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Oscillation physics with KM3NeT/ORCA

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The KM3NeT/ORCA experiment is a next-generation neutrino telescope, currently under construction in the Mediterranean Sea. The final detector geometry will reach an active volume corresponding to 7 Mtons of seawater, optimized to neutrino oscillation physics in the [1, 100] GeV energy range. In this way, the experiment is expected to reach a maximum sensitivity in the measurement of the neutrino mass ordering (NMO) by studying the oscillations of the atmospheric neutrino flux passing through the Earth. Thanks to the detector's modular structure that allows for collecting data in stable conditions also with a partially instrumented volume, the first neutrino oscillation analysis has been already delivered with only 6 detection units (KM3NeT/ORCA6) and 354.6 days of stable data taking. In this contribution, KM3NeT/ORCA's sensitivity to the GeV neutrino oscillation physics, NMO measurement, and tau appearance will be presented. Furthermore, the first results from the KM3NeT/ORCA6 detector performance and updated measurement of neutrino oscillation parameters, with almost two years of data taking, will be reported.

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1. Introduction

The KM3NeT experiment is a large-volume neutrino water Cherenkov telescope under construction in the Mediterranean Sea, foreseeing two detector sites and complementary physics programs, in the wide energy range from the GeV to the PeV energy scale. The KM3NeT/ARCA (*Astrophysics Research with Cosmics in the Abyss*) detector is at ~3500 m depth, 100 km off-shore from Capo Passero in Sicily, and it is optimized for astronomical studies in the [1 TeV; 10 PeV] energy range. KM3NeT/ORCA (*Oscillation Research with Cosmics in the Abyss*), instead, is at ~2450 m depth, 40 km off-shore from Toulon in France; its detector geometry is expected to have the maximum sensitivity to atmospheric neutrino oscillation physics in the [1; 100] GeV scale.

In KM3NeT/ORCA, the measurement of the atmospheric neutrino flux as a function of the energy and the zenith angle allows for exploiting the neutrino oscillation parameters with a wide baseline from a few tens to ~13000 of km, for the up-going neutrinos completely crossing the earth. From the atmospheric neutrino flux composition, two main channels can be studied: the ν_μ-disappearance, expected to contribute to a very precise measurement of the atmospheric oscillation parameters Δm^2_{32} and θ_{23}, and the ν_e-appearance; the latter case will lead to worldwide best sensitivity to the neutrino mass ordering (NMO) measurement, by studying the resonance oscillation in the earth's mantle due to the matter effect [1].

2. Detector description and current geometry

The key component of both the ARCA and ORCA detectors is an array of 31 photo-multiplier tubes (PMTs) installed into a spherical structure called Digital Optical Module (DOM) and ensuring 10 ns time-resolution and good spatial event reconstruction, of the order of 10 cm. A set of 18 DOMs is assembled into a Detection Unit (DU), standing vertically from the sea bed, which

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consequently determines the detector fiducial volume (building block, BB); each BB is made of 115 DUs (referred as full-ORCA). Depending on the final volume, the vertical distance between the DOMs, and the horizontal distance between the DUs, a better sensitivity either to astronomical or oscillation neutrino energies are reached. In the case of KM3NeT/ORCA, the DUs are spaced with a 9 m average distance between DOMs and ~20 m between DUs so that the final detection volume will cover about 7 Mton of seawater. The advantage of the KM3NeT technology lies in the possibility to perform neutrino physics studies also with a partially instrumented volume. KM3NeT/ORCA started collecting data in stable conditions in 2019, with 4 lines; in January 2020, the active volume increased to 6 DUs (referred as KM3NeT/ORCA 6) and has been stably operated in this configuration for almost two years. In this geometry, the first period, 354 days, allowed for investigating the detector performance and providing the first neutrino oscillation measurement; the second period, 539 days in total, is currently under study in order to provide an improved KM3NeT/ORCA 6 analysis, with a more robust fit strategy for the neutrino oscillation parameters. So far, about 13% of the nominal fiducial volume (15 DUs) has been instrumented.

