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The KM3NeT underwater neutrino telescope: status and future perspective

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The KM3NeT collaboration started to build a multi-km^3 neutrino telescope in the Mediterranean Sea. The telescope is composed of the ARCA detector, optimised for searches for high-energy neutrino sources in the Universe under construction at the Capo Passero site, Italy, 80 km offshore at a depth of 3500 m; and the ORCA detector, near Toulon, France, 40 km offshore at a depth of 2500 m, aimed at the determination of the mass hierarchy of neutrinos. In this contribution, an overview of the latest results and the future perspectives for the KM3NeT telescopes to detect the high energy neutrino sources in the Universe with the ARCA telescope and to determine the properties of the elusive neutrino particles with ORCA detector are presented.

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1. The Neutrino astronomy and the KM3NeT telescope

The observation of high-energy neutrinos of astrophysical origin [1, 2] has opened a new window for the study of our Universe. Although detecting very high-energy neutrinos of cosmic origin represents a breakthrough in Neutrino Astronomy and Multi Messenger Astronomy, the sources these neutrinos originate from remain unknown. The identification of cosmic objects emitting high energy neutrinos will provide a new insight of our Universe, leading to a deeper understanding of cosmic sources.

The KM3NeT Collaboration is currently building two underwater neutrino detectors in the Mediterranean Sea: the ARCA (Astroparticle Research with Cosmics in the Abyss) telescope, under construction at the Capo Passero site, Italy, 80 km offshore at a depth of 3500 m, optimised for the searches of high-energy neutrino sources in the Universe, and the ORCA (Oscillation Research with Cosmics in the Abyss) detector under construction near Toulon, France, 40 km offshore at a depth of 2500 m, aimed at investigating the Neutrino Mass Ordering (NMO) by detecting the neutrino flux generated in the Earth's atmosphere. The ARCA and ORCA detectors are optimized to be sensitive to neutrinos in complementary energy ranges, extending the exploration of neutrino astronomy from GeV to tens of PeV.

The basic detection element of the KM3NeT detector is the Digital Optical Module (DOM). The module is a pressure resistant glass sphere, containing 31 photo-multipliers tubes (PMTs). Eighteen modules are arranged in Detection Unit (DU), a vertical string anchored on the sea floor. The DUs are deployed on the seabed to form a three-dimensional array of optical modules to detect Cherenkov light produced by neutrino-induced particles. The detection of the time, position and amplitude of PMTs pulses (the so called *hits*) allow both direction and energy reconstructions of neutrino events. A seafloor network, composed of electro-optical cables and Junction Boxes (JBs) for DU power and optical connections, allows to communicate with the telescope and collect data from offshore to onshore. At the end of the construction phase, ARCA will consist of 2 Building Blocks (BB), each one consisting of 115 DUs, with a instrumented volume of about one cubic kilometer of seawater and a mass of one gigaton, while ORCA will cover approximately 7 megatons with 1 BB. Since the KM3NeT detector is under construction, ARCA and ORCA are taking data with evolving detector geometries. At the present moment, 28 DUs have been already deployed for ARCA and 19 for ORCA.

2. ARCA sensitivity studies

Sensitivities to point-like and extended neutrino sources The results of point source and extended source searches with ARCA data collected from May 2021 to December 2022 [3], taken with an evolving detector geometry, are here presented. A list of 101 astrophysical objects has been tested verifying whether the selected sources are high energy neutrino emitters. In order to reduce the atmospheric muon contamination and remove badly reconstructed events, event selection criteria have been used, based on the likelihood of the reconstruction, on the number of hits used in the reconstruction and on the reconstructed direction. To identify a cosmic neutrino signal, the selected events have been analysed through statistical methods based on Monte Carlo pseudo experiments and the expected sensitivity of ARCA6 (6 DU configuration) has been calculated in a binned likelihood analyses. For every (pseudo) dataset the compatibility of the dataset with the expected signal + background model, and with the background-only model has been determined. All candidate sources are consistent with a background-only hypothesis. A list of the most signal-like sources is reported in [3]. Since no significant detection was made, upper limits have been set on the flux.

