THE PENNSYLVANIA STATE UNIVERSITY
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DEPARTMENT OF PHYSICS

STUDYING THE USE OF MICHEL ELECTRONS TO CALIBRATE PINGU

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Abstract

The IceCube Neutrino Detector System, located in the South Pole, is the largest neutrino detector system ever made. A proposed addition to it is the Precision IceCube Next Generation Upgrade (PINGU), which would use more densely spaced detectors to allow for measurements of lower energy neutrinos, making it more sensitive to the neutrino mass hierarchy. A simulation of the PINGU detector system is used to determine its ability in making these measurements and to calibrate its reconstruction of neutrino events. The muon neutrino is one of the three different flavors of neutrino, and will, upon undergoing a charged current interaction, release a muon that will later decay into a Michel electron. In this thesis we use the simulation of PINGU to see whether the Michel electron can be used to calibrate its reconstructions.

Using ROOT to perform analysis on the data returned from our simulation, I found that we can expect that 0.2% of ν_μ events in PINGU should be highly suitable for use in calibration via the Michel electron. If a muon from a ν_μ charged current event stops beneath one of our DOMs, then the Michel electron that it later decays into will give light to this DOM. If we have multiple events where we know the time that their respective muons stopped at and have reconstructed them to have an endpoint under a DOM, then the light we expect to see from all these events put together will line up with the muon average lifetime. Unfortunately, we were unable to detect this in our ν_μ data. An alternate method is proposed which uses the double pulse structure of light that a muon emitting Cherenkov radiation that stops under a DOM and decays into a Michel electron (which will also emit Cherenkov radiation) produces, which can be seen by looking at individual ν_μ events where the created muon is seen to stop under a DOM.

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Acknowledgements

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Chapter 1

Introduction

1.1 Neutrinos

Neutrinos are some of the most recently discovered fundamental particles, and subsequently are the subject of much study in the realm of physics. The neutrino (specifically the electron neutrino) was first theorized by Wolfgang Pauli in 1930 to explain beta decay, which at the time seemed to ignore conservation laws. There are three types (or flavors) of neutrino: electron neutrino (v_e), muon neutrino(v_μ), and tau neutrino (v_τ), in order of discovery; they were discovered in 1956 by Clyde Cowan and Frederick Reines [1]; 1962 by Leon Lederman, Melvin Schwartz, and Jack Steinberger [2]; and 2000 by the DONUT collaboration [3], respectively. When a neutrino participates in a charged current interaction, they will produce either an electron, muon, or tau particle depending on their flavor. Each type of neutrino is neutral and does not interact through the strong force, meaning that it only can only interact with other particles via the weak force and gravity. Because of this, the neutrinos are very weakly interacting, so much so that neutrinos can easily pass through the entirety of the earth without significant interaction, and so are very hard to detect. Due to this difficulty, some aspects of neutrinos still remain mysterious, most notably their mass ordering:

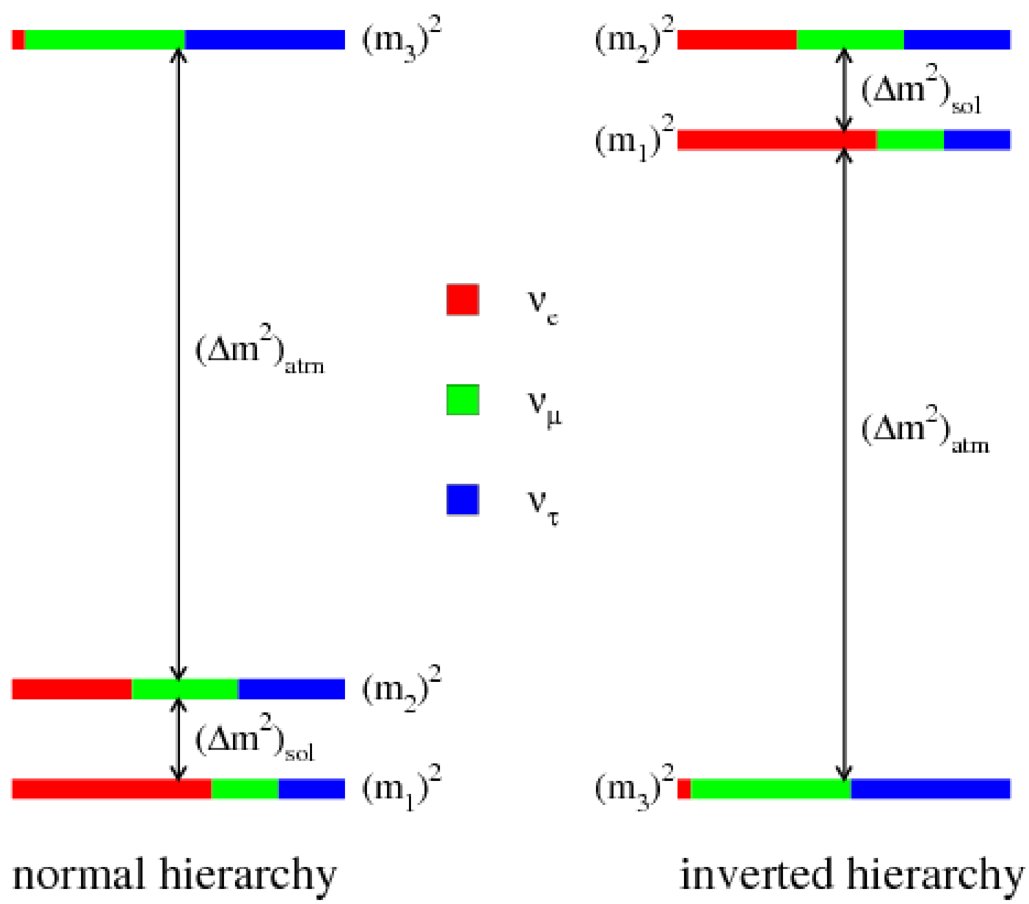

Figure 1.1: The two possible neutrino mass hierarchies, referenced from [4].

The neutrino mass ordering problem is, essentially, whether there are two neutrinos of significantly greater mass when compared to the lightest one, or two neutrinos of significantly lighter mass when compared to the heavier one. Determining this is one of the larger goals of PINGU.

While neutrinos are created with a specified flavor, as they propagate through space they oscillate between the three possible flavors. The UHE (ultra high energy, being the most easy to detect) astrophysical neutrinos are typically created by pion decay. The most likely form of pion decay (probability $= 0.999877$) is shown in Fig. 1.2:

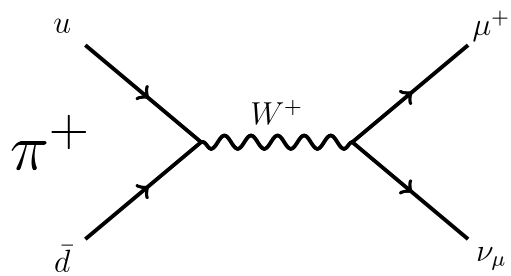

Figure 1.2: The most probable outcome of the decay of a positively charged pion, which creates both a muon neutrino and an antimuon.

As you can see, when a negatively (positively) charged pion decays, it creates one muon neutrino and one (anti)muon. This (anti)muon will then go on to decay as well. Muon decay is shown in Fig. 1.3:

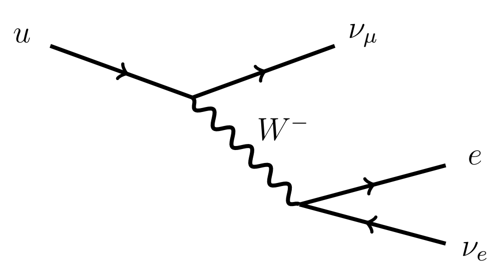

Figure 1.3: Muon decay, which creates a muon neutrino, an electron neutrino, and an electron.

When the (anti)muon decays, it creates two more neutrinos: a muon neutrino, and an electron neutrino. So, our greatest UHE neutrino source in astrophysical events creates neutrinos with the ratio $v_e : v_\mu : v_\tau = 1 : 2 : 0$. However, as mentioned, neutrinos oscillate between their different flavors over time, so that a muon neutrino created via pion decay might later be detected as a tau or electron neutrino. This effect can be seen in Fig 1.4:

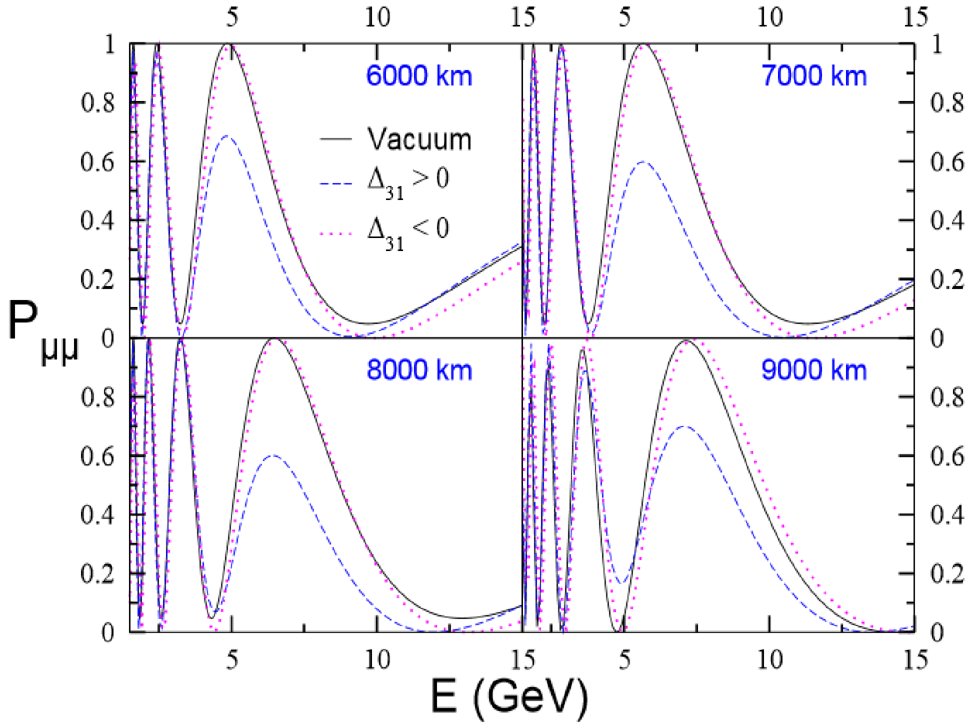

Figure 1.4: Muon neutrino survival probability $P_{\mu\mu}$ in matter (as well as in a vacuum) vs. its energy E (GeV), for four different pathlengths, and the two possible signs of Δ_{31} (i.e., the neutrino mass ordering). Referenced from [5].

The probability of whether or not a neutrino will change its flavor is essentially a function of the length traveled divided by its energy. At high energy and short length, it is unlikely to change, and at long length and low energy, the probability of it changing goes to 50% (the probability is also affected by moving through matter, such as the different layers of the Earth). Because of this, the flavor ratios of the aforementioned UHE neutrinos will have changed to $v_e : v_\mu : v_\tau = 1 : 1 : 1$ by the time they reach the Earth, with possibly some corrections given the possible existence of sterile neutrinos (hypothetical particles that interact only via the gravitational force) [6].

Aside from having pure scientific value, there are practical uses for neutrinos. Nuclear reactors create many neutrinos, so they can be used to detect undeclared nuclear activity, and depending on whether or not they violate charge-parity, they could be used as explanation for the matter/anti-matter asymmetry in the universe. They can be used to as another means to study anything that produces them, which includes the Earth, our sun, and even the big-bang. The big-bang neutrinos, known as the cosmic neutrino background (CνB), however, are very hard to detect due to their low energy [7]. Another application is that they can be used for astronomical mapping. Since neutrinos are so weakly interacting they can easily pass through planets and other material that would stop photons and other particles. Due to this, it's possible to use them to detect astronomical events that we may otherwise have missed. For instance, active galactic nuclei (AGNs), highly luminous regions at the center of galaxies, believed to be caused by the accretion of mass into a black hole; and gamma ray bursts (GRBs), sources of gamma rays typically from high energy events such as the collapse of stars, are both potential sources for UHE neutrinos. In general, we would be able to make a map of the sky, similar to our current ones using different wavelength ranges (gamma, radio, etc) of electromagnetic radiation, but with neutrinos that may reveal previously unseen events in our universe.

1.2 Muon Neutrinos and Michel Electrons

As muon neutrinos interact via the weak force, they can undergo neutral current and charged current interactions. Neutral current being when it interacts via the Z^0 boson. The neutral current interaction simply imparts some of the neutrino's energy to the struck particle, and, while this is detectable if the struck particle is charged and accelerated by the interaction to a speed where it emits Cherenkov radiation, it is not possible to detect what flavor of neutrino caused the interaction. When it undergoes a charged current interaction, however, a muon is created. This muon will go on to radiate a track of light as it moves, and then decay soon after.

