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TAU NEUTRINO DOUBLE BANG MIMICS WITH ICECUBE

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Abstract

Astronomy and particle astrophysics with the IceCube Neutrino Observatory benefit from tau neutrino detection. Tau neutrinos produce distinct, nearly background free electromagnetic showers within the volume of IceCube which may be reconstructed to find extragalactic point sources. Some of the properties of neutrinos useful to astrophysics are reviewed before discussing the importance of the tau neutrino in particular. The tau neutrino events occurring within the IceCube detector may be distinguished from other neutrino events by a characteristic electromagnetic cascade known as a "double bang". The reconstruction of these tau neutrino 'double bang' events may benefit greatly from calibration provided by flashing LEDs within IceCube to simulate the effect of the electromagnetic cascade generated by creation and annihilation of a tau lepton.

Flasher LEDs were deployed in situ in Digital Optical Modules and are utilized to recreate the "double bang" conditions. Although the search for the double bang tau neutrino event geometry with existing flasher data provided a few useful events for configuration, the possibility of creating a larger calibration data set was explored. A Monte Carlo simulation shows a quadratically increasing relationship between the number of actively flashing IceCube modules and the number of expected calibration events. Further analysis of previous flasher data showed a linear dependence on the number of launch channels triggered by an LED flash and both the brightness and module depth. Using the prior flasher data a novel data run utilizing 120 modules was run on January 14, 2011.

The large scale flasher run produced 21 tau neutrino mimic events. Further investigation revealed that the online trigger used to filter the events was suboptimal due to a strong dependence on the number of launch channels and radial distance from the center of IceCube DeepCore. The linear relationship between flasher radial distance and the number of launch channels provides a clear parameter for configuring a larger and more efficient flasher run in the future.

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1 Introduction

Neutrino astronomy opens a new window into the cosmos. Massive clouds of matter hide large portions of the sky, rendering much of the sky inaccessible to contemporary radio astronomy. Neutrinos, on the other hand, rarely interact with matter and carry cosmological information directly to Earth. Neutrinos born in the vicinity of gamma ray bursts, supernovae, active galactic nuclei, and exotic massive particle decays travel directly to Earth while charged particles are deflected. It is hypothesized that the neutrino flux will be highest from the direction of such high energy events such as black holes and supernova explosions [1].

The IceCube Neutrino Observatory at the South Pole observes the Cherenkov radiation resulting from neutrino collisions with antarctic ice. The three known "flavors" of neutrino - the electron (ν_e), the muon (ν_μ), and the tau (ν_τ) are assumed to be created in the ratio 1:2:0, respectively. Neutrinos should arrive at Earth with a flavor ratio 1:1:1 due to neutrino oscillation [2].

The search for energetic cosmic events profits heavily from the detection of ν_τ emission. Only distant sources significantly contribute to ν_τ flux since at relevant energies a ν_e or a ν_μ produced in the atmosphere must travel much farther than the Earth's diameter to oscillate into a ν_τ. The lack of astmospheric background distinguishes the tau neutrino from the other neutrino flavors in terms of astronomical importance. Locating high energy processes such as active galactic nuclei benefits from the accurate detection of ν_τ events within IceCube.

The reconstruction or analysis of events taking place within IceCube utilizes the precise timing information associated with the arrival of Cherenkov radiation at the different photomultipliers within the detector. Depending on the times at which the data acquisition system within IceCube recorded radiation at specific photomultiplier tubes, information such as the trajectory of an incoming ν_τ may be reconstructed. This crucial time and intensity information for incoming radiation must be calibrated for accuracy.

This paper considers whether flashing LEDs already deployed in the IceCube detector may be utilized to generate event geometry similar to the geometry of an interacting ν_τ for calibration purposes. Past flasher runs as well as Monte Carlo computer simulations demonstrated that flasher data has the ability to generate data useful for ν_τ event configuration. A flasher run reaffirmed the results of our Monte Carlo simulation by producing numerous ν_τ mimic events.

1.1 Neutrinos

The second half of the 20th century heralded the discovery of a family of particles known as the neutrinos. Wolfgang Pauli first proposed the existence of neutrinos to explain the apparent violation of energy and momentum conservation in radioactive decays in 1930 [3]. Neutrinos were integrated into the Standard Model as massless lepton charge characters, but despite the theory's internal consistency, these particles remained illusory for over twenty years before detection.

Detecting neutrinos proved troublesome due to their small interaction cross section and the relative abundance of background radiation. Despite these difficulties, in 1953 Clyde Cowan and Frederick Reines began a project to prove the existence of the neutrino using a liquid scintillator experiment to record the production of gamma rays produced as a result of the interaction

$$\bar{v}_e + p \to n + e^+ \tag{1}$$

Cowan and Reines overcame of the small interaction cross section of the hypothetical neutrino by moving their apparatus deep underground and close to a nuclear reactor since the flux (Φ) of incoming radiation exponentially decays with respect to depth (x) and interaction cross section (σ) $\Phi(x) = \Phi_0 e^{-\rho\sigma x}$ and nuclear reactors produce copious amounts of ν's. Cowan and Reines' liquid scintillator provided compelling evidence for the existence of a neutrino which couples to the electron (the electron neutrino) ν_e [4]. Experiments later found that at least two other neutrino flavors exist in addition to the ν_e [1,2].

The neutrino family consists of three flavors which correspond to the flavors of the three charged leptons: the electron, the muon, and the tauon. According to contemporary particle physics each of these neutrino flavors couples to its associated lepton by means of the weak force charged current interaction given by the Feynman vertex in FIG. 1 [3].

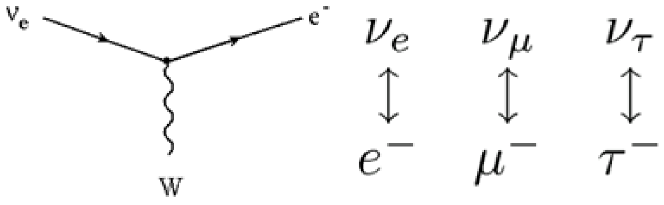

FIG 1: Charged current weak interaction involving an electron neutrino and an electron

These charged current interaction vertices allow observers to associate a lepton flavor with the incoming lepton and also help to explain small neutrino interaction cross sections. At sufficiently high energies the small interaction cross sections vary linearly with energy ($\sigma \propto E_\nu$). One may observe the linear relationship between neutrino energy and neutrino cross section for ν_μ in FIG. 2 [3].

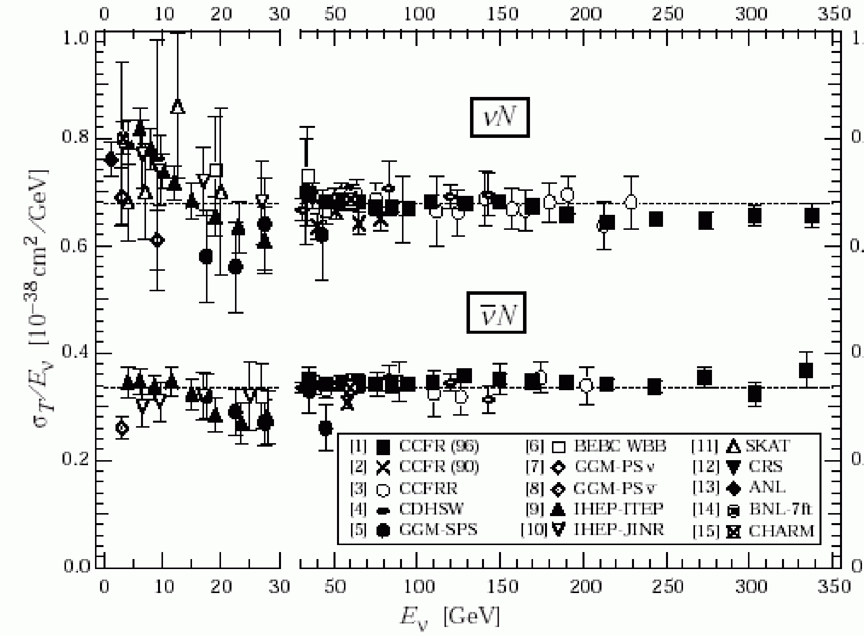

Figure 39.10: σ_T/E_ν, for the muon neutrino and anti-neutrino charged-current total cross section as a function of neutrino energy. The error bars include both statistical and systematic errors. The straight lines are the averaged values over all energies as measured by the experiments in Refs. [1–4]: $= 0.677 \pm 0.014$ $(0.334 \pm 0.008) \times 10^{-38}$ cm^2/GeV. Note the change in the energy scale at 30 GeV. (Courtesy W. Seligman and M.H. Shaevitz, Columbia University, 2001.)

FIG 2: Neutrino cross section per unit energy versus neutrino energy approaches a constant value at large energies. The flat curve shows that σ_ν increases with E_ν [3].

Although the tiny interaction cross section of the neutrino presents a technical challenge for observation, it also gives neutrino astrophysics its allure. The small interaction cross section allows neutrinos to pass almost entirely uninhibited through interstellar matter and to transmit astronomical information to Earth. Its also possible that these small interaction cross sections might be hiding new physics beyond the Standard Model.

