ANITA Detection Simulation

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Abstract

Summary of my work on the simulation of the ANITA detection system.

1 Background

1.1 GZK Neutrinos

GZK theories predict that ultra high energy cosmic rays cannot travel far through space, as they will interact with blue shifted photons from the cosmic microwave background producing a shower of particles, including high energy neutrinos. In this process, the cosmic rays lose enough of their energy that they are no longer considered ultra high energy cosmic rays. From the predicted interaction length of this GZK effect and the lack of local sources of ultra high energy particles, it follows that very few of these cosmic rays should arrive at the Earth. However, these cosmic rays are being detected, so either there is a problem with the GZK theories, or there is a local source of high energy particles. The detection of high energy GZK neutrinos could confirm theoretical predictions, indicating the culprit is a local source of high energy particles, or show that there is a problem with the GZK cutoff theory.

1.2 ANITA

The ANITA detection system is a balloon mounted array of antennas that will be used to detect neutrino interactions in the Antartica ice. Typical balloon flights hug the 80° S lattitude line and circle the continent during a two week period. The payload detects neutrinos by looking for the radio signals emitted when the neutrino interacts and produces Cerenkov radiation through the Askyrian effect. It targets high energy neutrinos, in tne 10^{18} to 10^{20} eV range, typical of GZK neutrinos.

1.3 Monte Carlo Simulation

The original code, written by Amy Connolly, generates a random neutrino interaction point in the ice as well as a random balloon position along the 80° S lattitude line. It finds the direction of the ray that is observed at the balloon having originated at the interaction point, taking as an initial guess the ray from the center of the earth through the neutrino interaction point to the ice surface. Then, it takes the line from the exit point in the ice to the balloon and finds the ray a radio signal would need to follow in order to be refracted to the exit ray and uses that as its new guess. After one more iteration, we have the exit ray directoin to within one meter. Figure 1 shows that this method is indeed converging. Once the exit ray of the radio signal is established, the simulation picks a direction such that the exit ray lies close to the Cerenkov cone that there is a chance in hell of seeing the interaction. The electric field emitted falls off exponentially with the angle from the Cerenkov cone, and beyond a certain angle is undetectable. By comparing the electric field with the trigger threshold for the payload, a maximum angle off the Cerenkov cone where the signal is still detectable is found, and the direction is chosen such that the ray lies within this angle. Without this biasing, the simulation would produce hardly any detectable interactions and would not be particularly helpful. For more complete documentation of the original code, see [3].

2 Plotting Simulated Neutrinos Back to their Sources

The question of where on the celestial sky the experiment is sensitive to is important, as theorists will want to look there for possible sources of high energy neutrinos.

2.1 The TimeConvert class and plotMoll

The locations, dates, and incident angles of each neutrino interaction were stored in the TimeConvert class, written by David Barnhill. This class stores a specific date, time, location, and incident angles, and converts all of this into right ascension and declination.

The actual plots were generated using code adapted from the plotMoll program. Inputting the right ascension and declination, the code gave a mollweide projection of the skymap. plotMoll was written by T. Ohnuki.

2.2 Locations of Interactions

The data from the simulation was given in the form of the balloon's angle ϕ measured from the 90° E longitudinal line, angle increasing as it moves west; the cosine of the angle θ that the neutrino direction makes with the vector from the center of the Earth to the balloon; the angle ϕ_ν which the neutrino direction makes with the east-pointing ray at the balloon location; and the base 10 logarithm of the weight of the event (the weight is a measure of the likelihood of the neutrino interacting in the earth before reaching the ice. Only events with weight > 0.1 are considered.).

