Identifying Weak Cosmic Ray Muon Signatures in Cascade-Like Events in IceCube

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Laura Wanjiru Mari

University of Nairobi, Kenya

Supervisor

Markus Ackermann

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Abstract

The IceCube detector is a cubic kilometer neutrino telescope set in the Antarctic Ice. It consists of 86 strings each with 60 Digital Optical Modules (DOMs) deployed 1.5 km deep in the ice. One of its main tasks is to detect astrophysical neutrinos. The Optical Modules are sensitive to the Cherenkov light produced by the secondary charged particles created when a neutrino interacts with the ice.

Cascade-like events are described by a distinct point-like, spherical signature in the detector volume. Such a signature is produced by charged current electron neutrino interaction with the ice. All flavor neutrino neutral current interaction with the ice also produces a cascade-like signature in the detector. Hence this channel is sensitive to all three neutrino flavors. Cosmic-ray muons provide the dominant background when searching for cascade-like events. A small fraction of this background is difficult to identify as a catastrophic energy loss along the muon track can mimic a cascade-like event signature. The goal of this study is to evaluate different cut strategies to remove this class of background events.

UNIVERSITY OF NAIROBI

Contents

1 Introduction

1.1 The Ice Cube Detector

High-energy neutrino astrophysics can address a number of fundamental questions in astrophysics and cosmology such as the nature of dark matter, the origin of cosmic rays and the physical processes associated with the origin of the highest energy particles in the universe.[1] Theoretical models predict neutrino emission from Cosmic Ray sources . The equation below shows the production of neutrinos from the decay of charged pions.

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu} \qquad (1.1)$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{\mu} + \nu_{e} \qquad (1.2)$$

Since neutrinos only interact via the weak force (gravity can be neglected due to their small mass), they propagate all the way to earth , pointing directly back to their origin. The cross section for a neutrino interaction is very low; For this reason, a large detector volume is needed to detect neutrino interactions.

The Ice Cube detector is located at the geographical South Pole,buried between 1450 to 2450 meters deep in the Antarctic Ice. The depth shielding it from cosmic ray muons and other charged particles . It consists of 86 strings with a horizontal spacing of 125m, each fitted with 60 Digital Optical Modules (DOMs) with a vertical distance of 17m between them. IceCube is designed to detect neutrinos with energies above some 100 GeV [3]. Secondary charged particles are produced when a neutrino interacts with the ice; if these particles travel faster than the speed of light in ice, Cherenkov radiation is produced, which is detected by the DOMs .There is a Deep Core section , sensitive to low energy neutrinos, where the DOMs are more closely spaced.
IceTop is an additional detector component on the surface, consisting 164 Cherenkov tanks that detect air showers. The experiment has a rich Physics program of its own; It has also been used to enhance the analysis of IceCube events, e.g. by identifying background events.

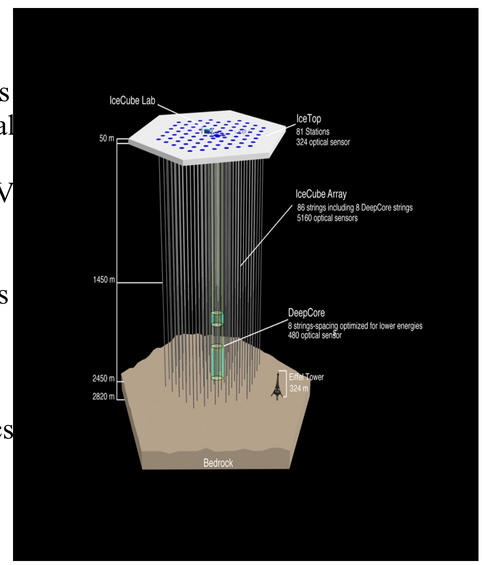

Fig1.1: The IceCube detector [1]

1.2 Digital Optical Module

The Digital Optical Modules consist of 35-cm-diameter pressure spheres, each containing
a photo multiplier tube which is sensitive to photons with wavelength 300-650 nm. Incident photons hit the photo cathode , from which electrons are emitted. The electrons accelerated , and the voltage drop over the resistor is the recorded signal. The Schematic drawing is shown below;