1.2 Neutrino flavor oscillation

Shortly after the discovery of the neutrinos, Bruno Pontecorvo hypothesized the existence of a unitary relationship between neutrino mass and flavor eigenstates [5]. The relationship between mass and lepton eigenstates known as flavor mixing would evolve according to the standard evolution operator $U(x) = e^{-ipx}$ producing neutrino flavor oscillations. Under a neutrino flavor oscillation a neutrino changes lepton flavor (i.e. $v_e \rightarrow v_\mu$). A remarkable consequence of relativity, momentum conservation, and the unitary transformation described is the emergence of apparent mass differences for oscillation neutrinos. The general result for the oscillation probability $P(v_l \rightarrow v_{l'})$ which may be computed using elementary quantum mechanics obeys the form

$$P(\nu_l \rightarrow \nu_{l'}) \propto sin^2(\frac{\Delta m^2}{4E}L) \tag{2}$$

where $\Delta m^2 = m_2^2 - m_1^2$ is the mass squared difference between two mass eigenstates, E is the neutrino energy, and L is the neutrino baseline distance [3]. Although the Standard Model assumes that neutrinos are massless, the existence of a unitary flavor transformation would indicate that at least two of the three known neutrino flavors would have mass.

In 1968 Davis, Harmer, and Hoffman found the first evidence of neutrino oscillation using an induced beta decay process $\nu_e + {}^{37}Cl \to {}^{37}Ar + e^-$ [6]. Davis and colleagues measured a solar electron neutrino flux significantly smaller than expected from the existing solar model. Additional evidence for neutrino oscillations have emerged in recent years from detectors such as Super Kamiokande which has seen a sinusoidal dependence of ν_μ interaction rate with $\frac{E}{L}$ as predicted by equation (2) [7].

Neutrino oscillation phenomena do not arise from the Standard Model of particle physics. In this way neutrino oscillations provide some of the first evidence for the limitations of the particle physics ideas which took center stage during the 20^{th} century.

1.3 Tau neutrinos

The third generation neutrino, the tau neutrino ν_τ, derives some striking properties for research at the edge of neutrino astrophysics. While ν_e and ν_μ commonly arise in nuclear processes, ν_τs appear far more rarely. One may expect extragalactic neutrinos to be created in the ratio ν_e:ν_μ:ν_τ = 1:2:0. The existence of flavor oscillation then implies that extragalactic neutrinos should arrive in the ratio 1:1:1 by (2) for $L \to \infty$. For recent experimental evidence one may see [8]. On the other hand, equation (2) surpresses oscillation into ν_τ for neutrinos created by nearby sources.

Consequently, ν_τ particles detected at experiments such as IceCube come almost entirely independent of background noise. Whereas ν_e and ν_μ come with significant atmospheric neutrino and atmospheric lepton radiation. One may be fairly certain that ν_τ arriving at the IceCube detector orginated at a highly luminous intergalactic sources such as active galactic nuclei or supernovae. Properly identifying the source of a ν_τ requires that a candidate reconstruction algorithm efficiently and accurately discern ν_τ events. The reconstruction algorithm must further reproduce the incoming angle of the interaction ν_τ.

In practice a ν_τ may be identified by its unique topology. During a charged current interaction a ν_τ exchanges a W boson with detector matter to produce a charged τ lepton along with a shower of other light emitting hadrons produced in the collision. The high energy τ particle travels from its point of creation at nearly the speed of light in vacuum until decaying in another shower. The resulting event topology may be characterized by two flashes of light produced during the shower of charged particles. By observing "double bang" events one may hope to find strong evidence for the 1:1:1 ratio for extragalactic neutrinos, while at the same time pin pointing the sources of these messenger particles. We may consider the conditions for detecting a "double bang" in the IceCube neutrino detector.

1.4 Double bang events

The twin flash of light characterizing a ν_τ interaction provides a useful criterion for determining whether an interaction has occurred within IceCube. A ν_τ with an energy of 2 - 20 PeV may produce a number of event topology variations within IceCube's effective volume: the double bang, the lollipop, the inverted lollipop, the sugardaddy, and the double pulse [9]. A double bang event should have a space (Δx) and time (Δt) separation obeying

$$|\Delta t - \frac{\Delta x}{c}| < \delta t \tag{3}$$

where δt represents the allowable deviation from light-like separation and c is the speed of light in vacuum. A double bang event satisfying (3) may be thought to correspond to a ν_τ, however events with this topology may be generated artificially by means of LED flashers. The purpose of this work is to find or create artificial tau neutrino double bang events for the purpose of improved tau neutrino event resolution.

2 Neutrino astronomy with IceCube

The IceCube Neutrino Observatory resides primarily beneath 1450 m of ice at the geographic South Pole. The observatory includes over 4800 digital optical modules (DOMs) both above and below the Antarctic ice. The DOMs in surface tanks constitute an air shower array capable of observing the flux of incoming cosmic rays, whereas the in-ice DOMs accomplish the task of neutrino detection. Beginning at the depth of 1450 m below the surface 80 strings of 60 DOMs each comprise an array which spans 1 km^3 [2]. The observatory includes an additional 6 strings of densely packed (7 m spacing) DOMs known as the IceCube Deep Core. With the addition of the DeepCore, the IceCube array may resolve neutrino events down to energies of 10 GeV [10].

The construction of IceCube commenced in the Austral Summer between 2004 and 2005. IceCube improves upon its predecessor known as the Antarctic Muon And Neutrino Detector Array (AMANDA) in both size and optical module design. The IceCube DOM increases measurement fidelity by digitizing and time-stamping incoming analog waveforms detected within the photomultiplier tube (PMT) equipped to each module. The original geometry configuration for IceCube with 80 strings is IC80, and with the addition of the 6 DeepCore strings the geometry configuration is IC86. Due to the construction of the detector, some of the data analyzed in this thesis comes from a pre-IC86 configuration. Consequently, effects which depend on geometry related factors such as DOM density may see shifts in the final detector. In section 3 we analyze data using a pre-IC86 geometry while in section 4 we look at recent data collected from the completed detector. A picture of the full detector including the DeepCore may be seen in FIG 3 [2].

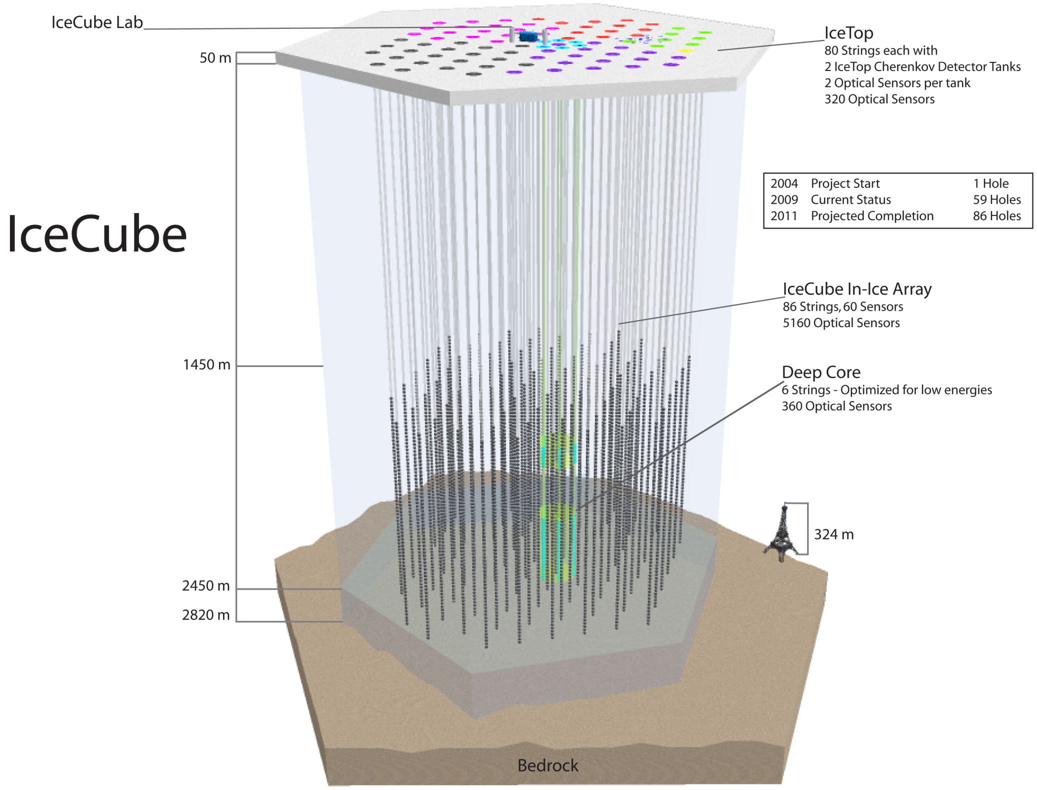

FIG 3: Artist's rendition of the IceCube array [2]

The detector capitalizes on the availability of a large volume of transparent ice to transmit Cherenkov radiation created by charged particles moving faster than the speed of light in the medium. By observing the time at which light reaches different DOMs, a reconstruction algorithm attempts to recreate the fermat surface of the Cherenkov cone eminating from the path of a charged particle moving through the detector. DOMs enable this feat by recording the intensity of light arriving at each

PMT as a function of time.

