1. INTRODUCTION

An important aspect of particle physics is the detection of particles via calorimetry. Typical detectors have two types of calorimeters, electromagnetic and hadronic. Currently the energy resolution of hadronic calorimeters is poor compared to electromagnetic calorimeters due to various effects. One of the dominating effects limiting the resolution stems from the fact that as hadrons interact with nuclei in the calorimeter, they can cause nuclear breakup. In this case, the energy necessary to overcome the binding energy of the nucleus is undetectable. This leads to the fact that the energy response of a hadronic calorimeter is nonlinear and peaks below the energy of the incident hadron with a rather wide distribution.

A promising idea to improve hadronic energy resolution is dual readout calorimetry, which has been shown to be successful by the Dual-Readout Module (DREAM) collaboration [1]. Dual-readout calorimeters would provide two channels of data: scintillation and Cerenkov light [2]. Scintillation occurs when electrons are excited due to the presence of a charged particle, then de-excite, and emit photons proportional to ionization energy. Cerenkov radiation occurs when a charged particle travels faster through a medium than the speed of light in that medium. The Cerenkov energy is proportional to the electromagnetic fraction of a shower. The simulations demonstrated a clear correlation between scintillation and Cerenkov energies (see Figure 1) as expected based on the work of the DREAM collaboration [1]. The idea of a dual-readout calorimeter is based on the assumption that the ratio between the energy deposited as

Cerenkov light and the energy deposited via scintillation losses allows us to correct for the energy lost to nuclear breakups [3].

This calorimeter was implemented in this simulation as a candidate to be used as part of a detector concept for the International Linear Collider (ILC). It was implemented as a total-absorption crystal calorimeter. Such a calorimeter is now technically feasible because heavy, scintillating crystals can be manufactured allowing dual readout, while recently developed silicon photomultipliers are capable of providing readout while occupying a small volume.

This calorimeter was simulated with a Monte Carlo program, and the correlation between ionization and Cerenkov light was studied. A set of energy corrections was obtained that provided linear energy response and excellent energy resolution for pions. These corrections do not depend on the energy of the incident particle [1]. The response of the calorimeter to single particles was studied and the performance of various physics channels will be studied.

2. MATERIALS AND METHODS

Simulations were conducted using GEANT4, a C++ Monte Carlo program [4]. The simulations used the Simulator for the Linear Collider (SLIC) [7] to manage input/output as well as running GEANT4. This allowed specific parameters to be defined at runtime. The simulations used both LCPHYS and QGSP_BERT physics lists, which define the manner in which particles interact with matter. Both lists were tested because the two lists are written differently, so agreement between the results of each list would imply a higher confidence in the simulation results. Detector geometry and optical properties were defined using extensible markup language (XML) and linear collider detector description (LCDD) [5] and converted using GeomConverter [6]. LCDD files were used in the simulations because they contained both geometric and optical information.

The original XML description came from a predefined detector called SiD01, which describes a simplified version of the SiD experiment. The calorimeter portion of the detector was modified to match the new design. The geometry was cylindrical, with the calorimeter made of crystal divided into layers. The layers are 6 cm thick in the electromagnetic calorimeter and 10 cm thick in the hadronic calorimeter.

In the simulation, particles were fired through the calorimeter to test the design. Initial simulations used electrons and pions at 2, 5, and 10, and 100 GeV. The crystals for the calorimeter were defined as Bismuth Germanate, $Bi_4Ge_3O_{12}$ (BGO) and Lead (II) Tungstate, $PbWO_4$. 100-GeV electrons were used to define the energy scale. Using the correlation between scintillation and Cerenkov radiation, functions to make energy corrections were implemented in the code.

The analysis was done in JAS3 [8], a Java-based analysis framework. Using pre-written classes, Java code was used for data analysis. Because electrons have high resolution, their energies are well measured by the calorimeter. We used their observed energy to shift the scale of observed energies closer to true incident energies, as follows:

$$A_S = E_{Ie} / \langle S \rangle$$

$$A_C = E_{Ie} / \langle C \rangle$$

where A_S and A_C are the scaling coefficients for scintillation and Cerenkov energies for electrons, respectively. E_{Ie} is the incident energy of the electron, and $\langle S \rangle$ and $\langle C \rangle$ are mean values of observed scintillation and Cerenkov energies, respectively. Then, for hadrons:

$$S' = S * A_S$$

$$C' = C * A_C$$

Then, S' / E_{Ih} is plotted as a function of C'/ S' (see Figure 2) where E_{Ih} is the incident energy of the hadron. This curve, f, is independent of incident energy [1]. Thus, when the curve is fitted, it can be used to obtain E_{Ih}.