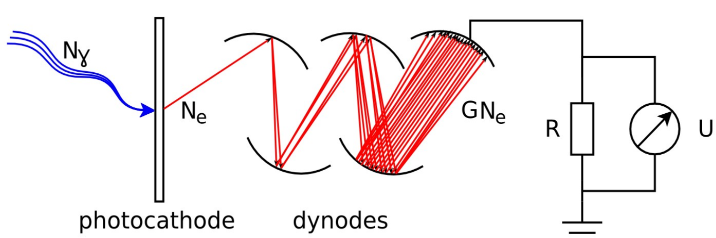

Fig 1.2 Schematic drawing of a photo multiplier[2]

The most important information for later event reconstruction is contained in the arrival times of the photons. This information should be digitized and time-stamped as soon as possible; hence it is done in the DOM. The data signal is digitized using an Analog Transient Waveform Digitizer (ATWD operated at a rate of about 300 MHz) which is complemented by a much slower 'fast Analog-to-Digital Converter' (fADC operated at 40 MHz) which gives a coarser readout of the PMT. A trigger in one DOM is called a launch.
The time resolved recording of the voltage drop over the resistor is called the Waveform. Using dedicated software, the waveform can be deconvoluted to obtain pulses; which is the response of the Photomultiplier Tube to a single photo electron. A pulse is described by the collected charge, time and width.

1.3 Event Signatures

There are two main events signatures in the detector volume; a spherical, point-like cascade signature and a track like signature.

1.3.1 Cascade-Like Event

A neutrino may interact with the nuclei in the ice either through charged current or neutral current interaction. All flavor neutrino neutral current interaction and electron neutrino charged current interactions produce a cascade like signature in the detector. In neutral current interactions, the neutrino transfers some of its momentum to the ice nuclei and escapes the detector leaving behind a hadronic shower with a cascade-like signature in the detector.
In an electron neutrino charged current interaction, an electron is emitted together with a hadronic shower. The electron loses most of its energy in producing an electromagnetic cascade creating a cascade-like event in the detector. Hence, the cascade channel is sensitive to all three neutrino flavors. This channel is also useful for energy studies since events are more likely to be fully contained within the detector volume. The Feynman diagrams illustrate the neutrino interactions.

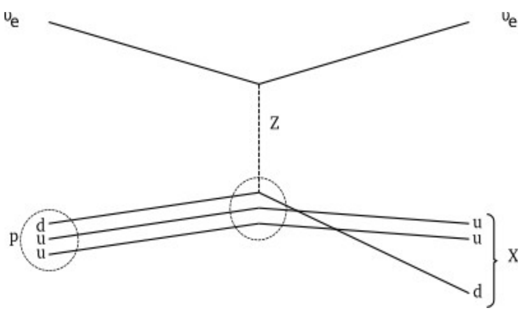

Fig 1.3 example of neutrino neutral current interaction[2]

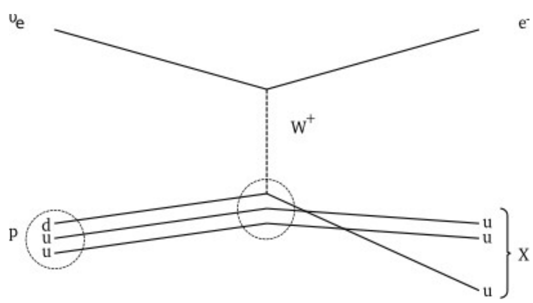

Fig 1.4 electron neutrino charged current interaction[2]

1.3.2 Track Like Event

A track like event is produced by a charged current muon neutrino interaction. Here, the muon produced emits mainly Cherenkov radiation without significantly losing its energy as it traverses the detector volume. This is because the production of Bremsstrahlung is inversely proportional to the square of the rest mass of the particle. This channel therefore has a good direction resolution; up-going and down-going neutrinos can easily be identified and can typically be used to point back to sources.

High energy collisions in the upper atmosphere produce cascades of lighter particles, among them charged pions and kaons are produced, which decay to produce muons. These cosmic-ray muons produce the dominant background in the cascade channel.

$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$ (1.3)
$\pi^{-} \rightarrow \mu^{-} + \nu_{\mu}$. (1.4)

In a year, they occur roughly 2800 signal events compared to 3 x 10^10 background events. Data is processed in levels; filters are developed and applied on the data eliminating most of the background. But sometimes, cosmic muons create a signature in the detector almost identical to a cascade and hence pass these filter levels . Such weak signatures may be caused by a catastrophic energy loss along the muon track. Another example of such an occurrence is a 'Corner Clipper'. This is a muon that intersects the detector volume only at the edges or corners , leaving a spherical signature. This is illustrated in Fig 1.5. Launch time is color coded from red to blue.