2.1 Detector geometry

The detector geometry plays an important role in data analysis and event reconstruction in IceCube. Reconstruction algorithms require information about what happened, when, and where. The detector geometry consists of the information concerning 'where' individual DOMs are located within the detector. DOMs are assigned X, Y, and Z coordinates in reference to an origin within the detector along with other useful information for different analysis. DOMs are spaced fairly evenly throughout the detector array. Modules are separated by horizontal distances of 72 or 125 meters and by vertical distances of 17 or 7 meters as may be seen in FIG 4. The regular layout of the array permits one to know the general X,Y,Z location of a module based on its string number and its ordered position on the string. As in FIG 4 the X and Y coordinates correspond to a particular string and the Z coordinate corresponds to a particular module along that string. It is convenient when discussing IceCube data to refer to DOMs by a combination of string and number (string:number i.e. 13:24). The coordinate geometry associated with DOMs forms the essential basis for detecting ν_τ mimic events since one must be able to compute the distance Δx between any two flashing DOMs.

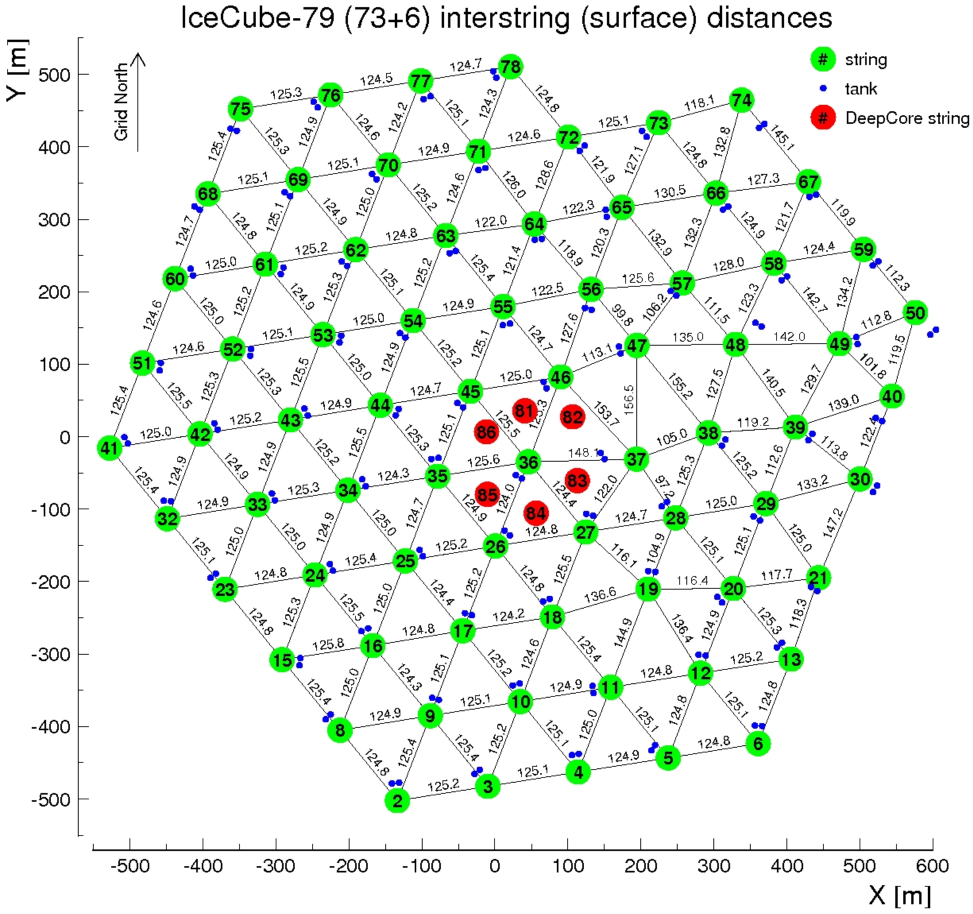

FIG 4: String spacing in the IceCube X,Y plane (IceCube Collaboration)

2.2 Observing events through Digital Optical Modules

IceCube data acquisition starts with DOMs. Each DOM possesses a photomultiplier tube (PMT) capable of detecting the arrival of Cherenkov light. Once a photomultiplier tube has been triggered the DOM digitially encodes the incoming electromagnetic waveform using two analog to digital converters. This triggered or hit launched DOM immediately signals its neighbors. If nearby DOMs indicate hits simultaneously a local coincidence has occurred and all DOMs begin transmitting recently digitized on-board waveform data (FADC and ATWD) to the data aquisition system (DAQ) at the surface. The DAQ decides if a relevant physical event has occurred and should be recorded to disk. The DAQ stores astrophysical data in the .I3 IceCube format which may be further analyzed by scientists in the Northern Hemisphere. These I3 files are transferred from the South Pole by satellite [11].

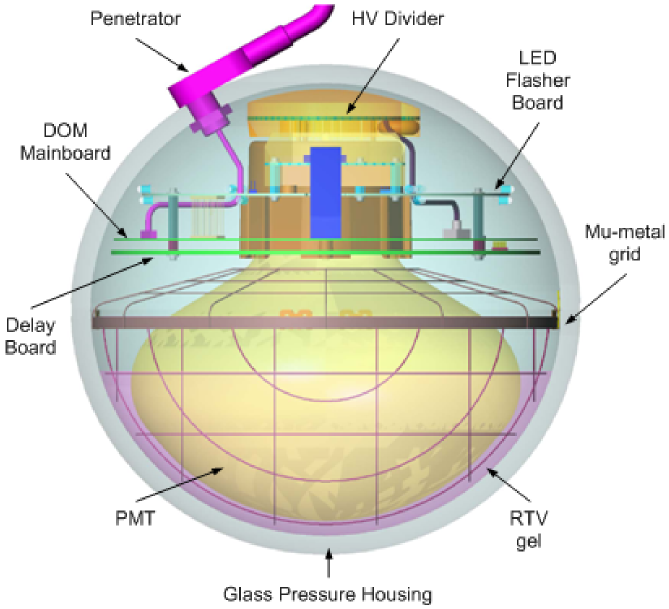

FIG 5: Diagram of a Digital Optical Module (IceCube Collaboration)

The Digital Optical Module with its primary components may be seen in FIG 5. Aside from the PMT and the waveform digitizer circuits, the DOM also includes an LED board. The station operators at the South Pole may signal individual DOMs to begin flashing LEDs at variable positions, brightness, and rates. After the deployment of each IceCube string, flashers were used to map out the relative locations of DOMs in the ice by measuring the time required for light leaving a flashing LED to reach an adjacent DOM. Each DOM contains 12 gallium nitride LEDs pointing radially outward from the DOM. This LED flasher board system is able to produce from 10^7 to 10^{10} photoelectrons, which is enough to illuminate a large portion of the detector. These LEDs are not only useful for mapping out the geometry of the detector however, they may also be used to mimic the geometry of ν_τ events. A ν_τ-like flasher event can have geometry similar to a ν_τ cascade, but with additional location about the position and time of the two pulses which is useful for testing and refining reconstruction algorithms.

The behavior of a flashing DOM relies on the LED bitmask, brightness, and frequency values. The bitmask consists of a 12 bit number which signifies which LEDs will be "on" while the LED brightness is a 7 bit number from 0-127 which determines the relative luminosity of an LED bulb. A bitmask number containing k 1s and $12 - k$ 0s would correspond to k LEDs being lit. The frequency with which these LEDs may flash is determined by the internal oscillators onboard the DOMs. It is important to consider that in practice these oscillators are not identical and DOMs set to the same frequency flash at slightly different rates. Not only do the relative rates differ, but in some cases the rates vary. Later sections focus on attempts to find or create "double flashes" similar to tau neutrino double bangs.

3 Searching for flasher double bangs

Calibrating the IceCube data acquisition system to accurately reconstruct ν_τ events requires some model events. The LED flashers equipped to IceCube DOMs provide a suitable means to generate IceCube data. As discussed in section 1.4, ν_τ events may be characterized by two flashes of light (a double bang). By instructing multiple DOMs to flash at regular intervals, eventually two DOMs will flash close enough in time and satisfy the condition specified in equation (3). The information detected around an event satisfying the criterion in equation (3) may be compared with expectations. The difference in the expected event topology may be compared with the topology of the reconstructed empirical data.

The simplest approach to locating these calibration pairs involves passively collecting data from a flasher run and then performing an offline analysis. The applicability of this approach relies chiefly on two factors. The number of flashing DOMs necessary to produce a sizable sample of calibration events must not be too high, and the average time between calibration events must not be too long. Furthermore, in an ideal case two DOMs will flash with nearly the same period (within a few nanoseconds of each other) so that multiple calibration events may be extracted from a single pair. However, since the times at which DOMs begin flashing during a flasher run are random, it is unlikely an ideal pair will crossover. During a calibration event the crossover of two DOM periods happens slowly enough that at least one pair of flashes satisfies equation (3).