$$f (C'/S') = S'/E_I$$

$$E_I = S' / f (C'/S')$$

3. RESULTS

Examining 10-GeV pions before energy corrections, the mean of the distribution was 7.48 GeV. After applying the correction as described above, the mean shifted to 9.78 GeV (see Figures 3 and 4). In BGO, the electron energy distribution had a standard deviation of 0.047 at 100 GeV while pion distributions at 100 GeV had a standard deviation of 2.81. Similar results were obtained when using different physics lists, different optical properties, and different incident energies.

4. DISCUSSION AND CONCLUSION

The focus of the project was to ensure that a dual-readout, total-absorption calorimeter is plausible, as well as checking the reliability of the software and analysis that we used to simulate the detectors.

The calorimeter demonstrated good energy resolution and response after the energy correction was applied. The results indicate that a total absorption dual readout calorimeter is possible. Similar results can be obtained with different physics lists and different optical properties, implying a high level of confidence in the detector design.

5. FUTURE WORK

Simulations will be conducted in order to study the energy resolution as a function of calorimeter depth by varying the incident beam angle. Resolution will also be examined as a function of a cross-calibration constant to determine the effect of noise and calibration error. In addition, jet and shower reconstruction algorithms will be implemented in the detector. Other crystals will be simulated in the detector. Finally, the entire detector will be tested using a well-understood physics process, such as $Z \rightarrow q\ \bar{q}$ and $W \rightarrow q\ q$.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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FIGURES

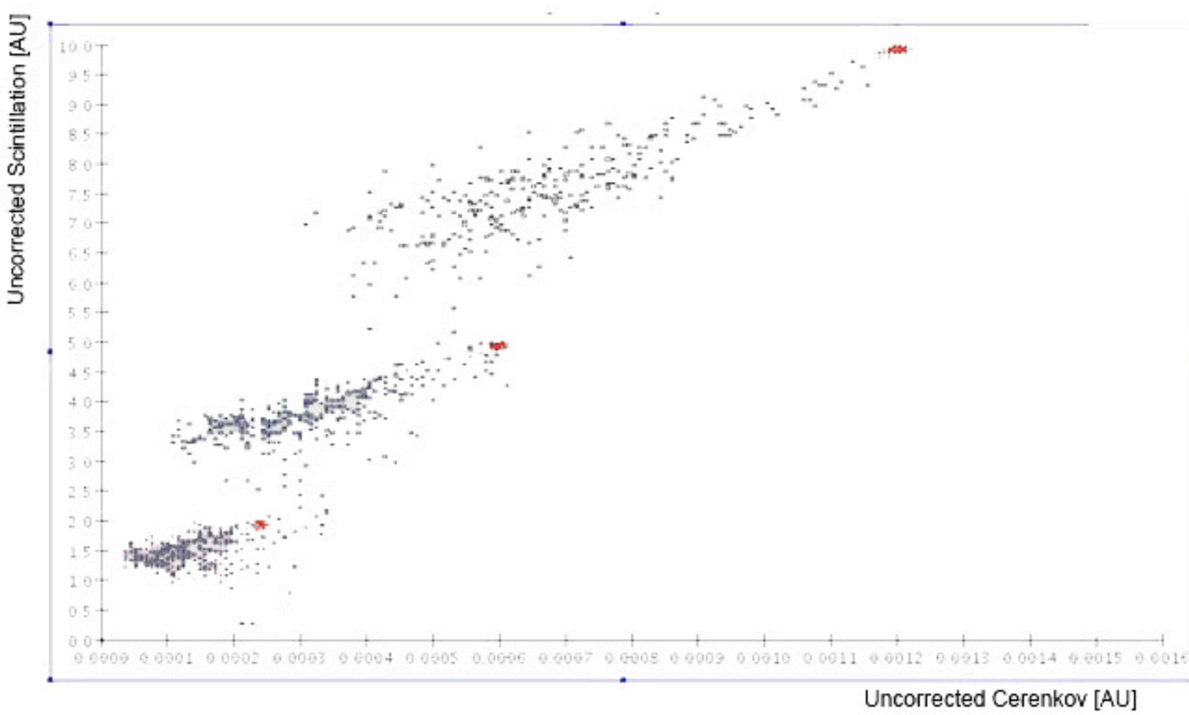


Figure 1: This demonstrates the correlation between scintillation and Cerenkov energies. Each dot represents an event. This plot shows electrons (red) and pions (gray) at 2, 5, and 10 GeV. Note the size of the distributions of electrons compared to the large spread of pions.