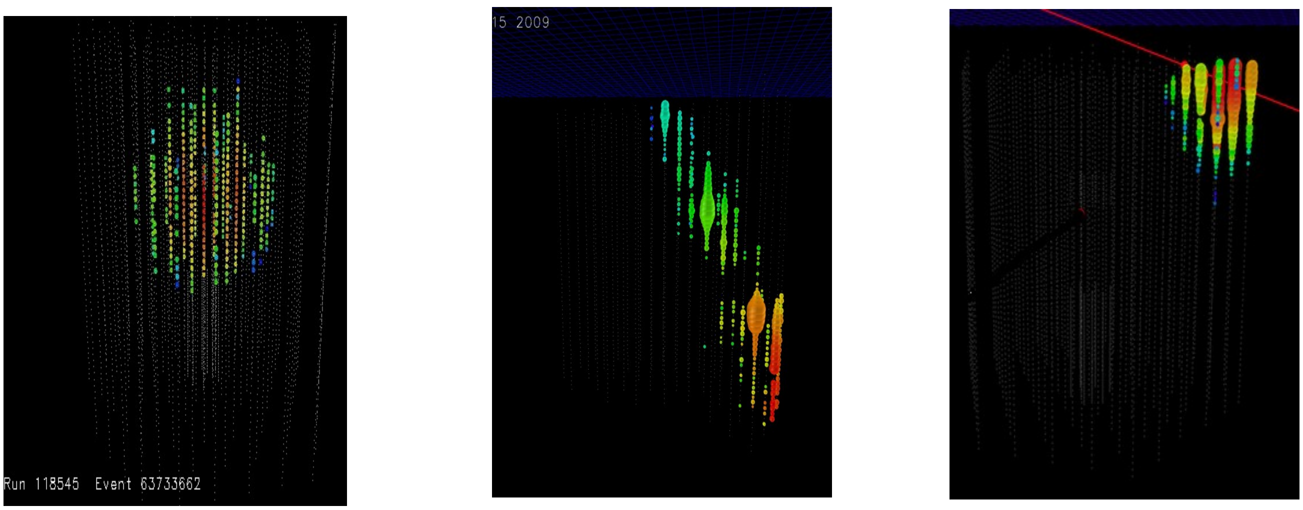

Fig 1.5: Example of Cascade-Like Signature(left) and Track-Like Signature in the Detector volume(center). An example of a 'Corner Clipper'(right)

2 Analysis

The data sets used are;
a) IC79[1] 5-Component CORSIKA for μ background
b) IC79 ν_e simulation for signal.
5-Component CORSIKA[2] refers to the 5 primary cosmic-ray particles that interact in the upper atmosphere to produce muons; H, He, N, Al and Fe nuclei.
The required keys or data needed was read and stored in HDF5 format.

2.1 Identifying weak Signatures in Waveforms and Pulses.

By studying the early waveforms and pulses of each DOM, weak signatures of muons might be

1 This refers to the IceCube detector with only 79 strings deployed.
2 **CORSIKA** (**CO**smic **R**ay **SI**mulations for **KA**scade) is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles.

identified. This is because, for a muon with Bremsstrahlung, the first early launches may be as a result of the Cherenkov radiation from its track.

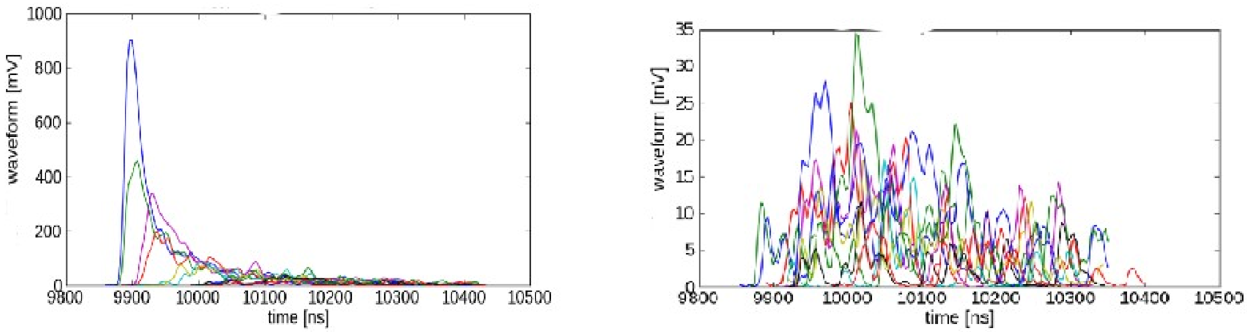

Fig 2.0 Illustrates the expected waveforms for a Cascade event(left) and for a Muon event with possible Bremsstrahlung (right). Optical Modules are represented with different colors.

