All-Sky Point-Source Search with 40 Strings of IceCube

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***Abstract*. During 2008-09, the IceCube Neutrino Observatory was operational with 40 strings of optical modules deployed in the ice. We describe the search for neutrino point sources based on a maximum likelihood analysis of the data collected in this configuration. This data sample provides the best sensitivity to high energy neutrino point sources to date. The field of view is extended into the down-going region providing sensitivity over the entire sky. The 22-string result is discussed, along with improvements leading to updated angular resolution, effective area, and sensitivity. The improvement in the performance as the number of strings is increased is also shown.**

***Keywords*: neutrino astronomy**

I. Introduction

The primary goal of the IceCube Neutrino Observatory is the detection of high energy astrophysical neutrinos. Such an observation could reveal the origins of cosmic rays and offer insight into some of the most energetic phenomena in the Universe. In order to detect these neutrinos, IceCube will instrument a cubic kilometer of the clear Antarctic ice sheet underneath the geographic South Pole with an array of 5,160 Digital Optical Modules (DOMs) deployed on 86 strings from 1.5–2.5 km deep. This includes six strings with a smaller DOM spacing and higher quantum efficiency comprising DeepCore, increasing the sensitivity to low energy neutrinos $<\sim 100\,\mathrm{GeV}$. IceCube also includes a surface array (IceTop) for observing extensive air showers of cosmic rays. Construction began in the austral summer 2004–05, and is planned to finish in 2011. Each DOM consists of a 25 cm diameter Hamamatsu photomultiplier tube, electronics for waveform digitization, and a spherical, pressure-resistant glass housing. The DOMs detect Cherenkov photons induced by relativistic charged particles passing through the ice. In particular, the directions of muons (either from cosmic ray showers above the surface, or neutrino interactions within the ice or bedrock) can be well reconstructed from the track-like pattern and timing of hit DOMs.

The 22-string results presented in the discussion are from a traditional up-going search. In such a search, neutrino telescopes use the Earth as a filter for the large background of atmospheric muons, leaving only an irreducible background of atmospheric neutrinos below the horizon. These have a softer spectrum ($\sim E^{-3.6}$ above 100 GeV) than astrophysical neutrinos which originate from the decays of particles accelerated by the first order Fermi mechanism and thus are expected to have an E^{-2} spectrum. This search extends the field of view above the horizon into the large background of atmospheric muons. In order to reduce this background, strict cuts on the energy of events need to be applied. This makes the search above the horizon primarily sensitive to extremely high energy ($>$ PeV) sources.

II. Methodology

An unbinned maximum likelihood analysis, accounting for individual reconstructed event uncertainties and energy estimators, is used in IceCube point source analyses. A full description can be found in Braun *et al.* [1]. This method improves the sensitivity to astrophysical sources over directional clustering alone by leveraging the event energies in order to separate hard spectrum signals from the softer spectrum of the atmospheric neutrino or muon background. For each tested direction in the sky, the best fit is found for the number of signal events n_s over background and the spectral index of a power law γ of the excess events. The likelihood ratio of the best-fit hypothesis to the null hypothesis ($n_s = 0$) forms the test statistic. The significance of the result is evaluated by performing the analysis on scrambled data sets, randomizing the events in right ascension but keeping all other event properties fixed. Uniform exposure in right ascension is ensured as the detector rotates completely each day, and the location at $90°$ south latitude gives a uniform background for each declination band. Events that are nearly vertical (declination $< -85°$ or $> 85°$) are left out of the analysis, since scrambling in right ascension does not work in the polar regions.

Two point-source searches are performed. The first is an all-sky search where the maximum likelihood ratio is evaluated for each direction in the sky on a grid, much finer than the angular resolution. The significance of any point on the grid is determined by the fraction of scrambled data sets containing at least one grid point with a log likelihood ratio higher than the one observed in the data. This fraction is the post-trial p-value for the all-sky search. Because the all-sky search includes a large number of effective trials, the second search is restricted to the directions of *a priori* selected sources of interest. The post-trial p-value for this search is again calculated by performing the same analysis on scrambled data sets.

III. Event Selection

Forty strings of IceCube were operational from April 2008 to May 2009 with $\sim 90\%$ duty cycle after a good run selection based on detector stability. The $\sim 3\times10^{10}$ triggered events per year are first reduced to $\sim 1\times10^{9}$ events using low-level likelihood reconstructions and energy estimators as part of an online filtering system on site. These filtered events are sent over satellite to a data center in the North for further processing, including higher-level likelihood reconstructions for better angular resolution. Applying the analysis-level cuts (described below) that optimize the sensitivity to point sources finally yields a sample of $\sim 3\times10^{4}$ events. Due to offline filtering constraints, 144 days of livetime were used to design the analysis strategy and finalize event selection, keeping the time and right ascension of the events blinded. This represents about one-half of the final 40-string data sample. Because the northern sky and southern sky present very different challenges, two techniques are used to reduce the background due to cosmic ray muons.

