Point Source Searches by IceCube: Recent Results and Progress

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Abstract

The IceCube Neutrino Observatory began full data-taking operations in May of 2011. During the previous years of construction, data-taking was performed with each growing stage of the detector. In these proceedings we review the most recent all-sky searches for point sources of neutrinos, based on data taken between 2008 and 2010 when IceCube was operated in its 40-string and 59-string configurations. Based on better than expected performance with the partial detectors, operation of the full IceCube detector is well on track to reach the sensitivity goals for detecting high energy astrophysical neutrinos.

Keywords: astroparticle physics, neutrino telescopes, neutrino point sources

1. Introduction

Construction of the IceCube Neutrino Observatory at the geographic South Pole was completed on December 18, 2010. It has been designed to operate for at least the next 15 years, with the principal aim of discovering sites of cosmic ray acceleration by detecting high energy ($\gtrsim 300\,\mathrm{GeV}$) neutrinos. Beginning in 2005, seven austral summer seasons were used to deploy a total of 86 strings of detector modules between 1.5 km and 2.5 km deep in the Antarctic ice sheet. Each string consists of 60 digital optical modules (DOMs), for a total of 5160 DOMs forming a three dimensional array spanning a cubic kilometer of ice. Data-taking has been possible almost continuously during construction, with new strings added to the data-taking configuration after each season. Neutrino point source searches have most recently been performed on data from the 40-string (2008 April 5 to 2009 May 20) and 59-string (2009 May 20 to 2010 May 30) configurations (see Fig. 1).

The DOMs are sensitive to the Cherenkov light produced when relativistic charged particles travel through the ice. High energy muon neutrinos which interact in the ice inside or near the detector volume can produce muons that travel over kilometers. The pattern of detected Cherenkov light from the muon can be used to infer the incoming direction of the original neutrino. To positively identify an astrophysical origin of such neutrinos, two backgrounds must be considered. First, the detector is exposed to a large flux of muons from cosmic ray interactions in the atmosphere directly above it, triggering at $\sim 2\,\mathrm{kHz}$. These are the so-called atmospheric muons. At a rate approximately 10^6 times lower, the detector is also triggered by muons from neutrinos which were created in similar cosmic ray interactions in the atmosphere. These are the so-called atmospheric neutrino events. Events induced by neutrinos of genuine astrophysical origin beyond Earth's atmosphere will occur at a rate far below the background rate of atmospheric muons and even that of atmospheric neutrinos.

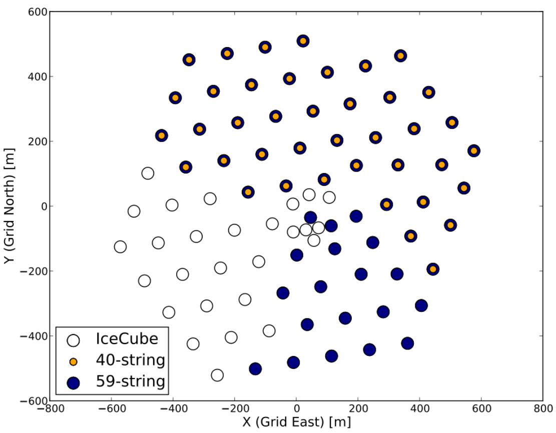

Figure 1: IceCube detector layout. The complete set of circles represents the full km^3 detector (86-strings) after construction finished in Dec. 2010. Data-taking with the partially-built detector took place during 2008-9 with 40-strings, and during 2009-10 with 59-strings.

2. Event Selection

There are two different strategies employed for each hemisphere, because of the different backgrounds. At trigger level, the down-going event sample (corresponding to

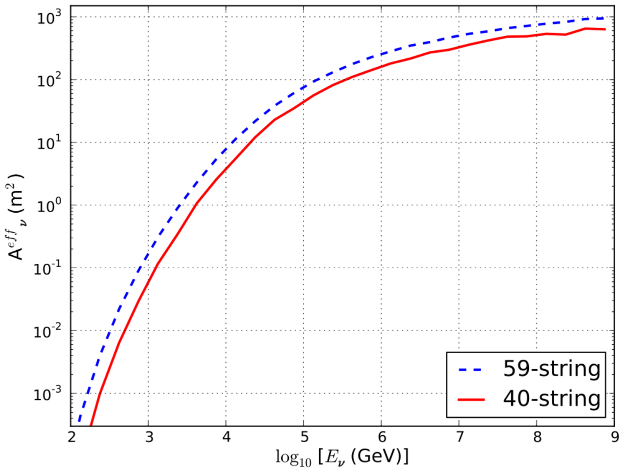

Figure 2: (Preliminary) Solid angle averaged $\nu_\mu + \bar{\nu}_\mu$ effective area, as a function of true neutrino energy, in the northern sky for the 59-string (dotted line) and the 40-string (solid line) IceCube detector configurations, from Aguilar et al. [2].

southern sky searches) is dominated by correctly reconstructed down-going muons. The main opportunity to see a neutrino point source is at high energies, where the cosmic ray background is much diminished. Therefore, the event selection for this hemisphere simply targets well-reconstructed high-energy events.

