# Atmospheric Neutrino Oscillation Measurements with IceCube

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***Abstract*. IceCube's lowest energy threshold for the detection of track like events (muon neutrinos) is realized in vertical events, due to IceCube's geometry. For this specific class of events, IceCube may be able to observe muon neutrinos with energies below 100 GeV at a statistically significant rate. For these vertically up-going atmospheric neutrinos, which travel a baseline length of the diameter of the Earth, oscillation effects are expected to become significant. We discuss the prospects of observing atmospheric neutrino oscillations and sensitivity to oscillation parameters based on a muon neutrino disappearance measurement performed on IceCube data with vertically up-going track-like events. We further discuss future prospects of this measurement and the impact of an IceCube string trigger configuration that has been active since 2008 and was specifically designed for the detection of these events.**

***Keywords*: Neutrino Oscillations IceCube**

## I. INTRODUCTION

The IceCube Neutrino Telescope is currently under construction at the South Pole and is about three quarters completed [1]. Upon completion in 2011, it will instrument a volume of approximately one cubic kilometer utilizing 86 strings, each of which will contain 60 Digital Optical Modules (DOMs). In total, 80 of these strings will be arranged in a hexagonal pattern with an interstring spacing of about 125 m, and 17 m vertical separation between DOMs at a depth between 1450 m and 2450 m. Complementing this 80 string baseline design will be a deep and dense sub-array named DeepCore [2]. For this sub-array, six additional strings will be deployed in the center, in between the regular strings, resulting in an interstring-spacing of 72 m. DeepCore will be densely instrumented in the deep ice below 2100 m, with a vertical sensor spacing of 7 m. This array is specifically designed for the detection and reconstruction of sub-TeV neutrinos. Further, the deep ice provides better optical properties and the usage of high quantum efficiency photomultiplier tubes will enable us to study neutrinos in the energy range of a few tens of GeV. This makes DeepCore an extremely ideal detector for the study of atmospheric neutrino oscillations [2].

In this paper we present an atmospheric neutrino oscillation analysis in progress on data collected with the IceCube 22-string detector during 2007 and 2008. This is an update on a previous report [4], with a larger, more complete background simulation and hence re-optimized selection criteria. An alternative background estimation using the data itself is also discussed.

The goal of this analysis is to measure muon neutrino ($\nu_\mu$) disappearance as a function of energy for a constant baseline length of the diameter of the Earth by studying vertically up-going $\nu_\mu$. Disappearance effects are expected to become sizable at neutrino energies below 100 GeV in these vertical events. This energy range is normally hard to access with IceCube. However, due to IceCube's vertical geometry, low noise rate, and low trigger threshold the observation of neutrino oscillations through $\nu_\mu$ disappearance seems feasible. Atmospheric neutrino oscillations have, as of today, not been observed with AMANDA or IceCube.

Based on preliminary selection criteria, we show that IceCube has the potential to detect low-energy vertical up-going $\nu_\mu$ events and we estimate the sensitivity to oscillation parameters.

## II. ATMOSPHERIC NEUTRINO OSCILLATIONS

Collisions of primary cosmic rays with nuclei in the upper atmosphere produce a steady stream of muon neutrinos from decays of secondaries ($\pi^\pm, \mathrm{K}^\pm$). These atmospheric neutrinos follow a steeply falling energy spectrum of index $\gamma \simeq 3.7$.

In IceCube these muon neutrinos can be identified through the observation of Cherenkov light from muons produced in charged-current interactions of the neutrinos with the Antarctic ice or the bedrock below. The main difficulty in identifying these events stems from a large down-going high energy atmospheric muon flux, that could produce detector signatures consistent with those produced by up-going muons. These events are the background to this analysis.

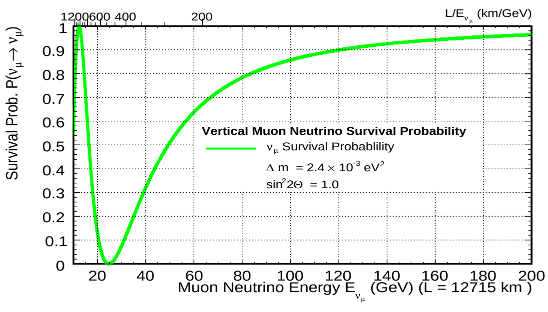


Fig. 1. Muon neutrino survival probability under the assumption of effective 2-flavor neutrino oscillations $\nu_\mu \leftrightarrow \nu_\tau$ as function of energy for vertically traversing neutrinos.

