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Results on Neutrino Non-Standard Interactions with KM3NeT/ORCA6 and ANTARES

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Neutrino Non-Standard Interactions appear naturally in several extensions of the Standard Model which try to accommodate mechanisms for the origin of neutrino masses. The Non-Standard Interactions are incorporated through effective four-fermion interactions which lead to both charged-current and neutral-current interactions. The latter affect coherent forward scattering of neutrinos on fermions in matter, ultimately leading to modifications of the oscillation probabilities of neutrinos experiencing matter potentials. Therefore, strong matter effects influencing the core-crossing trajectories of atmospheric neutrinos traversing the Earth would enhance such modifications, making neutrino telescopes ideal candidates for Non-Standard Interactions studies. This work presents the results of the Non-Standard Interactions search with the KM3NeT/ORCA6 and ANTARES neutrino telescopes, reporting bounds to the interaction coupling strengths at 90% CL which are comparable to the current most stringent limits in both cases.

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1. Introduction

1.1 Neutrino Non-Standard Interactions

Neutral-current (NC) Neutrino Non-Standard Interactions (NSIs) could modify the oscillation pattern of atmospheric neutrinos traversing the Earth. This new form of interactions would be allowed within extensions of the Standard Model, and are parameterised by with coupling strengths appearing in the effective neutrino propagation Hamiltonian as [1]

$$\mathcal{H}_{\text{eff}} = \frac{1}{2E}\mathcal{U}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{bmatrix}\mathcal{U}^{+} + A(x)\begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^{*} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^{*} & \varepsilon_{\mu\tau}^{*} & \varepsilon_{\tau\tau} \end{bmatrix}, \qquad (1)$$

where $A(x) = \sqrt{2}G_F n_e(x)$ is the standard matter potential for the electron number density at a given point, and $\mathcal{U}$ is the three-flavour PMNS matrix. The NSIs strength is therefore provided in relation to the standard electroweak interaction, and results from the incoherent sum of the neutrino scattering amplitudes on the three types of fermion found in matter ($e,\ u,\ d$): $\varepsilon_{\alpha\beta} = \varepsilon_{\alpha\beta}^{eV} + \frac{N_u}{N_e}\varepsilon_{\alpha\beta}^{uV} + \frac{N_d}{N_e}\varepsilon_{\alpha\beta}^{dV}$. In the following, only the NSIs couplings to the d quark are considered, since other choices can be derived by a simple rescaling given by the relative abundance of the other fermion.

1.2 KM3NeT/ORCA6 and ANTARES

KM3NeT/ORCA and ANTARES are water Cherenkov detectors in the Mediterranean Sea. Neutrino interactions near or inside the instrumented volume produce secondary charged particles, whose Cherenkov light yield is collected by a grid of vertical detection units (DUs) with optical modules hosting photomultiplier tubes (PMTs). In the case of ORCA, 31 PMTs are arranged inside Digital Optical Modules (DOMs) every 9 m along the DU, whereas ANTARES incorporates storeys of three single-PMT modules every 14.5 m. The ORCA detector is more densely instrumented with 20 m of horizontal line spacing compared to the 60 m of DU separation in ANTARES. In this way, ORCA can probe neutrino energies from 1 up to 100 GeV thus providing sensitivity to atmospheric neutrino oscillations, whereas ANTARES reaches higher energies with the ultimate goal of detecting neutrinos of astrophysical origin.

Since January 2020, the first ORCA configuration with six DUs (ORCA6) uninterruptedly took data until November 2021, when it was expanded with more detection units. ANTARES was completed in 2008 and operated until its decommission in 2022 with 12 DUs.

2. Event sample and selection

The ORCA6 dateset used in this analysis covers 433 kton-years of exposure, which were selected according to strict quality criteria on the environmental conditions and stability of the data-taking. After keeping only up-going reconstructed events (neutrinos crossing the Earth before reaching the detector) and filtering the pure-noise background based on trigger conditions, Boosted Decision Trees (BDTs) are employed to discriminate atmospheric neutrinos from the background of atmospheric muons, and further to isolate track-like event topologies (ν_μ charged-current, CC, and ν_τ with subsequent muonic τ decays) and shower-like ones (ν_e CC, ν NC and remaining τ

decays). Three event classes are distinguished with BDT cuts in ORCA6 as presented in figure 1 and combine to a total of 5828 observed events.

