Neutrino oscillations with IceCube

The IceCube Collaboration

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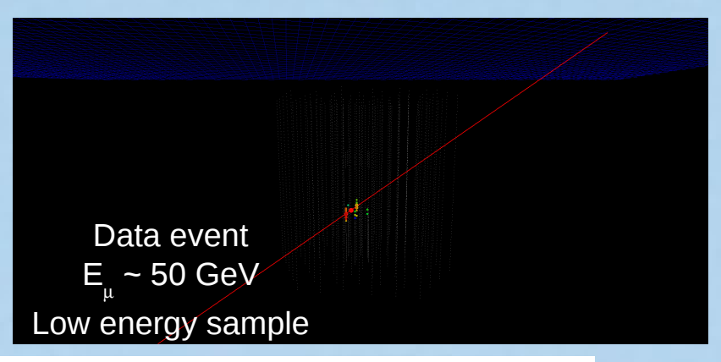
Introduction

Neutrino oscillation experiments have established that neutrino flavour and mass eigen states do mix [1]. So far, solar and long-baseline reactor neutrino experiments have measured the mass-mixing parameters (δm^2, θ_{12}) in the $\nu_e \rightarrow \nu_e$ channel (electron neutrino disappearance), while atmospheric and long-baseline accelerator experiments have measured (Δm^2, θ_{23}) in the $\nu_\mu \rightarrow \nu_\mu$ channel (muon neutrino disappearance).

The IceCube neutrino telescope instrumented with a low-energy core (DeepCore) is sensitive to neutrino oscillations in the $\nu_\mu \rightarrow \nu_\mu$ channel. By an analysis of data collected between May 2010 and May 2011, the disappearance of ν_μ versus zenith is clearly observed. The non-oscillation case is rejected with a p-value of 10^{-8} in a hypothesis test realized against the standard oscillation case with mixing parameters fixed at the global best fit value [3]. The systematic effects limiting this analysis are also discussed.

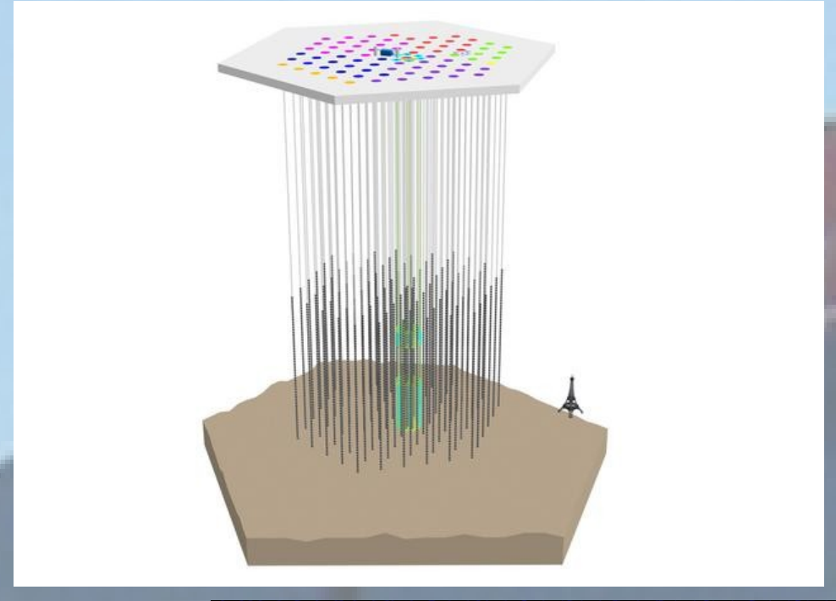
Atmospheric neutrinos in IceCube and DeepCore

