CALORIMETRY FOR FUTURE LEPTON COLLIDERS

SIST Program Final Paper

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The possibility of finding new physics on the Large Hadron Collider (LHC) in CERN requires us to be prepared to follow up with any type of research to keep learning about our universe. The LHC is limited by the nature of the proton-proton collisions to collect precise data. Today, several projects for new types of lepton colliders are emerging. These types of colliders are more precise since they collide elementary particles. These accelerators will require precise calorimeters capable of getting the most out of the collected data. In this project we simulated a dual readout detector to study the results obtained while applying a dual readout correction, a timing correction, and the development of response and resolution as a function of windows of time. The results were satisfactory although they will be determinant depending on the kind of particle accelerators used. On one hand, the dual readout correction increased the energy resolution for pions. On the other hand, the time of flight correction was successfully used to calculate response and resolution for pions and electrons. We learned from this project that dual readout calorimeters are fast enough to gather meaningful information from a lepton collider and its limitations will depend on the nature of the materials used to build it and the particles that will be collided in the accelerators.

1. Introduction

With the development of new technologies yielding towards new discoveries within the realm of high energy physics, the necessity for learning more about the building blocks of the universe increases. Scientists around the globe are working together in order to find answers for several questions about the universe. The development of powerful particle accelerators such as the LHC and Tevatron has increased our knowledge about a small part of the building blocks of the universe. But this is not enough; the increasing clues over the last decades about the existence of dark matter, dark energy and other kind of new physics require us to expand the possibilities of our current theories and back them up with meaningful research to help us deeply understand these realms of nature. Particle physics research in the future will be focused towards lepton colliders, which will uncover several unknowns and new physics. The most popular projects for a new lepton collider are the International Lineal Collider (ILC) and the Muon Collider.

Linear colliders are important because they will make more precise measurements of particles. Currently, the LHC is the most energetic accelerator in the world, and it encloses a large range of energies to study. However, its main purpose is to collect data that will lead us towards new physics. In brief, the LHC is limited by the nature of its design and can go only so far to study the details of the new process being discovered. Lepton colliders are important because they will be smashing leptons, and the physics describing the collisions is more localized and easier to study. It will be a better way to know about nature. For example, the ILC is a project developing the design and construction of a new particle accelerator. This accelerator will smash electrons with positrons at energies of 500 GeV. We do not know exactly what kind of new physics a lepton collider will reveal, but they are projected to answer certain questions. These questions involve details about the nature of dark matter, the existence of extra dimensions, the possibility of proving unifying theories of forces, and an explanation for the predominance of matter over antimatter. In addition, it will also be able to find the Higgs boson[1].

Some of the benchmarks for a new lepton collider are to be able to differentiate the energetic bi-jets of the Z and W bosons, which are hard to tell apart from data collected in current accelerators. The Z and W bosons are elementary particles that produce the weak force interactions in the nucleus of an atom. Another challenge for this type of colliders arises in the case of a muon collider. A muon half-life is of about 2 microseconds, and it is a highly penetrating particle. This means that we have to deal with high amounts of background radiation. However, this background comes in a timely basis, and we can get rid of most of it by making cuts of time and collecting most of the data as fast as possible. Nevertheless, timing is an important detail that we have to take care of in any type of detector. Fast timing will reduce the amount of time spent to make a new discovery when combined with high resolution for the detector. Resolution is especially important because it can help us differentiate one particle from another one.

In this project we will be using a dual readout calorimeter. A calorimeter is a device that measures the amount of energy

[1] linearcollider.org

absorbed by a certain material whenever an energetic particle passes through it. The calorimeter used in this project measures the amount of scintillation and Cerenkov photons produced. Scintillation is a measurement produced by pair production and Bremsstrahlung. Cerenkov radiation is light produced in the relativistic part of the shower. This means that when light changes medium, it actually travels faster than the speed of light. This creates a flash of light that is comparable to a sonic boom in sound. The actual physical processes that explain Cerenkov radiation are out of the scope of this paper.

The motivation of this project comes from the necessity of identifying the advantages and limitations for a dual readout detector. This detector will be used in a new lepton collider that will follow up with discoveries made on the LHC. During the project, different ways of constructing the detector were studied in order to find the best and fastest simulation. Once the best geometry construction was found, the simulated detector was used to test correction functions to overcome the hardware and physical processes limitations. We were also interested in resolution and timing details that different materials used in the detector can handle. For this reason we studied two correction parameters. A correction that will enhance the output energy resolution of the signal, and another correction for the flight time of the particle. These details will help us understand how the particle showers develop and create more adequate equipment and correction algorithms to achieve our goal.

