Search for extraterrestrial neutrino-induced cascades using IceCube 79-strings

THE ICECUBE COLLABORATION[1]

[1]*See special section in these proceedings*

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Abstract: IceCube, a cubic kilometer detector at the South Pole, is the largest neutrino telescope currently taking data. Utilizing the transparent ice of Antarctica as a detection medium, IceCube digital optical sensors observe Cherenkov radiation from secondary particles produced in neutrino interactions inside or near the detector. Charged current ν_μ interactions create muon tracks, while charged current ν_e interactions, and neutral current interactions of all flavors initiate electromagnetic and hadronic showers (cascades). The background coming from atmospheric muons and muon bundles is many orders of magnitude larger than the cascade signal and makes it difficult to observe cascades. However, cascades have better energy resolution and lower atmospheric background compared to track-like events. The energy spectrum of extraterrestrial neutrinos is expected to be harder than that of atmospheric neutrinos. Thus using cascade events to search for a hardening of the energy spectrum is advantageous compared to using muon tracks. The search for extraterrestrial neutrino-induced cascades with energies in the tens of TeV to a few PeV neutrino energy range using improved reconstruction methods will be presented. The analysis uses 317 days of livetime of the data taken from May 2010 to May 2011 when 79 IceCube strings were operational. The analysis method and new results from the fully unblinded dataset will be presented.

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1 Introduction

Extraterrestrial neutrinos, anticipated to be produced together with cosmic rays, might provide information about the mechanism of cosmic ray production and help to unveil cosmic ray sources. Although neutrino fluxes from such sources could be too low to be measured individually, an integrated flux over all sources might be possible to detect with IceCube [**?**], a cubic kilometer scale neutrino telescope located at the geographic South Pole. Incoming neutrinos interact mostly via deep-inelastic nucleon scattering and produce showers of secondary charged particles. Having relativistic velocities, these particles produce Cherenkov light that is detected by Digital Optical Modules (DOMs).

Neutrino-nucleon reactions are induced by all neutrino flavors via neutral current (NC) or charged current (CC) interactions. In charged current reactions the charged lepton is produced, which carries on average 50% (for $E_\nu \sim 10$ GeV) to 80% (at high energies) of the neutrino energy; the remainder of the energy is transferred to the nuclear target. Depending on the charged lepton created in CC reactions, neutrino flavor specific hit-patterns might be observed in the detector which allow the identification of the incoming neutrino flavor. Charged current ν_μ interactions create track-like hit patterns while CC ν_e reactions produce an electromagnetic and hadronic cascade which yields a spherical hit-pattern. The typical cascade analysis searches for ν_e and ν_τ from CC and all neutrino flavors from NC interactions.

A previous cascade analysis searching for an astrophysical neutrino flux in IceCube with 22-strings instrumented [**?**] set a limit of 3.6×10^{-7} GeV$\cdot$ sr^{-1}s^{-1}cm^{-2} at 90% C.L. on E^{-2} astrophysical neutrinos (assuming a 1:1:1 flavor ratio) with 90% of events in the energy range between 24 TeV to 6.6 PeV. Another IceCube cascade analyses looking for an extraterrestrial neutrino signal using 40 strings obtained preliminary results [**?**] and set a limit at 90% confidence level on an astrophysical neutrino flux of 9.5×10^{-8} GeV$\cdot$ sr^{-1}s^{-1}cm^{-2} with 90% of events in the energy range between 89 TeV to 21 PeV [**?**]. Preliminary cascade results using the 59-string configuration of IceCube were recently obtained and are presented at this conference [**?**].

In the recent 79- and 86-string IceCube detector, searches for extremely-high energy (EHE) neutrinos from all flavors from CC and NC interactions, two neutrino-induced cascade events at energies of 1 PeV were observed [**?**]. As a follow-up analysis, an all-sky search for all flavor neutrino events from CC and NC interactions with energies $E_\nu >$100 TeV and neutrino first interaction well contained in the 79- and 86-string IceCube detector, was performed and the preliminary results are presented in these proceedings [**?**].

