PROCEEDINGS OF SCIENCE

Combined KM3NeT-ARCA and ANTARES searches for point-like neutrino emission

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Neutrino telescopes are the leading-edge instrument for the detection of high energy cosmic neutrinos. The ANTARES detector operated offshore Toulon (France) for 16 years until 2022, while KM3NeT-ARCA is in construction in Southern Italy. The ANTARES telescope was composed of 12 strings of optical modules. Each optical module contained one 10” photomultiplier tube to detect the faint light produced by neutrinos interacting in the surrounding water. Similarly, the KM3NeT-ARCA detector will count 230 strings of 18 optical modules containing 31 3” photomultipliers. In recent years, there has been a growing interest in studying potential sources of neutrinos, as these sources can provide valuable information about the most extreme phenomena in the Universe. This contribution will showcase the analyses of the combined data sample of ANTARES and the first two years of KM3NeT-ARCA to detect high energy cosmic neutrinos from point-like sources.

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1. Introduction

In the year 2013, a groundbreaking discovery was made by the IceCube Neutrino Observatory, discovering the presence of a flux of astrophysical neutrinos at exceptionally high energy levels [1], followed by the measurement of cosmic neutrino from blazar TXS 0506 +056 in 2018 [2] and from Messier 77 in 2022 [3]. Despite these achievements, the origins of the majority of these neutrinos remain unknown. In the following years a significant contribution in the investigation of these sources will be played by the KM3NeT/ARCA detector [4], which is currently under construction and the data taking is already in progress.

The detector is located in the Mediterranean Sea offshore Sicily at a depth of 3500 m. It will comprise two building blocks, each one equipped with an array of 115 strings and housing 18 digital optical modules per string with 31 3-inch photomultiplier tubes per module. This apparatus is mainly devoted to neutrino astrophysics thanks to its excellent sub-0.2° pointing resolution for muon neutrinos with energies above 10 TeV. The KM3NeT/ARCA detector has remarkable sensitivity across a vast energy spectrum, spanning from hundreds of GeV to PeV, and possesses a unique vantage point that complements the coverage of the IceCube detector, including a very good visibility of the galactic center.

The ANTARES detector [5], the predecessor of KM3NeT, operated from May 2008 until February 2022 in the depths of the Mediterranean Sea offshore Toulon (France). The telescope consisted of 12 detection strings, each one with 25 storeys. Every storey counted a triad of 10-inch photomultiplier tubes housed within pressure-resistant glass spheres.

The neutrino detection mechanism of the above mentioned detectors is identical. The neutrino, interacting inside or in the surroundings of the detectors, produce charged particles. These particles, travelling at velocities surpassing that of light in the sea-water or ice medium, induce the emission of Cherenkov light. The detection of this radiation by the PMTs allows the reconstruction of the particle direction and energy using the temporal information and the spatial coordinates of these signals. In this way, this comprehensive reconstruction enables the determination of the region of the sky from where the neutrino has been produced.

In the pursuit of identifying cosmic neutrino signals among the background of atmospheric muons and neutrinos, efforts are being applied to develop statistical methodologies using Monte Carlo pseudo experiment approach. It is important to note that the methods presented in this contribution have been developed in the software framework of the KM3NeT collaboration that has been already presented in [6]. The main steps of the analysis frameworks are briefly summarized here below.

Once suitable criteria are established to enhance the signal-to-background ratio, the response functions of the detectors are derived. These distributions, including effective area, energy resolution, and angular resolution, are then transformed into probability density functions, serving as fundamental inputs for the binned likelihood analysis. Through this analytical approach, the sensitivity of the detectors to different predefined source locations can be evaluated. By checking the data with a background model one can estimate the significance of the observation and the upper flux limits in case significance is low. This is done for a set of locations in a source catalog comprising known gamma-ray and other multi-messenger emitters.

This contribution describes the effort to develop the analysis framework to combine the KM3NeT and ANTARES data sample.

2. Data sample

In order to harmoniously merge the diverse detector data in an already developed anlaysis framework the *data set* is introduced in a slightly different way. In particular, we consider that the data set refers to a particular detector period and a dedicated event selection. No overlaps between events are allowed.

The different data sets used in this analysis are

1. ANTARES tracks: This data set pertains to the ANTARES point source analysis, track events selection, incorporating data from the period spanning 2007 to 2020 [7];
2. ARCA6 tracks: KM3NeT/ARCA period with 6 working lines (around 100 days) [6];
3. ARCA8 tracks: KM3NeT/ARCA period with 8 working lines (around 200 days) [6].

