Observation of Atmospheric Neutrino-induced Cascades in IceCube-DeepCore

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

Abstract: Atmospheric neutrino-induced cascades are observed in the 79-string IceCube detector with the DeepCore extension. Using 23 days of data, a high statistics sample shows an excess of cascades at 8.2 sigma, and with tighter cuts 74 events are observed of which 62 % are predicted to be cascades. A full-year analysis is underway and a significant detection of atmospheric electron neutrinos is expected.

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1 Introduction

The main mission of the DeepCore extension to IceCube is to observe neutrinos at energies as low as 10 GeV [1]. At these energies there are valuable science topics such as neutrino oscillations [2] and neutrinos from low mass WIMP dark matter annihilation [3]. In order to detect these neutrinos, DeepCore uses denser module spacing, upgraded photomultiplier tubes (PMTs), and deployment in the clearest ice along with a lower trigger threshold than the surrounding IceCube detector. Full information about the DeepCore infill can be found here [4]. Figure 1 shows a schematic of IceCube with DeepCore.

In this paper, we discuss the performance of the first year DeepCore with 79 strings of IceCube installed (IC-79). In this configuration the DeepCore sub-array includes 6 densely instrumented strings optimized for low energies plus the 7 adjacent standard strings. Finally, we present preliminary results on the first observation of atmospheric neutrino-induced cascades in IceCube. A test set (7 % of full data) using 23 days is used in this work, and prospects for a full year are shown in Section 3.3.

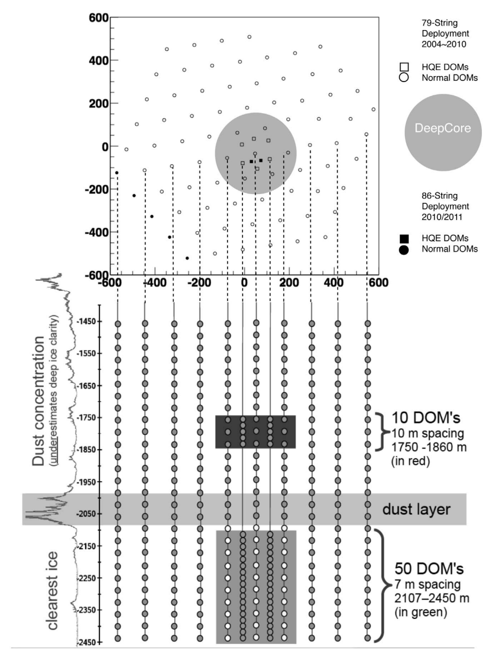

Figure 1: Schematic top and side views of IceCube in its 79-string configuration. The DeepCore infill array and the relative dust concentration are also shown.

2 Performance

The IC-79 detector finished a year-long data-taking cycle in May 2011 and these data have been processed and reconstructed.

Full PMT waveforms are read out from digital optical modules (DOMs) in hard local coincidence (HLC) which requires hits in a DOM and at least one nearest neighbor or next nearest-neighbor DOM must register a hit in a time span of ± 1000 ns. IceCube also records soft local coincidence hits (SLC), for which no neighboring hits are required [5]. Although the DOM noise rate is a factor of 50 higher in SLC mode than in HLC mode, with current software cleaning algorithms, SLC hits from physics interactions can be identified with over 90 % purity. This provides an advantage at low energies where the fraction of SLC hits is significant, because including the SLC hits improves reconstruction, background rejection, and particle identification.

A low trigger threshold (SMT3) is applied to all DOMs in the fiducial region (shaded area below the dust layer in Figure 1) by requiring 3 or more HLC hits within a 2500 ns time window. Additionally, the high quantum efficiency PMTs, with a 35 % increase in light collection with respect to regular IceCube PMTs, help trigger on neutrinos with energies as low as 10 GeV.

3 Observation of Atmospheric Cascades

Atmospheric neutrinos are the products of the interaction or decay of pions and kaons produced when cosmic ray primaries interact with nucleons in the upper atmosphere. Charged-current (CC) electron and tau neutrino interactions, and neutral-current (NC) neutrino interactions of any flavor, produce cascades that are approximately spherical. However, IceCube can not distinguish between a CC cascade and an NC cascade at considered energies. While atmospheric muon neutrinos have been observed in large quantities by IceCube [6] atmospheric cascades have a substantially lower flux and have not been identified in previous IceCube analyses. For current cascade searches above 1 TeV, there are on-going analyses with the 40 string IceCube detector [7, 8].

