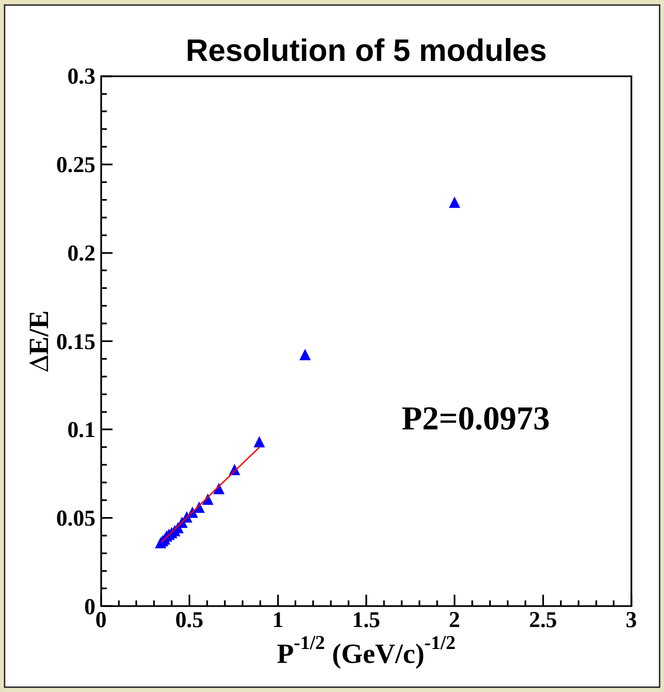

Figure 10. Energy resolution of five-module calorimeter. The slope, P2, is constant term.

Single Photon Detection Efficiency

The same sampling fraction cut, above 0.15, was applied to all versions. Both the five- and four-module versions had 99% efficiency above 0.5GeV while the three-module version had 99% efficiency above 1.5GeV (Figure 11).

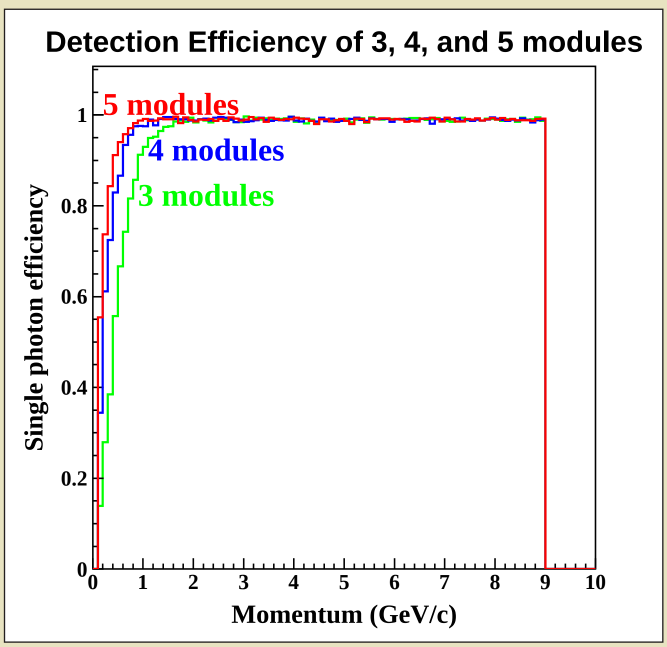

Figure 11. Photon detection efficiency for different calorimeter versions. A sampling fraction cut, above 0.15, was used.

DISCUSSION

π° Mass Reconstruction

The reconstructed π° mass was found to be 4MeV from the accepted π° mass. This can be attributed to error in the sampling fraction correction. The acceptable mean and sigma values verified that the five-module version has appropriate π° mass reconstruction and is a good model for comparison.

Fiducial Acceptance

Higher beam energies will require the CLAS12 detector upgrade to increase its detection and particle identification capabilities. This will be done many ways, including increasing the acceptance of photons and electrons to 5°–40° [2]. As seen from Figure 7, the additional surface area (5" per side) of the preshower widens the acceptance of the CLAS12 calorimeter to the specifications of the upgrade. This demonstrates that the five-module version is an acceptable standard model and that the geometry of the preshower has acceptable photon cluster acceptance.

Energy Resolution

The larger the constant term, the worse the energy resolution and the less accurate the calorimeter is at reconstructing the hit energy. The four-module version differed from the five-module version by only by 1.4% in resolution. The three-module version, however, showed a marked difference of 5% in resolution. The three-module version is not adequate because the decrease in resolution does not outweigh the saved financial cost of constructing the preshower with fewer scintillators.

Single Photon Detection Efficiency

It is believed that the depletion of low energy photons in the three-module version occurs because most of the low-energy photons lose all their energy in the first six layers of lead. In order to be reconstructed, a particle must hit all three stereo readout planes. Since the first six layers of lead have double thickness in the three-module version, many photons cannot be properly reconstructed because they do not have enough energy to reach the third stereo readout panel. In addition, fewer photons are able to hit the second set of readout panels. As a consequence, due to readout threshold, such photons will not be properly reconstructed. Failure to traverse the second set of readout panels results in a depletion of low-energy photons. In addition, the sampling fraction of the three-module version is considerably wider than either the four- or five-module version. Thus, more photons below the 0.15 sampling fraction cutoff lead to a possible depletion in low-energy photons. Although the four- and five-modules versions are almost indistinguishable, the three-module does not appear to be a good choice for the preshower geometry.

CONCLUSION

Considering there is a difference of only 1.4% in the energy resolution, and a negligible difference in single photon detection efficiency between the five- and four-module preshower calorimeters, the four-module preshower with twelve layers of scintillators and fifteen layers of lead is the best combination in resolution, efficiency, and cost. Additional GSIM simulations to verify that the four-module version has acceptable π° mass reconstruction will be undertaken, and Research and Development (R&D) analysis will continue.

ACKNOWLEDGMENTS

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