Latitude and Longitude In the simulation, the balloon is always considered to be at latitude 80° S. Longitude is calculated by converting the ϕ of the balloon into degrees, then

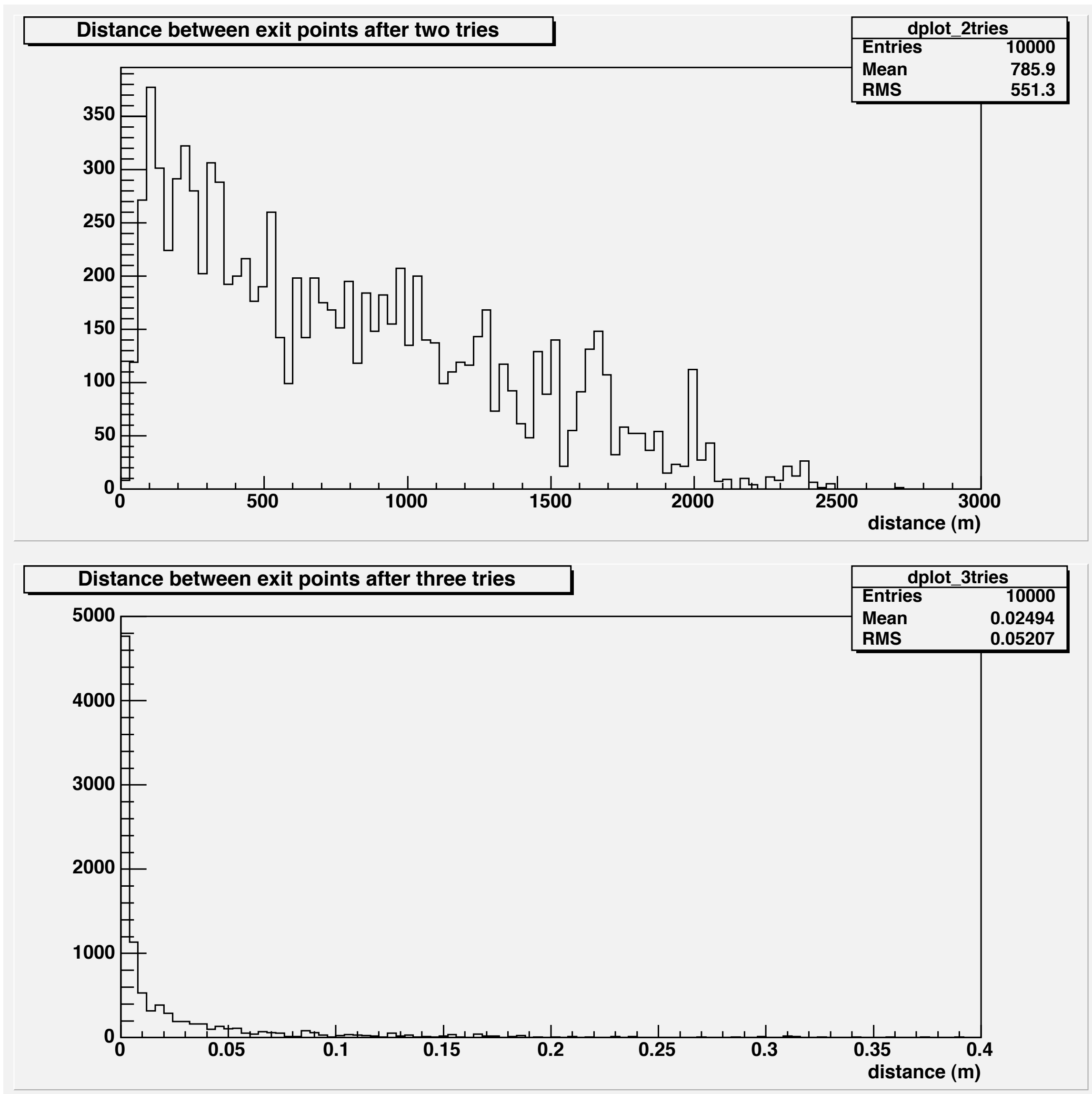

Figure 1: Distance between exit points for recursive method, showing that it is converging.

