Time-independent searches for astrophysical neutrino sources with the combined data of 40 and 59 strings of IceCube.

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

Abstract: We present the results of time-independent searches for astrophysical neutrino sources performed over the whole sky using data collected between April 2008 and May 2010 with the 40-string and 59-string configurations of the IceCube Neutrino Observatory. Muon tracks arriving in the detector from neutrino interactions are reconstructed using the time and charge information detected by an array of photomultiplier tubes (PMTs). In the northern sky, the data sample consists of 14,121 events collected with 40 strings and 43,339 with 59 strings, mostly muons induced by atmospheric neutrinos. In this sky region the search is sensitive to point sources of neutrinos with E^{-2} spectra mainly in the TeV-PeV energy range. In the opposite hemisphere, a much larger background of high-energy atmospheric muons dominate the data set. A zenith dependent energy cut is used to reduce the number of background events. This weakens the sensitivity for point sources with E^{-2} spectra with respect to the upgoing region. The downgoing region is more sensitive to harder-spectrum sources for which the bulk of events can be detected between PeV-EeV energies. An unbinned maximum likelihood ratio test is used to search for astrophysical signals. For the first time it was adapted to combine data from different detector configurations. The combined sensitivity is about a factor ~ 2.5 better than the previous 1-year limit of the 40-string configuration alone. A dedicated search based on a catalog of sources is also presented.

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Keywords: neutrino astronomy; point sources; likelihood method

1 Introduction

The IceCube Neutrino Observatory is a neutrino telescope installed in the deep ice at the geographic South Pole. The final configuration comprises 5,160 photomultiplier tubes (PMTs) [1] along 86 strings instrumented between 1.5–2.5 km in the ice sheet. Its design is optimized for the detection of high energy astrophysical neutrinos with energies above $\sim$ 100 GeV. The observation of cosmic neutrinos will be a direct proof of hadronic particle acceleration and will reveal the origins of cosmic rays (CR) and the possible connection to shock acceleration in Supernova Remnants (SNR), Active Galactic Nuclei (AGN) or Gamma Ray Bursts (GRBs). The IceCube detector uses the Antarctic ice as the detection volume where muon neutrino interactions produce muons that induce Cherenkov light. The light propagates through the transparent medium and can be collected by PMTs housed inside Digital Optical Modules (DOMs). The DOMs are spherical, pressure resistant glass vessels each containing a 25 cm diameter Hamamatsu photomultiplier and its associated electronics. Detector construction finished during the austral summer of 2010-11.

During its construction, the IceCube telescope ran in various configurations. From April 2008 to May 2009, 40 strings of IceCube were operational and collecting scientific data. The data analyzed for that period has provided until now the best sensitivity to high energy neutrino point sources. In this article we describe the analysis of the combined data of the previous 40 strings of IceCube with the 59-string configuration data from May 2009 to May 2010 (see Fig. 1). With the combined information from both data samples we are able for the first time to probe beyond the initial estimates of the 1-year sensitivity of the completed IceCube detector [2].

2 Method

The method used for this analysis is an unbinned maximum likelihood ratio test [4]. This test allows to calculate the significance of an excess of neutrinos above the background for a given direction. The method uses both the reconstructed direction of the events as well as the reconstructed visible muon energy, to discriminate between signal and background [3]. This method improves the sensitivity to astrophysical sources over directional clustering

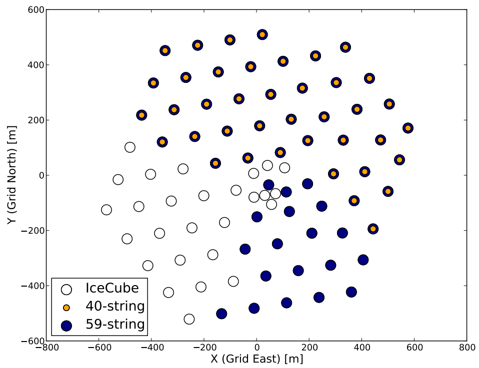

Figure 1: Detector layout. The empty circles represents the string positions that corresponds to the geometry of the whole IceCube detector. The 40-string configuration is represented with the small dots and the 59-string configuration with filled circles.

