Atmospheric neutrino oscillations with DeepCore

THE ICECUBE COLLABORATION[1]
[1]*See special section in these proceedings*

Abstract: IceCube DeepCore can study atmospheric neutrino oscillations through a combination of its low energy reach, as low as about 10 GeV, and its unprecedented statistical sample, of about 150,000 triggered atmospheric muon neutrinos per year. With the diameter of the earth as a baseline, the muon neutrino disappearance minimum and tau neutrino appearance maximum are expected at about 25 GeV, which is considerably lower energy than typical IceCube neutrino events, but higher than the energies at which accelerator-based experiments have detected oscillations. We present here the status of the newly developed low energy reconstruction algorithms, the expected experimental signatures, and the proposed approach for such neutrino oscillation measurements.

Corresponding authors: Sebastian Euler[2] (seuler@icecube.wisc.edu), Laura Gladstone[3](gladstone@icecube.wisc.edu), Jason Koskinen[4](koskinen@psu.edu), Donglian Xu[5](dxu@crimson.ua.edu) DOI: 10.7529/ICRC2011/V04/0329

[2]*III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany*
[3]*Dept. of Physics, University of Wisconsin, Madison, WI 53706, USA*
[4]*Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA*
[5]*Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA*

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1 IceCube DeepCore

IceCube is a cubic-kilometer neutrino observatory located at the geographic South Pole. IceCube construction began in 2004 and was completed in December 2010. The complete detector consists of 86 strings deployed into the glacial ice, each of which consists of 60 Digital Optical Modules (DOMs) located between depths of 1450 m and 2450 m. Seventy-eight strings are arranged on a hexagonal grid with an average 125 m horizontal spacing and 17 m vertical DOM spacing. The remaining 8 strings are more closely spaced in the center of the detector, with horizontal distances of 40 - 70 m and vertical DOM spacing of 7 m. The 8 inner densely instrumented strings, optimized for low energies, together with the surrounding 12 IceCube standard strings, form the DeepCore inner detector (Fig. 1). These 8 inner strings have 10 DOMs located between 1750 m and 1850 m in depth and 50 DOMs located between 2100 m and 2450 m. The ice at depths between 1970 m and 2100 m, formed about 65,000 years ago [1], has a relatively short absorption length, and is known as the "dust layer". The 10 DOMs on each DeepCore string deployed above the dust layer help reject cosmic ray muons which are the major background to atmospheric neutrino studies. The ice below 2100 m has a scattering length about twice that of the ice in the upper part of the IceCube detector [2]. The lower 50 DeepCore DOMs are deployed in this very clear ice. DeepCore DOMs contain high quantum efficiency photomultipliers (HQE PMTs [3]) which add $\sim$ 35% increase in efficiency compared to the standard IceCube DOMs. With denser string and DOM spacing, clearer ice, as well as higher efficiency PMTs, DeepCore is optimized for low energy neutrino physics [4]. Fig. 2 shows the predicted ν_μ and ν_e effective areas at both trigger and online veto levels. Below 100 GeV the addition of DeepCore increases the effective area of IceCube by more than an order of magnitude.

2 Neutrino Oscillation Physics in DeepCore

The IceCube DeepCore sub-array has opened a new window on atmospheric neutrino oscillation physics with its low energy reach to about 10 GeV. The oscillation measurement is also made feasible by DeepCore's location at the bottom center of IceCube, which allows the surrounding IceCube strings to act as an active veto against cosmic ray muons, the primary background to atmospheric neutrino measurements. A muon background rejection of 8×10^{-3} for the overall IceCube trigger ($\sim$ 2000 Hz) is achieved by applying a veto algorithm which rejects events with particle speed (defined as the speed of a particle trav-