The result of the muon decay, as seen in Fig. 1.3, is two neutrinos and an electron. The two neutrinos are very unlikely to interact again for a while, but the electron, being charged, will radiate light for a short amount of time and a short distance (significantly shorter than the muon) as it moves. An electron created by muon decay is called a Michel electron, named after Louis Michel after his work done creating the Michel parameters which are used to describe leptonic decay for charged leptons, which he first applied to muon decay [8][9]. This electron has an energy spectrum upon creation with a peak at about 50MeV, enough to allow the electron to radiate Cherenkov light. As mentioned, it will lose the necessary energy relatively quickly, and so, rather than a track, it produces a small flash of light after the muon decays.

1.3 IceCube and PINGU

Due to how weakly neutrinos interact, large detector systems are necessary to make modern relevant measurements of neutrino properties. The largest neutrino detector in the world is the IceCube detector system, which is roughly $1km^3$ in volume. A schematic of the IceCube Detector system can be seen in Fig. 1.5:

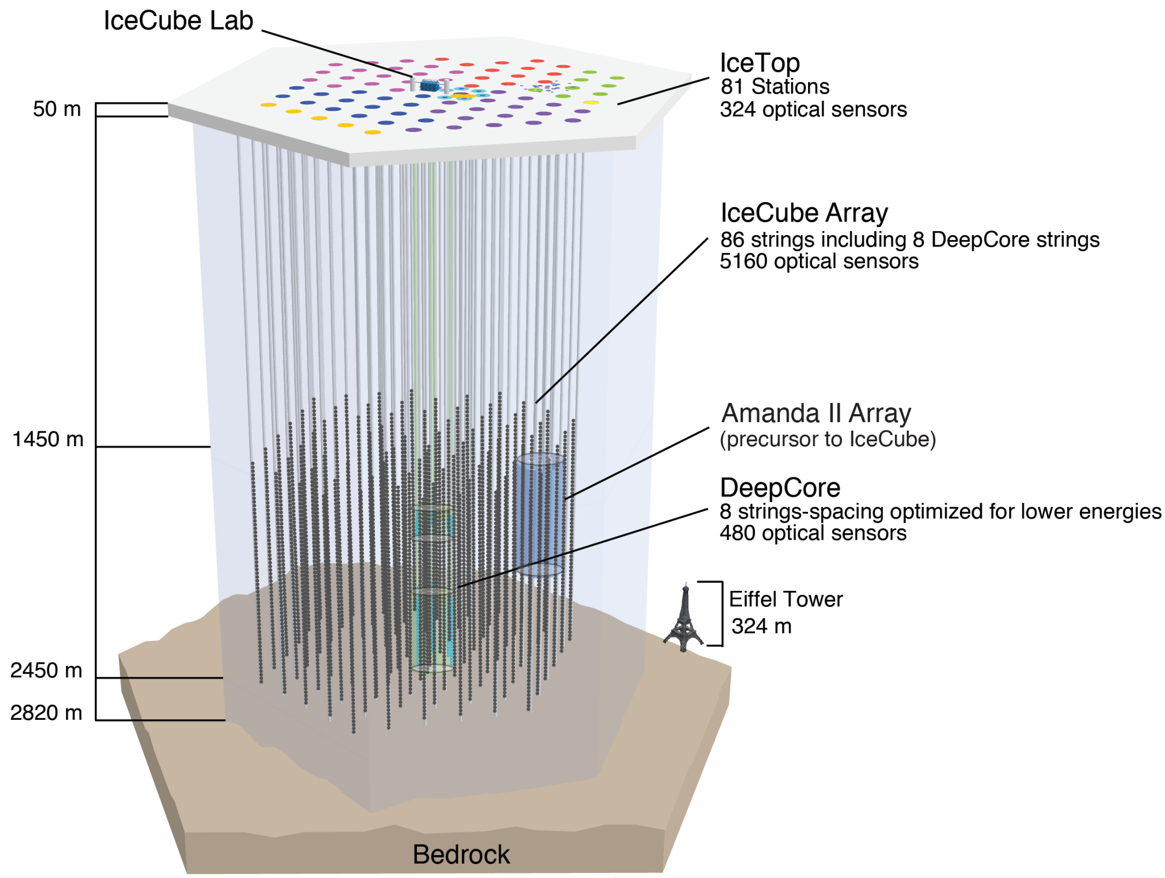

Figure 1.5: The IceCube detector system, showing the strings (represented by lines under the ice), holding the detectors (represented by the spheres on the lines starting at $-1450m$), with the volume of the AMANDA-II Array in the dark cylinder. Referenced from [10].

IceCube is located in the Antarctic ice, and was built surrounding the previous detector system, AMANDA. The AMANDA system consisted of strings holding multiple DOMs (digital optical modules that hold photo-multiplier tubes used to detect light, and face downwards to bias them towards upgoing events, which would mostly be neutrinos as it's unlikely for other particles to be able to pass through the whole earth to the detector). The first string was deployed in 1993, but it was found that the ice was too impure due to air bubbles at that depth in the ice (around $800m - 1000m$). This discovery is shown in the lower depth that the strings start at in Fig. 1.5. After the initial strings were deployed at a deeper depth, AMANDA successfuly detected neutrinos, and eventually the AMANDA-II addition was built, which "by 2000 consisted of 19 detector strings holding 677 optical sensors" [11]. With the success of the AMANDA project, a much more ambitious project called IceCube was set into motion, the end result of which was 86 strings with 5160 optical sensors. Each string is spaced 125 meters away from the other, except for the eight DeepCore strings, which are closer together and have their DOMs spaced closer vertically. This allows for lower energy neutrinos to be detected [12]. A history of the IceCube Construction can be seen in Fig. 1.6:

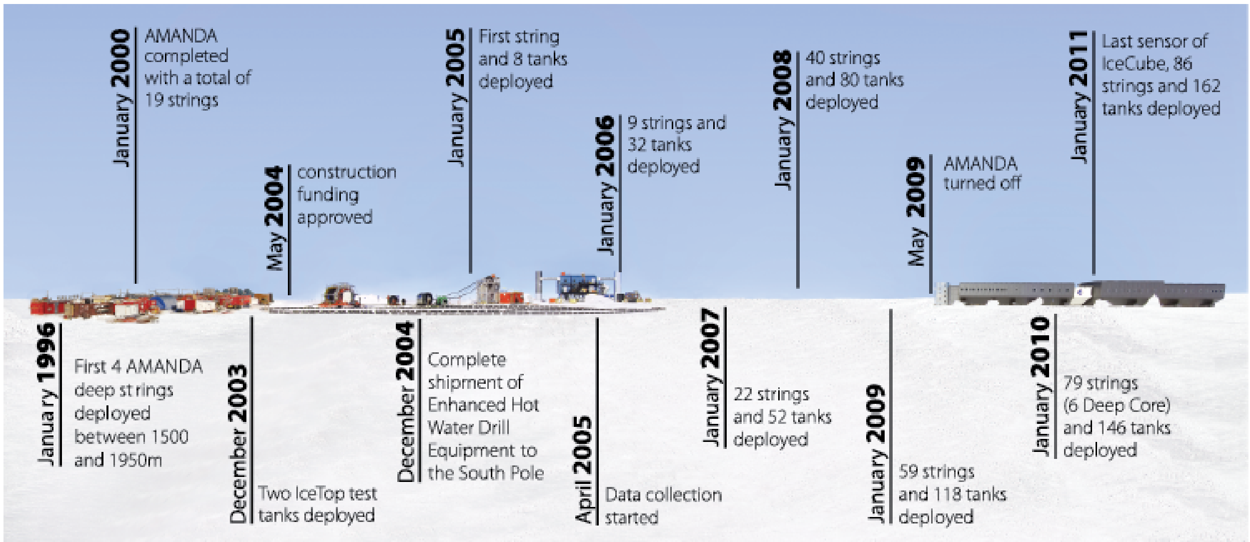

Figure 1.6: The history of the IceCube Detector system, including its predecessor AMANDA. Referenced from [13].

Since its construction, the IceCube project has made important measurements. Some of its most significant successes include finding the first evidence of astrophysical neutrino flux, via neutrino detections with energies too high to have been created in our atmosphere, as well as detecting three neutrinos with energy over 1PeV, making them the most energetic neutrinos ever detected [14].

PINGU (Precision IceCube Next Generation Upgrade) is a proposed addition to the IceCube detector system. PINGU would have the closest spacing of strings horizontally, and the closest spacing of DOMs vertically, allowing it to detect even lower energy events than DeepCore is able to. This lower energy threshold would give PINGU the potential to measure the neutrino mass hierarchy, as, at lower neutrino energies, more significant differences arise between the two hierarchies. For instance, the ν_μ survival probability when traveling through the earth differers at low energies depending on the mass hierarchy, which can be seen in Fig 1.7:

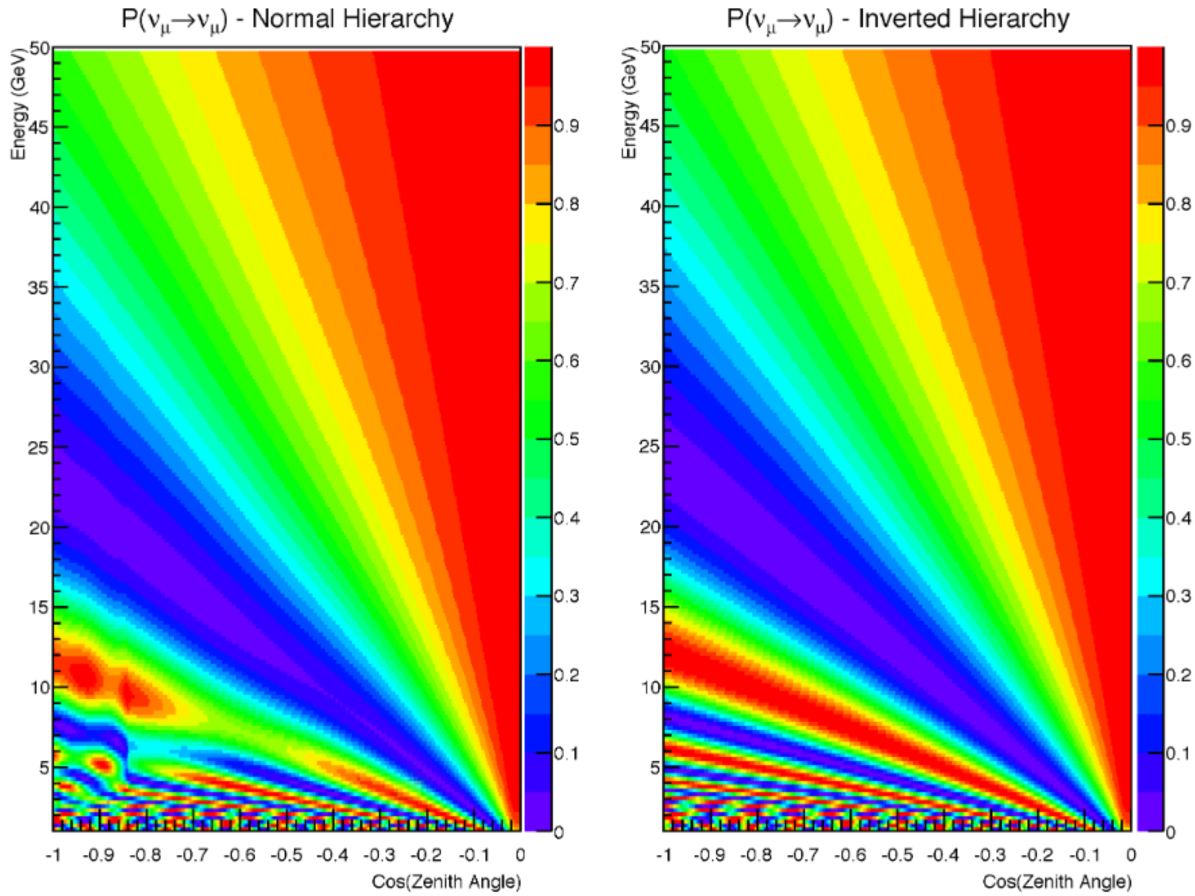

Figure 1.7: The difference between ν_μ survival probabilities at the detector after traveling through earth as a function of their energy and angle (Cos(Zenith Angle)=-1 corresponds to them traveling straight through earth from the opposite side) given the two different hierarchies. Referenced from [15].

PINGU would also be useful in the search for WIMPs, which could produce neutrino streams via annihilation; PINGU would allow us to probe for WIMPs of a lower mass than IceCube or DeepCore allows [15]. Before building PINGU, however, many tests are done to see how we expect it to perform. These tests are carried out via computer simulations of how PINGU will work when implemented, which is the basis of this thesis.