The analysis described here was developed using Monte Carlo simulation and searched for an E^{-2} astrophysical neutrino-induced cascade flux within IceCube with 79 strings instrumented. In these proceedings, we present all flavor sensitivity using high-energy contained cascade events in the IceCube detector. We also discuss adding partially contained events, to increase the effective volume. The neutrino energy range in this analysis is between 44 TeV and 7.7 PeV.

2 Data sample

The data used in this analysis were collected from May 2010 to May 2011 with 79 operational strings of IceCube. The analysis was performed as a blind analysis, the selection criteria to reject the background were developed using 10% of the data ("burnsample"). This burnsample consists of data uniformly distributed over the year to avoid biases in muon background rate due to seasonal variations. The burnsample livetime was 33 days. The numbers presented here are based on the remaining 90% of the data, 317 days.

The main background for a search for cascade-like events comes from cosmic ray muons with a faint track and a single catastrophic energy loss from a bremsstrahlung. The background of atmospheric muon events was simulated with the air-shower program CORSIKA [?]. The main goal was to simulate high energy muons that radiate bremsstrahlung secondaries with energies that can mimic cascade events. In this analysis, the CORSIKA background simulation generated for the primary cosmic ray energy higher than 30 TeV per nucleon was used. A sample of 300 days of atmospheric muon events in the energy range above 30 TeV per nucleon was generated.

The signals in this analysis are ν_e and ν_τ from CC and all neutrino flavors cascades from NC interactions. The all flavor neutrino events were simulated with the neutrino generator ANIS [?] for energies from 1 TeV to 1 EeV at the surface of the Earth with E^{-2} energy spectrum. Equal amounts of ν and $\bar{\nu}$ was produced. IceCube does not distinguish ν from $\bar{\nu}$ and in this paper ν denotes the sum of ν and $\bar{\nu}$. In this analysis we used the flux normalization of signal events of

$$\Phi_{model} = 1.0 \times 10^{-8} (\mathrm{E/GeV})^{-2} \mathrm{GeV}^{-1} \mathrm{s}^{-1} \mathrm{sr}^{-1} \mathrm{cm}^{-2}. \quad (1)$$

The background from atmospheric neutrinos was estimated assuming the conventional [?] and prompt [?] flux contributions.

3 Analysis

3.1 Cascade reconstruction variables

To isolate the cascade signal from muon background, different selection criteria were applied. Among these were simple quality criteria like the specific topology of cascade-like events, the development of the hit pattern in time, as well as causal and likelihood criteria.

A widely utilized topology criterion for cascade analysis was provided by `TensorOfInertia` [?]. This reconstruction considered the hit-pattern as a rigid body, with the optical modules as mass points with their charge equivalent to their mass. For this rigid body, the mass-eigenstates and corresponding eigenvalues were calculated. The ratio of the highest eigenvalue and the sum of all three eigenvalues is a measure how spherical the hit-pattern is and thus can be used to separate cascade-like from track-like events.

To separate a cascade-like hit pattern, which is a stationary source of light and a track, a moving source of light, the hits in the detector were projected along a track moving through the detector with `LineFitVelocity` [?]. For cascade-like events its value is much smaller then for track-like events and the identification of both hit patterns was possible.

In the analysis chain the following likelihood reconstruction algorithms were used: `ACER` [?], which is a deterministic energy estimator, `CascadeLlh` [?], which uses probability density functions (pdfs) to perform a 4-dimensional fit, and `Credo`, which is more sophisticated algorithm that incorporates a model of light propagation in the ice, the full timing information and reconstructs the energy and direction of the incident neutrino.

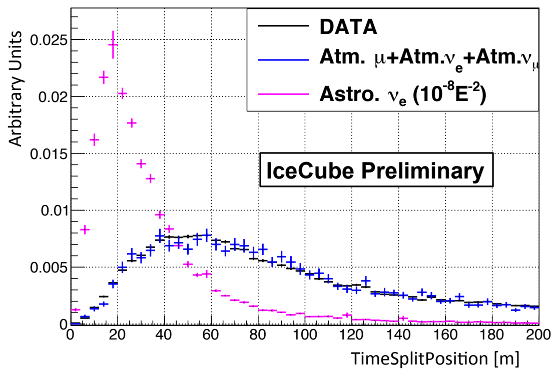

Figure 1: Normalized TimeSplitPosition distributions for data (black points), sum of muon and atmospheric neutrino backgrounds (blue) and E^{-2} astrophysical ν_e signal (magenta).

