PROCEEDINGS OF SCIENCE

Investigating high-energy neutrinos from blazars with a maximum-likelihood analysis of the IceCube Observatory data

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In the past decade, the IceCube observatory has established the presence of a diffuse flux of high-energy neutrinos (≥ 100 TeV to 10 PeV) that is consistent with an astrophysical origin [1], [2]. The population of sources responsible for this flux remains largely unknown.
Among the candidate sources of neutrinos, blazars have recently been suggested as promising emitters of the high-energy events detected by IceCube [3]. Our recent studies have provided evidence of a statistically significant spatial correlation between blazars from the 5th Roma-BZCat catalog (5BZCat) [7] and the IceCube southern [4], [5] and northern [6] celestial hemisphere data.
In this contribution, we present a Python-based tool, that performs an extended unbinned likelihood maximization on the recently released public IceCube's 10-year neutrino point source event sample [8]. Upon its development and testing phase, the software will be released publicly as an open-source and user-friendly code.

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1. Introduction

The recent discovery of a diffuse high-energy astrophysical neutrino flux by the IceCube collaboration [1], opens a new research field in astrophysics and astroparticle physics. Identifying the astrophysical origin of this high-energy component, represents one of the most compelling challenges. Among the plausible sources of high-energy neutrinos there are blazars, a class of active galactic nuclei (AGN). AGN are extremely bright objects in the universe and consist of a compact region that contains a supermassive black hole surrounded by an accretion disk and emit a relativistic jet of plasma. AGN, among which blazars, are thought to be good candidates as astrophysical neutrino emitters according to theoretical models (see [10, 11], and references therein). Relativistic jets could be capable to accelerate hadrons (and leptons) at very-high energy. The presence of external radiation fields (e.g. from the broad-line-region), can lead to the production of neutrinos trough photo-hadronic processes. A first potential association of the γ-ray bright blazar TXS 0506+056 with putative neutrino emission (chance probability at the 10^{-4} level [3]) has encouraged the scientific community to investigate in that direction. Other parallel works from our group are further exploring this path [22], [23].

The IceCube Neutrino Observatory, which has been operational for over 10 years, is currently the most sensitive detector for high-energy neutrinos. It is a large-scale experiment that extends nearly 3 kilometers into the Antarctic ice and consisting of 86 strings equipped with optical sensors. Composed of photo-multiplier tubes, these sensors can detect the Ĉerenkov light produced by charged particles resulting from the interaction of neutrinos with the ice nuclei through weak-force interactions. However, the number of astrophysical neutrinos tracked by the detector is only a small fraction, approximately 0.1%, of the background noise primarily caused by atmospheric neutrinos and muons. Therefore, it is crucial to develop a robust statistical framework that can pinpoint possible clusters of astrophysical neutrino events in the sky and associate them with their potential sources. The maximization of the extended unbinned likelihood is a widely used statistical method. In the following sections, we present this method used by currently available codes, such as SkyLLH, as well as in a code under development, presented in this proceeding. The code is designed to be an open-source and user-friendly framework specifically tailored for analyzing the publicly available 10-year neutrino point source event sample [8] released by the IceCube collaboration in 2021.

2. Maximization of the extended unbinned likelihood

The likelihood quantity $\mathcal{L}$ is build as the joint probability density function (PDF) f of observing N events x_i in the dataset with certain properties defined by the parameters $\vec{\theta}$. The closer the parameters associated $\vec{\theta}$ are to the real ones $\vec{\theta}^*$, the higher the likelihood value is. In experiments following a Poisson distribution, the extended likelihood formalism is used,

$$\mathcal{L}\left(\vec{\theta}\right) = \exp\left(-\lambda\right) \prod_{\mathrm{i}=1}^{N} \lambda \cdot f\left(x_\mathrm{i}|\vec{\theta}\right) , \tag{1}$$

where λ is the expectation number of detected events.