Each data set is accompanied with its instrument response functions (IRF) needed for the signal simulation and the backgrounds simulated from the data itself as it will be described in the following.

Both ANTARES and KM3NeT/ARCA detectors provides also selection of the events reconstructed as cascades. The developed update for the KM3NeT framework can deal with these non-overlapping additional data sets, however, in this contribution we will not show the results on this yet.

3. Background and signal model

In this analysis the determination of the background rate, as a function of the reconstructed energy and declination, has been estimated with a data-driven approach; we hence do not rely on atmospheric neutrinos and muon simulations for this. In view of the limited statistical data available, the employed model applies a factorization technique to account for the dependence on both declination and energy. This factorization is expressed as follows:

$$N_{bg} = n \cdot F(\delta) \cdot F(E)\,\mathrm{sr}^{-1}, \tag{1}$$

Here, the normalization factor n is chosen to ensure that the integration over the celestial sphere and energy range precisely yields the total number of events recorded in the data, for each respective data set. To justify the sampling of the background from the aforementioned function, previous ANTARES and ARCA6+8 analyses have confirmed the flatness of the data sets with respect to right ascension.

It is important to note that when constructing background histograms for parameters such as the distance from the source center and energy, solely the declination of the source center is considered. Although this approximation may introduce some degradation for bins situated farther away from the source center, it remains a practical approach for the purposes of analysis.

The model employed to represent the detector response for the signal includes several key components:

1. the effective area, dependent on true neutrino energy and zenith/declination. It serves as a measure of the detectors sensitivity to neutrinos at different energies and incoming angles;
2. the neutrino energy resolution estimated as the fraction of the events with a given reconstructed neutrino energy for a given bin of true neutrino energy and zenith/declination;
3. the point spread function estimated as the fraction of the events with a reconstructed angular distance from the true source center for a given bin of true neutrino energy.

The point spread function was summed over zenith angles in simulation in order to increase the statistics. The point spread function can be further convoluted with the source extension if it is provided in the source catalogue.

4. Likelihood formalism

The compatibility of the data with a background or signal hypothesis is quantified by filling the histograms of α (angular distance of the reconstructed event from the source center) and $\log_{10}(E_{\rm rec})$ (event energy estimation) with the events. In this framework each data set has its own range and number of bins. For the ANTARES track events 20 bins for α in the range $[0, 10]$ and 12 bins in $\log E[\mathrm{GeV}] \in [0, 12]$ are used, while for both ARCA data sets there are 50 bins in $\alpha \in [0, 5]$ and 14 bins for $\log E[\mathrm{GeV}] \in [0, 8]$.

For each data set the following histograms are created: the one with a number of observed/simulated events N, the one with an estimate of the number of signal events, S, expected for a reference flux Φ_0 and the one with a number of background events, B. The log-likelihood is the Poisson probability of the bin-contents:

$$\log L = \sum_{\rm bins} \log\left[\exp(-B_i - \mu S_i)(B_i + \mu S_i)^{N_i}/N_i!\right], \tag{2}$$

where μ is the "signal strength", which is the scaling factor of the provided reference flux Φ_0. Summing over bins of each data set and then summing $\log L$ is equivalent to summing over generic bin number i through each data set histogram bins. Omitting all terms that do not depend on μ:

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

Note, that for empty expectation, i.e. $B_i + \mu S_i = 0$, $B_i + \mu S_i = 1e - 8$ is explicitly assumed. For a given data in N the best signal strength,$\hat{\mu}$, is determined by maximizing $\log L$.

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:

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

For a true value of the signal strength $\mu_{\rm true}$, pseudo-experiments (PE) can be generated by randomly drawing each N_i from a Poisson distribution with mean $B_i + \mu_{\rm true} S_i$. Each PE then undergoes the treatment described above (a maximum likelihood fit yielding $\hat{\mu}$ which is then used to compute the test statistic λ for that PE. In this way, distributions of $\lambda(\mu_{\text{true}})$ are obtained. In the current update of the KM3NeT framework the λ distributions for pseudo-experiments are stored as vectors of λ values instead of histograms which improves precision on the median values calculation.

