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A joint search for neutrino point-like sources and diffuse flux using KM3NeT/ARCA and ANTARES data

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Neutrino telescopes play a fundamental role in highlighting the hadronic component of cosmic ray accelerators in the Universe. The ANTARES underwater neutrino telescope was operated for more than 15 years in the Mediterranean Sea off shore the coast of Toulon, France. The KM3NeT/ARCA detector, designed for the observation of high energy cosmic neutrinos, is under construction at the KM3NeT site off shore Portapalo di Capo Passero, Sicily, Italy.

In this contribution, the first combined analysis of the full ANTARES dataset and the datasets from the partially completed KM3NeT/ARCA neutrino detector is presented. Point-like and extended sources are tested for neutrino emission. The list of sources includes bright γ-ray emitters, galactic γ-ray sources with hints of hadronic components, extragalactic AGN with high flux observed in radio bands. The diffuse flux search with both detectors is also presented, enhanced by an excellent Galactic centre visibility.

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1. Introduction

Situated in the Mediterranean Sea off the coast of Sicily at a depth of 3500 meters, the KM3NeT/ARCA detector will consist of two building blocks [1]. Each block will feature 115 strings, with each string containing 18 digital optical modules [2]. Each module houses 31 three-inch photomultiplier tubes (PMTs). This setup is primarily designed for neutrino astrophysics, offering exceptional sub-degree pointing accuracy for muon neutrinos with energies above 10 TeV. The KM3NeT/ARCA detector sensitivity extends across a broad energy range, from hundreds of GeV to PeV with its excellent view of the galactic center. The KM3NeT/ARCA detector is currently under construction and the data collection is already underway.

ANTARES [3], the predecessor of KM3NeT, operated from May 2008 until February 2022 in the Mediterranean Sea near Toulon, France. It consisted of 12 detection strings, each with 25 floors, and each floor housed three 10-inch photomultiplier tubes enclosed in pressure-resistant glass spheres.

The detection mechanism for neutrinos in these observatories is the same. Neutrinos interacting within or near the detectors produce charged particles. These particles travel faster than light in the water, inducing the emission of Cherenkov radiation. The PMTs detect this radiation, allowing for the reconstruction of the particle direction and energy based on the timing and spatial information of the detected signals. This enables the determination of the sky region where the neutrino originated. To identify cosmic neutrino signals amidst the background noise of atmospheric muons and neutrinos, statistical methods using Monte Carlo simulations are required. The analysis framework is based on a binned likelihood approach.

2. Point-like and extended source analysis

In this joint analysis, each data set refers to a distinct detector period and dedicated event selection, ensuring no event overlaps. The datasets used in this analysis include:

- ANTARES tracks: track-like events selection from ANTARES point source analysis [4];
- ANTARES showers: shower-like events selection from ANTARES point source analysis [4];
- ARCA6 tracks: KM3NeT/ARCA period with 6 working lines (92 days) [5];
- ARCA8 tracks: KM3NeT/ARCA period with 8 working lines (210 days) [5];
- ARCA19 tracks: KM3NeT/ARCA period with 19 working lines (53 days) [6];
- ARCA21 tracks: KM3NeT/ARCA period with 21 working lines (70 days) [6].

The compatibility of the data with a point-like or extended source hypothesis is quantified by comparing histograms of events in α (angular distance of the reconstructed event from the source center) and $\log_{10}(E_{\mathrm{rec}})$ (event energy estimation). In this framework each data set has its own range and number of bins in α and $\log_{10}(E_{\mathrm{rec}})$.