On the other hand, the up-going event sample at trigger level is dominated by mis-reconstructed down-going muons, rather than genuine up-going muons induced by neutrino interactions. Separating the real up-going events from the much larger set of fake up-going events requires careful application of cuts on a wide range of track reconstruction parameters.

The event selection for the 40-string data sample is discussed in detail in Abbasi et al. [1], and for the 59-string sample in Aguilar et al. [2]. A comparison of the neutrino effective areas at final cut level for upgoing event samples (northern sky) is shown in Fig. 2. At high energies, the effective area for the 59-string sample is about 50% greater than for 40-strings, while at low energies it is several times greater. The large improvement at low energies is partly attributable to the additional strings; in particular, as more volume is instrumented in which muon tracks are measurable over a full kilometer, the longer lever arm makes lower energy events easier to reconstruct and separate from mis-reconstructed down-going events.

The more significant factor contributing to the improvement is the use of a machine learning algorithm for the final event selection of the 59-string data. The 40-string event sample was selected using a set of "straight" cuts on seven event parameters to optimize the sensitivity to neutrino point sources with an E^{-2} power law spectrum. For the 59-string sample, Boosted Decision Trees (BDTs) using 12 event parameters were trained on a subsample of the data as background and simulated neutrino events as signal. Two sets of BDTs were trained, one with

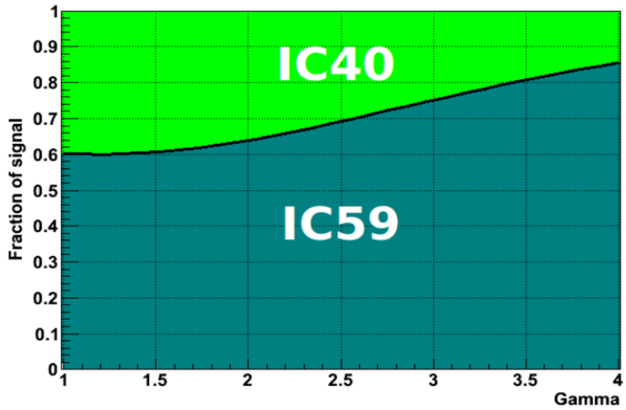

Figure 3: Example (for a source at $\delta = +16°$) of the fraction of total signal events expected in each of the data samples, as a function of the source spectral index γ.

an E^{-2} signal neutrino spectrum, and one with a softer $E^{-2.7}$ spectrum, which is more suited for lower energy signals or emission with ~TeV cutoff. A combination of the two BDT scores is used for the final event selection in order to optimize the sensitivity over a wide range of neutrino energies.

The livetime for the 40-string data sample is 375.5 days; for 59-strings, 348 days. These livetimes correspond to an approximately 90% duty cycle including the summer construction seasons. The up-going event sample for 40-strings consists of 14 121 events; for 59-strings, 43 339 events. Both are estimated to be approximately 95% pure samples of atmospheric neutrino events, based on simulation of atmospheric neutrinos and atmospheric muons. The down-going event samples are essentially pure high-quality, high-energy atmospheric muon events, with about 23 000 and 64 000 events in the 40-string and 59-string samples, respectively.

3. Analysis Method

The point source searches discussed here were performed using maximum likelihood methods, similar to those described in detail in Braun et al. [3] for time-integrated searches and Braun et al. [4] for time-dependent searches. The hypothesis is that the total sample of events consists partly of signal events, emitted from a given source direction $\vec{x}_s$ with some unknown spectral index γ, and the rest background events. The likelihood can be expressed as:

$$\mathcal{L}(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma) + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \right) \tag{1}$$

for which the product over all N events is maximized to give the best-fit values for the spectral index γ and the number of signal events n_s in the sample. $\mathcal{S}_i$ is the probability distribution function (PDF) hypothesized for the ith signal event, consisting of a Gaussian point spread function