The $\lambda(\mu_{\text{true}})$ distributions are used to extract Neyman upper limits. For a given data, N, one has λ_{obs} that is applied as threshold to calculate the confidence level, which is a fraction of pseudo-experiments with a given μ_{true} and $\lambda(\mu_{\text{true}}) > \lambda_{\text{obs}}$. The maximum value of μ_{true} reaching requested confidence level is the upper limit on μ. The sensitivity is defined as the upper limit on μ at 90% confidence level, μ_{90}, for the median of the pure background pseudo-experiments, $\lambda_{\text{obs}} = \tilde{\lambda}(\mu_{\text{true}} = 0)$, i.e. median upper limit. This limit is converted to the flux as follows:

$$\Phi_{90} = \mu_{90}\Phi_0. \tag{5}$$

Of course, one can use real data to build the histograms of N_i and use them to fit μ (μ_{obs}). The value of $\lambda(\mu_{\text{obs}})$ can be used to calculate the observed upper limit at 90% confidence level. Additionally, p-value can be calculated as $P(\lambda \geq \lambda(\mu_{\text{obs}}))$ for distribution of pure background pseudo-experiments. The p-value further can be converted to significance in number of σ following 1-sided convention.

5. Results

The sensitivities for ARCA6 and ARCA8 track data set, the ANTARES 2007–2020 track data set and for their joint analysis are estimated within this framework. The results for the sensitivity on a grid of declinations is reported in Table 1 and plotted in Figure 1.

From the number of signal and background events of both detectors that are also shown in Figure 2 one can see that despite different detector geometry, KM3NeT/ARCA is already running in a similar signal to noise ratio to the ANTARES detector. The event reconstruction quality is expected to improve with bigger detector configuration and with higher statistics more stringent event selection can be applied. This will further improve signal to noise ratio for the KM3NeT/ARCA detector.

As one can see the sensitivity of the joint data analysis is dominated by the ANTARES 2007-2020 data set. The ARCA6 and ARCA8 contribution improves the sensitivity by 0–10%; the fluctuations are mostly dominated by the statistical fluctuations and limited number of pseudo-experiments. With the rapidly growing ARCA detector configurations and more statistics, the joint analysis will exploit data from ARCA and ANTARES detectors at the best during the upcoming years. The KM3NeT collaboration runs ARCA with 19–21 strings since summer 2022. For this contribution no data was unnecessary spoiled and both collaborations will present the standalone analysis updates [8, 9]. In order to perform the real data analysis this analysis will be completed with the cascade events, the full ANTARES data set (2007–2022) and bigger ARCA data sets in the near future.

Table 1: Summary of the sensitivity studies with ARCA6, ARCA8 and ANTARES 2007–2020 track data sets. The total number of signal events for the reference one flavour flux $d\Phi_{\nu+\bar{\nu}}/dE = 10^{-4}\,(E[\mathrm{GeV}])^{-2}$ $\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}$ in the 10° search cone, the number of background events in the search cone and the median signal strength of the reference flux, $\tilde{\mu}_{90}$.

decl.[deg]	signal ARCA	signal ANTARES	background ARCA	background ANTARES	sensitivity ARCA	sensitivity ANTARES	sensitivity joint
-90	0.54	4.14	45.95	165.79	7.87	0.53	0.54
-80	0.54	4.14	45.96	165.73	7.96	0.56	0.54
-70	0.56	4.06	46.03	165.30	7.26	0.56	0.53
-60	0.58	4.02	46.32	163.48	7.06	0.55	0.53
-50	0.61	4.01	46.67	158.41	6.18	0.55	0.50
-40	0.43	3.56	39.88	141.31	9.32	0.57	0.55
-30	0.37	2.95	25.91	113.25	9.63	0.69	0.66
-20	0.35	2.70	22.98	100.44	9.91	0.71	0.67
-10	0.33	2.56	21.58	89.57	9.86	0.72	0.66
0	0.32	2.33	23.48	76.51	9.89	0.75	0.73
10	0.31	2.16	25.35	62.59	10.55	0.78	0.77
20	0.30	1.97	24.39	50.63	10.65	0.89	0.81
30	0.29	1.64	26.36	41.71	10.39	1.02	0.97
40	0.27	1.42	28.75	28.63	11.30	1.12	1.05