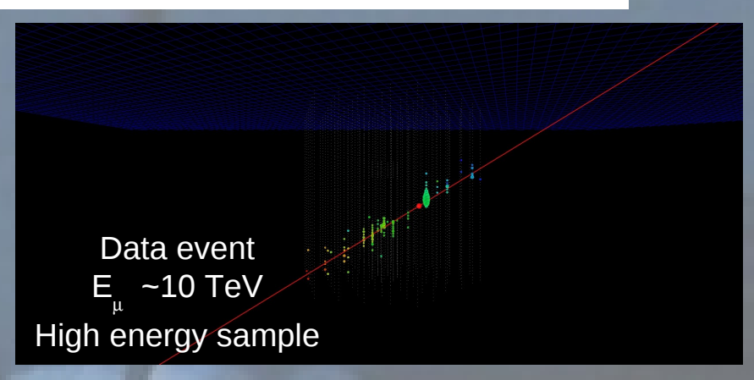
IceCube is the world's largest neutrino telescope with an instrumented volume on the cubic kilometer scale. In total, 86 strings have been deployed in the ice at the geographic South Pole in a depth of 1450 to 2450 m. Each string holds 60 digital optical modules (DOMs) each with a photomultiplier tube. 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 [4], 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 [6], systematic uncertainties are taken from a comparison to [7].


Data event

E_μ ~ 50 GeV

Low energy sample




Data event

E_μ ~10 TeV

High energy sample

ν_μ disappearance

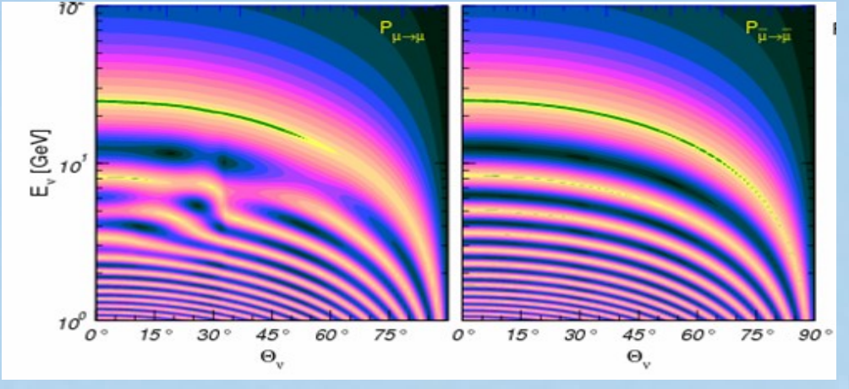


Fig. 1: survival probability of muon neutrinos (left) and anti-neutrinos as a function of energy and nadir angle [4].

We use the effect of nm disappearance in order to detect neutrino oscillations in IceCube. While our calculations include the 3-flavour formalism, the leading effect of oscillations can be described approximately by the 2 flavour formula $p_{\mu\mu} = 1-\sin^2(\theta_{23}) \sin^2 (\Delta m_{23}{}^2/4E)$. In the energy range above 10 GeV, matter effects in the Earth are negligible.

Data sample

We use data collected by IceCube and DeepCore between May 2010 and May 2011 with 79 operational strings (including 6 infill strings for DeepCore). Two event samples were selected, one at low-energies (10-100 GeV) and one at high-energies (100 GeV-50 TeV). The low-energy event sample is sensitive to oscillations while for the high-energy sample no effects due to standard oscillations are expected. The oscillations manifest as a zenith-dependent disappearance of ν_μ. Hence the reconstruction of the zenith at low-energies is important.

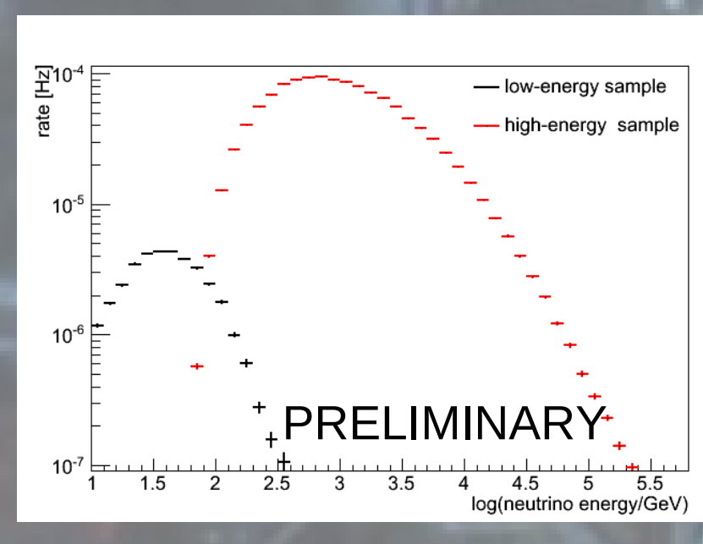


Fig. 2: true energy of neutrinos detected in DeepCore (low-energy, black) and in IceCube (high-energy, red).

