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Sensitivity of the KM3NeT/ORCA detector to the neutrino mass ordering and beyond

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The KM3NeT collaboration is currently building a new generation of large-volume water-Cherenkov neutrino telescopes in the Mediterranean sea. Two detectors, ARCA and ORCA, are under construction. They feature different neutrino energy thresholds: TeV range for ARCA and GeV range for ORCA. The main research goal of ORCA is the measurement of the neutrino mass ordering and atmospheric neutrino oscillation parameters, while the detector is also sensitive to a wide variety of other physics topics, including non-standard interactions, sterile neutrinos and Earth tomography, as well as low-energy neutrino astronomy. This contribution will present an overview of the updated ORCA sensitivity projection to its main science objectives, including - but not limited to - the measurement of the neutrino mass ordering and oscillation parameters Future perspectives for ORCA to serve as far detector for a long baseline neutrino experiment with a neutrino beam from the U70 accelerator complex at Protvino in Russia will also be discussed.

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1. Introduction

The KM3NeT collaboration is building the next-generation large-volume neutrino telescopes at the bottom of the Mediterranean sea at ∼3 km depth [1]. The detectors are constructed as 3-dimensional grids of Digital Optical Modules (DOMs), each DOM housing 31 photomultiplier tubes (PMTs) for the detection of Cherenkov light emitted by charged particles emerging from from neutrino interactions in sea water. The DOMs are attached to Detection Units (DUs), which are vertical strings anchored to the seabed. Each DU holds 18 DOMs. The spacing between the DOMs on a DU and the DUs themselves is configurable. The KM3NeT/ARCA detector is being built off-coast Italy and will instrument ∼1 km^3 of sea water with two blocks of 115 DU, with the main physics goal of detection of TeV-scale neutrinos from cosmic sources. The KM3NeT/ORCA detector is being built off-coast France and will instrument $\sim 5.5 \times 10^{-3}$ km^3 of sea water with 115 DU and with smaller spacing between the DOMs compared to KM3NeT/ARCA. The main physics goal of ORCA is to determine the neutrino mass ordering (NMO). This contribution focuses on the KM3NeT/ORCA detector, its sensitivity to the NMO and other oscillation phenomena, and its potential use as a far detector for a long baseline neutrino experiment of a new kind with a tagged neutrino beam from U70 in Russia. The results reported here refer to the full detector. Note that the modular design of the detector allows to collect and analyse data already during the construction.

2. Sensitivity to the oscillation parameters using atmospheric neutrinos

The method to estimate the sensitivity to neutrino oscillation parameters is described in details in [2]. These parameters are measured by using the modifiations they induce on the distributions of the neutrino events in the plane energy - cosine zenith angle. The efficiency to detect, reconstruct and select the neutrino to be analysed is graphically reported in Figure 1 as the effective volume of the detector.

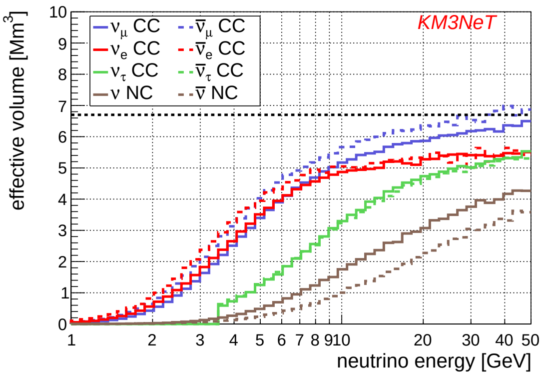

Figure 1: Effective detector volume as a function of true neutrino energy E_ν for different neutrino flavours and interactions. The dashed black line indicates the instrumented volume of the detector.

The sample of neutrino events are split in three populations using a classifier trained to separate track-like events from shower-like ones. The three classes used are named *track*, *shower* and *intermediate* and contains respectively a majority of track-like events, shower-like events and an admixture of the two. The performance of the classifier is illustrated in Figure 2.