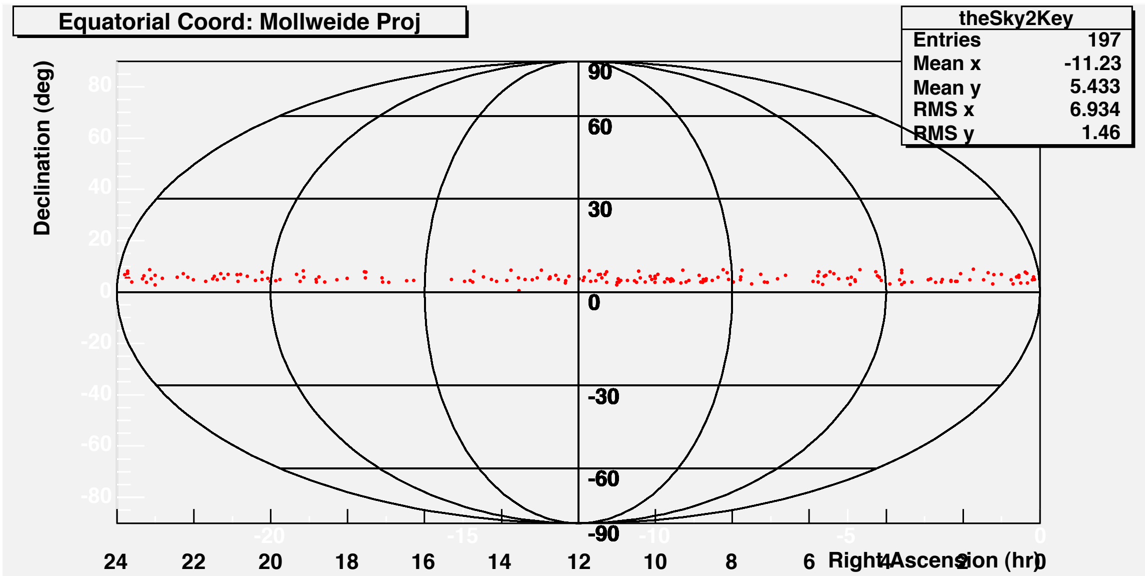

Figure 2: Sources of neutrinos that could be detected by ANITA

subtracting 90°, putting $\phi = 0$ at the prime meridian (in TimeConvert, longitude is measured positive going west).

Date and Time The date and time of the interaction was calculated using the start date of December 17, 2003 at 6:00 UTC. The balloon moves at a constant speed of 1.13924 degrees/hr, chosen such that the balloon will finish its trip in two weeks. Assuming a starting longitude of 0°, the time it reaches each lattitude can be calculated and added to the starting date and time.

2.3 Mollweide Projection

With the location and time extracted from the information, it was converted to right ascension and declination and plotted on a Mollweide projection. Figure 2 shows the sources of detected neutrinos with a 10 percent or greater chance of surviving the trip through the Earth for the simulation. We can look only at these events because percent of the interactions seen have weight > 0.1. The thin band along the 0° declination line is expected, as downgoing (traveling from the south pole towards the north pole) neutrinos are generally not detected due to the geometry, and any that come from higher in the sky would have longer chords to travel through the earth, making it more likely for them to be absorbed. Typical GZK theories predict that the rate of detection is approximately five events per three flights, so this sky map represents data from 120 flights.

3 Incorporating Tau Decay into the Simulation

3.1 ANIS and TAUOLA

Initially, I was directed to the ANIS program [1] as a way of modeling tau decay. The ANIS program, however, is a simulation of neutrino interaction, not of tau decay. ANIS took its tau decay information from a program called TAUOLA [2]. ANIS used a table of ten thousand tau decays and the resulting energy fractions taken by various decay products to model tau decay. The information from this chart is loaded into an array at the beginning of the simulation and used to find the energetics of a given tau decay.