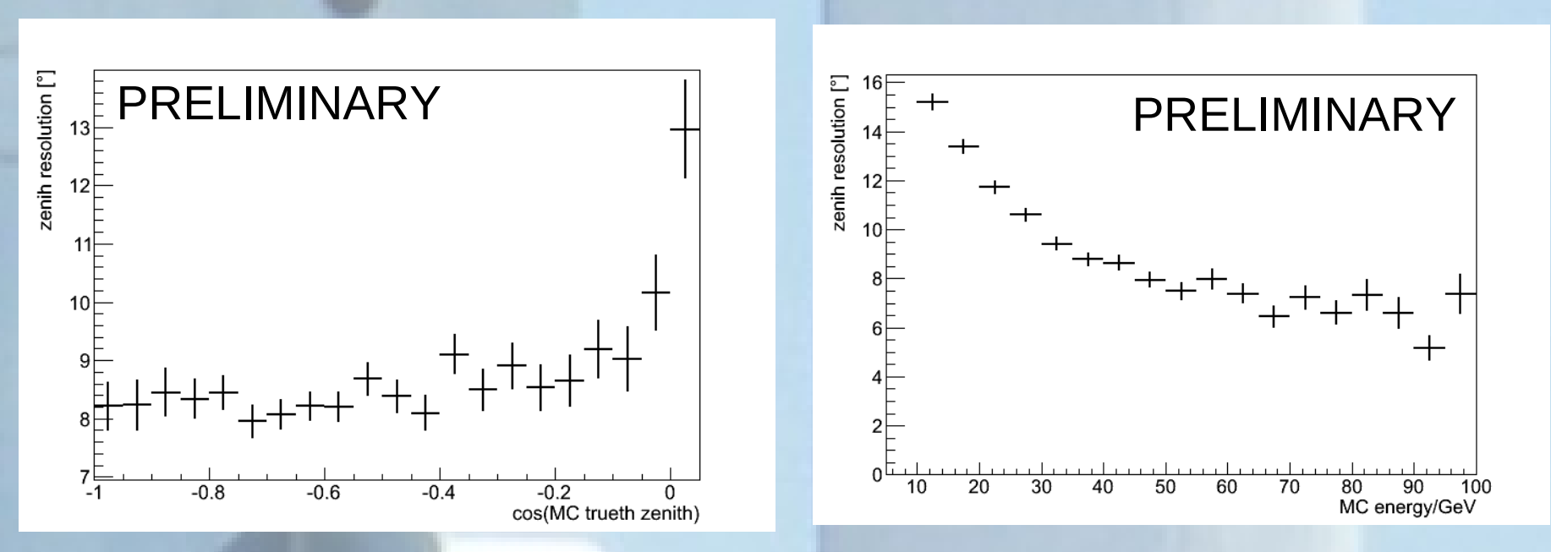


Fig. 3: mean zenith resolution of atmospheric neutrinos selected for the IceCube/DeepCore low-energy sample as a function of true zenith (left) and true energy (right). The kinematic angle between neutrino and muon is included here.

Results: zenith distribution

We have evaluated the distribution of the reconstructed zenith angle for two samples:

1) Low-energy sample based on DeepCore events

2) High-energy sample based on IceCube events.

Given the good zenith resolution and the statistics, a binning of 0.1 in cos(theta) is used. The experimental result is compared with the expectation from MC simulations. Two cases are considered, the hypothesis of no neutrino oscillations and the case of standard oscillations defined by global fit parameters [3]. The χ^2 is calculated in a global analysis of the low-energy sample and the high-energy sample simultaneously. It is evaluated with respect to both hypotheses, taking into account systematic errors by the method of the covariance matrix [2]. While in the high-energy sample oscillation effects are negligible, the high statistics atmospheric neutrino data give an important contribution to mitigate the effects of systematic uncertainties in this analysis. For the oscillation case, χ^2/ndof=19.4/20, while for the no-oscillation case χ^2/ndof=52.7/20. According to MC simulations, a difference in χ^2 of 33.3 or higher is expected only in 10^{-8} toy experiments representing the non-oscillation scenario.

