PROCEEDINGS OF SCIENCE

Exploring tau neutrino appearance measurements in KM3NeT/ORCA

Chiara Lastoria[a,*] **on behalf of the KM3NeT Collaboration**

[a] *LPC Caen, CNRS/IN2P3,*
6 Bd Maréchal Juin, 14000 Caen, France

E-mail: lastoria@lpccaen.in2p3.fr

Next-generation neutrino experiments aim at ensuring high-precision measurements of the oscillation parameters to reveal the main unknowns in neutrino physics. Among them, validating the three-flavors paradigm remains one of the most stimulating because it allows for exploring physics beyond the Standard Model.

KM3NeT/ORCA is a water Cherenkov neutrino telescope, under construction in the Mediterranean Sea, whose primary physics goal is an early measurement of the neutrino mass ordering from the oscillation of atmospheric neutrinos traversing the Earth. In addition, thanks to its huge fiducial mass, KM3NeT/ORCA will have unprecedented statistics to exploit the tau neutrino appearance channels as an indirect test of the PMNS matrix unitarity and, thus, of the three-neutrino flavors paradigm. In this proceeding, the results from the first blind measurement of the tau neutrino normalization performed by exploiting data collected with a partially instrumented volume (5% of the nominal, operated from 2020-2021) will be presented.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

*Speaker

PoS(ICHEP2024)119

Contents

1. Physics motivation

The experimental observation of neutrino oscillations opened the way to explore physics beyond the Standard Model. Thanks to many successful experiments, the current knowledge of neutrino properties reached a relatively coherent picture. Neutrinos have been observed in three families (ν_e, ν_μ, ν_τ). Despite being predicted to be massless, the oscillation mechanisms demonstrated that leptons mix, hence neutrinos have non-zero mass. However, the origin of such masses is not understood yet. Based on experimental observations, the neutrino mixing is assumed to take place uniquely among the three observed families, and the neutrino mixing matrix (U_{PMNS}, from Pontecorvo-Maki-Nakagawa-Sakata, who postulated it) is assumed to be unitary. However, many critical questions still need to be addressed to reach a more robust understanding of the nature of neutrinos. Among them: clarifying the neutrino mass ordering; establishing the presence of the charge-parity violation in the leptonic sector; and testing the U_{PMNS} unitarity. Answering these questions requires reaching similarly large statistics in the measurement of oscillation probabilities involving all three neutrino flavors to ensure high precision in the elements of the PMNS matrix. Whereas, the achievable precision in the third row of the PMNS matrix is currently limited by the low statistics in the detection of ν_τ. Constraining it will allow either to confirm the 3ν-paradigm scenario or give hints on how to extend it.

The KM3NeT experiment is a water Cherenkov neutrino telescope under construction in the Mediterranean Sea [1]. Two detectors, exploring neutrinos in the GeV to PeV energy scale are under construction to cover a complementary physics program. The KM3NeT/ORCA detector, which is situated South of France, is expected to have the maximum sensitivity to atmospheric neutrino oscillation physics in the [1; 100] GeV scale, with the primary physics goal of determining the neutrino mass ordering [2]. Thanks to its nominal active volume (7 Mton of seawater), the unprecedented statistics of ~ 3000 charge-current (CC) $\nu_\tau$per year will make KM3NeT/ORCA one of the leading experiments in exploring ν_τ-appearance channel, from the maximal oscillation of a pure ν_μ and ν_e initial flux crossing the Earth, and use this channel to test the 3ν-paradigm.

2. The KM3NeT/ORCA experiment

The key components of the KM3NeT detector is an array of 31 photo-multiplier tubes (PMTs) hosted in a spherical Digital Optical Module (DOM); 18 of them are assembled into a Detection Unit (DU), standing vertically from the sea bed. Data from the installed DUs is transmitted to shore where it is filtered and stored for calibration and analysis. The number of installed DUs determines the active detector volume; this modular structure allows the KM3NeT experiment to perform physics studies already from the installation phase, with a partially instrumented volume.

