Search for a diffuse flux of astrophysical muon neutrinos with the IceCube Detector

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

Abstract: The discovery of a cumulative flux of high-energy neutrinos from the sum of all cosmic sources in the Universe is one of the central goals of the IceCube experiment. The experimental signature of isotropically distributed astrophysical sources is an excess of high-energy neutrinos with a characteristic angular distribution over the background of less energetic neutrinos produced when cosmic rays interact with the Earth's atmosphere. Such searches are challenging because of systematic uncertainties in these fluxes and the detector response. The distribution of reconstructed neutrino energies is analyzed using a likelihood aproach that takes into account these uncertainties and simultaneously determines the contribution of an additional diffuse extraterrestrial neutrino component. This analysis is applied to the data measured with the IceCube detector in its 40 and 59-string configurations, covering the period from April 2008 to May 2010. No evidence for an astrophysical neutrino flux was found in the 40-string analysis. The upper limit obtained for the period from April 2008 to May 2009 is $d\Phi/dE \leq 8.9 \cdot 10^{-9}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ at 90% confidence level in the energy region between 35 TeV and 7 PeV. For the 59-string data from May 2009 to May 2010, an improved analysis technique including the angular distribution in the likelihood approach is presented. The preliminary sensitivity is $d\Phi/dE \leq 7.2 \cdot 10^{-9}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$.

Corresponding authors: Anne Schukraft[2] (*schukraft@physik.rwth-aachen.de*), DOI: 10.7529/ICRC2011/V04/0736
Sean Grullon[3] (*sean.grullon@icecube.wisc.edu*), Marius Wallraff[2] (*mwallraff@physik.rwth-aachen.de*)
[2] *III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany*
[3] *Dept. of Physics, University of Wisconsin, Madison, WI 53706, USA*

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1 Introduction

The study of cosmic rays is one of the main aspects of current research in astroparticle physics. Despite all efforts, charged cosmic rays have not yet revealed their sources. A candidate source class is active galactic nuclei, which are believed to accelerate particles up to energies of several EeV by the mechanism of Fermi acceleration, e.g., in the vicinity of their central supermassive black holes. Through hadronic interactions with the surrounding matter and radiation, high-energy neutrinos can be produced. Unlike charged cosmic rays and photons, neutrinos propagate almost unaffected by magnetic fields or intervening matter through the universe. This makes them an ideal messenger particle for astrophysics.
The neutrino telescope IceCube was built at the geographic South Pole with the purpose of detecting neutrinos with energies from several tens of GeV to EeV [1]. It consists of 86 strings each equipped with 60 optical sensors, distributed over an area of roughly $1\,\mathrm{km}^2$ and instrumented in depths from 1.5 to 2.5 km in the Antarctic ice. This huge volume is necessary to compensate for the very low interaction probability of neutrinos with matter. After seven years of construction, the IceCube telescope was completed in December 2010 and is currently the largest detector of its kind in the world.
The detection principle is based on the observation of secondary charged leptons and hadrons produced in interactions of neutrinos in the surrounding ice and rock. These emit Cherenkov light which is detected by IceCube's optical sensors. From the number of photo-electrons and their arrival times, detected by the optical sensors, the neutrino's initial direction and energy are reconstructed. Although no specific neutrino emitting sources have been discovered yet, it is believed that the combined flux of many weak sources distributed all over the sky could be detected with IceCube. This flux would exceed the flux of cosmic ray induced atmospheric neutrinos at high energies and would arrive almost isotropically from all directions. Since it would not be possible to identify individual neutrino sources, this analysis is known as a search for a diffuse neutrino flux.

2 Neutrino Event selection

The first step in the searches for a diffuse astrophysical neutrino flux is to select a sample of neutrino events with high

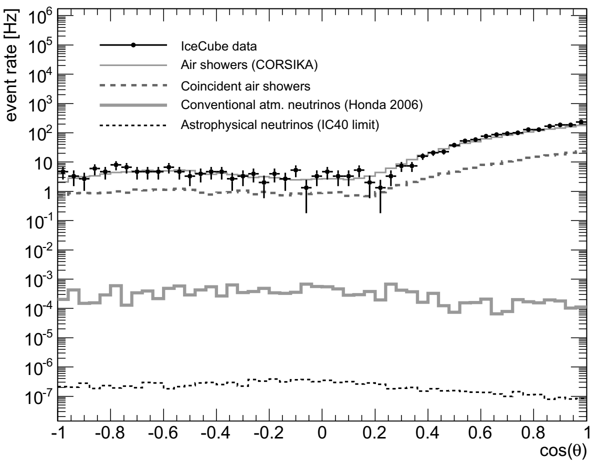

Figure 1: Reconstructed zenith angle distribution of one day of experimental data, and of simulated muons from air showers and neutrino-induced muons with the 59-string configuration at trigger level. The distribution of astrophysical neutrinos is normalized to the 40-string analysis upper limit.