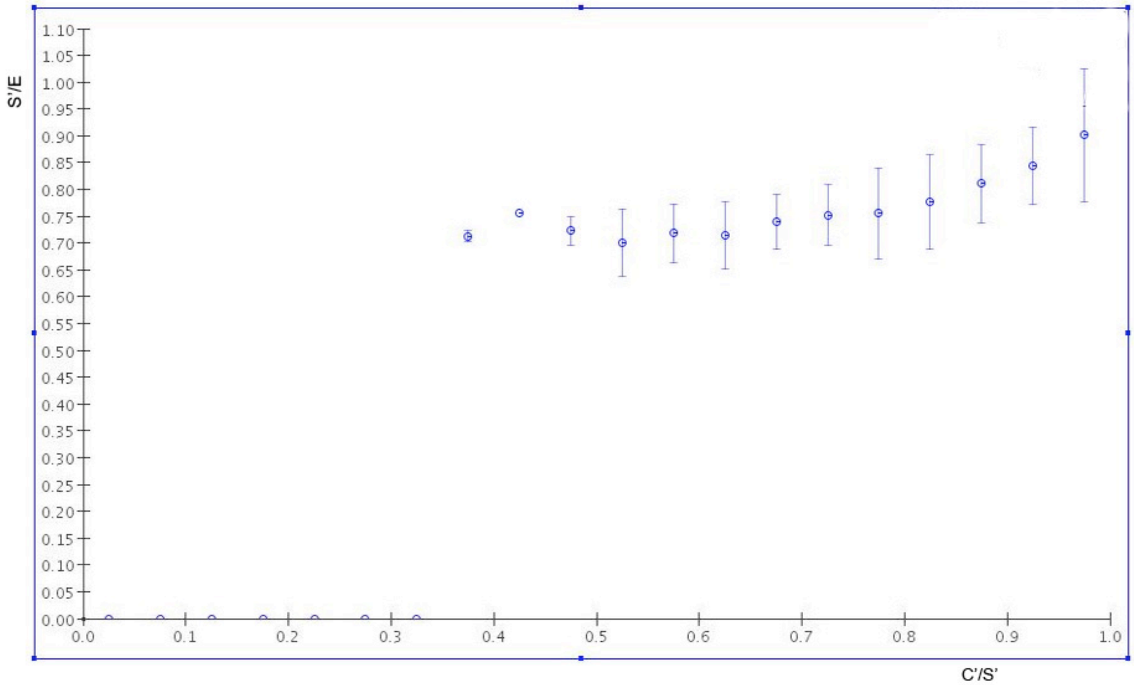
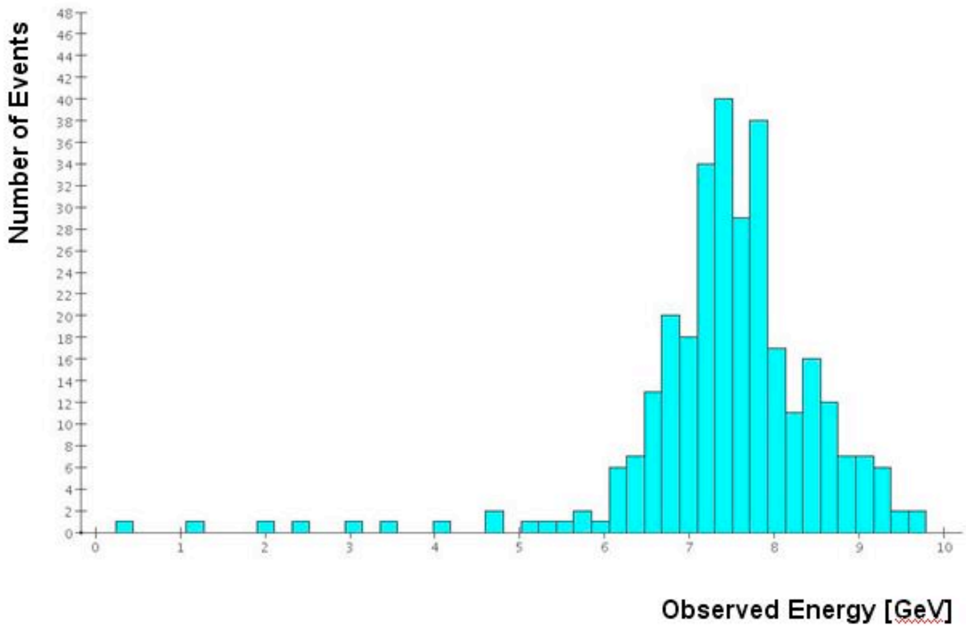