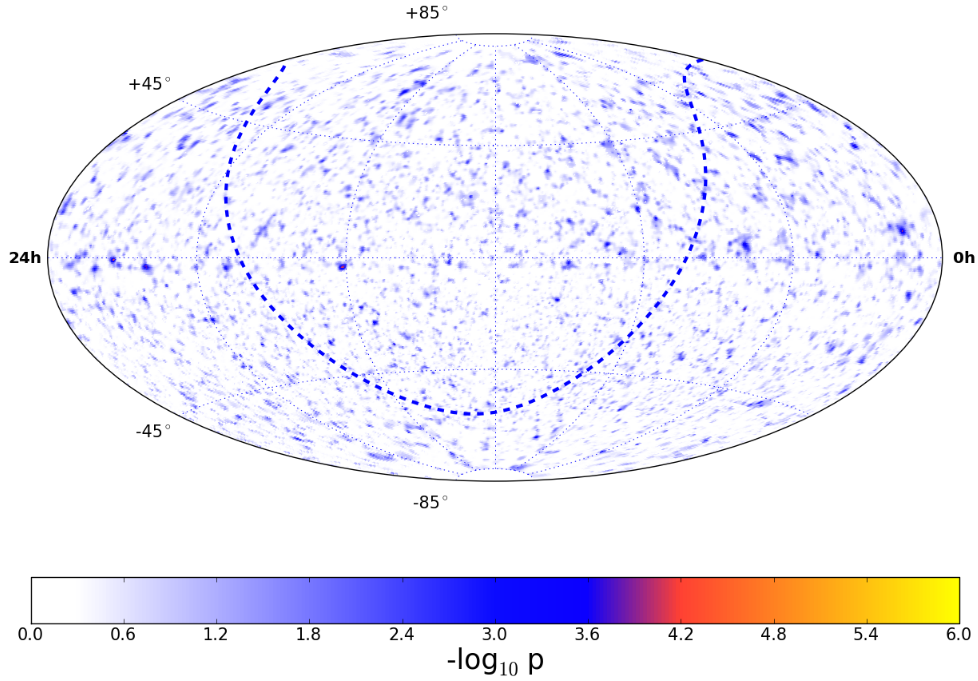

Figure 4: (Preliminary) Skymap in equatorial coordinates (J2000) showing the significance (negative of the log of the p-value) of the point source analysis performed in each direction of the sky using the combined data sample from the IceCube 40-string and 59-string detector seasons. The dotted line shows the galactic plane. From Aguilar et al. [2].

and a PDF of reconstructed energy values for simulated neutrino events of the given γ:

$$\mathcal{S}_i = \frac{1}{2\pi\sigma_i^2} e^{-|\vec{x}_i - \vec{x}_s|^2/2\sigma_i^2} \cdot P(E_i|\gamma), \qquad (2)$$

while $\mathcal{B}_i$ is the corresponding directional PDF and energy PDF of the background (constructed from the data sample itself). The signal and background energy PDFs are declination-dependent; the signal term S_i also uses the individual angular uncertainty of each event. For a joint analysis on the 40-string and 59-string data, the likelihood can be applied to the complete set of events in both samples, so long as the PDFs for each event are based on the correct sample. Additionally, a given source flux (and spectral index γ) corresponds to a different n_s in each sample, since the effective areas are different. The likelihood therefore fits for a different n_s for each sample, but with the ratio fixed. The ratio is calculated depending on the source declination and spectral index being fitted, as illustrated in Fig. 3.

4. Time-Integrated Search: 40+59 Strings

The point source search described above has been applied to the joint sample of 40-string and 59-string events, with the likelihood function maximized at each direction in the sky on a fine $0.1° \times 0.1°$ grid. This is well below the best median angular resolution of the 59-string sample, about $0.5°$ for high energy events [2]. The result of this scan of the sky for point sources is shown in Fig. 4. At each point, the estimated (pre-trial) significance of the best-fit likelihood result is shown. The smallest p-value is $10^{-4.65}$ found at r.a.$= 75.45°$, dec$= -18.15°$. However, the scan over the whole sky introduces a large trial factor. To correct for this, the data sample is scrambled in r.a. and the analysis re-performed. In 74% of randomly scrambled data sets, a similar or more significant p-value is found somewhere in the sky. The obtained result is thus typical of background-only samples and no evidence for a point source is found. The same analysis restricted to a pre-defined list of 43 candidate neutrino sources yields a similar result consistent with background.

5. Time-Dependent Search: 59 Strings

A time-dependent PDF can be added to the likelihood expression, to effectively constrain the point source search to a particular time-window. Braun et al. [4] describe a general search in which the time and the duration of the emission are not known. A Gaussian time PDF (with central time T_0 and width σ_T as fit parameters) is used for the unknown signal emission. For a fixed source direction, the likelihood is maximized with respect to n_s, γ, T_0 and σ_T, where σ_T can range from fractions of a second to the whole data-taking period.

