# Search for diffuse astrophysical neutrinos with cascade events in the IceCube-59 detector

THE ICECUBE COLLABORATION[1]

[1] *See special section in these proceedings*

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**Abstract:** We report the results of a search for a diffuse flux of high-energy (> 30 TeV) astrophysical neutrinos using data from the IceCube neutrino observatory in its 59 string configuration. The data was taken between May 2009 and April 2010, yielding a total live time of 335 days. Two complementary analyses were performed on this dataset following different strategies for the selection of shower-type events that arise from all neutrino flavors. One of these analysis finds 8 neutrino candidates (for an expected background of $4.0 \pm 0.3_{\mathrm{stat}}$ events) above the energy threshold of 38 TeV (the results of the second analysis will be reported later somewhere else). A likelihood analysis of the energy spectrum of these events shows that their spectrum is compatible with expectations from the background of atmospheric muons and neutrinos. Therefore an upper limit on a diffuse isotropic astrophysical neutrino flux with a power-law spectrum $d\Phi/dE = \Phi_0 \cdot E^{-2}$ is derived from the likelihood fit. Assuming a neutrino flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$, we preliminary constrain the astrophysical neutrino flux normalisation ($\Phi_0$) to be smaller than $1.7 \cdot 10^{-8}\,\mathrm{GeV\,s^{-1}\,sr^{-1}\,cm^{-2}}$ in the energy range between 43 TeV and 6310 TeV.

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## 1 Introduction

Astrophysical neutrinos are diagnostic probes of possible acceleration processes in the universe. In contrast to gamma rays, they are only produced in hadronic interaction processes, mainly via p-p or p-$\gamma$ interactions. Therefore a detection of sources of astrophysical neutrinos would probe the galactic and extragalactic acceleration sites of cosmic rays. No such sources have been found yet [1]. Even if individual sources are too weak to be resolved, the cumulative emission from all the sources in the universe might be discovered. We expect a harder energy spectrum from such astrophysical neutrino sources than from the atmospheric neutrino and muon backgrounds that are often present in such a search when performed with a ground-based telescope. The Fermi shock acceleration process [2] that is usually assumed to be responsible for the acceleration of cosmic rays produces a power-law spectral index of $\gamma \approx -2$. Neutrinos in astrophysical environments are dominantly produced by the decay of pions and therefore follow a flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$. Flavor oscillations during their propagation to Earth then change the flavor ratio to $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$ [3, 4].

Shower-type neutrino events, i.e. neutrino interactions that produce a localized hadronic or electromagnetic shower within a neutrino detector, are particularly well suited to a search for diffuse astrophysical neutrinos as they allow a calorimetric measurement of the full energy deposited in the neutrino interaction. They arise from the neutral-current (NC) interactions of all neutrino flavors as well as from charged-current (CC) interactions of $\nu_e$ and $\nu_\tau$.

IceCube is a neutrino observatory located at South Pole and consists of 5160 Digital Optical Modules (DOMs) instrumenting a volume of 1 $\mathrm{km}^3$ between depths of 1450 m and 2450 m. The DOMs are designed to detect the Cherenkov light emitted from muons and showers produced in neutrino interactions. See [5, 6] for detailed information on the IceCube detector and DOMs.

In this proceeding, two complementary searches for shower-type events are presented. Both use data from the IceCube Neutrino Observatory in its 59-string configuration between May 2009 and April 2010 (335 days of live time). They follow different strategies to remove the abundant background of atmospheric muons and neutrinos produced in cosmic-ray interactions in the atmosphere. Both astrophysical neutrino event selections were developed on a 10% sub-sample of the full dataset to avoid the introduction of statistical biases in the event selection. One of the searches (denoted as "Analysis A" below) has recently been applied to the full dataset and we report the results from this search. The results of the second analysis ("Analysis B") will be reported elsewhere.

## 2 Event selection

Most of the events recorded by the IceCube detector are muons from cosmic-ray air showers. Their rate was 1.6 kHz in the 59-string IceCube configuration. These events usually produce track-like patterns and the vast majority of them can be distinguished well from shower-like events. Both analyses presented here use a common filter designed to remove such track-like events and to select candidate shower-like events. It is based on simple reconstruction algorithms, e.g. to exploit their different geometrical patterns in the detector, described here [7]. This common filter reduces the data rate to about 1 Hz. 78% of simulated $E^{-2}$ neutrino showers which triggered the detector survive this filtering.

