PROCEEDINGS OF SCIENCE

First neutrino oscillation measurement with KM3NeT/ORCA

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The KM3NeT/ORCA detector is a next-generation neutrino telescope at the bottom of the Mediterranean Sea. Optimized for the detection of atmospheric neutrinos with energies between 1 GeV and 100 GeV, KM3NeT/ORCA will offer competitive sensitivity for measuring the neutrino mass ordering, as well as θ_{23} and Δm^2_{23}.

Currently under construction, 6 of the 115 planed Detection Units are already installed and are steadily taking data since January 2021. This contribution will present the results from the first neutrino oscillation analysis with 1 year of data. These early results already out-perform ANTARES measurements, and approach the sensitivity of current world-leading atmospheric neutrino experiments. The latest estimates of the sensitivity of the complete KM3NeT/ORCA detector are also discussed.

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1. Introduction

The KM3NeT Collaboration is building two next-generation large volume neutrino telescopes in the Mediterranean Sea. Both detectors rely on the same technology to detect the Cerenkov light emitted by secondary particles from the neutrino interaction. Digital Optical Modules (DOMs), each housing 31 PMTs, are combined on a line to form a Detection Unit (DU). The ARCA detector (Astroparticle Research with Cosmics in the Abyss) is located close to Sicily (Italy) at 3450 m depth and optimized for neutrinos of energies above 1 TeV. To reach a km^3 volume, it will consist of two building blocks of 115 sparsely separated DUs. ORCA (Oscillation Research with Cosmics in the Abyss) is the low energy counterpart, situated at 2450 m depth on Toulon's (France) shores. It is optimized for neutrino energies between 1 GeV and 100 GeV, making it especially suited for atmospheric neutrino detection. This is achieved with a vertical spacing between DOMs of about 9 m and an inter-DU distance of 20 m. When completed, the 115 DUs of the ORCA detector will achieve a detection volume of about 7 Mton.

Atmospheric neutrinos are offering a great source to study neutrino oscillations. While covering a large energy range, they also provide a large range of propagation distances, from tens of km to tens of thousands km. Coupled with the large detection volume of a deep-sea Cerenkov telescope, KM3NeT/ORCA aims to probe the atmospheric oscillation parameters Δm^2_{23} and θ_{23} with world leading sensitivity. The long path of neutrinos through the Earth also offers a competitive sensitivity to probe the neutrino mass ordering [1].

Since mid-2019 4 DUs are steadily taking data in the ORCA detector. This initial detector configuration was raised to 6 DUs after a deployment campaign in January 2020. Since December 2021, the detector has been operated with 10 DUs. In this communication, the emphasis will be on the 6 DUs configuration between January 2020 and February 2021.

Neutrino interactions are simulated with gSeaGen [2] and weighted using the HKKM2014 [3] atmospheric flux at Frejus location (France). Oscillations are propagated using NuFit 5.0 [4] best-fit values and Earth PREM model [5]. Atmospheric muon events are generated using the MUPAGE package [6].

2. Data taking and selection criteria

The considered data taking period is 402.1 days with an uptime of $\approx$ 97 %. Removing the calibration periods, as well as some runs for which DAQ issues were encountered, the analysed period is 354.6 days. On average, the detector trigger rate was 8.5 Hz. According to Monte-Carlo simulation, we expect this rate to contain 7.2 Hz of atmospheric muons related events and $\approx$0.2 mHz of neutrino, the remaining contribution being pure noise events.

All the events are reconstructed as track-like events. For a given hypothesis of a $\mu^\pm$ crossing the detector, it is possible to compute the residuals between the measured hit times and the expected ones. This metric is minimized to select the best hypothesis. The reconstruction provides the starting and stopping point of the track, its direction as well as quality metrics and an energy estimator [7].