For the northern sky, the Earth filters out atmospheric muons. Only neutrinos can penetrate all the way through the Earth and interact near the detector to create up-going muons. However, since down-going atmospheric muons trigger the detector at $\sim 1\,\mathrm{kHz}$, even a small fraction of mis-reconstructed events contaminates the northern sky search. Events may be mis-reconstructed due to random noise or light from muons from independent cosmic ray showers coincident in the same readout window of $\pm 10\,\mu$s. Therefore, strict event selection is still required to reject mis-reconstructed down-going events. This selection is based on track-like quality parameters (the reduced likelihood of the track fit and the directional width of the likelihood space around the best track fit [2]), a likelihood ratio between the best up-going and down-going track solution, and a requirement that the event's set of hits can be split into two parts which both reconstruct as nearly-upgoing. Although the track-like quality parameters have very little declination dependence, these last two parameters only work for selecting up-going neutrino candidates and remove down-going events. This event selection provides an optimal sensitivity to sources of neutrinos in the TeV–PeV energy range.

In the southern sky, energy estimators were used to separate the large number of atmospheric muons from a hypothetical source of neutrinos with a harder spectrum. After track-quality selections, similar but tighter than for the up-going sample, a cut based on an energy estimator is made until a fixed number of events per steradian is achieved. Because only the highest energy events pass the selection, sensitivity is primarily to neutrino sources at PeV energies and above. Unlike for the northern sky, which is a $\sim 90\%$ pure sample of neutrino-induced muons, the event sample in the southern sky is almost entirely well-reconstructed high energy atmospheric muons and muon bundles.

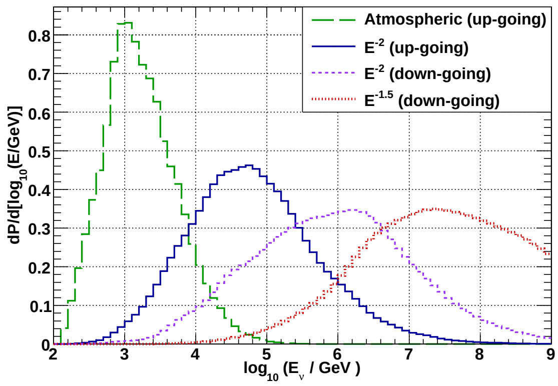

Fig. 1: Probability density (P) of neutrino energies at final cut level for atmospheric and an E^{-2} spectrum of neutrinos averaged over the northern sky and $E^{-1.5}$ in the southern sky.

IV. Performance

The performance of the detector and the analysis is characterized using a simulation of ν_μ and $\bar{\nu}_\mu$. Atmospheric muon background is simulated using CORSIKA [3]. Muon propagation through the Earth and ice are done using MMC [4]. A detailed simulation of the ice [5] propagates the Cherenkov photon signal to each DOM. Finally, a simulation of the DOM, including angular acceptance and electronics, yields an output treated identically to data. For an E^{-2} spectrum of neutrinos the median angular difference between the neutrino and the reconstructed direction of the muon in the northern (southern) sky is $0.8°$ $(0.6°)$. The different energy distributions in each hemisphere shown in Fig. 1 cause this effect, since the reconstruction performs better at higher energies. The cumulative point spread functions for the 22-, 40-, and 80-string configurations of IceCube are shown in Fig. 2 for two different ranges of energy. Fig. 3 shows the effective area to an equal-ratio flux of $\nu_\mu + \bar{\nu}_\mu$. Fig. 4 shows the 40-string sensitivity to an E^{-2} spectrum of neutrinos for 330 days of livetime and compared to the 22-string configuration of IceCube, as well as ANTARES sensitivity, primarily relevant for the southern sky. The 80-string result uses the same methodology and event selection for the up-going region as this work.

V. Discussion

The previous season of IceCube data recorded with the 22-string configuration has already been the subject of point source searches [7]. The analysis included 5114 atmospheric neutrino events including a contamination of about 5% of atmospheric muons during a livetime of about 276 days. No evidence was found for a signal, and the largest significance is located at

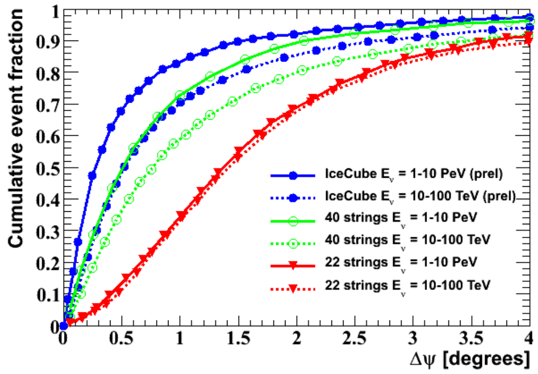

Fig. 2: The point spread function of the 22-, 40-, and 80-string IceCube configurations in two energy bins. This is the cumulative distribution of the angular difference between the neutrino and recostructed muon track using simulated neutrinos. The large improvement between the 22- and 40-string point spread function at high energies is due to an improvement in the reconstruction, which now uses charge information.