The `FillRatio` was used to distinguish cascade-like events from muon-like tracks. Firstly, the mean distance between the vertex position and all hit DOMs in an event was calculated. Then, the ratio of number of hit DOMs to the total of all DOMs in the sphere of this mean radius was obtained. For a neutrino signal (cascade-like events) we expect this number to be close to one while for the track-like events this number would be uniformly distributed. This allows us to separate signal from background.

Another topology variable used in this analysis was `TimeSplitPosition`. Each event was split into two halves based on the charge-weighted mean time, and the cascade reconstruction was run on each half separately. Then, the difference `TimeSplitPosition` between reconstructed vertex positions for both halves was calculated. For the events consistent with a signal cascade hit pattern this number has a smaller value than for track-like events and allows separation of signal from background, as shown in Fig. **??**. Figure **??** shows the normalized `TimeSplitPosition` distributions for data, Monte Carlo background and E^{-2} astrophysical ν_e signal. The shape of the data distribution is nicely reproduced by the sum of muon and atmospheric backgrounds and represents the typical data-Monte Carlo shape agreement at different cut levels in the analysis presented here.

The ratio of maximum total charge on a single DOM in a given event and the total charge in this event `MaxQTotRatio` allowed the identification of the events, where most of the charge was recorded by a single DOM. These events might be created by a low energy muon having a catastrophic energy loss next to a DOM.

The variable `DelayTime`, defined as a minimum of the time difference between the first hit on a DOM and the time of the reconstructed vertex was also used. It allows the separation of a muon-track and cascade-like events as for the former this time difference is bigger than for the latter.

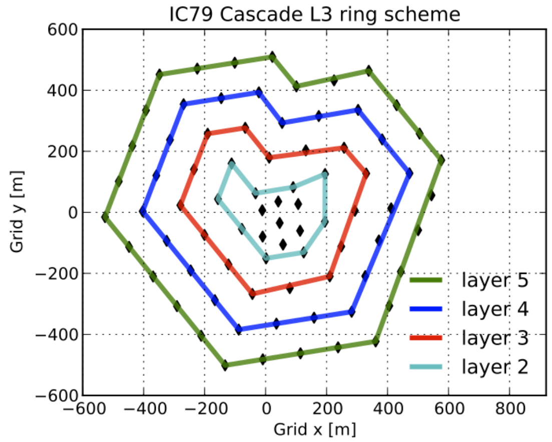

Figure 2: Schematic top view of IceCube with 79-strings. The green denotes the most outer layer of strings.

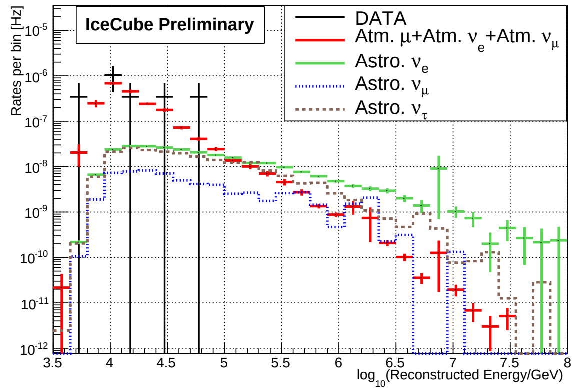

Figure 3: Distribution of the reconstructed energy before final energy cut.

