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Undersea measurements of neutrino oscillations with KM3NeT/ORCA

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KM3NeT/ORCA is a water Cherenkov detector under construction in the Mediterranean Sea, whose geometry has been optimised for the detection of [1, 100] GeV atmospheric neutrinos. After completion the ORCA detector will comprise an array of optical modules supported by 115 vertical Detection Units. Its main goals are the determination of the neutrino mass ordering and the measurement of the atmospheric neutrino oscillations. In addition ORCA is sensitive to tau neutrino appearance resulting from atmospheric neutrino oscillations. The full detector will collect a few thousands charged current tau neutrino events per year. In this contribution a first measurement is presented with ORCA6, an early subarray corresponding to about 5% of the final detector. A sample of 5828 neutrino candidates has been selected from the analysed exposure of 433 kton-years. With this dataset, the ν_τ normalisation was measured to be $S_\tau = 0.48^{+0.5}_{-0.33}$, which translates into a charged current cross section measurement of $\sigma_\tau^{\mathrm{meas}}(E_\nu) = (2.5^{+2.6}_{-1.8}) \times 10^{-38}\mathrm{cm}^2$ nucleon^{-1} at the median charged current ν_τ energy of 20.3 GeV. In addition, the unitarity of the neutrino mixing matrix was probed and allowed to improve the current limit on the non-unitarity parameter affecting the τ-row of the mixing matrix, with α_{33} > -0.05 at the 2σ confidence level. A larger data sample, consisting of 715 kton-years, yielded a measurement of the oscillation parameters as $\sin^2\theta_{23} = 0.50 \pm 0.07$ and $\Delta m^2_{31} = -2.09^{+0.17}_{-0.21} \times 10^{-3}$ eV^2.

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1. KM3NeT

KM3NeT is an undersea Cherenkov neutrino telescope under construction at the bottom of the Mediterranean Sea offshore the Italian Sicily coast (KM3NeT/ARCA) and 40 km offshore Toulon, France (KM3NeT/ORCA) [1]. The two detectors are optimised for different neutrino energy ranges. They are composed of vertical Detection Units (DUs), each supporting of 18 multi-PMT optical modules (referred to as DOMs) [2]. Between 6 and 11 DUs were operational in ORCA when the data used in this analysis were acquired. The kinematical properties of the event are determined by using a maximum-likelihood method based on a set of causally-connected hit times and positions. For the track reconstruction the hits are fitted under the assumption of a Cherenkov-light-emitting muon. The muon is assumed to follow a long, straight trajectory and to propagate practically at the speed of light in vacuum through water.

The data used in this analysis were collected between mid-February 2020, and mid-November 2021 for a total of 510 days equivalent to a total exposure of 433 kton-years. Quality cuts on the number of used hits $\geq$ 15, the likelihood $\geq$ 40 and the direction (up-going) of the track reconstruction were applied to remove poorly reconstructed events, noise events from ^{40}K decay, and most of the atmospheric muon background. In addition a larger data set was also analysed which uses data collected between February 2020, and December 2022 for a total of 715 kton-years.

2. Results

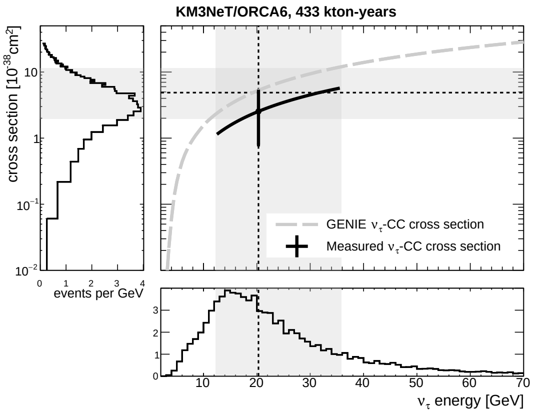
Based on the data sample taken with ORCA6, the configuration of KM3NeT/ORCA with 6 DUs, a measurement of the tau neutrino appearance was performed. The oscillation probabilities were calculated using dedicated software [3]. The tau normalisation S_τ and the corresponding 1σ uncertainty were measured to be $S_\tau = 0.48^{+0.5}_{-0.33}$ including Feldman-Cousin corrections. The best fit corresponds to the observation of a total number of 92^{+90}_{-63} charged current tau neutrino events. The median of the ν_τ CC true energy distribution E_{ν_τ} is at 20.3 GeV and 68% of the events have an energy between 12.3 and 35.9 GeV. The corresponding theoretical expectation is $\sigma^{\text{th}}_\tau(E_{\nu_\tau}) = 5.29 \times 10^{-38}\text{cm}^2$. Hence, the measured cross section is $\sigma^{\text{meas}}_\tau(E_{\nu_\tau}) = (2.5^{+2.6}_{-1.8}) \times 10^{-38}\text{cm}^2$ as shown in Figure 1a.