2. Methods

The dual readout calorimeter project was developed under the operative system of Scientific Linux (SLF) release 5.5. The geometry and physics lists were done with the physics toolkit Geant4.9.4.p01 which also models the passage of particles through matter. Root 5.28/00d was used to create the histograms and the statistical analysis. The software gcc 4.1.2 also was used and the high energy physics library CLHEP 2.1.0.1. All these software are based on c++.

The detector model is called DRCal, which is a dual readout calorimeter made of a cube of BGO crystal (Density of 7.13 g/cm^3) of 5cm each side, and a thin square sheet of silicon detector (Density of 7.13 g/cm^3) with a thickness of 0.3 mm placed in front and behind the cube (See figure 1). This detector cube was duplicated across the x, y and z axis 30 times. The calorimeter modeled the decaying of particles with the QGSP_BERT physics list from the Geant4 package. BGO crystals are sensitive to scintillation and Cerenkov photons while silicon is just sensitive to scintillation.

Figure 1. Figure of a single calorimeter cube of BGO (gray) and silicon (red)

The simulation was run with different amounts of electrons and pions. There were usually 4000 electrons and 2000 pions used, both at 15 GeV. Simulations from this project using other parameters will specify their ranges. Within the simulation, these particles were always shot towards the origin, at a distance of 200 cm from the center of the cube in the Z axis. The side of the detector was at 76.8cm (see figure 2). Different parameters were manipulated from the stepping and stacking action of Geant4. The tracking action creates the particle and gives information about its position, time and static information. The stepping action contains information about the change of state of the particle, e.g. it measures time of flight, amount of output energy, etc. In this simulation we measured the amount of energy deposited on a specific interval of time and over the entire event of the electron and pion showers. The integration curves showed in this paper were coded for a root macro. We also worked with the resolution and response of the shower with different integrating windows of time by applying a Gaussian fit in Root. In addition, we tested a dual readout correction from the energy deposited and amount of Cerenkov photons.

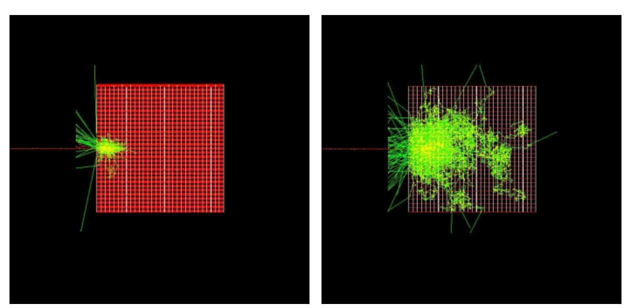


Figure 2. Side view of the development shower of a single event for an electron (left) and a pion (right)

3. Results

The simulation project studied aspects that could be helpful in the design for a future lepton collider. We started with a dual readout correction that is intended to increase the output resolution for pions. We also studied the time of flight correction for the data. This will be helpful in the design for a muon collider since it analyses the speed of the shower development. Finally, we used this information to study the evolution of the response and resolution as a function of time windows for showers of electrons and pions.

A. Dual readout correction

It has been proposed that the energy resolution can be increased by using a correction function that takes advantage of the scintillation and Cerenkov radiation information. Calorimeters used in this detector are able to measure both of these processes. Data from electrons is best to calibrate the system since the resolution for electrons is almost perfect and there are fewer losses of energy. For this calibration we used 4000 electrons at 15 GeV. Then, we measured its mean output energy and the mean of energetic Cerenkov photons produced. Refer to picture 3 and 4.