For most of this study, the differences in the early waveforms are used in an attempt to come up with a powerful cut strategy.

For each event, individual waveform plots were made for each Optical Module that was triggered. The extracted pulses were also included in the same plots and the early launches were studied. For a cascade event, which is point-like, it is expected that the first peak/launch should be the highest. The plots below show two DOMs on the same string for a muon event.
A small early feature is seen in Fig 2.2, but this is missed by the pulse reconstruction.

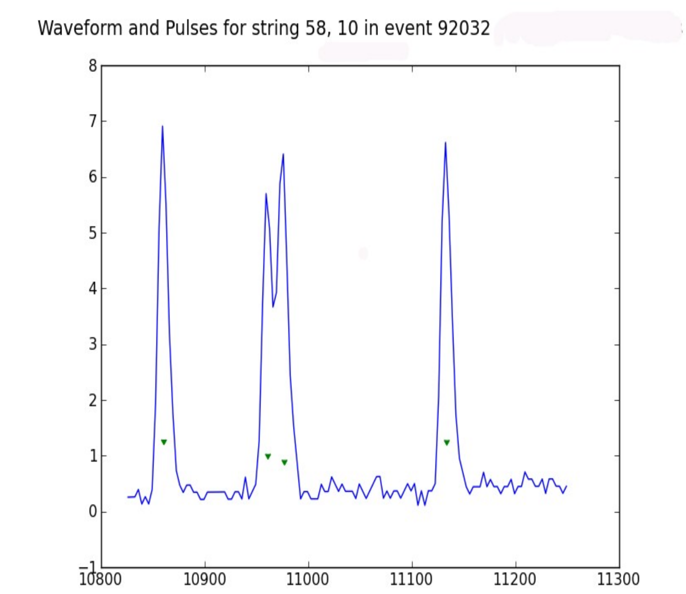

Fig2.1 Waveform and extracted pulses for a DOM. The pulses are shown as a scatter plot in green. The x-axis is time in ns

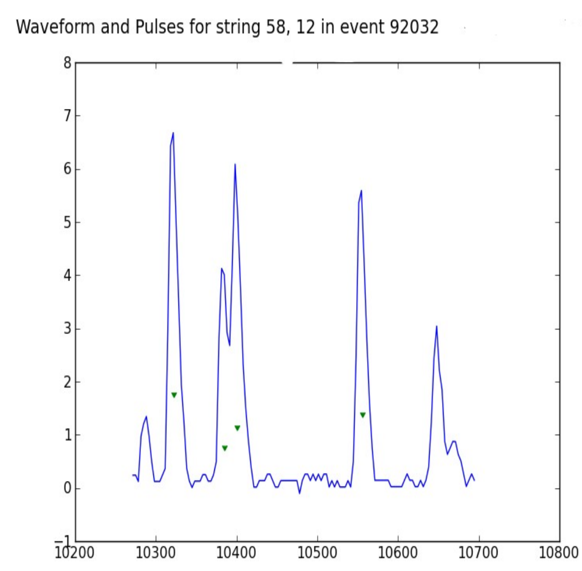

Fig 2.2 Waveform and extracted pulses for the same CORSIKA event. Pulses in the small features are missing

In the study, it was noted that some waveforms did not have pulses in the small features , as illustrated in Fig 2.2. This might be a problem in the method of the reconstruction of the pulses which involves smoothing out smaller features considered as electrical noise. This needs further investigation.