Vertically up-going atmospheric neutrinos travel a distance of Earth diameter, which corresponds to a baseline length L of $12,715$ km. The survival probability for these muon neutrinos can be approximated using the two-flavor neutrino oscillation case and is shown in Figure 1 for maximal mixing and a $\Delta\mathrm{m}^2$ consistent with Super-Kamiokande [6] and MINOS [7] measurements. It illustrates the disappearance effect (large below energies of 100 GeV) we intend to observe.

## III. Oscillation Analysis

To probe oscillation effects, our selection criteria need to be optimized towards the selection of low-energy vertical muon events. The selection should also retain some events at higher energies (with no oscillation effects), that could be used to verify the overall normalization. Low energy vertical up-going muons in IceCube predominantly result in egistered signals ("hits") on a single string. The muon propagates very closely to one string, such that the Cherenkov light can be sampled well from even low-energy events. The probability of observing hits on a second string is very small due to the large interstring distance of 125 m, and is further suppressed through a local trigger condition known as HLC (Hard Local Coincidence). The HLC condition requires that a DOM only registers a hit if a (nearest or next-to-nearest) neighbor also registers a hit within 1 $\mu$s. IceCube was operational in this mode for the 22 and 40-string configuration.

Given the nature of the signal events, the oscillation analysis can be performed very similarly on the different IceCube string configurations. To verify our understanding of the detector, we perform this analysis in steps. First, we use a subset of the 22-string configuration to develop and optimize the selection criteria, then cross check them on the full 22-string dataset and perform the analysis on the IceCube datasets acquired following the 22-string configuration.

The IceCube 22-string configuration operated between May 31, 2007 and April 5, 2008. In this initial study, we analyze only a small subset of the data acquired over this period with a total livetime of 12.85 days, using randomly distributed data segments of up to 8 hour length collected during the period of 22-string operations. The dataset was triggered with the multiplicity eight DOM trigger and then preselected by a specific analysis filter running at the South Pole, selecting short track-like single string events. The filter requires after removal of potential noise hits, that all hits occur on a single string and that the time difference between the earliest and latest hit be less than 1000 ns. To partially veto down-going muon background it requires no hits in the top 3 DOMs. Further, the hit time difference between at least two adjacent DOMs must be consistent with the speed of light within 25% tolerance, and the first DOM hit in time needs to be near the bottom or top within the series of DOMs hit on the single string. All filter selection criteria are designed to be directionally independent so that vertical up-going events are collected as well as vertical down-going. The described analysis only uses the up-going sample collected by this filter. The down-going sample could be used in the future for flux normalization purposes, if we succeed in extracting a pure atmospheric neutrino sample against the large down-going atmospheric muon flux [3].

To isolate our signal sample of vertical up-going $\nu_\mu$ events we apply a series of consecutive selection criteria. We require that the majority of time differences between adjacent DOMs are consistent with unscattered Cherenkov radiation (direct light) off a vertically up-going muon (L4). In addition, a maximum likelihood fit is applied requiring the muon to be reconstructed as up-going (L5). After these selection criteria, the dataset is still dominated by down-going muon background mimicking up-going events. This background is estimated using two CORSIKA [8] samples: one with an energy spectrum according to the Hörandel polygonato model [5] and a second over-sampling at the high energy range. Simulations agree well with data in shape, but the normalization is found to be slightly high. Based on background and signal simulations (atmospheric $\nu_\mu$ were generated with ANIS [9]) we define a set of tight selection criteria (that do not correlate strongly) and show good signal and background separation. These selection criteria are as follows: Event time length greater than 400 ns (L6), mean charge per optical sensor larger than 1.5 photo-electrons (pe), total charge collected during the first 500 ns larger than 12 pe (L7), and an inner string condition (the trigger string completely surrounded by neighboring strings) (L8). The tight selection criteria were independently optimized at this level in order to have high statistics and smoother distributions which would not be available at higher selection criteria levels. Thereafter, we reject all events in the available background CORSIKA sample corresponding to an equivalent detector livetime of at least two days. Part of the parameter space was oversampled by the weighted CORSIKA sample an equates to several weeks of equivalent livetime. Using a conservative approach with two days of livetime equivalent we can set a 90%C.L. upper limit on the possible background contamination in the data sample of 14.8 events, in 12.85 days of livetime. In this sample we further expect $2.13\pm0.07$ ($1.68\pm0.06$) signal events (with oscillation effects taken into account) from atmospheric neutrinos. See Table I for event counts as function of the selection criteria. Figure 2 shows the track length distribution after final selection criteria. The track length serves as an energy estimator working well at the energy range of interest since a muon travels roughly 5 m/GeV. As expected, short tracks show larger disappearance effects. Figure 3 shows the fraction of events selected by this analysis that are below a certain muon energy for different track lengths.

