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The search for point-like neutrino sources with ANTARES and KM3NeT-ARCA telescopes

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Abstract. The multi-messenger approach has recently paved the way for possible breakthroughs in our comprehension of high energy particle emission in the Universe. Neutrino telescopes are essential for highlighting the hadronic component of these phenomena, in addition to testing possible correlation with known sources of gamma rays. Joint analyses of data from complementary facilities may provide enhanced sensitivity. This contribution explores the sensitivity as a function of the source declination for a combined analysis of data collected by two neutrino telescopes located in the depths of the Mediterranean Sea, ANTARES and KM3NeT/ARCA. A catalogue of approximately one hundred point-like and extended sources is presently investigated for neutrino emissions: the list encompasses bright γ-ray emitters, galactic γ-ray sources, extragalactic sources as radio-loud AGNs and the most significant candidate sources studied by IceCube.

1 Introduction

KM3NeT is a research infrastructure that hosts two deep seawater neutrino telescopes: ARCA (Astroparticle Research with Cosmics in the Abyss) and ORCA (Oscillation Research with Cosmics in the Abyss)[1]. Both detectors are made of a three-dimensional grid of optical modules that detect Cherenkov radiation induced in the sea water by charged secondary particles created by neutrino interactions. These particles travel faster than light in the water, inducing the emission of Cherenkov radiation. The photomultiplier tubes (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.

The ARCA detector is under construction at a depth of 3500 m on the seabed of the Mediterranean Sea, offshore Capo Passero, Sicily, Italy: the complete detector will consist

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of two building blocks [1]. Each block will feature 115 strings, with each string containing 18 digital optical modules housing 31 three-inch PMTs. ARCA is optimized for astrophysical neutrinos, offering exceptional sub-degree pointing accuracy for muon neutrinos with energies above 10 TeV. The ARCA field of view for upgoing neutrinos covers mainly the Southern sky, enabling the study of potential Galactic sources. The detector is currently composed of 33 lines out of the 115 of the first complete building block and the data collection is already underway.
ANTARES [2], was in operation in the Mediterranean Sea near Toulon, France, from May 2008 until February 2022: it consisted of 12 detection strings, each with 25 floors, and each floor housed three 10-inch PMTs enclosed in pressure-resistant glass spheres.
To identify a cosmic neutrino signal outside of the large background due to atmospheric muons and neutrinos, statistical methods have been developed based on Monte Carlo pseudo experiments: the expected sensitivity of KM3NeT/ARCA to neutrino point-like and extended sources is calculated in a binned likelihood framework. The main steps of the analysis framework are briefly outlined below.

2 Data samples

Data selections cuts are established to improve the signal-to-background ratio, and the detectors' response functions derived accordingly [3-6]. The present analysis includes all ANTARES dataset and KM3NeT/ARCA data taken, respectively, with 6, 8, 19, and 21 detection units. In detail:

- ANTARES tracks: track-like events from ANTARES point source analysis[4];
- ANTARES showers: shower-like events 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].

Each data set refers to a distinct detector period and dedicated event selection (tracks or showers), and it is paired with the instrument response functions necessary for signal simulation and background modelling.

3 Point-like source sensitivity

The compatibility of the data with a point-like hypothesis is quantified by comparing 2D histograms of events in α (angular distance of the reconstructed event from the source center) in the range [0 - 5] degrees versus $\log_{10}(E_{rec})$ (event energy estimation) in the range [1 - 8] in $\log_{10}$(GeV). In this framework each data set has its own range and number of bins in α and $\log_{10}(E_{rec})$: scanning through all the bins of each data set histogram is equivalent to scanning over generic bin number i for a joint data set.

For each energy bin i, the histogram of the observed events, N_i, has to be compared with the estimate of the number of signal events, S_i, expected for a reference flux Φ_{ref} and the number of background events, B_i.

The signal expectation, S_i, is computed from simulations, for each source declination δ, as the product of three terms: the rate R of the events in the true energy bin, E_{true}, derived from the effective area of the detector, the fraction f_a of the events in the reconstructed angle bin, α, computed from the detector point spread function and the fraction f_{Etrue} of the events reconstructed within the bin of E_{rec} [5].

The background rate, B_i, as a function of E_{rec} and δ, is obtained by following two different data-driven approaches.