3. KM3NeT/ORCA sensitivity to atmospheric neutrino oscillation physics at the GeV scale

The energy and direction of the atmospheric neutrinos are reconstructed by detecting the Cherenkov radiation produced by secondary particles interacting with the seawater. Depending on the neutrino flavor and the kind of interaction via charge (CC) or neutral (NC) currents, two different topologies of events can be reconstructed: *track*-like events, every time a muon is produced as a secondary particle, and *shower*-like events in all the other cases. The event reconstruction is based on maximum-likelihood algorithms that compute the residual time between the measured and the expected hits. For the best hypothesis on the reconstructed topology, the algorithms provide the energy and the direction of the interacting neutrinos, as well as the arrival time in each PMT and the position of the interaction vertex. The same algorithms also allow for good background rejection. Down-going atmospheric muons, the main source of background, are discarded based on their direction; similarly, the optical noise, induced by ^{40}K decays, bio-luminescence, and PMT dark counts, is rejected by requiring a minimum number of reconstructed hits. In the full-ORCA geometry, above 10 GeV, the spatial resolution is expected to reach 5 degrees and good linear energy reconstruction is observed in the full energy range. In addition to that, multivariate methods (e.g. Random Decision Forest, Boosted Decision Tree, etc..) or other neural network techniques (e.g. Convolutional or Graphical Neural Networks) allow for more robust particle identification selecting the purest neutrino sample against the main background sources and classifying them into different classes. Based on the probability of an event being classified as a track , the neutrino sample can be separated into three classes used as inputs for the neutrino oscillation fit: the purest *track*-like and *shower*-like classes, and an intermediate *middle*-class.

3.1 Sensitivity to NMO, atmospheric neutrino oscillation parameters, and ν_τ-appearance

For the NMO sensitivity, a log-likelihood minimization is performed in each bin of the bi-dimensional reconstructed cosine zenith angle as a function of the reconstructed energy distributions. All the three *track*, *shower*, and *middle* classes are used as an Asimov data set to derive the median sensitivity to the physics study[1]. The modeling of the atmospheric neutrino flux represents the main source of systematics, affecting the energy spectral index, the relative number of $\nu_{e,\mu}$ and $\bar{\nu}_{e,\mu}$, as well as their direction. In addition to that, the lack of precise knowledge on the neutrino cross-section is taken into account in the systematics related to the number of NC, and ν_τ and $\bar{\nu}_\tau$-CC events. Finally, systematics related to the detector response are assigned to take into account the PMT quantum efficiency, the light yield in the hadronic showers, and the normalization of the number of events in each class [1]. In this approach, the presence of the *middle*-class, independent from the physics case, becomes extremely helpful for constraining the systematics [1].

By choosing the inverted ordering (IO) as the *alternate* hypothesis to the normal ordering (NO), the NMO measurement appears as an asymmetry between the *track* and the *shower* in the aforementioned 2D distributions of the reconstructed cosine zenith angle and energy. Given the dependence with sinθ_{23}, the KM3NeT/ORCA sensitivity to the NMO varies as a function of it. After only 3 years of data taking, the nominal sensitivity to the NO will be already reached; on the other hand, at least 10 years would be needed in order to reach the same sensitivity for the IO. Nevertheless, a joint analysis with other experiments would significantly speed up this measurement, as recently shown in the combined fit with the JUNO experiment. In particular, the advantages are due to the JUNO non-sensitivity to the sinθ_{23} parameter, the negligible ORCA sensitivity to θ_{12} and Δm^2_{21}, and in the tension between the two experiments in Δm^2_{31}. If this is taken into account in the joint fit, the time needed to reach 5 σ sensitivity to the IO would decrease to only 6 years [4]. Under both hypotheses on the neutrino mass ordering, the KM3NeT/ORCA experiment is expected to contribute with good precision to the measurement of the neutrino oscillation parameters, sin θ_{23} and Δm^2_{32}, after 3 years of data taking, as shown in the 90 % contours in Fig. 1.