3.2 Tau Decay Probabilities

The lifetime of a tau, here denoted τ_τ, is 260.6×10^{-15} seconds. The probability of a tau surviving for a time t is

$$P_{survive}(t) = e^{-\frac{t}{\tau_\tau}} \tag{1}$$

However, the taus are moving at relativistic speeds, and we are interested in the probability that the tau will decay within a certain distance. The tau is moving at very nearly the speed of light, so first we define

$$L = \tau_\tau c \frac{E_\tau}{m_\tau} \tag{2}$$

Where c is the speed of light, E_τ is the tau's energy, and m_τ is the tau's mass. Now, the probability that the tau will decay in a distance d is

$$P_{decay}(d) = 1 - e^{-\frac{d}{L}} \tag{3}$$

Figure 3 shows the distribution of probabilities of a tau decaying in the ice, given that the tau was produced from a tau neutrino interacting in the ice, from a run of the simulation with the neutrino energy at 10^{19} eV.

3.3 Tau Energy Loss

There are two methods by which the tau can lose energies, radiation and collisions with nuclei. The rate of energy loss from radiation is independent of E_τ, while the rate from collisions is directly proportional to it. Thus, radiation tends to dominate at lower energies, while collisions dominate at higher energies. The energy loss due to radiation is independent of energy, and on order of $10^{12}eV/m$. The rate of energy loss for collisions is

$$\frac{dE}{dl} = 2.16 \times 10^{-6} m^{-1} \times E \tag{4}$$

so the τ energy as a function of distance traveled is

$$E_\tau(l) = e^{2.16\times10^{-6}m^{-1}\times l} \tag{5}$$

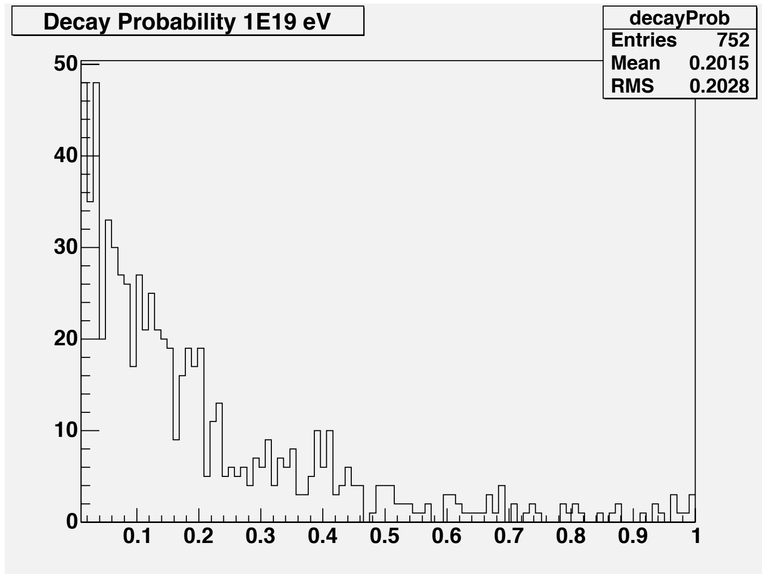

Figure 3: Probability distribution for tau decay with neutrino energy of 10^{19} eV.

The numbers in these equations came from [4]. To find the τ decay probabilities, I divided the distance into 100 intervals, and calculated the energy at the beginning of these intervals. Then, using these energies, I calculated the amount of time spent in each interval in the τ's reference frame, then used the total time to find the probability that the τ would decay inside the distance. At the tau energies and time periods we are examining, neither effect is significant, changing probabilities by only a percent.

3.4 Possible Double Bang Events

There are five possible double bang events.

- The neutrino interacts in the Earth and the tau decays in the ice. Here, only the tau decay is detected.
- The neutrino interacts in the ice and the tau decays in the ice but only the tau decay is detected.
- The neutrino interacts in the ice and the tau decays in the ice but only the neutrino interaction is detected.
- The neutrino interacts in the ice and the tau decays in the ice and both are detected.
- The neutrino decays in the ice and the tau does not decay in the ice. Only the neutrino interaction is detected.