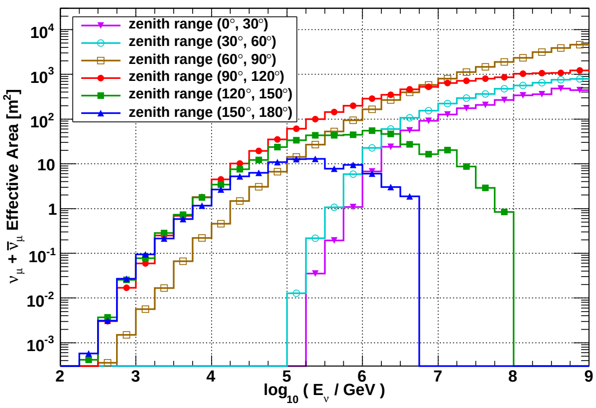

Fig. 3: The IceCube 40-string solid-angle-averaged effective area to an equal-ratio flux of ν_μ and $\bar{\nu}_\mu$, reconstructed within 2° of the true direction. The different shapes of each zenith band are due to a combination of event selection and how much of the Earth the neutrinos must travel through. Since the chance of a neutrino interacting increases with its energy, in the very up-going region high energy neutrinos are absorbed in the Earth. Only near the horizon do muons from $>$PeV neutrinos often reach IceCube. Above the horizon, low energy events are removed by cuts, and in the very down-going region effective area for high energies is lost due to insufficient target material.

$153.4°$ r.a., $11.4°$ dec. Accounting for all trial factors, this is consistent with the null hypothesis at the 2.2 σ level. The events in the most significant location did not show a clear time dependent pattern, and these coordinates have been included in the catalogue of sources for the 40-string analysis.

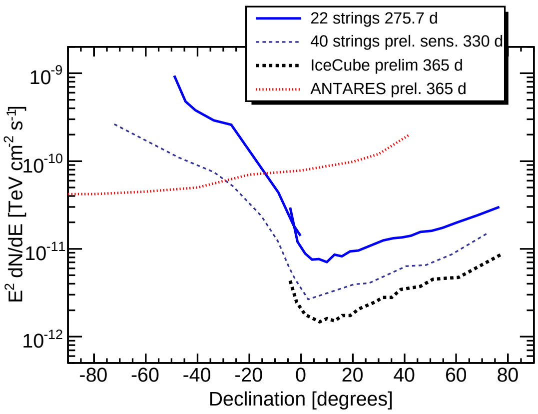

Fig. 4: 40-string IceCube sensitivity for 330 days as a function of declination to a point source with differential flux $\frac{d\Phi}{dE} = \Phi^0(E/\text{TeV})^{-2}$. Specifically, Φ^0 is the minimum source flux normalization (assuming E^{-2} spectrum) such that 90% of simulated trials result in a log likelihood ratio $\log\lambda$ greater than the median log likelihood ratio in background-only trials ($\log\lambda = 0$). Comparison are also shown for the 22-string and the expected performance of the 80-string configuration, as well as the ANTARES [6] sensitivity.

Since the 22-string analysis, a number of improvements have been achieved. An additional analysis of the 22-string data optimized for E^{-2} and harder spectra was performed down to $-50°$ declination with a binned search [8]. These analyses are now unified into one all-sky search which uses the energy of the events and extends to $-85°$ declination. Secondly, a new reconstruction that uses the charge observed in each DOM performs better, especially on high energy events. Third, an improved energy estimator, based on the photon density along the muon track, has a better muon energy resolution.

With construction more than half-complete, IceCube is already beginning to demonstrate its potential as an extraterrestrial neutrino observatory. The latest science run with 40 strings was the first detector configuration with one axis the same length as that of the final array. Horizontal muon tracks reconstructed along this axis provide the first class of events of the same quality as those in the finished 80-string detector.

There are now 59 strings of IceCube deployed and taking data. Further development of reconstruction and analysis techniques, through a better understanding of the detector and the depth-dependent properties of the ice, have continued to lead to improvements in physics results. New techniques in the southern sky may include separating muon bundles of cosmic ray showers from single muons induced by high energy neutrinos. At lower energies, the identification of starting muon tracks from neutrinos interacting inside the detector will be helped with the addition of DeepCore [9].

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