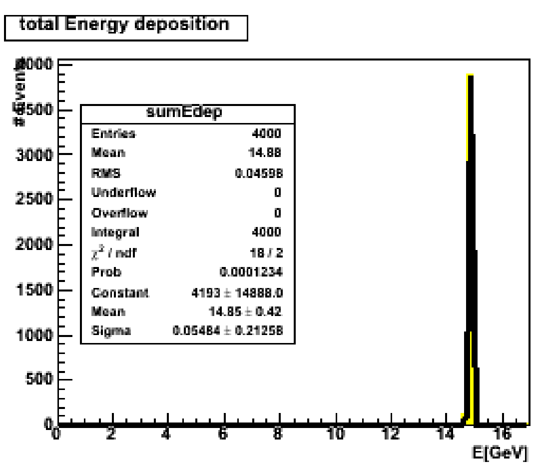


Figure 3. Graph of the total energy deposition. Notice that the mean from the Gaussian is 14.85 GeV

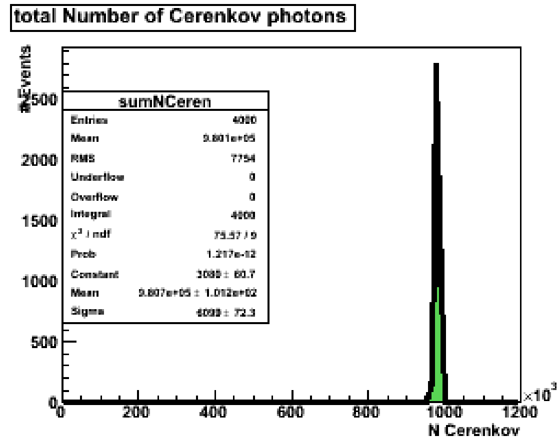


Figure 4. Graph of total number of Cerenkov photons. Notice that the mean is 9.801E5 Cerenkov photons

As mentioned before, the correction is done by combining information obtained from the shower development of electrons, and then used to correct the data obtained from the pions. Since electrons deposit almost all of their energy into the crystal, we can get a correction factor out of the mean of the energy. This correction factor comes from the fact that the input energy is equal to the output energy times a constant factor (or $E_{in} = C_S \cdot E_{out}$). We can get the same type of constant factor for the Cerenkov photons produced by electrons. The input energy is equal to the number of Cerenkov photons produced times a constant (or $E_{in} = C_C \cdot N_{Cerenkov}$).

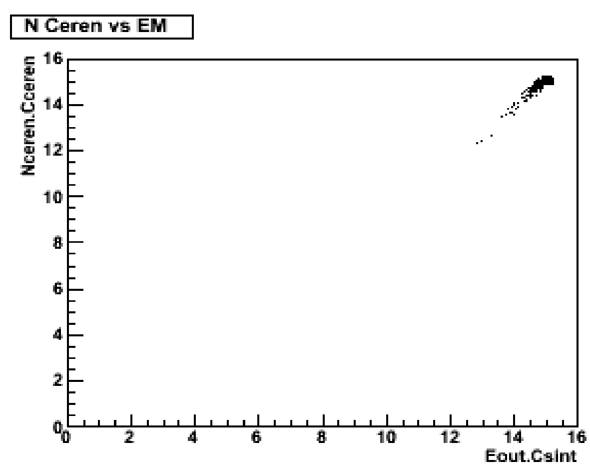


Figure 5. Graph of the corrected values of Cerenkov photons vs energy output for 4000 electrons at 15 GeV

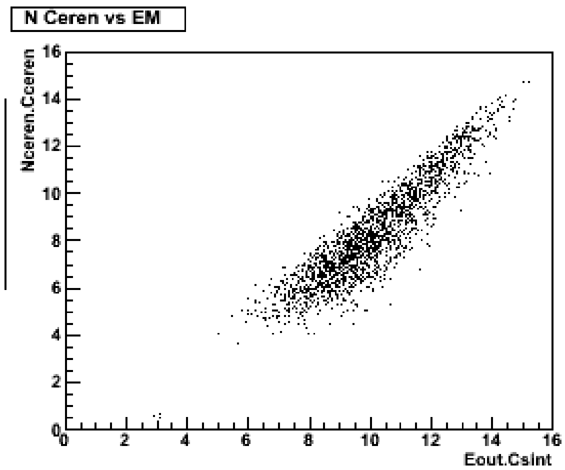


Figure 6. Graph of the corrected values of Cerenkov photons weighted by energy output for 2000 pions at 15 GeV

After we obtain the correction factors, we can plot this corrected information. Refer to figure 5. Electrons show a localized amount of energies. It is also important to notice that the maximum number of corrected Cerenkov photons produced equals the input energy. This information is equivalent to the output energy, which happens to be 15 GeV as well. Now refer to figure 6. It is noticeable that there is a trend. When the output energy is low, the number of Cerenkov photons produced is also low. The same is true when the output energy is high. This behavior suggests that we can correct the information for pions even further. The growth is not linear, so we can fit a 2nd degree polynomial function to the data in order to obtain further correction parameters. Figure 7 shows the data normalized and fitted with a 2nd degree polynomial.

