Neutrino oscillations with IceCube

The IceCube Collaboration

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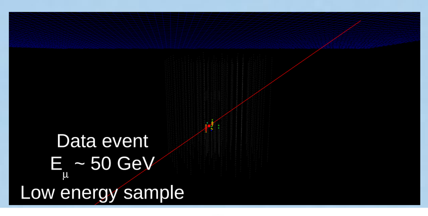
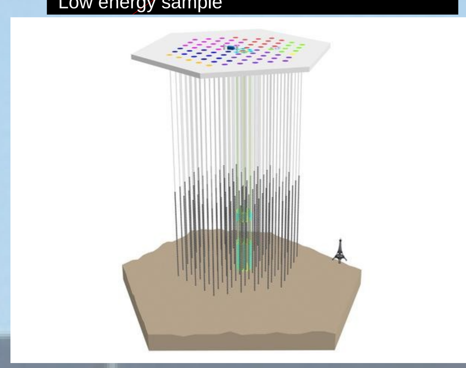
Introduction

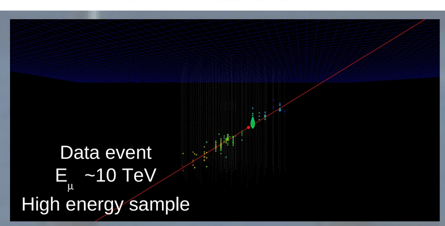
We present the results of an analysis of data collected by IceCube/DeepCore in 2010-2011 resulting in the first significant detection of neutrino oscillations in a high-energy neutrino telescope. A low-energy muon neutrino sample (20 - 100 GeV) containing the oscillation signal was extracted from data collected by DeepCore. A high-energy muon neutrino sample (100 GeV - 10 TeV) was extracted from IceCube data in order to constrain the systematic uncertainties. The non-oscillation hypothesis was rejected with more than 5 sigma. We fitted the oscillation parameters Δm^2_{23} and $\sin^2(2\theta_{23})$ to these data samples. In a 2-flavor formalism we find $\Delta m^2_{23} = (2.5\pm0.6) \times 10^{-3}$ eV^2 and $\sin^2(2\theta_{23}) > 0.92$ while maximum mixing is favored. These results are in good agreement with the world average values.

Atmospheric neutrinos in IceCube and DeepCore

IceCube is the world's largest neutrino telescope with an instrumented volume on the cubic kilometer scale. In total, 86 strings have been deployed in the ice at the geographic South Pole in a depth of 1450 to 2450 m. Each string holds 60 digital optical modules (DOMs) each with a photomultiplier tube. IceCube is sensitive to the Cherenkov light emitted by charged particles created in neutrino interactions. The most sensitive channel is the detection of muon tracks due to the large propagation length of muons. With a string spacing of ~125 m, IceCube is mainly sensitive in the 100 GeV – 1 PeV energy band. With the DeepCore sub-detector [1], the central volume in the cleanest deep ice is more densely instrumented by 8 additional infill strings. With DeepCore the performance (effective area, energy+track reconstruction) in the 10-100 GeV energy range has been significantly improved. We use the parametrization of the atmospheric neutrino flux given in [4], systematic uncertainties are taken from a comparison to [5]. Taking into account recent CR measurements, we modified the neutrino spectrum to a harder spectral index by 0.05.







Data sample

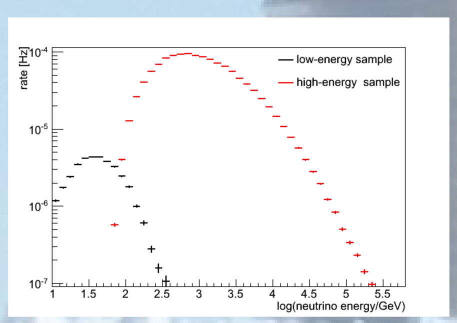


Fig. 1: true energy of neutrinos detected in DeepCore (low-energy, black) and in IceCube (high-energy, red).

