Fundamental Neutrino Measurements with IceCube DeepCore

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***Abstract*. The recent deployment of the first string of DeepCore, a low-energy extension of the IceCube neutrino observatory, offers new opportunities for fundamental neutrino physics using atmospheric neutrinos. The energy reach of DeepCore, down to ~ 10 GeV, will allow measurements of atmospheric muon neutrino disappearance at a higher energy regime than any past or current experiment. In addition to a disappearance measurement, a flavor-independent statistical analysis of cascade-like events opens the door for the measurement of tau neutrino appearance via a measurable excess of cascade-like events. In the event of a relatively large value of $\sin^2 2\theta_{13}$, a multi-year measurement of the suppression of muon neutrino disappearance due to earth matter effects may show a measurable dependence on the sign of the mass hierarchy (normal vs. inverted).**

***Keywords*: Oscillations, DeepCore, hierarchy**

I. ICECUBE DEEPCORE

The IceCube neutrino telescope is a multipurpose discovery detector under construction at the South Pole, which is currently about three quarters completed [1]. After completion in 2011, IceCube will have instrumented a volume of approximately one cubic kilometer utilizing 86 strings, each instrumented with 60 Digital Optical Modules (DOMs) at a depth between 1450 m and 2450 m. Eighty of these strings (the baseline design) will be arranged in a hexagonal pattern with an inter-string spacing of about 125 m and with 17 m vertical separation between DOMs. This baseline design is complemented by six more strings, that form a more densely instrumented sub-array, located at the center of IceCube. These strings will be spaced in between the regular strings, so that an interstring-spacing of 72 m is achieved. Together with the seven adjacent standard IceCube strings these six strings form the DeepCore array in the center of IceCube (shown in Figure 1). DeepCore strings have a different distribution of the 60 DOMs on them. Fifty out of the 60 DOMs on a DeepCore string will be installed in the deep clear ice, below an ice-layer of short absorption length (1970 2100 m) also labeled ”dust-layer”. The top 10 DOMs on the DeepCore strings will be deployed above this dust-layer. Those DOMs add to the effective veto capability of the surrounding IceCube strings against down-going muons.

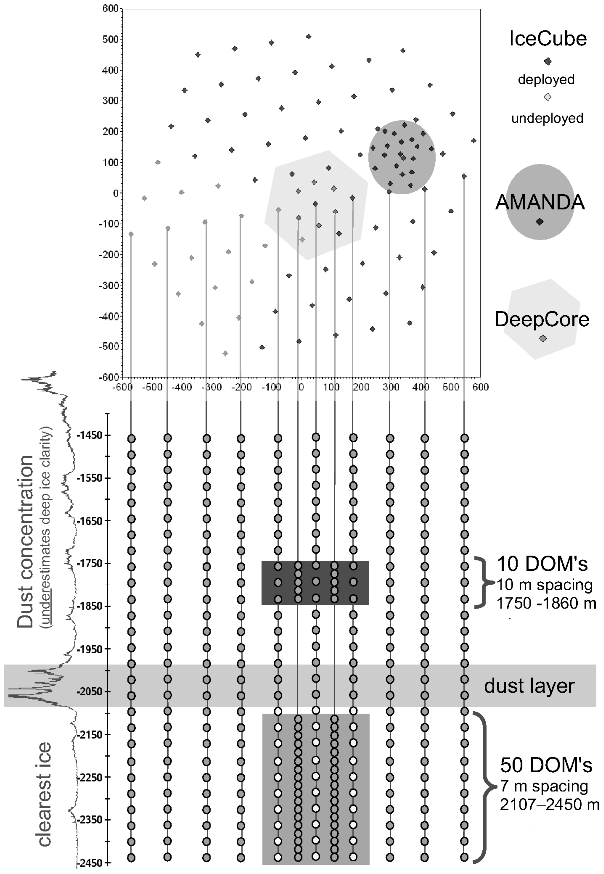

Fig. 1: IceCube with the DeepCore sub-detector in the center deep clear ice. The illustration on the left shows the depth-profile of the optical transparency of the ice.

