Neutrino Oscillation Measurements with IceCube

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We present preliminary results for a neutrino oscillation analysis in progress on data collected with the IceCube 22-string detector during 2007 and 2008. The goal of this analysis is to measure muon neutrino disappearance as a function of energy for a constant baseline length of the diameter of the Earth by studying vertically up-going muon neutrinos. At this baseline disappearance effects are expected to become sizable at neutrino energies below 100 GeV. This energy range has not been previously explored with IceCube, however due to IceCube’s vertical geometry there is some sensitivity for this specific class of events. Based on preliminary selection criteria, we show that IceCube has the potential to detect these events and we estimate the sensitivity to determining oscillation parameters.

1. IceCube Neutrino Observatory

The IceCube Neutrino Telescope [1] is a multipurpose discovery experiment under construction at the South Pole. It is currently about half completed and is taking physics data. Upon completion in 2011, IceCube will instrument a volume of one cubic kilometer with 4800 Digital Optical Modules (DOMs). These will be vertically spaced with 17 m separation at a depth between 1450 m and 2450 m in the ice on 80 strings that are arranged in a hexagonal pattern with an inter-string spacing of about 125 m. An additional six strings will be deployed in-between the hexagonal pattern at the center of IceCube in the deep very clean ice region with DOMs more densely spaced and equipped with high quantum efficiency photomultiplier tubes. They will form together with the adjacent IceCube strings the Deep Core [2] subdetector. The first of these Deep Core strings will be deployed at the end of this year.

2. Neutrino Oscillation Analysis

Cosmic rays interacting with Earth’s atmosphere generate a steady flux of secondary particles including muon neutrinos produced in kaon and pion decays. These atmospheric neutrinos can be identified by IceCube through the observation of Cherenkov light from muons produced in charged-current interactions of the muon neutrinos with the Antarctic ice. The main difficulty in identifying these events stems from an overwhelmingly large down-going high energy muon flux produced in the atmosphere, that penetrates the Earth several kilometers to IceCube depths and can be misreconstructed as up-going events.

In IceCube vertically up-going atmospheric neutrinos travel a distance of the diameter of the Earth (a baseline length L of about 12700 km). The survival probability for these muon neutrinos is shown in Figure 1 for maximal mixing and a $\Delta m^2$ consistent with measurements by Super-Kamiokande [3] and MINOS [4]. It illustrates the disappearance effect we intend to observe. Oscillation effects become large for neutrino energies below 100 GeV. This energy range is normally hard to access with IceCube; however, due to IceCube’s vertical geometry, low noise rate, and low trigger threshold (SMT8 - multiplicity eight DOM) the observation of neutrino oscillations through muon neutrino disappearance seem feasible. We require tracks to be vertical and near a string, so that the Cherenkov light can be sampled well from even low-energy events.

Atmospheric neutrino oscillations have never been observed with AMANDA or IceCube. However, searches for non-standard oscillation mechanisms that lead to observable differences at higher energies have been performed and constraints on these scenarios were placed [5].

To search for muon neutrino disappearance we select vertical low energy muon neutrino candidate events through the application of a series of consecutive selection criteria. First, events are preselected from the data sample by a

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specific analysis filter, which selects short track-like single string events. We then require that the events are vertically up-going through a directionality selection, which requires that the majority of time differences between adjacent DOMs are consistent with coming from unscattered Cherenkov radiation of a vertically up-going muon. After these selection criteria the dataset is still dominated by down-going muon background mimicking up-going events. This background is estimated from CORSIKA simulations and agrees well with data. Based on background and signal (atmospheric $\nu_\mu$ were generated with ANIS) simulations we define a tight set of selection criteria to further reduce the background. Thereafter, we reject all events in the available background MC sample, which has the equivalent of about 1.45 days of livetime. We expect 1.81 (1.42) signal events (with oscillation effects taken into account) from atmospheric neutrinos in 12.85 days of livetime, which represents a small fraction of the IceCube 22-string dataset. For these signal events the estimated expectation distribution of the track length, which serves as an energy estimator and works well at the energy range of interest as a muon travels roughly 5m/GeV, is shown in Figure 2. As expected, short tracks show larger disappearance effects. The optimization and cross-check on the small subset of available data have been performed in a blind manner. We observe three signal candidate events after final selection, which is consistent with the predictions. This initial result confirms that we understand and model the low-energy atmospheric neutrino region reasonably well. However, a larger MC background sample is needed to estimate any possible remaining background after tight selection criteria. The analysis on the full dataset is in progress, including a larger background MC sample and a detailed study of systematic uncertainties.

Based on the selection criteria for this IceCube 22-string analysis we have evaluated the sensitivity for the IceCube 40-string detector with one year of data using a $\chi^2$-test on the track length distribution. Figure 3 shows the theoretical sensitivity limits obtained in this way as function of the oscillation parameters. The trigger system for the 40-string detector has also been significantly improved over the 22-string detector through the addition of a string trigger, which roughly doubles the vertical muon neutrino candidate events per string.

3. Conclusions

We present preliminary results obtained with a subset of IceCube 22-string dataset collected during 2007 and 2008. The results demonstrate that IceCube is sensitive to a $\nu_\mu$ energy range in which atmospheric neutrino oscillations become important. We estimate the sensitivity to oscillation parameters in the IceCube 40-string dataset and find that we can potentially constrain them, pending the finalization of the systematic uncertainties associated with the predicted distributions. Understanding of this energy region is extremely important also for dark matter annihilation signals from the center of the Earth and further provides the groundwork for Deep Core, which will probe neutrinos at a similar and even lower energy range. This analysis allows to test our understanding of these events as part of a physics analysis. Deep Core, which will significantly improve IceCube’s sensitivity in the energy range below 100 GeV...
Figure 3: Theoretical sensitivity $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$ distribution for the IceCube 40-string detector based on the selection criteria defined in the presented analysis, assuming no remaining background. Contours correspond to $\chi^2_{\text{min}} + 2.3, 4.6, 6.0$.

(see also Figure 4), will allow not only to observe muon neutrino disappearance but also possibly appearance of tau neutrinos as well as to measure oscillation effects as a function of the zenith angle. It has generated further interest in the community with its capability to potentially resolve the neutrino mass hierarchy [9].

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