3.1 Past flasher run analyses

The event analysis necessary to find a ν_τ mimicking event may be performed offline on data acquired during a flasher run. I utilized the IceTray software suite produced by the IceCube collaboration to study the data produced at the South Pole during flasher runs. IceTray provides a reliable framework for manipulating and parsing a large amount of physical data in a fairly straight forward manner. Within this context I was able to search through records of flash times, flash frequencies, photon arrival times, physical module positions, and other run related information in order to find potentially interesting events. Data files arrive dense with encoded data which must first be processed using IceTray.

IceTray provides a programmer with numerous modules which operate on a unit of data called a frame. A frame represents data collected within a 40 μs time window. The South Pole DAQ inspects a continuous stream of data, most of which is noise, until an interesting physical event occurs. Upon detecting an event, the DAQ reads out all data within its buffer from 40 μs surrounding the physical event to output. IceTray provides feature extractor modules for opening an IceCube data file, interpreting the raw binary data, and filling the IceCube frames with useable information. After these IceCube events have been written back to disk they may be processed.

Within an IceCube file each frame contains either physics, geometry, or other information pertinent to data analysis. These frames may be processed in Python by accessing the IceTray framework. The example code below examines a physics frame in search of LED flasher data.

```
if "I3EventHeader" and "flasher" in frame:
  eventHeader = frame["I3EventHeader"]
  frameStartTime = eventHeader.StartTime.GetUTCDaqTime()
  frameID = "%d.%d.%d" % (eventHeader.RunID, \
    eventHeader.SubRunID, eventHeader.EventID)
  self.record.updateTime(frameStartTime)

  flasherMap = frame["flasher"]
  for flash in flasherMap:
    flashtime = flash.GetFlashTime()
    omKey =  flash.GetFlashingOM()
    self.record.addOM(omKey, flash.GetRate())
    self.events.append(flashtime + frameStartTime,\
      self.positions[omKey], self.record, frameID, \
      frame, omKey)
```

A natural reduction to the data from the South Pole flasher runs may be performed by reading data files event by event and totaling the number of DOMs flashing within the time window of the event. Since a tau lepton crosses the entirety of the IceCube detector in a few microseconds, a pair of flashes mimicking a tau event must occur within the same event frame (within 40 μs). These particular events may then be written to disk for further study. A reconstruction from a frame with two flashes may be seen in FIG 6. The DOMs in FIG 6 are an example of a candidate flasher pair for

ν_τ calibration.

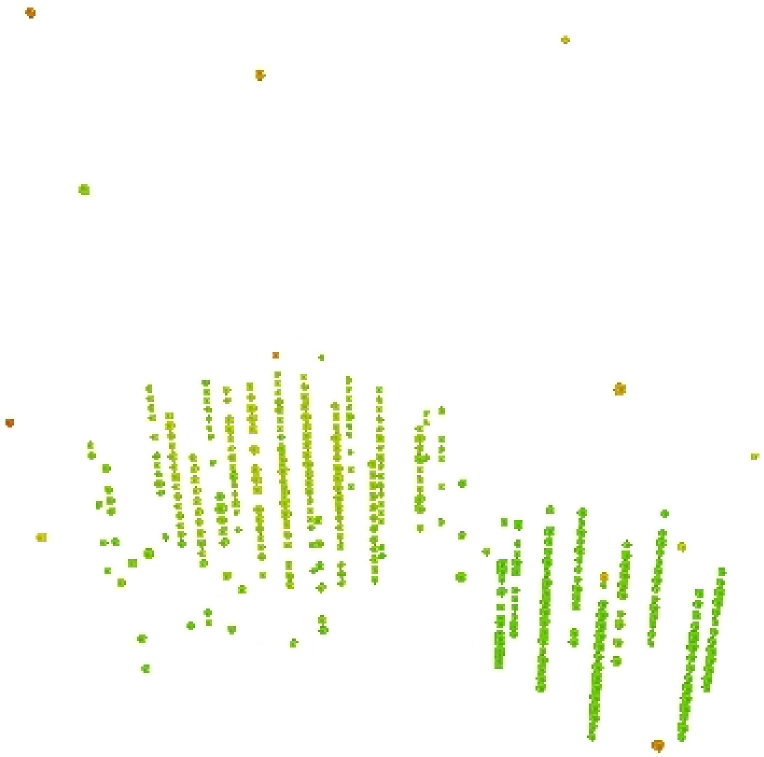

FIG 6: Reconstruction of a tau neutrino mimic event. Colored points denote light triggered DOMs. Colors denote arrival time.

Table 1: ν_τ mimics found in runs 114431, 115615, 115617

Run ID	Active DOMs	Two Flashes	ν_τ Mimics	Duration (s)
114431	17	456	3	1059
115615	4	0	0	1055
115617	11	340	3	1174

The search for ν_τ mimic events in past data proved successful for two data runs. However, the limited number of ν_τ mimic events fell short of the desired amount. Table 1 shows the number of active modules, the number of events containing multiple flashers, the duration of the runs, and the number of ν_τ mimics detected. The findings of this study prompted a Monte Carlo investigation into its results.

3.2 Flasher run simulation

Computer Monte Carlo simulations help develop a concrete understanding of the relationship between different adjustable parameters and the average number of tau neutrino mimics expected during a flasher run. By basing simulation variables on values seen at the South Pole and producing expectations we compared simulation predictions to the number of mimics seen at the South Pole. These flasher simulations used the number of flashing or active DOMs N_{dom}, DOM flasher periods, DOM positions, and run duration to compute the number of tau neutrino mimics created N_{ν_τ}.

Computer Monte Carlo simulations allow a concrete understanding of the relationship between the number of active DOMs N_{dom} and the average number of tau neutrino mimic events created $\bar{N}_{\nu_\tau}$. A simulation written in Python used realistic detector parameters to predict the number of candidate tau mimicking pairs in a fixed length data run. The simulation model considered the detector geometry, DOM flasher period, and the number of DOMs. Since DOMs in IceCube flash at slightly different rates, the simulation assigns DOMs randomized periods according to a gaussian distribution. The empirical data from previous flasher run data contained the information necessary to compute a realistic standard deviation in this flasher period.

After generating a randomized list of N_{dom} DOMs with realistic coordinate positions and flasher periods, the simulation takes discrete steps forward in time determining whether two or more flashes would have occurred within the IceCube trigger window of 40 μs. The flasher periods and beginning times are selected according to a gaussian distribution taken from the prior data analyzed in section 3.1. Two simulated flashes occurring within the same 40 μs window are referred to as double flashes. Additionally, flashes separated according to equation (3) constitute ν_τ mimic events. Since the number of ν_τ mimics (N_{ν_τ}) observed during one simulated flasher run varied greatly, we instead instead report the average result of 1000 runs for each value of N_{dom}.

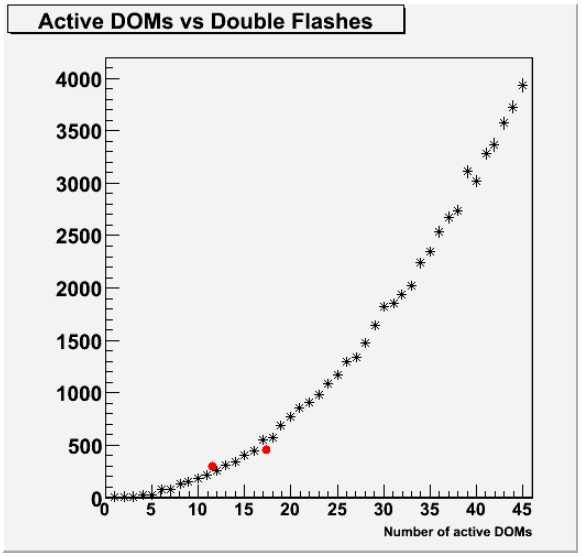

FIG 7: Simulated N_{dom} vs events with two flashes

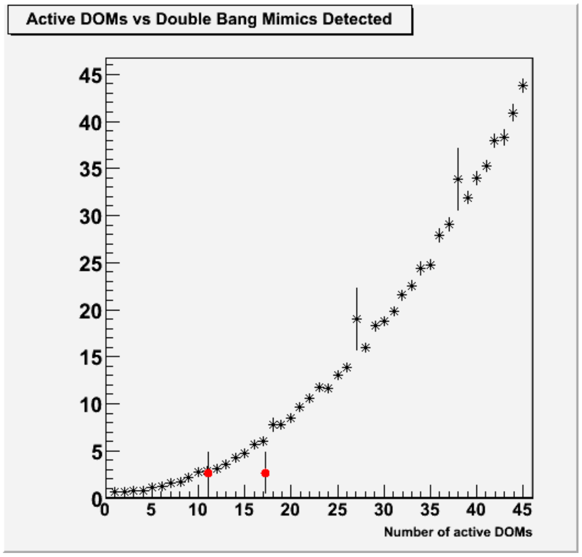

FIG 8: Simulated N_{dom} vs $\bar{N}_{\nu_\tau}$

Various Monte Carlo simulations were run for a simulated time of 1100s to explore the relationship between the number of expected ν_τ mimics ($\bar{N}_{\nu_\tau}(t = 1100s)$) the number ($N_{dom}$) and positions of DOMs. No difference in $\bar{N}_{\nu_\tau}(t = 1100s)$ was observed for algorithms which chose DOM locations according to geometries such as cylinders, spheres, or homogeneous DOM placement configurations. A plot of the number of expected mimic events for arbitrary DOM number N_{dom} may be seen in FIG 7 and FIG 8 with observed data overlaid in red. Consequently, it is seen that the average number of ν_τ mimic events $\bar{N}_{\nu_\tau}(t = 1100s)$ varies according to the formula:

$$\bar{N}_{\nu_\tau}(t = 1100s) = 0.02 \times N_{dom}^2 \tag{4}$$

3.3 Filtering flasher events based on N_{chan}

According to the results of section 3.2, to create a statistically significant number of tau neutrino mimics, say twenty, one must employ a large number of flashing modules. Flashing so many modules at the same time presents a potential problem. A limit exists on the amount of events which may be recorded by the DAQ in a short period of time, or in other words the DAQ bandwidth is limited. Every time an LED flash occurs within IceCube, the DAQ collects all observed data within a 40 μs time window. As a consequence bounds may be placed on the number of events which may be collected each second. The bandwidth necessary to record events in IceCube during a flasher run, B, will be proportional to the number of recorded events N_E times some unit of data $B \propto N_E$. However, the vast majority of events contain only a single flashing DOM so that most bandwidth is wasted.