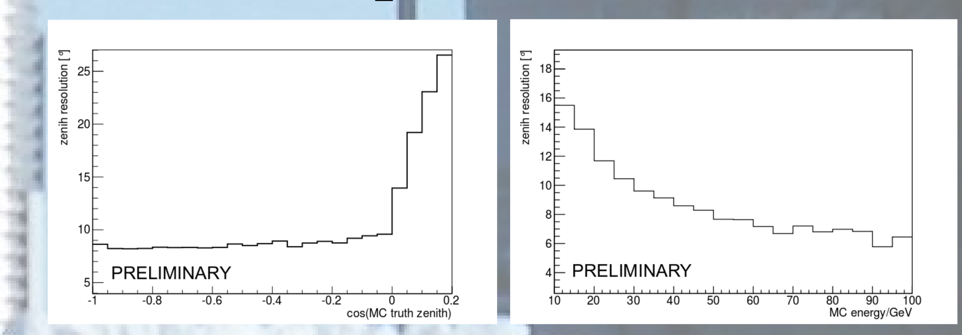


Fig. 2: mean zenith resolution of atmospheric neutrinos selected for the IceCube/DeepCore low-energy sample as a function of true zenith (left) and true energy (right). The kinematic angle between neutrino and muon is included here.

We extracted two samples of upwards going neutrino events from data collected by IceCube-79, one at relatively high energies using data from the entire IceCube detector and one at lower energies selected in the DeepCore volume, rejecting backgrounds by an active veto. Neutrino oscillations are expected to affect only the low-energy sample. The high-energy sample provided large statistics outside the signal region and served to constrain systematic uncertainties. Quality cuts like the number of unscattered photons and the track likelihood allowed for the rejection of misreconstructed downwards going muon background.

In Fig. 1, the neutrino energy distributions of the low-energy and the high-energy sample are shown. The resolution of the reconstructed zenith angle is essential because the propagation length is proportional to cos(zenith). A variation of the zenith thus represents a variation of L/E. As displayed in Fig. 2, a resolution of 8° is achieved for the low-energy sample, independent from the zenith. This resolution only slightly degrades with energy. The kinematic angle between the neutrino and the muon produced in a charged current interaction amounts about half of the zenith resolution, the balance is due to reconstruction inaccuracies.

ν_μ disappearance

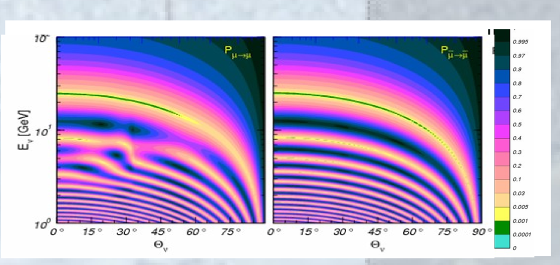


Fig. 3: Oscillogram: survival probability of muon neutrinos (left) and anti-neutrinos as a function of energy and nadir angle [3].

We use the effect of ν_μ disappearance in order to detect neutrino oscillations in IceCube. The leading effect of oscillations can be described approximately by the 2 flavor formula in vacuum, $p_{\mu\mu} = 1-\sin^2(\theta_{23}) \sin^2 (\Delta m_{23}{}^2/4E)$. We have checked the validity of such a formula using full numerical three-flavor calculations in matter and found deviations of less than a few percent. Given the resolution of the present analysis, this approximation is sufficiently accurate.

Systematic uncertainties

A covariance matrix in a χ^2 fit was used to consider systematic uncertainties in the analysis of the data. In order to obtain the most likely value of the individual sources of systematic errors, the pulls as defined in [2] were used. The following sources of systematic uncertainties were considered explicitly and propagated by MonteCarlo simulation to the final selection level:
* the absolute sensitivity of the IceCube sensors (10%) and the relative efficiency of the more efficient DeepCore DOMs (1.35±0.03)
* the optical parameters (scattering, absorption) of the ice as detector medium: the uncertainty is estimated by the difference of the optical parameters obtained by the extraction methods [6] and [7]
* the absolute normalization of the cosmic ray flux (±25%) and its spectral index (±0.05)
* the uncertainty of the neutrino production rate in the atmosphere: the difference of calculations by [4] and [5] were used for ν_μ and for ν_e.

Zenith distribution

During May 2010 to May 2011, we collected 318.9 days of high quality data, excluding periods of calibration runs, partial detector configurations and detector downtime. The low energy sample contained 719 events, while the high energy sample contained 39 638 events after final cuts. In a first step, we evaluated the χ^2 for the data collected by IceCube for two different physics hypotheses: the standard oscillation scenario represented by the world average best fit parameters and the non-oscillation case. With a $\chi^2 = 30$, we rejected the non-oscillation hypothesis with a p-value of 10^{-8}, corresponding to 5σ. Systematic uncertainties were included in the calculation using a χ^2 with covariance matrix. For the significance evaluation, a toy MC was used in order to consider deviations from a χ^2 distribution. The measured zenith distribution and the expected distribution at best fit (oscillation parameters and systematics) are shown in Fig. 4.