The DeepCore extension will significantly improve IceCube's low energy performance and allow neutrino detection to approximately 10 GeV (see Figure 2). This is accomplished by having DeepCore strings with a dense vertical spacing of 7 m between DOMs, which are deployed in the deepest ice where the scattering length is approximately twice that compared to the upper part of the IceCube detector [2]. Coupled with the spacing and ice clarity the DOMs themselves are instrumented with high quantum efficiency photomultiplier tubes (HQE PMTs), that have a 40% efficiency increase, wavelength dependent, compared to regular IceCube PMTs [3]. The aforementioned properties make the DeepCore an ideal detector for low energy-low rate neutrino physics.

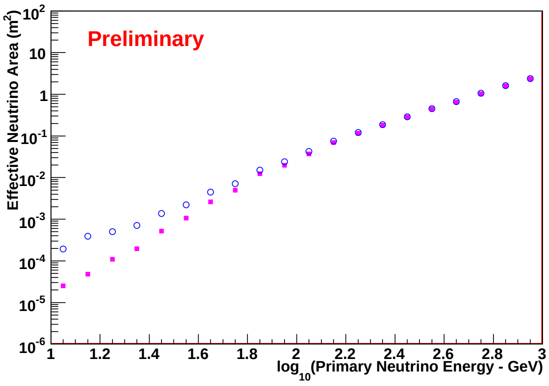

Fig. 2: Comparison of preliminary study of effective area $\mathrm{A_{eff}}$ at trigger level for the 80 IceCube string array without DeepCore (squares) and in addition with the six DeepCore strings (open circles). The addition of DeepCore increases the effective area of the detector at low energies significantly.

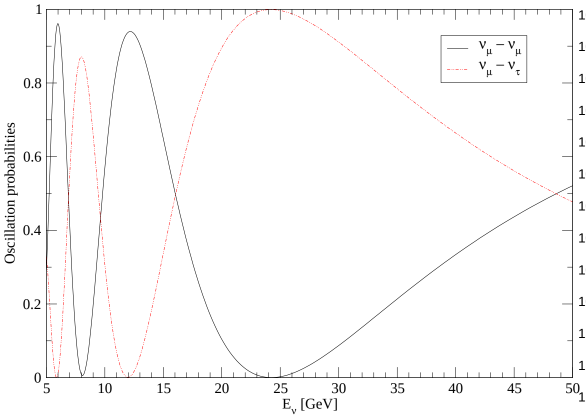

Fig. 3: ν_μ survival probability and $\nu_\mu \longrightarrow \nu_\tau$ oscillation probability for vertically upward going neutrinos, where $\sin^2 2\theta_{13}$ =0.1 [6].

II. DeepCore Neutrino Oscillation Physics

The lower energy reach achieved with the DeepCore opens the possibility to investigate atmospheric neutrino oscillations in the primarily unexplored energy regime of a tens of GeV. In Figure 3 we show the expected ν_μ survival probability and $\nu_\mu \longrightarrow \nu_\tau$ oscillation curves for which the DeepCore will have sensitivity and relate directly to the potential measurements discussed in the following subsections. In addition to the improved energy reach, part of what make such measurements possible is the innate background rejection built into the DeepCore design: increased overburden reduces the number of atmospheric muons and the surrounding IceCube strings provide an in situ veto. Simple veto methods have achieved background reductions of four orders of magnitude with excellent signal retention and have potential for greater than 6 orders of magnitude rejection utilizing reconstruction veto methods [3].

A. *Muon-Neutrino Disappearance*

Previous measurements of neutrino oscillations at the atmospheric-scale have been significantly decreased in both energy reach and active volume size of the detectors compared to DeepCore. With an approximate 13 MT fiducial volume, DeepCore has the capacity to make a precision measurement of atmospheric neutrino oscillations above 10 GeV [4]. The ν_μ survival probability curve shown in Figure 3 illustrates an expectation for a significant deficit in neutrino flux, shown in Fig. 4 at a previously unexplored energy region. An issue associated with such an analysis is the angular resolution of neutrino induced muon tracks at these energies is fundamentally limited by the kinematics of the neutrino-nucleon interaction. Low energy ν_μ interactions have a much bigger opening angle between the incoming neutrino and outgoing muon than high energy interactions, which leads the muon to have a higher probability of being noncollinear with the incoming neutrino. The intrinsic uncertainty on the opening angle reduces any experiments ability to identify perfectly upward going neutrinos, where the uncertainty can be approximated, in the full data sample, by $\Delta\phi \simeq 30^\circ \times \sqrt{(\mathrm{GeV})/E_{\nu_\mu}}$. However, oscillations can be observed with very high significance with an inclusive measurement over the zenith angle range $-1.0 < \cos\phi < -0.6$, and incorporation of angular dependence will only improve the result. Fig. 4 shows a simulation of this muon disappearance effect, which would be an approximate 20 sigma effect with just one year of IceCube DeepCore data. The current study only discusses the effect on the signal, taking statistical uncertainties into account. Systematic uncertainties remain to be studied, as well as the background prediction to this measurement.