The IceCube collaboration released the public IceCube's 10-year neutrino point source event sample in 2021 [8], which consists of a subsample of track-like events collected between 2008 and

2018. The background of this analysis is primarily composed of atmospheric neutrinos and muons, with smaller contributions from the actual neutrino signal. It aims testing two hypotheses in each region of interest in the sky; the background hypothesis $\mathcal{H}_0$ and the signal hypothesis $\mathcal{H}_1$. The signal hypothesis assumes the presence of both background events and an astrophysical point source emitting n_s neutrino events, following a power-law spectrum with spectral index γ,

$$\frac{\mathrm{d}\phi}{\mathrm{dE}_\nu} = E^{-\gamma} \, . \tag{2}$$

The PDF $f\left(x_\mathrm{i}|\vec{\theta}\right)$ for each neutrino event x_i is a weighted sum of the signal term $\mathcal{S}_\mathrm{i}$ and the background term $\mathcal{B}_\mathrm{i}$,

$$f\left(x_\mathrm{i}|\vec{\theta}\right) = \frac{n_\mathrm{s}}{N}\mathcal{S}_\mathrm{i} + \frac{N - n_\mathrm{s}}{N}\mathcal{B}_\mathrm{i} \, . \tag{3}$$

Under the signal hypothesis, the extended likelihood function may be written as,

$$\mathcal{L}\left(\vec{\theta}\right) = \exp\left(-N\right) \prod_{\mathrm{i}=1}^{N} \frac{n_\mathrm{s}}{N}\mathcal{S}_\mathrm{i} + \left(1 - \frac{1}{N}\right)\mathcal{B}_\mathrm{i} \, . \tag{4}$$

The signal $\mathcal{S}_\mathrm{i}$ and the background $\mathcal{B}_\mathrm{i}$ PDFs can be factorized in two independent spatial (S_i, B_i) and energy ($\mathcal{E}_{\mathcal{S}\mathrm{i}}$, $\mathcal{E}_{\mathcal{B}\mathrm{i}}$) terms. The spatial term S_i of the signal PDF is, as in [8, 9, 12, 21], modeled as a bivariate Gaussian function. While the spatial term B_i of the background PDF is modeled as the density of neutrino events in stripes equally spaced in $\sin\left(\delta\right)$ in the celestial sky. We have,

$$S_\mathrm{i} = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{|\vec{x}_\mathrm{i} - \vec{x}_\mathrm{s}|^2}{2\sigma_\mathrm{i}^2}\right) , \tag{5}$$

$$B_\mathrm{i} = \frac{N_\nu \in \delta_\mathrm{i} \pm [\delta_\mathrm{min}; \delta_{max}]}{2\pi \cdot (\sin(\delta_\mathrm{max}) - \sin\left(\delta_\mathrm{min}\right)))} , \tag{6}$$

where σ_i is the estimated angular error of the event $\vec{x}_\mathrm{i}$.

The energy PDFs are constructed as bidimensional histograms based on the energy proxy of the muon event in GeV and $\sin\left(\delta\right)$ [18]. The background energy term $\mathcal{E}_{\mathcal{B}\mathrm{i}}$ is obtained from the real data, while the signal energy term $\mathcal{E}_{\mathcal{S}\mathrm{i}}$ can be obtained trough *Monte Carlo* simulations. The likelihood function for the signal hypothesis includes two free parameters, the spectral index γ and the emitted signal neutrinos n_s, while the background hypothesis assumes $n_\mathrm{s} = 0$,

$$\mathcal{L}\left(\vec{x}_\mathrm{i}, E_\mathrm{i}|n_\mathrm{s}, \gamma\right) = \exp\left(-N\right) \prod_{i=1}^{N} \left(\frac{n_\mathrm{s}}{N}\mathcal{S}_\mathrm{i}\left(|\vec{x}_\mathrm{i} - \vec{x}_\mathrm{s}|, \mathrm{i}; \gamma\right) + \left(1 - \frac{n_\mathrm{s}}{N}\right)\mathcal{B}_\mathrm{i}\left(\sin\delta_\mathrm{i}, E_\mathrm{i}\right)\right) , \tag{7}$$

$$\mathcal{L}\left(\vec{x}_\mathrm{i}, E_\mathrm{i}|n_\mathrm{s} = 0\right) = \exp\left(-N\right) \prod_{\mathrm{i}=1}^{N} \mathcal{B}_\mathrm{i}\left(\sin\delta_\mathrm{i}, E_\mathrm{i}\right) \, . \tag{8}$$