This project approached the bandwidth constraint in a conservative way by attempting to minimize the bandwidth wasted during flasher runs. Recording fewer events would certainly allow one to better harness the available bandwidth. The method proposed to reduce the number of events recorded by the DAQ was to require a sufficiently high number of launch channels (N_{chan}) before recording an event. Under this scheme an event with a high N_{chan} is considered to contain two LED flashes. An investigation into the number of hit modules or N_{chan} demonstrated that the number of modules hit by two DOMs flashing in unison equals the number the two DOMs hit separately. Some figures demonstrating this effect may be seen in 9. This simple result confirms basic intuition about the difference in N_{chan} for two DOMs and one N_{chan}. One may also see from FIG 9 that the number of modules hit by a DOM differs from module to module.

Further analysis suggested three significant factors influencing N_{chan} for a flashing DOM. These factors include the brightness, flasher bitmask, and module depth as discussed in section 2.2. The brightness and flasher bitmask refer to which LED lights a module flashes and how intensely they radiate and combine to determine the luminosity of a DOM flash. The relationship between N_{chan} and depth may be seen in FIG 10. The slight disconnect in the plot of N_{chan} versus depth corresponds to a region of IceCube known as the "dust layer" in which light scatters off dust in the ice. Outside the "dust layer" a fairly regular relationship between N_{chan} and depth exists.

Using the relationships between N_{chan}, depth, and brightness one may attempt to configure DOMs flashing at different depths to produce events with similar N_{chan} values. If each single flasher event has the same N_{chan} then one may filter out single

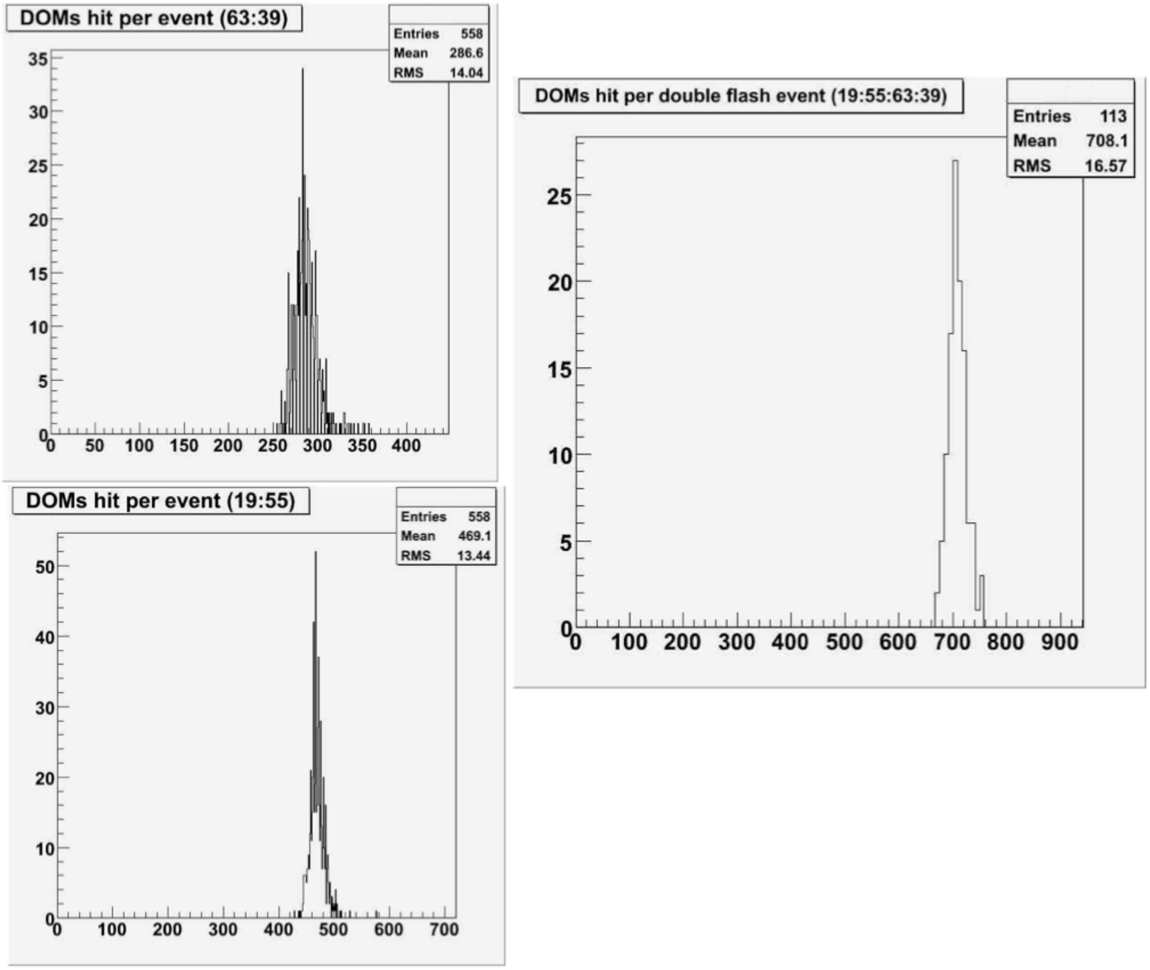

FIG 9: Histograms of N_{chan} for single DOM and twin DOM flasher events

flasher events by setting the SMT trigger threshold sufficiently high. Data taken at the South Pole using this scheme is considered in the next section.

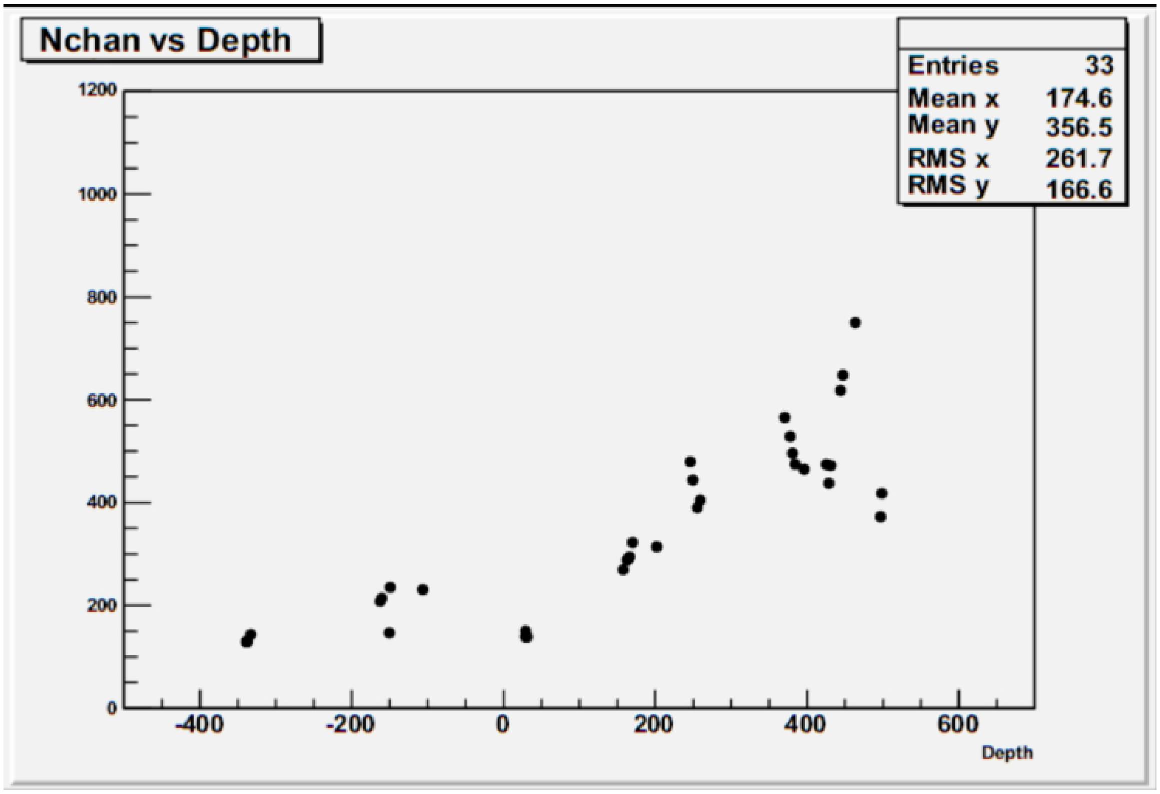

FIG 10: Mean N_{chan} versus depth (in meters) according to IceCube coordinates

4 Results

Based on the results of section 3 flasher run 117775 ran on February 14, 2011 with over 100 DOMs in each of its 6 subruns. DOMs were manually selected so that three DOMs per string would be chosen for over 40 strings in each subrun. This run used more DOMs than previous data runs and also attempted to use an SMT 200 trigger to filter undesirable events from being collected by the DAQ. That is to say that events with $N_{chan} < 200$ were ignored. A preliminary analysis of this data involved counting the number of single flasher events, the number of double flasher events, and recording any tau neutrino mimic events for further study as had been done in section 3.1. We also use the frequency of DOMs to compute the number of flashes expected to have occurred within IceCube in order to find the efficiency of the SMT filter on N_{chan}.