Fig. 5 compares the sensitivity and the discovery potential of the time-dependent search to that of the standard, time-integrated search, for the 59-string data sample. As described in Braun et al. [4], the analysis accounts

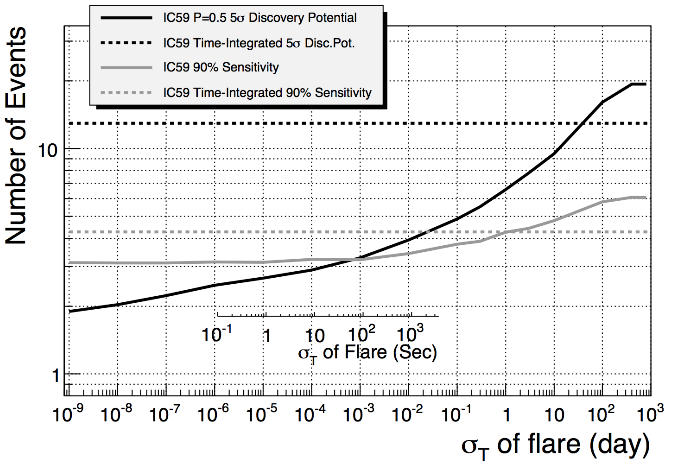

Figure 5: (Preliminary) Comparison of sensitivity (median 90% C.L. upper limit) and discovery potential (50% chance of $5\,\sigma$) for the time-dependent and time-integrated point source analyses of IceCube 59-string data, in terms of number of signal events at final cut level. This example is for a fixed source location at $\delta = +16°$ and an E^{-2} neutrino source spectrum. The full width at half maximum (FWHM) of the flare duration corresponds to $\sim 2.35 \times \sigma_T$. From Baker et al. [6].

for the internal trials that arise from searching many possible time-windows at a given source direction. As can be seen, if the duration of the emission (FWHM) is more than a hundred days, the internal trial factor penalty makes the discovery potential weaker than the standard time-integrated search. On the other hand, three or four neutrinos on time-scales of an hour or less can result in a discovery, whereas the same events would be at the level of a typical upper limit in the time-integrated search.

The 59-string data was analyzed with this time-dependent search again using a fine grid of directions over the whole sky. (For this analysis, there is little gain in combining with the 40-string data; those results are reported in [5].) The most significant direction in the sky is found at r.a.$= 21.35°$, dec$= -0.25°$ with estimated pre-trial p-value of $10^{-6.69}$ and best-fit parameters: $n_s = 14.5$, $\gamma = -3.9$, $\sigma_T = 5.5\,\text{days}$, and $T_0 = 55259\,\text{MJD}$ (see Fig. 6). Re-performing the analysis on scrambled data sets to account for the trials introduced by scanning the whole sky, 1.4% of the scrambled data sets have a similar or more significant result somewhere in the sky. Thus no evidence of a neutrino signal is found.

6. Conclusions

With two years of data from the partially constructed IceCube detector, neutrino point source searches have been performed which approach the anticipated sensitivity of one year of the full 86-string detector. In the most sensitive region of the sky between dec $0°-40°$, a sensitivity to fluxes below $E^2 \cdot d\Phi/dE = 2 \times 10^{-12}\,\text{TeV}\,\text{cm}^{-2}\,\text{s}^{-1}$ is reached [2]. This performance puts IceCube well on track to detect neutrino emission from a number of suspected

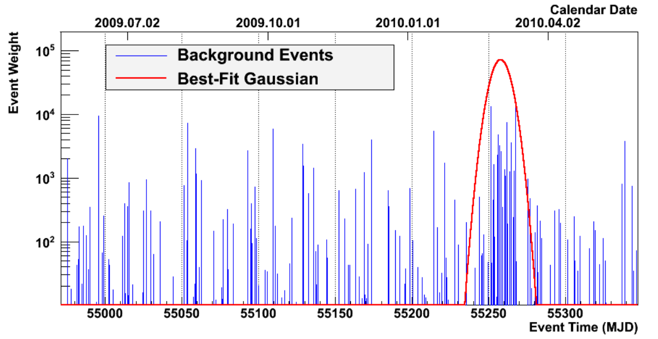

Figure 6: (Preliminary) Result of the 59-string time-dependent search, for r.a.$= 21.35°$, dec$= -0.25°$. Shown are the times (MJD) of all of the events in the vicinity of this direction, where the y-axis gives each event's signal weight $\mathcal{S}_i$ (Eq. 2) with respect to the specified source direction and best-fit $\gamma = -3.9$. The best-fit time-window has FWHM duration ~ 13 days, and the soft spectral index indicates that these are low energy events consistent with atmospheric neutrinos.

galactic cosmic ray sources within a few years of full operation [7]. Powerful all-sky time-dependent searches meanwhile increase the opportunity to discover brief emission from unexpected sources.

Acknowledgments

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