	Data (317.9 days)	MC, std oscillation	MC, no oscillation
Low energy	719	789 +- 28 (stat)	1015 +- 32 (stat)
High energy	39639	33710 +- 770 (stat)	33810 +- 770 (stat)

Table 1.: Number of events observed and expected in the high-energy and in the low-energy event selection. Systematic errors on the integral amount to 30% resp. 35%.

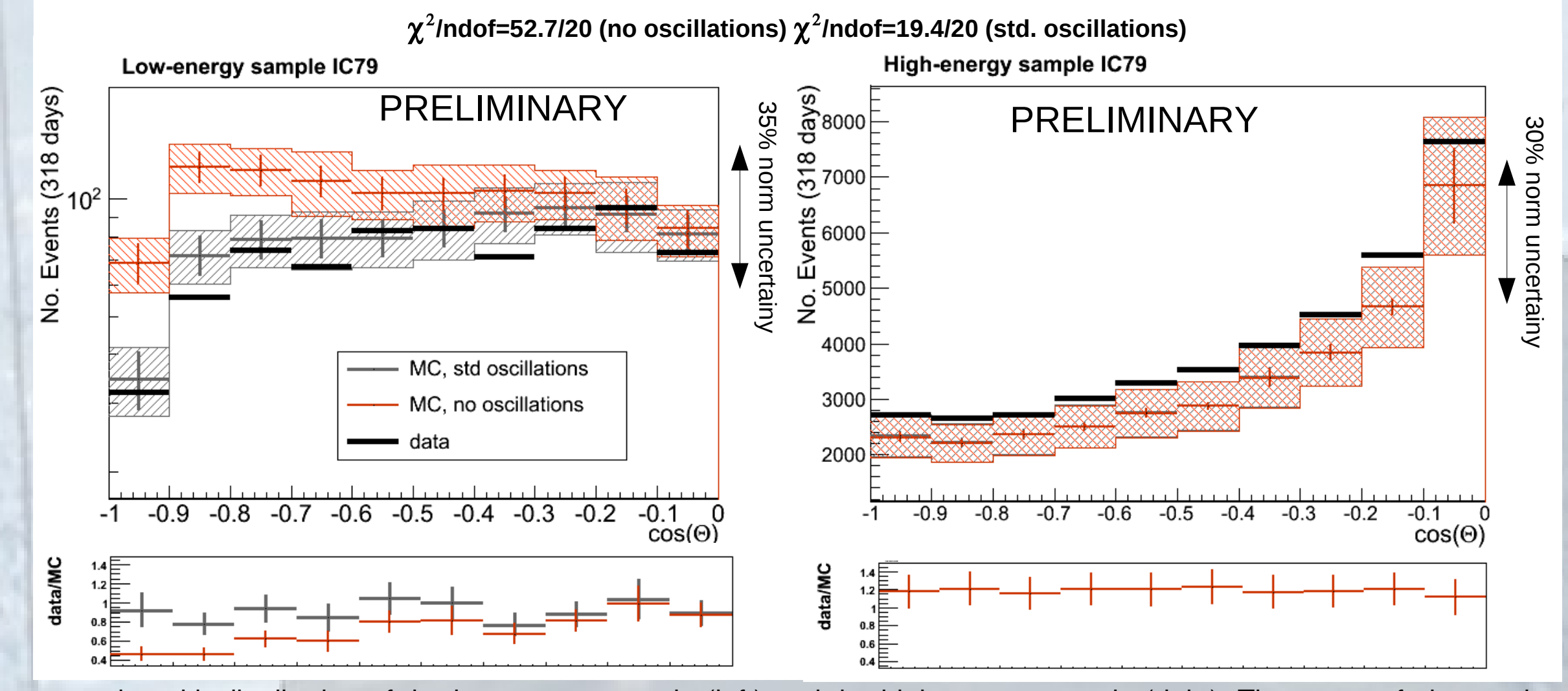


Fig. 4: Reconstructed zenith distribution of the low-energy sample (left) and the high-energy sample (right). The range of observations allowed by MC simulations including statistic and shape-dependent systematic fluctuations is indicated by the boxes, while the error bars indicate only statistical fluctuations. The normalization of the predicted event count is uncertain to 35% for the low-energy and 30% for the high-energy sample as indicated by the arrows in the figure. This uncertainty is due to the systematic effects described below. Because of the partial correlation of systematic uncertainties between the low-energy and high-energy zenith distributions, however, the normalizations of the individual samples may only be shifted by 20% with respect to each other.