Table 2 shows the number of ν_τ-mimics created during the flasher along with the percentage of expected frames which were not seen. One immediately notices from this table that numerous mimics were created, but also that the filter only rejected $\frac{1}{3}$ of all single flasher events. These results are looked at more closely in the following sections.

4.1 Expectations

Prior to the experiment at the South Pole the expectation for a simulated 1100 second run was examined in detail. In FIG 11 and FIG 12 we see the number of expected events with two flashes and the number of expected ν_τ mimics.

Table 2: Results of run 117755

Subrun No	N_{dom}	$\bar{f}$ (Hz)	Two Flashes	ν_τ Mimics	Duration (s)	Filtered Frames
0	122	3	398	3	104	32.22%
1	121	3	383	4	106	31.56%
2	125	3	291	1	106	33.69%
3	127	3	449	4	105	34.29%
4	130	3	438	3	105	35.76%
5	122	3	408	4	64	32.73%
TOTAL	747	3	2367	19	590	33.46%

4.2 Detection of tau neutrino mimics

Analysis of the run 117775 flasher data revealed 19 ν_τs to be in good agreement with our expectation value, but also within reasonable statistical fluctuation for the model proposed in section 3.2. By fitting an equation of the form (4) to to our data run we expect $\bar{N}_{\nu_\tau} = 16$ with a statistical uncertainty $\delta\bar{N}_{\nu_\tau} = 3.5$ from $\delta\bar{N}_{\nu_\tau} = 2\alpha N_{dom}\delta N_{dom}$. Some examples of the ν_τ may be seen in FIG 13 and FIG 14 below. One clearly sees the 'double bang' topology which characterizes a tau neutrino cascade. One may also see the IceCube DeepCore as a higher concentration of hit DOMs may be seen towards the center of the detector in FIG 14 in the form of a cylindrical region of higher string density.

More insight into the ν_τ mimics may be gained by considering both the distance between two flashing DOMs during a mimic event and how well the mimic event satisfies equation (3) where the expression on the left hand side refers to spacetime separation and Δx refers to spatial separation. In FIG 15 - 19 one may see the number of tau neutrino mimics and double flashes for different spatial separations and different spacetime separations.

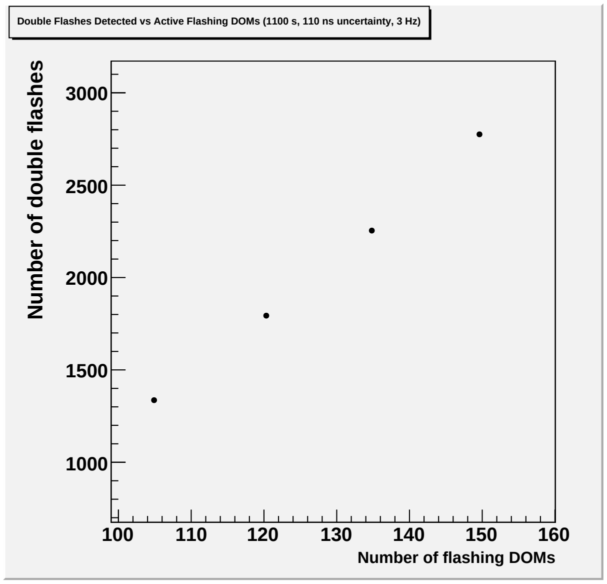

FIG 11: Simulated two flash event expectation value versus N_{dom}

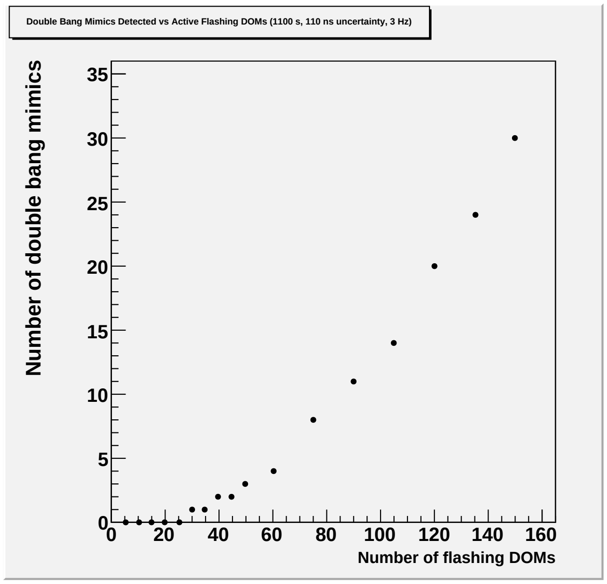

FIG 12: Simulated mimic expectation value versus N_{dom}

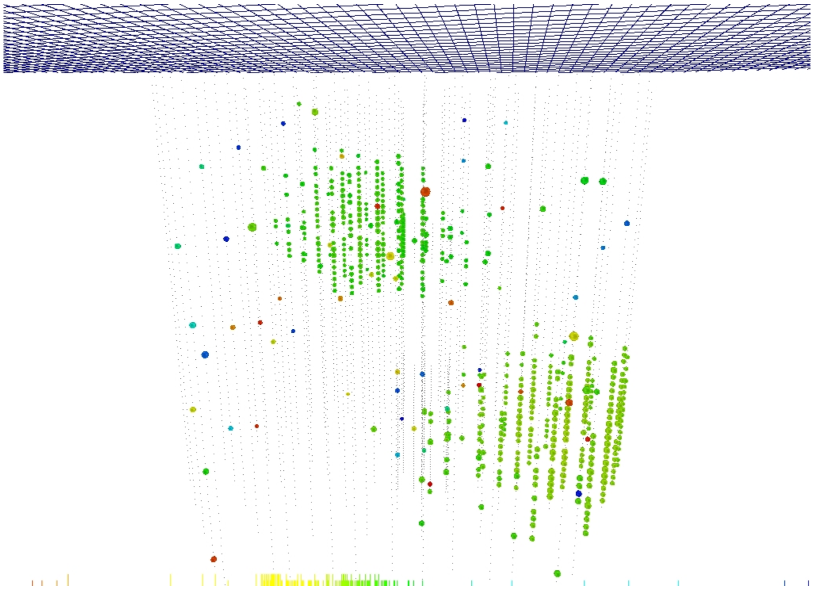

FIG 13: Tau neutrino mimic recorded during run 117755 with pulse times discernible along bottom

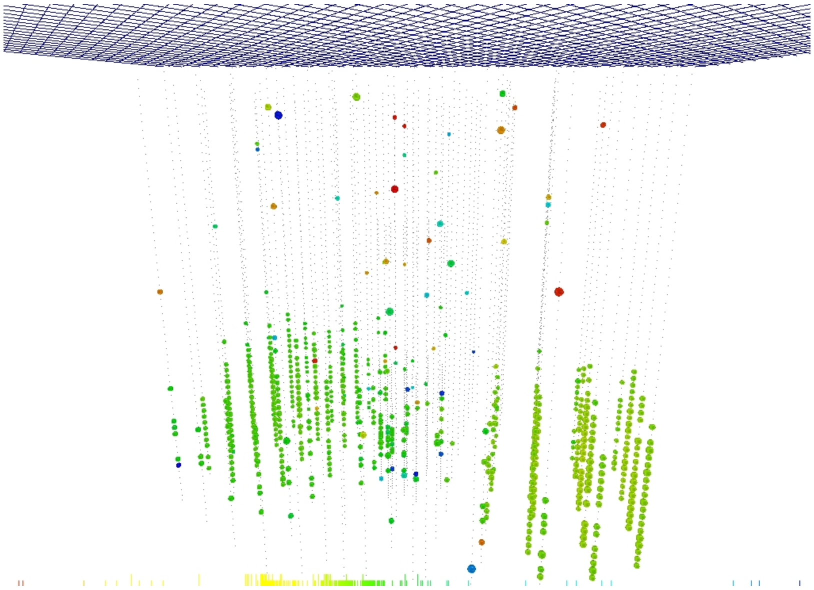

FIG 14: Tau neutrino mimic recorded during run 117755 with pulse times discernible along bottom