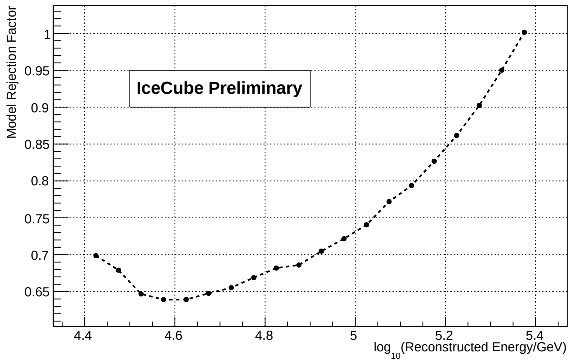

Figure 4: Model Rejection Factor (MRF) as a function of reconstructed energy.

3.2 Online filters

To reduce the background coming from atmospheric muons and muon bundles several filters were applied to the data. The online filtering process begins at the South Pole with a trigger logic to suppress electronic noise and noise induced by radioactive processes of the detector itself.

The main physics trigger in IceCube is a "Simple Multiplicity Trigger" (SMT) that requires photon signals in at least 8 DOMs. The average trigger rate for the IceCube 79-string configuration was 1970 Hz. In the cascade online filter the cuts on `TensorOfInteria` and `LineFitVelocity` were applied to select cascade-like signal events from track-like background. The online filter reduced the data rate to 21 Hz , about a factor of 100 below the trigger rate. The cascade filter retained 75% of the ν_e signal. After applying the online filter, the data stream was transferred to the North where more elaborate `CascadeLlh` and `ACER` cascade reconstructions were performed.

3.3 Event selection

Selection criteria to reject muon and atmospheric neutrino backgrounds were developed. The Level3 filter retained events that fulfilled either a combined criterion of a cascade and track likelihood ratio `LlhRatio` as well as an energy dependent zenith angle cut or had a reconstructed `ACER` energy larger than 10 TeV.

Then the data stream was split into two branches: fully contained and partially contained events and each branch was analyzed separately. Only the fully contained events selection criteria are described here but the partially contained events were used to enhance the sensitivity of this analysis for neutrino events with energies $E > 100$ TeV.

The fully contained events were considered those with both the reconstructed vertex and the first hit inside the most outer string layer of the detector, the green polygon in Fig. **??**. In addition, we required that the first hit in the event occurred between ±430 meters in depth and the reconstructed `Credo` vertex position Z was between ±450 meters in the detector. We rejected the event if the earliest hit occurred in the seven topmost DOMs. The `FillRatio` was calculated for this branch and only events with value higher the 0.6 were retained.

At Level4, further cuts were applied to reduce the background from atmospheric muons. Based on the time and position of the pulses in a given event, the events seen by 4 or more strings were selected. In the next step of Level4, we required that the reconstructed energy was higher that 10 TeV.

At Level5 we retained events with `TimeSplitPosition` smaller than 40 meters and rejected events with `MaxQTotRatio` bigger than 0.35. In addition, we required that the `DelayTime` was bigger than 100 ns.

Finally, using the Feldman-Cousins method [**?**], a cut on reconstructed energy (see Fig. **??**) was optimized and used to suppress remaining muon and atmospheric neutrinos background. The Model Refection Factor (MRF) [**?**] was calculated as a function of reconstructed energy as shown in Fig. **??**. The minimum of the MRF distribution was found at an energy of E=40 TeV and the energy cut was placed at this value. The energy resolution for an E^{-2} astrophysical spectrum for fully contained events is $\Delta(\log_{10}\mathrm{E}_\nu) \sim 0.04$ and the vertex position resolution is ~ 4 meters.

The analysis aiming at partially contained astrophysical neutrino search has a poorer energy resolution of $\Delta(\log_{10}\mathrm{E}_\nu) \sim 0.3$, and the vertex resolution of ~ 10 meters.

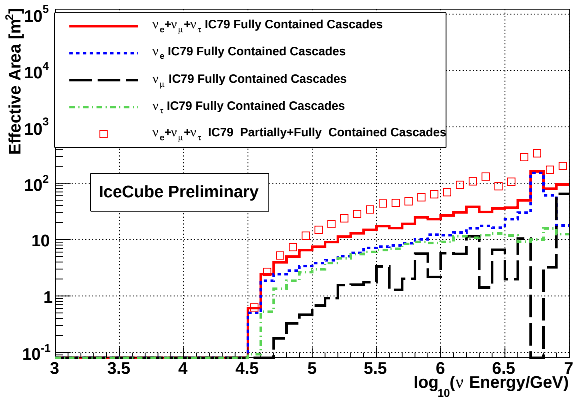

Figure 5: Effective area after the final event selection.