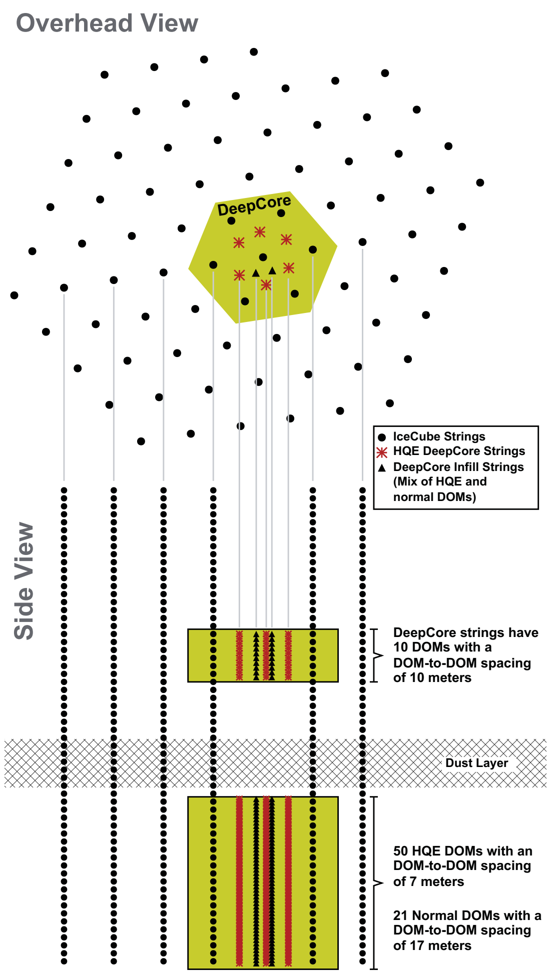

Figure 1: Overhead and side views of the IceCube DeepCore detector. The shaded hexagon in the overhead view shows the area covered by the DeepCore sub-array. On the side view, the hatched region shows the dust layer, and shaded boxes indicate the location of the DeepCore DOMs, 10 in each string above the dust layer, and 50 in each string below the dust layer.

eling from the hit in the surrounding region to the center of gravity (COG) in DeepCore) between 0.25 m/ns and 0.4 m/ns. The scheme of this veto algorithm is demonstrated in Fig. 3. With further expected improvements in the veto and event reconstruction algorithms, DeepCore expects to achieve a cosmic-ray muon rejection factor of 10^6 or better [6]. Specific methods to investigate the oscillation phenomenon will be discussed in detail in the following subsections.

2.1 ν_μ Disappearance

The earliest atmospheric neutrino oscillation evidence can be traced back to the zenith angle dependence of the double ratio measurement at few GeV energies in Super-Kamiokande [7]. IceCube DeepCore, with its approximately 13 MT fiducial volume, is capable of making atmospheric neutrino oscillation measurements above 10 GeV, an energy region that has not been well explored by previous atmospheric neutrino oscillation experiments. From Fig. 4, a significant deficit in the neutrino flux at 25 GeV is expected from the $\nu_\mu \to \nu_\mu$ survival probability. In Fig. 5 this disappearance signature is shown for one year of simulated DeepCore data. The disappearance signal assumes that the path length is the diameter of the Earth, and therefore the ideal neutrino sample should contain only up-going neutrino-induced muons. An intrinsic difficulty for all experiments in identifying perfectly up-going neutrino-induced muon tracks is that the average opening angle, defined as the angle between the final state lepton direction and the incoming neutrino direction, increases with decreasing energy. The uncertainty in the opening angle can be approximated as $\Delta\Phi \simeq 30^\circ \times \sqrt{(1GeV)/E_{\nu_\mu}}$. This effect will smear the oscillation signature in the neutrino flux at lower energies. However, as shown in Fig. 5, DeepCore simulations indicate the potential to measure oscillations even if "up-going" tracks are defined to include measured directions over the wide range of values, $-1.0 < \cos(\theta) < -0.6$ [4].

2.2 ν_τ Appearance

The OPERA neutrino detector, located at the underground Gran Sasso Laboratory (LNGS), was designed for direct observation of $\nu_\mu \to \nu_\tau$ appearance. OPERA announced a first tau lepton candidate from ν_μ oscillation, and continues operation to achieve a statistically significant observation [8, 9]. DeepCore is currently acquiring data and will collect the world's largest inclusive sample of ν_τ. From Fig. 4, the region where ν_μ flux reaches its minimum is the same region where ν_τ flux shows its corresponding maximum from $\nu_\mu \to \nu_\tau$ oscillation. ν_τ that interact in DeepCore will produce an electromagnetic or hadronic shower, or "cascade". Events with short tracks which are beyond DeepCore's ability to separate from cascades, are an irreducible background to cascade-like events. Therefore, cascade-like events include: 1) neutral current (NC) events from all three neutrino flavors (e, μ, τ), 2) ν_μ charged current (CC) events with short tracks ($< \sim$ O (10) m), 3) ν_τ charged current events with τ-leptons decaying into electrons or hadrons, 4) ν_τ charged current events with τ-leptons decaying into muons whose track length is less than O (10) m. DeepCore should detect an excess of cascade-like events due to oscillation compared to the number of cascade events expected without oscillation. DeepCore may also be able to detect a distortion in the energy spectrum of cascade events due to ν_τ appearance. The simulated excess of cascade-like events above $\sim$ 25 GeV in DeepCore is shown in Fig. 6. The deficit of oscillated cascade-like events compared to unoscillated below $\sim$ 25 GeV is due to the rapid oscillation in the ν_μ and ν_τ survival probabilities shown in Fig. 4. Within the rapid oscillation regime,