Chapter 2

Simulations

2.1 How Our Simulation Works, and Testing

To run the simulation available on our network, I would have to input both various parameters (which particles to simulate, where they should be placed, their initial energy, etc) and a detector geometry. The detector geometry defines the placing of the strings and DOMs (Digital Optical Module) in the detector system. For my research, I used the PINGU v36 geometry, shown in Fig. 2.1:

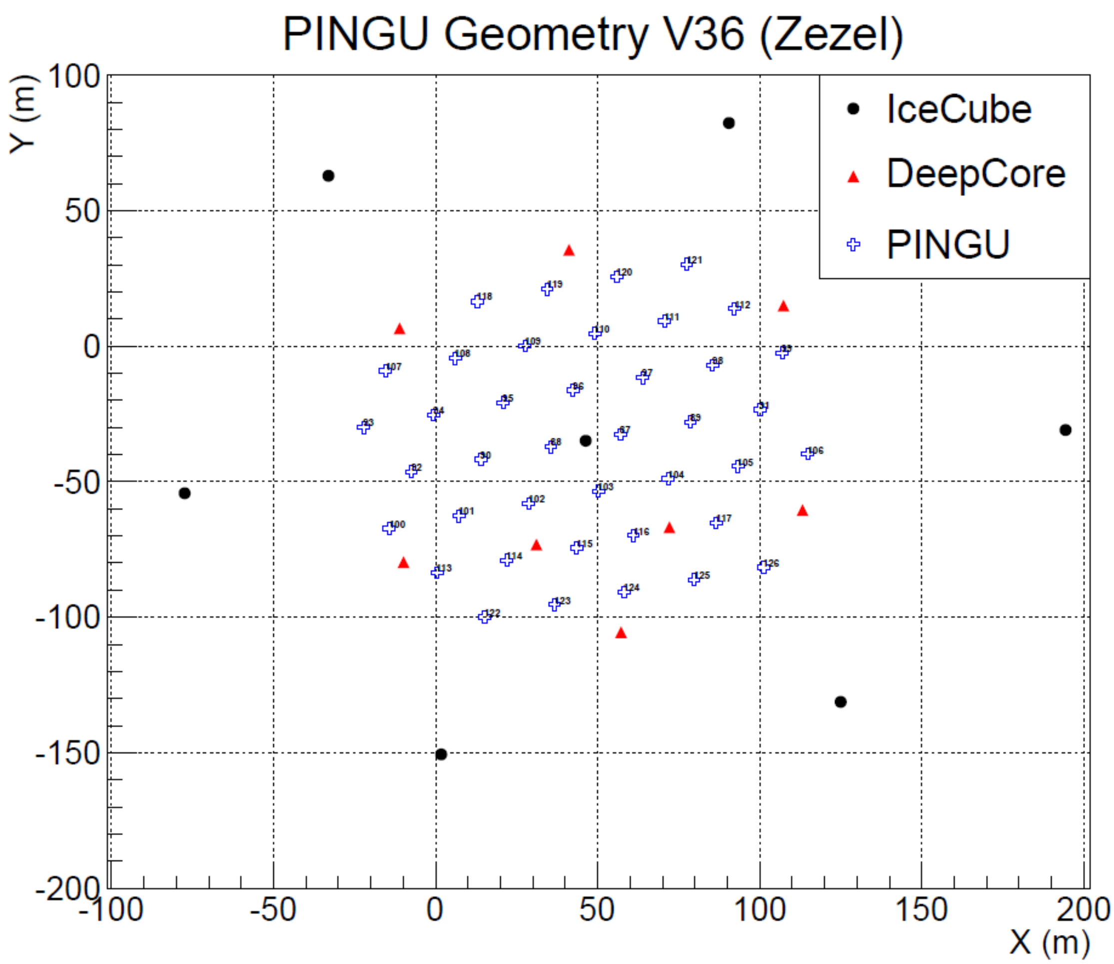

Figure 2.1: The V36 PINGU Geometry, showing the placement of the PINGU, DeepCore and IceCube strings in the ice.

The DOMs on the PINGU strings run from $-181m$ to $-466m$ with a spacing of 3 meters between the middle of each DOM. As with the IceCube and DeepCore strings, the DOMs are placed facing downwards, to reduce sensitivity to particles created in our atmosphere. To give an example of how choosing parameters works, the simulation gives options for parameters such as "Particle-Type", which takes PDG encodings; EnergyMin and EnergyMax, which define the minimum and maximum energy that the particles can have; CylCenter, which defines the center of a cylinder using x, y, and z coordinates; Zmax and Zmin, which define the top and bottom of the cylinder; and

InjectionRadius, which defines the radius of the cylinder. This cylinder will be where the particles are placed in the simulation relative to the detector geometry selection. A function can be used to specify a more complex particle placement throughout the cylinder, and without one it will simply place them randomly throughout the cylinder according to a seed. I also specify the number of particles to simulate. For example, when the simulation is told the parameters ParticleType = 11 (PDG Encoding for electrons), EnergyMin=EnergyMax=50MeV (most likely energy for a Michel Electron), CylCenter= (x,y,z)= (50m,-35m,-324.0m) (roughly the center of the PINGU Geometry), Zmax=-Zmin= 148m (large enough to reach both the top-most DOM and the lower-most DOM on the PINGU strings), InjectionRadius = 80m (large enough to reach the outer-most PINGU string), and to use 10^6 particles, it will simulate 10^6 electrons at 50MeV placed randomly throughout the PINGU detector system. The way it simulates them is done one-by-one, simulating each electron until there is no more activity, recording the data, then moving on to the next electron. The final result is shown in Fig. 2.2 and Fig. 2.3:

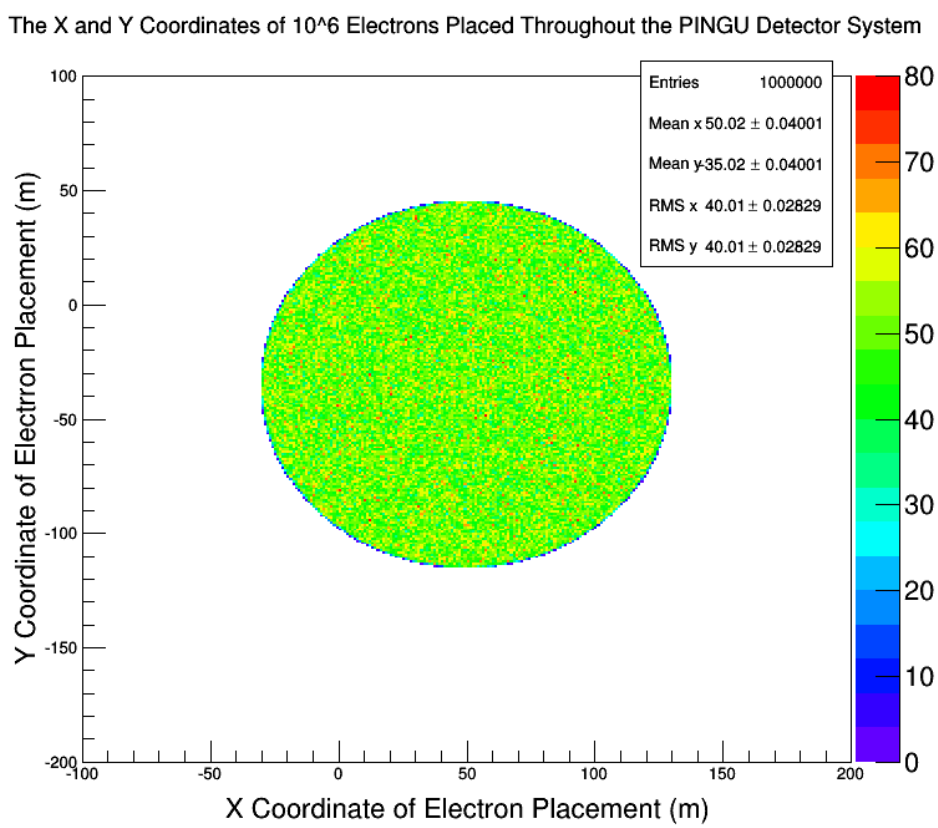

Figure 2.2: The X vs Y placement of 10^6 electrons by our simulation, showing the desired uniformity.

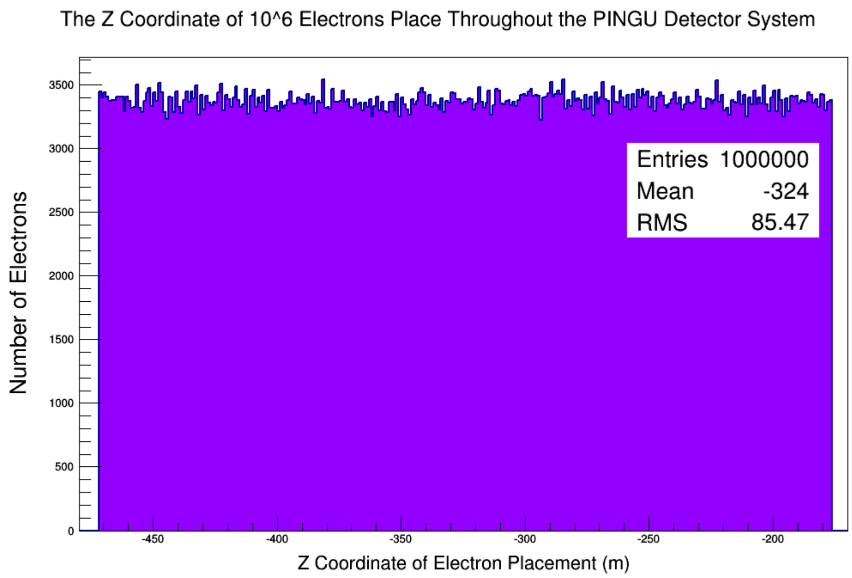

Figure 2.3: The Z placement of 10^6 electrons by our simulation, showing the desired uniformity.

If you compare Fig. 2.2 to Fig. 2.1, you can see how the placement of the electrons lines up with the PINGU geometry. These graphs show that the simulation is working as expected.

Another important test is to check if our simulation properly simulates muon decay. That is, if it creates the Michel electron daughter particle after the muon decays. Since the version of the simulation I was using didn't give back this information explicitly (for instance, when checking the PDG encoding data for a test with Muons, it gives back "13", which is the PDG encoding for muons, but no PDG data for any other particles created after the muon in the simulation), to confirm it I ran a simulation using zero energy muons under a DOM. The idea here being that if the simulation was ignoring the Michel electron creation, then it would not record having received any light in the DOMs. However, it did show that a fair amount of light had been received in the DOMs (particularly the one the muons were placed under), as can be seen in Fig. 2.4:

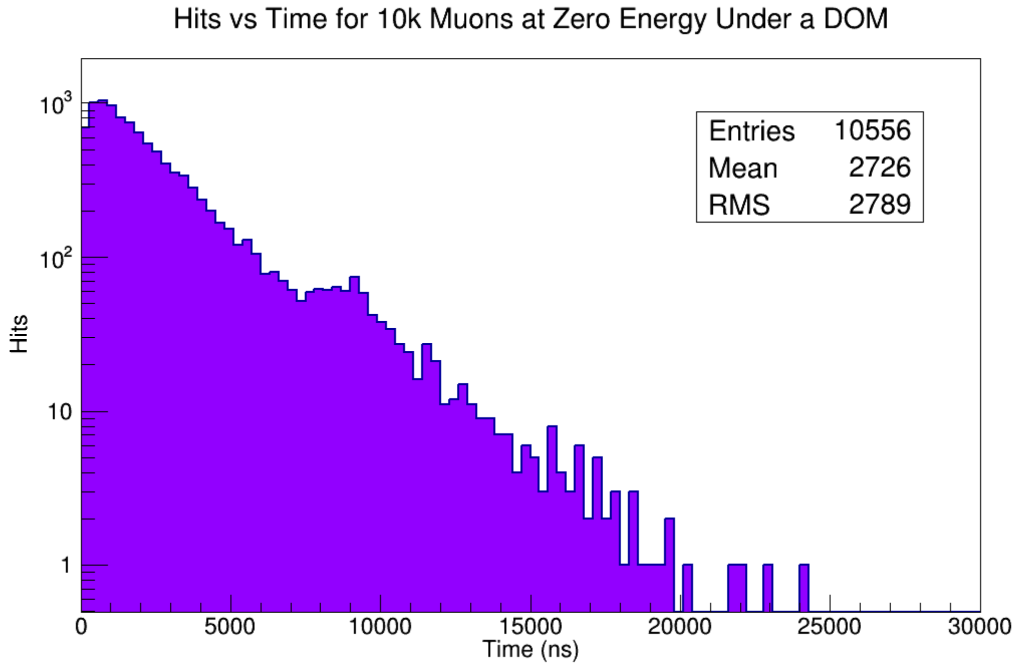

Figure 2.4: Hits versus Time for 10k zero energy muons, confirming that our simulation properly handles muon decay.