In the following analyses the cut efficiencies of different variables are tested. The peak of the Cut Efficiency plot may act as a guide in applying data cuts. An efficient variable is one that identifies and masks out as many background events without compromising too much signal .For each possible cut value, the cut efficiency is described by;

$$\text{Cut Efficiency} = \frac{\textit{number of remaining signal events}}{\sqrt{(\textit{remaining background events})}}$$

Before plotting, weights were applied to the both data sets; This is because the CORSIKA events simulation is not according to the cosmic ray spectrum, instead , higher energies are over-sampled,and weights are then applied to take the over-sampling into account. For the ν_e simulation a weight needs to be applied because the simulated interaction in the detector volume was forced, as an unweighted simulation with such low interaction cross sections would not be feasible. [5]
The normalized cumulative plots are included to give a visualization of the signal efficiency. For each possible cut value , the relative amount of signal compromised can be determined.

2.2 Delay time window, dt_nearly

For a given reference position and interaction time, *dt_nearly* is the smallest delay time of all DOMs. [4] dt_nearly is determined as follows; For each event, a reference position is chosen as the interaction point. The distance between each DOM that was triggered and the ref position is determined. The expected arrival time of light from the reference position is calculated using the speed of light in vacuum(c_v) and in ice(c_{ice}). dt_nearly is then the difference between the expected arrival time and the actual arrival time(only the first reconstructed pulse is considered)
Because the ice properties vary within the detector volume, the dust and air bubbles concentration vary with depth, hence affecting the scattering and absorption of light, c_{ice} is not an absolute value. The speed of light in vacuum is therefore used a limiting value.
Two different reference positions and corresponding reference times were chosen.
2.2.1 Vertex position as reference position
2.2.2DOM with the highest charge as reference position

2.2.1 Vertex Position as Reference Position

The vertex position can be defined as the interaction point of a neutrino in the detector volume. Here, CredoFit[3] is used to determine the vertex position and interaction time of each event.
The efficiency of this variable is illustrated in Fig 2.3. The histograms have been normalized to unity.