alone by leveraging the event energies in order to separate hard-spectrum signals from the softer spectra of the atmospheric neutrino or muon backgrounds. For each tested direction in the sky, the number of signal events over background, n_s, and the index of a power law, γ, for the spectrum of the signal events are determined that maximize the likelihood function. The likelihood ratio between the best-fit hypothesis and 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 by the daily rotation of the detector with respect to the sky. Events that are close to the polar regions of the sky (declination $< -85°$ or $> 85°$) are excluded from the analysis, since the scrambling in right ascension does not work in these 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 of $0.1° \times 0.1°$, 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 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.

3 Data selection and Detector Performance

From April 2008 to May 2009, 40 strings of the IceCube detector were operational. The duty cycle at analysis level for that period was $\sim 90\%$ after selecting good runs based on the detector stability and the total livetime was 375.5 days. The event selection for the 40-string configuration data sample is described in detail in Ref. [3]. In the analysis of the data from the 40 strings of IceCube no significant excess over fluctuations of the background was found, and upper limits have been published (see Ref. [3]). Here we report on a combined analysis using the data corresponding to the 40 strings period plus the 59-string configuration data taken from May 2009 to May 2010. The livetime corresponding to the 59-string configuration is 348 days with a similar $\sim 90\%$ duty cycle at final analysis level as in the previous year.

The trigger rate of the 59-string configuration is of the order of 1.5 kHz for events based on a simple multiplicity trigger requiring 8 triggered DOMs. This trigger rate is strongly dominated by the muon background produced in cosmic rays interactions in the atmosphere. A first level of background rejection of poorly reconstructed up-going events and a selection of high energy muons for the southern sky is done on-site at the South Pole (Level 1 filter). The data sent through the satellite to the North undergo further processing that includes a broader range of more CPU consuming likelihood-based reconstructions at the so-called Level 2 and Level 3 filters. This offline processing also provides useful parameters for background rejection and measurements of the energy and of the angular uncertainty. The data rate at Level 3 is of the order of 3 Hz and still dominated by atmospheric muons. Because the northern sky and the southern sky present very different challenges, two separate techniques for background rejection are used for each hemisphere.

In the northern sky the 59-string configuration event selection was performed using a multi-variate classification algorithm. Boosted Decision Trees (BDTs) were used in the final analysis step to classify events as signal-like or background-like. Twelve event observables, split in two sets of 8 and 4 respectively, were selected by choosing variables with low correlation for a background dominated dataset (correlation coefficient $|c| < 0.5$), but high discriminating power between signal and background. Training was done using a subsample of the data as the background and simulated neutrino events as signal. We trained two sets of BDTs, one with a neutrino spectrum of E^{-2}, and one with a neutrino spectrum of $E^{-2.7}$ in order to account for softer neutrino spectra and possible TeV cut-offs in the expected neutrino emission. The usage of data as the background sample for training is an important aspect since it makes the analysis independent of the systematic uncertainties of the simulation of the muon background. The combination of the two BDT scores for both the softer neutrino spectrum and the standard E^{-2} is used as a selection criterion and the cut that optimizes the discovery potential for neutrino point sources over a wide energy range is chosen.

The southern sky is filtered by using energy estimators to separate the large amount of down-going atmospheric muons from a hypothetical neutrino signal with a harder spectrum. For vertically down-going events with zenith angles between 0 and 50 degrees, we take advantage of the IceTop detector in order to reject atmospheric muons originating from a shower that produces a signal in at least two of the PMTs of the IceTop detector. This IceTop veto allows us to reject background with $\sim$ 99% efficiency in the very vertical zenith angles without losing signal neutrino efficiency (< 1 %).