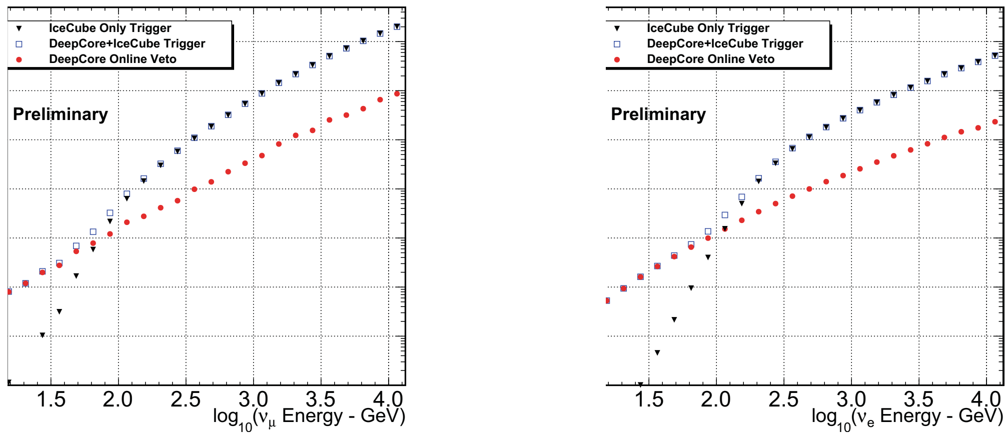

Figure 2: Effective areas for muon neutrinos (left) and electron neutrinos (right). Triangles: IceCube standard strings only, trigger level. Squares: IceCube including DeepCore strings, trigger level. Circles: IceCube DeepCore after applying the online veto.

a large fraction of ν_μ charged current (CC) events oscillate into ν_τ events. The produced tau lepton from those ν_τ CC events always decay to at least one neutrino, reducing the visible energy and possibly resulting in an event below the detector energy threshold. However, without oscillation, these low energy ν_μ CC events would be classified as cascade-like due to their short tracks. This significant deficit between the oscillated and unoscillated cascade-like event rates near the detector threshold may offer an opportunity to measure ν_μ disappearance in the cascade channel. The feasibility of measuring the excess of cascade-like events above 25 GeV, as well as systematic effects due to the ice properties, DOM efficiency and other factors, are under study.

2.3 Reconstruction Algorithms

Several reconstruction algorithms are being developed specifically for low-energy analysis in DeepCore. With shorter muon track lengths, low-energy events include a higher proportion of "starting" and fully contained muon events as opposed to through-going muons. The oscillation analysis also depends on separating track-like ν_μ charged current events from cascade-like all-flavor neutral current and ν_e and ν_τ charged current events. Fully-contained-muon reconstruction algorithms calculate the length of the track from the reconstructed beginning and end points of the track. Fig. 7 shows the difference between reconstructed and true track length from simulated data reconstructed with one such algorithm. The starting muon event signature consists of a cascade associated with the charged-current muon neutrino interaction and a track associated with the resulting muon. Reconstructions of such events therefore include the contributions of the cascade and the track. An algorithm under development for seeding these reconstruc-

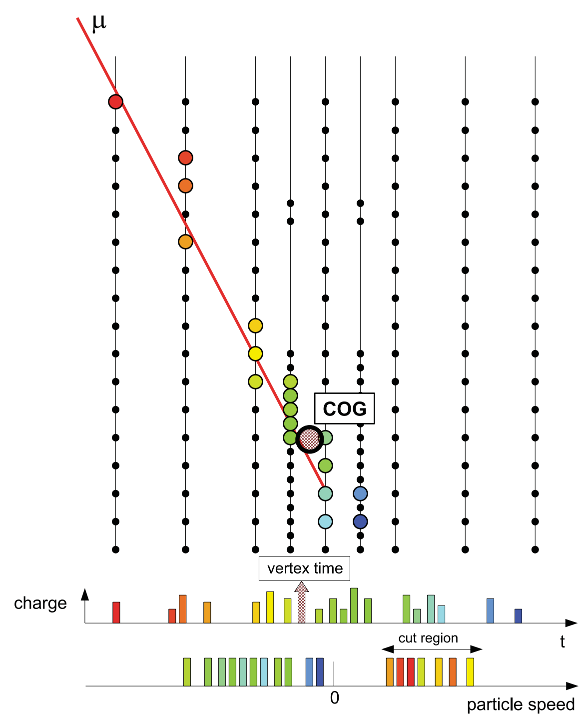

Figure 3: Scheme of veto algorithm based on simulation. Upper part demonstrates a down-going muon hitting the DOMs with hit sequence varying from earliest in red to latest in blue. The big black circle exhibits the COG of the hits in DeepCore. Bottom part includes the vertex time and particle speed per hit. The "cut region" illustrates a cut based on the particle speeds which are consistent with down-going muons.