The test statistic ($\mathcal{TS}$) is calculated to assess the validity of the model, for best parameters $\hat{n}_\mathrm{s}$ and $\hat{\gamma}$. The Wilk's theorem [14] provides a suitable $\mathcal{TS}$,

$$\begin{aligned}\mathcal{TS} &= -2\log\left(\frac{\mathcal{L}(n_\mathrm{s}=0)}{\mathcal{L}\left(\hat{n}_\mathrm{s},\hat{\gamma}\right)}\right)\,,\\ &= 2\sum_{i=1}^{N}\log\left(1+\frac{\hat{n}_\mathrm{s}}{N}\left(\frac{S_\mathrm{i}\left(|\vec{x}_\mathrm{i}-\vec{x}_\mathrm{s}|\right)}{B_\mathrm{i}\left(\sin\delta_\mathrm{i}\right)}\times\frac{\mathcal{E}_{\mathcal{S}\mathrm{i}}\left(\sin\delta_\mathrm{i},E_\mathrm{i};\hat{\gamma}\right)}{\mathcal{E}_{\mathcal{B}\mathrm{i}}\left(\sin\delta_\mathrm{i},E_\mathrm{i}\right)}-1\right)\right)\,.\end{aligned} \tag{9}$$

The $\mathcal{TS}$ value can be converted to p-value, which represents the probability of observing a discrepancy from the background,

$$p\text{−value} = \int_{\mathcal{TS}_\mathrm{obs}}^{\infty} \mathrm{g}\left(\mathcal{TS}|\mathcal{H}_0\right)\,, \tag{10}$$

where g is the normalized distribution of test statistic founded under the assumption $\mathcal{H}_0$.

The framework under development is based on this formalism and is written in Python and optimized to produce full sky map or maps around regions of interest. As part of the development process of such framework, the open-source Python3-based tool SkyLLH, was used for cross-checking purposes.

3. SkyLLh

SkyLLH [15] is a Python-based tool for log-likelihood analyses. It is available as an open-source project on the IceCube collaboration's GitHub repository [16]. The tool provides a modular framework for implementing the likelihood functions and performing statistical tests based on the Wilks' theorem. SkyLLH provides a tutorial that shows how to handle the public 10-year IceCube point-source event sample. At the time of the writing, the tutorial includes an example applied to the position of TXS 0506+056. In our analysis, we used SkyLLH to perform a point-source likelihood analysis in a 20 × 20 matrix (covering 0.2 squared degrees) at the position of the latter blazar. We saved the results for each tested position, including the best-fit parameters, $\hat{n}_s$ and $\hat{\gamma}$, as well as the resulting test statistic value $\mathcal{TS}$.

The Fig. 1 shows the analysis performed with SkyLLH at the position of TXS 0506+056, marked by a red cross. The map displays $\mathcal{TS}$ values. The green dot represents the $\mathcal{TS}$ best-fit position and the area around the $\mathcal{TS}$ best-fit is highlighted by 68%, 90% and 95% containment levels. The angular distance between the position of TXS 0506+056 and the best-fit $\mathcal{TS}$ value is of 0.21°, compatible within the error of the map resolution and with the median source offset of the best-fit position provided for the blazar (0.21°) [19]. We are developing an open-source and user-friendly framework, with the aim of allowing full reproducibility of the results. An initial example will be presented in the next section, with comparison with SkyLLH to cross-check our preliminary results.

4. The framework

The framework presented here is a Python-based, object-oriented code that aims to implement the maximization of the extended unbinned likelihood detailed in the previous sections. It is designed to analyze the publicly available IceCube's 10-year neutrino point source data. The