3.5 Detecting Both Interactions

Working with the code already written, the fourth scenario is the easiest to incorporate. Assuming the tau continues in the same direction as the original neutrino (a good assumption at these high energies), once the location of the second decay is found, the code for the neutrino interactions is easily adaptable to the tau interactions.

Finding the Tau Decay Location To find the location, the Monte Carlo acception-rejection technique was used. In this technique, a random number u is chosen, and a random distance d between zero and the distance to the exit point is chosen. If

$$u > 1 - e^{-\frac{d}{L}} \tag{6}$$

where L is defined in equation 2, then another random number and random distance is chosen. This forces the tau to decay in the ice, and also forces the decay lengths to follow an exponential distribution. Figure 4 shows the distance between bangs, time between bangs, and the angle between the exit rays. The distance between bangs follows an exponential curve, as the Monte Carlo technique requires.

Detecting and Weighting the Second Bang The number of times this second bang is actually detected is low, of the tau neutrinos which produce a detectable signal, only 2 percent of the taus produce a detectable signal when decaying. These events are given weight

$$w_2 = e^{-\frac{l}{\sigma}} \times (1 - e^{-\frac{d}{L}}) \tag{7}$$

where l is the chord the neutrino travles, σ is the neutrino cross section, L is defined in equation 2, and d is the distance from the neutrino interaction point to the position where the τ would leave the ice. Figure 3 shows the distribution of tau decay probabilities, which is also a distribution of the weights.

3.6 Events where the Neutrino Interacts in the Earth

Looking for interactions where the neutrino is not detected is more difficult than looking for ones where it is detected, because in the simulation, the direction is biased towards detecting the neutrino interaction, so simply looking at events where the neutrino interaction isn't detected will not yield detectable events. So, for half of the tau neutrinos, the interaction position in the ice is taken as the tau decay. This allows us to count events where the tau decay was detectable in the ice and the neutrino interaction occured in the earth. The direction is chosen such that the tau decay will be detectable.

Finding the Neutrino Interaction To find where the neutrino interaction occurs, the Monte Carlo rejection-acceptance technique is again used, as described in section 3.5. But in

