Search for atmospheric neutrino induced particle showers with IceCube 40

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

Abstract: One of the guaranteed fluxes under study by the IceCube neutrino telescope are neutrinos originating from cosmic ray induced air showers. These neutrinos come from the decay of π and K mesons (the conventional flux) and from the decay of charmed mesons (the prompt flux). Although several flux predictions exist, the electron neutrino flux has been measured only up to GeV energies. At TeV energies, where atmospheric neutrinos are an inevitable source of background events for astrophysical neutrino searches, the prompt flux becomes important and the flux predictions vary greatly. The detection of electromagnetic and hadronic particle showers, which are not only produced by electron neutrinos but which can be found in the final states of charged and neutral current interactions of all neutrino flavours, remains challenging. Given the sensitivity to all neutrino flavours, the good energy resolution that will be possible with fully contained shower events and the possibility to isolate the prompt from the conventional flux, the prospects of this detection channel are very promising. This poster will present an analysis done on a data sample collected with IceCube in its 40 string configuration as it was running from 2008 to 2009. The development of the event selection on a small part of the sample will be discussed.

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1 Observing Neutrinos at the South Pole

The possibility to measure or constrain the flux of astrophysical neutrinos could help to solve a number of questions of which one of the most prominent, the question of the origin of cosmic rays, remains unanswered nearly a century after their discovery. Experiments that aim at the detection of these neutrinos must compensate for the small interaction cross sections and the low expected fluxes with increased size. With this year's completion of IceCube [1], the biggest neutrino detector to date, such an experiment is now available. For the experiment a cubic kilometer of glacial ice below the geographical South Pole was instrumented with photomultiplier tubes in order to detect the Cherenkov light of charged secondaries generated in neutrino interactions.

During the last 7 austral summers 86 holes were melted 2.5 km deep into the ice and into each a cable holding 60 so-called Digital Optical Modules (DOMs) has been deployed. The light sensors on 78 of these strings form a grid with a horizontal spacing of 125 m and a vertical distance of 17 m. As the spacing basically determines the energy threshold, the detector center was augmented with the denser DeepCore infill array between 2009 and 2010. The data-taking started already during the construction phase. This work uses data recorded between April 2008 and May 2009 when 40 strings were operational (IceCube 40).

IceCube's main physics goal is the detection of astrophysical neutrinos at energies above 100 GeV. These neutrinos must be isolated from the much larger flux of leptons created in cosmic ray induced air showers [2]. Among these a huge number of muons originating mostly from pion and kaon decays form the biggest part of the background. In the same air showers also atmospheric neutrinos are created [3]. In order to separate them from the astrophysical neutrinos a good understanding of their energy spectrum, flavour ratios and angular distribution will be helpful. This in turn is tightly coupled to our knowledge of the cosmic ray composition and hadronic interactions at energies that are out of reach of accelerator experiments.

The atmospheric neutrino spectrum is expected to consist of two components, the conventional flux from decaying pions and kaons [4, 5] and the prompt neutrinos from decays of short lived charmed mesons [6, 7]. The existing flux predictions for the latter vary widely and current measurements of the muon neutrino flux [8] are not yet able to resolve any prompt from the conventional component (see Fig. 1). Compared to muon neutrinos the flux of atmospheric electron neutrinos is lower and falls with a similar steep power law. Taking advantage of the lower energy threshold of the DeepCore array, IceCube has recently

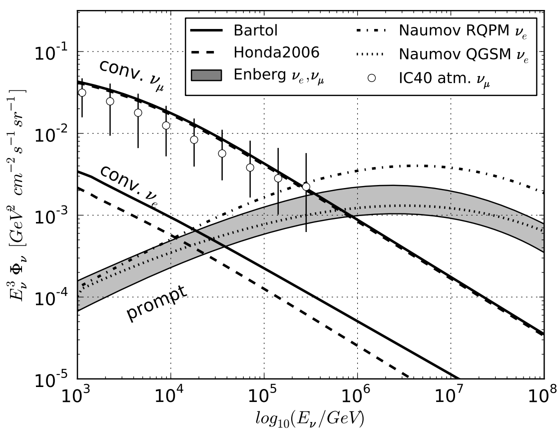


Figure 1: Different flux predictions for atmospheric neutrinos (taken from [4]-[7]) compared to a measurement of the atmospheric ν_μ-flux with IceCube 40 [8].

detected atmospheric neutrino induced showers around a mean energy of $40\,\mathrm{GeV}$ [9]. However, at TeV energies this measurement remains challenging, and only recently an analysis on the same IceCube 40 dataset started to find several promising candidate events [10]. In the energy spectrum of neutrino induced particle showers the prompt component is expected to emerge from the conventional at about 10^5 GeV which is about an order of magnitude lower than for muon neutrinos (see Fig. 1 and [11]). This makes shower events a suitable tool to isolate the prompt component.