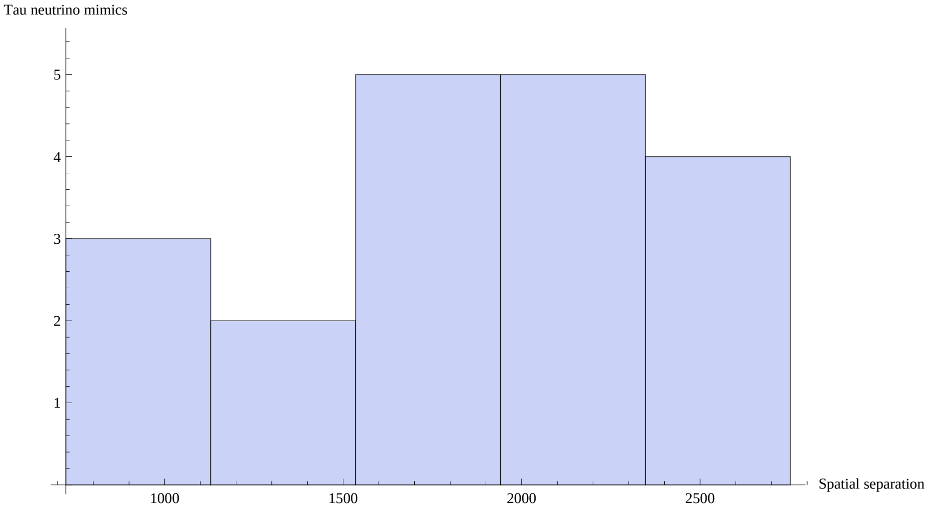

FIG 15: ν_τ mimics versus spatial distance between two flashes (in meters)

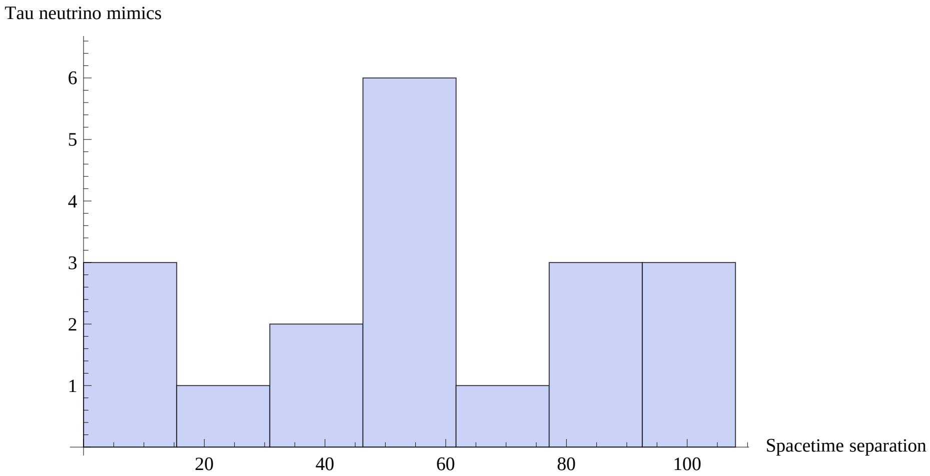

FIG 16: ν_τ mimics versus spacetime distance ($|\Delta t - \frac{\Delta x}{c}|$) between two flashes (in ns)

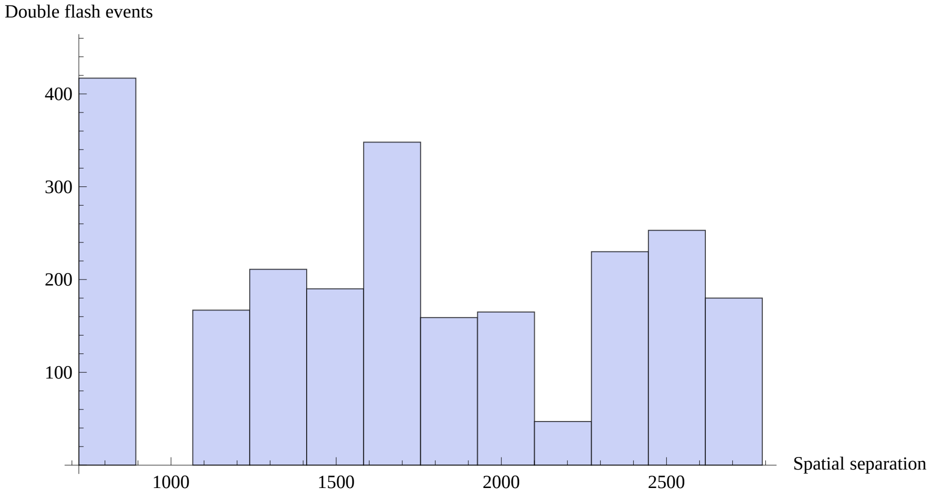

FIG 17: Events with two flashes versus spatial distance between two flashes (in meters)

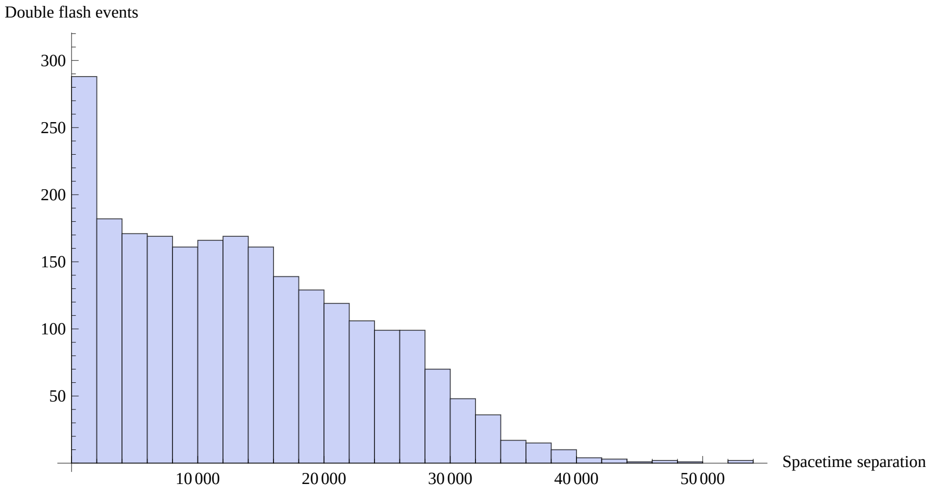

FIG 18: Events with two flashes versus spacetime distance ($|\Delta t - \frac{\Delta x}{c}|$) between two flashes (in ns)

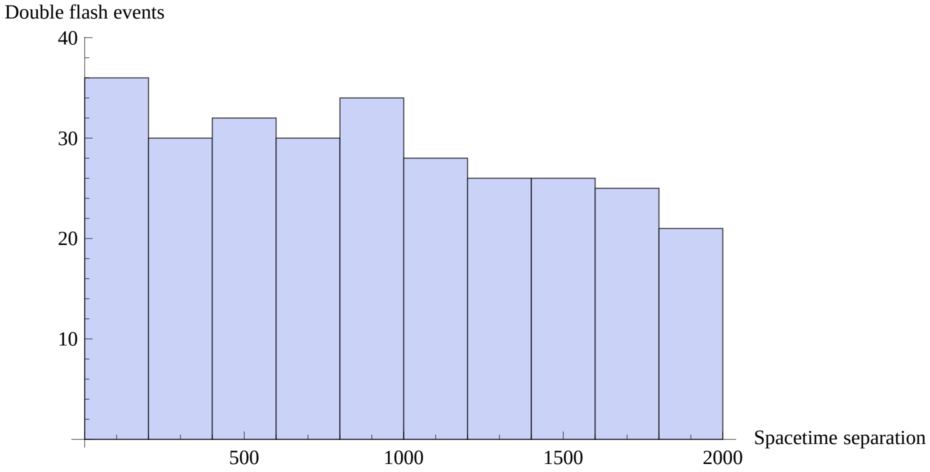

FIG 19: Events with two flashes versus small spacetime distance ($|\Delta t - \frac{\Delta x}{c}|$) between two flashes (in ns)

4.3 Hit DOMs and radial dependence

Investigating the low filter rate seen in table 2 revealed a new and useful result. Where it had previously been seen that the number of N_{chan} varies by flasher depth, the data from run 117775 allowed us to explore the dependence of N_{chan} on flasher distance from the center of the detector. In FIG 20 and FIG 21 one may observe a linear dependence of N_{chan} on the radial distance from DeepCore. The range in N_{chan} from FIG 20 due to radial dependence is greater than the dependence on depth seen in section 3.3. A DOM flashing in the center of the detector hits a far larger number of modules than a DOM at the boundary of the detector.