The optimization and cross-check on the small subset of available data have been performed in a blind manner. One event was observed after final selection

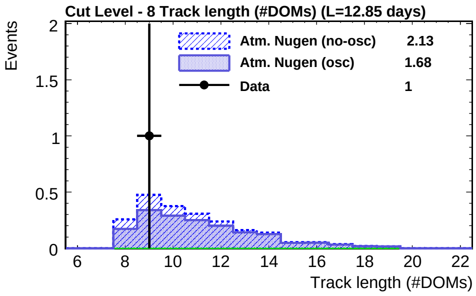


Fig. 2. Expected track length of the signal, with and without oscillations taken into account, and compared to data after final selection criteria. .

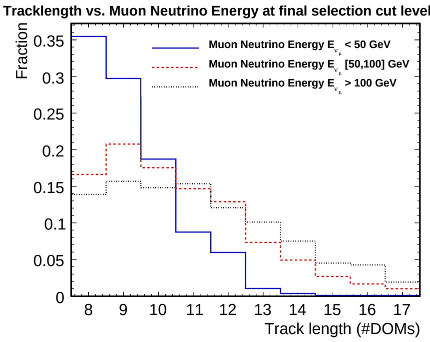


Fig. 3. Fraction of events in a given muon neutrino energy range as function of their track length defined by the number of DOMs hit at final selection.

which is consistent with the prediction. This initial result indicates that we understand and model the low-energy atmospheric neutrino region reasonably well. The analysis on the full dataset is in progress, including a larger background MC sample and a more detailed study of systematic uncertainties. Figure 4 shows the effective area for vertical up-going neutrinos in the 22-string detector at filter level and final selection.

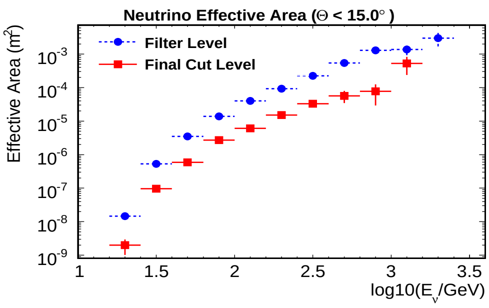


Fig. 4. Average muon neutrino effective area for vertical up-going neutrinos (within 15 degree's of vertical direction) as function of neutrino energy.

## IV. Background Estimation

The background has been estimated using CORSIKA simulations. However, due to limited MC statistics there remains a large uncertainty at final selection.

To cross-check the background estimation using simulations and to provide a second independent way to obtain a background estimate, we use the data itself to determine the remaining background.

| Cut | Corsika | Sig. (with osc) | Effect | Data |
|---|---|---|---|---|
| L3 | $439 \pm 2 \cdot 10^4$ | $20.3(17.3) \pm 0.4$ | 15% | $331 \cdot 10^4$ |
| L4 | $54 \pm 2 \cdot 10^3$ | $20.0(17.0) \pm 0.3$ | 15% | $32 \cdot 10^3$ |
| L5 | $464 \pm 175$ | $11.8(9.7) \pm 0.2$ | 18% | 321 |
| L6 | $351 \pm 171$ | $10.7(8.8) \pm 0.2$ | 17% | 207 |
| L7 | $151 \pm 41$ | $9.6(7.9) \pm 0.2$ | 17% | 145 |
| L8 | 0 | $2.1(1.7) \pm 0.08$ | 21% | 1 |

TABLE I

Summary of number of events in data and as predicted by simulations as function of the selection criteria "cut" level: L3 - initial processing (trigger, filter), L4/L5 - reconstructed track is vertical up-going, L6/L7 - charge based selection criteria, L8 - inner strings only. See text for detailed description of the selection criteria. Effect refers to the size of the disappearance effect.

The nature of the signal events (low energy vertical tracks on a single string) allows us to estimate the background based on the completeness of the veto region defined by the surrounding strings, using geometrical phase-space arguments.

The total number of events observed is the sum of the passing signal events and background faking a signal. The two categories display very different behavior with respect to tightening the selection criteria. Signal events produce predominately real vertical tracks, so that the rate on strings regardless of their position is very similar (see Figure 5).