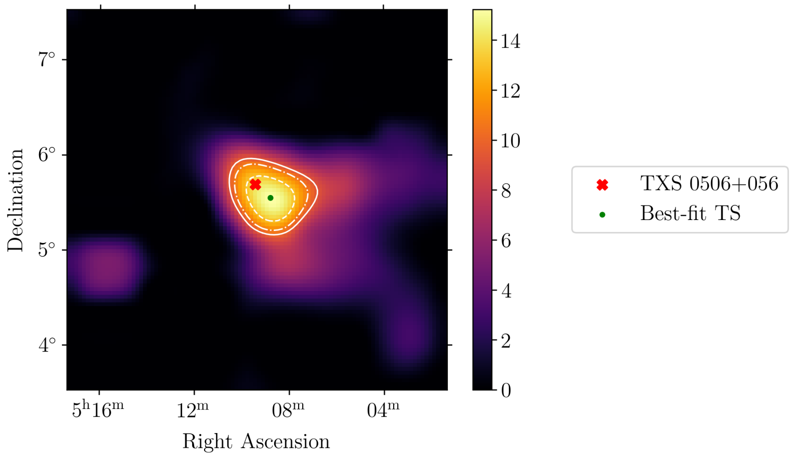


Figure 1: $\mathcal{TS}$ map around the position of TXS 0506+056 realized with SkyLLH. The red cross represents the position of the blazar, the green dot represents the position of best-fit for the $\mathcal{TS}$. The contour lines are shown respectively by a white dashed line for 68%, a dashed-dot line for 90% and by a continuous line for the 95% of containment levels.

framework allows for the maximization of the likelihood using either spatial term alone or combined spatial and energy term. To date, the framework provides test statistic maps, as future development we plan to include the possibility to also generate p-value maps. We simulated the emission of neutrino events [20] from point-like sources incorporating the Poisson distribution to emulate the IceCube detector response. The instrument response function (IRFs) of the instrument, provided by the IceCube collaboration along with the 10-year neutrino point source dataset, is also taken into account.

5. Results

In this section, we will present the first preliminary results of our framework, along with a comparison with SkyLLH.

Fig. 2 illustrates a background test statistic sky map created using our framework. The code utilizes the Python library Healpy to generate and visualize the celestial coordinates of the analysis. In this case, the sky map has a resolution of NSIDE = 256, resulting in a pixel coverage of approximately 0.05 square degrees. The data used to generate this map are from periods between 2011 and 2018, representing events detected in the final configuration of the IceCube experiment with all its 86 strings deployed. To construct the background maps, the data were randomized in right ascension while preserving the distinctive distribution in declination. This randomization effectively disrupts the presence of any astrophysical signals while retaining the inherent structure of the dataset. At the current stage of development, it takes approximately 4 hours to generate such a map assuming a fixed value of $\gamma = -2.0$.

The code provides the option to apply a close-up view in the test statistic map, allowing for a more detailed analysis on the region of interest.

On Figs. 3a and Fig. 3b, we present the results obtained from an analysis of 400 pixels, each covering an area of 0.2 square degrees, at the position of TXS 0506+056, respectively with the

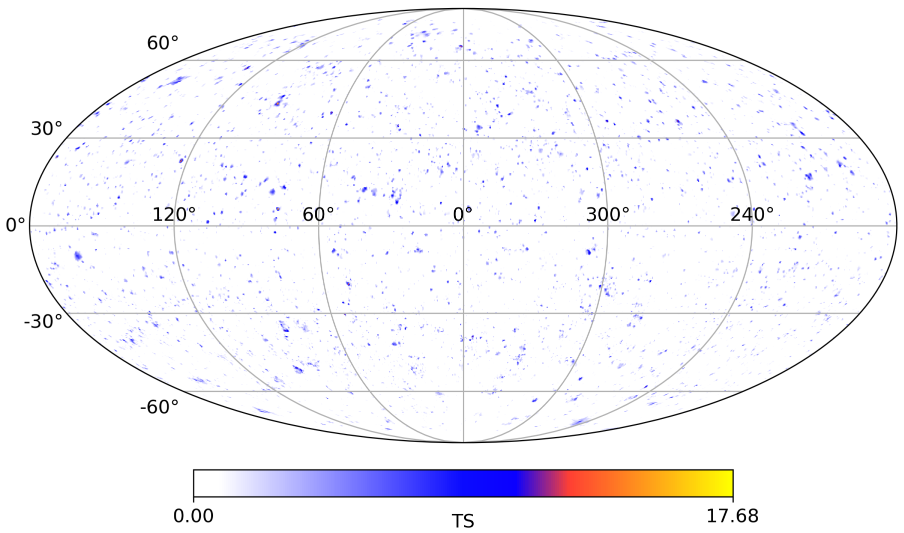
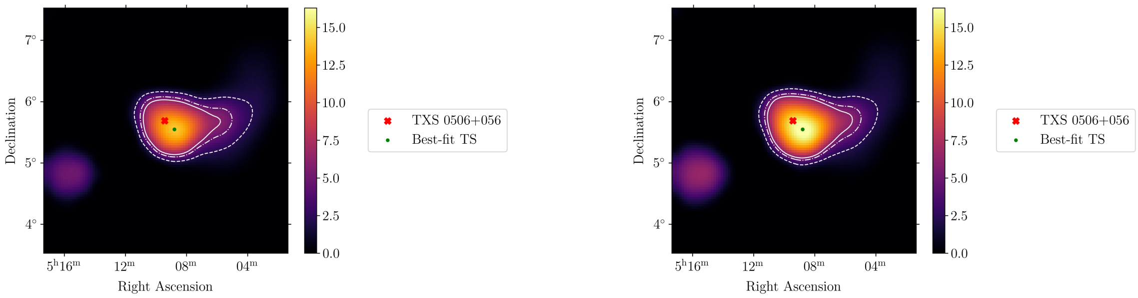


