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A new and improved IceCube point source analysis

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Abstract: The IceCube Neutrino Observatory, a cubic kilometer scale Cherenkov detector deployed in the deep ice at the geographic South Pole, investigates extreme astrophysical phenomena by studying the corresponding high-energy neutrino signal. Its discovery of a diffuse flux of astrophysical neutrinos with energies up to the PeV scale in 2013 has triggered a vast effort to identify the mostly unknown sources of these high energy neutrinos. Here, we present a new IceCube point-source search that improves the accuracy of the statistical analysis, especially at energies of a few TeV and below. The new approach is based on multidimensional kernel density estimation for the probability density functions and new estimators for the observables, namely the reconstructed energy and the estimated angular uncertainty on the reconstructed arrival direction. The more accurate analysis provides an improvement in discovery potential up to ~30% over previous works for hard spectrum sources.

Keywords: Analysis and statistical methods; Cherenkov detectors; Neutrino detectors

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1. Introduction

Although discriminating the small fraction of astrophysical neutrinos IceCube detects from the overwhelming atmospheric background [1–3] is challenging, in 2017 IceCube identified the flaring blazar TXS 0506 + 056 as the first potential source of astrophysical neutrinos at a 3.5σ level of significance [4, 5]. More recently, the nearby active galaxy NGC 1068 stood out in a time-integrated point source search as a possibly interesting source, showing a 2.9σ excess of soft-spectrum neutrino events coming from a direction consistent with its location in the sky [6]. IceCube is starting to localize interesting objects, but the sources of high-energy astrophysical neutrinos still remain a mystery almost completely unrevealed, which motivates further improvement in the methods to search for neutrino point sources. Here we present a time-independent analysis to search for clustering of neutrino events in the Northern Sky that will be applied to IceCube data recorded with the full 86-string detector configuration from 2011 to 2020. The sample includes track-like neutrino-induced muon events [3, 7] reprocessed to include the latest detector calibration and filtering [8].

2. Methodology: a more accurate likelihood function

IceCube point source searches use the unbinned likelihood formalism [9] and the related likelihood-ratio hypothesis testing [10] to discriminate a point-like spatial clustering of astrophysical neutrinos from the atmospheric and diffuse astrophysical neutrino background. The signal hypothesis consists of point-like neutrino emission from a location $\vec{d}_s$ and following a power-law spectrum $\Phi = \Phi_0 \cdot (E_\nu/E_0)^{-\gamma}$ with neutrino energy E_ν, spectral index γ, and flux normalization Φ_0 at normalization energy E_0. Thus, the likelihood is a superposition of signal (f_s) and background (f_b) probability density functions (PDFs) for each event i in the sample of size N:

$$\mathcal{L}\left(\vec{d}_s, \mu_{ns}, \gamma | \vec{x}, N\right) = \prod_{i=1}^{N} \left[\frac{\mu_{ns}}{N} f_S\left(\vec{x}_i | \gamma, \vec{d}_s\right) + \left(1 - \frac{\mu_{ns}}{N}\right) f_B\left(\vec{x}_i\right)\right]. \tag{1}$$

Here, μ_{ns} is the mean number of signal events. The PDFs depend on the event observables $\vec{x}_i = (\hat{\vec{d}}_i, \hat{\sigma}_i, \hat{E}_{\mu,i})$, i.e. the reconstructed muon energy $\hat{E}_\mu$ and direction $\hat{\vec{d}}$, and the estimated uncertainty on the latter, $\hat{\sigma}$. Due to Earth's rotation, the time-integrated background PDF is uniform in right ascension:

$$f_{\text{B}}(\vec{x}_i) = f_{\text{B}}(\hat{\vec{d}}_i, \hat{\sigma}_i, \hat{E}_{\mu,i}) = \frac{1}{2\pi} f_{\text{B}}(\sin\,\hat{\delta}_i, \hat{\sigma}_i, \hat{E}_{\mu,i}), \tag{2}$$

where $\hat{\delta}_i$ is the reconstructed declination for the event i. The signal PDF, instead, depends on the angular separation between the reconstructed event direction and the source position, Ψ. By using the law of conditional probability, f_s can be split in a spatial and an energy term:

$$f_{\text{S}}\left(\hat{E}_\mu, \hat{\vec{d}}, \hat{\sigma} |\sin\,\delta_{\text{s}}, \gamma\right) = \frac{1}{2\pi\,\sin\,\hat{\psi}} f_{\text{S}}\left(\hat{\psi}|\hat{\sigma}, \hat{E}_\mu, \gamma\right) \cdot f_{\text{S}}\left(\hat{E}_\mu, \hat{\sigma}|\sin\,\delta_{\text{s}}, \gamma\right), \tag{3}$$

where the factor $1/(2\pi\,\sin\,\hat{\psi})$ ensures proper normalization on the sphere, and the dependency of the spatial term on the event declination is absorbed by the angular error estimator. Until now, the spatial term of the signal PDF was approximated using a spectral index independent 2D Gaussian [9]. However, it has to be noted that eq. (3) depends on γ, making this approximation imprecise in the low energy region of the observable space, especially for soft spectral indices (see figure 1). Here we do not rely on the Gaussian assumption but construct the PDFs in eqs. (2) and (3) from Monte Carlo via kernel density estimation (KDE) [11, 12]. In this way the spectral index dependency of the spatial term is accounted for by construction and simulated data are described much better by the PDF, as can be seen in figure 1.

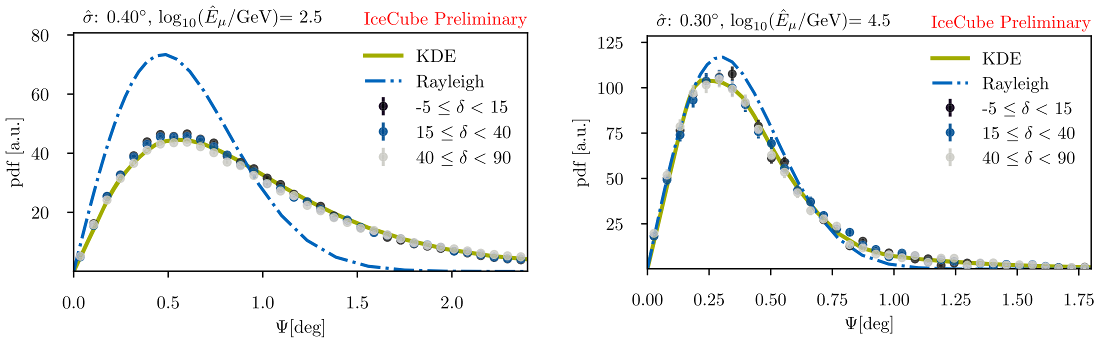

Figure 1. Description of the spatial term for $\gamma = 3.2$. The distribution of the angular separation between the muon true and reconstructed direction is shown for a sub-TeV (left) and a higher energy event (right). The dots show the Monte Carlo truth, different colors for different declination bands; the Rayleigh (projection of the 2D Gaussian) approximation and the KDE description are shown in blue and green respectively.

3. The new estimators for the event observables

DNN energy estimator. In this work a deep neural-network (DNN) is used to estimate the muon energy at detector entry as a proxy variable for the neutrino energy [8]. Contrary to the traditional reconstructions [13], the DNN estimates are unbiased in the entire muon energy range,

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also below few TeV, where the energy-independent ionization becomes dominant over radiative losses. Furthermore, the DNN estimator improves the energy resolution by up to 40% in $\log_{10}(\hat{E}_\mu)$ at all muon energies.

BDT angular uncertainty estimator. We use a Boosted Decision Tree (BDT) to parametrize the median opening angle between the reconstructed and the true muon direction as a function of 17 observables, including various estimations of the muon direction and its angular uncertainty [8]. By including this additional single event information and by taking into account the variable detector response to different track events, the new angular uncertainty estimate, for example, restores the independence of the spatial PDF on the event declination also at sub-TeV energies (see figure 1), where the previous estimator and likelihood approach were less accurate.

4. Analysis performance

To quantify the improvement produced by the new implemented methods and reconstructions, we compare the new analysis capability of recovering the injected source parameters with respect to the previous analysis [6] by generating pseudo-data with simulated point sources of varying strength and spectral index. Thanks to the improved modelling of the spatial PDF, the bias in the fitted number of injected neutrino events is removed at all declinations for both hard and soft spectra, as evidenced in figure 2. The better performance of the new energy estimator leads to a decrease in the variance of the estimated spectral index, especially for soft spectra. Finally, the average flux needed by the new analysis to discover a point source at the 5σ level of significance is considerably improved, up to 20%–30% at $\gamma = 2.0$ and 5% at $\gamma = 3.2$, see figure 3.