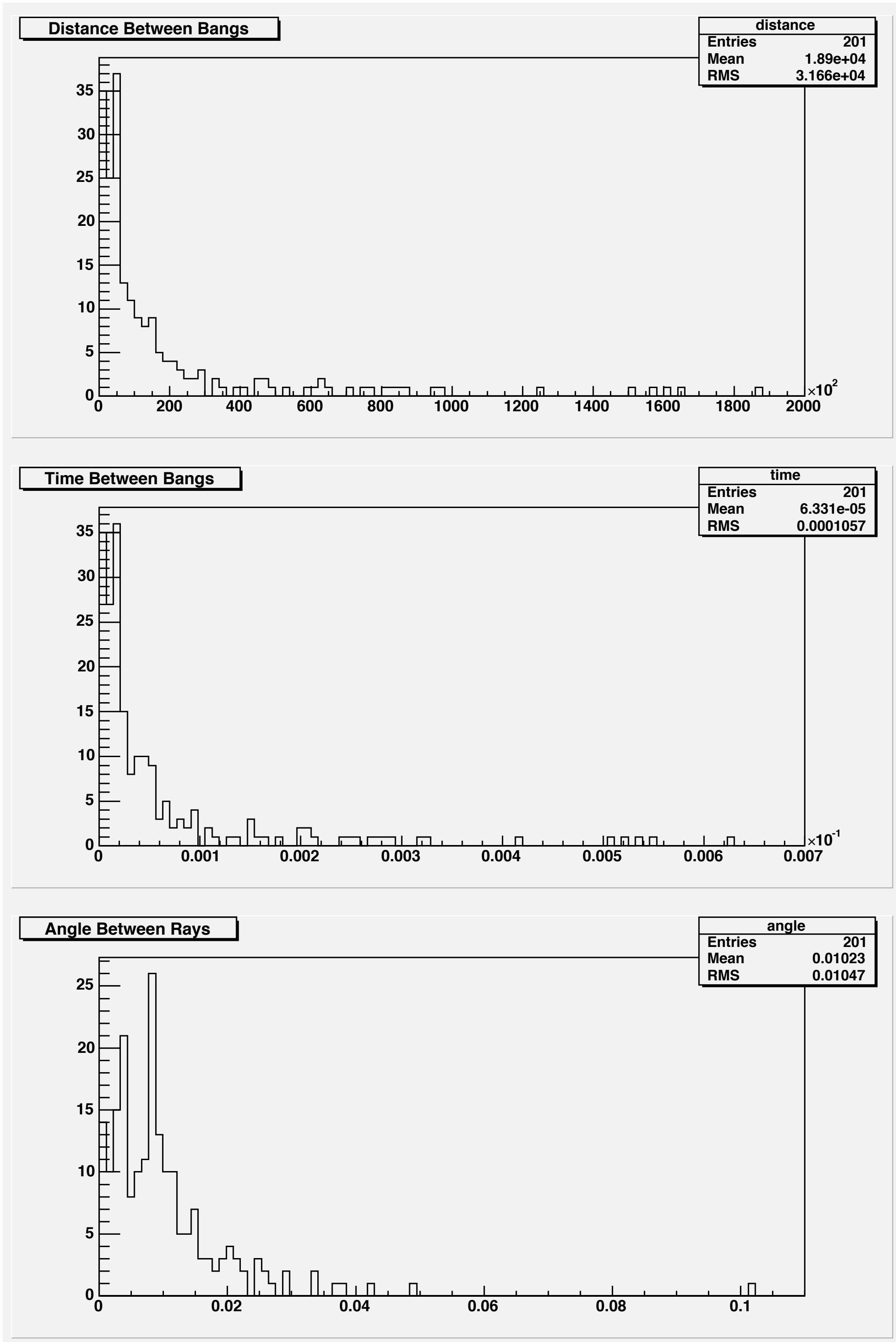

Figure 4: Length between bangs, time between bangs, and angle between bangs distributions for tau decay with neutrino energy of 10^{20} eV.

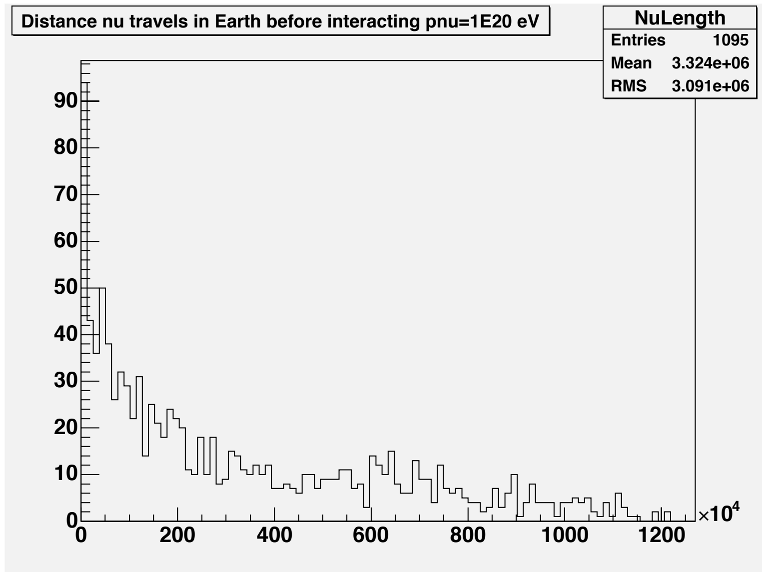

Figure 5: Distance neutrino travels in Earth before interacting, $p_\nu = 10^{20} eV$.

this case, d is between zero and the length of the chord through the earth and u is compared to the probability that the neutrino interacts, so if

$$u > 1 - e^{-\frac{d}{\sigma}} \tag{8}$$

where σ is the interaction length in kg/m^2, then a new u and d are chosen, otherwise that d is used to find the neutrino interaction point. Figure 5 shows the distribution of distances the neutrino traveled in the earth before interacting.