KM3NeT/ORCA is sensitive to many other new physics cases; in particular, thanks to its unprecedented statistics in the full geometry, KM3NeT/ORCA will allow for a quicker search of ν_τ-appearance compared to other experiments. About 3000 ν_τ/year are expected from the oscillation of a pure ν_μ and ν_e initial flux crossing the earth; consequently, given the τ production branching ratio in ν_τ-CC interactions, the tau neutrinos will appear as a statistical excess in the shower sample. Already after 1 year of data taking, the ν_τ-normalization will be constrained up to ± 30% at the 3 σ level and up to ± 10%, after 3 years [1]. The importance of this search is due to the fact that it allows for testing the PNMS matrix unitarity, and, consequently, exploring new physics scenarios by proving the three-flavor neutrino paradigm and indirect constraint on the ν_τ cross-section.

4. KM3NeT/ORCA results with 6 detection units

One of the peculiarities of KM3NeT is the possibility to perform physics studies since the commissioning phase. The longest stable data-taking geometry has been obtained with KM3NeT/ORCA 6. Its overall duration lasted almost two years that have been analyzed in two sub-periods. The first one, corresponding to 354 days, has been used to perform the first neutrino oscillation analysis from the ν_μ-CC *track*-sample; additionally, it has also allowed for a robust study of the detector's stability and performance. In particular, a precision in the track direction, lower than the nominal one (~ 10 cm) has been measured by including a dynamic positioning of the DUs.

[1]The model used in the fit procedure is weighted with HKKM15 atmospheric flux [2] in the ORCA site (Frejus, France); for the oscillation probabilities the PREM model is used for modeling neutrinos' path through the earth.