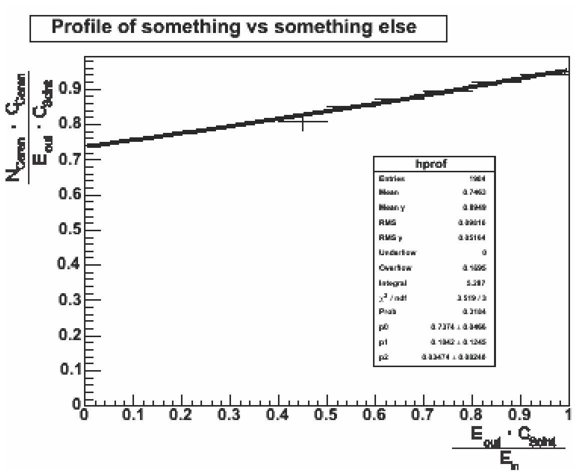


Figure 7. Graph of polynomial function fitted to enhance the final resolution of pions

The normalization was done by plotting $C_C \cdot N_{Cerenkov}/C_S \cdot E_{out}$ vs $C_S \cdot E_{out}/E_{in}$. The ratio of these values represents the electromagnetic fraction of visible light, and we can use it to increase the resolution of the collected data.

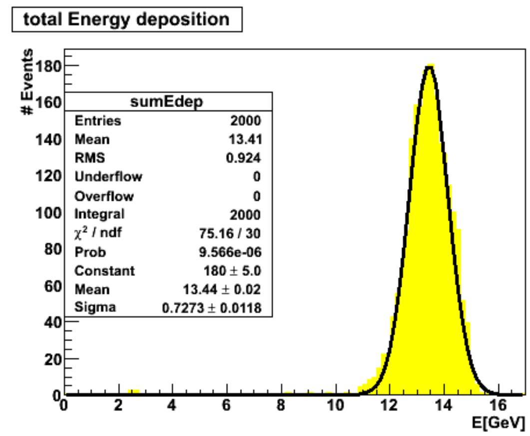


Figure 8. Graph of the output energy of pions without fitting

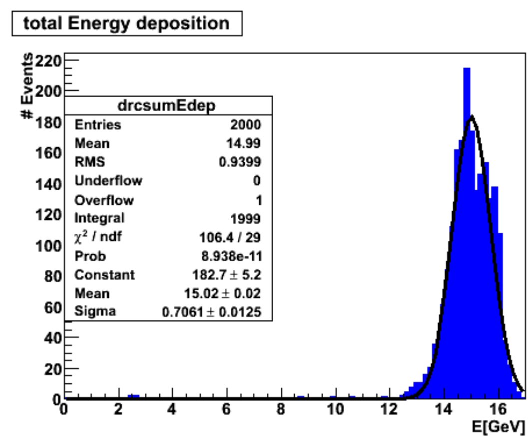


Figure 9. Graph of output energy of pions with fitting

Now we have everything to make a dual degree correction. In Figure 8 we can see the data collected without any type of correction. Notice that it has a mean of 13.44 GeV and a Sigma of 0.73. Corrected data is shown in figure 9. Notice the mean of the output energy is 15.02 GeV and the sigma has decreased to 0.71. This means that the resolution increased! We will explain the details of how resolution is calculated in part E.

B. Time-of-flight correction

The Time-of-flight correction lets us see how fast the shower develops. In other words, we can study the time of the reaction without worrying about the time the particle is moving. This is an important measurement since, in the case of a muon collider, it is possible to reduce great amounts of background by making cuts on the detection time.

This correction is done by subtracting the global time, given by the simulation software, minus the distance divided by speed of light. The new time calculated is called t prime (t'), the global time is represented by (t_g), the distance from the gun to the deposition place by (l), and the speed of light by (c). The following formula summarizes the last description and figure 10 shows and schematic of the details.

$$t' = t_g - \frac{l}{c}$$

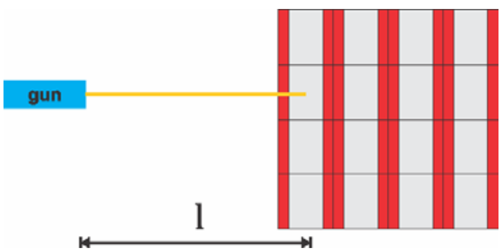


Figure 10. Representation of the time of flight correction. Detector not to scale.