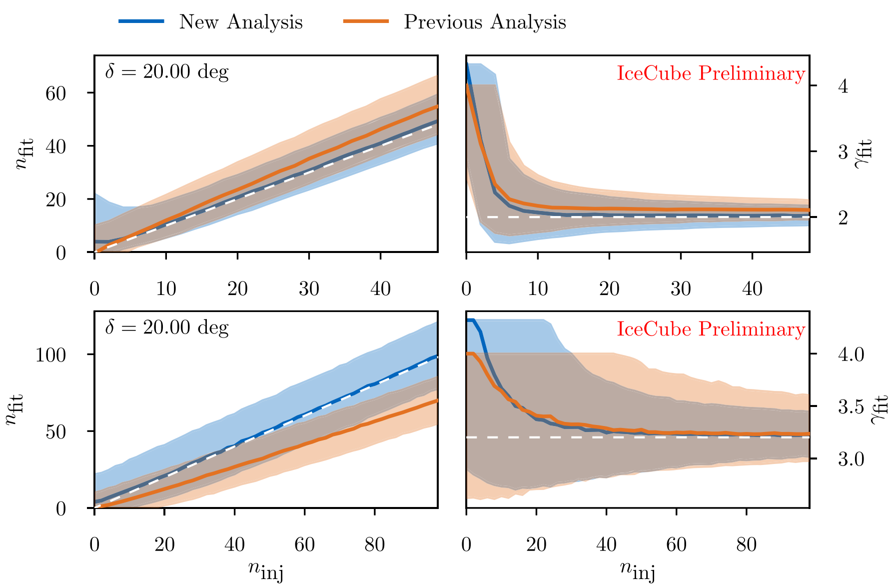

Figure 2. Recovery of source parameters as a function of the signal strength at a declination of $\delta = 20°$ for $\gamma = 2.0$ (top row) and $\gamma = 3.2$ (bottom row). The unbiased expectation is shown as a white dashed line for both the number of signal events (left) and the spectral index (right). Median fitted values for the new (blue) and the previous (orange) analysis [6] are shown as solid lines. Shaded areas show 68% central quantiles.

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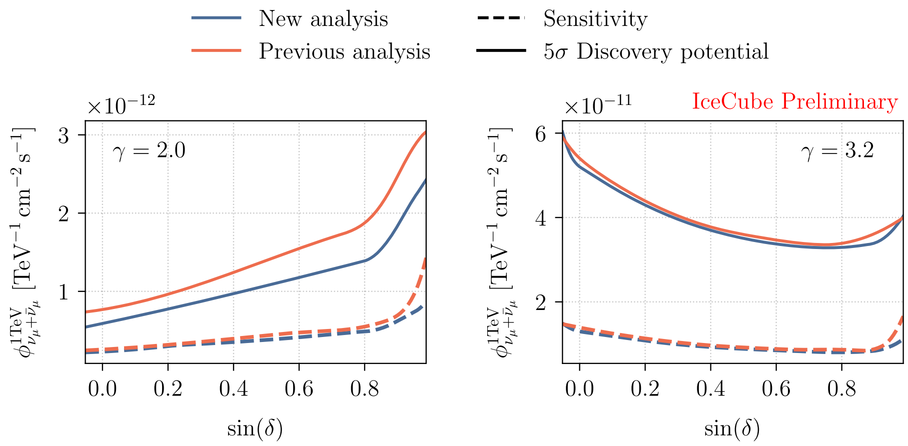

Figure 3. Fluxes for sensitivity and 5σ discovery potential as a function of declination shown as dashed and solid lines, respectively. The fluxes are shown for a harder spectrum $\gamma = 2.0$ (left) and a softer spectrum $\gamma = 3.2$ (right). The blue (orange) lines show the measured fluxes using the new (previous [6]) analysis.

5. Discussion and outlook

We have presented a new, rigorous statistical analysis to search for neutrino point sources in the Northern Sky, together with new machine learning algorithms for the reconstruction of the energy and direction observables. The novel non-parametrical construction of the likelihood using KDEs and the improved reconstruction of the properties of single events — especially in the low energy region (O TeV) — make the new analysis an accurate and robust tool to characterize a potential source. The new methods, together with the more precise calibration of IceCube's data, give the analysis an enhanced discovery potential, by up to 30% ($\gamma = 2.0$). The results of a search for point sources in the Northern Sky using 9 years of reprocessed data, the new likelihood and the improved reconstructions are currently under internal review for publication.

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