The KM3NeT detection principle is based on the collection of the Cherenkov radiation induced by relativistic charged particles in seawater; the event reconstruction uses maximum-likelihood algorithms based on the comparison of the residual time between the measured and the expected hits in each PMT to reconstruct the energy and the direction of each event. Two main event topologies can be reconstructed in the detector: *track*-like events, every time a muon passes in the vicinity of the detector, and *shower*-like events otherwise. All flavors atmospheric neutrino interactions (both via CC and neutral currents, NC) are the main signal; atmospheric muons and optical noise (due to bioluminescence, ^{40}K decays in the seawater, and PMT dark rates) are the two main sources of background.

2.1 The six line geometry

The KM3NeT/ORCA detector is being operated in stable conditions since 2020, starting with 6 installed DUs ($\sim$ 5% of the nominal, referred to as ORCA6 geometry in the text). Since then, larger geometries have been alternated up to the current coverage reaching 20% of the nominal volume (115 DUs), expected to be completed in 2028.

2.2 Data sample, event selection, and analysis strategy

The analysis presented below is performed by exploring ORCA6 data, operated from January 2020 to November 2021. The data-taking period is divided into runs, with a typical 6 hours duration. Data quality criteria are applied to exclude unstable data-taking periods due to high-bioluminescence activity, bad timing accuracy, and high trigger rates [3]. By applying these selections, the analyzed ORCA6 live-time for this analysis corresponds to 510 days (433 kton-years exposure). Additionally, events are selected based on a cut selection applied to variables from the maximum likelihood reconstruction algorithms and classified using Boosted Decision Trees algorithms to reject the main background and identify a pure neutrino sample. Based on this classification, the overall neutrino sample made of 5828 candidates is divided into three classes: low/high purity track classes (depending on the allowed atmospheric muons contamination), and the shower class.

3. ν_τ-appearance analysis in ORCA6

In the 3ν-paradigm, 12 conditions on the PMNS matrix elements exist; six of them are given by the sum of the elements in each row (referred to as *normalization* and expected to be equal to 1). By measuring them and verifying their consistency with 1, the 3ν-paradigm description can be validated. In the same scenario, and restricting to measuring the ν_τ-normalization, the

ν_τ cross-section, one of the main sources of systematics in the oscillation analysis, can be further constrained. Alternatively, the $U_{\rm PMNS}$ non-unitarity can be directly tested by measuring neutrino oscillation in an extended $n \times n$ framework. In the ORCA6 analysis, the formalism proposed by [4] is considered. In this formalism, the $U_{\rm PMNS}$ is not unitary anymore but expressed in terms of a lower triangular matrix (α), introducing 9 extra parameters to describe the neutrino oscillation as in [5]. Hence, the ν_τ-normalization is expressed in terms of the α_{33}-element of this matrix.

In ORCA6, a binned log-likelihood fit of the 2D reconstructed energy, E, and cosine of the reconstructed zenith distributions angle, θ, used as an approximation of the oscillation baseline L, is performed on the three aforementioned classes of events. The parameter of interest is measured by fitting a model to the observed event distribution in data. The analysis is performed with two different approaches. The first assumes the 3ν-paradigm to be valid, hence measuring the ν_τ-normalization (referred to as S_τ) and inferring it as a measure of the $\nu_\tau$cross-section. In this approach, only a variation of the ν_τ-CC rate is expected. The second, instead, explicitly measures α_{33}. The fit is done including S_τ as a nuisance parameter, which is either kept fixed at 1 or allowed to vary 20% prior to it. In contrast with the previous approach, both the ν_τ-CC and NC event rates can vary in this measurement.

4. Results

Given the τ production branching ratio in ν_τ-CC interactions and the intrinsic difficulties in identifying ν_τ on an event-by-event basis in ORCA6, the appearance of ν_τ is quantified on a statistical basis, as the excess in the *shower*-class compared to the hypothesis of non-oscillation. The oscillation probability as a function of the L/E ratio for the shower class is shown in Fig. 1. Each colored line represents the ratio of the observed data compared to the best-fit model assuming