Sensitivity to diffuse astrophysical neutrino fluxes In order to investigate the sensitivity of ARCA to detect a diffuse flux of astrophysical neutrinos at the early stages of the detector construction, the analysis of the data taken during 2021-2022 has been performed [8]. In the present contribution the results of the analysis of the full data sample of the ARCA6 and ARCA8 running periods and for recent detector configurations, ARCA19 and ARCA21, are presented. The event selection for those two periods is described in [8]. Data samples consist of signal events, reconstructed as track coming from neutrinos and anti-neutrinos of astrophysical origin of all 3 flavours and both interaction channels (CC and NC), and of background events due to atmospheric (anti)neutrinos and atmospheric muons. The rejection of the atmospheric muon background is done through a Boosted Decision Tree (BDT) classifier, based on a ROOT MVA (Multi-Variate-Analysis) [9], and selecting only upgoing events. Selected data samples are then analyzed according to the binned-likelihood method described in [10]. The energy distributions of the events surviving the final selection for ARCA8 event sample are shown on the left panel of Fig.1. On the right panel the convolution of sensitivities and U.L.s in terms of energy-flux, for selected spectral indices in the range [2.1,2.5], versus the (anti)neutrino energy, calculated for the central 90% energy range of the signal events, is presented. For comparison the IceCube's and ANTARES' 1-flavour best fit flux is also shown.

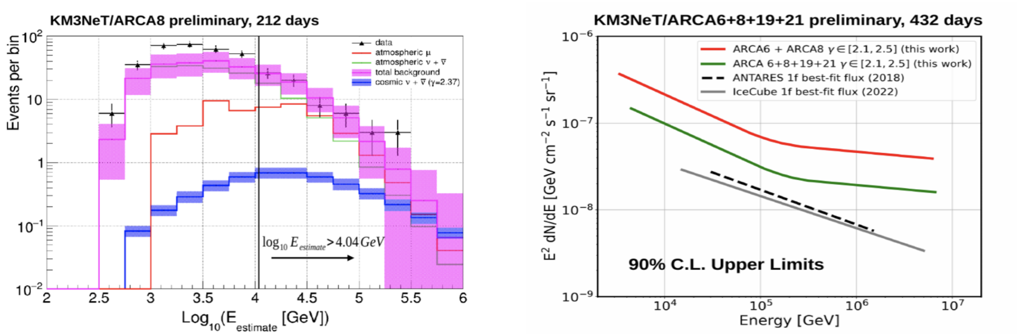

Figure 1: On the left the distributions of the energy estimate for ARCA8 after applying the BDT score cut is shown [8]. The total background of atmospheric neutrinos and muons (purple) and signal (blue) are shown with uncertainties. The vertical line provides the optimal threshold of the energy estimate. On the right, the convolution of U.L.s at 90% C.L. for the selected spectral indicies and energy ranges are presented [8].

Astronomy potential for the full ARCA detector The sensitivity estimates and the astronomy potential of the full ARCA detector for diffuse, point-like and extended neutrino sources have been also estimated [11]. After applying the quality cuts to increase the signal to background ratio, the detector response functions, like the so called *effective area*, the *energy resolution* and *angular resolution* are converted to probability density functions and are used as an input for the unbinned likelihood analysis to calculate the expected sensitivity of ARCA to diffuse, point source and extended sources in our Universe. The sensitivities of ARCA to point sources with an E^{-2} energy spectrum have been estimated as a function of the sources declination for 3 and 7 years of data taking. These results are shown in Fig. 2 (left) in comparison to similar studies for 13

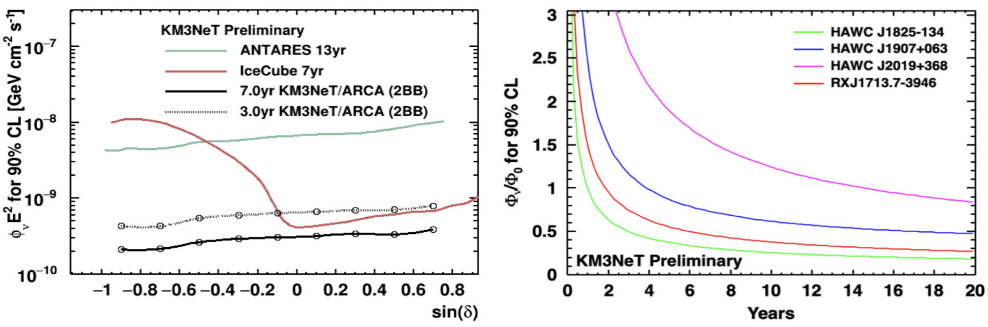

Figure 2: On the left the flux normalisation for 90% CL limits to detect a E^{-2} point source with ARCA in comparison with ANTARES 13 years and and IceCube 7 years [5]. On the right the expected sensitivity at 90% CL for the E^{-2} energy spectrum for promising extended sources.

years of data taking with ANTARES and 7 years for IceCube [5]. For the extended source analysis the results are summarised in Fig. 2 (right). This study demonstrates the capability of the ARCA detector to achieve a 90% CL sensitivity for 3 of the 4 considered sources in less than 4 years, while for the most promising source (HAWC J1825-134) the sensitivity is achieved approximately in 1 year.