3 A cascade reconstruction algorithm, typically used in cascade analyses.

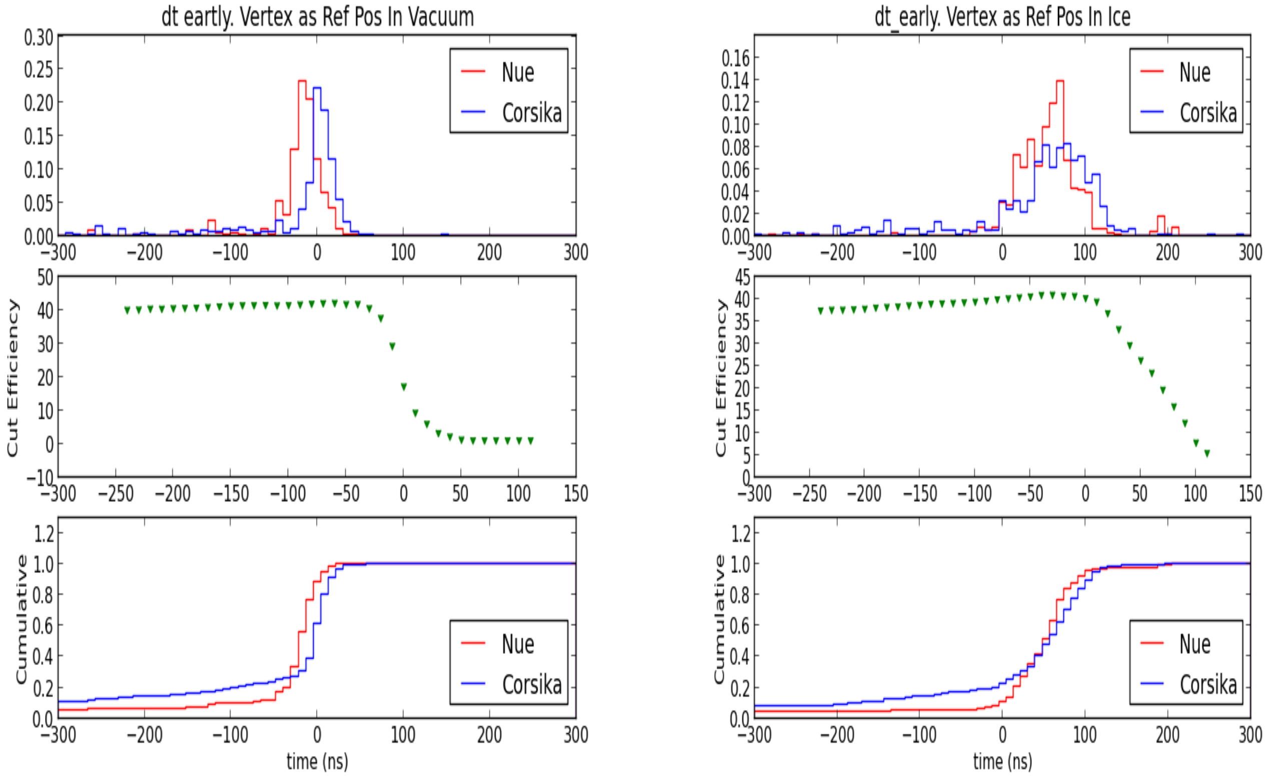

Fig 2.3 dt_early in Vacuum(left) and Ice(right) with the Vertex position as the reference position. x-axis is dt_nearly (ns)

From the histogram plots, a clearer distinction between signal and background is observed in vacuum. The peak or maximum of the Cut Efficiency plot may act as a guide in applying a cut. But, from the cumulative distribution curve, applying a cut at the maximum of the cut Efficiency would compromise almost all signal This variable effectively separates the μ background from signal events, and hence has a good cutting efficiency, but low signal efficiency.

2.2.2 DOM With the Highest Charge as Reference Position.

Since a cascade event is point-like, the position of the DOM with the highest charge can be interpreted as the interaction point. For each event, the Optical Module that recorded the highest charge was determined. The reference time was then the time of the first reconstructed pulse. The efficiency of the variable is illustrated with the following graphs.

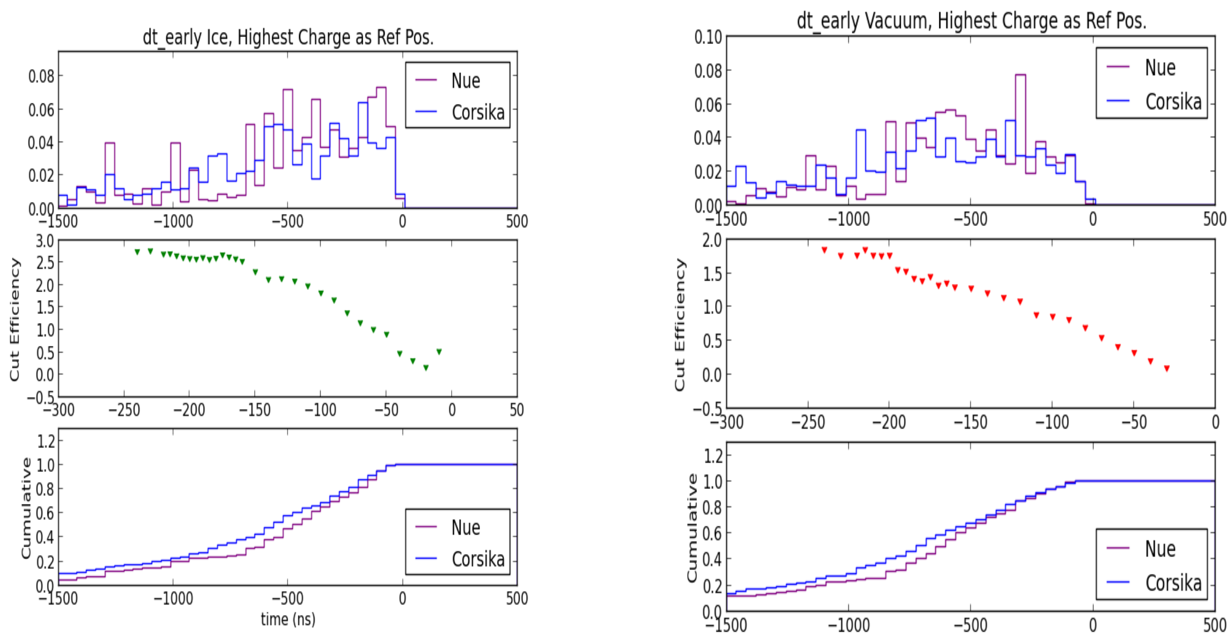

Fig 2.4: dt_early in Ice(left), and in vacuum(right), highest charge as reference. X-axis is dt_nearly(ns)

Using the DOM with the highest charge as a reference position, this variable does not perform as well as using the vertex as the reference position.