2 Neutrino Induced Particle Showers

The events of interest in this study are particle showers emerging from deep-inelastic neutrino nucleon scattering. Particle showers can be found in the final states of charged current (CC) electron and tau neutrino interactions and in all neutral current (NC) interactions. Since IceCube cannot distinguish ν_e and low-energy ν_τ CC interactions from all-flavour NC interactions, analyses tailored to this event signature are effectively sensitive to all neutrino flavours. In NC interactions neutrinos deposit only parts of their energy so they show up as less energetic cascades. This leads to a lower effective area for muon neutrinos.

At TeV energies the particle showers have lengths of a few meters. But due to the large DOM spacing and the scattering of light in the ice showers appear as nearly point-like light sources. This results in spherical hit patterns which at higher energies appear significantly different from the hit patterns of muon tracks.

The separation from the muonic background is mostly impeded by the fact that high energetic muons stochastically undergo catastrophic energy losses in the form of bremsstrahlung showers along the track. Because of the considerable energy deposition these bright electromagnetic showers change the appearance of the track and make them less distinguishable from the searched signal. This has also a connection to the cosmic ray composition because proton air showers produce more often single highly energetic muons than for e.g. iron showers. From the latter often whole bundles of muons reach the detector and traverse the detector nearly in parallel. As the individual muons will have their stochastic energy losses at different positions, the whole bundle appears sufficiently different from a single particle shower and is easier to reject. Extensive simulations performed in the context of similar analyses done on the IceCube 22 dataset confirmed this effect albeit with low statistics. Those muons which passed all cuts were originating from proton air showers [12].

For electromagnetic showers the light yield scales linearly with energy. It has been shown in a Monte Carlo study that for electron neutrino interactions with energies of $10\,\mathrm{TeV}$-$1\,\mathrm{PeV}$ and well contained interaction vertices the energy may be reconstructed with a precision of about $\Delta \log_{10}(E_\nu) = 0.13$ [17].

3 Event Selection

In order to minimize statistical bias a blind analysis is performed. From the 364 days of usable data, 32 days are chosen to develop the event selection. The data was sampled uniformly over the year in order to reflect seasonal variations in the muonic background rate. Secondly, a large background sample of simulated muons from more than 10^{12} air showers were generated. A version of CORSIKA [13] with the Sibyll interaction model was adapted for IceCube and used to simulate the Hörandel polygonato cosmic ray spectrum [14]. Additionally more statistics of protons are currently produced in order to study the impact of composition uncertainties on the background prediction. For the expected signal interactions electron, muon and tau neutrinos were generated with a collaboration-internal simulation package that is based on ANIS [15].

The IceCube 40 detector operated at a trigger rate of about $1300\,\mathrm{Hz}$. An online event selection based on two quickly calculable variables selected events at a rate of $16\,\mathrm{Hz}$. A straight line fit through all hit DOMs at position $\vec{x}_i$ and time t_i yields a parametrization of the form $\vec{x}_i = \vec{x}_0 + \vec{v} \cdot (t_i - t_0)$ where the parameter $|\vec{v}|$ denotes how fast the hit pattern evolves. The second variable uses an analogy to classical mechanics in which it interprets the hit pattern as a rigid body and the recorded amount of light in each DOM as a mass. Spherical hit patterns can then be selected by calculating the eigenvalues of the tensor of inertia and requiring that all three eigenvalues are nearly of the same size. This online filter starts to get efficient above an energy threshold of about 1 TeV and is optimized for the search for the expected astrophysical E^{-2} flux for which it yields an efficiency of about 73%. For the less energetic atmospheric electron neutrino flux the efficiency is only about 35%.

The selected events were transmitted via satellite to institutes in the North where more elaborate track and vertex likelihood reconstructions can be performed. They provide a sufficient angular resolution for incident muons and with the likelihood value of the vertex reconstruction a quality parameter to select particle showers. Based on the vertex reconstruction also an energy estimator that considers the depth dependent optical properties of the ice [16] is run. Cuts based on these variables reduce the data rate to 2 Hz while keeping about 60% of the atmospheric ν_e signal. According to a predicted atmospheric neutrino flux [5] the sample contains at this point about 1200 ν_e and 10000 ν_μ (CC+NC) events which are still buried below $50 \cdot 10^6$ atmospheric muon events. The effective areas up to this cut level are shown in Fig. 2.