The same data were also used to test a model of non-unitarity as described in [4]. The most competitive sensitivity was found for the single parameter α_{33}. The best-fit value is $\alpha_{33} = -0.007^{+0.026}_{-0.025}$ including Feldman-Cousins correction. The profiled log-likelihood ratio is presented in Figure 1b and the 2σ current bound is taken from [5]. The 2σ confidence interval is slightly reduced with Feldman-Cousins correction α_{33} > -0.05 at 2σ CL.

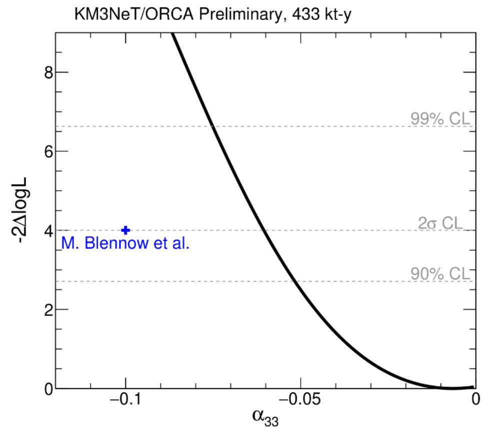
In addition, based on a larger data sample taken with several partial configurations, from ORCA6 to ORCA11 (where the number indicates how many DUs were active), the measurement of the atmospheric oscillation parameters was improved with respect to the results described in [6]. The oscillation parameters are measured as

$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\,\text{eV}^2, & \text{Inverted Ordering} \\ [2.10, 2.37] \times 10^{-3}\,\text{eV}^2, & \text{Normal Ordering} \end{cases}$$

$$\sin^2\theta_{23} = 0.50 \pm 0.07$$



(a) The measured charged-current tau neutrino cross section in black, compared to the $\nu_\tau/\bar{\nu_\tau}$ averaged theoretical expectation in grey as a function of the energy. The light grey bands represent the 68% range of the distributions.



(b) Measured log-likelihood profile for the model probing non-unitarity with the single α_{33} parameter free.

and the 90% contours are provided in Figure 2.

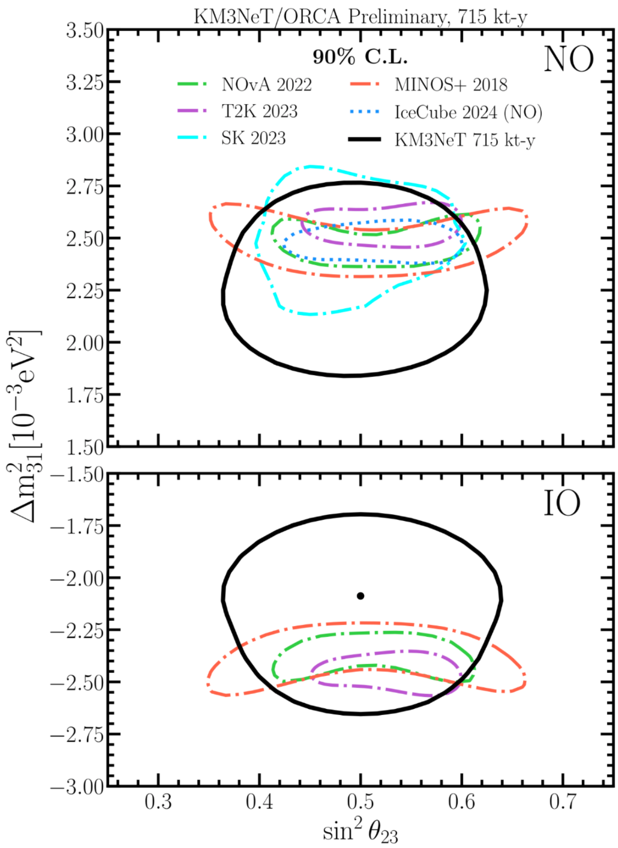


Figure 2: Contour at 90% CL of KM3NeT/ORCA using 715 kton-years for the oscillation parameters $\sin^2\theta_{23}$ and Δm^2_{31} compared with other experiments.

3. Conclusion

The tau neutrino appearance has been measured using a partial configuration of KM3NeT/ORCA comprising 6 active detection units. It was translated into a measurement of other experiments of the charged-current tau neutrino cross section. The data were also used to test a non-unitarity model, which improved the current bound on α_{33}. In addition, a larger data sample was used to better constrain the standard atmospheric oscillation parameters, resulting in a precision on $\sin^2\theta_{23}$, comparable to the current best measurements. Higher sensitivities are expected from larger statistics and also from the better energy resolution of the larger detector configuration, as well as improvements in the event reconstruction algorithm.

References

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