Double bang flashes 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. The search for tau neutrino extragalactic point sources requires accurate event reconstruction. Utilizing LED flashers within IceCube allows for the simulation and calibration of the detector for tau neutrino event reconstruction. The search for the classic double bang tau neutrino event geometry within existing flasher data provides only a few useful events for configuration. A Monte Carlo simulation shows a quadratic relationship between the number of actively flashing IceCube modules and the number of expected calibration events. Consequently, data with more active flashers should be collected to produce the events useful for tau neutrino event configuration.

1 Introduction

Neutrino astronomy opens a new window into the cosmos. Massive clouds of matter hide large portions of the sky rendering much inaccessible to contemporary astronomy. Neutrinos on the other hand rarely interact with matter and carry cosmological information to Earth nearly uninhibited. Neutrinos born in the vicinity of gamma ray bursts, supernovae, active galactic nuclei, and exotic particle events travel directly to Earth while other particles become deflected. It’s 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 resultant from neutrino collisions with antarctic ice. The three known “flavors” of neutrino -the electron (νe), the muon (νμ), and the tau (ντ) neutrinos created in a ratio 1:2:0 respectively. The tau neutrino (ντ) in particular promises insight into the phenomenon known as neutrino flavor oscillation. Neutrinos should arrive at Earth with a flavor ratio 1:1:1 due to neutrino oscillation [2].

The search for energetic cosmic events profits from the detection of ντ. Only distant sources significantly contribute to ντ flux since a νe or a νμ produced in the atmosphere must travel much farther than the Earth’s diameter to oscillate into a ντ . 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 ντ 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 ντ may be reconstructed. This crucial time and intensity information for incoming radiation must be calibrated for accuracy.

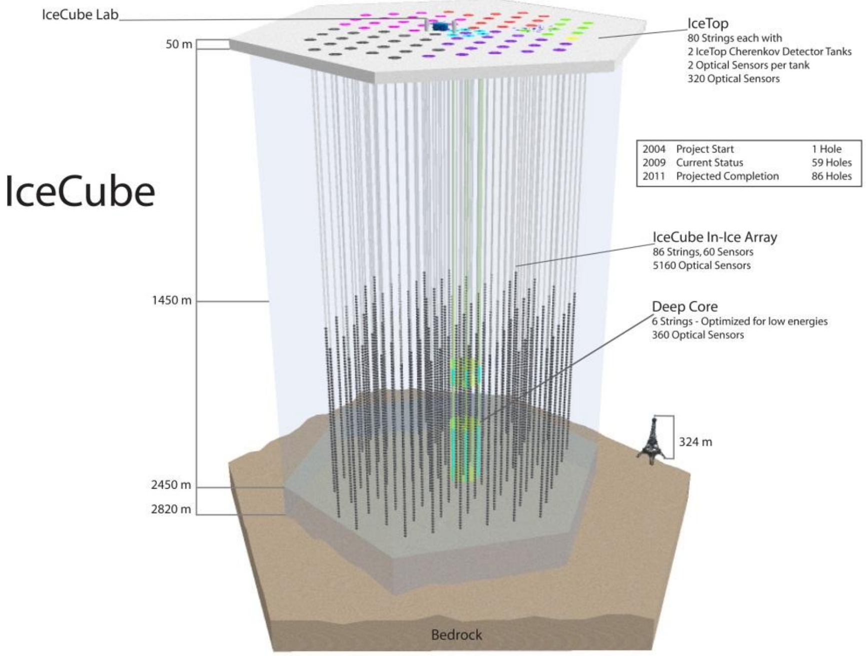
This paper considers whether flashing LEDs already deployed in the Ice-Cube detector may be utilized to generate event geometry similar to the geometry of an interacting ντ for calibration purposes. Past flasher runs as well as Monte Carlo computer simulations demonstrate that flasher data has the ability to generate data useful for ντ event configuration.

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 $1\ \text{km}^3$ [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 Deep Core the IceCube array may resolve neutrino events down to energies of 5 GeV [3].

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. IceCube currently collects data while under construction until 2011 when the last DOMs will be deployed [4]. A picture of the full detector including the Deep Core may be seen in FIG 1 [2].

FIG 1: Artist's rendition of the IceCube array



2.1 Double bang events

Neutrinos interact only by means of the weak nuclear force. During a weak force interaction between a ντ and an in ice atom, the exchange of a boson transforms the ντ into a charged tau lepton τ along with a shower of light emitting hadrons. This high energy τ moves through the ice at nearly the speed of light in vacuum and it moves faster than the speed of light in the medium due to the Rayleigh scattering of light in ice [5]. The Cherenkov cone of light following the τ triggers DOM PMTs revealing the path taken by the τ. At the end of its lifetime the τ decays, producing another flash of light.