Figure 2: This shows S'/E_I as a function of C'/S'. This curve is the same for all energy levels, allowing corrections for E as a function of C' and S'.

(a)



(b)

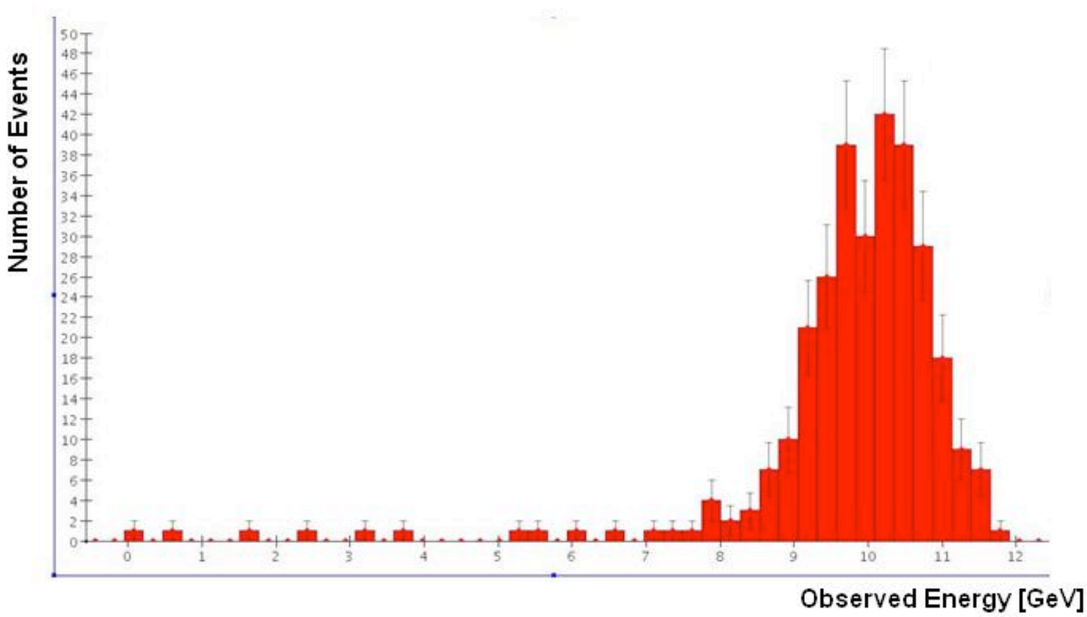
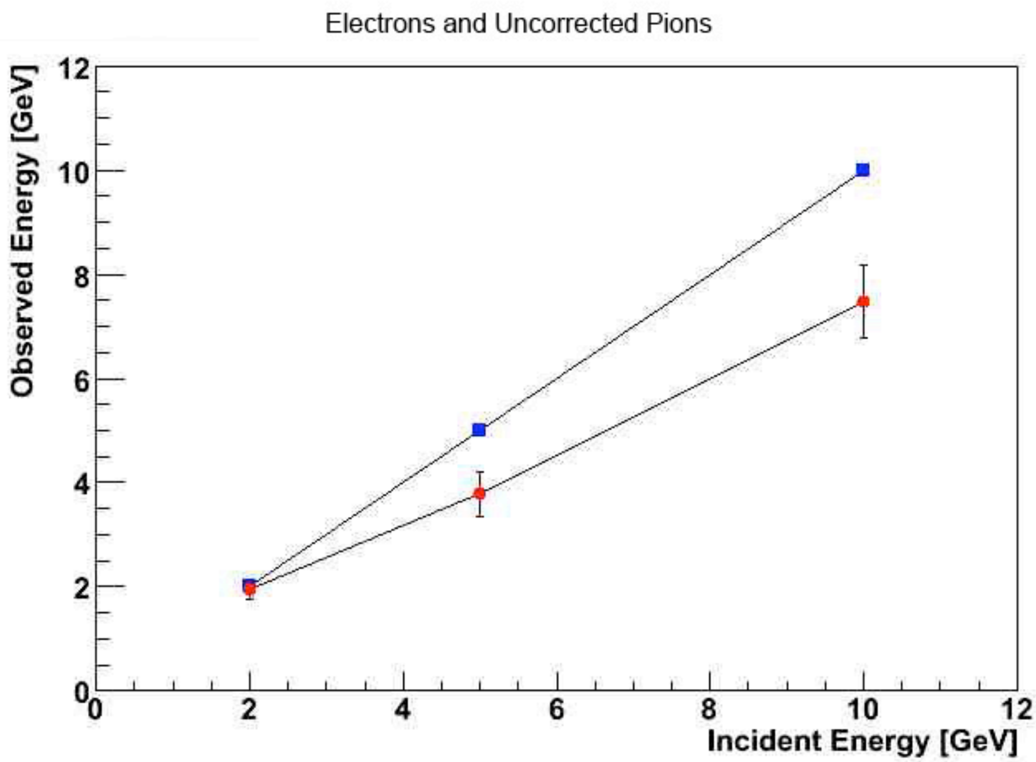