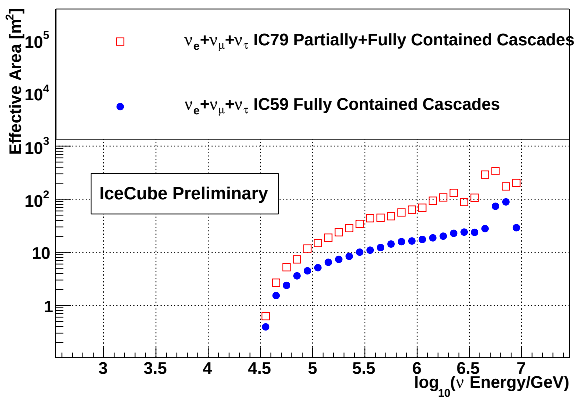

Figure 6: Comparison of effective area for sum of all flavor neutrinos (open squares) for the analysis presented here and the cascade neutrino search with IC59 string configuration [**?**] (filled circles).

4 Results

The selection criteria rejected all of the CORSIKA events and the conservative estimate on the number of cosmic-ray muons at the final level was taken as an upper boundry at 90% C.L. interval of 1.6 events. One burn sample data event of 70 TeV reconstructed energy was retained.

From the analysis presented here 4.1 ± 0.2 (stat) ν_e, 0.83 $\pm$ 0.07 (stat) ν_μ and 2.76 $\pm$ 0.06 (stat) ν_τ signal events for an astrophysical flux defined in Eq. (**??**) are expected in 317 days (90% of the experimental data). Thereby, the predicted number of astrophysical ν_μ events from CC interactions is 0.31 $\pm$ 0.04 (stat), while from NC is 0.52 $\pm$ 0.05 (stat).

The expected number of atmospheric neutrino background events from ν_e is 2.5 ± 0.2 (stat) +3.1-2.5 (syst) and from ν_μ 1.8 ± 0.2 (stat) $\pm$ 0.6 (syst). The statistical uncertainties come from the Monte Carlo statistics. The uncertainties of the theoretical models in the predicted fluxes are dominating sources of systematic uncertainties for estimating atmospheric neutrino background. The uncertainty of 25% for conventional [**?**] and the factor of two for prompt flux [**?**] were assumed. These atmospheric background estimates include the neutrino events that would be accompanied by a muon bundle [**?**] and therefore removed by the analysis selection cuts. The estimated background could hence be lowered by a factor of ∼2.

Figure **??** shows the effective area versus neutrino energy after all cuts applied. The Glashow resonance [**?**] contribution is clearly visible for ν_e. The effective areas for ν_e and ν_τ are higher than for ν_μ as this analysis was optimized for cascades and removed muon tracks.

The comparison of the all neutrino flavor effective area for combined fully and partially contained analyses with 79 IceCube strings and the cascade search with the 59-string IceCube configuration is shown in Fig. **??**. The effective area for the 79-string configuration is bigger than for a smaller detector, as expected.

The sensitivity for the diffuse all flavor flux of extraterrestrial neutrino signal, defined as the average flux upper limit at 90% C.L. in the absence of signal was calculated and resulted in 2.3×10^{-8} GeV s^{-1} sr^{-1} cm^{-2} for the all flavor neutrino energies between 42 TeV and 6 PeV. No systematic uncertainties were taken into account. Including partially contained events increases the sensitivity to 1.8×10^{-8} GeV s^{-1} sr^{-1} cm^{-2} for all-flavor neutrino events with energies between 44 TeV and 7.7 PeV. The obtained result is more stringent than the expected upper limits from previous IceCube cascade analyses with smaller sized detector configurations [**?**, **?**, **?**]. The systematic uncertainties are currently being evaluated.

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