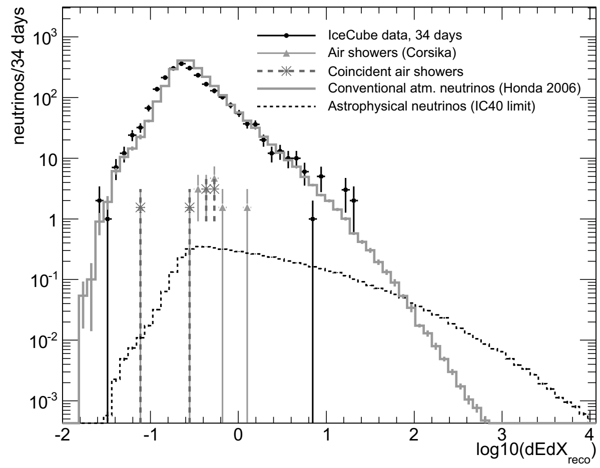

Figure 2: Distribution of the reconstructed muon energy loss for 10% of the 59-string data after neutrino selection.

purity. This contribution presents two searches for a diffuse neutrino flux with data from two consecutive years during the construction of IceCube. Both analyses focus on the selection of high-energy secondary muon tracks. Data was taken from April 2008 to May 2009 in the 40-string configuration and from May 2009 to May 2010 with 59 deployed strings. The event selections and analysis techniques are very similar. The analysis of the 59-string sample has not been finalized.

The reconstructed zenith angle distribution of detected events is shown in Fig. 1. The dominant background in this analysis are muons from cosmic-ray air showers. At trigger level, they outnumber the detected neutrino-induced muons by several orders of magnitude. In contrast to neutrinos, muons are easily absorbed by the Earth. Therefore, muons produced in the atmosphere enter the detector from above and are primarily reconstructed as downward going tracks, while muons originating from neutrinos interacting with the matter surrounding the detector come from all directions.

To reject a large amount of air shower background the analysis is restricted to upward reconstructed muon tracks. The remaining background is misreconstructed air-shower-induced muon tracks, containing a large fraction of muons arriving from coincident but independent air showers. For the further selection, an algorithm searches for patterns separated in space and time in the ensemble of recorded light-sensor pulses. This allows rejection of coincident events as well as tracks associated with random noise hits.

For the selection of a high-purity upward-going neutrino sample, the remaining data is reduced by a series of quality-criteria applied to reconstructed variables like the directional estimate of the reconstruction. They are described in detail in [5]. The final event sample consist of 12877 neutrino candidate events for the 40-string configuration and about 25000 expected events for the 59-string configuration after finalization of the analysis. Based on Monte Carlo simulation, the expected contamination of remaining background events is less than 1%.

Figure 2 shows the distribution of the reconstructed average energy losses for the selected muon tracks along their path in the detector. The experimental data is largely consistent with the expectation from atmospheric neutrinos. Most interesting for this analysis are events with high energy depositions.

3 Analysis method

The irreducible background for astrophysical neutrino searches consists of conventional atmospheric neutrinos. These neutrinos are produced in the decay of pions and kaons in cosmic-ray air showers in the Earth's atmosphere. They are described by an energy spectrum following a power law of about $d\Phi/dE \propto E^{-3.7}$ and by a characteristic zenith angle distribution related to the meson's path through the atmosphere. Another – not yet observed – type of atmospheric background are so called prompt neutrinos. Prompt neutrinos originate from the decay of heavier mesons, typically containing a charm quark[3]. They are produced at a higher cosmic-ray energy threshold and because of their comparably short lifetimes their energy distribution is predicted to follow a harder energy spectrum of $d\Phi/dE \propto E^{-2.7}$ with an almost isotropic angular distribution.