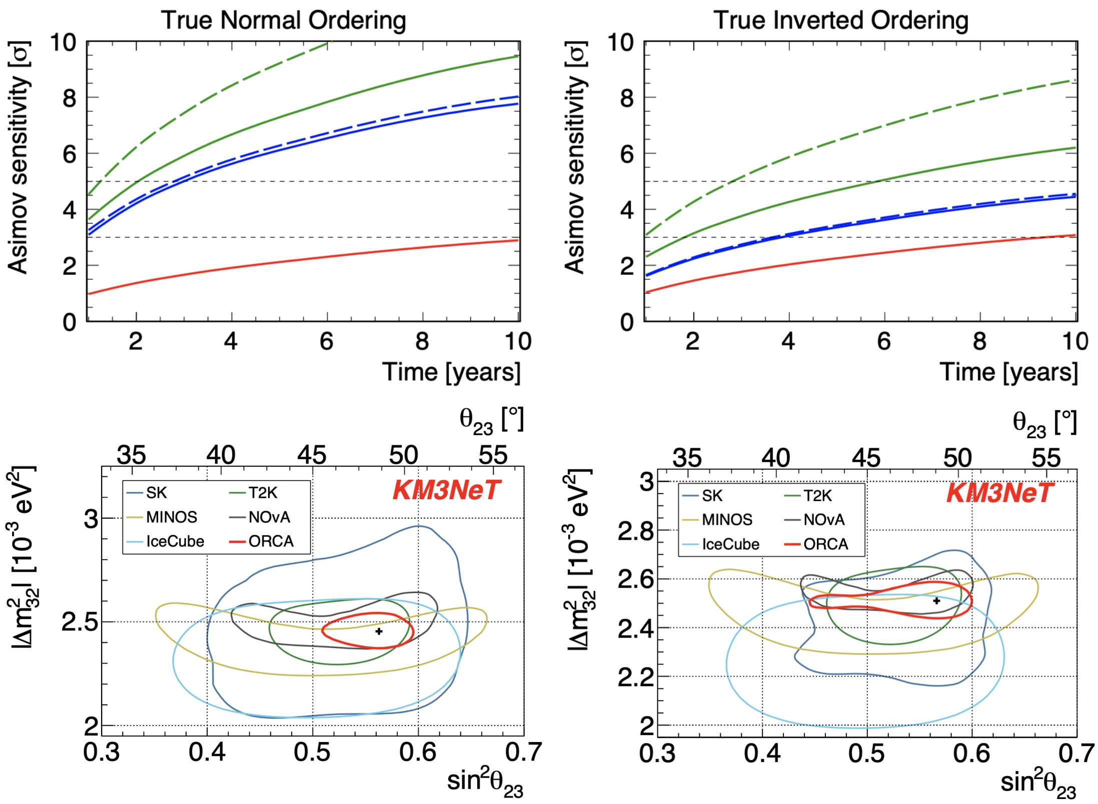

Figure 1: Top: Sensitivity to neutrino mass ordering as a function of time for JUNO (red), KM3NeT/ORCA (blue), and the combined analysis of JUNO and KM3NeT/ORCA (green). **Bottom**: Sensitivity to Δm^2_{32} and $\sin\theta_{23}$ for NO (left) and IO (right) after 3 years of data taking at 90 % confidence level (red).

Similarly, by measuring the shadow created either by the Sun or the Moon in the cosmic muon flux, an accuracy of less than 1 degree in the reconstruction of the track direction can be reached [5].

Confident in the goodness of the detector response in this geometry, the first neutrino oscillation parameters analysis has been performed by including only the *track*-sample. Similarly to the sensitivity studies, a pre-selection has been applied in order to reject the down-going atmospheric muons and pure noise events: the former have been rejected based on the maximum-likelihood algorithm optimized for the reconstruction of the *track*-topology and considering their direction and the position of the reconstructed interaction vertex; while the others by requiring a minimum positive value on the likelihood. The final neutrino sample is then made of about 1237 neutrino candidates. The goodness of the selection has been evaluated on the data/Monte Carlo[2] (MC) comparison of the 1D cosine zenith angle and energy distributions; both before and after the pre-selection, a good agreement between data and MC is observed. Finally, by performing the log-likelihood fit in the 2D reconstructed cosine zenith angle and energy distributions, assuming the NO hypothesis, and the best values from NuFit 5.0, a 5.9 σ-sensitivity to the oscillation hypothesis is found in the L/E plot. Similarly, the first evaluation of the 90 % contour of the $\sin\theta_{23}$-Δm^2_{32} parameter space confirmed KM3NeT/ORCA potentials in the atmospheric neutrino oscillation [7].

[2]The atmospheric cosmic ray flux is obtained by MUPAGE [6] and neutrinos are generated using gSeaGen [3].

Currently, significant improvements on different levels are ongoing in order to enhance such measurements. As a first step, the impact of the increased statistics including the full almost 2 years of data-taking in the KM3NeT/ORCA 6 geometry and the *shower*-class significantly increases the 90 % sensitivity contours. In addition to that, the inclusion of *shower*-reconstruction has been made available on the full data sample, allowing for enhanced event classification, the comparison among different techniques for the classification (e.g. based on both boosted decision trees or graphical neural networks), and a more robust treatment of the systematics.

5. Conclusions

KM3NeT/ORCA is a water Cherenkov neutrino telescope under construction in the Mediterranean Sea. With an active volume corresponding to 7 Mtons of seawater and an optimized geometry for atmospheric neutrino oscillation in [1, 100] GeV, KM3NeT/ORCA is expected to reach the best sensitivity in the determination of the neutrino mass ordering as well as in the high-precision measurement of the atmospheric neutrino oscillation parameters.

The advantage of the detector's structure is in the possibility to perform physics studies also with a partially instrumented volume, thanks to its modularity. So far, with less than 10 % of the fiducial mass (6 DUs), KM3NeT/ORCA has already performed a first atmospheric neutrino oscillation fit which showed a clear preference for the oscillation hypothesis. Currently, significant improvements, including a large statistics data sample and a better treatment of the systematics, are under study in order to improve this first measurement of the atmospheric neutrino oscillation parameters.

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