Events remaining after the application of the common filter are still dominated by muons from cosmic-ray air showers. However, these muons mimic shower-type events, either because they feature a large catastrophic energy loss via emitting a bremsstrahlung photon along their track, or because the muons only graze the corners and edges of the instrumented volume. Different strategies have been employed to remove these muons and to obtain a sample of neutrino induced showers. Both strategies have been developed based on the event patterns observed in Monte Carlo simulations of cosmic-ray induced muons, neutrino induced muons and showers. The effective simulated live time for all simulations was larger than the actual observation period of 335 days in the energy ranges relevant for the two analyses.

The differences between the two strategies are briefly described. The two strategies are denoted as "Analysis A" and "Analysis B".

## 2.1 Analysis A

Analysis A selected events that are fully contained in the detector. Containment was defined by requiring the x-y position (horizontal plane) of the reconstructed event vertex to be within the green polygon displayed in Fig. 1. The z-position of the reconstructed vertex was required to be between $-450$ m $< z <$ 450 m, i.e. at least 50 m inward away from the top and bottom of the detector. Events were also rejected if the DOM that recorded the highest number of photons was located on a string outside the green polygon. Furthermore, only those events that had recorded light patterns on more than three strings were considered.

More complex event properties to remove remaining background events have also been exploited, including the fraction of DOMs that recorded light in a virtual sphere around the reconstructed vertex (Fill Ratio), the difference between earliest expected and actual arrival time of the first photon in the event, and the likelihood value of the vertex, direction and energy reconstruction. At this point, the remaining event sample was dominated by atmospheric neutrinos from $\nu_e$ and $\nu_\mu$ NC interactions that are expected at a rate of $(2.1 \pm 0.1_{\text{stat}})$ $\mu$Hz.

The final step in the event selection was then to choose an energy threshold that optimized the sensitivity of a search for an astrophysical signal based on count statistics. Only events with reconstructed energies of $\log_{10}(E/\text{GeV}) > 4.58$ were used for the likelihood fit. No simulated cosmic ray shower-induced muons with a reconstructed energy above this threshold remained. Based on an extrapolation of the distribution of cosmic ray shower-induced muons below the threshold, their contribution above threshold was estimated to be $0.65 \pm 0.25_{\text{stat}}$ events.

The number of atmospheric neutrinos from $\pi$ and K-meson decay expected in this sample was $2.0 \pm 0.2_{\text{stat}}$ events based on flux calculations of [8] and after applying corrections for slope changes in the CR spectrum described in [9]. An additional atmospheric neutrino contribution from the decay of charmed mesons ("prompt" contribution) has large theoretical uncertainties. Using the model of [10] we can estimate this contribution to $1.3 \pm 0.1_{\text{stat}}$ , however the current experimental upper limits for the atmospheric neutrino flux [11] from charged mesons is several times this flux. Based on MC data an all-flavor sensitivity (see [12]) of the analysis of $2.5 \cdot 10^{-8}\,\text{GeV}\,\text{s}^{-1}\,\text{sr}^{-1}\,\text{cm}^{-2}$ was derived.

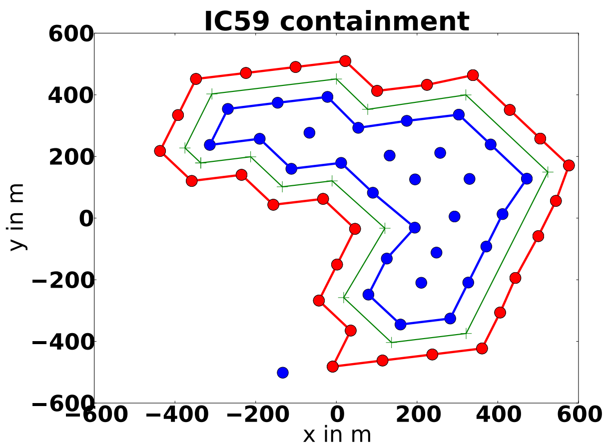


**Fig. 1**: Definition of containment in the x-y (horizontal) plane for the analyses presented here. Each dot represents an IceCube string, the outermost layer is marked by a red line, the second layer by a blue line, the green line is halfway between the two layers of strings. Analysis A requires the reconstructed event vertex to be within the area bounded by the green line, analysis B requires the reconstructed vertex to be within the red line.