After applying cuts on the reconstruction quality metric and the number of detected photons, the atmospheric muon contribution dominates, while the pure noise is almost entirely removed

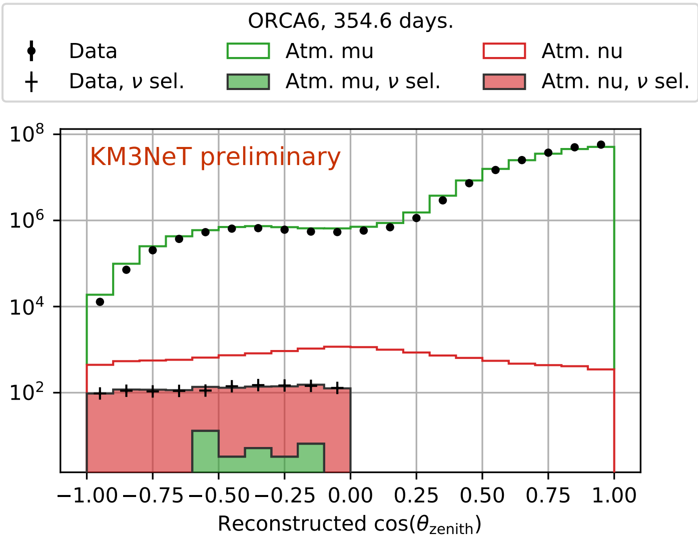

Figure 1: Reconstructed zenith angle $\cos(\theta_{\mathrm{zenith}})$ for data, atmospheric muons Monte-Carlo(MC) and neutrinos MC. The data points are compared with the MC expectations (histograms) after a pre-selection based on minimal cuts on quality and number of hits, and after the neutrino selection (full histograms for MC).

(Fig. 1). The background from atmospheric muons is further reduced by selecting only events reconstructed as up-going ($\cos(\theta_{\mathrm{zenith}}) < 0$). The remaining atmospheric muon contamination corresponds to mis-reconstructed events, typically due to ambiguities induced by events passing close to the detection volume without crossing it.

By applying additional selection criteria on the number of hits, the track quality and the position of the reconstructed vertex, 1247 data events are selected. For the same selection and period, 1239.9 ± 3.9 neutrino events and 31.2 ± 9.9 atmospheric muons are expected. The reconstructed $\cos(\theta_{\mathrm{zenith}})$ and energy of the sample are presented on Fig. 2. Overall, the data and MC show a good agreement, both in rate and shapes. Since all the events are reconstructed as tracks, the reconstruction quality cut tends to be more efficient on track-like events, leading to a track enriched sample. Due to the geometry of a 6 lines detector, most of the track events are not contained and therefore the track length is under-estimated particularly for higher energy tracks with an average measured track length of ≈ 40 m. The effect on the energy distribution is seen in Fig. 2 and will be resolved as the detector grows. This induces a very small leverage from the energy in the oscillation sensitivity.

3. Neutrino oscillations measurement

To determine the oscillation parameters, a negative log-likelihood minimization method is applied to the binned 2D distribution of energy vs $\cos(\theta_{\mathrm{zenith}})$. The model used in the fit is based on the HKKM15 atmospheric flux [3], considering a PMNS matrix parametrization based on NuFit 5.0 [4], except for Δm^2_{31} and θ_{23} which are kept free. The systematic uncertainties considered