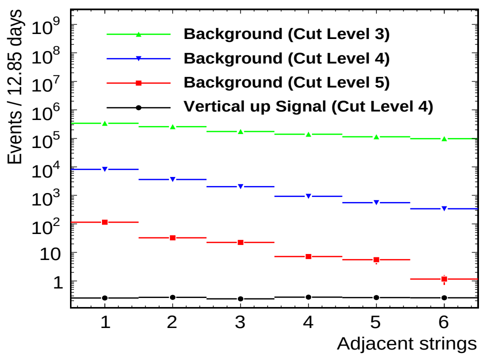


Fig. 5. Number of events for 12.85 days of data at different cut levels as function of number of adjacent strings. The signal prediction is shown for comparison. Note that the number of adjacent strings does not affect the signal as those events are predominately single string events.

Up-going $\nu_\mu$ of higher energies and non-vertical $\nu_\mu$ have a small impact on the overall rates. As selection criteria become more stringent, the rates on the strings become more homogeneous as they are dominated by "high quality" low-energy vertical muon neutrino events.

Background behaves very differently under tightening selection criteria, as it becomes more difficult to produce a fake up-going track when the parameter space is taken away and the veto condition tends to have a larger impact.

We determine the ratio between the average number of events observed on a string with $n$ adjacent strings[1] and those with $n+1$. At a low selection criteria cut level, the rate on all strings is completely dominated by background. At high selection level, strings having less than four adjacent strings are also background dominated. We use these first three bins to scale the ratio distributions from an earlier selection level to the final selection level. Figure 6 shows the predicted number of events at final selection criteria level obtained with this method. The background estimatation method from data itself needs to be finalized, including a study of the systematic uncertainites. It provides a cross-check to the predictions from simulation and may ultimately be used as the preferred background estimation method in this analysis.

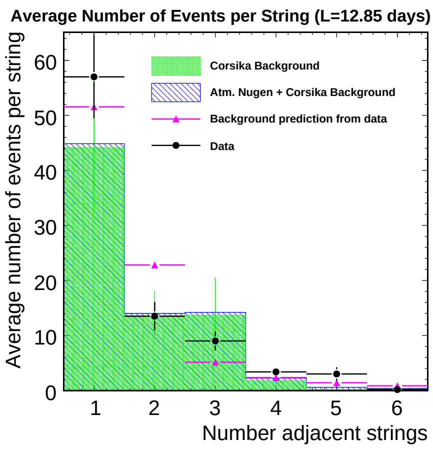


Fig. 6. Average number of events per string at selection criteria L7 as function number of adjacent strings. Note that the right most bin corresponds to the final selection.

## V. Discussion of Sensitivity for 40-string and full IceCube

The IceCube 40-string dataset is in many ways superior to the 22-string dataset. The trigger system has been significantly improved over the 22-string detector through the addition of a string trigger [10], roughly doubling the vertical muon neutrino candidate events per string. In order to reject efficiently against down-going muon background, we require that a string be entirely surrounded by adjacent strings (inner strings criterion) as part of the final selection. The 40-string detector has about a factor of three more inner strings.

Based on the selection criteria for the IceCube 22-string analysis, we have evaluated the sensitivity of the 40-string detector with one year of data using a $\chi^2$ test on the track length distribution. Selection criteria are identical as those presented here, but the number of expected signal events is scaled according to expectation for the 40-string array. We expect about 400 signal events, based on the detector livetime, number of inner strings, and a factor two increase in number of events due to the string trigger operational beginning with the 40-string array. Figure 7 shows the expected sensitivity limits obtained in this way as function of the oscillation parameters. Systematic uncertainties are still being investigated and are not included; They are dominated by the atmospheric neutrino flux uncertainty, optical module sensitivity and ice effects.

[1]We define adjacent strings as those that are within the nominal interstring-distance (roughly 125 m) of the hexagonal detector pattern.

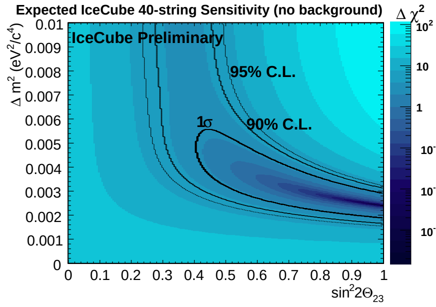


Fig. 7. Expected constraints on oscillation parameters using the IceCube detector in the 40-string configuration under the assumption of zero background .

## VI. Conclusions

Preliminary results obtained with a subset of the data collected with the IceCube 22-string configuration active during 2007 and 2008, suggest that IceCube may have sensitivity in the energy range where atmospheric oscillations become important. We estimate the sensitivity to oscillation parameters in the IceCube 40-string dataset and find that IceCube can potentially constrain them, pending the determination of the systematic uncertainties associated with the predicted distributions. Understanding of this energy region is also important for dark matter annihilation signals from the center of the Earth and further provides the groundwork for DeepCore, which will probe neutrinos at a similar and even lower energy range [2].

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