3.1 Background

Before seeing neutrinos in DeepCore, one must remove the cosmic ray muon background. Furthermore, the poor directionality in cascades as compared to tracks makes it difficult to use the Earth as a shield from the cosmic ray muon background as is done in conventional ν_μ^{CC} detection [6]. The signal is therefore required to be contained in DeepCore, and veto techniques are applied to remove about six orders of magnitude of background events while retaining reasonable signal efficiency for atmospheric neutrino-induced cascades in the fiducial volume.

3.2 Event Selection

IC-79 was operational from June 2010 to May 2011 with over 90 % up-time for physics analysis. The DeepCore SMT3 trigger fired at a rate of 180 Hz, which was reduced to 17 Hz using an on-line filter run at the South Pole. In the DeepCore on-line filter, an estimate of a neutrino interaction vertex and its time is obtained by calculating the center of gravity (COG) of all HLC hits in the fiducial region. An event is rejected when hits in the veto region have

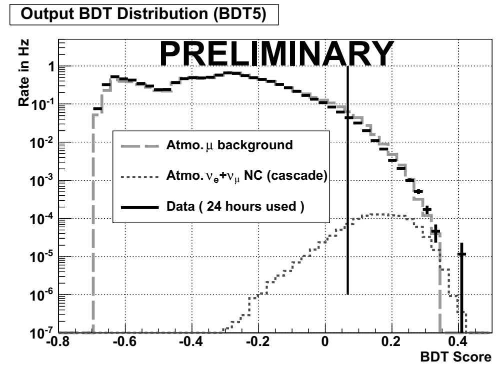

Figure 2: Output BDT5 Distribution based on the five variables. Cut on BDT5 >0.067 is indicated with vertical line.

times consistent with an incoming muon. A 90 % cosmic ray muon background rejection is achieved with respect to the trigger while keeping $>$ 99 % atmospheric neutrinos that interact in the fiducial volume. Noise cleaning algorithms remove noise hits which are not correlated in space and time with other hits. Then, events with at least 8 total remaining hits and at least 4 hits in the fiducial region are selected.

In order to attain a manageable data volume for time-consuming reconstructions, the first background rejection is achieved by an initial selection with a Boosted Decision Tree (BDT) [9]. The “BDT5” has 5 simple observables which quantify the event topology in the detector. These are constructed from the position and shape of the hits in the detector, and their time and charges. Figure 2 shows the output distribution and the reduction cut is made at 0.067. After the BDT5, the data rate is reduced to 0.1 Hz and atmospheric ν_e rate is predicted as 6.3×10^{-4} Hz, corresponding to 63 % retention with respect to the trigger.

This reduced data set was then processed with iterative likelihood reconstructions taking into account detailed Cherenkov light propagation in the ice [10]. Hits falling outside a time window [-3000 ns, +2000 ns] with respect to the trigger, or outside of 150 m radius of a neighboring hit within a 750 ns time window are removed. Then, with the cleaned hits, after demanding 8 or more hits in the fiducial region within a 1000 ns sliding window, another BDT is formed with 7 input parameters (BDT7). The first two variables measure the locations of the earliest hits in terms of radial and vertical coordinates to select contained events. The next three variables separate cascade-like events from muon-like events; an event is split in half then charge deposition, COG, and particle speed are compared between the two separate halves. The final two compare a likelihood of a cascade hypothesis to that of a muon hypothesis. The top left plot of Figure 3 shows the output BDT7 distribution. A cut at $\mathrm{BDT7} > 0.22$ reduces the atmospheric muon background to 5.0×10^{-4} Hz by rejecting a factor of 200 more (3.6×10^5 cumulatively) background while retaining