This information will be useful in the next studies.

C. Time evolution of shower

As previously mentioned, in the case of a muon collider, timing needs have to be addressed in future colliders. By using the information calculated from the time of flight correction we can know how fast a shower develops. With this simulation we can precisely know how long it takes to deposit a certain amount of energy in a certain amount of time. Also, it let us know how the electromagnetic and hadronic parts of the shower developed and which one contributes more to the final energy deposition. Finally, this will let us know how fast we can make cuts of readings so we can get rid of background signal just by time cutting.

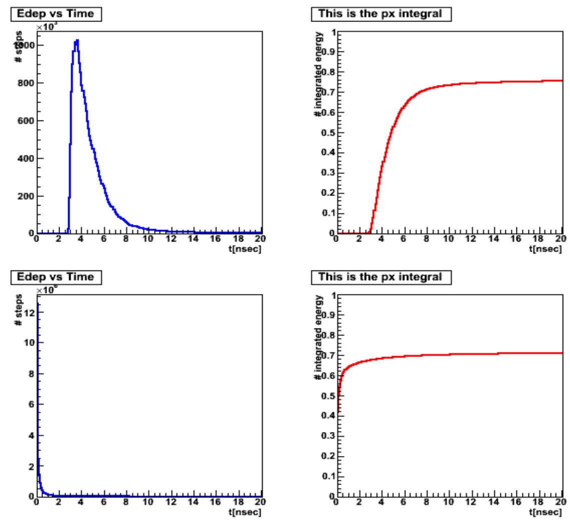
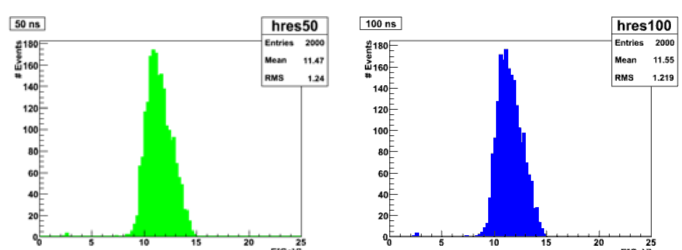


Figure 11. Graph showing the comparison of global time and time-of-flight corrected data

Figure 11 shows a group of plots that show us how the time correction looks. In the top-left a plot of the amount of energy deposited in the crystal by time is shown. The top-right graph shows an integral of the previous plot. The bottom-left plot shows the energy deposition by time, with the flight-of-time correction. The last plot shows the integral of the previous described plot. It is noticeable that the plots from the bottom develop a lot faster than plots from the top.

D. Response as a function of windows of time

Now that we have corrected time, we can use this information to study some other aspects of the shower development such as the response. The response describes how much of the total energy is detected as time passes. We use the time-of-flight correction to create windows of time more effectively. Every window of time collects the entire amount of energy absorbed by the detector in the amount of time that has passed. Figure 12 shows four of these windows of time. We can see that as time increases, the mean of output energy increases as well. However, as time increases the width described by the root mean square (RMS) decreases.



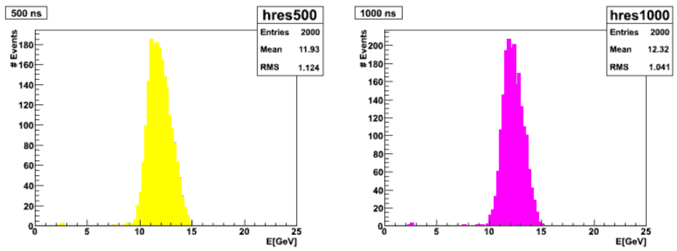


Figure 12. Response graphs for different windows of time. from top left to bottom right the times are 50, 100, 500 and 1000 nanoseconds

If we plot the information gathered for several windows of time, we obtain Figure 13.