Weighting the Events Weights for the events are found from the probability that the τ will decay at the right position given the location of the neutrino interaction. If the probability that a τ will decay before reaching a distance d is given by equation 3, then the probability that a tau will decay at a given distance d per unit length is the derivative of equation 3

$$P_{decay} = \frac{1}{L} e^{-\frac{d}{L}} \tag{9}$$

where L is defined in equation 2. So the event is given weight

$$w = 2 \times t \times P_{decay} \times (1 - e^{-\frac{l}{\sigma}}) \tag{10}$$

where t is the distance through the ice the tau must travel, P_{decay} is definied in equation 9, l is the chord the neutrino would travel if it did not interact at its interaction point, and σ is the neutrino interaction length. The factor of two comes from the division of the possible double bang events into this case and the case where teh neutrino interaction is in the ice.

3.7 Increase in Sensitivity

The increase in sensitivity from adding these processes to the simulation is measured by the detection volume in km^3sr. The increase from the interactions where we detect both bangs is insignificant, less than a tenth of a percent. Adding this process only shows that we can see these spectacular double bang events. The τ decay events where the neutrino interacts in the earth dominate the increase in detection volume. At $p_\nu = 10^{19}eV$, this process increases the sensitivity by 6.2 ± 0.986157 percent.

4 Checking the Simulation

Comparing the results of the simulation against reality is important because if the simulation does not behave like reality, it is worthless. One way to check is to plot energy against fraction of events detected for each type of neutrino. Disregarding tau decay, at high energies the fraction of events detected should be equal for all three neutrino types. As energy decreases, the fraction of events seen which are electron neutrinos should increase because all the decay products of the electron are detectable while only the hadronic portions of the mu and tau neutrinos are detectable.

$$\nu_e + n \rightarrow e^- + X_{had} \tag{11}$$

$$\nu_\mu + n \rightarrow \mu^- + X_{had} \tag{12}$$

$$\nu_\tau + n \rightarrow \tau^- + X_{had} \tag{13}$$

Most of the energy goes into the e^-, μ^-, or τ^-, but only e^- and X_{had} are detectable, so at lower energies mu and tau neutrinos are more difficult to detect since most of their energy goes into products which cannot be detected.

With tau decays included, the tau neutrino fraction should be higher at high energies, as the tau can also be detected. At lower energies, it should drop off, as lower energy taus are harder to detect.

Figure 6 shows the fraction detected for each type of neutrino versus energy both with and without tau decay.

5 Acknowledgements

I'd like to thank Professor David Saltzberg and Amy Connolly for mentoring me (despite their periods of abscence). I'd also like to thank NSF for funding the REU and Francoise Queval for organizing the entire experience.