B. *Tau-Neutrino Appearance*

Returning to Figure 3 and looking at the $\nu_\mu \longrightarrow \nu_\tau$ oscillation curve, we expect a fraction of the incoming atmospheric neutrino flux to have a ν_τ component. Given the higher parent ν_μ flux and different decay kinematics of tau events relative to that of ν_e charge-current (CC) and ν_x neutral current (NC) (x=e, μ, τ) events, we should be able to detect ν_τ both via the excess of cascade (hadronic and electromagnetic shower) events and possibly through the resulting spectral energy distortion. This measurement would not only represent the largest sample of tau neutrinos ever collected (albeit inclusively), it may also be competitive with OPERA [5] in making an appearance measurement of tau neutrinos due to oscillations.

Future components of this analysis comprise developing a dedicated energy reconstruction for low energy cascade events as well as examining the background caused by short muon tracks that mimic cascades as well as the impact of misidentification of up versus down going neutrinos. Good energy resolution will increase sensitivity to ν_τ appearance over regions where neutrino oscillations are maximal.

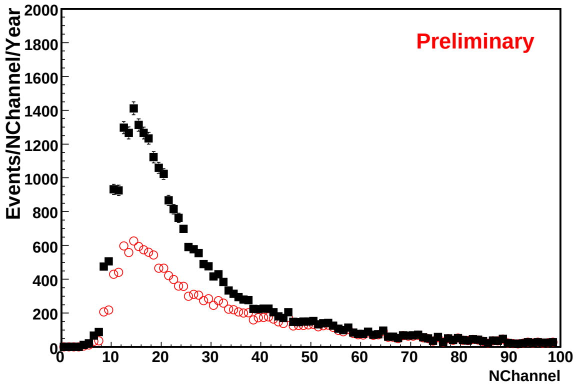

Fig. 4: Simulated ν_μ disappearance with 1 year of DeepCore data. The lower curve (open circles) show the number of upward-going muons observed over the zenith angle cosϕ $<$ -0.6 with oscillations, while the upper curve (squares) is the corollary without oscillations. No systematic errors or background have been included. The effect is approximately 20 sigma based purely on statistical errors (approximately 28000 events per year without oscillations and 16000 events with oscillations assuming $sin^2 2\theta_{23}$=1.0 and Δm^2_{23}=0.0024). Note that NChannel is a crude energy estimator for the detector based on the number of hit DOMs.

C. Matter Effects and Neutrino Mass Hierarchy

Depending on detection efficiency and purity, a sufficiently large value of $\sin^2\theta_{13}$ [6], and control of systematics the DeepCore detector may be used in an ambitious multi-year effort to determine the sign of the neutrino mass hierarchy. This may be accomplished by measuring a small enhancement/supression from the MSW effect [11] of the expected number of ν_μ events. The ν_μ oscillation probability, shown in Figure 5, indicates that the neutrino rate over the 8-25 GeV energy region is enhanced for the normal hierarchy (NH), and enhanced for anti-neutrinos for the inverted mass hierarchy (IH). A complication of this measurement is that DeepCore cannot distinguish between neutrino and anti-neutrinos, however at the relevant energy range of 10 GeV $< E_\nu <$ 30 GeV the interation cross-section between neutrinos and anti-neutrinos differs by a factor of two; $\sigma(\nu_x) \simeq 2\sigma(\bar{\nu_x})$. The difference in interaction cross-section translates into a difference in the number of observed muon neutrino candidate events. Based on statistical discrimination only, it may be possible to distinguish normal from inverted hierarchies. In Fig. 6 we show the expected results from 5 years of DeepCore data, with a statistical separation between the normal and inverted hierarchies of approximately 10 sigma. The described effect is pending on a sufficiently large value of θ_{13} (that is expected to be measured by the time of the data for this measurement has been obtained). Further the signal systematic uncertainties need to be sufficiently small and remaining background need to be effectively removed.