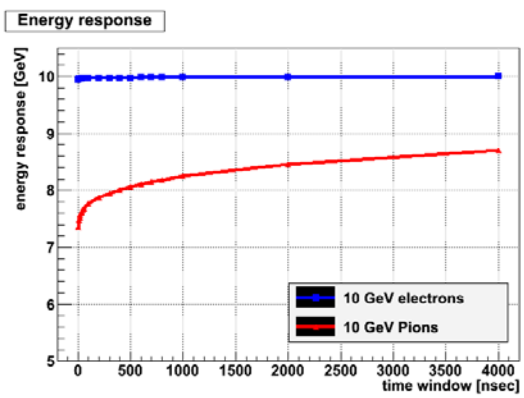


Figure 13. Graph of response for electrons and pions during the first four microseconds

From the graph, we can see that electrons achieve all of their energy in the first few nanoseconds, while pions take some microseconds to fully achieve their maximum. This maximum will always be lower than the input energy, since some of the pions decay into neutrinos that cannot be detected.

E. Resolution as a function of windows of time

Another quantity that can be obtained from the time-of-flight correction is resolution. Resolution is a measurement of the uncertainty of our measurement. In simple words, we want to know how thin this group of data looks. Resolution is also a direct indicator of the precision of the detector. The following study was done with the same data used for the Response part of this paper. This study is important because in the case of a muon collider, it will help us decide how much data we can sacrifice in order to avoid background radiation.

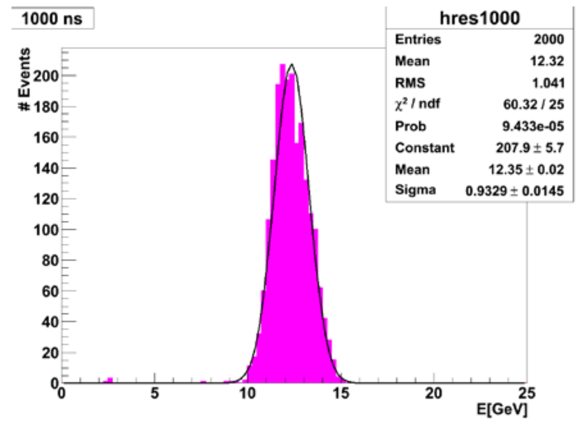


Figure 14. Graph showing the parameters used to calculate resolution

Figure 14 shows an example of the data we extracted for every integrating window of time. We fitted the data with a Gaussian function. Then we took the mean and sigma information to calculate resolution. This calculation is done by dividing sigma by the mean given by the Gaussian fit. Now we have everything we need to study how the energy resolution evolves as time passes.

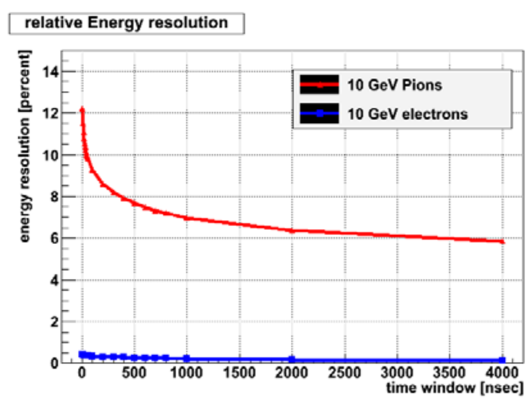


Figure 15. Graph showing resolution for electrons and pions during the first four microseconds

In figure 15 we can see how the energy resolution evolves as time passes. We can see that electrons achieve their best resolution in just a few nanoseconds. For pions, however, even after 4 microseconds, the resolution is still getting better. It is also important to notice that resolution for pions is not as good as for electrons.

4. Discussion

We learned a lot after all these studies on the calorimeter construction. We proved that the dual readout correction increases resolution, which will be very helpful in a future lepton collider. The timing correction works, and its importance depends on the type of lepton collider that will be built. This information is especially important in the case for a muon collider. We see that response and resolution for electrons is always good. On the other hand, pions resolution is better than the resolution achieved by current detectors. This resolution fits the necessities of resolution for future lepton colliders. In the same manner, this resolution can be increased even more with the dual readout correction.

5. Future Work

Considering the learning curve and other factors that happened during the summer, three months was very little time to make more advances on this research. Future research should take into consideration different physics lists for Geant4. Also, it should study the effect and parameters that different materials, such as PbWO4, W or Fe, give as an outcome. It is also important to sample with an active layer of plastic scintillator, since this experiment (and the amount of time required to simulate it), did not let us do it. This will help us see the effect of neutrons in the process. The current model is very idealistic as well, so it will be interesting to study different physics processes contributing to the signal and take into consideration other sources of background. It will be also interesting to modify the Hit-class to include other type of timing information.

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