2.2 Data Analysis via ROOT

After the simulation completes, it gives out the data in the form of an .i3 file. While it is possible to view the data in this file, I can only do so event by event, meaning that it's not useful for getting a big picture, and is only really used to look at specific data from individual events. To actually perform data analysis on what our simulation produces, I convert the .i3 files to .root files. Once done, the data can be efficiently viewed through the ROOT data analysis software first released in the early 2000s, but still worked on and updated to this day. The conversion from .i3 to .root concatenates the data from each event, so that the results from the simulation can be viewed all at once, instead of event by event. Different types of data are sorted into different ”trees”, which then have multiple ”leaves” that represent the specific type of data, for instance, you will find the x, y, and z leaves (representing the starting positions for particles) in the I3MCTree tree, and time, and string leaves (representing the hits vs. time, and the hits sorted by what string they are received from) in the WavedeformPulses tree, and all leaves are stored under the MasterTree tree. From this point, there are a couple ways to use the ROOT software to analyze a .root file. The simplest way is to use the command ”TBrowser tb”, which opens up a GUI that allows me to view the different trees and their respective leaves and select which ones to graph, shown in Fig. 2.5:

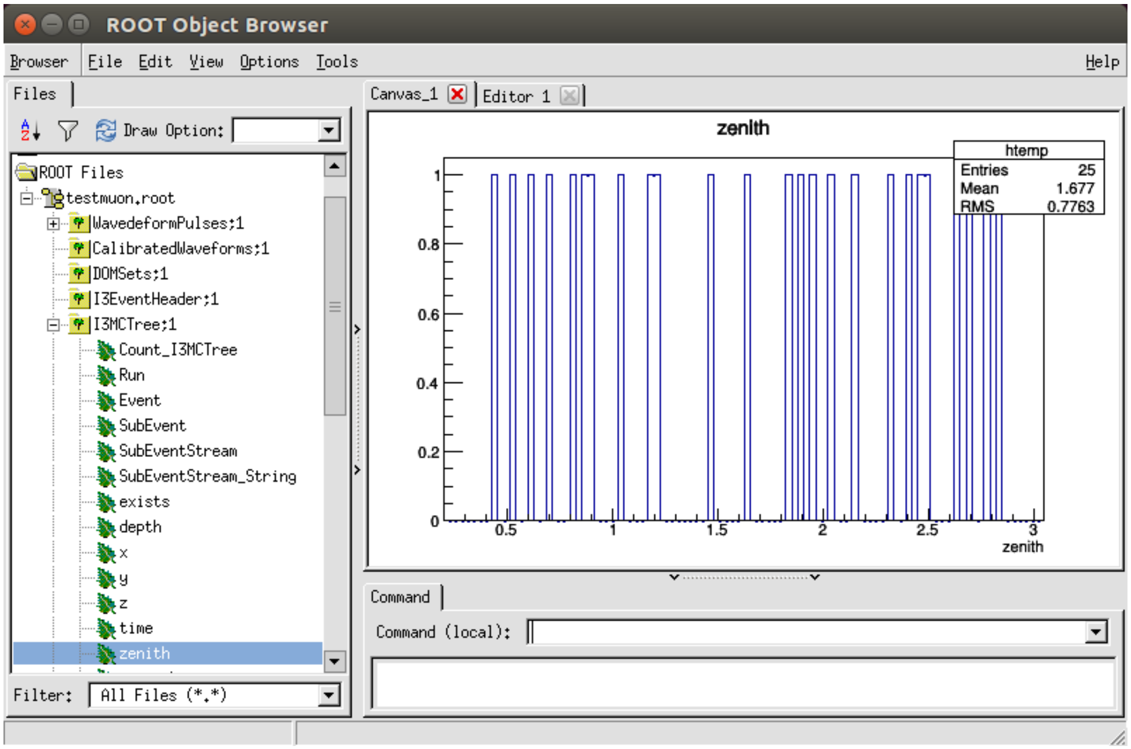

Figure 2.5: The ROOT GUI, showing the zenith leaf selected under the I3MCTree.

Once you've selected a leaf, you can then use the editor and other various options on the GUI to make changes to the style and content of the graph. This method, though simple, is somewhat clunky and, when I know specifically what I want to graph, it is faster to just use the ROOT command line, shown in Fig. 2.6:

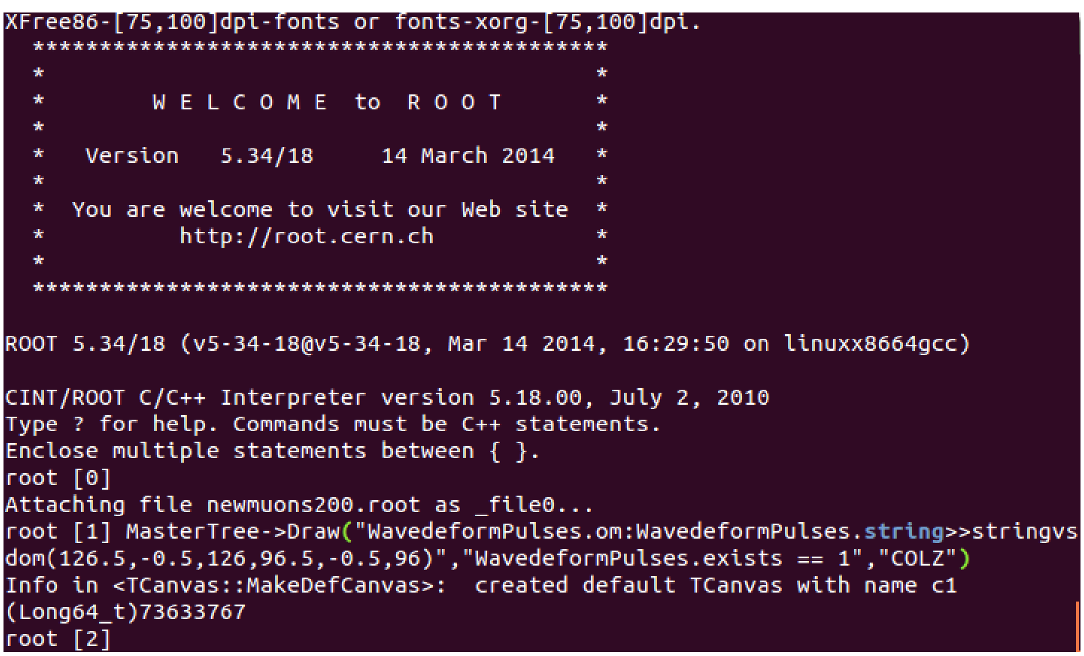

Figure 2.6: The ROOT command line, showing the command to make a simple 2d graph.

What the command you see above does is tell ROOT to look at the MasterTree, and select the om leaf (hits by DOM) for the y axis, and the string leaf (hits by string) for the x axis. It then sets up the number of y and x bins and their range. The command after this, "WavedeformPulses.exists == 1" tells it only use data for which that is true. In this case, that means that it excludes all data from events that didn't have any hits (which would otherwise be assigned to the 0 x-y position on the graph). Finally, the command "COLZ" tells the graph to use color to show the magnitude of hits in each bin. The resulting graph is shown in Fig. 2.7:

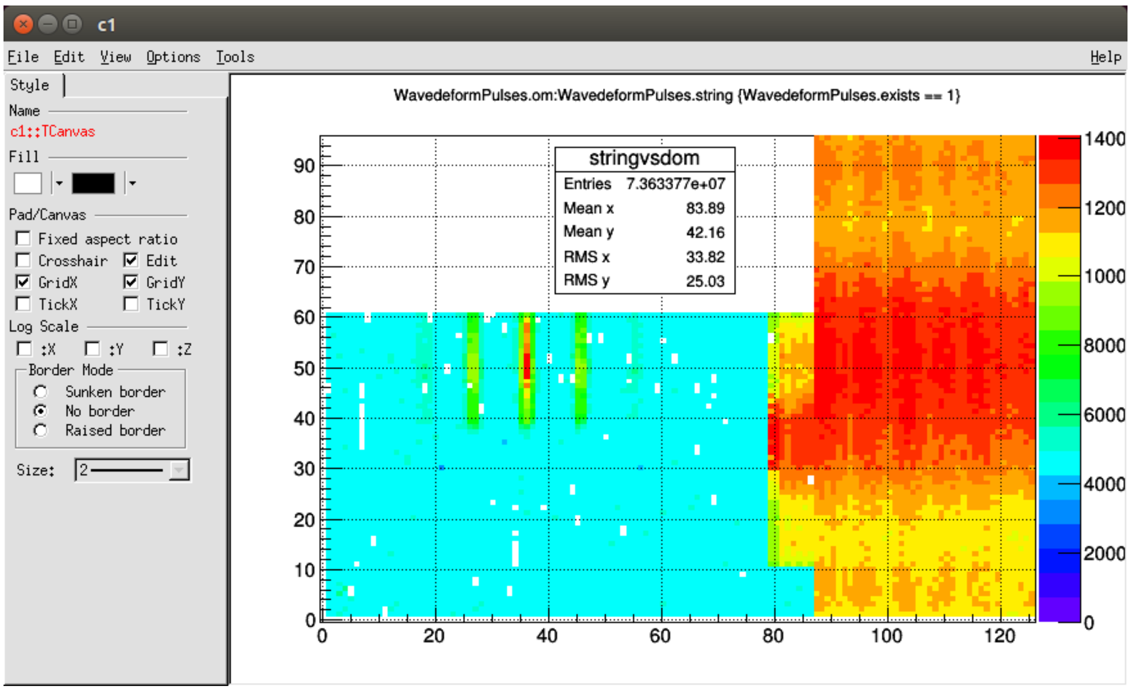

Figure 2.7: Hits on each string vs hits on each DOM created with the command shown in Fig. 2.6.

This method is the quickest when I know exactly what I what and what I want is relatively simple. However, both of these methods are only useful when what I want is simple and doesn't require much manipulation of the data. Where ROOT really becomes useful is in its C++ functionality. ROOT can use C++ code for more advanced data analysis on .root files. With its C++ integration, there are not many limits on how you can analyze data. For instance, say I have a .root file containing muon neutrino events. If I want to track the created muons in this dataset to their endpoints (done using the data root gives regarding the created muon's azimuthal, and zenith directions as well as its energy); and make a graphs of the hits that DOMs receive vs. time during each event with the following cuts and options:

- only use hits received by DOMs that are nearby the muon (defined by a 6x10 (radius by height) cylinder around each DOM)
- only accepting hits with charge greater than 1 SPE
- weigh each hit by its charge
- set the t=0 point for each event to their respective muon stop times

I can write a relatively simple C++ program to do this (which can be applied to any .root file by simply referring to the .root data file in it), run it in ROOT, and it will return the graph in Fig. 2.8 (I've inserted some stylistic options in the code, which can also be done afterwards in the GUI editor):

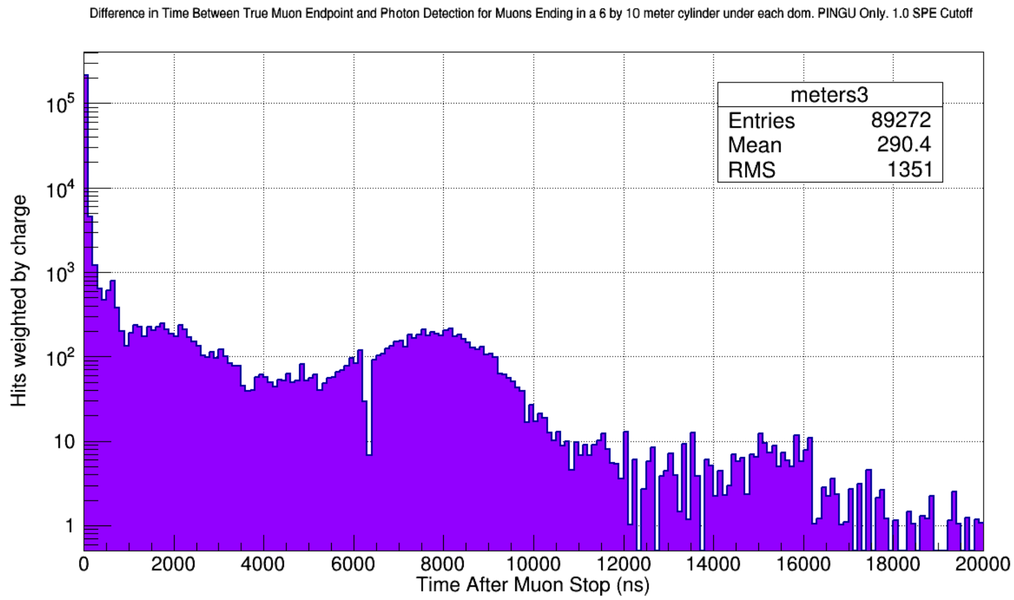

Figure 2.8: Hits vs. time using Muon neutrino data, showcasing the ability of the ROOT software in conjunction with C++ for data analysis. As as side note: the dip at 6000ns is due to how the DOMs digitizer works, not the underlying physics.

