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Searches for neutrino point sources with the IceCube Observatory

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Summary. — We have performed searches for point-sources of neutrinos with a multi-messenger approach using IceCube data. Information from high-energy astronomy experiments, such as Fermi, can be used to search for neutrinos in coincidence with high photon flux states, enhancing the potential for source discovery over a time-integrated search. A sample of results for point source searches with data taken in the 40-string configuration for transient sources will be presented.

PACS 95.55.Vj – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS 98.54.Cm – Active and peculiar galaxies and related systems (including BL Lacertae objects, blazars, Seyfert galaxies, Markarian galaxies, and active galactic nuclei).

1. – Introduction

The final season of deployment is underway at the South Pole, with IceCube having an expected completion date of January 2011. The IceCube Neutrino Observatory is a kilometer-scale detector currently under construction at the geographic South Pole. IceCube will use 5160 optical modules deployed on 86 vertical strings between 1450 and 2450 m under the ice surface to detect and reconstruct high-energy neutrino-induced charged leptons. Eight densely spaced strings in the center of the detector, named Deep Core, have also been deployed to lower the energy threshold. The main science goal of the IceCube experiment is the detection of sources of astrophysical neutrinos which will help identify the origins of the highest energy cosmic rays. Muons passing through the detector emit Čerenkov light allowing reconstruction with median angular resolution of less than $1°$ for $>$ TeV energy particles in the 40-string configuration. In this paper we describe the introduction of a time-dependent term to searches for steady emission of neutrinos presented in [1]. We apply this term in searches for neutrino emission from a

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generic time-dependent search and from a catalogue of flaring sources occurring when IceCube was taking data in its 40-string configuration.

2. – Time-dependent point source searches

An unbinned maximum likelihood ratio method which models the data as a mixture of signal and background has been used for the search for point sources of neutrinos in IceCube [2]. We use the angular and energy distribution of events as information to characterize the signal with respect to the background. An energy estimator is used based on the photon density along each reconstructed muon track. The analysis returns a best-fit number of signal events and spectral index, as well as other free parameters, such as timing information.

The IceCube 40-string data at analysis level consists of 36900 selected events, 14121 are upward-going TeV energy neutrino candidate events and 22779 are downward-going, mainly PeV energy muons from atmospheric air showers. Data were collected in 375 days of livetime between April 5, 2008 and May 20, 2009 (corresponding to 92% uptime). Selection cuts for the final sample are based on the quality of the reconstruction, on the angular uncertainty of the track reconstruction ($\sigma < 3°$) and on other variables such as the number of DOMs hit by the direct Čerenkov light produced by muons.

Neutrinos from a point source are expected to cluster around the direction of the source and to have a spectrum $\mathrm{d}N/\mathrm{d}E \propto E^{\gamma}$ with $\gamma \sim -2$ as predicted by 1st-order Fermi acceleration mechanisms. The background is distributed uniformly in right ascension.

The signal probability distribution function (pdf) is a 2-dimensional Gaussian centered on the source hypothesis, with a width given by the reconstructed angular error of the event, the energy pdf which includes a variable spectral index and varies depending on zenith angle, and the time pdf of the event. The background pdf depends on the local coordinates ϕ_i and azimuth θ_i of the event, which is important for short flares, the energy pdf is the zenith-dependent energy distribution of background, and the background in time is the inverse of the livetime. The background pdf is determined using the data, and the final p-value for each analysis is obtained by comparing scrambled equivalent experiments to data.

3. – All-sky time scan

This all-sky time scan is designed to cover cases of emission at any timescale and direction. This also covers cases where photons are absorbed after production and neutrinos are not.

3˙1. *Method and expected performance.* – This analysis method was developed and tested using a simulation of a generic km^3 neutrino detector in [3], and has been adapted for use with a detector with non-uniform acceptance and dead time. The time-dependent probability density function for this search is a Gaussian function, with its mean and width as free parameters, returning the most significant flare from a particular direction. The method is applied as an all-sky scan over a $0.5° \times 0.5°$ grid in right ascension and declination, scanning for flares with widths of $20\,\mu$s to 150 days. The improvement in the discovery potential for a single flaring source can be seen in fig. 1. The final result is the set of best-fit parameters from the location with the highest test statistic value. This best test statistic for data is converted into a p-value by comparing to the distribution of the highest test statistics found by scanning over scrambled samples.