Scanning through all the bins of each data set histogram is equivalent to scanning over generic bin number i for a joint data set. The histogram of the observed events, N, is compared bin by bin versus a scalable estimate of the number of signal events, S, expected for a reference flux, Φ_{ref}, and the number of background events, B, as follows:

$$\log L = \sum_{\text{bins}} N_i \log(B_i + \mu S_i) - (B_i + \mu S_i), \tag{1}$$

where μ is the signal scale. The logarithm of the likelihood ratio is used as a test-statistic to quantify the compatibility of the data with the signal/background hypotheses and it is described as follows:

$$\lambda = \log L(\mu = \hat{\mu}) - \log L(\mu = 0). \tag{2}$$

The λ distributions are built for each signal scaling μ and they are used to extract limits with the Neyman approach. The sensitivity is defined as the median upper limit on μ for 90% C.L. that can be converted to the flux as $\Phi_{90} = \mu_{90}\Phi_{\text{ref}}$.

Signal estimation, S_i, is computed as a function of the angular distance α and the logarithm of the reconstructed energy E_{rec} for each source declination. In particular, at a given declination:

$$S_i = \sum_E R(\delta, E) \cdot f_\alpha(E, \alpha) \cdot f_E(\delta, E, E_{\text{rec}}), \tag{3}$$

where R is the rate of the events in the true energy bin, E, derived from the effective area of the detector; f_α is a fraction of the events in the reconstructed angle bin, α, computed from the detector point spread function; f_E is the fraction of the events within the bin of E_{rec}. The rate of events and the energy fraction are evaluated for each source declination, δ.

For the estimation of the background B_i two different approaches have been implemented. In case of low statistics samples, the 2D histogram is computed as a function of the angular distance α and the logarithm of the reconstructed energy E_{rec}, as follows:

$$B_i = n \cdot f(\delta) \cdot f(E_{\text{rec}}) \cdot \Delta\alpha, \tag{4}$$

where $f(\delta)$ and $f(E_{\text{rec}})$ are two independent 1D parametrisations of energy and declination distributions of data events: $f(E_{\text{rec}})$ is the energy fraction in bin E_{rec}, while $f(\delta)$ is the cubic spline of the event declination distribution. The normalisation n is chosen such that the integral of $n \cdot f(\delta) \cdot f(E_{\text{rec}})$ over the sphere (δ, ϕ) and over E_{rec} gives exactly the total number of events in the data. The bin size is $\Delta\alpha = 2\pi * (\cos\alpha_{\text{min}} - \cos\alpha_{\text{max}})$.

For larger statistics samples the Kernel Density Estimation (KDE) approach [7, 8] is used as follows:

$$B_i = n \cdot \text{KDE}(\delta, E_{\text{rec}}) \cdot \Delta\alpha, \tag{5}$$

where KDE gives independent declination parametrisations for several energy bins. Depending on the statistics, the KDE functions may be derived from data or Monte Carlo simulation. The KDE function derived for several data sets are provided in Fig. 1.

The S and B histograms computed for KM3NeT/ARCA21 are shown in Fig. 2. For a true value of the signal strength μ_{true}, pseudo-experiments can be generated by randomly drawing each N_i from a Poisson distribution with mean $B_i + \mu_{\text{true}} S_i$.

Point source search sensitivity flux as a function of declination is shown in Fig. 3 for KM3NeT/ARCA, ANTARES and joint analyses. In the currrent work, ANTARES contributes