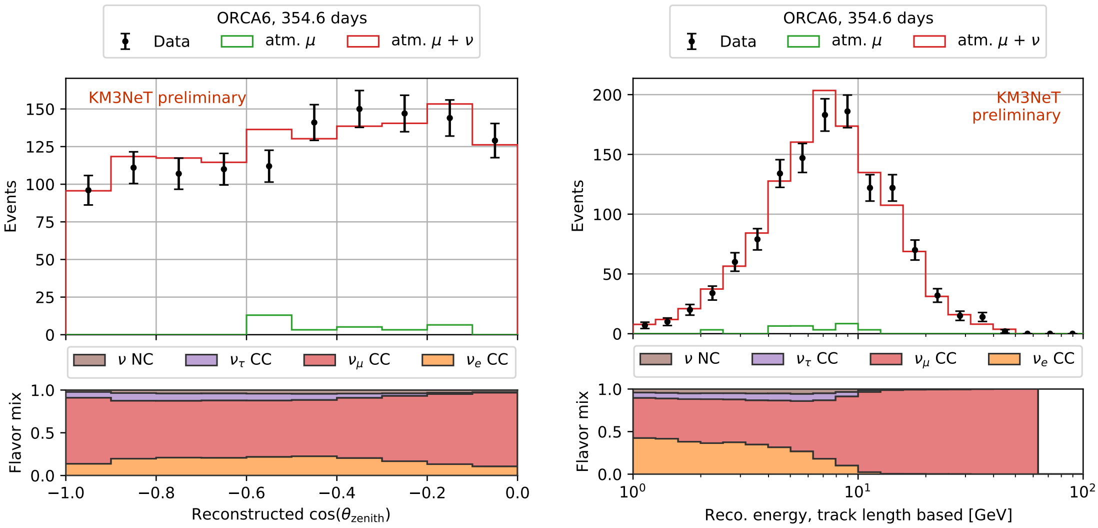

Figure 2: Left: zenith angle $\cos(\theta_{\text{zenith}})$ distribution for selected events. Right: reconstructed energy for selected events, based on the reconstructed track length. Bottom lines indicate the flavour mixing for the selected sample from MC simulation.

Type	Parameter	Treatment
Oscillations	Δm^2_{31} $[10^{-3}\ \text{eV}^2]$	Free
	θ_{23} [deg]	Free
Model	Normalisation	Free
Flux shape	Spectral index	$\mathcal{N}(0, 0.3)$
	$n_{\nu_{\text{up}}}/n_{\nu_{\text{down}}}$	$\mathcal{N}(0, 0.07)$
Flux composition	$n_{\nu_\mu}/n_{\bar{\nu}_\mu}$	$\mathcal{N}(0, 0.1)$
	$n_{\nu_e}/n_{\bar{\nu}_e}$	$\mathcal{N}(0, 0.1)$
	n_{ν_μ}/n_{ν_e}	$\mathcal{N}(0, 0.03)$
Cross section	n^{NC}	$\mathcal{N}(1, 0.1)$
	n_τ^{CC}	$\mathcal{N}(1, 0.2)$
Detector	Energy scale	$\mathcal{N}(0, 0.1)$

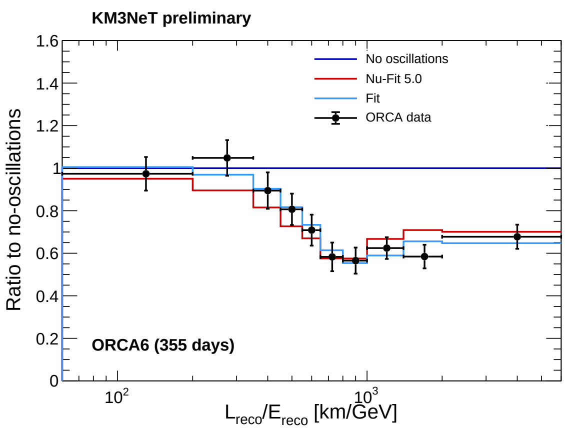

Figure 3: Left: table showing the parameters adjusted in the fit process. Oscillations parameters and model normalisation are totally free, while systematic uncertainties related to flux shape and composition, cross section and detector response are constrained by priors. Right: reconstructed L/E distributions, normalized to the no-oscillation hypothesis. The points are showing the data, while the full lines shows the fitted model (blue) and the NuFit 5.0 scenario (red).

are summarized in the Fig. 3 (left), as well as the Gaussian prior used for the fitting process. More details about the fit process can be found in [8].

The best fit is obtained for $\Delta m^2_{31} = 1.95^{+0.24}_{-0.22}$(stat. + syst.) and $\sin^2\theta_{23} = 0.50^{+0.10}_{-0.10}$(stat. + syst.). This result already out-performs the ANTARES measurement [9], for which the results are based on 10 years of exposure. After obtaining the propagation path of the neutrino L from $\cos(\theta_{\text{zenith}})$, the model is displayed in the L/E plan and normalized to the no-oscillation hypothesis, for illustration, as presented on Fig. 3. A good agreement between NuFit 5.0 and the best fit can be observed.