In case of small statistics samples, the 2D histogram as a function of the angular distance α and the logarithm of the reconstructed energy E_{rec} is filled according to:

$$B_i = n \cdot f(\delta) \cdot f(E_{rec}) \tag{1}$$

where $f(\delta)$ and $f(E_{rec})$ are two independent 1D parametrisations of energy and declination distributions of data events, randomized in right ascension: for the declination a cubic spline $f(\delta)$ is fitted, while the energy dependence $f(E_{rec})$ is parameterised by a fit with two or three Gaussians. The normalisation n is chosen such that the integral of $n \cdot f(\delta) \cdot f(E_{rec})$ over the sphere $(\delta, R.A.)$ and over E_{rec}, gives exactly the total number of events in the data.

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

$$B_i = n \cdot KDE(\delta, E_{rec}) \tag{2}$$

where KDE provides independent declination parametrisations for several energy bins and therefore a more accurate description of the background. Depending on the statistics, the KDE functions may be derived from data or Monte Carlo simulation. The signal and background histograms computed for KM3NeT/ARCA21 are shown in Fig. 1.

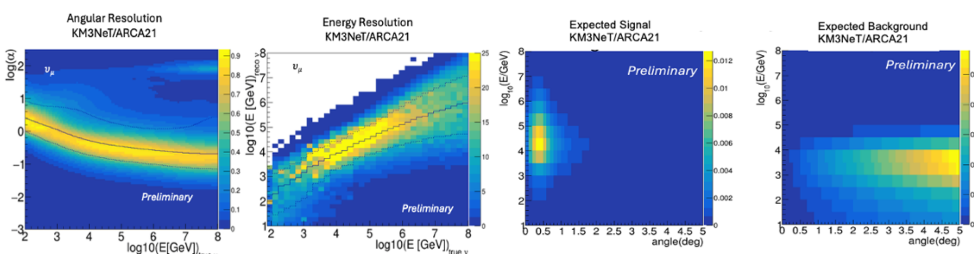

Fig. 1. Angular and energy resolution of the KM3NeT/ARCA21 detector and the expected signal and background 2D histograms for the ARCA21 data sample at 0° declination.

The compatibility of the observed data with a point-source hypothesis is then evaluated in a binned likelihood formalism, by comparing bin by bin the histogram of the observed events, N_i, with the expectation from background B_i and a scalable amount of signal S_i (Fig. 1 left panels)

$$\log(L) = \sum_{bins} N_i \; log(B_i + \mu S_i) - (B_i + \mu S_i) \tag{3}$$

where μ is the signal scaling factor. The logarithm of the likelihood ratio λ is the used as a test-statistic to quantify the compatibility of the data with the signal/background hypothesis:

$$\lambda = \log(L(\mu = \hat{\mu})) - \log(L(\mu = 0)) \tag{4}$$

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 $\Phi_{90} = \mu_{90} \, \Phi_{ref}$.

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 $B_i + \mu_{true} S_i$.

The point source search sensitivity flux as a function of declination is shown in Fig. 2 for the ANTARES+KM3NeT/ARCA6-8-19-21 joint analysis. Presently ANTARES is contributing most significantly to the joint analysis, but the inclusion of KM3NeT/ARCA data yields an improvement of 10%. The combined analysis will become more and more effective as soon as the KM3NeT/ARCA detector configuration expands and more data are collected, so that it will exploit the best from both the detectors. The first KM3NeT/ARCA building block (consisting of 115 lines) is expected to be completed by the end of 2026. By leveraging both the track and shower observation channels, the full KM3NeT/ARCA detector (2 blocks) should achieve in 10 years a sensitivity below $2{\cdot}10^{-10}$ GeVcm^{-2} s^{-1} for -1 < $sin(\delta)$ < 0.7 [3,6], improving by an order of magnitude the IceCube (10 y) one for $sin(\delta)$ < - 0.4 .

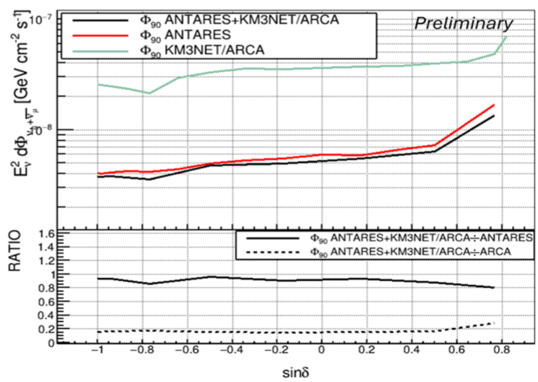

Fig. 2. Sensitivity fluxes of ANTARES, KM3NeT/ARCA and of the combination of the two neutrino telescopes (top). Ratio of combined sensitivity over ANTARES and over KM3NeT/ARCA (bottom).

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