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Methods for a time-dependent neutrino flare search with the KM3NeT/ARCA telescope

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Abstract. Neutrino astronomy has made significant progress over the last decade, with the discovery of the first cosmic neutrino sources, though unambigous identification remains challenging. This contribution provides an overview of the statistical methods under development by the KM3NeT Collaboration for time-dependent searches for neutrino flares. Two approaches are discussed: a triggered search for sources correlated with other messengers and an untriggered, all-sky scan for astrophysical neutrino flares, assuming Gaussian or box-shaped temporal profiles. The analysis emcompasses instrument response functions expressed as Probability Density Functions (PDFs).

1 KM3NeT/ARCA telescope and dataset

KM3NeT/ARCA [1], located 100 km offshore Portopalo di Capo Passero in Sicily at a depth of 3.5 km, is an undersea neutrino telescope dedicated to high-energy neutrino studies (up to multi-PeV). Upon completion, it will comprise 230 Detection Units (DUs), each carrying 18 multi-PMT optical modules [2] to detect Cherenkov light induced by relativistic charged particles, produced by the interaction of neutrinos in the seawater. Muons produced in charged current interactions traverse the detector's volume, leaving a distinct track-like signature. Using information from the PMTs, KM3NeT's reconstruction algorithms can determine the energy and direction of the incoming neutrinos. Currently, 33 DUs (ARCA33) are operational. The dataset we will be using in future analyses comprises the data taking period of ARCA in a 21-strings configuration.

2 Methodology

Unbinned likelihood methods model data as a two-component mixture of signal and background, fitting the data to determine the relative contribution of each component. Both the triggered and untriggered searches presented here are based on this method. The likelihood method considers the variables of interest in the analysis and evaluates the probability of an event being either signal or background. Let N represent the total number of events in the sample, and n_s denote the fitted signal. The likelihood function is defined as:

$$L(n_s) = \prod_{i=1}^{N} \left[\left(\frac{n_s}{N} \right) \cdot P_{sg}(\alpha|E) P_{sg}(E) P_{sg}(t) + \left(1 - \frac{n_s}{N} \right) \cdot P_{bkg}(\delta) P_{bkg}(E) P_{bkg}(t) \right] \quad (1)$$

The variables involved are: the distance of the event to the hypothesis source (α), its energy (E), its time (t) and the declination under study δ. Probability density functions (PDFs) of these variables, denoted as P, are used for both the signal (sg) and background (bkg) components. To better understand what these PDFs are and how they are generated, one can refer to [3], where similar instrument functions are used. In the analysis, an E^{-2} spectrum is assumed, where the assumed normalization flux corresponds to the diffuse cosmic neutrino flux fitted from IceCube data in [4]: $E_\nu^2 \phi_0 = 2 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$.

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2.1 Triggered time-dependent approach

The triggered approach involves implementing the unbinned maximum likelihood method using temporal PDFs derived from the periods of interest provided by external observatories detecting various cosmic messengers. A gamma-ray follow up is performed searching for flares in the candidate source light curves [5], and using these to construct the temporal signal PDF in the search for possible correlated neutrino emission. To analyze multiple sources a physical selection criterion is defined, based on the visibility of the KM3NeT telescope, the amount of flux coming from the source, its significance and its variability, to identify the most promising candidates.

2.2 Untriggered time-dependent approach

Neutrino flares, such as the one observed from the direction of TXS 0506+056 [6], can be detected without the need for an electromagnetic counterpart. Untriggered searches investigate temporal clustering of events deviating from background expectations through an all-time all-sky scan using only neutrino data. The signal is modeled using temporal PDFs, either Gaussian or rectangular, evaluated at the extracted event times. Background PDFs are data-driven and constructed from the Modified Julian Dates (MJD) distributions of events recorded during the ARCA21 observation period. The likelihood framework includes three free parameters: the signal normalization (n_s), the central emission time of the flare (T_0), and the flare duration (σ_t). This methodology enables a search for time-dependent sources based solely on neutrino observations.

3 Conclusion and Outlook

Unbinned likelihood methods are currently being developed to search for neutrino flares in KM3NeT/ARCA data. As more data are being collected, this search will be expanded to include the additional available livetime. Additionally, combined analyses with the ANTARES telescope, which has collected over 15 years of data, are foreseen to further enhance its scientific output.

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