Detecting Stopping Track Muons with the IceCube Neutrino Observatory

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ABSTRACT

Neutrinos have become an important tool in the study of the universe because of their weak interaction with matter, but due to this property it is also difficult to detect them. One way to indirectly detect them is through another particle, the muon. This method is being carried out in the IceCube Neutrino Observatory. Currently the detector has limited information about the interaction of low energy muons and the effect they have on the detectors. It is therefore necessary to study these low energy muons at their minimum ionizing energy to find the probability of them hitting a Digital Optical Module (DOM). This will allow us to calibrate the detector for low energy muons and neutrinos. This was done by using simulated data with the COsmic Ray SImulations for KAscade (CORSIKA) program which runs Monte Carlo simulations.

I. INTRODUCTION

Optical telescopes have been used since the 1600s to probe the cosmos. They have provided us with a wealth of information about our universe. But we are limited by the amount of information we can obtain since they operate in the range of the visible spectrum, which is only a small fraction of the entire electromagnetic spectrum. This problem becomes apparent when one tries to study an object or phenomena that are obstructed by a cloud of dust. Visible light cannot penetrate through matter and this makes it impossible to study such phenomena. There are alternatives to study objects like nebulas (cloud of dust) or other objects that cannot be observed with optical telescopes. Such alternatives are X-ray and radio telescopes which use different electromagnetic wavelengths. These types of telescopes enable us to study objects through most obstructions. But telescopes that use electromagnetic radiation will be affected by objects that will not let the radiation penetrate through even if the wavelength is small. Such problem can be solved by using a different type of telescope, one that depends on a carrier of information which does not interact much with matter or electromagnetic fields. This elusive carrier of information is called the neutrino and it can be studied using a neutrino telescope.

A. Background

Neutrinos are neutral subatomic particles with very small mass. They have become a source of mystery to physicists since very little is known about them and yet they are very abundant in the universe, this opens up the possibility for discovery. There are three types of neutrinos which are the tau neutrino, electron neutrino, and muon neutrino. They are named this way because of the particles the leave behind once they interact with matter. A neutrino can go from one type of neutrino to another through a phenomenon called neutrino oscillations. Neutrino oscillations have allowed us to demonstrate that neutrinos have mass since only things with mass can change over time. In 1998 using Super-Kamiokande, one of the first water based Cherenkov light detectors, confirmed this by studying neutrino oscillations [2]. Now it is estimated that the mass of the neutrino is at least a million times smaller than that of the electron. Because of its small mass, the neutrino is minimally affected by gravity and it is unaffected by electromagnetic fields because it is neutral. The only interaction it has is through the weak interaction force. The interaction with matter is so weak that a neutrino produced in fusion reactions in the sun could go through a light year of lead before having any interaction [2]. Because of its weak interaction with matter the neutrino is ideal to study phenomena which cannot be done using the methods discussed earlier. But how is it detected if a neutrino does not like to interact?

Fortunately there are billions of neutrinos that hit the Earth every second. This means that there is a non-zero probability that a neutrino will be detected. A neutrino can be detected using radiochemical devices or a water based Cherenkov detector. A radiochemical detector is not ideal since it can only give us the count of neutrinos that bombarded the device. It will not give us the direction from which they came from nor the energy [2]. A neutrino observatory that uses Cherenkov light is more useful since this can give us the direction and energy of the neutrino in real time. Cherenkov light is produced when a charged particle travels faster than light in that medium. This produces a cone of light from which the intensity and angle is obtained. We can then tell the energy and the direction it came from with these parameters. The light is usually detected using a photomultiplier tube (PMT). Since the neutrino has a neutral charge it must interact with the nuclei of atoms in the atmosphere or any other medium to produce a charged particle, often a muon. A muon is a charged subatomic particle similar to the electron except for the mass which is much larger and it is often a byproduct of the interaction of neutrinos in the atmosphere or other mediums.