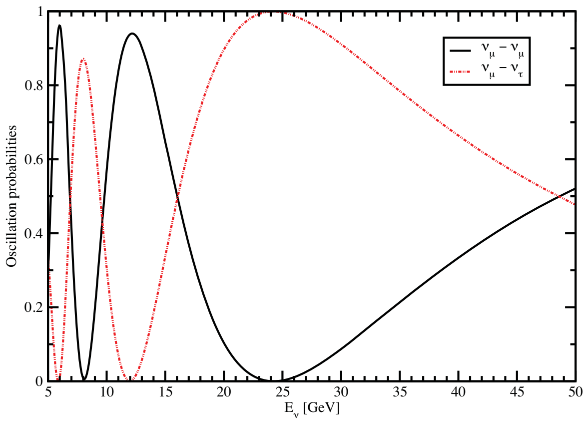

Figure 4: Oscillation probabilities for ν_μ with $sin^2 2\theta_{13} = 0.1, \Delta m^2_{31} = 2.5 \times 10^{-3} eV^2, L = 12757$ km [5].

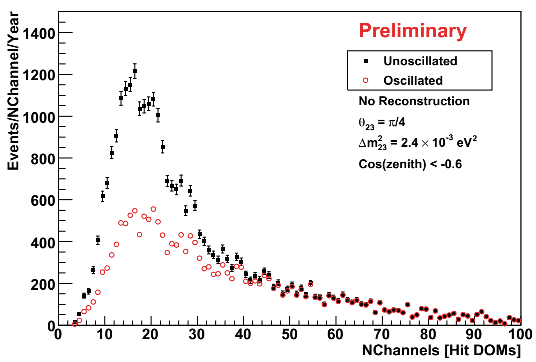

Figure 5: Simulated ν_μ disappearance with one year DeepCore data. Filled squares: Distribution of number of hit DOMs (NChannel) assuming no oscillation. Empty circles: Distribution of number of hit DOMs (NChannel) with oscillation.

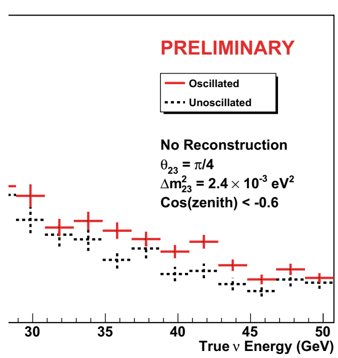

Figure 6: Simulated ν_τ appearance with one year DeepCore data. Dotted lines: Distribution of true neutrino energy assuming no oscillation. Solid lines: Distribution of true neutrino energy with oscillation.

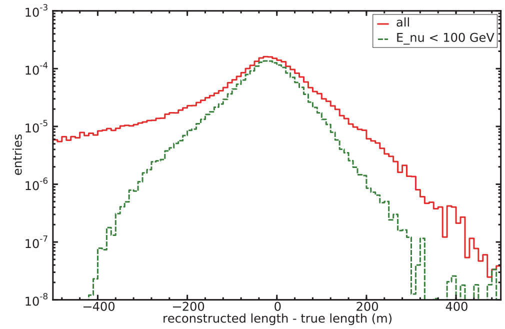

Figure 7: Difference between reconstructed track length and Monte Carlo simulation true track length.

tions and thereby separating tracks from pure cascades is based on a Fermat Surface [10].

3 Conclusions

Simulations suggest that IceCube DeepCore may have the capability to measure atmospheric neutrino oscillations in an energy range which complements existing accelerator measurements. DeepCore construction is complete and the detector is already collecting data. New reconstruction algorithms suited to low energy measurements will enable IceCube to fully exploit the physics capabilities of DeepCore.

References

[1] P. B. Price, K. Woschnagg, and D. Chirkin, Geophys. Res. Lett. **27**, 2129-2132 (2000)
[2] A. Achterberg et al. [IceCube Collaboration], Astroparticle Physics, **Volume 26**, Issue 3, October 2006, Pages 155-173
[3] R. Abbasi et al., Nuclear Instruments and Methods **A618** (2010) 139-152, 1-21 June 2010
[4] Darren Grant, D. Jason Koskinen, and Carsten Rott [IceCube Collaboration], Proceedings of the 31st ICRC, LODZ, POLAND, 2009
[5] O. Mena, I. Mocioiu and S. Razzaque, Phys. Rev. D **78**, 093003 (2008)
[6] Olaf Schulz, Sebastian Euler, and Darren Grant [IceCube Collaboration], Proceedings of the 31st ICRC, LODZ, POLAND, 2009
[7] Y. Fukuda et al. [Super-Kamiokande Collaboration], Phys. Rev. Lett. **81**, 1562 (1998)
[8] R. Acquafredda et al. [OPERA Collaboration], New J. Phys. **8**, 303 (2006)
[9] N. Agafonova et al. [OPERA Collaboration], Phys. Lett. **B691** 138-145 (2010)
[10] J. G. Learned, [arXiv 0902.4009 (2009)]