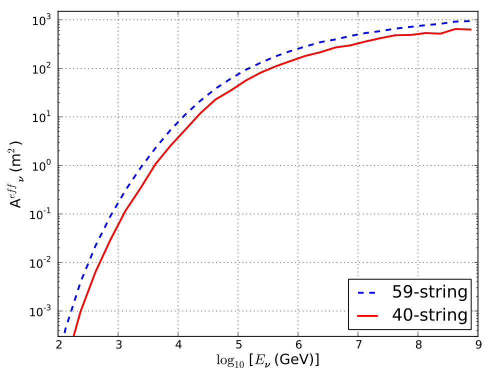

Figure 2: Solid angle averaged neutrino effective area in the northern sky for the 59-string IceCube configuration (dotted line) and the 40-string configuration (solid line) for an equal ratio of ν_μ and $\bar{\nu}_\mu$ as a function of the true neutrino energy.

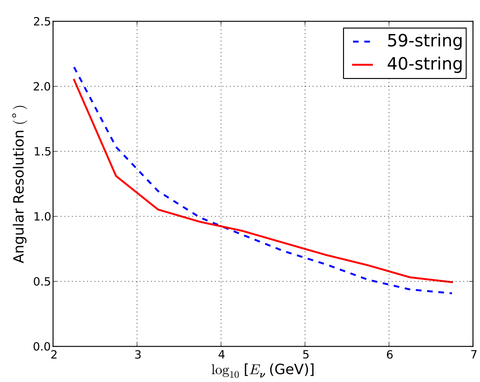

Figure 3: Nuetrino angular resolution as a function the true neutrino energy for the 59-string IceCube configuration and the 40-string configuration.

The final data sample for the 59-string configuration has a total number of 107,569 events, among them almost 2/3

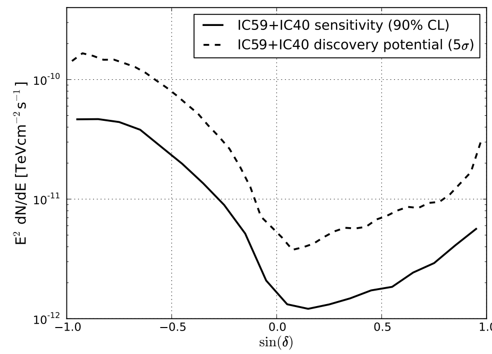

Figure 4: Expected sensitivity (solid line) for 90 % C.L. using the classical (frequentist) construction of upper limits, and discovery potential defined as the minimum flux required to have a 50% probability to claim a discovery of a point-source with a E^{-2} neutrino spectrum with confidence level equivalent to 5σ, (dotted line), for the combined analysis using the 40-string and 59-string configuration data. Both lines are shown as a function of the declination.

come from the southern sky and the rest from the up-going region. The estimated atmospheric muon contamination in the northern sky is $\sim$5 %. The solid angle averaged neutrino effective area for both detector configurations in the northern sky is shown in Fig. 2 as a function of the true neutrino energy. The overall increase in neutrino effective area in the up-going region of the 59-string configuration with respect to the previous IceCube configuration of 40 strings is a factor of $\sim$ 1.3 for energies $>$ 1 TeV and up to a factor of 2 at lower energies due to the event selection based on BDTs trained with softer neutrino spectra. Fig. 3 shows the angular resolution defined as the median of the point spread function (PSF) as a function of the true neutrino energy. The PSF is defined as the angle between the reconstructed muon track and the true neutrino direction. The BDT used in the 59-string configuration allows more low energy signal events to pass the event selection with worse angular resolution, that explains why the median distribution is worse compared to the 40-string configuration at energies below 10 TeV.