B. The IceCube Detector

For this study the IceCube neutrino observatory was used. IceCube is a 1 km^3-scale Cherenkov light detector deployed in the glacial ice at the geographic South Pole, shown in Figure 1, which uses the ice as a its detection medium. The Cherenkov light is detected by 5160 DOMs frozen in the ice between 1450m and 2450m below the surface of the total volume of $1km^3$. Each DOM consists of a 10in photomultiplier tube (PMT) and the electronics for signal digitization are housed inside a pressure-resistant glass sphere. The DOMs are attached to 86 strings that provide mechanical support, electrical power, and a data connection to the surface [1]. The DOMs are separated by 17m vertically in the string and the strings are horizontally separated by 125m. The construction of IceCube began in 2005 and it was completed in 2010.

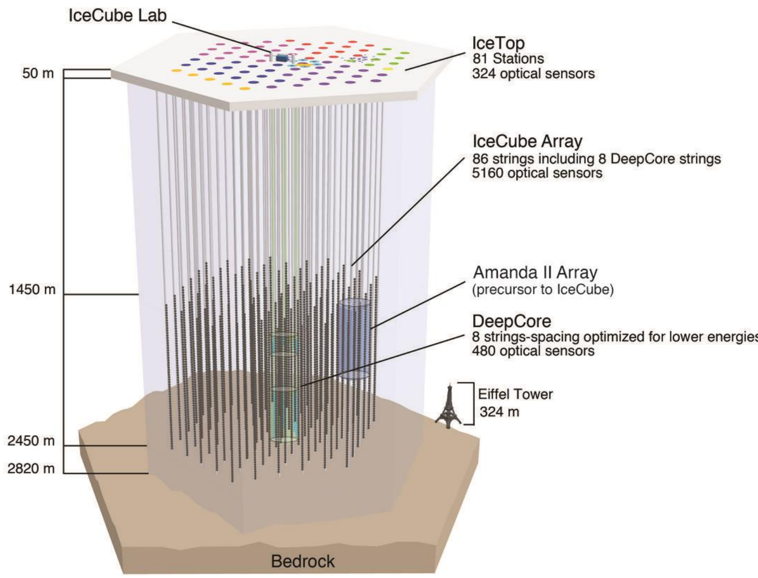


Figure 1: Artist's rendition of the IceCube Observatory [1]

The DOMs are responsible for capturing and digitizing real time pulses from the PMT and when requested transmitting the data to the surface data acquisition (DAQ) system. The DAQ is responsible for messaging, keeping the dataflow, filtering, monitoring, calibration, and implementing the control functions [4]. Most of the data acquired by the DAQ is noise, which it discards, but when it finds an interesting event it will report it. The noise might be other charge particles that are not desirable, but it could also include interesting events that could occur at low energies.

C. Theory

A muon loses energy as it transverse through the ice due to ionization. Since the muon is charged it creates an electric field which interacts with the outer electrons of the atoms in the ice. This interaction might knock out some electrons or it might excite them, as this occurs the muon loses energy. The energy loss per meter, for a muon propagating through ice, is related to its energy:

$$-\langle\frac{dE}{dX}\rangle = \alpha(E) + \beta(E)E \qquad (1)$$

where E is the muon energy, $\alpha \approx 0.24 GeV/m$ is the ionization energy loss per unit length, and $\beta \approx 3.3 \times 10^{-4} m^{-1}$ is the radiative loss through bremsstrahlung, pair production, and photonuclear scattering [5]. Since most of the muons I will be studying are in the GeV range they will not be affected by radiative loss, also most muons will stop within 1000 meters in the detector.

For this reason it is necessary to study the behavior of muons in the ice and the effects that they have on the DOMs. It is possible that the DAQ could be filtering out some low energy muons. I will be looking at low energy muons in the GeV (giga-electronvolt) range that may stop within the detector. I will isolate a sample of muons near the point where they are minimally ionizing. The behavior of these types of muons is well understood in different forms of matter, but not in the detector [7]. So it will be necessary to run multiple simulations to recreate their paths and measure the probability that they will hit a DOM. The findings of this study will enable us to calibrate the detector for low energy muons which will help us detect neutrinos that are in this range of energy too. Studying neutrinos at this range of energy will help us understand their fundamental properties.