The aim of this analysis is to identify a possible astrophysical component in the neutrino sample. An astrophysical flux can be distinguished from a conventional atmospheric

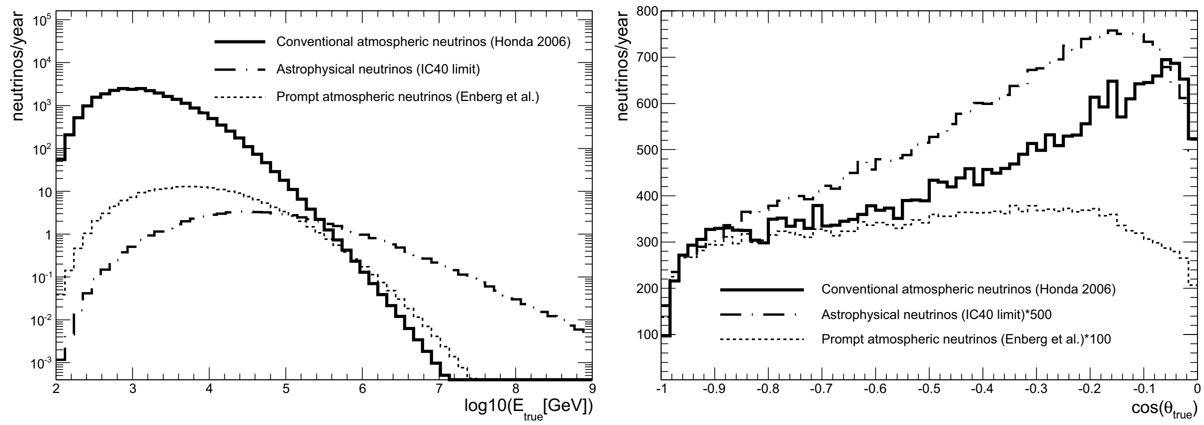

Figure 3: Expected energy (left) and zenith (right) distribution for detected conventional atmospheric neutrinos, prompt atmospheric neutrinos and astrophysical neutrinos in the IceCube detector with 59 strings. Left: The astrophysical neutrino flux is normalized to the upper limit (90% CL) of the 40-string analysis presented here. Right: The astrophysical and prompt fluxes have been renormalized for better visualization.

flux by its harder energy spectrum. Assuming shock acceleration in the extragalactic sources, an astrophysical neutrino flux would follow a $d\Phi/dE \propto E^{-2.0}$ power law (see Fig. 3). With the presumption of isotropically distributed sources over the whole sky, the arrival directions of these neutrinos would be isotropic. Their energy spectrum being harder than that of conventional atmospheric neutrinos, prompt neutrinos are an important background in a search for a diffuse flux.

Relative to the 40-string analysis[5], the ongoing 59-string analysis improves the sensitivity to an astrophysical flux by considering directional information in addition to energy. Figure 3 shows the expected zenith angle distribution of arrival directions when considering the energy-dependent absorption in the Earth, the angular detector acceptance and event selection efficiency. The significant differences in angular distribution for neutrinos of different origin adds separation power between the three components.

A likelihood method is applied to the experimental data to fit for the contributions of conventional atmospheric neutrinos, prompt atmospheric neutrinos and astrophysical neutrinos. In the 40-string analysis, the corresponding one-dimensional probability density functions (pdf) of the reconstructed energy are used to determine the probability for an astrophysical and prompt component. For the 59-string analysis, two-dimensional pdfs of reconstructed energy loss and zenith angle are used to account for both parameters and their correlation. Systematic uncertainties are taken into account by incorporating nuisance parameters in the likelihood function. These uncertainties are discussed in the next section.

The test statistic is a profile likelihood based on a likelihood ratio of the best fit of all physics and nuisance parameters to the experimental data compared to a fit of only the nuisance parameters for each point in the physics parameter space. Confidence regions are constructed according to the Feldmann & Cousins approach by generating a large number of random experiments based on Monte Carlo simulations[7]. In order to estimate the sensitivity of the analysis to a signal of diffuse astrophysical neutrinos, random experiments assuming the zero-signal hypothesis are generated.

4 Systematic uncertainties

A challenge in the search for a diffuse neutrino flux is the treatment of systematic uncertainties. Unlike other analyses of IceCube data, the background cannot be estimated from an off-source region in the experimental data. Therefore, the background estimation relies on a full-chain detector simulation. Inputs are, amongst others, air showers simulated with CORSIKA [4] and atmospheric neutrinos based on [2, 3]. More details can be found in [5, 6].

Main uncertainties at high energies are the conventional and prompt atmospheric neutrino flux predictions, the calculated neutrino cross sections and in particular the modeling of the detector response. Examples for the latter are the optical properties of the Antarctic glacial ice and the absolute efficiency of the optical sensors. The influence of these uncertainties on the final result is determined by studying simulations with different settings of these parameters. Some uncertainties, such as in the spectral index of atmospheric neutrinos, are taken into account with nuisance parameters in the likelihood fit. Additional information on the sytematic uncertainties can be found in [5, 6].