Fig. 4 shows the sensitivity to Δm^2_{31} and θ_{23} oscillation parameters. For each point, the log-likelihood is minimized with all nuisance parameters. From this likelihood landscape, the 90 % CL contour is drawn. NuFit 5.0 scenario is within the 90 % confidence level in this analysis. The result also shows KMNeT/ORCA's potential, which already starts being competitive to other experiments with only a fraction of the detector deployed and only 1 year of data.

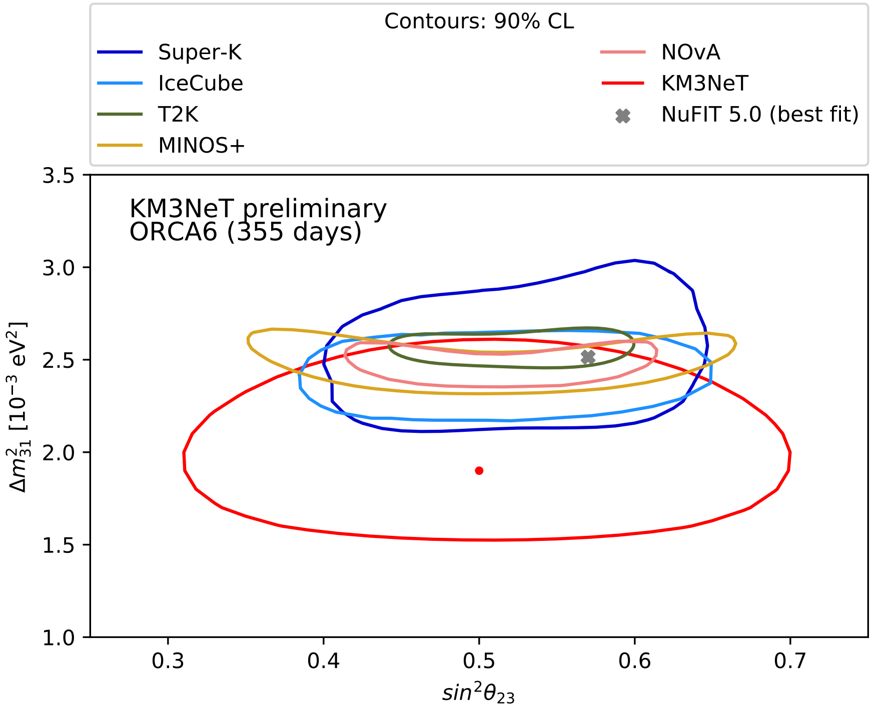

Figure 4: Contour at 90 % CL of ORCA6 towards the oscillation parameters Δm^2_{31} and θ_{23}, with the latter shown in the $\sin^2$ basis. Contours of other experiments have been added for comparison purposes as well as the NuFit 5.0 best fit value.

4. Summary and discussion

In this communication, a first neutrino oscillations measurement is reported on a 1 year data set obtained with the KM3NeT/ORCA detector in a 6 detection lines configuration. While being highly dominated by atmospheric muon background at the reconstruction level, a S/B of about 40 is achieved after applying the event selection.

The oscillation parameters Δm^2_{31} and θ_{23} were then extracted from this sample, including a full treatment of the systematic uncertainties. The KM3NeT/ORCA results already out-perform the ANTARES sensitivity, obtained with 10 years of exposure [9]. The 90 % confidence level contour shows that the experiment is in shape to compete with the most precise measurements to-date.

Due to the small detection volume, a significant fraction of the track's energy is deposited far away from the light sensors, thus limiting the energy resolution. This effect will disappear as the detector grows. This, coupled with a track/shower topology identification, better reconstruction and larger statistics, will provide significant improvement of the neutrino oscillations sensitivity in the coming years.

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