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Exploiting KM3NeT/ORCA data to study ν_τ and testing the non-unitary mixing

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After the measurement of the θ_{13} mixing angle of the oscillation matrix, neutrino physics entered in its precision era. Validating the 3ν-flavor paradigm through high-precision measurements of the mixing matrix elements is crucial, while exploiting neutrino oscillations to explore physics beyond the Standard Model remains a central focus in neutrino experiments.

The water Cherenkov neutrino telescope KM3NeT is under construction in the Mediterranean Sea at two sites: ARCA, offshore Sicily in Italy, and ORCA, offshore Toulon in France. KM3NeT/ORCA is being built to study neutrino oscillations in atmospheric neutrinos traversing the Earth, in the 1-100 GeV energy range. The sensitivity to this energy scale and to effects of matter on the oscillation probabilities enables KM3NeT/ORCA to achieve an early measurement of neutrino mass ordering and to constrain the atmospheric oscillation mixing parameters. Thanks to its huge fiducial mass, KM3NeT/ORCA will collect unprecedented statistics to exploit tau neutrino appearance, enabling an indirect test of the unitarity of the PMNS matrix. In this proceeding, the results of the first unblinded comprehensive study of this detection channel, based on the data collected with a partially instrumented volume (5% of the nominal), will be presented.

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1. Physics motivation

Due to many successful experiments, the current knowledge of neutrino properties has reached a fairly coherent picture. Neutrinos have been observed in three families (ν_e, ν_μ, ν_τ). The experimental observation of neutrino oscillations demonstrates that leptons mix and that neutrinos have non-zero mass. Nonetheless, massive neutrinos require an extension of the Standard Model (SM) of particle physics that has not yet been identified and represents a central goal of current and next generation neutrino experiments. The fundamental assumption of the experimental measurements of the oscillation parameters[1], currently reaching a few percent precision, is that the neutrino mixing takes place uniquely among the three observed families and, therefore, that the unitarity of the neutrino mixing matrix (U_{PMNS}, from Pontecorvo-Maki-Nakagawa-Sakata, who postulated it) holds. On the other hand, experimental observation of anomalies in the oscillation probabilities over short baselines, the low statistics particularly impacting the ν_τ flavor, and, thus, the higher uncertainties impacting the third row of the U_{PMNS} represents a strong motivation to test a non-unitarity extension of the mixing matrix and search for physics beyond the SM. Because of this landscape, the critical questions to be answered in neutrino oscillation physics can be summarized as clarifying the neutrino mass ordering, establishing the presence of the charge-parity symmetry violation in the leptonic sector, and testing the U_{PMNS} unitarity. Answering them requires reaching similarly large statistics in observation of the three neutrino flavors and high precision in the determination of the PMNS matrix' elements.

Focusing on atmospheric neutrinos in the 1-100 GeV energy range that completely propagate through the Earth and by exploring the ν_μ-disappearance channel, KM3NeT/ORCA is expected to constrain the corresponding oscillation parameters. On the other hand, by exploring mainly the ν_e-appearance channel KM3NeT/ORCA is expected to determine the neutrino mass ordering [2]. Thanks to its nominal active volume (7 Mton of seawater), the unprecedented statistics of ~ 3000 charge-current (CC) ν_τ per year will make KM3NeT/ORCA one of the leading experiments in exploring the ν_τ-appearance channel, from the maximal oscillation of a pure ν_μ and ν_e initial flux crossing the Earth.

[1] http://www.nu-fit.org/?q=node/228

2. The KM3NeT/ORCA experiment

The KM3NeT experiment is a water-Cherenkov neutrino telescope currently under construction in the Mediterranean Sea [1] at two detector sites. The two detectors, ORCA and ARCA, are being built to explore atmospheric and cosmic neutrinos in the GeV to above the PeV energy scale in a complementary physics program. The KM3NeT detection principle is based on the collection of Cherenkov radiation induced by relativistic charged particles traveling in seawater, produced after the neutrino interaction. The key components of the KM3NeT detector for the light detection is an array of 31 photo-multiplier tubes (PMTs) installed in a spherical Digital Optical Module (DOM). Grouped in sets of 18, they are assembled into Detection Units (DUs), standing vertically above 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 collaboration to perform physics studies already during the installation phase, with a partially instrumented volume.

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 following). Since then, larger geometries have been operated up to reaching the current coverage, corresponding to 29% of the nominal volume (115 DUs). The completion of the ORCA detector is expected in 2028. The data-taking period is divided into runs and data quality criteria are applied to exclude unfavorable periods due to high-bioluminescence activity, limited timing accuracy, and high trigger rates [3]. By applying such a run selection for more than 3 years of data taking and 11 detector configurations, both in ARCA and ORCA, an overall efficiency of 95% has been reached. The analysis in this work is performed by exploring ORCA6 data-taking, operated from January 2020 to November 2021, corresponding to a live-time of 510 days of high-quality data (433 kton-years exposure).