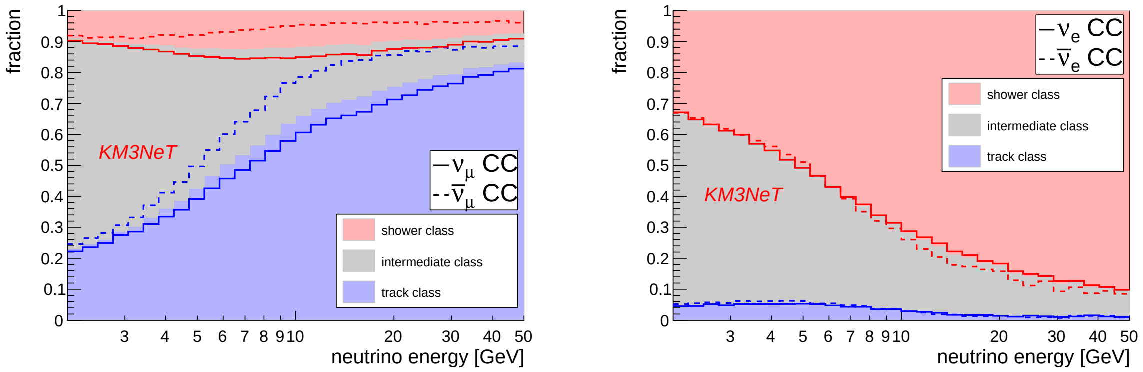

Figure 2: Fractions of preselected neutrino events of different types that are classified in the track class, the intermediate class, and the shower class, as a function of true neutrino energy. Coloured areas correspond to the composition of the atmospheric neutrino flux. Solid and dashed lines show individual fractions for neutrinos and anti-neutrinos, respectively.

The resolution on the neutrino energy is $\Delta E/E \approx 25\%$ for $\overset{(-)}{\nu}_e$ CC events with $E_\nu = 10\,\mathrm{GeV}$, and it is dominated by the intrinsic light yield fluctuations in the hadronic shower [3]. For $\overset{(-)}{\nu}_\mu$ CC, the resolution on the neutrino energy levels off at $\Delta E/E \approx 35\%$ as the reconstructed muon track tends not to be fully contained inside the instrumented volume.

The median neutrino direction resolution is dominated by the intrinsic ν–lepton scattering kinematics [3] and is 9.3°/7.0°/8.3°/6.5° for $\nu_e/\bar{\nu}_e/\nu_\mu/\bar{\nu}_\mu$ CC events, respectively.

Based on the detector response, on the neutrino flux and on the oscillation probabilities a model of the experiment is built to estimate the sensitivity to various observables. This model is used to generate Asimov data-sets representing the average data-sets expected under any given sets of oscillation parameters. The compatibility between each of these datasets and any other hypothetical oscillation parameter value is assessed by fitting the data-set with the experiment model corresponding to this hypothesis. During the fitting procedure several systematic uncertainties related to the neutrino flux, the detector response and the oscillation parameters are considered by allowing some of the model parameters to vary. The full description of these parameters is available in [2].

2.1 Neutrino mass ordering

The sensitivity to the NMO after three years of data taking is reported as a function of θ_{23} for both NMO in Figure 3. Assuming the current best estimates for θ_{23}, the NMO sensitivity is 4.4σ if the true NMO is NO and 2.3σ if it is IO.

Figure 3 shows also the sensitivity for both NMO as a function of data taking time. The NMO can be determined at 3σ level after 1.3 years if the true NMO is NO, and after 5.0 years if it is IO.

2.2 Oscillation parameters

The atmospheric neutrino collected with KM3NeT-ORCA will also allow to measure Δm^2_{32} and θ_{23}. The 90% confidence level contours on these parameters for both NMO are shown in Figure 4. The 90% confidence level interval on Δm^2_{32} and θ_{23} are $85 \cdot 10^{-6}\,\mathrm{eV}^2$ and $(^{+1.9}_{-3.1})^\circ$ for NO and, $75 \cdot 10^{-6}\,\mathrm{eV}^2$ and $(^{+2.0}_{-7.0})^\circ$ for IO.