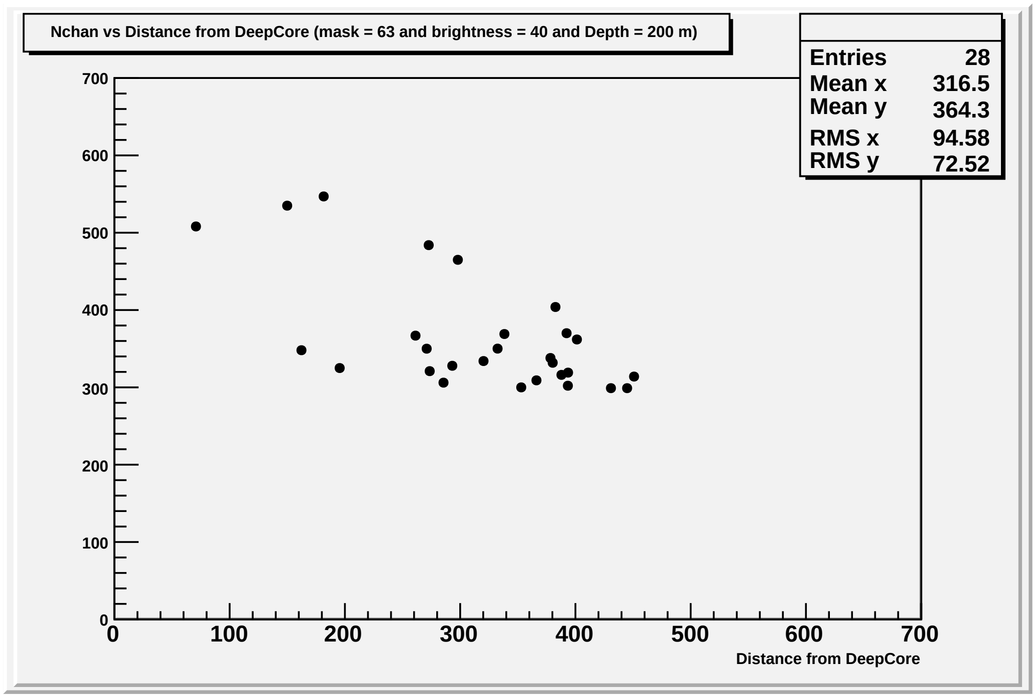

FIG 20: N_{chan} versus radial distance from DeepCore in X,Y plane at depth = 200m

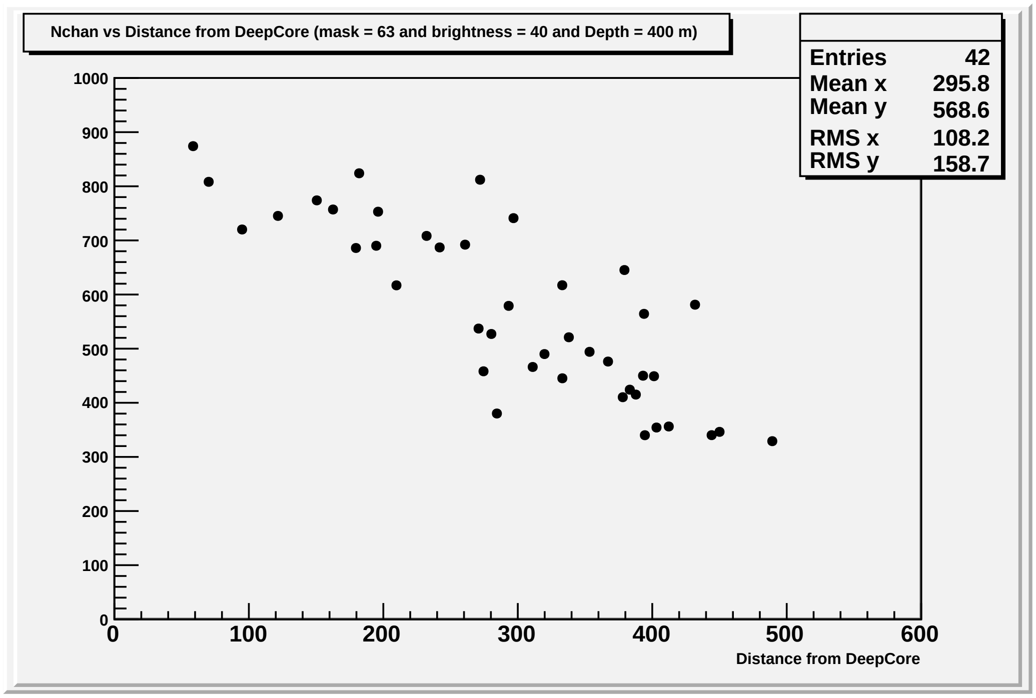

FIG 21: N_{chan} versus radial distance from DeepCore in X,Y plane at depth = 400m

5 Discussion

This research shows that tau neutrino mimics may be created reliably in statistically significant numbers according to the $N_{\nu_\tau} \propto N_{dom}^2$ model discovered through Monte Carlo simulations. The February 14, 2011 flasher run verified our understanding of N_{ν_τ} by producing a number of tau neutrino mimics in agreement with our expectation we have seen that large flasher runs can successfully create tau neutrino mimics. Although the SMT 200 trigger failed to remove the majority of single flasher events, a closer investigation revealed the source of this anomalous behavior. The number of modules hit by a single flash depended linearly on the radial distance from the IceCube DeepCore. By configuring flasher brightnesses in terms of radial distance and in terms of depth one should be able to normalize the number of modules hit by independent flashes.

One aspect of ν_τ-mimic event creation not explored in this research was the nature of the relationship between N_{chan} and DOM total brightness. Attempts to understand N_{chan} in terms of brightness failed due to the overwhelming effect of radial distance and limited variation in total brightness. The relationship between distance from DeepCore and N_{chan} may enable future researchers in attempts to uncover the exact relationship between brightness and N_{chan}.

Equipped with a more accurate relationship between N_{chan} and the coordinates of particular flashing modules, future efforts to create tau neutrino cascades may institute more effective SMT triggers. Section 3.3 discussed bandwidth constraints as a limit to the number of flashing modules able to participate in a flasher run. By establishing an effective filter to ignore single flasher events one can employ a higher event rate. These larger runs permit for a faster collection of ν_τ-mimics with higher density of tau mimics. Future efforts may thereby create tau neutrino mimics without requiring a large amount of detector downtime.

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Education

B.S. Physics, Pennsylvania State University, 2011.
Math Minor. Research in Neutrino Astrophysics.
Schreyer Honors College. GPA: 3.96.

Research Experience

Research assistant to Doug Cowen 2010–2011.

I worked for the IceCube Collaboration under physics professor Doug Cowen. In my analyses I utilized C++, Python, and the IceCube IceTray software framework to search data and simulate expected results. My thesis research focused on find and producing ν_τ-like events using LED flashers already existing in the IceCube detector array and overcoming bandwidth limitations by utilizing a selective event filtering trigger. Present work focuses on analyzing the disappearance of muon neutrino flux over different azimuthal incidence angles as evidence of $\nu_\mu \to \nu_\tau$ oscillation.

Teaching Experience

ROTC Tutor 2009–2010.

Learning Center Tutor 2008–2009.

Student Instructor for PHYS 211 (Mechanics) 2008.

Awards

- University Physics Competition, Bronze Medal 2010.
- John Holmes Teas Scholarship 2010.
- Clifford J. Campo Trustee Scholarship 2009.
- Lane B Granville Memorial Award 2009.
- Penn State Berks Physics Award 2008.
- David G. Guy Trustee Scholarship 2008.
- Penn State Campuses Scholarship 2007.
- President's Freshman Award 2008.

Class Projects

First order differential equation solver 2008

Using the C programming language I wrote program to solve first order differential equations in two variables. The program employed Euler's method, linked lists, binary trees, and other recursive techniques to find numeric solutions to general first order differential equations.

Quantum tunneling effects 2009

As a part of an honors study in quantum mechanics I read documents on quantum tunneling and wrote Python programs to simulate the effect of a quantum particle incident upon a barrier. Numerous papers and topics were discussed including the WKB approximation. I modified a python library to numerically simulate the behavior of a quantum wave packet incident upon several novel barriers such as a sine barrier, an exponential barrier, and a tangential barrier.

Differential equation manipulation 2009

For an honors project in advanced calculus I assisted Professor Anna Mazzucato in her research on second order parabolic partial differential equations by working on a Maple CAS program to automate the process of computing commutators, dialations, and symbolic integrations.

University Physics Competition 2010

During this 48 hour competition my team created two different computer models from scratch to simulate the effect of using Neptune's atmosphere to slow down a spacecraft enough to enter a circular orbit. We successfully predicted a small family of impact parameters for which a circular orbit could be obtained at virtually no cost.

Neutrino oscillation 2010

As a part of particle physics I prepared a lecture presentation on neutrino mass and neutrino oscillation. This project involved researching the experimental evidence for neutrino mass, the conceptual framework for neutrino oscillation, and the possible discovery of the 'new' neutrino flavor.

Publications

"Double bang flashes with IceCube". Penn State McNair Journal. Volume 17. Anticipated 2011.

Presentations

Presenter. "Double bang flashes with IceCube". 2010 McNair Achievement Conference.

Panelist. Study skills panel for the Penn State Berks Learning Center 2008.

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