3. ORCA sensitivity studies

Measuring atmospheric neutrino oscillations with ORCA6 The measurement of the neutrino oscillation parameters, $\sin^2\theta_{23}$ and Δm^2_{31}, as well as the sensitivity to determine the neutrino mass ordering [12] based on data taken during 2020 and 2021, with an early configuration of the ORCA detector with six lines, are presented. A run selection has been applied according to quality criteria resulting in a total of 510 days of data and corresponding to 433 kton-years. To constrain the oscillation parameters a maximum likelihood approach has been used. The analysis is based on the maximisation of a binned likelihood for the 2-dimensional distribution of events in $\log_{10}(E_{\mathrm{reco}}/\mathrm{GeV})$ and $\cos\theta_{\mathrm{reco}}$, comparing the observed data to a model prediction. The sensitivities are computed using the Asimov approach. The 90% CL contour for both parameters constrained simultaneously is shown in the left panel of Fig.3 in comparison to other experiments.

Measurement of the atmospheric muon neutrino flux with ORCA6 The ability of ORCA to provide significant information concerning the atmospheric neutrino flux in the energy range 1-100 GeV is presented [13]. The data used in this analysis have been collected with the early-stage detector configuration with 6 DUs, ORCA6, operating from January-2020 to November-2021 and corresponding to a livetime of 555.7 days. Monte Carlo (MC) simulations of the event sample has been used to estimate the contribution of atmospheric muons and atmospheric neutrinos. To unsure a high-purity atmospheric neutrino sample, an event selection procedure has been performed using a Machine Learning classifier (Boosted Decision Tree). A detailed description of the MC simulations and the event selection criteria used in this analysis is reported in [13]. In order to deconvolute the ν_μ+$\bar{\nu}_\mu$ CC energy spectrum from the measured data energy distribution an unfolding scheme is applied and the *TUnfold* software is used [15]. Finally, the unfolded number of events per energy bin is converted into flux. The atmospheric muon neutrino flux measurement obtained with ORCA6 data is shown in Fig.3. For comparison, the results of other measurements are also reported.

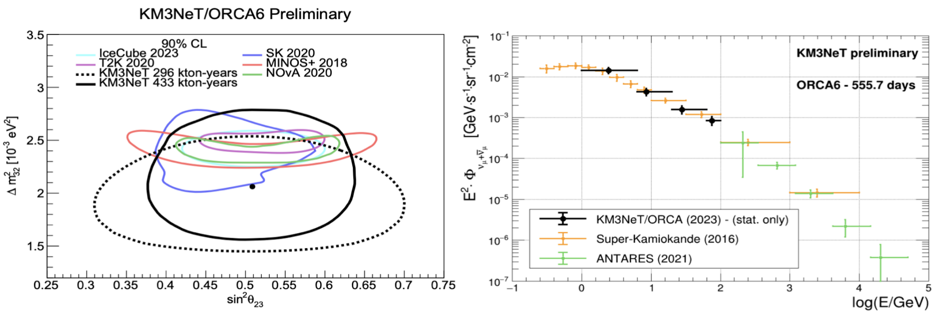

Figure 3: On the left the contour at 90% CL of ORCA6 for the oscillation parameters $\sin^2\theta_{23}$ and Δm^2_{31} compared with other experiments is presented [12].In the right panel the atmospheric muon neutrino flux measurement using ORCA6 data is shown together with the measurements obtained by other measurements [13].

4. Conclusions

In these proceedings, the first results of the analyses of ARCA and ORCA data, taken with the early stages of the detector construction, are presented. Even though these results are not competitive with the results reported by ANTARES and IceCube, these studies have already shown the great potential of the KM3NeT detectors contributing both to neutrino physics and multi messenger astronomy. The detector deployment is progressing continuously. The increase of detector volumes will lead to an improvement of event reconstructions and selection efficiencies enhancing the current results.

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