In KM3NeT/ORCA, the event reconstruction is obtained by applying maximum-likelihood algorithms, exploiting the residual time between the measured and the expected photon arrival times for each PMT; from this information, the time, the position, the energy, and the direction of each event is reconstructed. Two main event topologies can be reconstructed: *track*-like events, due to muons passing the detector volume, and *shower*-like events otherwise, that correspond to a localised source of light compared to the muons. All flavors of atmospheric neutrino interactions (both via CC and neutral currents, NC) are signal for ORCA, while atmospheric muons and optical noise (due to bioluminescence and ^{40}K decays in the seawater, as well as intrinsic PMT dark rates) are the two main sources of background. Detailed Monte Carlo (MC) simulations are generated both for the neutrino signal and the two main backgrounds.

3. ν_τ-appearance analysis in ORCA6

The study of the ν_τ-appearance channel in ORCA6 has been performed under two main different hypotheses, assuming or not the unitarity of the U_{PMNS} matrix. In this proceeding, the results detailed in [4] are summarized.

Given the intrinsic difficulties in identifying ν_τ-CC interactions on nucleons on an event-by-event basis in ORCA6 and due to the τ lepton decay branching ratios, the appearance of ν_τ is quantified on a statistical basis, as the excess in the *shower*-like event class when compared to the hypothesis of non-oscillation. The rejection of the two main backgrounds, the event classification between the two topologies, and the identification of a pure neutrino sample is based on algorithms exploiting Boosted Decision Trees techniques using variables from the maximum likelihood reconstructions and trained on the MC simulations. The corresponding statistics of the neutrino sample is of 5831 candidates in MC and 5828 candidates in data. This sample is divided into three classes: low/high purity track classes (depending on the allowed atmospheric muon contamination), and the shower class; the latter, with a statistics of 1959 events in MC and 1958 in data.

A binned log-likelihood fit of the 2D reconstructed energy, E, and cosine of the reconstructed zenith angle, θ, used as an approximation of the oscillation baseline L, is performed on the three aforementioned classes of events. Under the hypothesis of the mixing matrix unitarity to be true, the 3ν-paradigm is considered valid. Consequently, among the conditions on the PMNS matrix elements, six are defined as *normalizations*; they correspond to the sum of the squared elements in each row and column and are expected to be equal to 1. In the same scenario, restricting to the ν_τ-appearance channel, the parameter of interest is the ν_τ-normalization (referred to as S_τ), measured by fitting a model to the observed event distribution in data, and defined as the ratio of the number of observed and expected ν_τ neutrinos, in the 3ν-paradigm. In this approach, only a variation of the ν_τ-CC rate is expected; therefore, the information of the ν_τ-CC normalization can be inferred as a constraint of the ν_τ cross-section.

Alternatively, the neutrino mixing can be tested considering a *seesaw* type-I mechanism as the origin of the neutrino masses, relying on the existence of *Heavy Neutral Leptons*, as proposed in [5]. In this description, the neutrino oscillation matrix is unitary in $n \times n$ dimensions, while the U_{PMNS} is not because it is multiplied by a lower triangular matrix (α). This parametrization introduces 9 extra parameters to describe the neutrino oscillation. Therefore, the ν_τ-normalization is measured considering the variation of the expected ν_τ under this other hypothesis and it corresponds to the α_{33}-element of the triangular matrix. The impact is expected to be maximal around the standard oscillation maximum of the ν_τ-appearance oscillation channel. In this case, the fit is done including S_τ as a nuisance parameter. In contrast with the previous approach, in this case, both the ν_τ-CC and NC event rates can vary.

4. Results

In order to measure the ν_τ-normalization, the corresponding parameter of interest is profiled between 0 and 2, as shown in Fig. 1; on the left (right) plot, the result for the S_τ (α_{33}) parameter is reported. In the figure, the solid line corresponds to the profile at the best-fit, while the dashed lines represent the 68% and 90% confidence levels (CL) thresholds, according to Wilks' theorem. For better uncertainty evaluation the Feldman-Cousins (FC) method is used to define the confidence intervals through the generation of 1000 pseudo experiments for the parameter of interest. The FC corrections and the corresponding 1σ uncertainty are reported by the coloured lines in both plots. From the S_τ profile, the ν_τ-normalization is found to be $0.48^{+0.49}_{-0.33}$. This value corresponds to a total number of 92^{+94}_{-64} observed ν_τ-CC interactions. Similarly, but under the non-unitarity neutrino mixing hypothesis, the fit of the α_{33} parameter is reported. For this measurement the S_τ is included as a nuisance parameter, which is either fixed at 1 or as a prior with 20% uncertainty. 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