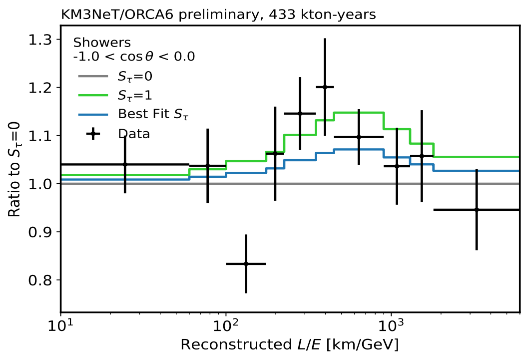

Figure 1: Distribution of the measured oscillation probability as a function of L/E for the shower class. The different tested models correspond to the colored lines, while data are reported in black.

the extreme case of S_τ=0 and S_τ=1, while the data are reported in black. Although the data reflects well the model shape, it is still difficult to distinguish between the two hypotheses on S_τ, given the dominance of the statistical uncertainties in each bin.

The log-likelihood profile of the S_τ parameter is scanned between 0 and 2, as shown in the left plot of Fig. 2. The resulting measurement of the ν_τ-normalization is $0.48^{+0.49}_{0.33}$, reported with

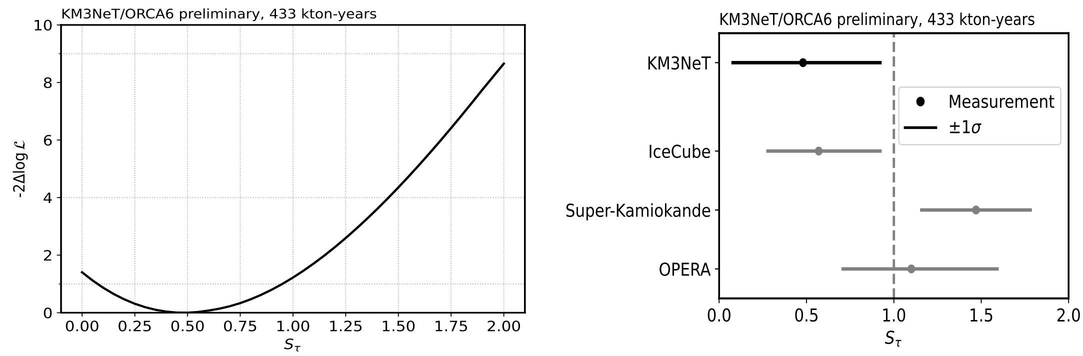

Figure 2: **left**: Measured log-likelihood profile of the $S_\tau$parameter scanned between 0 and 2. **right**: Comparison of ORCA6results with previous measurements on the ν_τ-CC normalisation.

1σ uncertainty; this corresponds to a total number of 92^{+94}_{-64} observed ν_τ-CC interactions. A comparison with the reported ν_τ-normalization measurement by other experiments is given on the right plot of the same figure. The KM3NeT/ORCA result is in agreement with the others. The comparison of the achieved precision of data collected with only 5% of the nominal volume with other measurements is remarkable. Despite the much shorter data-taking period, the competitiveness of KM3NeT/ORCA in the field is demonstrated by the current precision, which is comparable with SuperKamikande and IceCube results. The enlargement of the detector volume will further reduce the KM3NeT/ORCA uncertainties from the analysis of the data collected in larger geometries.

In Fig. 3, the interpretation of the ν_τ-normalization (S_τ) as a scale factor on the ν_τ CC cross-section is reported. The energy-dependant theoretical expectation from GENIE [6] is scaled

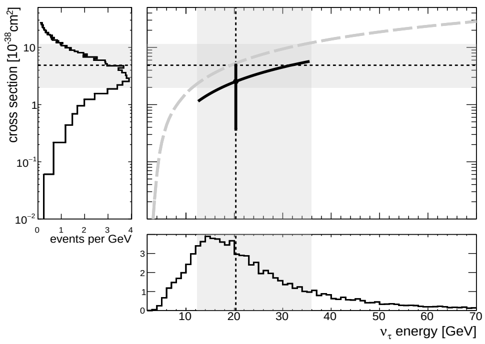

Figure 3: Measurement of the -CC cross section in black, com- pared to the averaged theoretical expectation given by GENIE, in gray, as a function of the true neutrino energy.

considering $\sigma_{meas}(E_\nu) = S_\tau \times \sigma_{th}(E_\nu)$ and using the S_τ best-fit value, around the median of the ν_τ CC true energy distribution (E_{ν_τ} = 20.3 GeV, at 68% C.L. between 12.3 and 35.9 GeV). Therefore, the measured cross section, $\sigma_\tau^{\rm meas}(E_{\nu_\tau})$, is found at $(2.54^{+2.38}_{-2.17}) \times 10^{-38}\mathrm{cm}^2$ nucleon^{-1}.