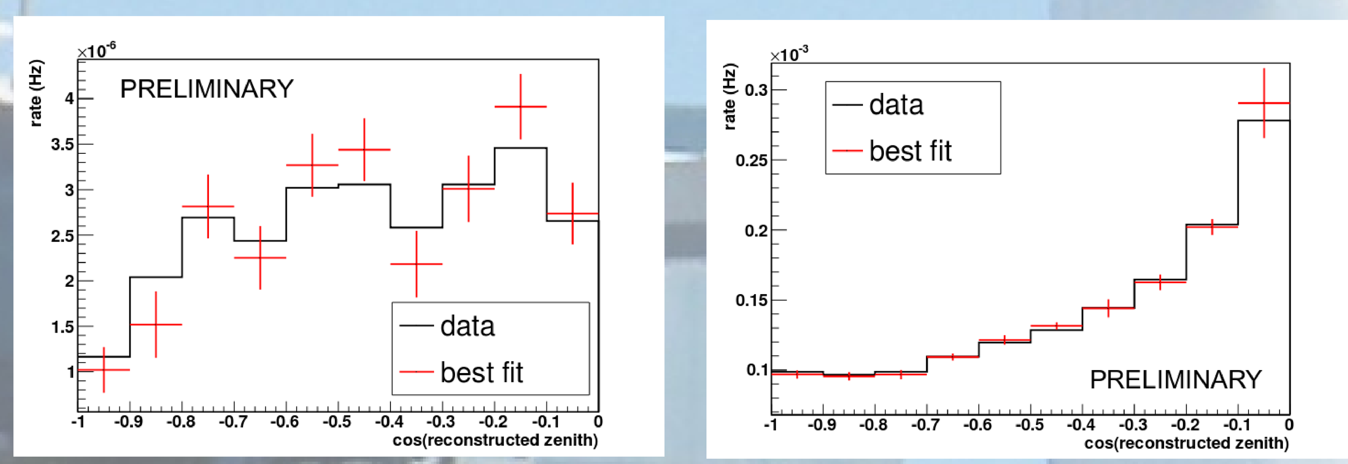


Fig. 4: measured zenith distribution (black) for low-energy sample (left) and high-energy sample (right) together with the expectation from MC simulations at best fit (oscillation parameters and pulls on systematic uncertainties).

Scan of oscillation parameters

We fitted the oscillation parameters a to the data by evaluating the χ^2 for a large set of oscillation parameters. We obtained a best fit value of $\Delta m^2_{23} = 2.5 \times 10^{-3}$eV^2 and $\sin^2(2\theta_{23}) = 1$, with the absolute $\chi^2 = 11.3$ (ndof=18) indicating a good agreement of data to MC within the assumed uncertainties. The equivalent χ^2-pull method [2] allowed to calculate the most likely values of the considered systematic uncertainties, which are represented in Fig. 6. The result is in good agreement with other experiments, which measured the atmospheric oscillations with a high resolution at lower energies[9]. The two dimensional confidence regions of the oscillation parameters in this measurement were determined from the χ^2 around the best fit with two degrees of freedom (68% CL: $\chi^2 = 2.30$ and 90% CL: $\chi^2 = 4.61$), see Fig. 5. The confidence regions of the individual parameters were determined by marginalization analogous to a profile likelihood method. We obtain 68% confidence intervals of $\Delta m^2_{23} = (2.5\pm0.6)\times10^{-3}$eV^2 and $\sin^2(2\theta_{23}) > 0.92$ using the χ^2 distribution with one degree of freedom. All pulls on the systematic uncertainties are within the 1σ uncertainty range, indicating the internal consistency of the analysis.