Since this method of analysis is the most powerful and versatile, the majority of what follows is done using the C++ method, without which much would be very frustrating, if not impossible, to complete.

Chapter 3

Using the Michel Electron to Identify Muon Neutrino Events

3.1 Identifying the Michel Electron from Muon Truth Information

The first step to determining the viability of using Michel electrons to identify muon neutrino events is to understand the Michel electrons themselves. Particularly, how easy is it for our PINGU DOMs to detect the light that they give off. To understand this, I made a simulation of 1 million electrons at 50MeV (approximately the most probable energy for a Michel electron to have directly after creation by muon decay) spaced throughout the PINGU detector system. Then, I looked at each individual electron creation point and recorded when each electron gave light to a DOM at most 10 meters away, then 20 meters, etc. The resulting graph is shown in Fig. 3.1:

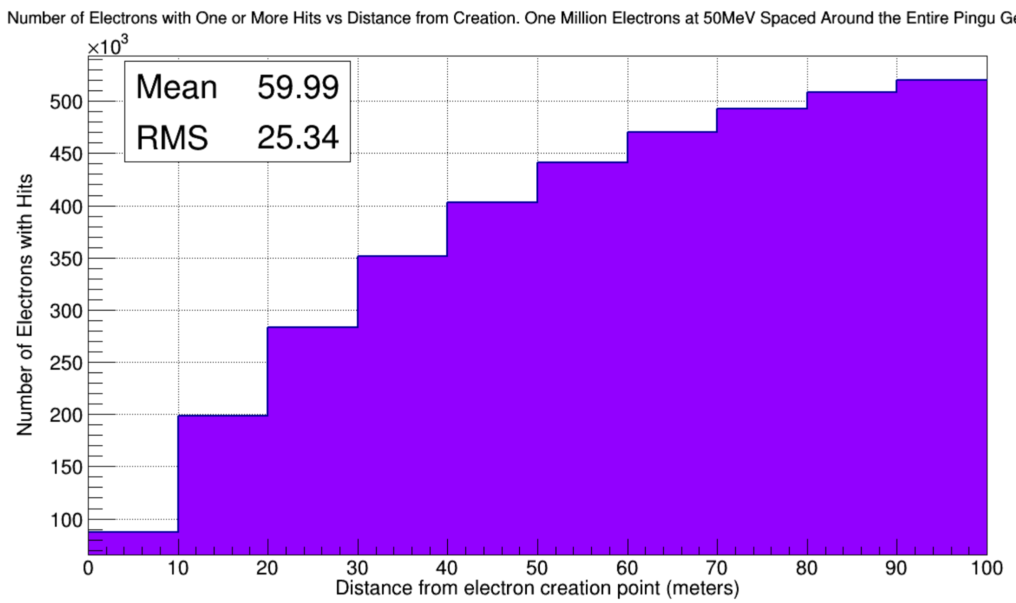

Figure 3.1: The number of electrons with at least one hit vs the distance away from the electron creation point that we look for the hit, showing the probability for us to detect light from a Michel electron by the distance away from it that we look

What this graph shows is that, out of a million electrons, if we look ”x” bins away (bins corresponding to 10 meters each) we will find that ”y” out of the million electrons has given light to at least one of the DOMs in that volume. So if we look 50 (10) meters away, we find that about 40.3% (8.7%) of the Michel electrons created in the volume of the PINGU detector system produce light that is detected by one of our DOMs.

Now that we know how often we can expect light from a Michel electron, it's useful to know how to tell whether that light was from a Michel electron. So, we need to know what it looks like when they inject light into our DOMs as a function of time. One way to do this is to simulate muons with zero kinetic energy placed one meter under a DOM, which lets us see what it should look like if a muon created in a muon neutrino interaction comes to rest under one of our DOMs. Muons have an average lifetime of $2196.98ns$, and once these muons decay we should be able to see the light from the Michel electron they create. With this in mind, I simulated 10^5 zero energy muons under a single PINGU DOM. Since we should only see light from the Michel electrons, the light that that DOM receives should basically match up with the rate that the muons decay at. So if we take a graph of the amount of light received in that DOM vs. time and give it an exponential fit, then the inverse of the exponential slope of that fit should be the average muon lifetime. This is because, given $N_0 = N(0)$ muons initially, the remaining undecayed muons at time t, N(t), is given by the following formula:

$$N(t) = N_0 e^{-\lambda t}$$

and the mean lifetime, τ, is given by

$$\tau = \frac{1}{\lambda}$$

The "slope" value that ROOT gives upon making an exponential fit corresponds to $-\lambda$, so we only need to take the negative inverse of that to obtain τ. However, before we can do that, we have to deal with the effects of afterpulsing, shown in Fig. 3.2:

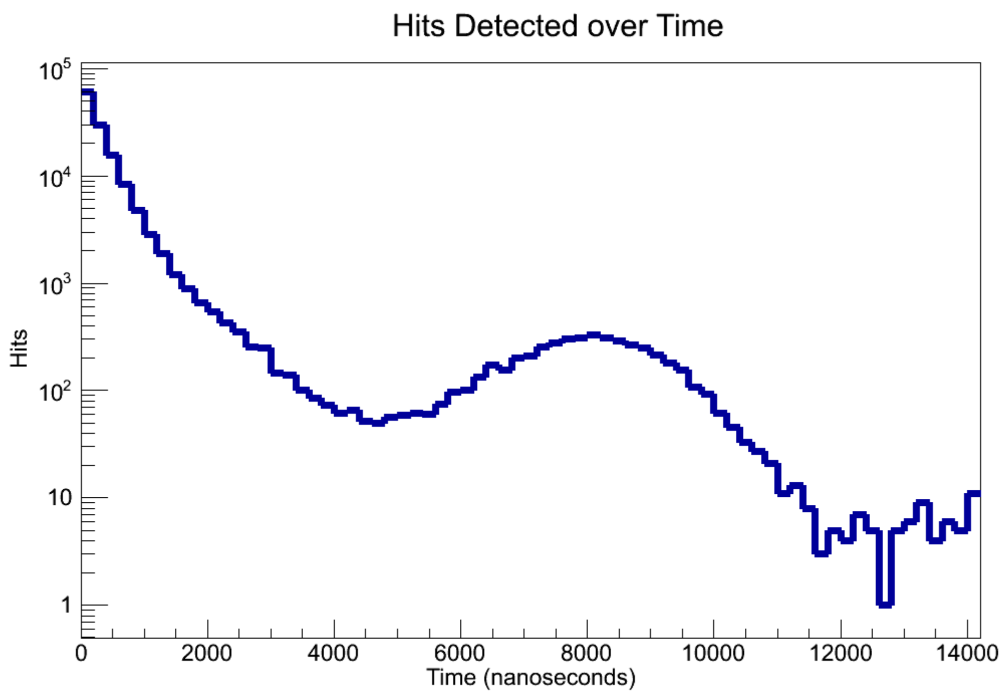

Figure 3.2: Hits versus Time for 125K 50MeV electrons, showing the effects of afterpulsing

Unfortunately, afterpulsing is a significant background. Afterpulsing is when light received in a DOM causes it to register a hit at a later time than it is received. Because of this effect, our exponential fit is marred and becomes inaccurate. To rectify this we can either chose to only accept the first hit received for each particle simulated, or for our fit to range only up to $3000ns$, as the effects of afterpulsing become most noticeable after that time. Fig. 3.3 shows the previous graph in Fig. 3.2 using only the first hit received:

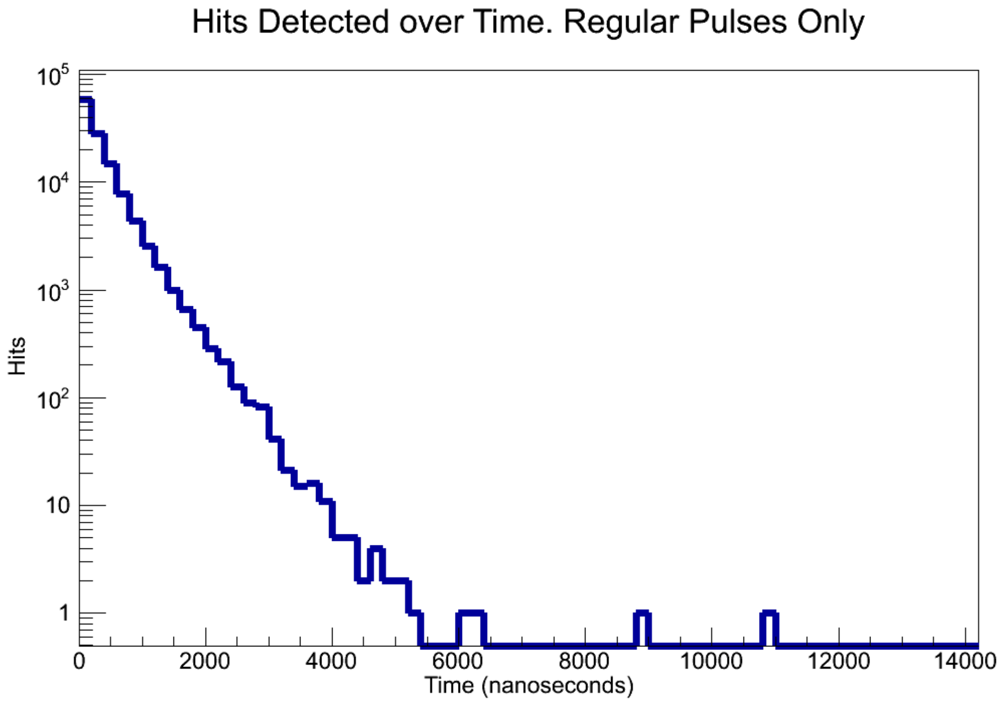

Figure 3.3: Hits versus Time for 125K 50MeV electrons, showing the the removal of afterpulsing

This method, though effective, is not always advisable due to the large amount of hits it removes, so depending on how many hits you are able to eliminate and still receive enough data, the method of using data from the time period where afterpulsing is less significant may be the better option. A third option is to simply remove afterpulsing using truth information, as the simulation records what type of pulse each hit is. Of course, at some point this no longer works, as you cannot look at truth information in real life. In this case, however, it is acceptable as we just want to see the muon decay, so we can take the previously done test of 100k zero energy muons mentioned above, and remove the afterpulsing via the truth information (though, either of the other two methods would have worked as well). Then we add the exponential fit and obtain the graph in Fig. 3.4:

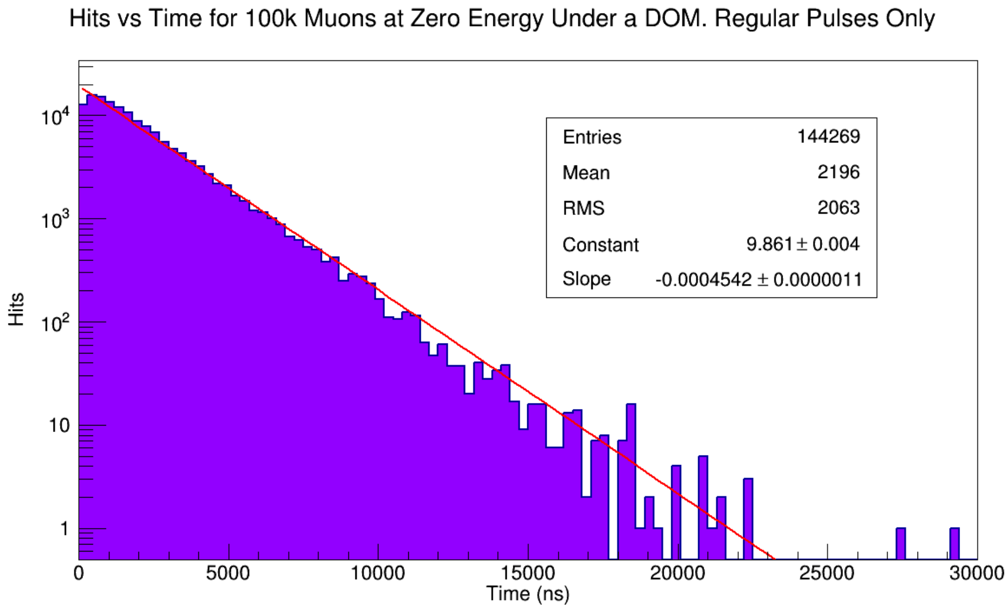

Figure 3.4: Hits versus Time for 100k zero energy muons, showing the fit that we compare with the muon average lifetime.

The fit when afterpulsing is removed has $\lambda = 0.0004542$, which gives

$$\tau = \frac{1}{\lambda} = 2201ns \tag{3.1}$$

This lines up very well with the average muon lifetime, which gives us a way to determine muon neutrino events. However, this was the most ideal situation, where the muon lands very close to a DOM, with no noise, and we don't receive any excess light from the charged current muon neutrino interaction. To determine its viability, we will eventually have to simulate the most realistic possible situation, the next step to this is to use simulation data that starts with muon neutrinos.