One possibly significant uncertainty not taken into account in the 40-string analysis is the effect of the knee in the cosmic-ray spectrum on the energy spectrum of conventional atmospheric neutrinos. This leads to an expected steepening of the neutrino spectrum above several tens of

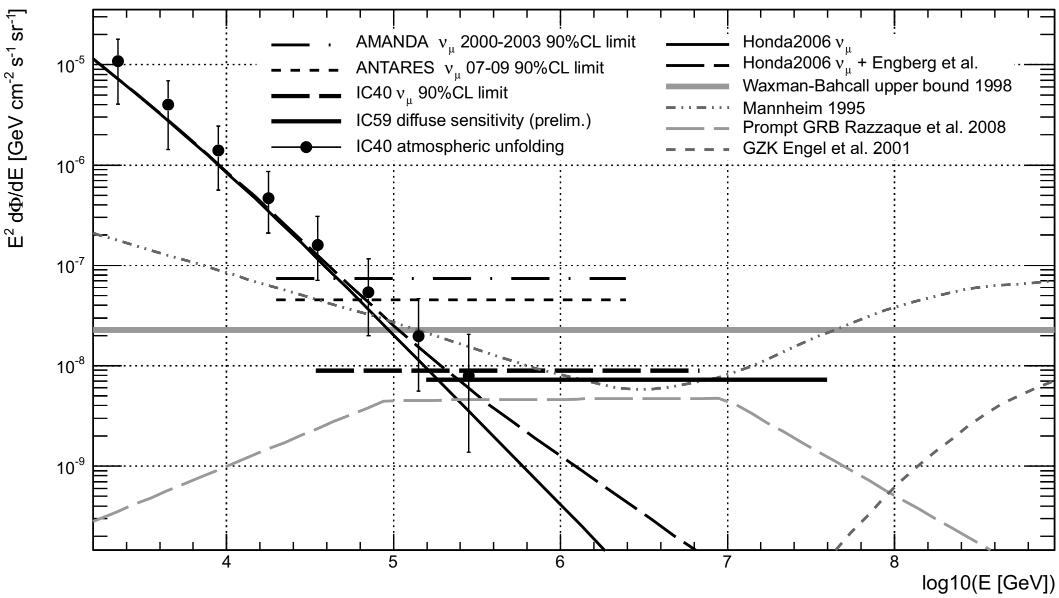

Figure 4: Limits and predictions for diffuse muon neutrino fluxes. The thin black lines show the expected flux for atmospheric neutrinos without and with an additional prompt component together with the unfolded atmospheric neutrino spectrum by IceCube[6]. The black horizontal lines represent 90%-confidence-level upper limits from different experiments [8, 9, 5]. The gray curves represent theoretical flux predictions for AGN models [11], gamma ray bursts [12] and GZK neutrinos [13]. The thick gray line shows the Waxman-Bahcall upper bound [10].

TeV, which is within the energy range relevant for this analysis but which has so far not been included in our simulations. The systematic uncertainties related to such a neutrino knee will be incorporated into the 59-string analysis using parameterizations of the measured cosmic-ray spectra.

5 Results

The result of the 40-string diffuse neutrino search has been published in [5]. The measured energy distribution is consistent with the expectation from conventional atmospheric neutrinos only. No prompt atmospheric nor astrophysical flux component was found. A small underfluctuation relative to the expectation was observed in the high-energy tail. This results in an upper limit on an astrophysical neutrino flux $d\Phi/dE \propto E^{-2.0}$ of $d\Phi/dE \leq 8.9{\cdot}10^{-9}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ integrated over the energy range between 35 TeV and 6.9 PeV with 90% confidence. This is currently the most constraining limit on a diffuse astrophysical neutrino flux and about a factor of two below the Waxman-Bahcall upper bound for an astrophysical neutrino flux [10]. At the same confidence level, a prompt atmospheric flux at 70% of the most probable flux predicted by Enberg et al.[3] was ruled out.

The higher statistics of the neutrino sample from the larger 59-string detector improves the sensitivity to astrophysical fluxes by about 35% compared to the 40-string analysis. The additional gain from using directional information is about 10% and results in a sensitivity of $d\Phi/dE \leq 7.2{\cdot}10^{-9}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ (Fig. 4). A further gain of roughly 10% in sensitivity for astrophysical fluxes is expected when taking into account the effect of the knee in the cosmic-ray spectrum.

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