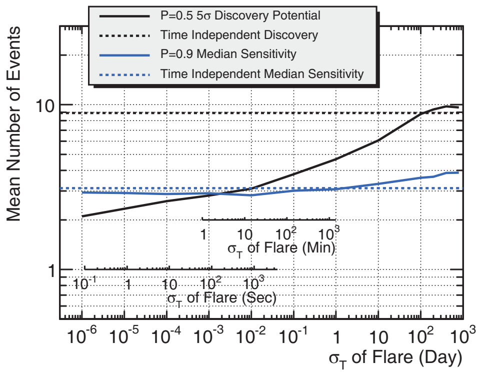

Fig. 1. – The 50% 5σ discovery potential and 90% sensitivity in terms of the mean number of events for a fixed source at $+16°$ declination. The number of events for the sensitivity and discovery potential for the time-independent search are also shown. Flares with a σ_T of less than 100 days, or a FWHM of less than roughly half the total livetime, have a better discovery potential than the steady search.

3˙2. *Results*. – Using the 40-string data, the location which deviates most from background is found at $(\mathrm{RA}, \mathrm{Dec}) = (254.75°, +36.25°)$. Two events are found, with a best-fit spectrum γ of 2.15 (with uncertainty of ± 0.4), mean of the flare T_o of MJD 54874.7 and width σ_T of 15 seconds. The two events are $2.0°$ apart in space and 22 seconds in time. The $-\log_{10}$ (p-value) corresponding to this observation is 4.67. A clustering of greater significance is seen in 56% of scrambled skymaps, which is consistent with background.

4. – Triggered search for flares

When there is specific timing information about the activity of an astronomical object, that information can be used to reduce the background of atmospheric neutrinos or atmospheric muons. For triggered sources, the focus is on objects such as blazars, which exhibit variability on timescales of hours to weeks. When flares are seen with comprehensive coverage, flux measurements are made on a regular basis and this continuous lightcurve can be used to define the activity at any point in time as low or high. This improves the ability to define periods of high flux state with a clear beginning and end. This analysis utilizes 1-day binned lightcurves from the Fermi LAT.

4˙1. *Method and expected performance*. – Sources for this search were selected considering alerts for sources in outburst $> 2 \times 10^{-6}$ photons/s/cm^2 and are listed in table I. A Maximum Likelihood Block (MLB) algorithm [4, 5] is used to de-noise the lightcurves by iterating over the data points to select periods from the lightcurves which are consistent with constant flux taking statistical errors into account. The hypothesis is that the neutrino emission follows the lightcurve, but only when the photon flux goes above a certain threshold F_{th}. The value of F_{th} is used as a free parameter, finding the value of the threshold which maximizes the significance of the data.

$F(t_i)$ is defined as the value of the denoised lightcurve at t_i and F_{th} is the flux threshold below which no neutrino emission is assumed (*i.e.* $S_i^{\mathrm{time}}{=}0$ if $F(t_i) \le F_{th}$). In the case of $F(t_i) \ge F_{th}$, the probability of neutrino emission is assumed to be proportional

TABLE I. – *Sources tested with the* 40 *string data and pre-trial p-values for the flare search with continuous lightcurves. In the event of an underfluctuation no p-value is calculated. The overlap between the Fermi public release data and the* 40*-string data-taking period is* 282 *days, that being the maximum duration of the lightcurve above* F_{th}.

Source	Pre-trial p-value	Threshold (10^{-6} cm^{-2} s^{-1})	Duration above threshold (days)
PKS 1510-089	—	0	282
3C 66A/B	0.47	0.675	57
3C 454.3	0.20	9.47	2.5
PKS 1454-354	—	0	282
3C 279	0.47	2.34	6
PKS 0454-234	—	0	282
PKS 1502+106	0.049	3.13	8
J123939+044409	—	0	282

to the flux level above that threshold:

$$S_i^{\text{time}} = \frac{(F(t_i) - F_{th})}{N_f}\,; \tag{1}$$

where the normalization factor N_f is the integral of the denoised lightcurve above the threshold. The effect of adding this additional degree of freedom is small compared to the penalty of fixing the threshold to an incorrect value. Allowing a lead of lag of up to 50 days was also tested. This resulted in a markedly higher number of events for discovery, so we constrained the neutrinos to come within ±1 day of the photons.

4˙2. *Results*. – The most significant source is PKS 1502+106, which has a pre-trial p-value of 5%. The results from all sources are listed in table I. With the method, we find one high-energy event during the August 2008 flare. The post-trial p-value is 29%, which is compatible with background fluctuations.

5. – Conclusion

We have analyzed data from the IceCube observatory from the season 2008-9 when the detector consisted of 40 strings. Searches for untriggered flaring and flares from blazars seen with Fermi show no evidence of a neutrino signal.

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For acknowledgements see `http://www.icecube.wisc.edu/`.

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