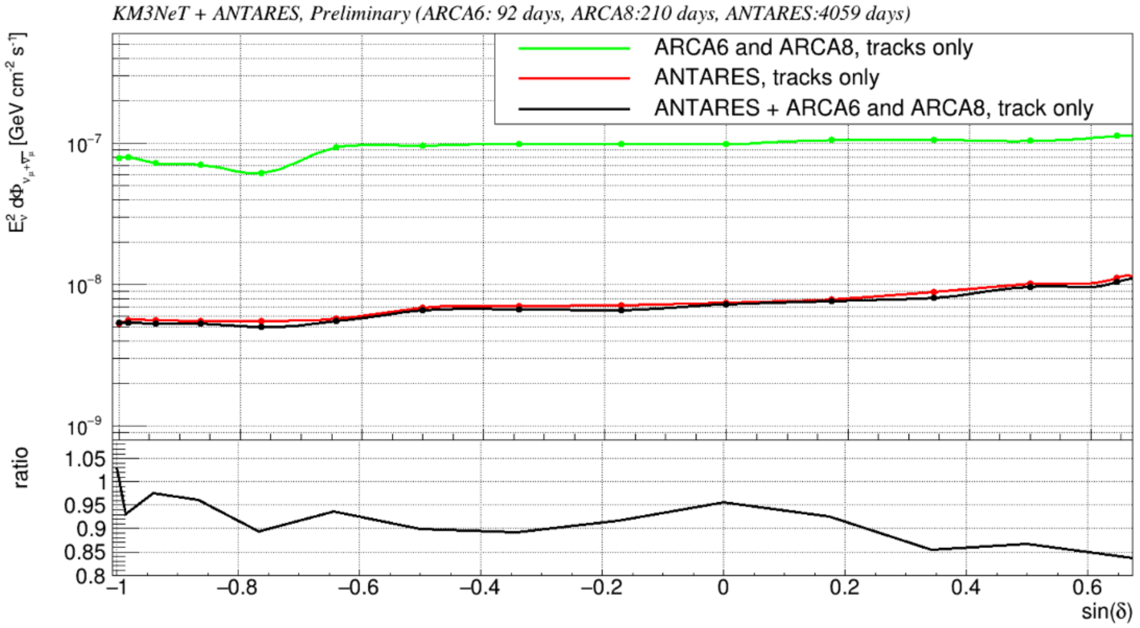

Figure 1: Sensitivity as a function of source declination for ARCA6 and ARCA8 track data sets with about 300 days (green), ANTARES track data set for 2007–2022 period (blue) and ARCA6/ARCA8/ANTARES combined analysis (red). The ratio of the latter two sensitivities is shown in the bottom plot.

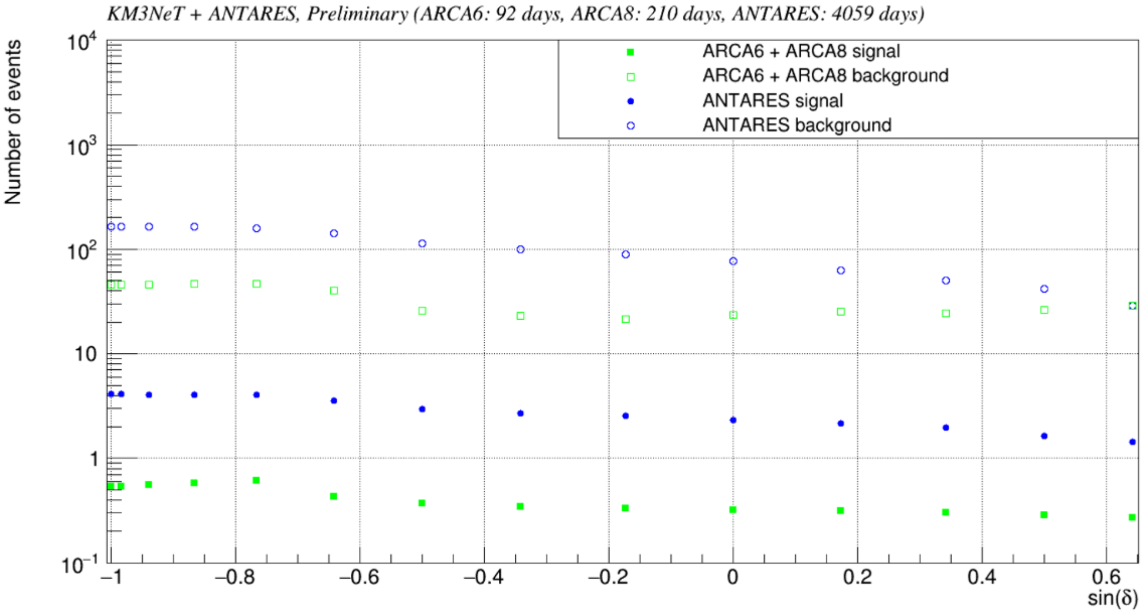

Figure 2: Mean number of signal and background events for ARCA6/ARCA8 and ANTARES track data sets.

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