3.2 Identifying the Michel Electron using Reconstructed and True Muon Neutrino Information

To do this we take some of the latest muon neutrino simulation data, which has 221369 simulated muon neutrino events. The x-y location of these events can be seen in Fig 3.5:

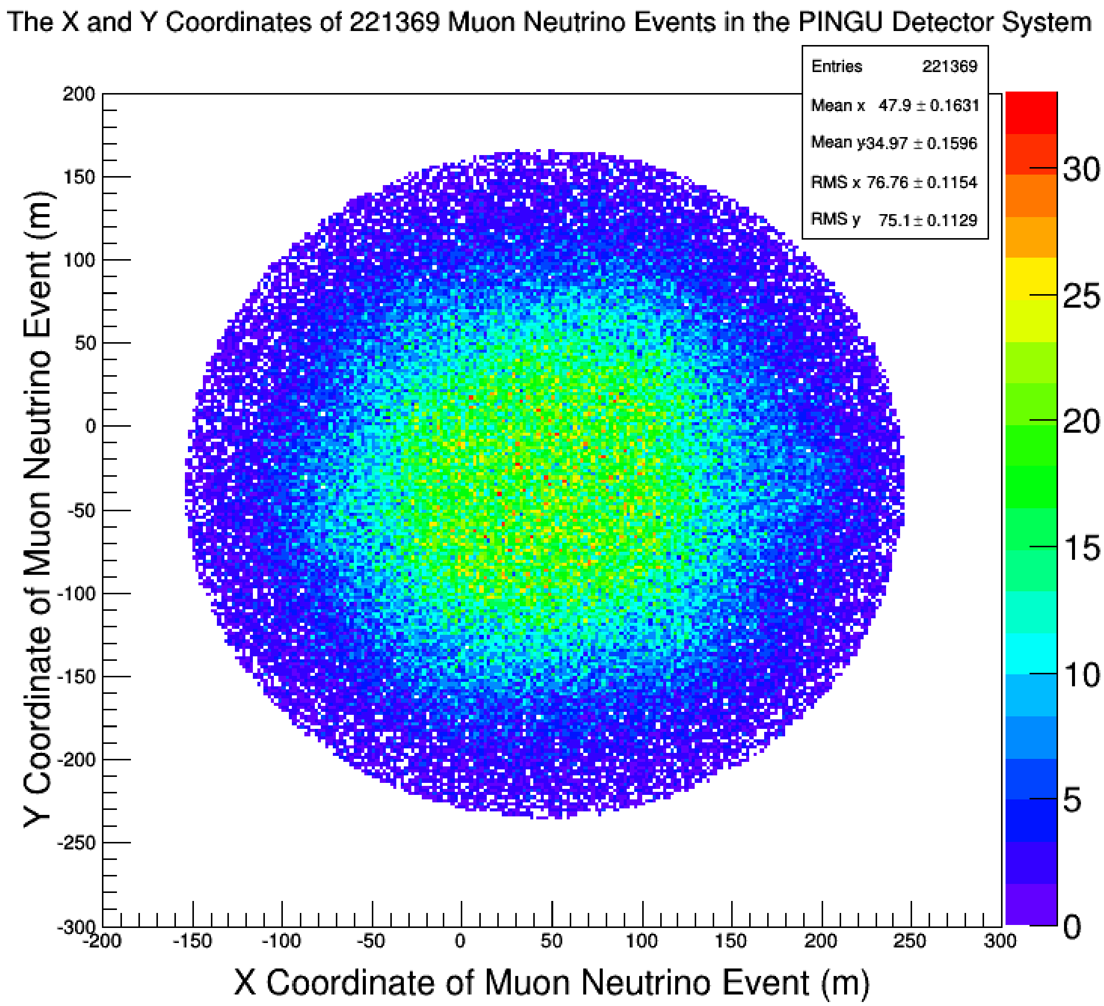

Figure 3.5: The X and Y Locations for each ν_μ event.

It should be mentioned here that the way we simulate neutrino events is different from the simulations I've shown previously. The neutrino flux through the detector system is very high, but the probability that one interacts is very low. So this simulation wasn't made by placing 221369 neutrinos in the detector system and simulating them, but rather by simulating 221369 neutrino events that triggered the PINGU DOMs to start recording data. This is why the X vs Y of the events is not homogeneous, and the largest concentration of events is at the center of the detector system, because a neutrino interaction in the middle of PINGU is more likely to give ample light to our DOMs than one near the edge.

Along with the simulated truth information that is given in this simulation, we also have reconstruction data, which shows how well we'd be able to reconstruct each event. For instance, these are muon neutrinos, so they will be producing track-like events. We can know exactly the energy and direction of the muon created in the neutrino interaction from truth information, but we also have reconstruction data for this based on the light given to our DOMs during the event, which will typically not be exactly the same as the truth data, but is how we actually reconstruct the events in real life. Since we are interested in where the muon from the neutrino interaction stops before it decays, we want to see how well we can reconstruct its endpoint. Now, out of the 221369 events, some will be neutral current interactions instead of charged current, which won't produce a muon, so we already know not to look at those, it's also best to cut based on the reconstructed distance that the muon will travel. Our best reconstructions will typically have the muons traveling between 20 and 35 meters, so that the path isn't too short that it's difficult to reconstruct, and not too long so that the muon doesn't leave the detector system, so we cut all events where the muon isn't reconstructed with a length greater than 20 meters and less than 35 meters. Finally, we apply various standard, more complicated, cuts that eliminate ν_μ events with what seem to be poor reconstructions.

As mentioned, we are interested in how well we can reconstruct the endpoint of the muon created in a muon neutrino interaction. The best way to do this is to make a graph of the distance in meters between the true endpoint and the reconstructed endpoint, in a similar style to Fig 3.1. These graphs are shown in Fig. 3.6 and Fig. 3.7:

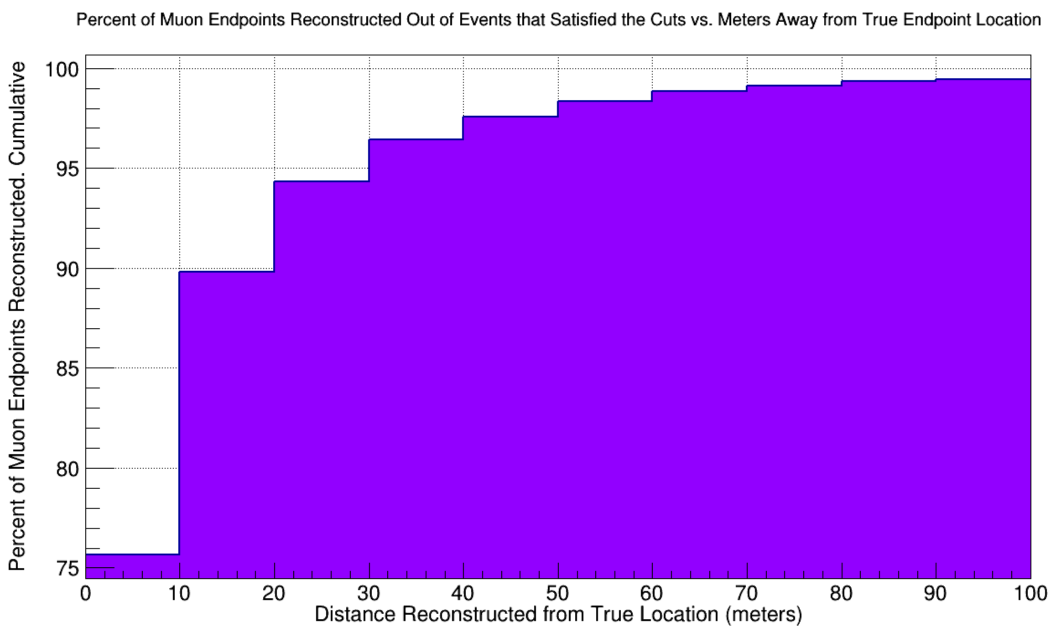

Figure 3.6: The percent of muons reconstructed of (Out of Those Selected After the Cuts) vs the distance they are reconstructed away from the true muon endpoint.

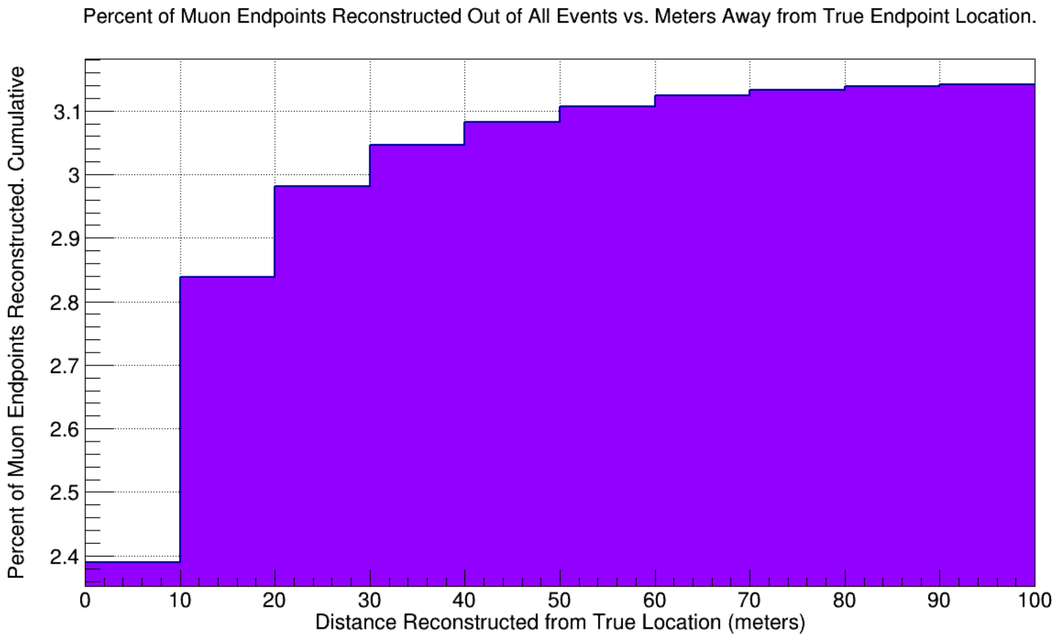

Figure 3.7: The percent of muons reconstructed (Out of Every ν_μ event) vs the distance they are reconstructed away from the true muon endpoint.

After our cuts, we were left with 6994 ν_μ events (roughly 3 percent) where we assume our reconstruction to be satisfactory. From Fig. 3.6 we can see that, out of these events, our reconstruction correctly determined the endpoint of the muon within 10 meters for about 76% of the events, and about 97% within 50 meters. Looking back at Fig 3.1, we can combine our results as follows: If PINGU detects X muon neutrino events per year, then $X * \frac{6994}{221369} = 0.0316X$ events will pass the cuts I applied. Of those, $0.0316X * 0.76 = 0.0240X$ will properly reconstruct the endpoint of the created muon to within 10 meters of its true endpoint. Finally, if we look ten meters away from the reconstructed endpoint, we'll find that $0.0240X * 0.087 = 0.00209X$ of the events will have a Michel electron that gives a hit to a DOM at most ten meters away from the reconstructed endpoint. The final part of this calculation is a little rough, as Fig. 3.1 deals with truth data rather than reconstruction data. However, since there is roughly double the amount of Michel electrons that give a hit to a DOM at most 20m away from their creation than there are Michel electrons that give a hit to a DOM at most 10m away, and the far edge of the 10m sphere around the reconstructed muon endpoint can be, at most, 20m away from the true muon endpoint (the true muon endpoint being the same as the true Michel electron creation point), this is assumed to not be a large issue with this calculation.