The twin flash of light characterizing a ντ interaction provides a useful criterion for determining whether an interaction has occurred. A ντ 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 [6]. A double bang event should have a space (Δx) and time (Δt) separation obeying

$$|c\Delta t - \Delta x| < \delta t \quad (1)$$

where δt represents the allowable deviation from light-like separation and c is the speed of light in vacuum. A double bang event satisfying (1) may be inferred from DOM measurements.

2.2 Digital optical modules

IceCube data acquisition starts with DOMs. Each DOM possesses a photomultiplier tube (PMT) capable of detecting the arrival of light. Once a photomultiplier tube has been triggered the DOM digitially encodes the incoming electromagnetic waveform. If multiple nearby DOMs indicate the arrival of a waveform, all DOMs send their on-board data to the surface. The data acquisition system on the surface decides whether or not a relevant physical event has occurred before recording the result to disk. Satellites may transfer relevant South Pole data to the northern hemisphere for analysis [4].

A ντ event within the effective volume of IceCube manifests itself through electromagnetic radiation and charged particles. These charged particles further excite the electromagnetic field through their movement. By collectively considering the intensity and arrival time of these wave fronts at many DOMs the source of light may be deduced.

DOMs may also utilize onboard flashers to produce electromagnetic radiation. Each DOM contains 12 gallium nitride LEDs pointing radially outward from the DOM. These LEDs connect to a flasher board and may produce 10^7 to 10^{10} photoelectrons. These LEDs have uses for calibrating the timing systems within and between DOMs in IceCube. The geometry of the light produced by these flashers may be used to simulate the geometry of ντ events. An IceCube event containing two DOMs satisfying (1) may be considered a ντ event mimic. These mimic events may be used to configure the IceCube array for more accurate event reconstruction.

3 Searching for flasher double bangs

Calibrating the IceCube data acquisition system to accurately reconstruct ντ events requires some model events. The LED flashers equipped to IceCube DOMs provide a suitable means to generate IceCube data. As discussed in section 2, ντ events may be characterized by a double bang release of light. By instructing multiple DOMs to flash at regular intervals eventually two DOMs will flash close enough in time and satisfy the condition specified in (1). The information detected around an event satisfying the criterion in (1) 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 chiefly relies on two factors. The number of flashing DOMs necessary to produce a sizeable 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’s 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 (1).

3.1 Flasher run analysis

The event analysis necessary to find a ντ mimicking event may be performed offline on data acquired during a flasher run. I utilized the IceTray software suite produced from within the IceCube collaboration to dissect 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.