Figure 2: Background sky map realized with our framework, selecting the events collected between 2011 and 2018 from the IceCube 10-year dataset. The $\mathcal{TS}$ map is done with the Healpy library, choosing a NSIDE resolution of 256 and fixing spectral index to $\gamma = -2.0$.



(a) Same as Fig. 1, with the SkyLLH code.

(b) Same as Fig. 1, with our current framework.

Figure 3: $\mathcal{TS}$ map around the position of TXS 0506+056, assuming $\gamma = -2.0$.

SkyLLH code and with the code presented here, fixing the spectrum index to −2.0 in both cases. The livetime considered for this analysis is the same as that of the background map. However, unlike the background map, the events used for the likelihood analysis in those cases were not randomized in right ascension. Here, we are able to reproduce the same $\mathcal{TS}$ map with compatible values. The angular separation between the best-fit $\mathcal{TS}$ position and the blazar is, for both the codes, of 0.21°, compatible again within the median source offset. In addition, SkyLLH estimates at the best-fit position a number of expected neutrino events $n_s = 11$, while our code finds a compatible result of $n_s = 12$ events.

In Fig. 4, we show a comparison between the two codes applied around the same region of TXS 0506+056. It shows some differences of $\mathcal{TS}$ obtained through the two codes. We can see a recurrent excess, indicating that our framework seems to systematically slightly over-estimated the $\mathcal{TS}$.

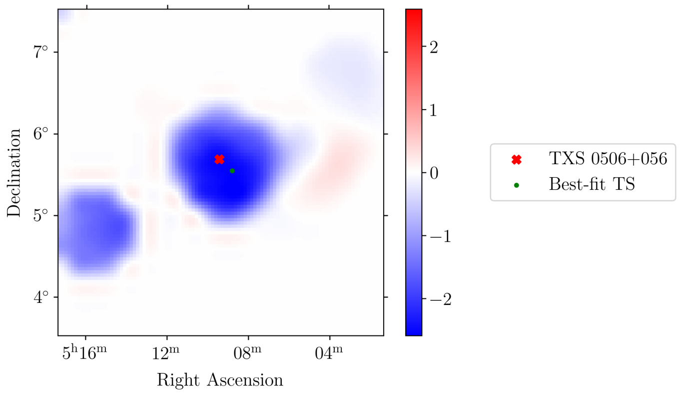


Figure 4: $\Delta\mathcal{TS}$ map, showing the pixel per pixel difference between the $\mathcal{TS}$ maps showed in Fig. 3a and in Fig. 3b.

6. Conclusion

In this study, we present a consistent framework applied to the IceCube's 10-year dataset. Similarly to other frameworks developed before, we utilize the extended unbinned likelihood analysis, which is a robust statistical framework to identify possible clusters of astrophysical neutrino events in the sky and associate them with their potential sources. The code under development is optimized to allow extensive $\mathcal{TS}$ sky map computation, in full or zoom mode. In order to cross-check this code, we use the publicly available SkyLLH code.

In this contribution, we present the initial stage in a sequence of cross-validation procedures for the framework currently being developed. Concerning our preliminary comparison, we were able to reproduce the $\mathcal{TS}$ map around the blazar TXS 0506+056, that is a candidate blazar-neutrinos association. We also obtained a number of expected neutrino events compatible with the SkyLLH tool. We reconstructed with both codes the actual position of the blazar within the 95% containment region. Although, discrepancies are seen between the two codes in the $\mathcal{TS}$ values obtained. Those differences are currently studied, and forthcoming analysis will be done to characterize the differences, and the background signal.

Acknowledgments

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