## 2.2 Analysis B

The main difference from analysis A is the use of a multivariate analysis (MVA) as part of the final cut level. The machine learning algorithm used for the MVA was a Boosted-Decision-Tree (BDT). Only contained events were used to train the BDT. Containment was defined slightly different in this analysis in comparison to the containment definition described for analysis A. Events were considered contained if they met the following conditions:

- **X-Y-Z Containment:** the reconstructed X-Y position of the event vertex had to lie within the most outer ring of detector strings (red polygon in Fig. 1) and the reconstructed Z position must be $-450\,\text{m} < Z < 450\,\text{m}$, where $Z = 0$ is the center of the detector along the z axis.

- **Charge Containment:** the DOM with the maximum charge is not allowed to be on the outer ring of detector strings (red polygon in Fig. 1).

- **NString:** number of strings with a hit DOM in an event had to be greater than 3.

The BDT was trained using a sample of electron neutrinos, with an $E^{-2}$ spectrum, for the signal, and a sample of simulated cosmic-ray air showers to describe the atmospheric muon flux, considered to be the dominant background. The BDT was trained using the following variables:

- **NCh:** the number of channels hit during the event.

- **Fill Ratio:** ratio of the DOMs hit within a sphere (with a radius to fully contain the event) around the reconstructed vertex position to the total number of DOM hits.

- **Log-likelihood difference:** Difference in the log-likelihoods for the event, when reconstructed as a cascade or a track.

- **Eigenvalue ratio (of the tensor of inertia):** Topology of the event.
- **Zenith:** Reconstructed zenith angle of the event.
- **Total charge over length ratio:** ratio of the total charge of an event and how elongated an event is.
- **Position:** distance from the centre of the detector.
- **Total charge per string:** amount of charge per string for an event.
- **Difference in linefit velocity:** difference in the z-component of the particle velocity for the two halves of an event.

After BDT training, a BDT response score was calculated for each event. This BDT score influenced the final selection, along with the reconstructed energy of the event. The energy and BDT score range for the final data sample were optimized to deliver the best possible average upper limit on an astrophysical neutrino flux with a power-law spectrum with spectral index $\gamma = -2$. Events with an energy above 50 TeV in energy and a BDT score higher than -0.13 were selected.

## 3 Results

We present results from "Analysis A" which has been applied to the full dataset. Two data events were found that fulfilled all selection criteria in the 10% of the data sample that was used to develop the event selection. (The development of Analysis B is not yet complete, but the same two events were found in the 10% data sample.) Six more events were found in the remaining sample for a total of 8 events (for an expected background of $4.0 \pm 0.3$ ). Table 1 lists the properties of these events. Figure 2 shows the energy distribution of the 8 events which were found between 39 TeV and 67 TeV.

| event | sample | E/TeV | x/m | y/m | z/m | q/pe |
|---|---|---|---|---|---|---|
| 1 | 10% | 67 | 266 | 325 | -397 | 5152 |
| 2 | 10% | 52 | -227 | 213 | 321 | 1404 |
| 3 | 90% | 42 | 452 | 32 | 369 | 1108 |
| 4 | 90% | 39 | 200 | 240 | -259 | 2510 |
| 5 | 90% | 61 | 123 | 8 | 43 | 2552 |
| 6 | 90% | 43 | 442 | 192 | 400 | 567 |
| 7 | 90% | 48 | 422 | 125 | 213 | 1948 |
| 8 | 90% | 39 | 126 | -98 | 61 | 3643 |

**Table 1**: Event parameters in the 10% and 90% data samples: energy in TeV, event coordinates x, y and z, sum of charge over all DOMs in number of photoelectrons (pe).