Significance calculation

For the calculation of the significance of the analysis, a large set of pseudo-experiments was done. In each pseudo-experiments the MC expectation is varied by Gaussian fluctuations of the true parameters covering several sources of systematic uncertainties. Then the number of events is varied according to Poisson statistics around these expectations. Simulations of the non-oscillation case provide the test statistics to determine the significance of the observation. Simulations of the standard oscillations case allow for a consistency check between the observation and the standard oscillation parameters.

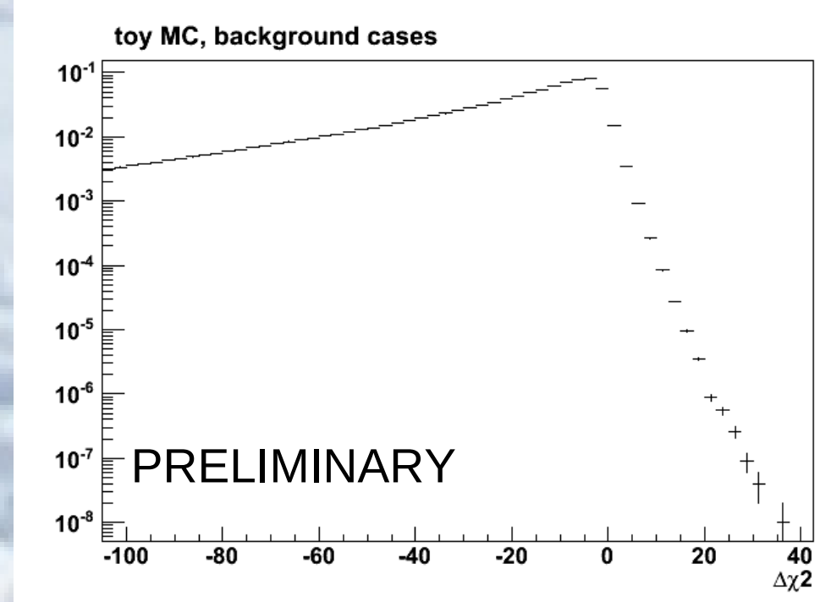


Fig. 7: Simulation of the non-oscillation case: distribution of the χ^2 difference between non-oscillation case and standard oscillation case. A value of 33.7 or higher is observed only in 10^{-8} of the simulated cases.

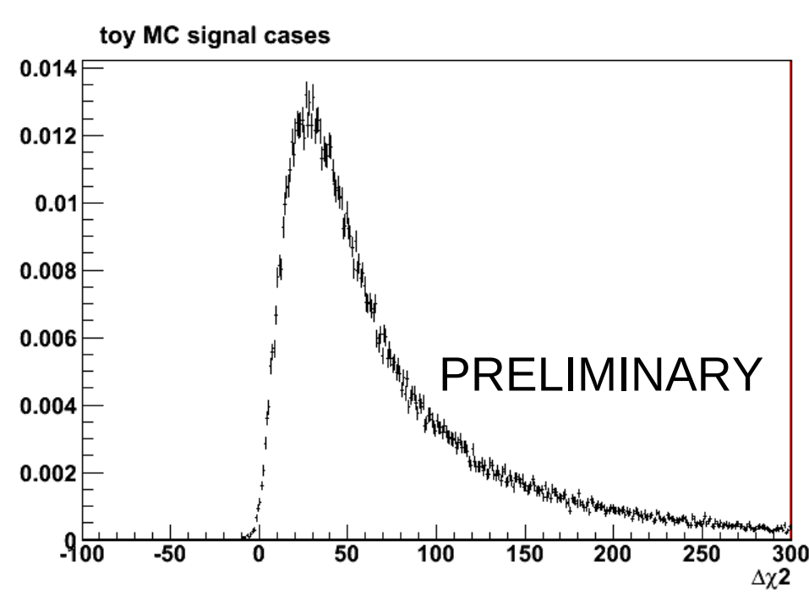


Fig. 8: Simulation of standard oscillation case: distribution of the χ^2 difference between non-oscillation case and standard oscillation case.