Now let's look back at Fig. 3.4 and see if we can recreate it starting from the muon neutrino, rather than zero energy muons. To start with, we'll look at truth data so as to get an idea of what our reconstruction should look like. To recreate Fig. 3.4, we want muons that stop near the underside of a DOM. So we'll define cylinders throughout the PINGU system, each with their top at the middle of the DOM, and their bottom at the middle of the next lowest DOM, so that each PINGU string is fully covered in cylinders. We then look at the truth information for each event, and if the muon created by a ν_μ charged current interaction enters one of those cylinders, we record the hits over time of the DOM directly above it. Unlike Fig. 3.4, where every muon is stationary at $t = 0$, the time at which the muon stops under a DOM will be different for each event here, so we have to set a specific and different $t = 0$ point at the time when the muon stops for each event respectively. This way the beginning of the graph starts when every muon stops, and is the same as Fig. 3.4. The graphs using this idea, with the choice of 5m and 8m for the cylinder radius, are shown in Fig 3.8, and 3.9 respectively:

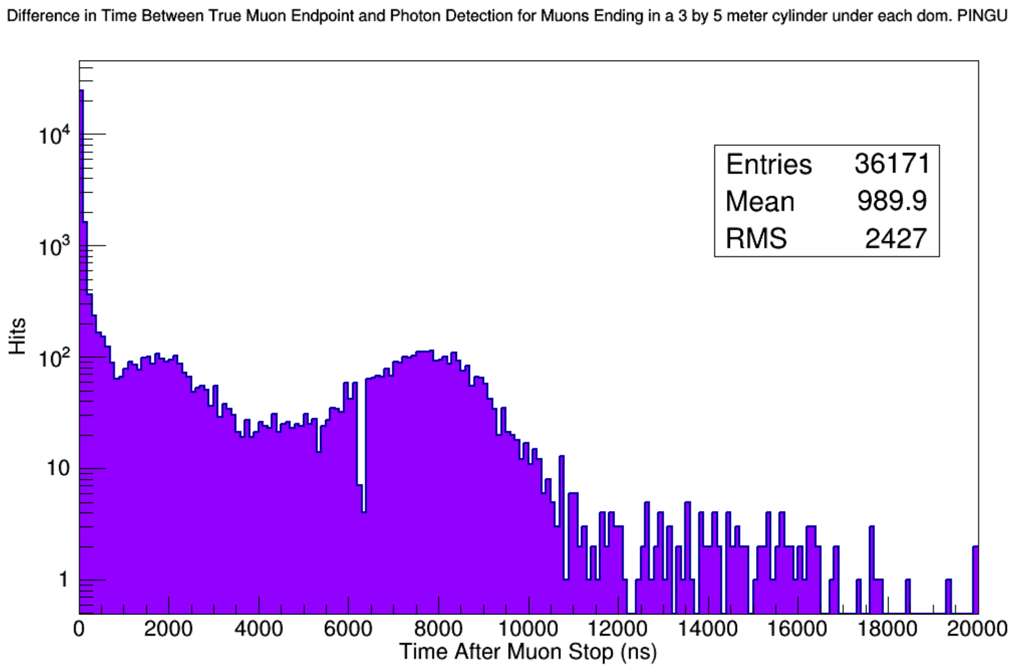

Figure 3.8: Hits vs. Time for ν_μ events where the created muon lands in a 3x5m cylinder under a PINGU DOM. Only using hits from that DOM.

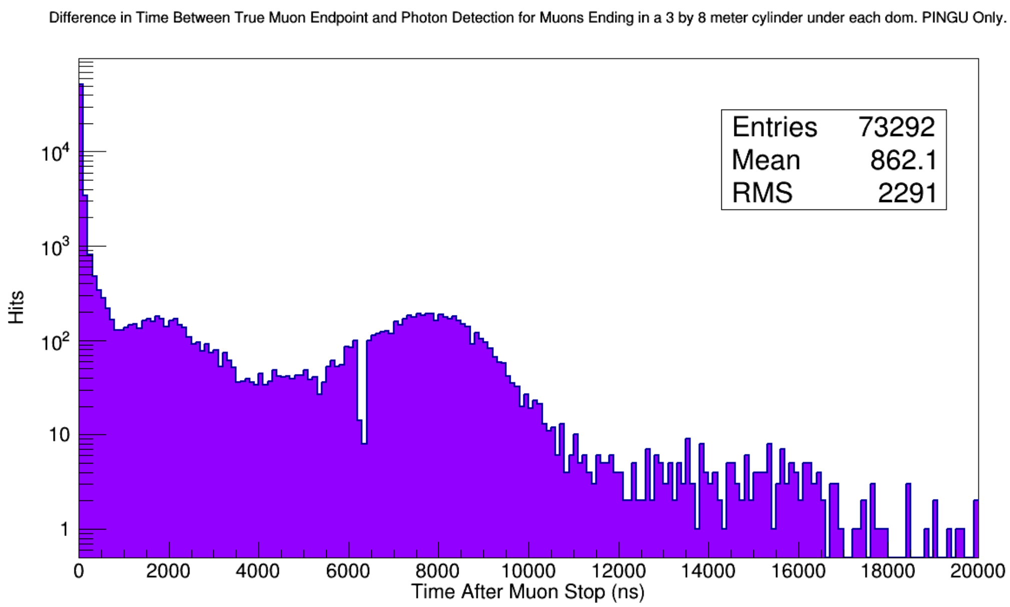

Figure 3.9: Hits vs. Time for ν_μ events where the created muon lands in a 3x8m cylinder under a PINGU DOM. Only using hits from that DOM.

Neither of these graphs seem to show the muon average lifetime in them. To test whether noise (noise in DOMs typically gives hits with less than 1SPE charge, so using a charge cut can eliminate a large amount of it) or afterpulsing is having a significant affect on the results, graphs using the first-hit method or a charge cut-off were made and can be seen in Fig. 3.10, 3.11, 3.12, 3.13 and 3.14:

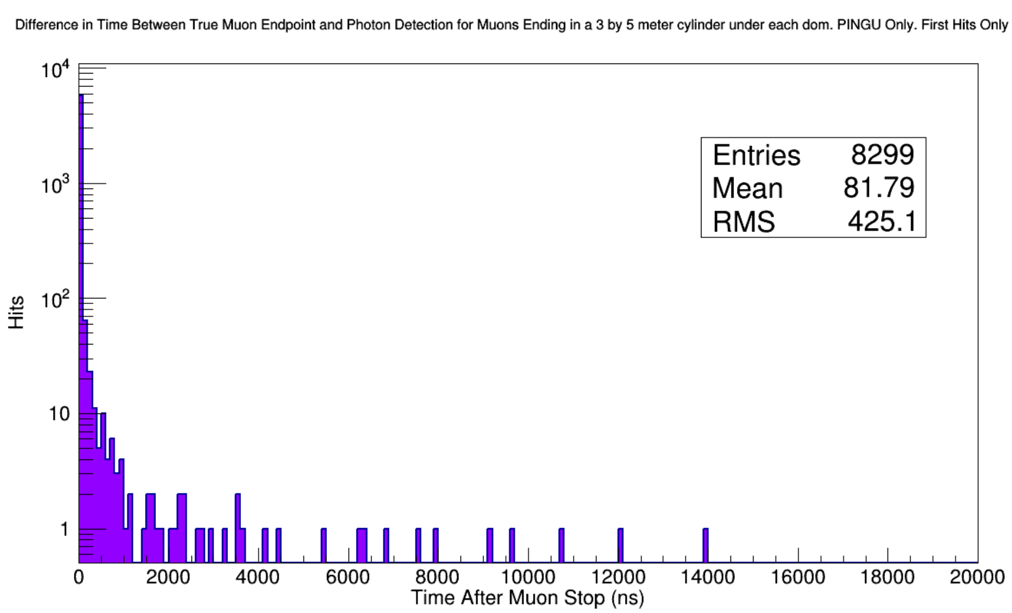

Figure 3.10: Hits vs. Time for ν_μ events where the created muon lands in a 3x5m cylinder under a PINGU DOM. Only using hits from that DOM, and only using first hits.

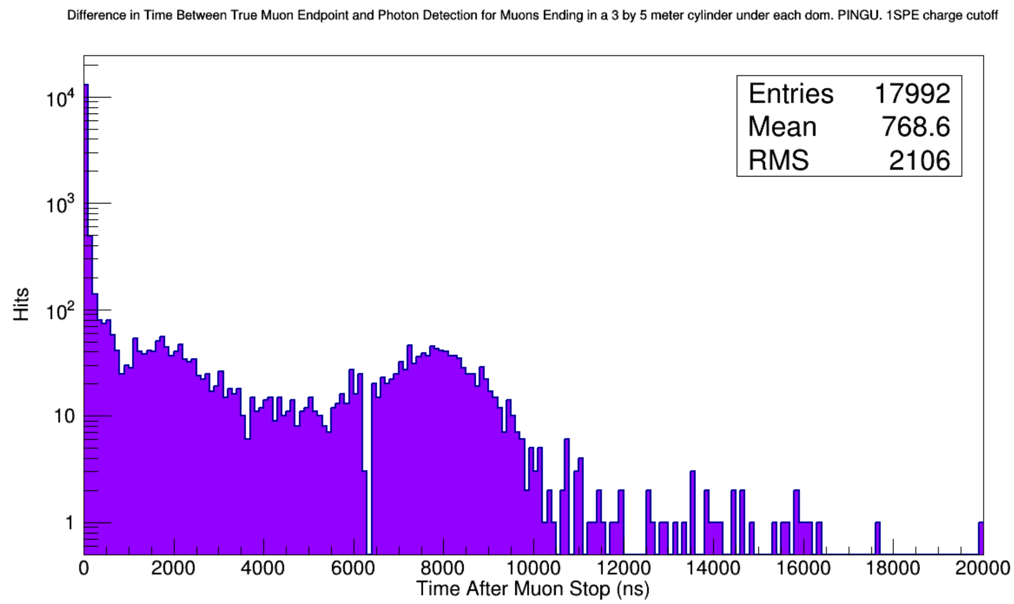

Figure 3.11: Hits vs. Time for ν_μ events where the created muon lands in a 3x5m cylinder under a PINGU DOM. Only using hits from that DOM, with a charge cutoff of 1SPE.

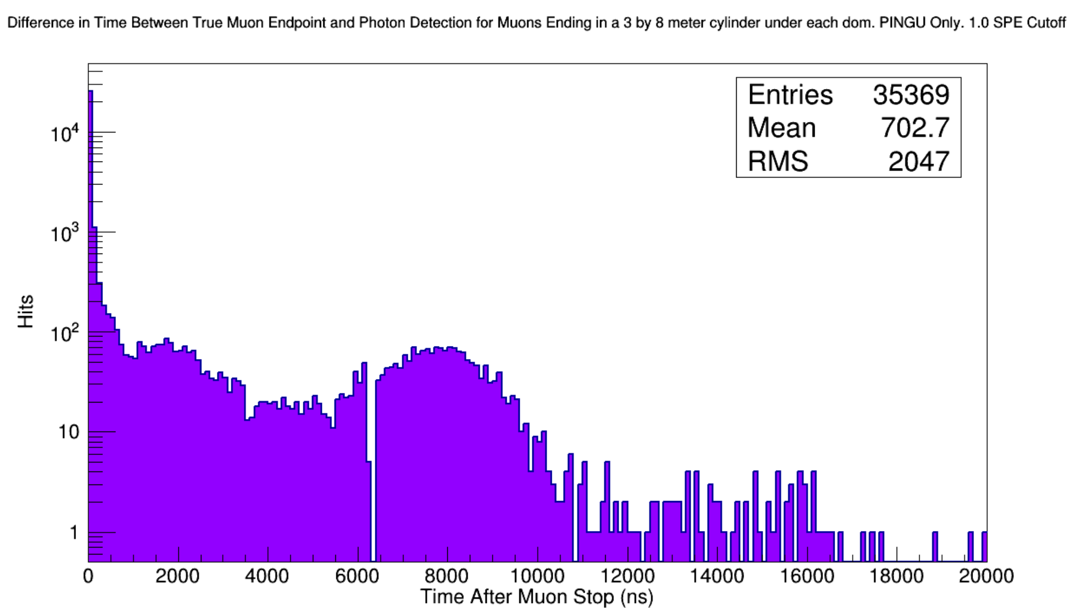

Figure 3.12: Hits vs. Time for ν_μ events where the created muon lands in a 3x8m cylinder under a PINGU DOM. Only using hits from that DOM, with a charge cutoff of 1SPE.

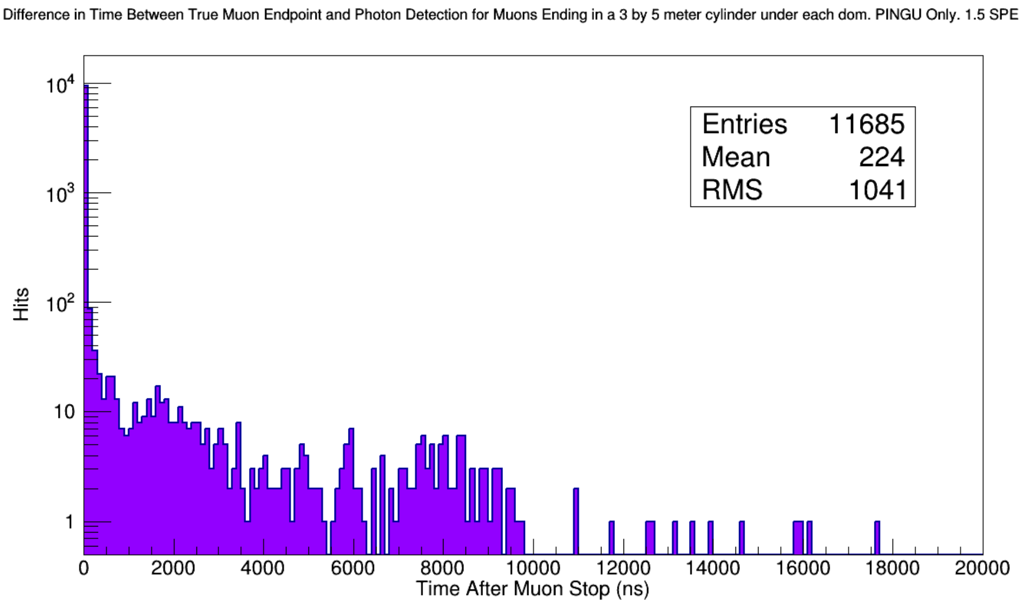

Figure 3.13: Hits vs. Time for ν_μ events where the created muon lands in a 3x5m cylinder under a PINGU DOM. Only using hits from that DOM, with a charge cutoff of 1.5SPE.