A binned maximum likelihood fit was applied to the energy distribution of the events in Fig. 2 to determine the uncertain contribution to the atmospheric neutrino flux from charmed meson decay and a possible contribution from an astrophysical neutrino flux. The parameters of the fit are the normalization of the charm contribution, and normalization and spectral index of an astrophysical neutrino flux with a power-law spectrum. The spectral energy distribution of the charm contribution is taken from [10] for this work. Systematic uncertainties on the K/$\pi$ induced atmospheric neutrino flux and spectrum, the absolute scale of the energy reconstruction, and the residual contamination from atmospheric muons have been included in the likelihood fit as nuisance parameters that are allowed to vary within their respective uncertainty ranges. Table 2 shows parameter uncertainty and the pulls of the nuisance parameters of the likelihood fit to the data. The energy scale is slightly shifted upwards by 4%, the normalisation of the atmospheric neutrino flux (from K/$\pi$ decays) is slightly increased by 4% and the normalisation of the muon flux (created in interactions of the cosmic rays within the atmosphere) is slightly increased by 8%.

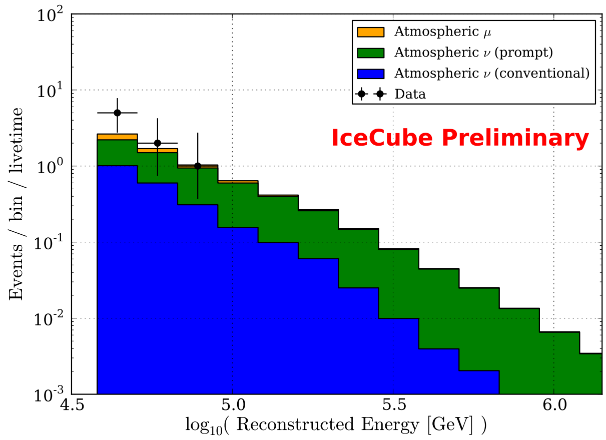


**Fig. 2**: Energy spectrum of the events found in the data sample obtained from IceCube in its 59-string configuration. Data events are marked in black, the yellow area is the predicted contamination with atmospheric muons, the blue area is the expected contribution of atmospheric neutrinos from $\pi$-meson and K-meson decays. The green area represents the best-fit contribution from prompt atmospheric neutrinos corresponding to $2.9^{+3.2}_{-2.6}$ times the flux predicted in [10]. The best likelihood in the fit was obtained without any additional astrophysical neutrino contribution.

| parameter | pull | parameter uncertainty |
|---|---|---|
| $\phi_{conv}$ | 0.16 | $\sigma[\phi_{conv}] = 0.25$ |
| $\phi_{\mu}$ | 0.16 | $\sigma[\phi_{\mu}] = 0.5$ |
| cosmic ray index | 0.1 | $\sigma[\text{index}] = 0.5$ |
| energy scale | 0.27 | $\sigma[\text{energy scale}] = 0.15$ |

**Table 2**: Parameter pulls and parameter uncertainties of the nuissance parameters of the likelihood fit: $\phi_{conv}$ is the change in the normalisation of the atmospheric neutrinos from $\pi$-meson and K-meson decays, $\phi_{\mu}$ is the change in the normalisation of muons produced in the atmosphere, the cosmic ray index is the change of the index of cosmic rays and the energy scale is a possible shift in the energy.

The best fit to the data has no astrophysical neutrino contribution and an atmospheric flux from charmed meson decays corresponding to $2.9^{+3.2}_{-2.6}$ times the flux predicted in [10]. The likelihood profile shown in Figs. 3 and

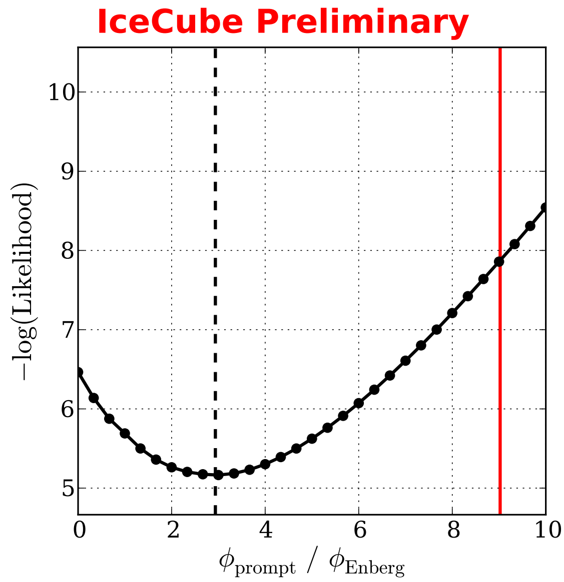


**Fig. 3**: Results of the Likelihood fit. The plot shows the likelihood profile varying the prompt atmospheric neutrino flux in units of the Enberg flux (see [10]). The black dashed line marks the best fit value. The red line shows the upper limit at 90%-confidence level on the prompt atmospheric neutrino flux.