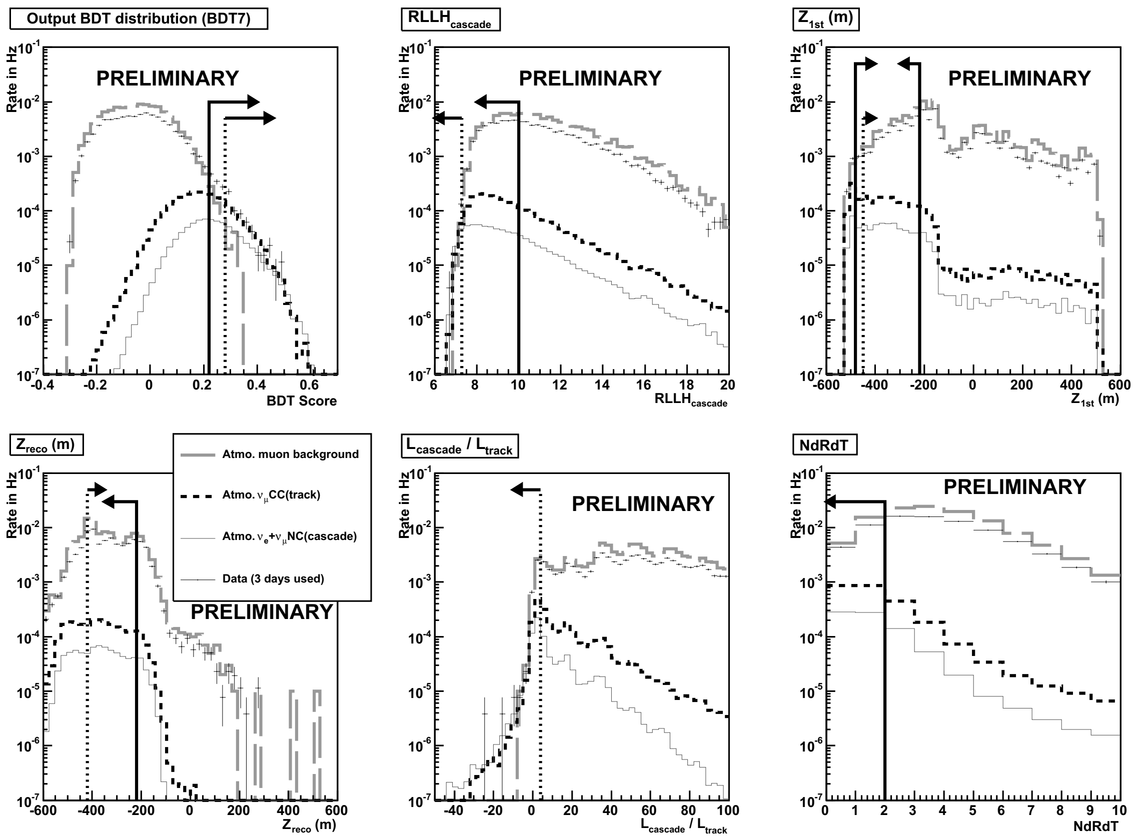

Figure 3: The output distribution of BDT7 in shown upper left corner and extra cuts to select two neutrino samples are listed as well. These plots are after BDT5 cut. Solid vertical lines indicate the final loose cut sample while the dotted vertical lines are for final hard cut sample. Arrows indicate events kept.

~ 40 % of the ν_e signal (2.6×10^{-4} Hz) compared to the previous BDT5 cut.

3.3 Results

Two sets of cuts on input variables to BDT7 were used for the final selection of neutrino-rich samples. The first aims for a high efficiency (Loose Cut) while the second aims for a higher purity (Hard Cut). Figure 3 shows two combinations of these cut options. The Loose Cut option is indicated in solid vertical lines. Two containment cuts $\mathrm{Z_{1st}}$ (upper right) and $\mathrm{Z_{reco}}$(lower left) based on the vertex depth measurements ensure that most signal events are well contained inside the DeepCore fiducial volume. The NdRdT (lower right) extends the on-line veto method by adding a travel speed window to catch only muon-produced light in the veto region and therefore removes residual muon background events. Finally, the cut $\mathrm{RLLH_{cascade}}$ (upper middle) selects events that fit a cascade hypothesis well, as measured by the log likelihood from a fit. With the Loose Cut options, the events observed are consistent with $\nu_\mu^{\rm CC}$, $\nu_\mu^{\rm NC}$, and ν_e interactions with only two cosmic ray muon events expected in 28 hours of simulation. 824 events are observed in 23 days of a test data with 590 total background event expectation ($\nu_\mu^{\rm CC}$ + μ) corresponding to a cascade excess of 8.2 sigma. Systematic errors are not included.

Signal simulation of atmospheric neutrinos predicted approximately 5,000 cascades and 9,400 $\nu_\mu^{\rm CC}$ events per year (three flavor oscillations included based on the parameters in [11]) as shown in Figure 4 with an estimated mean energy of 40 GeV. Unfortunately, events below 10 GeV are not accurately simulated in current neutrino generation and are not included in this work [12]. When considering oscillations of atmospheric neutrinos the data rate of $\nu_\mu^{\rm CC}$ events is reduced by 20 % with the Loose Cut selection. The effect of oscillations on ν_e and $\nu_x^{\rm NC}$ ($x = \mu, e, \tau$) is marginal compared to the data rate indicated as a dotted line in Figure 4. The ν_τ oscillation from ν_x in these energies is not yet included and under active development with a new simulation package, GENIE [13]. Since there is no distinction among ν_e, ν_τ, and $\nu_x^{\rm NC}$ in the IceCube detector at these energies, a small amount of the 20 % disappeared ν_μ events may be re-introduced as cascades if they oscillate to ν_τ.