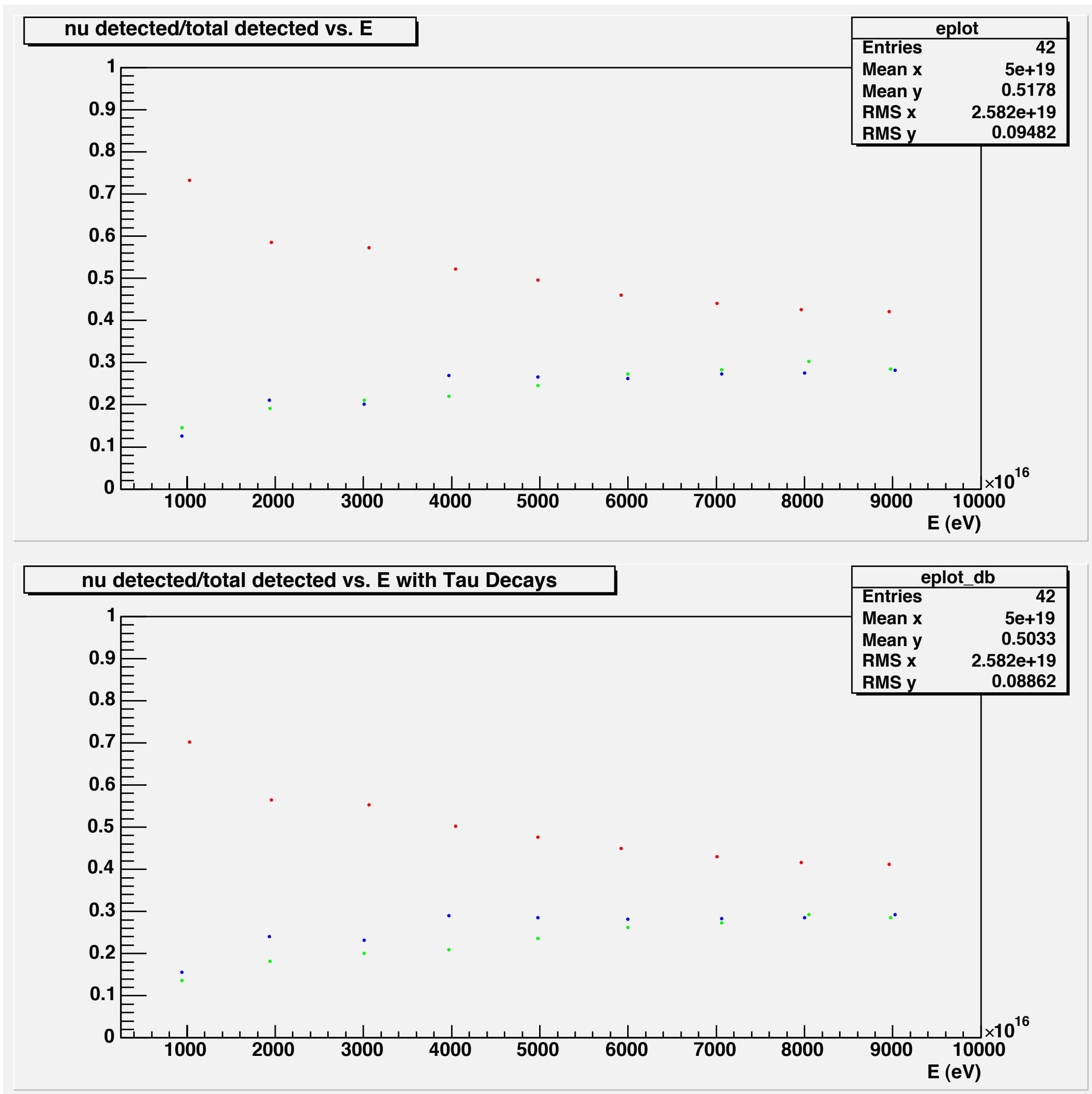

Figure 6: (a) Fraction of events seen without tau decays, (b) fraction of events seen with tau decays. Red is ν_e, green is ν_μ, and blue is ν_τ.

References

[1] ANIS (All Neutrino Interaction Generator), http://www.ifh.de/ mkowalsk/anis/html/

[2] Was, Z. Tauola Program, http://wasm.home.cern.ch/wasm/Welcome.html

[3] Connolly, A. and Saltzberg, D. Summary of a Simulation of the ANITA Detector, http://www.physics.ucla.edu/ connolly/icemc.ps

[4] David Saltzberg, personal communication.