II. METHODS

To analyze the data I will use IceTray which is the framework developed by the IceCube collaboration. A framework is a set of rules, interfaces, and services provided to the programmer who can use it to perform a set of tasks [5]. In a modular framework the user only changes a few lines in a command file to modify the analysis chain. A programmer can then implement algorithms and the framework will figure out how they will interact. This means that in a modular approach each subsystem can be modified, added or replaced without altering others. The IceTray framework follows these principles and it consists of modules which are independent code units that can be used to obtain data or to manipulate it. These modules can then be linked into the framework which can be used later. Once an event in the detector is found it is then stored in data containers called frames which can be processed using the modules. This framework is used for simulation, reconstruction of events, and for developing IceCube applications.

The data used was simulated using CORSIKA which is a detailed Monte Carlo program used to study the evolution of extensive air showers initiated in the atmosphere by photons, protons, nuclei, or any other particle [3]. This program is then able to generate the paths and energies of the particles. The files that I used had proton and other primary particle which generated muons. It was then necessary to use one of the modules in IceTray to begin the process of isolating the low energy muons. To do this we needed to use the single photoelectron (SPE) fit, which is a likelihood reconstruction that uses the arrival time of the first photoelectrons in all hit DOMs [5]. A photoelectron is an electron emitted from the PMT when light hits it. With this reconstruction I will be able to obtain the direct length and total charge. The direct length is the length of the track, which is the distance along the track from the first hit DOM to the last hit DOM from the light perpendicular to the track direction. The total charge is the number of photoelectrons detected in by the DOM. I also used steamshovel, which is an event viewer able to display the track of the muon and the angle at which it enters the detector. This will allow me to make cuts from my data and only study stopping track muons which have low energy.

Once a sample of low energy muons has been isolated the probability of them hitting a DOM can be obtained. This can be done by studying the track of the muons. This result will allow us to know how many of these type of events can be detected by the DOMs. I also used ROOT which allowed me to output this data into histograms. ROOT is data analysis software which uses C++ and is a standard tool for analyzing data graphically in the particle physics community.

III. RESULTS

Applying the SPE fit to the CORSIKA files I obtained 19310 events. I was then able to obtain the variables of length direct and total charge using the common variables script which calculated them. These were then plotted, Figure 2 shows the results. This plot was used to determine how many events have a small direct length and total charge which is a characteristic of stopping track muons. All of the events were within the length of 1500m which is largest length a track can have within the detector. The plot shows that there is a large amount of events that have small length and charge which could be stopping track muons. But it is also possible that these events might be due to muons hitting the corners of the detector (corner clippers) which will also register as a small length and charge. The next step is to then study these muons that have a small length and charge. This was done with the IceTray module steamshovel.

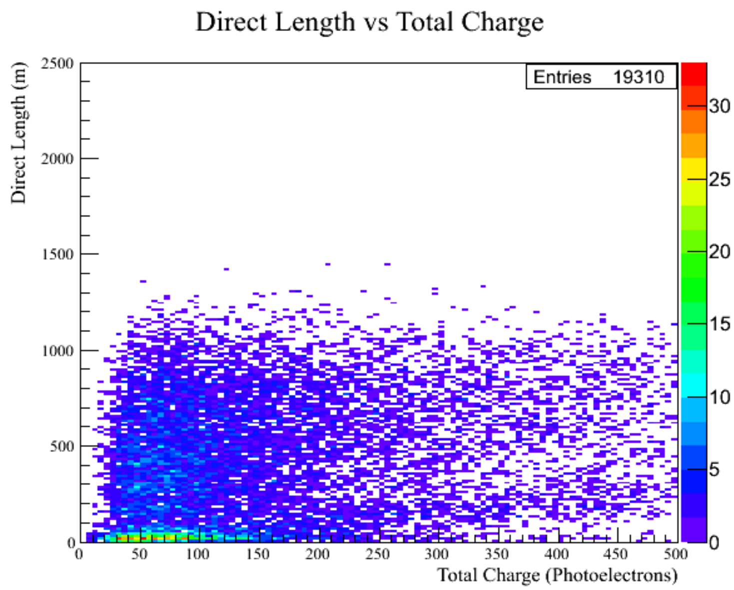


Figure 2: The scatter plot shows the Direct Length vs. The total charge (number of PE detected) detected. The color scale indicates the number of events in each bin.