Finally, the results from testing the neutrino mixing matrix non-unitarity are summarised in Fig. 4. On the left plot, the profiled likelihood of the α_{33} parameter is reported; the dotted line corresponds to the hypothesis of fixing S_τ=1, while the solid line includes S_τ as a nuisance

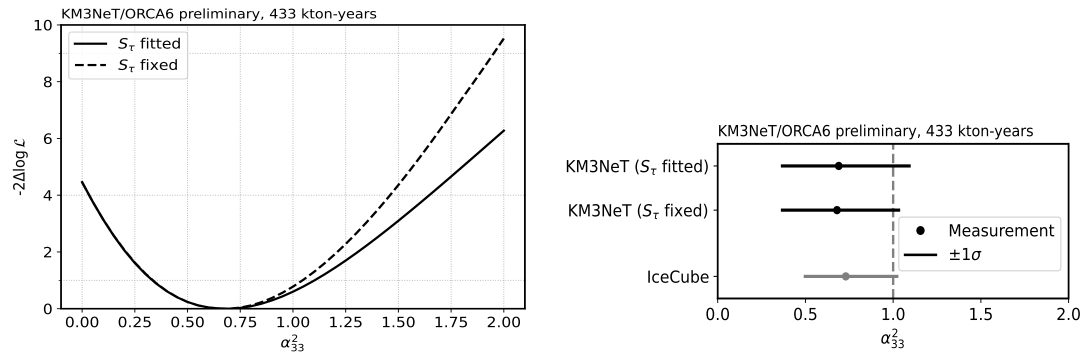

Figure 4: left: Measured log-likelihood profile of the α_{33} parameter scanned between 0 and 2. **right**: Comparison of ORCA6results with CC+NC ν_τ-normalisation measurement reported by IceCube.

parameter with 20% uncertainties. In the first (second) case, the maximum of the likelihood is found at α_{33} = $0.68^{+0.36}_{-0.32}$ ($0.69^{+0.41}_{-0.33}$); the discrepancy between the two models becomes more evident for higher values of α_{33}. Due to the expected variation in both the ν_τ CC and NC event rate, the α_{33} fit with S_τ=1 allows for a direct comparison with the CC+NC ν_τ-normalization measurement by the IceCube Collaboration, as reported in the right plot of Fig. 4. In all results, the ν_τ-normalization is compatible with 1; hence, none of the three results is able to exclude the 3ν-paradigm. Also in this case, the competitiveness of KM3NeT/ORCA with 6 operational DUs in precision analysis is showcased.

References

[1] KM3NeT collaboration, *Letter of intent for KM3NeT 2.0*, J. Phys. G 43 (2016) 084001613 [1601.07459].

[2] Aiello, S., Albert, A., Alves Garre, S. et al. *Determining the neutrino mass ordering and oscillation parameters with KM3NeT/ORCA*, Eur. Phys. J. C 82, 26 (2022).

[3] S. Aiello et al., *Measurement of neutrino oscillation parameters with the first six detection units of KM3NeT/ORCA*, (2024), arXiv:2408.07015v1 [hep-ex].

[4] S. Antusch, and O. Fischer, *Non-unitarity of the leptonic mixing matrix: Present bounds and future sensitivities*, JHEP 10 (2014) 094.

[5] M. Blennow, P. Coloma, E. Fernandez-Martinez, J. Hernandez-Garcia and J. Lopez-Pavon, *Non-Unitarity, sterile neutrinos, and Non-Standard neutrino Interactions*, JHEP 04 (2017) 664153.

[6] C. Andreopoulos et al, *The GENIE Neutrino Monte Carlo Generator: Physics and User Manual*, (2015) arXiv:1510.05494 [hep-ph]