Figure 3: (a) The energy distribution before energy corrections are applied for 300 10-GeV pions in BGO. The mean is 7.48 and standard deviation is 0.70. (b) The energy distribution after corrections is applied. The mean shifts to 9.78 and standard deviation is 0.72.

(a)



(b)

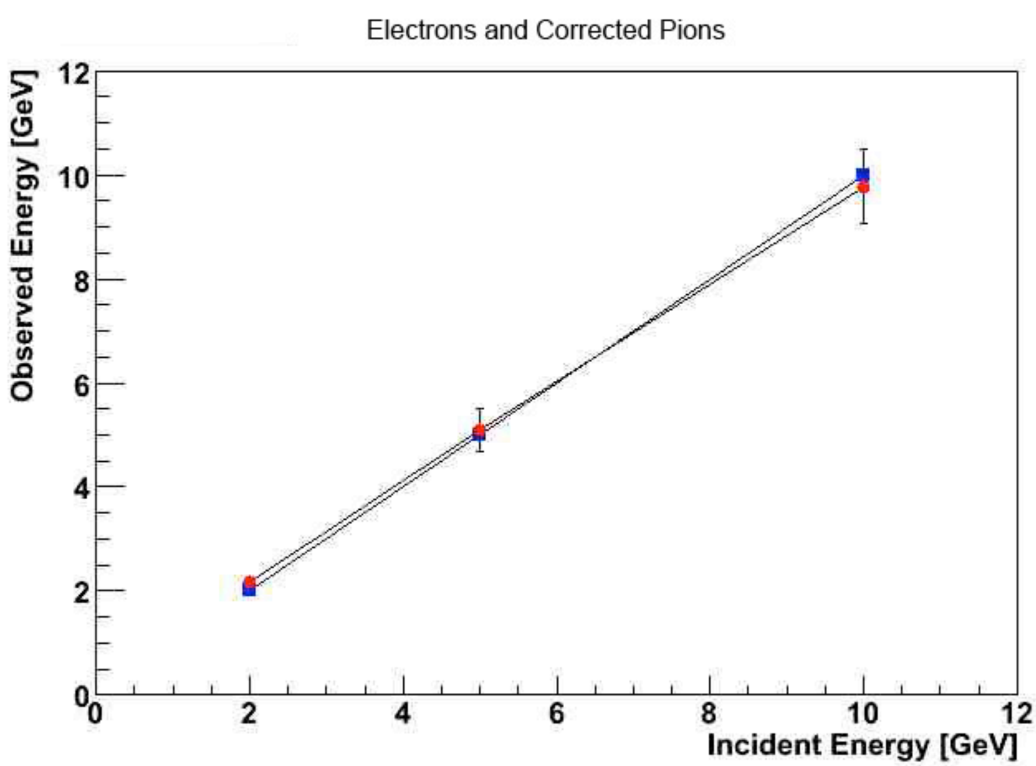


Figure 4: This demonstrates the effect of applying the energy correction. The mean shifts pions (red) closer to electrons (blue).