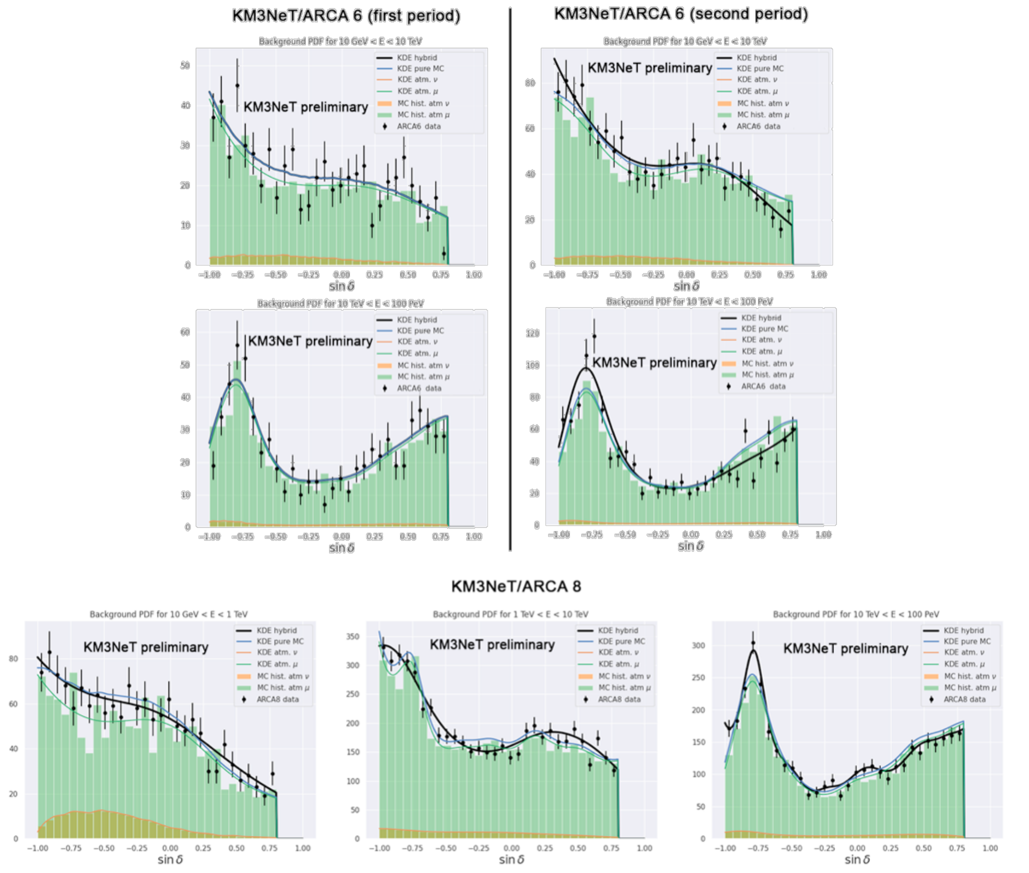

Figure 1: KDE functions for various data sets and energy ranges. Top left: KM3NeT/ARCA6 (first period); top right: KM3NeT/ARCA6 (second period); bottom: KM3NeT/ARCA8.

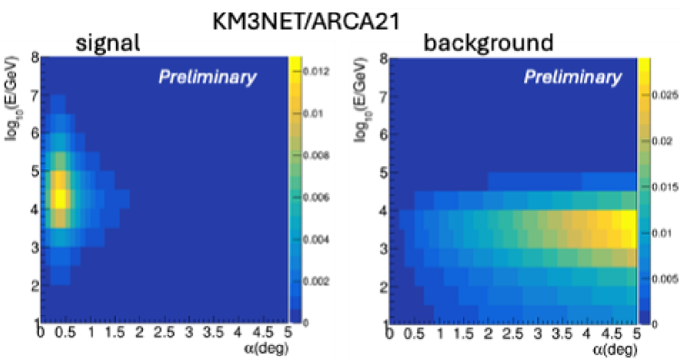

Figure 2: Signal and background 2D histograms for KM3NeT/ARCA21 data set at 0° declination.