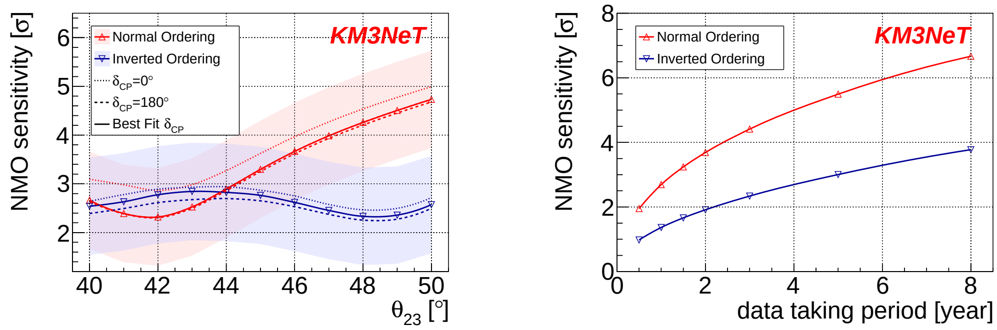

Figure 3: (left) Sensitivity to NMO after three years of data taking, as a function of the true θ_{23} value, for both normal (red upward pointing triangles) and inverted ordering (blue downward pointing triangles) under three assumptions for the δ_{CP} value: the world best fit point for NO, IO (plain line), 0° (dotted line) or 180° (dashed line). The coloured shaded areas represent the sensitivity that 68% of the experiment realisation would yield, according to the Asimov approach [7]. (right) Sensitivity to NMO as a function of data taking time for both normal (red upward pointing triangles) and inverted ordering (blue downward pointing triangles) and assuming the oscillation parameters reported in [4].

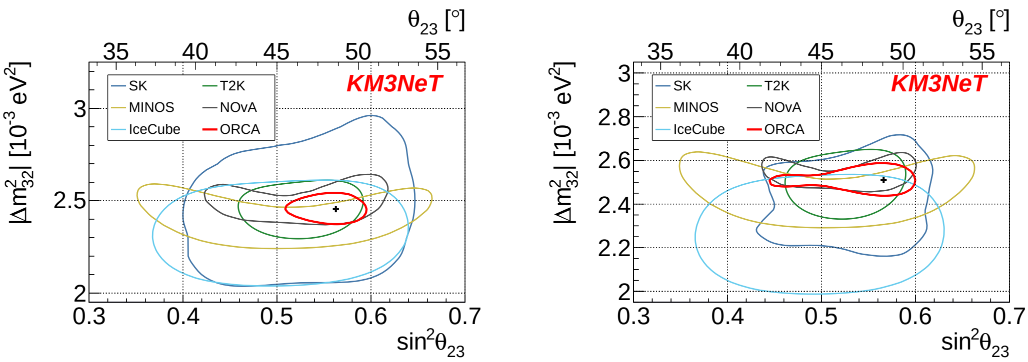

Figure 4: Expected measurement precision of Δm^2_{32} and θ_{23} for both NO (left) and IO (right) after 3 years of data taking at 90% confidence level (red) overlaid with results from other experiments [8–12] and the oscillation parameters reported in [4] (black cross).

The same analysis allows to calculate the significance to determine the octant of θ_{23}. The results are shown in Figure 5, which illustrates the needed data taking time to reach a 1, 2 and 3σ octant significance as a function of the true value of θ_{23}. Dashed lines ignore the NMO, while for solid lines the NMO is assumed to be known.

2.3 ν_τ appearance

Finally the unitarity of the PMNS matrix will be tested using the $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\tau$ channel. About 3000 $\overset{(-)}{\nu}_\tau$ per year will be collected with the full detector. The appearance of $\overset{(-)}{\nu}_\tau$ is determined by measuring the normalisation factor of the $\overset{(-)}{\nu}_\tau$ contribution. For this study, NO is assumed. In Figure 6, the sensitivity is presented as a function of operation time. KM3NeT/ORCA will already be able to confirm the exclusion of non-appearance with high statistical significance with few months of data-taking. The normalisation can be constrained to ±30% at 3σ-level and to ±10% at 1σ-level after one year of data taking.

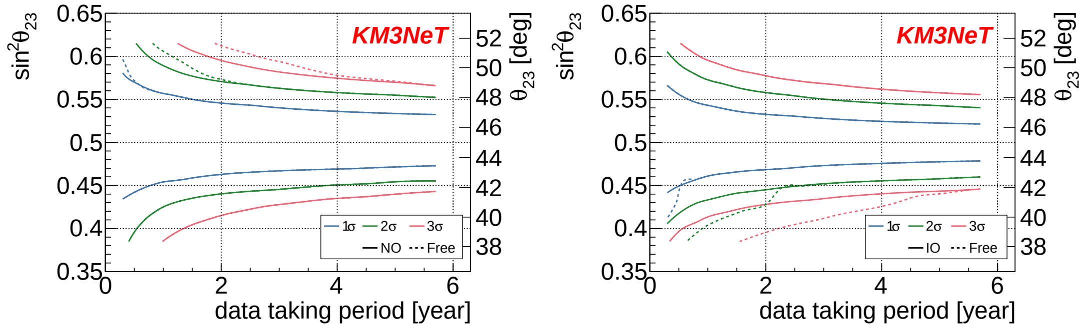

Figure 5: Expected sensitivity to determine the θ_{23} octant at 1 (blue), 2 (green) or 3σ (red) as a function of data taking time for both NO (left) and IO (right) assuming the true NMO is known (solid line) or unknown (dashed line). The dashed lines differ from the plain ones when the fit converges to the wrong NMO.

