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Tau neutrino appearance measurement in ORCA 6

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KM3NeT/ORCA is a next-generation water Cherenkov neutrino telescope currently under construction in the Mediterranean Sea. By studying the oscillations of the atmospheric neutrino flux passing through the Earth, thanks to the detector geometry and its unprecedented statistics, KM3NeT/ORCA's primary physics goal is an early measurement of the neutrino mass ordering as well as the direct observation of tau neutrino appearance; the last, allowing for a test of the standard three-neutrino flavours paradigm.

Due to the detector's modular structure, neutrino oscillation analyses are already possible with a partially instrumented volume. Given that the neutrino flux composition is dominated by muon neutrinos producing a track-like topology in the detector, the tau neutrinos can be identified as an excess into the shower-like topology, and the tau appearance, quantified in terms of the ν_τ-normalization, can be performed on statistical basis. In this summary, the focus will be given to the analysis of the data collected in the ORCA 6 geometry (6 Detection Units, equivalent to 5% of the final geometry); the description of a novel *Random Grid Search* algorithm developed to optimize the track-shower selection will be reported.

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1. Introduction

Next-generation experiments will reach high-precision measurements of the neutrino oscillation parameters, clarify the neutrino mass ordering, and observe possible CP violation in the leptonic sector. Additionally, validating the three-flavour paradigm remains one of the most stimulating goals because it allows for exploring new physics beyond the Standard Model (SM). The current precision on the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix elements reached a few percent[1]. Even though it will be decreased at the sub-percent level, it will remain relatively low (∼10%) in the τ-row; hence, ν_τ-appearance is a compelling channel to verify the non-unitary of the PMNS matrix, test the 3+1 light neutrinos hypothesis, and explore the sterile neutrino coupling with ν_τ. The ν_τ-normalization (n_τ) measurement, as the ratio of the detected ν_τ from oscillations to the SM prediction, represents a model-independent measure of new physics if tension with ν_τ= 1 arises.

The KM3NeT experiment is a large-volume neutrino water Cherenkov telescope under construction in the Mediterranean Sea, foreseeing two detector sites with complementary physics programs and exploring neutrinos in a wide energy range, from GeV to PeV. The KM3NeT/ARCA detector is optimized for astronomical studies; instead, KM3NeT/ORCA is expected to have the maximum sensitivity to atmospheric neutrino oscillation physics in the [1; 100] GeV scale. 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 will lead to worldwide best sensitivity to the neutrino mass ordering measurement, by studying the resonance oscillation in the earth's mantle due to the matter effect [1]. In addition to that, thanks to the accessible unprecedented statistics, KM3NeT/ORCA will have high sensitivity for the direct observation of ν_τ-appearance and use this channel to test the standard three-neutrino flavours paradigm.

1.1 The KM3NeT detector

The key KM3NeT detector's component is an array of 31 photomultiplier tubes (PMTs) hosted in a spherical Digital Optical Module (DOM); 18 DOMs are assembled into a Detection Unit (DU), standing vertically from the sea bed. The number of installed DUs determines the fiducial detector volume and will reach 7 Mton (115 DUs) in the nominal geometry. The detection principle is based on the collection of the Cherenkov radiation produced by secondary particles interacting with seawater; the event reconstruction uses maximum-likelihood algorithms to compute the residual time between the measured and the expected hits in each PMT. Two main event topologies can be identified: *track*-like events, every time a muon interacts with water, and *shower*-like events otherwise. The separation between the two topologies allows for identifying neutrinos interacting via charge (CC) or neutral (NC) currents and, possibly, their flavour.

Thanks to its modular structure, KM3NeT/ORCA can perform neutrino physics studies with a partially instrumented volume; currently, covering 16% of the nominal volume. The first complete neutrino oscillation analysis used the active volume of 6 DUs (∼ 5% of the nominal, named ORCA 6) and has been stably operating for 510 days (433 kton-years). The ORCA 6 data analysis allowed for investigating detector performance, developing the main neutrino oscillation analysis framework [2], and exploit the capabilities for the ν_τ-appearance measurement.

[1]Uncertainties on the lepton mixing PMNS matrix are from http://www.nu-fit.org/?q=node/238

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2. ν_τ-appearance analysis in KM3NeT/ORCA 6

KM3NeT/ORCA will have the unprecedented statistics of $\sim$ 3000 ν_τ/year [1] expected from the maximal oscillation of a pure ν_μ and ν_e initial flux crossing the earth. 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 ORCA 6 , ν_τ can be quantified as the excess in the *shower*-class, compared to the hypothesis of non-oscillation; hence, the n_τ measurement, as the number of observed ν_τ, is performed on a statistical basis. To do so, a strong background rejection and a robust event classification are required; these two goals are fulfilled by combining information from maximum likelihood algorithms and multivariate methods. The main sources of uncertainties affecting the n_τ measurement are due to CC neutrino cross-section [4] and the PMNS mixing matrix unitarity [5]. In the n_τ fit, both possibilities are investigated by scaling only the CC component (CC-only) or by allowing also the scaling of the expected NC fraction produced by tau neutrinos (CC+NC).