It should be noted that despite the problem identified with the pulse reconstruction of small waveform features in section 2.1, this variable still uses the reconstructed pulses in determining the interaction time. This might be a contribution to the low cutting efficiency observed.

2.3 Ratio of the First Charge to The Highest Charge

Using the assumption that for a point-like event , the first charge recorded by a DOM should be the highest. Hence, for cascade events, a ratio of the first charge to the highest charge should be much higher than for μ background events. The performance of the variable is illustrated in Fig 2.5

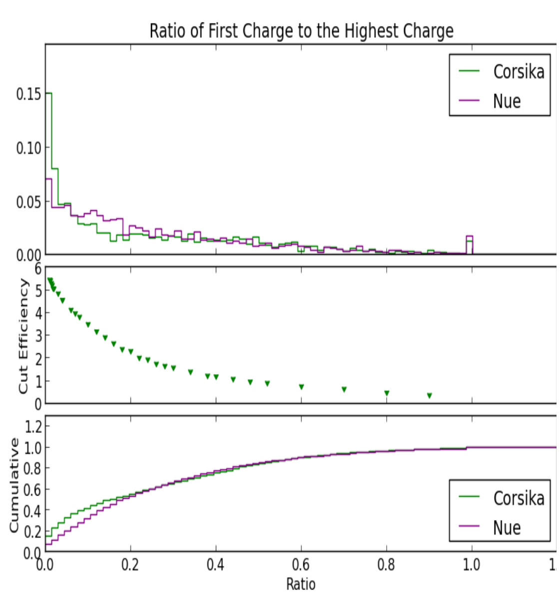

Fig 2.5 Ratio of the first charge to the highest charge for each event.

2.4 Ratio of the First Charge to The Sum of All Charges

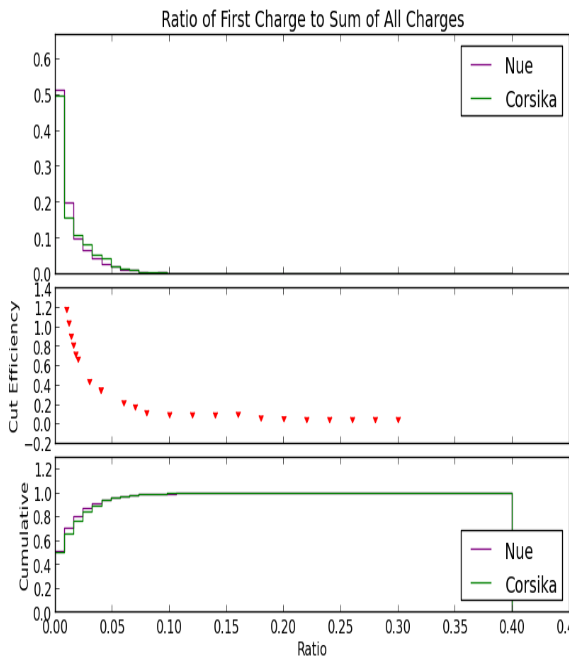

Fig 2.6 Ratio of the First Charge to the sum of all charges for each event

A similar variable to the one in section 2.3 was implemented. In this case, for each event, the value of the first recorded charge and the total collected charge for all triggered DOMs was determined. The ratio was tested as a variable, the efficiency is shown below.
Comparing both variables, it can be seen from the cumulative graphs, that it would be difficult to get a cut with a high signal efficiency,i.e a cut that masks away almost all background while still keeping as much signal as possible. The above two variables, Ratio of the First Charge to the Highest Charge(2.3) and Ratio of the First Charge to the Sum of all Charges(2.4) may be promising variables if developed, since there is a clear separation of muon and signal in the histogram plots

Conclusions.

A powerful and effective variable is one that makes a clear distinction between signal and background. The analysis illustrates *dt_early* with vertex reference position as a variable with a strong cutting efficiency.

The problem of the reconstruction of pulses of small features in the waveforms needs further investigation. Despite this ,the reconstructed pulses were still used in the preceding variables, and this may have had an influence in the cutting efficiencies.

By exploiting the differences in the waveforms and charge distributions of muon and signal events simple variables can be developed, and existing ones optimized to enable the detection of weak muon signatures that mimic cascade events. For example, investigating the ratio of the charge at the border to the total charge of an event that occurs detector edges; cascade events should have a lower charge ratio than muon events.

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