The Hard Cut selection for higher purity is shown with dotted vertical lines on the plots in Figure 3. Compared to the Loose Cut option, these cuts are stronger and mainly focused on rejecting $\nu_\mu^{\rm CC}$ events. The containment cuts are

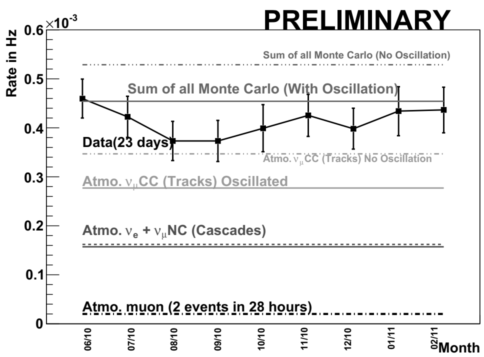

Figure 4: Loose Cut result. The event rate in hertz as function of months is shown. The squares are 23 days of test data while simulations are indicated with the various lines. Dotted lines are the rates without ν_μ oscillations and horizontal solid lines are with oscillation. The data rate shows an excess over the ν_μ prediction and can be explained with two contributions; oscillation and cascades. Here, the signal predictions are based on Barr *et al.* [14]

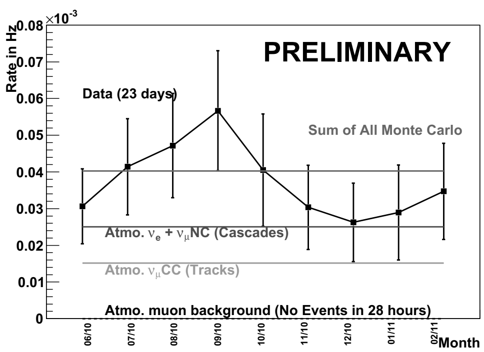

Figure 5: Hard Cut result. The sum of all Monte Carlo is consistent with 23 days of data rate. The cascades are expected to contribute 62 % and the tracks are expected to be 38 %. No atmospheric muon background event remain in 28 hours. The oscillation effect is less than 3 % due to higher energies of cascades and not included here.

enforced to a volume smaller than the fiducial region to identify an outgoing track from a $\nu_\mu^{\rm CC}$ interaction. With 23 days of test data, we observe 74 total events (50 cascades and 30 tracks are expected from simulation), showing a 5 sigma excess of cascades. A sample of about 790 cascades per year with a background of about 480 $\nu_\mu^{\rm CC}$ events are expected from Figure 5. The remaining $\nu_\mu^{\rm CC}$ events have short muons with a median track length of 80 m where the muon tracks are not easily visible due to detector granularity. Half of the cascades are predicted to be ν_e events and the other half are $\nu_\mu^{\rm NC}$ events. This selection favors higher energy cascades and the mean cascade energy increases to

	Loose Cut			
	N^{obs}	C^{sig} (C^{bg})	σ	N^{sig} (N^{bg})
23 days	824	312 (590)	8.2	208 (694)
1 year	-	4951 (9364)	-	3285 (11030)
	Hard Cut			
	N^{obs}	C^{sig} (C^{bg})		N^{sig} (N^{bg})
23 days	74	50 (30)	5.0	25 (55)
1 year	-	791 (479)	-	404 (866)

Table 1: The number of events are shown with two final selections. N^{obs} means observed events in real data. C^{sig} and C^{bg} refer predictions of the cascade signal and its background respectively. N^{sig} and N^{bg} refer predictions of the electron neutrino signal and its background respectively.

200 GeV, so that oscillation of $\nu_\mu \rightarrow \nu_x$ has a small (< 3 %) effect. The atmospheric muon simulation predicts zero events in 28 hours. A seasonal effect in rates will be studied more carefully with the full data.

3.4 Conclusion

In conclusion, we observe atmospheric neutrino-induced cascade events with 23 days of test data for the first time with IceCube 79 string detector and a highly significant detection of atmospheric electron neutrinos is expected with forthcoming full-year analysis. The preliminary numbers are summarized in Table 1. Possible sources of systematic errors include ice modeling, detection efficiency of DOMs, neutrino-nucleon cross-sections, and atmospheric neutrino flux normalizations. Those uncertainties are under evaluation.

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