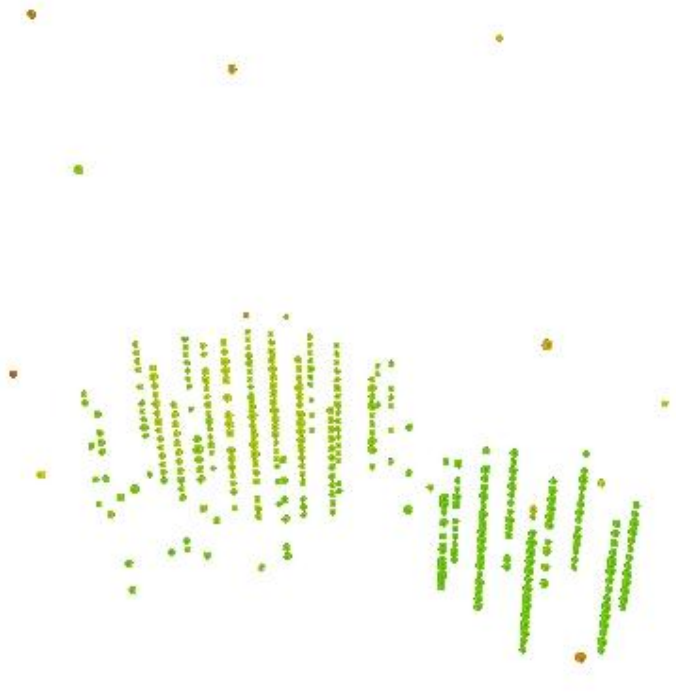
Within an IceCube file each frame contains either physics, geometry, or other information pertinent to data analysis. These frames may be processed in Python by accessing the IceTray framework. The example code below examines a physics frame in search of LED flasher data.

```
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 = f l a s h . 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 active DOMs in that time window. 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. 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 2. The DOMs in FIG 2 are an example of a candidate flasher pair for ντ calibration.

FIG 2: Reconstruction of a tau neutrino mimic event. Colored points denote light triggered DOMs. Colors denote arrival time.



To explain the density of potential tau mimicking events within a given flasher run, the frequency and number of active DOMs was again considered by collecting lists of relevant information event by event. An example table may be seen in section 4 along with other results.

3.2 Flasher run simulation

Computer simulations allow a concrete understanding of the relationship between the number of active DOMs Ndom and the average number of tau neutrino mimic events created $<N\nu_\tau>$. 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 DOMs with realistic position coordinates 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. Additionally, flashes separated according to (1) constitute ντ mimic events. A plot of the number of expected mimic events for arbitrary DOM number may be seen in section 4.

Results

Section 3 describes a method for locating flasher ντ mimics events which have occurred within the IceCube detector array. A search for ντ mimic events proved successful for two data runs. However, the number of flasher induced calibration events fell short of expectations. Table 1 shows the number of active modules, the number of events containing multiple flashers, the duration of the runs, and the number of ντ mimics detected. The findings of this study prompted a Monte Carlo investigation into its results.

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

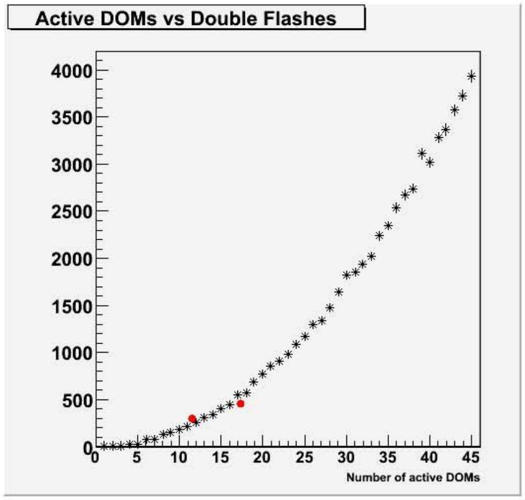
Run ID	Active DOMs	Two Flashes	ντ Mimics	Duration (s)
114431	17	456	3	1059
115615	4	0	0	1055
115617	11	340	3	1174

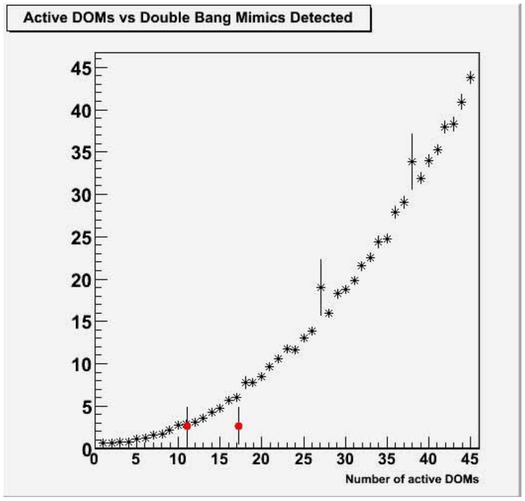
The Monte Carlo simulation described in section 3 was run for 1100 seconds with Ndom randomly selected DOMs. For each Ndom the number of flashes within 40 μs time windows as well as the number of ντ mimic events satisfying (1) was averaged over 1000 independent simulations for each value

of Ndom. The results of the flasher simulation may be seen in FIG 3 and 4 where the red points denote data from table 1. Consequently, it’s seen that the average number of ντ mimic events $\langle N\nu_{\tau} \rangle$ (1100s) varies according to the formula:

$$\langle N\nu_{\tau} \rangle \text{ (1100s)} = 0.02 \times N^{2} \quad (2)$$

FIG 3: Simulated N_{dom} vs events with FIG 4: Simulated N_{dom} vs $\langle N\nu_{\tau} \rangle$two flashes





Conclusion

The number of potential ντ configuration events currently known do not provide a statistically significant sample. Many more configuration events must be created before they will be useful for detector calibration.

According to the results in section 4 a significant number of ντ mimics should be produced by using a larger number of DOMs as flashers. Utilizing this Monte Carlo model one may predict $\langle N\ \nu_{\tau} \rangle = 1900$ for Ndom = 300 for a 1100 s run. It’s recommended that future ντ event configuration data be collected with as many DOMs as possible. More Monte Carlo simulations are planned in the near future to ascertain whether different DOM flasher geometries should produce a higher number of ντ mimic events.

References

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