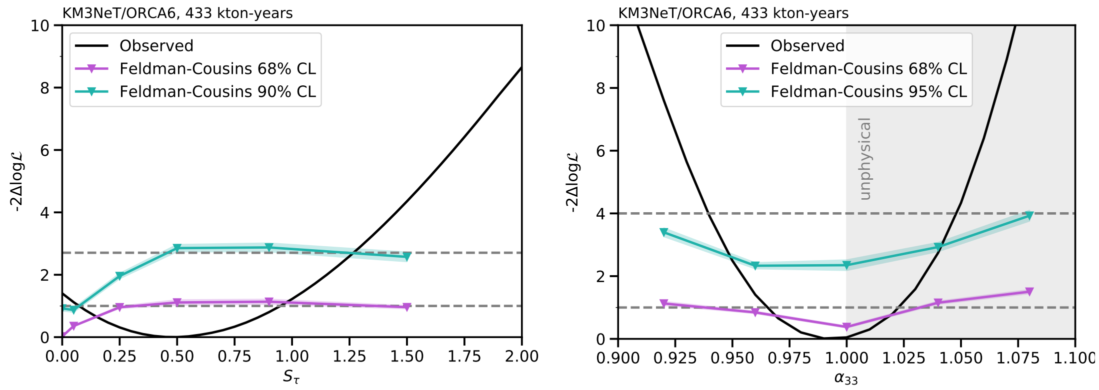

Figure 1: Measured log-likelihood profile of the ν_τ-normalisation in the 3ν-paradigm(S_τ parameter, as in the **left** plot) and in the non-unitarity framework (α_{33} parameter, as in the **right** plot).

comparison with the CC+NC ν_τ-normalization measurement by the IceCube Collaboration [6]. In the first case, the maximum of the likelihood is found at $\alpha_{33} = 0.83^{+0.20}_{-0.25}$; in the second, α_{33} is found at $0.993^{+0.026}_{-0.025}$. If S_τ is fixed, the corresponding number of total observed CC interactions is 132^{+60}_{-61} and the number of NC interactions is 313^{+11}_{-13}; otherwise, the total number of CC and NC interactions vary to 170^{+5}_{-9} and 325^{+1}_{-4}, respectively.

On the left side of Fig. 2, the ORCA6 ν_τ-normalization in the standard 3ν-paradigm is compared with the three other experiments which performed this analysis: OPERA [8], SuperKamiokande

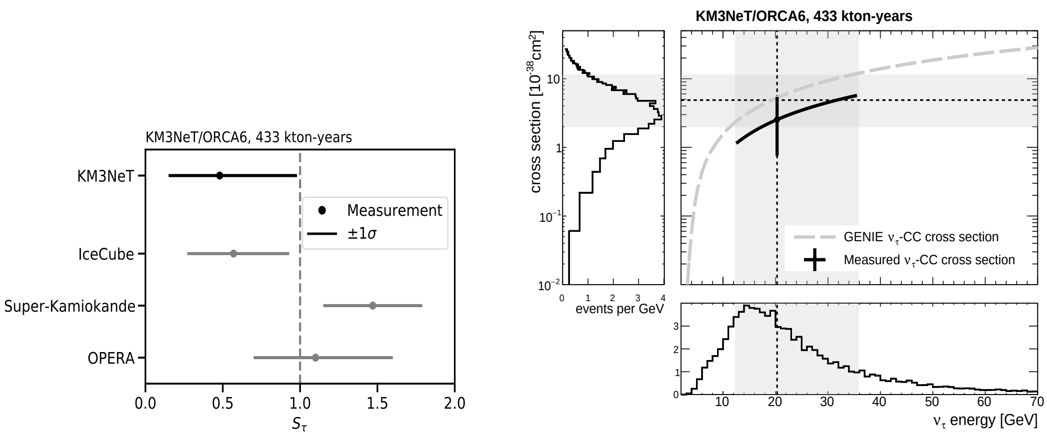

Figure 2: **Left**: Comparison of ORCA6 results with previous measurements on the ν_τ-CC normalisation. **Right**: Measurement of the ν_τ-CC cross section in black, compared to the averaged theoretical expectation given by GENIE, in gray, as a function of the true neutrino energy.

[9], and IceCube [6]. All the measurements are in agreement. In all results, the ν_τ-normalization is compatible with 1; hence, none of them is able to exclude the 3ν-paradigm.

In this paradigm in which only the ν_τ-CC event rate is expected to vary, the ν_τ-normalization (S_τ) can be interpreted as a scale factor on the ν_τ CC cross-section. The corresponding impact is reported in the right plot of Fig. 2. The energy-dependent theoretical expectation from the GENIE

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simulation [7] is scaled 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). The measured cross section, $\sigma_\tau^{\mathrm{meas}}(E_{\nu_\tau})$, is found at $(2.54^{+2.38}_{-2.17}) \times 10^{-38}\mathrm{cm}^2$ nucleon^{-1}. By comparison with similar measurements, this result is very well in agreement; in particular, in the similar energy range explored also by OPERA.

5. Conclusions and outlook

The ORCA6 analysis exploring the ν_τ-appearance channel is performed exploiting the data collected in an active volume corresponding to 5% of the nominal one and a dataset corresponding to 433 kton-years. Considering the significantly smaller exposure compared to previous experiments and the active volume very small ORCA volume compared to the nominal, the achieved precision is remarkable. This result demonstrates the competitiveness of KM3NeT/ORCA in the field and showcases its analysis strategy.

The enlargement of the detector volume and the corresponding data sample, a fine tuning of the fit methodology as well as an ongoing treatment of systematic uncertainties aim at further increasing KM3NeT/ORCA's precision in the exploration of the ν_τ-appearence oscillation channel.

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