The expected sensitivity for the 2 years (375 + 348 days) of combined data and the discovery potential is shown in Fig. 4 as a function of declination for a E^{-2} neutrino spectrum. The overall improvement with respect to the 40-string configuration sensitivity is about a factor of $\sim$ 2.5 making it comparable to the projected 1-year sensitivity of the completed IceCube detector.

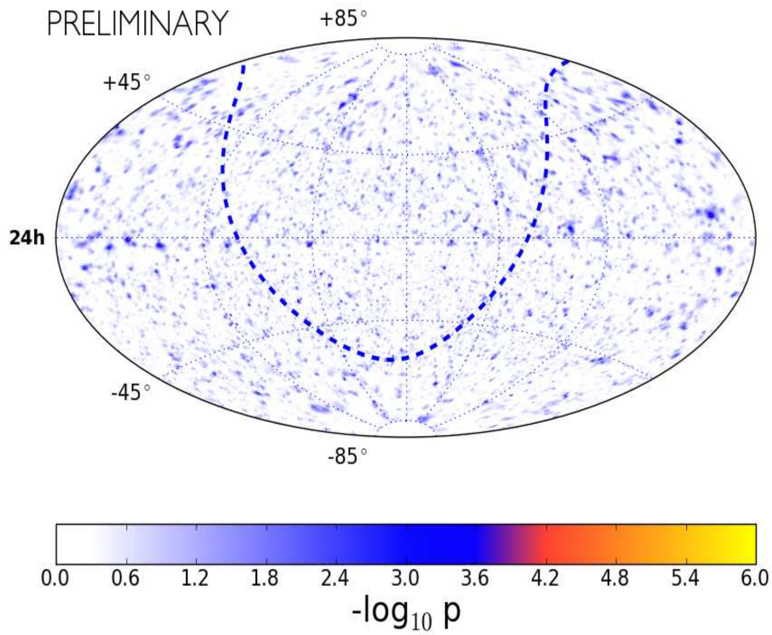

Figure 5: Significance skymap in equatorial coordinates (J2000) of the all-sky point source scan. The dotted line indicates the galactic plane.

4 Results

The results of the all-sky scan are shown in the preliminary pre-trial significance map in Fig. 5. The most significant deviation from background is located at 75.45° r.a. and $-18.15°$ dec. The best-fit parameters for this location are $\hat{n}_S$ = 18 and $\hat{\gamma}$ = 3.9. The pre-trial p-value is 2.23×10^{-5} which corresponds to a post-trial p-value of 67% calculated as the fraction of scrambled sky maps with at least one source with an equal or higher significance. The most significant source from the *a priori* source list is PKS 1454-354 with a pre-trial estimated p-value of 14%. The equivalent post-trial p-value was calculated as well using scrambled sky maps and correspond to a value of $\sim$ 95%. The 90% CL upper limits for both searches will be provided as the systematic uncertainties are evaluated and incorporated in the Feldman & Cousins confidence belt construction.

5 Conclusions

Between April 2008 and May 2009 the IceCube detector recorded 375 days of data with 40 instrumented strings. The analysis included 36,900 events in the whole sky where no evidence for a signal was found. The 40-string configuration analysis provided the best flux upper limits on point sources of astrophysical neutrinos up to now. Here we presented an analysis of a combined data sample in 40-string and 59-string configurations of IceCube. The sensitivity of this analysis is already beyond the initial estimates of the expected sensitivity of 1 year of the IceCube detector. Two searches were performed; an all-sky scan and a search on specific locations based on *a priori* list of candidate sources. In both cases no significant excess was found.

References

[1] R. Abbasi *et al.* [IceCube Coll.], Nucl. Inst. Meth. A, 2010, **618**: 139.
[2] J. Ahrens *et al.* [IceCube Coll.], Astropart. Phys., 2004, **20**: 507-532.
[3] R. Abbasi *et al.* [IceCube Coll.], Astrop. J., 2011, **732**: 18.
[4] J. Braun *et al.* , Astropart. Phys., 2010, **33**: 175.