2.1 The Random Search Grid selection as an alternative particle identification method

Two maximum likelihood algorithms respectively optimized for tracks and showers provide the energy and direction reconstruction of atmospheric neutrinos as well as the rejection of the main background (atmospheric muons and ^{40}K decays); a classification based on Boosted Decision Trees (BDT) allows for further background suppression and better classification between the two topologies. Due to the ORCA 6 dimensions, an alternative selection using a *Random Grid Search* (RGS) algorithm has been developed [3]. This innovative approach aims at improving the shower sample purity and possibly optimize the sensitivity to the n_τ measurement; its main advantages are in the minimal and well-selected number of variables, without any training, optimized to select events in the region maximizing the signal-over-background fraction. As shown in Fig. 1 (left), the variables' choice is determined by their 2D separation power: given the phase space defined by two variables A and B, the RGS algorithm tests all possible combinations of cuts in this phase space, an example is given by the two red lines. For all tested cuts, the purity and the contamination of the

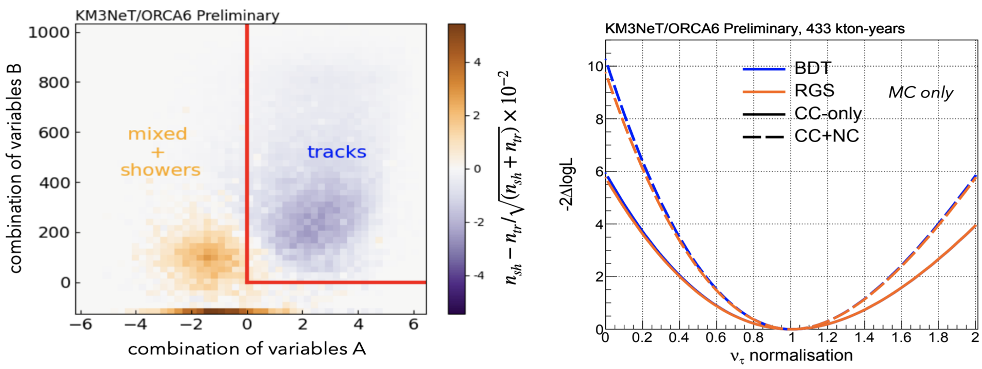

Figure 1: **left**: 2D phase space of variables A and B to explore cuts from RGS; **right**: ORCA 6 sensitivity to n_τ fit from RGS and BDT selection.

selected sample are quantified and the best combination is chosen by optimizing between the signal purity and reasonable statistics in the shower sample. Both selections led to a ν_τ sample of fewer than 200 events [3]; their performance has been studied in terms of their impact on the sensitivity to the n_τ fit. As for the neutrino oscillation analysis, a binned log-likelihood fit of the 2D reconstructed energy and cosine zenith distributions is performed on three classes of events (the purest *shower* and *track* samples and one contaminated *track* class, to better constrain the systematics). In Fig. 1 (right), the $\Delta\chi^2$ for a scan of the n_τ between 0 and 2 is shown, either varying only the CC-only contribution and keeping fixed the NC ones (solid lines) or by varying both (dotted lines): the orange and blue lines correspond to the RGS and BDT selections, respectively. Both results are strongly consistent, demonstrating the robustness of the RGS selection for this analysis.

2.2 ν_τ-normalization results

Ultimately, the first unblinded measurement of the n_τ of ORCA 6 data has been performed using the BDT selection [6]. As reported in Fig. 2, left, the n_τ is found to be $(0.50\pm^{0.46}_{0.42})$, disfavouring

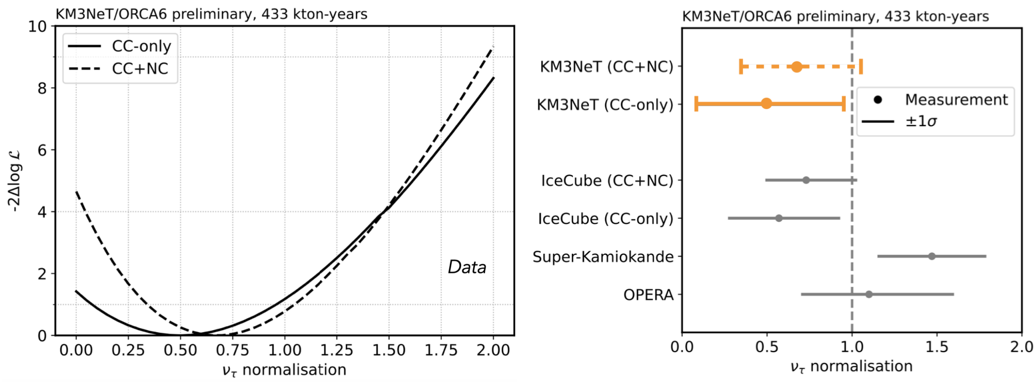

Figure 2: left: unblinded n_τ measurement in ORCA 6 ; **right**: comparison with other worldwide experiments.

$n_\tau = 0$ at 1.2 σ, under the hypothesis of having only CC interaction. In the case of CC+NC, instead, the curve shifts slightly to the right, disfavouring this possibility within 2.2 sigma, and the n_τ is measured at $(0.67\pm^{0.37}_{0.33})$. By comparing with other experiments (Fig. 2, right), a very nice agreement is observed, even though using data from a detector geometry corresponding to only 5% of the total active volume and a ν_τ sample still statistically limited.

References

[1] 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).

[2] V. Carretero, on behalf of the KM3NeT Collaboration *Measuring atmospheric neutrino oscillations with KM3NeT/ORCA6*, PoS(ICRC2023)996 (2023).

[3] L. Cerisy, A. Lazo, C. Lastoria, M. Perrin-Terrin, J. Brunner, and V. Dabhi *Particle identification in KM3NeT/ORCA*, PoS(ICRC2023)1191.

[4] Y. S. Jeong and M. H. Reno *Tau neutrino and antineutrino cross sections*, Physical Review D 82.3 (2010).

[5] S. Parke and M. Ross-Lonergan *Unitarity and the three flavour neutrino mixing matrix*, Phys. Rev. D 93 (11 2016), p. 113009.

[6] Nicole Geißelbrecht, for the KM3NeT collaboration *First measurement of tau appearance with KM3NeT/ORCA6*, PoS(ICRC2023)1107.