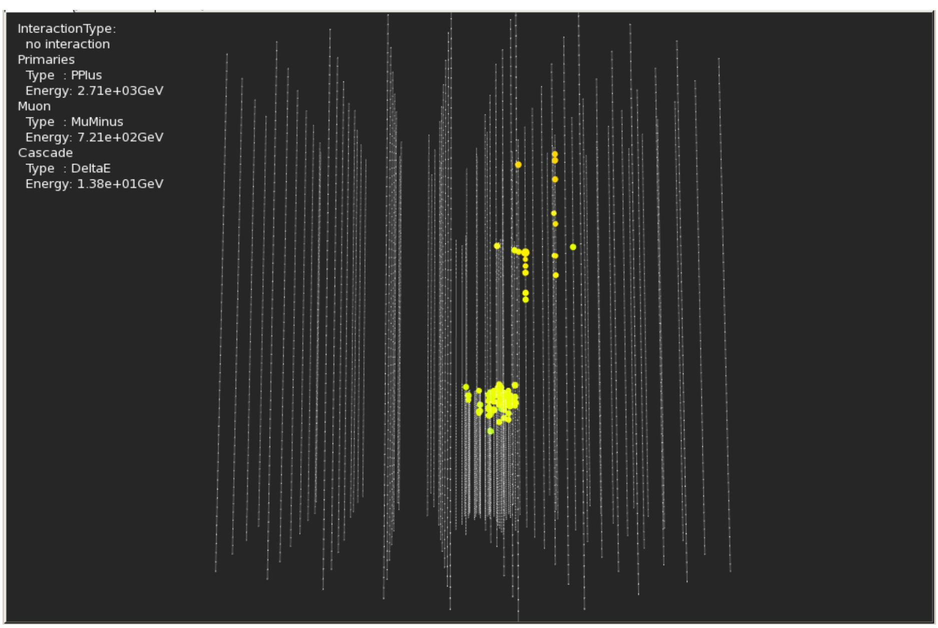
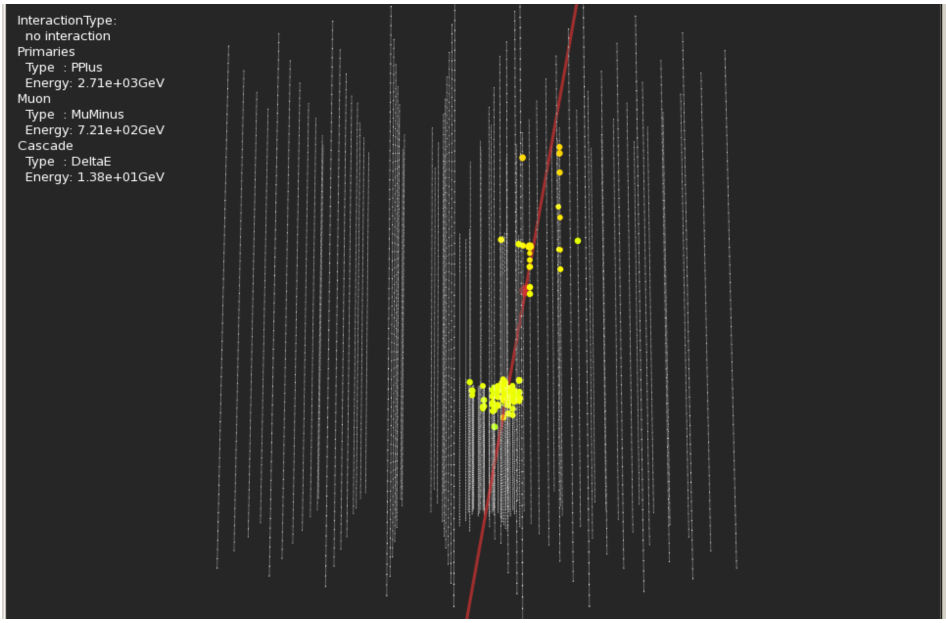
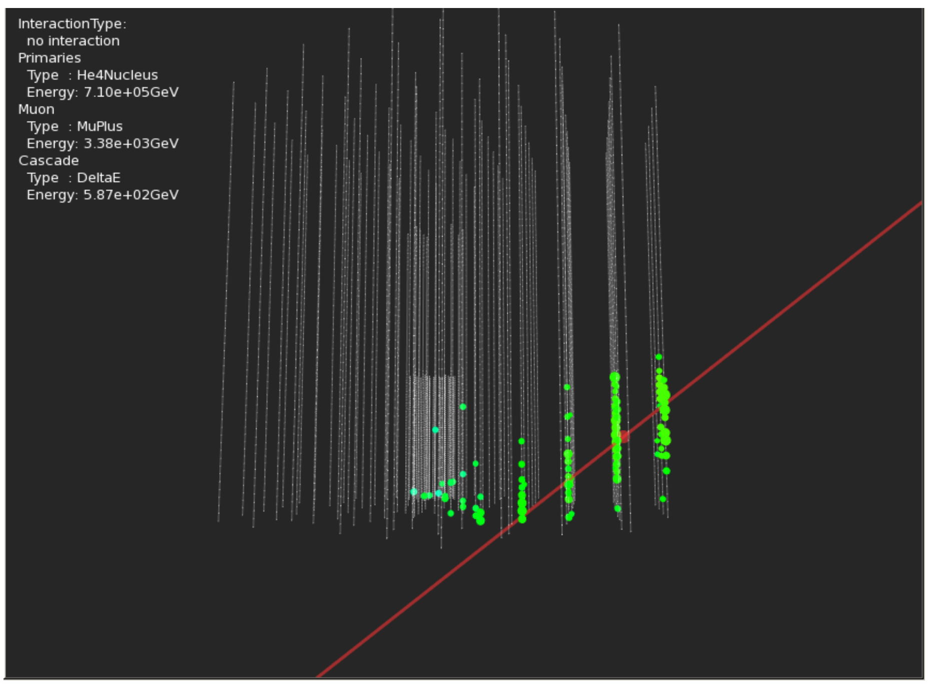