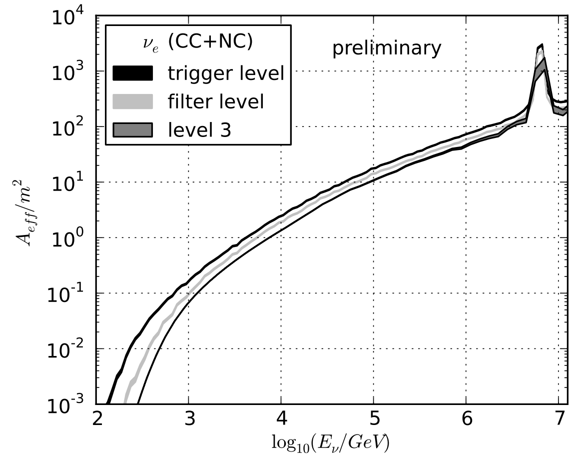
All passing events are fed into a more elaborate likelihood reconstruction [17]. This takes into account the full timing and amplitude information of the recorded light as well as tabulated results of detailed simulations of how light propagates in the ice [18]. For showers this provides estimates for the time and position of the interaction as well as the amount of deposited energy. Also the track reconstruction is repeated with an iterative optimization strategy in order to avoid local minima of the likelihood and to improve the angular resolution for background events [19].

So-called split reconstructions, which split the recorded photons by time into two sets and reconstruct each set individually, provide further information about the event due to the different timing behaviour of tracks and showers. For a track, later hits are downstream along the track while for particle showers they are centered around the vertex but at larger distance.

Based on an argument that shower induced hit patterns should be spherical another cut variable can be constructed. For an imaginary sphere with a given radius and centered at the reconstructed vertex one can calculate the fill ratio N_{hit}/N_{sphere}, where N_{sphere} denotes the number of all DOMs in the sphere and N_{hit} the number of triggered DOMs. This is especially useful to reject events containing several coincident atmospheric muons because the hit patterns of e.g. two coincident but well separated tracks can have many untriggered DOMs in between.

In order to further reduce the muonic background, DOMs at the surface of the instrumented volume are used to veto tracks that appear to enter and traverse the detector. Events for which the first triggered light sensor is located on the outer layer of the detector are rejected. Together with the requirement that the reconstructed vertex is located inside the fiducial volume, this forms a strict containment cut.

Finally those variables that still provide separation power are combined with a machine learning algorithm. In the TMVA framework [20] a boosted decision tree is trained which provides a final cut variable to select particle showers. Current investigations suggest that this event selection is able to remove the remaining background while keeping the prospect to find a few atmospheric neutrinos in the whole sample.



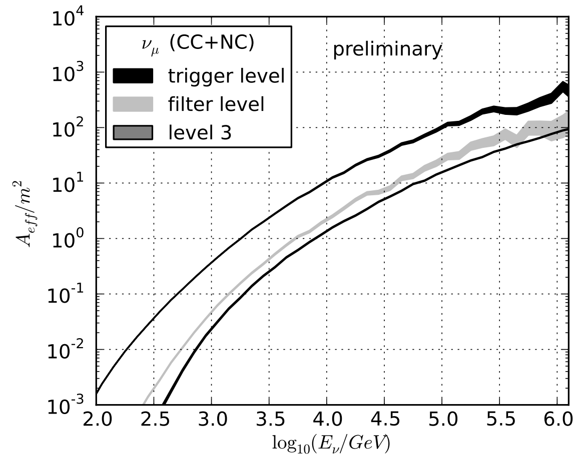


Figure 2: Effective areas for electron and muon neutrinos for the early stages of the analysis. The width of the bands denotes the statistical error. This differs between cut levels because datasets of different size have been used. The peak at 6.3 PeV for electron neutrinos is due to the Glashow resonance. The drop in effective area for muon neutrinos between trigger and online filter level illustrates the effect of tailoring the analysis to neutrino induced particle showers. At the presented cut levels the contribution of muon tracks from charged current interactions is still present. Therefore the effective area is still higher for muon than for electron neutrinos.

However, this statement relies on the Monte Carlo background prediction which has to be scrutinized before unblinding. Accordingly, studies of the systematic uncertainties in the simulated background sample (like for example a lighter cosmic ray composition) are ongoing and will be presented together with the final event selection at the conference.

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