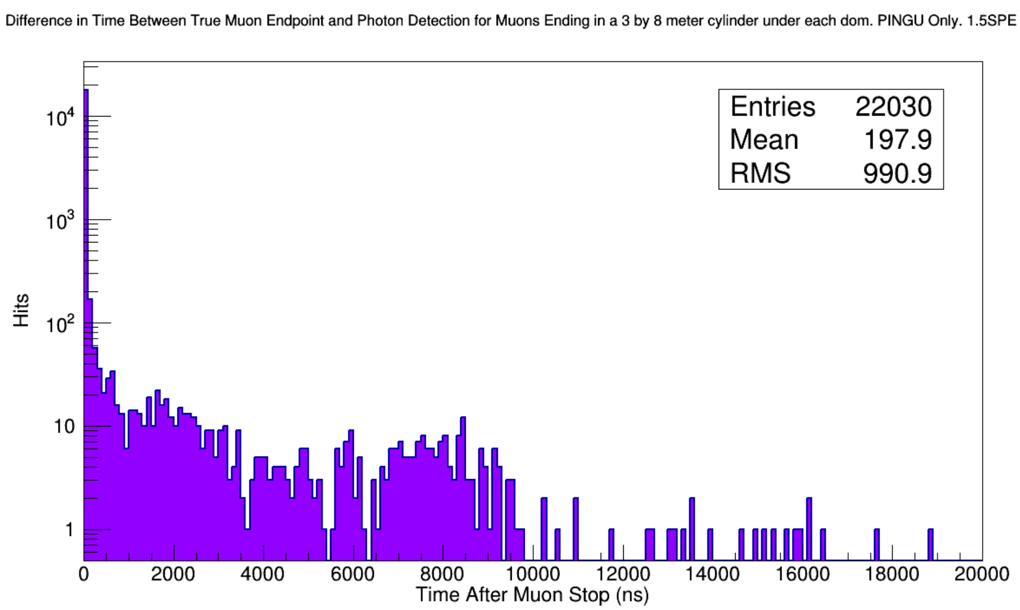

Figure 3.14: Hits vs. Time for ν_μ events where the created muon lands in a 3x8m cylinder under a PINGU DOM. Only using hits from that DOM, with a charge cutoff of 1.5SPE.

Unfortunately, no cuts seem to show any evidence of the muon average lifetime. This might be due to light from the other particles in the system after the ν_μ charged current event, or possibly just that the ending point of the muon needs to be more perfectly under a DOM. The latter could be tested with unlimited data, but shortening the radius of the cylinder quickly becomes too heavy a cut for our 221369 ν_μ events. In any case, it means that we have to reevaluate our method and approach from a different angle.

3.3 An Alternative Method

It is somewhat out of the scope of this thesis, as what was shown previously makes up the main body of my work, but this section will briefly go over an alternative method that might be more fruitful. When the muon created in a CC interaction approaches a DOM, the light from it will be received by that DOM. If the muon then stops near the DOM, a short while later the Michel electron it decays into may also give light to that DOM (probably less than the amount of light the muon gave). This would result in a double pulse structure when looking at the graph of hits over time for that single event on that single DOM. So, if one looks on an event by event basis, one might be able to confirm a ν_μ track-like event by seeing that the double pulse structure is evident in a DOM that the reconstruction says the muon stopped under. With this in mind, I made a program that would create a graph for each event individually that passes the 3x5 cylinder cut discussed previously. Here is a small selection of those graphs, showing both what they typically look like and some more promising events, in Fig. 3.15 and 3.16:

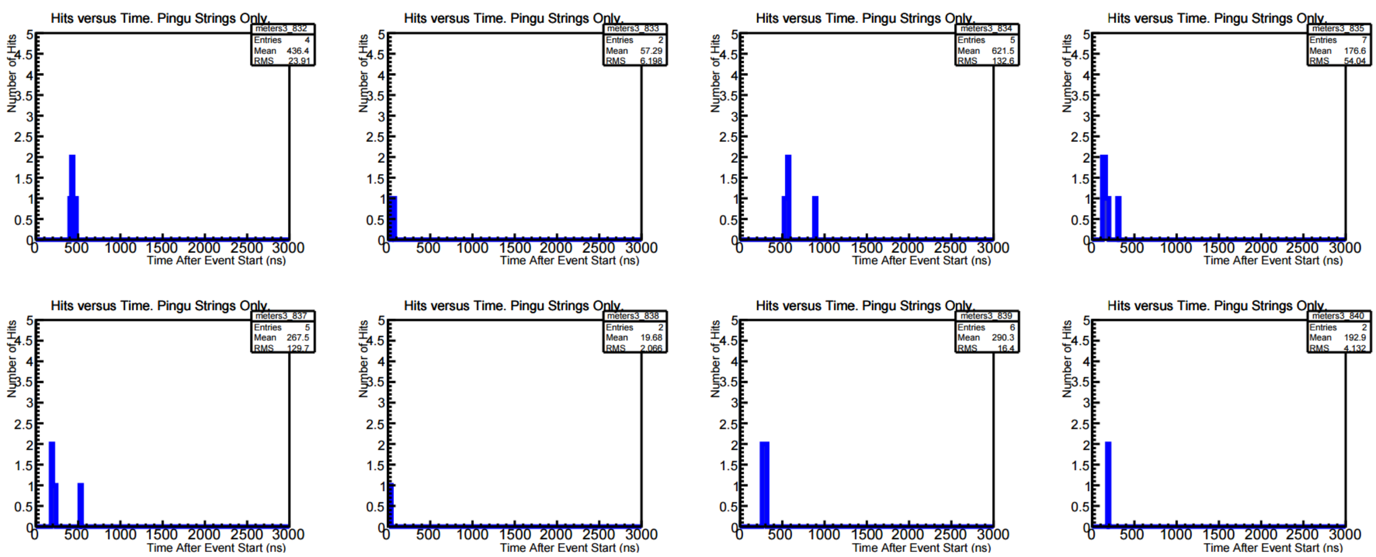

Figure 3.15: Hits vs. Time for eight charged current ν_μ events where the created muon's endpoint is in a 3x5m cylinder under a PINGU DOM. Only using hits from that DOM

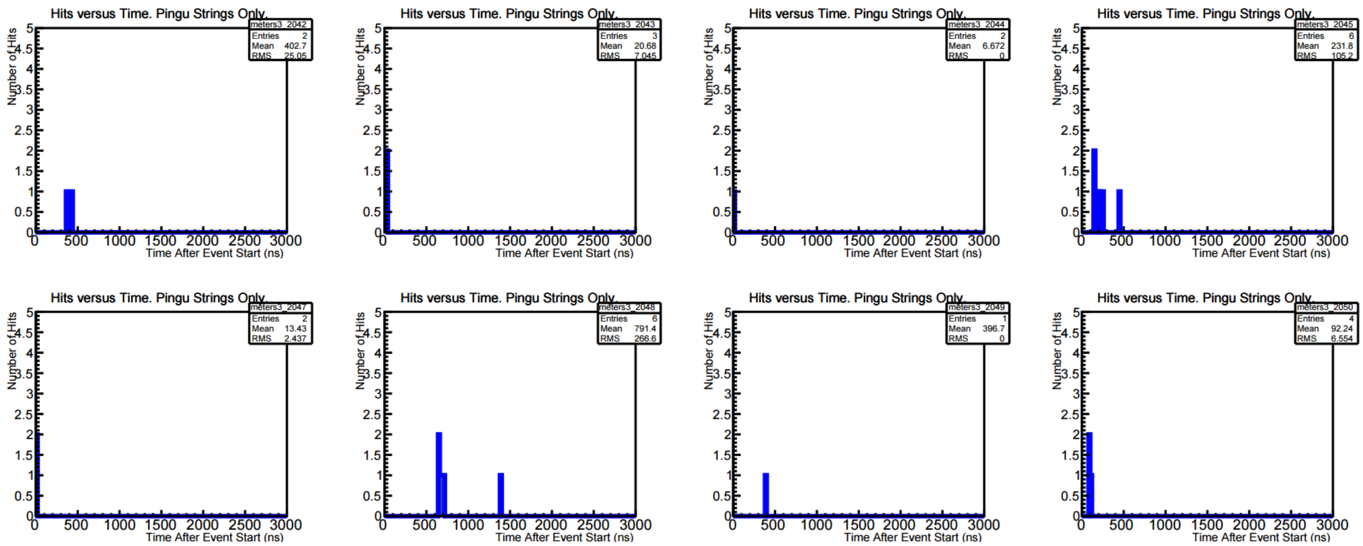

Figure 3.16: Hits vs. Time for eight charged current ν_μ events where the created muon's endpoint is in a 3x5m cylinder under a PINGU DOM. Only using hits from that DOM

Counting from the top-left to the bottom right, in Fig 3.14, events 3, 4, and 5 have a double pulse structure, and events 4 and 6 in Fig 3.15 are promising as well. Given more research into this, one could write code that automatically detects this structure and use that to strengthen and calibrate our reconstructions. I would quickly recommend that, if this is done, to immediately cut the hits by requiring that charge > 1.0, so as to remove noise from the events which could easily cause some of them to have a double-pulse structure due to the low amount of hits we expect from the Michel electron.

Chapter 4

Summary and Conclusion

Neutrinos are a group of three chargeless particles that interact only via the weak force and gravity, which makes them very hard to detect. They have three different flavors that they oscillate between: ν_μ, ν_e, and ν_τ. These flavors define the fundamental particle that they create upon undergoing a charged current interaction. This thesis focuses on the ν_μ, which produces a muon in a charged current interaction, which later decays into a Michel electron. One of the biggest mysteries of the neutrinos is their mass hierarchy, or their relative mass ordering. The IceCube project has led to the world's biggest neutrino detector: a $1km^3$ system located deep in the ice of the South Pole, which has detected three of the most energetic neutrinos ever, among other successes. PINGU is a proposed addition to that detector that would allow it to detect lower energy neutrinos, which would give PINGU the increased sensitivity necessary to measure the neutrino mass hierarchy. Before implementation, we simulate how PINGU will work in the detector system, to determine its ability to measure things like the neutrino mass hierarchy, and to increase its ability to do so by strengthening our understanding of it and changing how it reconstructs via various calibrations and cuts.

To perform analysis of PINGU, I used the simulation of PINGU available on our network, the ROOT data analysis software, and already available ν_μ data (which takes significantly longer to create than regular simulations, due to how ν_μ events are simulated and the added reconstruction data). I found that, given a Michel electron created in the PINGU detector system, it has a 40.3% (8.7%) chance of giving light to one of our doms within 50 (10) meters; that, given the appropriate cuts, PINGU can reconstruct the endpoint of a muon created in a charged current ν_μ event to within 10 meters about 76% of the time; and that these cuts will leave about 3% of the ν_μ events remaining. This means that, given X amount of detected ν_μ events, we will have $0.00209X$ events where we reconstruct the endpoint of a muon created via a charged current interaction to within 10 meters of its true endpoint, and where that muon has produced a Michel electron that gives a hit to a DOM within ten meters of this true endpoint (the true endpoint also being the Michel electron creation point).

The goal was to see if the muon average lifetime could be used to see ν_μ events, as, given a muon created from a ν_μ event that lands under a DOM, if we wait for this muon to decay the Michel electron that it creates may give light to the DOM. If it does, the time that the DOM receives this light will match up with the time of muon decay, and this can be used to calibrate our reconstruction of the event. Initial tests of this seemed to indicate that this method had potential, as putting zero energy muons under a DOM (which will not produce light until they decay) and looking at the hits that this DOM received gives a graph that matches up very closely with the muon average lifetime. However, when tests moved on to using ν_μ data to follow the event from beginning to end and trying to perform the same analysis with created muons that have endpoints close to the underside of a PINGU DOM, we were no longer able to see any evidence of the muon average lifetime. As an alternative to this method, it may be possible to use the double pulse structure, that a muon heading towards a DOM and its subsequent decay into a Michel electron can create, as a method of calibration for our reconstruction.

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