Figure 3: This is a picture of a simulation of a muon stopping in the detector. This simulation shows the energy the muon has and the effect it has on the DOMs.


InteractionType:
no interaction
Primaries
Type : PPlus
Energy: 2.71e+03GeV
Muon
Type : MuMinus
Energy: 7.21e+02GeV
Cascade
Type : DeltaE
Energy: 1.38e+01GeV

(a)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Type : He4Nucleus
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Muon
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Energy: 3.38e+03GeV
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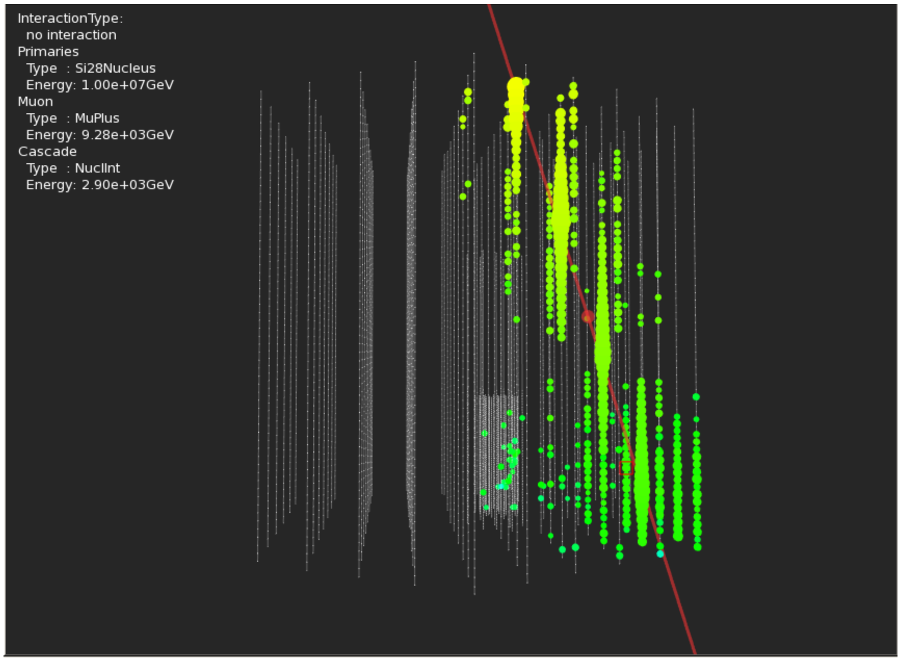
(b)

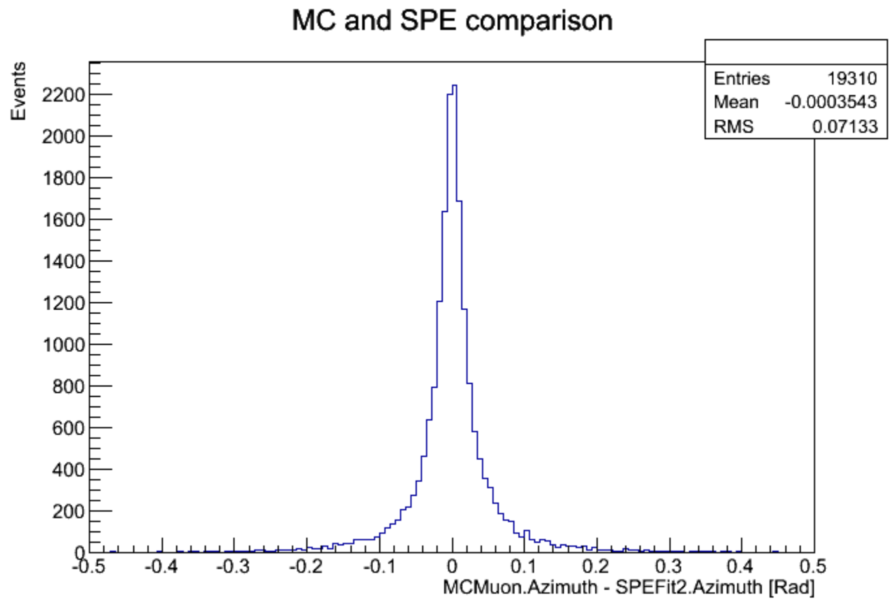


(c)

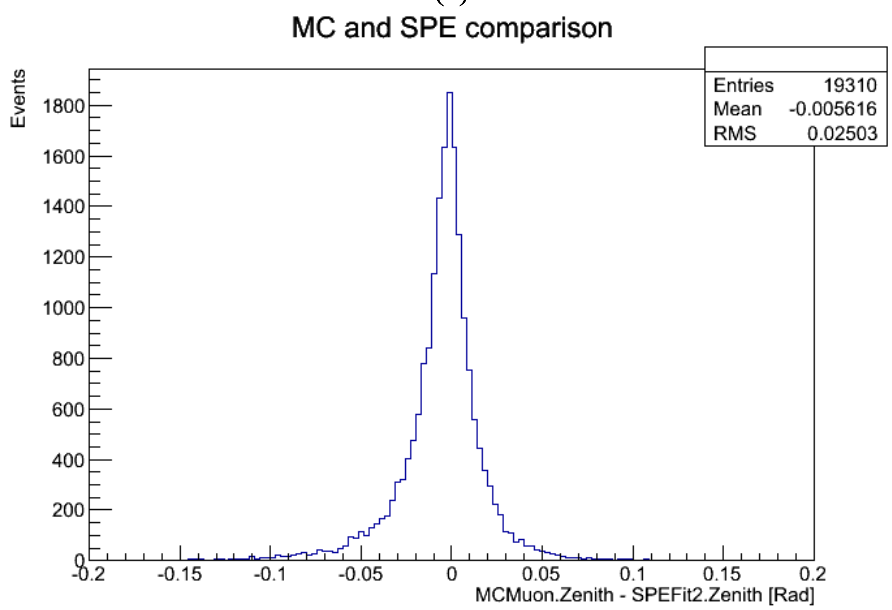
Figure 4: (a) Simulation with the SPE fit reconstruction which shows a track of a stopping muon. (b) The track of corner clipper muon. (c) The track of a muon that goes through the detector