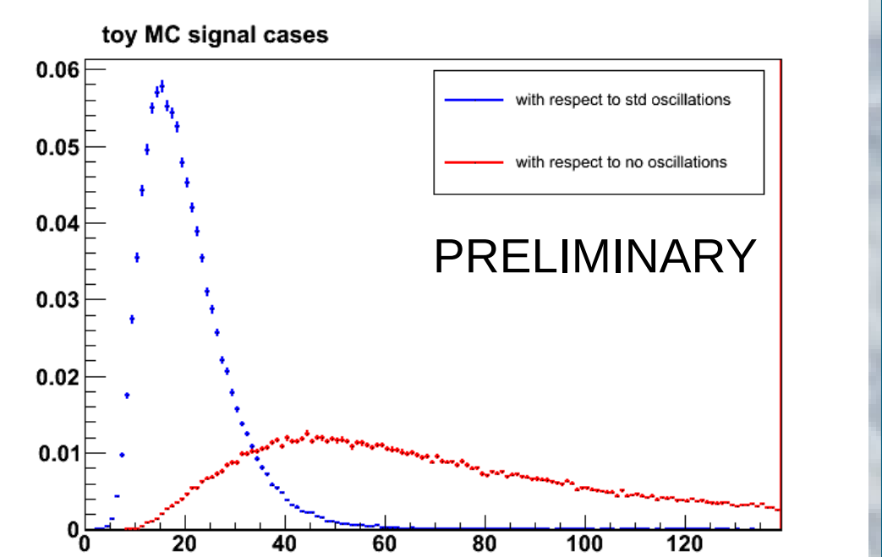


Fig. 9: Simulation of standard oscillation case: distribution of the χ^2 for non-oscillation case (red) and of χ^2 for standard oscillation case (blue).

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.

Results: energy distribution

Fig. 1 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.

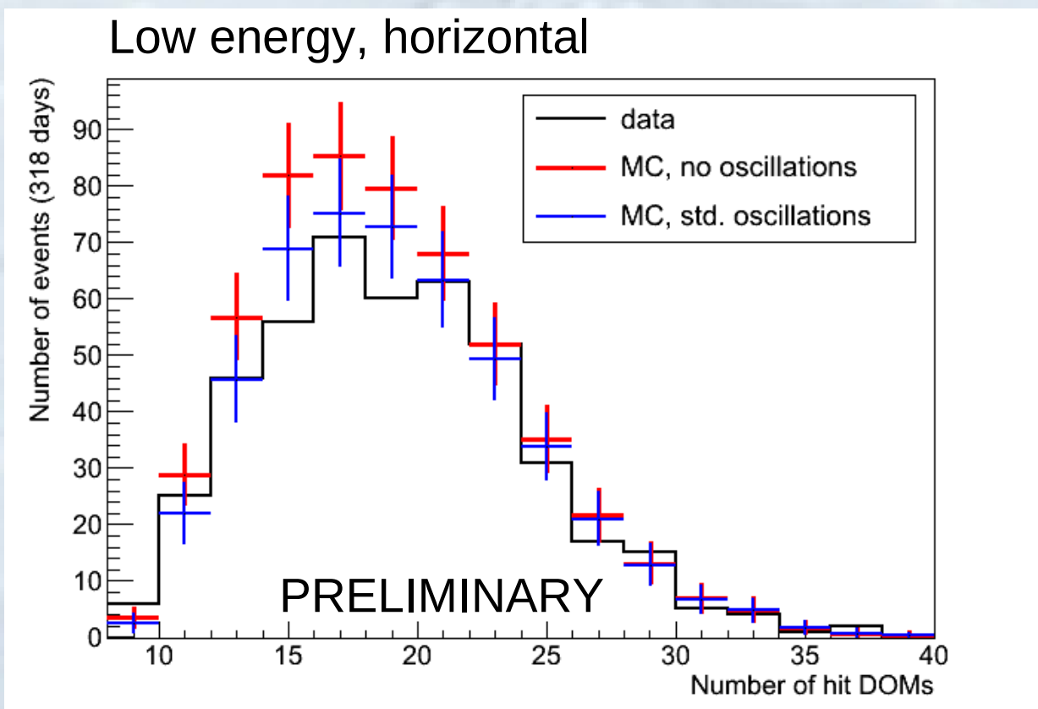


Fig. 5: Distribution of the number of hit DOMs for horizontal events (cos(theta)>-0.55) of the low-energy event selection. Error bars represent statistical errors only.