III. CONCLUSIONS

We have completed a full Monte Carlo study of the IceCube DeepCore detector that shows the potential for measurements of fundamental neutrino properties. We have discussed the expected effects on the signal for ν_μ disappearance at energies higher than previously measured, a measurement of ν_τ appearance as well as resolution of the neutrino mass hierarchy.

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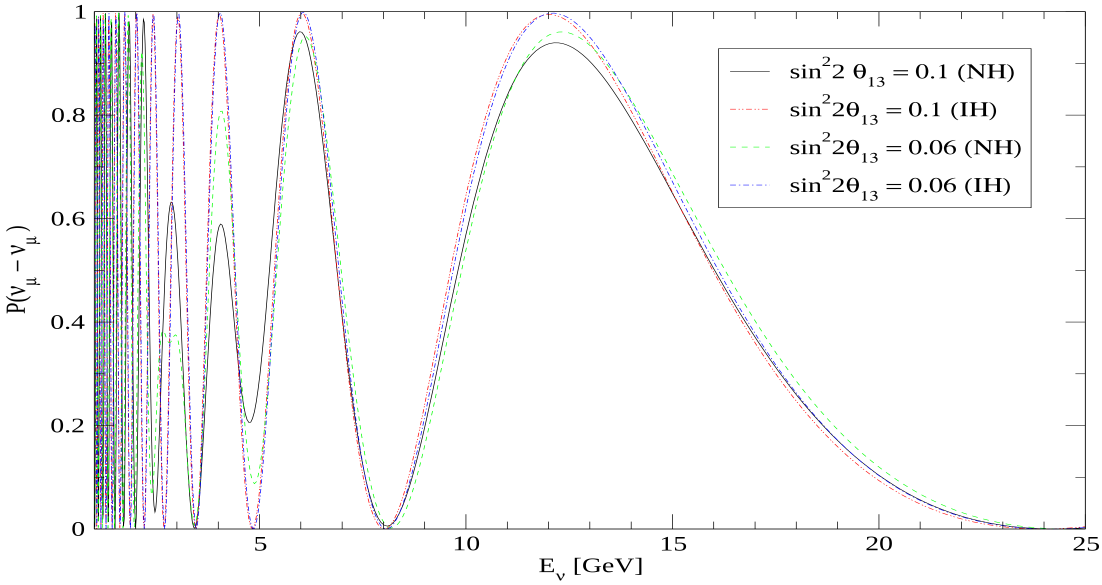

Fig. 5: Oscillation probabilities for $\nu_\mu \longrightarrow \nu_\mu$ transitions for upward going neutrinos [6]. For a value of $\sin^2 2\theta_{13}$=0.1, the difference in the survival probability between the normal hierarchy (solid black line) and inverted hierarchy (dashed red line) is $\approx$ 7%, and increases for higher values of $\sin^2 2\theta_{13}$. Recent measurements [7] as well as global fits [8], [9] prefer that $\sin^2 2\theta_{13}$ is non-zero, while the value of 0.10 reflects the 90% Confidence Limit set by CHOOZ [10].

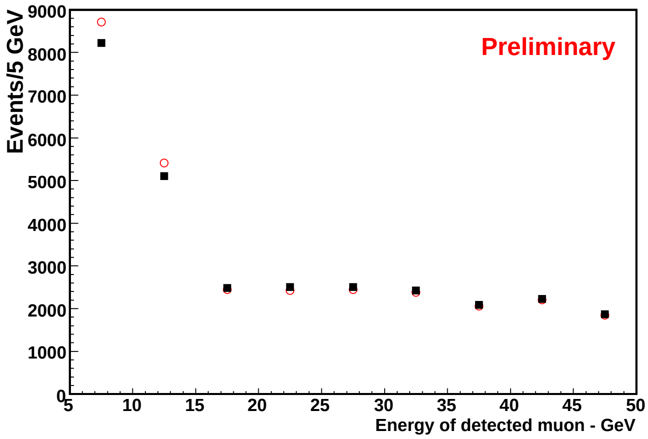

Fig. 6: Predicted rate with 5 years of data for normal (squares) and inverted (open circles) hierarchy, for ν_μ induced muon tracks within 45 degrees of vertical that start within the DeepCore fiducial volume. We find that in the first two bins the rate for the inverted hierarchy is above that for the normal hierarchy and that in the remaining bins the rates overlap. Systematic errors are not yet estimated. Statistical errors are too small to be visible. Note that $\sin^2 \theta_{13}$=0.1 in the presented case.