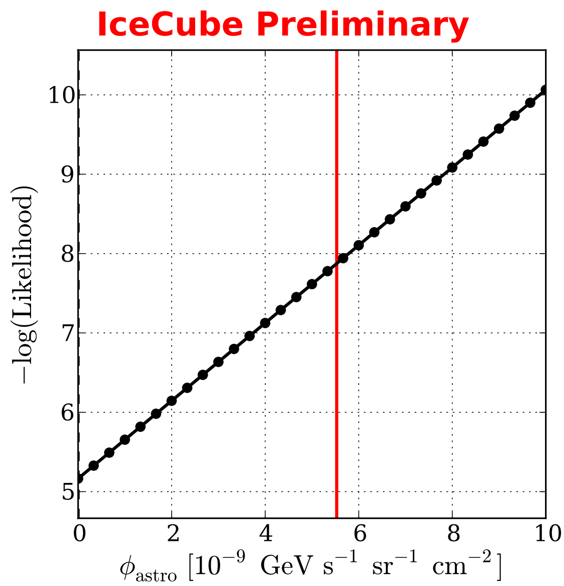


**Fig. 4**: Results of the Likelihood fit. The plot shows the likelihood profile for an astrophysical flux (per flavor) assuming a power-law with an index of $\gamma = -2$. The best likelihood is obtained with no astrophysical flux. An upper limit can be obtained from the likelihood profile. The red line indicates the per-flavor upper limit of the astrophysical flux at a 90%-confidence level.

4 is used to determine upper limits on the prompt atmospheric neutrino and the astrophysical neutrino contributions. To derive the upper limits the spectral index of the astrophysical neutrino contribution in the fit is fixed to $\gamma = -2$, in accordance with the Fermi acceleration prediction. From the likelihood profile we derive a preliminary 90%-confidence upper limit on the astrophysical neutrino flux of $1.7 \cdot 10^{-8}\,\text{GeV}\,\text{s}^{-1}\,\text{sr}^{-1}\,\text{cm}^{-2}$ in the energy range between 43 TeV and 6310 TeV. We note that the limit given above applies to an unbroken power law extending over the entire energy range, and a higher normalization would be allowed in part of the energy range if the spectrum were cut off at some energy. This limit is more than an order of magnitude more constraining than the one from an earlier IceCube analysis (see [7]), which had reported an upper limit on the astrophysical flux of $3.6 \cdot 10^{-7}\,\text{GeV}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$ in the energy range between 24 TeV and 6600 TeV. A preliminary 90%-confidence upper limit on the contribution of charm decays to the atmospheric neutrino flux was found at 9.0 times the flux predicted by [10] (including a modification to the prompt atmospheric neutrino spectrum of [10] that is described in [9] and caused by a steepening of the primary cosmic-ray spectrum at PeV energies that was not considered in the original calculation).

## 4 Conclusions

We report a search for the isotropic diffuse flux of astrophysical neutrinos in data recorded with the IceCube neutrino observatory between May 2009 and April 2010. No indications for such a flux were found based on the outcome of a likelihood fit to the energy distribution of the observed neutrinos. The observed events are compatible with atmospheric origin and therefore a preliminary 90% upper limit of $1.7 \cdot 10^{-8}\,\text{GeV}\,\text{s}^{-1}\,\text{sr}^{-1}\,\text{cm}^{-2}$ can be set on an astrophysical neutrino flux with an unbroken power-law type spectrum power-law type spectrum of index $\gamma = -2$ in the energy range between 43 TeV and 6310 TeV. This is currently the best upper limit on such an astrophysical flux. Again we stress that this limit is only valid for an unbroken power law extending over the entire energy range.

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