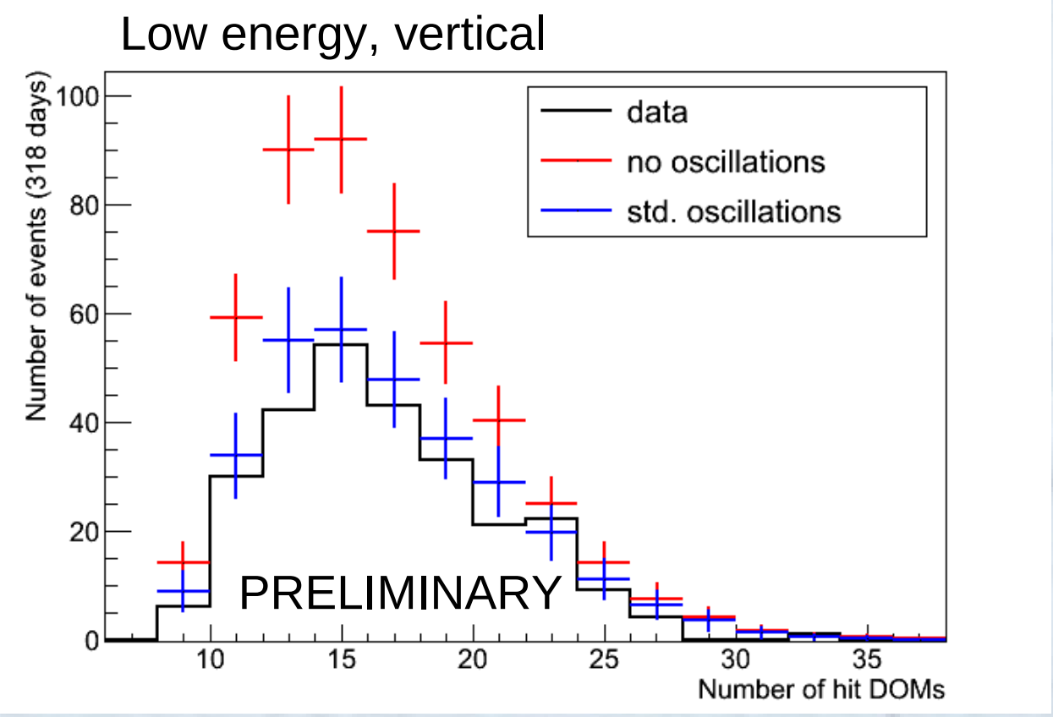


Fig. 6: Distribution of the number of hit DOMs for vertical events (cos(theta)<-0.55) of the low-energy event selection.

Systematic uncertainties

The systematic uncertainties of this analysis are characterized by five dominant effects, the uncertainty of

* the absolute efficiency of the DOMs (+-10%)

* the optical parameters of the Antarctic ice

* the flux parametrization of atmospheric neutrinos

* the normalization of cosmic ray (CR) flux

* the spectral index of CRs

The impact of these uncertainties is estimated by dedicated simulations representing the range of uncertainties. The differences of these simulations define the covariance matrix, taking into account the correlations, see e.g. [2]. In this procedure, Gaussian distributions of the systematic error parameters are assumed.

For illustration purposes, the systematic errors are decomposed into a shape component and a normalization component.

Systematics source	Norm Low energy	Norm High energy	Correlated Low energy High energy	Uncorrelated Low energy High enegy
DOM efficiency	10%	15%	10%	5%
Ice model	20%	5%	5%	15%
Atm ν flux model	5%	7%	5%	2%
CR norm	25%	25%	25%	0%
CR index	3%	7%	0%	10%
Total	35%	30%	28%	20%

Tab. 2: normalization component of different sources o systematic errors for low-energy and high-energy event selection. For all sources of systematic errors except the ice model, the shape component is smaller than the normalization component.

References

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Acknowledgments

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