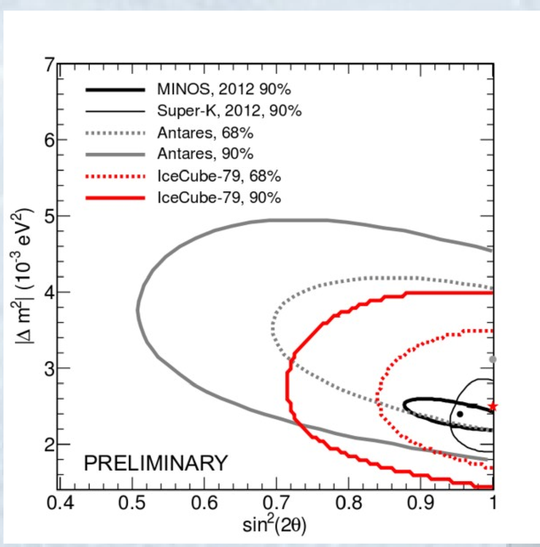
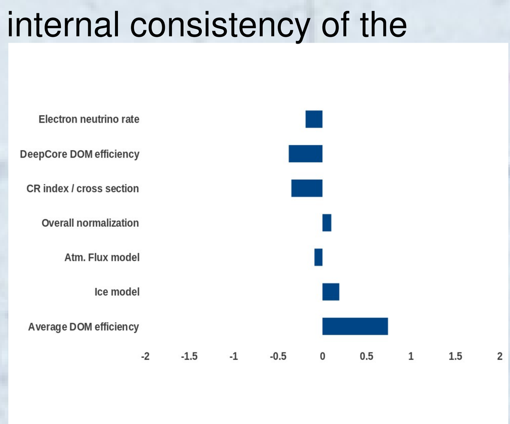


Fig. 5 (left): 68% and 90% CL contour line of the result of the IceCube-79 oscillation analysis in comparison with the results of Antares[11], Minos and SuperKamiokande[12]..

Fig. 6 (right): Pulls on the systematic uncertainties at best fit value $\Delta m^2_{23} = 2.5 \times 10^{-3}$eV^2 and $\sin^2(2\theta_{23}) = 1$



Energy distribution

Fig. 3 shows the energy dependence of the oscillation signal as a function of the zenith angle and energy. In this analysis neutrino oscillations are analyzed by the zenith-dependent disappearance of ν_μ. Here we plot the distribution of the number of hit DOMs as an energy proxy for vertical and horizontal events from the low-energy event selection. This provides additional evidence for oscillations, not included in the statistical tests.

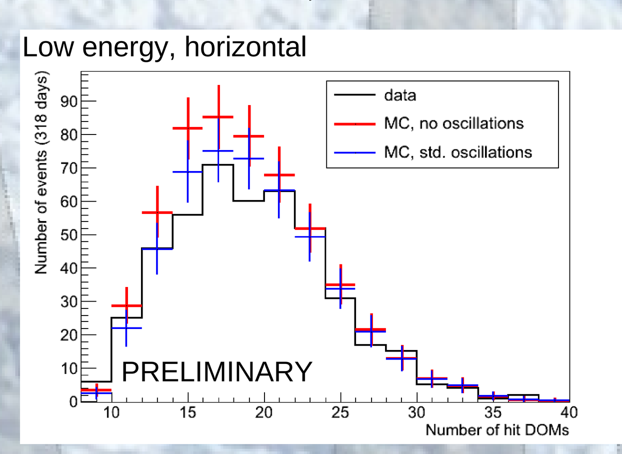


Fig. 7: Distribution of the number of hit DOMs for horizontal events (cos(θ)>-0.55) of the low-energy event selection. Error bars represent statistical errors only.

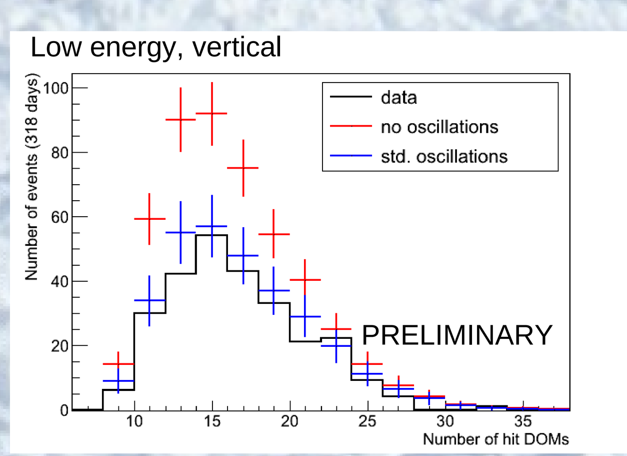


Fig. 8: Distribution of the number of hit DOMs for vertical events (cos(θ)<-0.55) of the low-energy event selection.

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Outlook

This analysis represents a starting point for IceCube/DeepCore concerning the physics of neutrino oscillation. Several improvements are expected due to improved reconstruction algorithms and due to the inclusion of two more DeepCore strings in data taking from May 2011 on. For a more detailed measurement of the oscillation parameters it will be essential to reduce systematic errors by improving the knowledge about optical ice parameters and photomultiplier tubes' absolute efficiency. These are the subject of ongoing investigations in the IceCube collaboration.