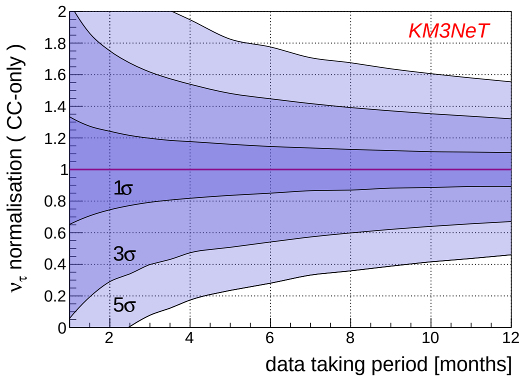

Figure 6: Sensitivity to $\overset{(-)}{\nu}_\tau$ appearance as a function of data taking period.

3. A new kind of long baseline neutrino experiment

The precise determination of the CP violating phase, $\delta_{\rm CP}$, is one of the keystones of neutrino physics in the coming decade. KM3NeT-ORCA could be used to make this measurement as a far detector in a long baseline neutrino experiment (LBLNE) with a neutrino beam produced in U70 at Protvino in Russia. A first version of this project, called P2O is described in [13].

Given the large mass of KM3NeT-ORCA, compared to other future LBLNE [14, 15], a modest beam intensity of $O(100)$kW is sufficient to collect a large sample of neutrino: $O(10^3)$ per year. At these intensities, it appears feasible to instrument the beam line with trackers. These trackers would allow to reconstruct kinematically the properties of the neutrinos produced by $\pi^\pm \to \mu^\pm\nu$ decays. Energy resolutions better than 1% are accessible with this method. In addition, each and all neutrinos from $\pi^\pm \to \mu^\pm\nu$ are reconstructed individually which removes the systematic uncertainties on the beam composition. Finally, provided that the far detector is synchronized with the trackers, the property of the neutrino kinematically reconstructed can be assigned to the interacting neutrino. The far detector is thus left with the unique task of identifying the flavor of the neutrino after propagation. In addition, as the chirality is determined by the trackers, both neutrino and anti-neutrino can be collected together which helps to resolve the θ_{23}–$\delta_{\rm CP}$ degeneracy. More details on this method can be found in [16, 17].

The precision on δ_{CP} is represented as function of δ_{CP} in Figure 7 (left) together with the expectation for DUNE assuming a 450 kW beam. The precision is stable over the whole span of δ_{CP} values and ranges between 6° and 8°. These two extreme values are obtained for 0 and 90°. The precision at these two values is shown as a function of the exposure in Figure 7 (right). Overall, P2O with a tagged beam appears a valuable and complementary approach to next generation of LBLNE.

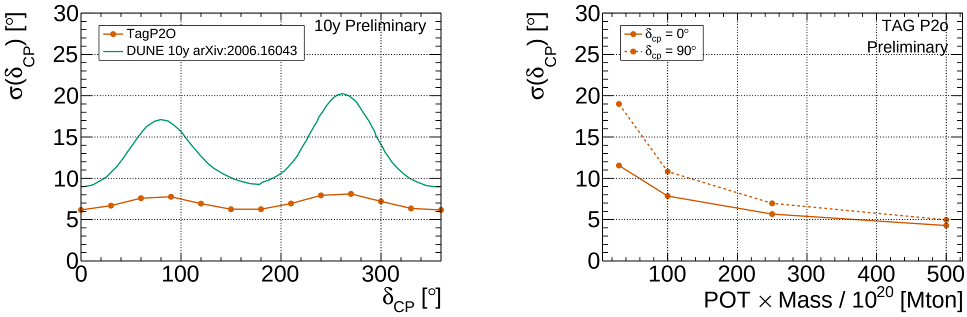

Figure 7: (left) Precision to measure δ_{CP} as function of δ_{CP} and (right) as function of exposure.

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