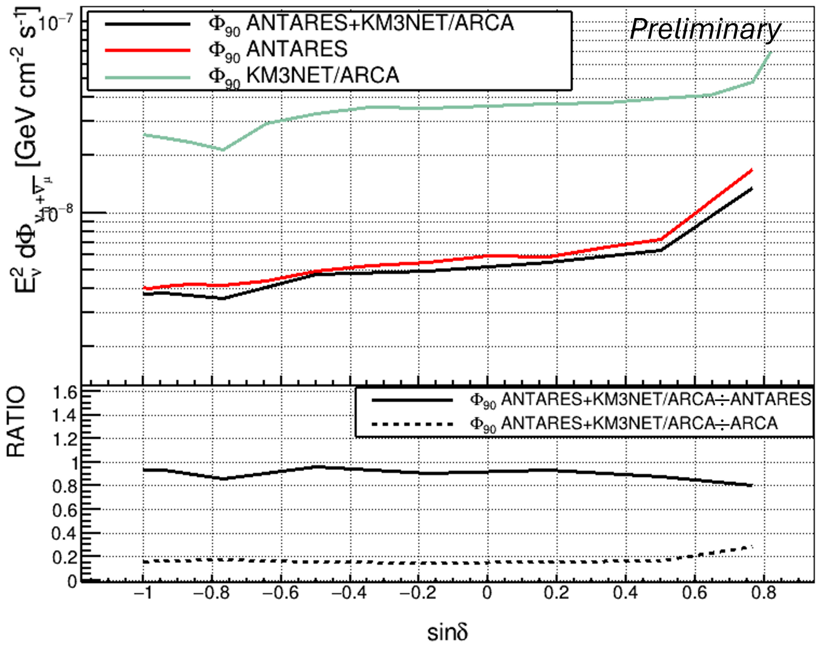

Figure 3: Sensitivity fluxes of ANTARES, KM3NeT/ARCA and of the combination of the two neutrino telescopes (top). Ratio of combined sensitivity over ANTARES and over KM3NeT/ARCA (bottom).

most significantly to the joint analysis, combining with KM3NeT/ARCA the performance enhances by 10%. Both collaborations are in process of the current analysis unblinding. The first KM3NeT/ARCA building block is expected to be completed in few years, indicating rapid growth for KM3NeT in the near future. As the KM3NeT/ARCA detector configuration expands and more data are collected, the contributions will be more balanced and the joint analysis will exploit the best from the both detectors.

3. Diffuse flux analysis

Similarly to the point-like and extended source analysis, a joint analysis has been developed for a diffuse flux search. In this analysis an excess of the high energy cosmic neutrino events with respect to the secondary atmospheric muons and neutrinos is searched over the whole sky. Binned framework with 1D histograms of E_{rec} is applied to the following four datasets: ANTARES tracks, showers, and low-energy showers [9], KM3NeT/ARCA full period with 21 working lines (287 days). The sensitivity comparison is shown in Fig. 4 and the analysis is in the process of unblinding.

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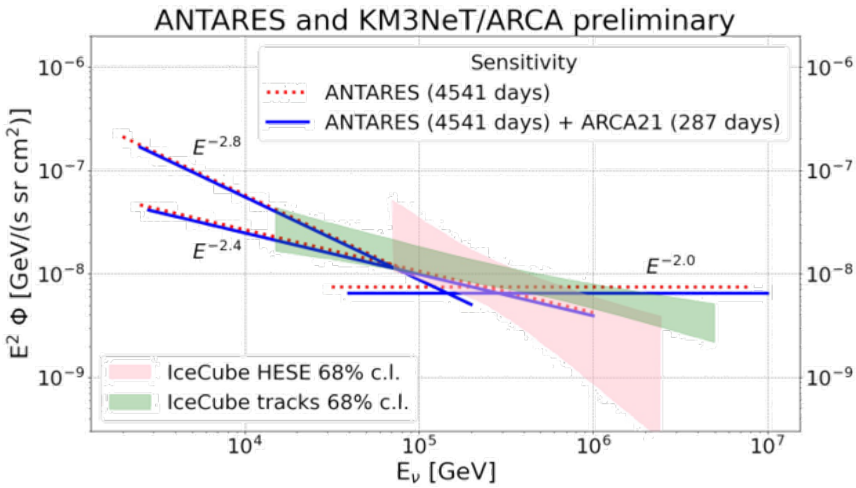

Figure 4: Sensitivity fluxes of ANTARES, and of the combination of the ANTARES and KM3NeT/ARCA21 datasets in comparison with the IceCube diffuse flux measuremens by IceCube [10, 11].

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