Steamshovel displays the track of the muon and the Cherenkov light it deposits on the DOMs. The DOMs are displayed by the dots and the different colors show the time of arrival in the event. Red color indicates that light arrived early in the event while blue color means it arrived late. This is used to check if the reaction of the DOMs are related and caused by the same muon. Also the charge detected by the DOMs is shown by the size of the colored spheres. A large sphere will indicate large amounts of charge while a small sphere will indicate small charge. Figure 3 shows a picture of the event viewer which has a simulation of a muon. This figure only shows the reaction of the DOMs. Figure 4 (a) shows the path reconstructed from the reaction of the DOMs which is what the SPE fit script calculated. The picture of the simulation shows that the muon stops within the detector. Figure (b) and (c) show the events that need to be cut: (b) shows the track of a muon clipper which has a small length and charge. These type of events need to cut since they are not stopping in the detector. Also the muons that go through the detector are not needed; such events are similar to Figure 4 (c).

In order to check if the SPE Fit constructed the events correctly it was necessary to compares the angles outputted with those of the CORSIKA simulation. I decided to use both the zenith and azimuth angles to include all the directions a particle can enter through the detector. The zenith angle has a range of 0°-180° and is measured from the top of the detector to the bottom. The azimuth has a range of 0°-360° and is measured around the detector. To compare these two angles it was necessary to get the difference between them as shown in Figure 5 (a) and (b). A good reconstruction will have a difference of zero. In (a) the majority of the events were within the ranges of$\pm 0.1\, rad$, this is the same as$\pm 5.73°$. For (b) these values are then $\pm 0.05\, rad$ which is$\pm 2.86°$. This values show that the reconstruction was good since there is not much angle separation.



(a)



(b)

Figure 5: The histograms show the difference between the angles from the Monte Carlo (MC) simulation and the SPE fit at which the particle entered the detector. (a) This shows the difference between the azimuth angles and (b) shows the difference between the zenith angles.

Since the reconstruction was generated correctly I made cuts on the data and selected the events that had a length of 800m and total charge of 200. This gave me a total of 2951 events. I compared the number of stopping muon with and without the cuts. I did this by using the point where the muon entered the detector and the distance it traveled. I looked at muons that stop within 1550m and 2350m in the detector. I obtained 741 muons out of 19310 events that stop without the cut and 356 out of 2951 with the cut. This are very few muon which means that the cut might be getting rid of a lot of muons that might be stopping in the detector or that most of the muons are very energetic. It is therefore necessary to implement a new cut on the number of events or use a different set of data.

IV. CONCLUSION

The data processed was selected to include only low energy muons. The values of the SPE fit and MC were compared to show that the reconstruction was adequate. The results show that they were. Finally a percentage of the total muons that stop within the detector was determined with and without the cut. A larger percentage of muons with the cut was found but the number of muons is very low. In order to have an accurate probability of a DOM getting hit a larger number of muons is needed. Therefore a better method for the cut is needed or it is also possible to get a large number by studying a different range of the direct length and total charge.

References

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