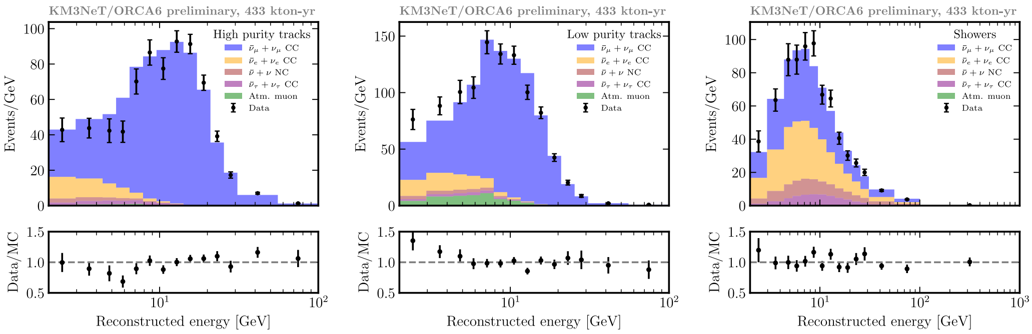

Figure 1: Event classes used in ORCA6. High purity tracks result after strict BDT cuts removing most of the atmospheric muons and shower-like interactions, whereas low purity tracks allow larger background contamination. The shower class presents the largest abundance of $\nu_e/\bar{\nu}_e$ and $\nu_\tau/\bar{\nu}_\tau$.

The ANTARES dataset covers 2830 days of livetime collected from 2007 to 2016, with 7710 observed events clustered into a single track-like class. Details on the selection can be found in [2]. The reconstructed energies resolved by ANTARES in the low-energy range go from 16 GeV up to 100 GeV. In comparison to ORCA6, which can more accurately constrain NSI effects around the oscillation valley (10-40 GeV) and coming from higher energy neutrinos (>40 GeV), ANTARES sensitivity to NSIs is mostly provided in the latter case.

3. Analysis

3.1 Method

The analyses proceed by comparing our observation with Monte Carlo (MC) templates weighted according to the hypothesis being tested. We use a Maximum Likelihood Estimator (MLE) of the NSIs and nuisance parameters, which uses the Poisson likelihood ($\mathcal{L}$) of observing the data given our MC expectation, binned in reconstructed zenith angle (baseline) versus reconstructed energy. Confidence intervals of the parameters are constructed by scanning the negative Log-Likelihood Ratio ($-2\log(\mathcal{L}_{NSIs}/\mathcal{L}_{bf}) = -2\Delta\log\mathcal{L}$) of each point in the NSIs space, computed using $\mathcal{L}$ at fixed NSIs over the likelihood at the global best fit. Fifteen nuisance parameters are profiled over in the MLE of the parameters. They model a variety of systematic uncertainties of the atmospheric neutrino flux (composition, energy and directional dependence), detector-related uncertainties (water properties, light propagation), interaction cross-section uncertainties (NC, ν_τ and individual class normalisations) and background modelling.

3.2 Results

In [3], figure 4, the ANTARES Collaboration presented the allowed regions at different confidence levels for $\varepsilon_{\mu\tau}$ in correlation to $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$. The bounds obtained from the ANTARES dataset are shown in comparison with ORCA6 and other experiments in figure 2. For ORCA6, the allowed

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regions at 90% CL are shown in figures 2 and 3 of [4] assuming complex-valued off-diagonal NSI couplings. The 90% CL limits are obtained in both ANTARES and ORCA6 from the likelihood ratio scans by assuming Wilk's theorem.

The width of the 90% CL allowed regions for the NSIs coupling strengths inspected in this study are shown in figure 2, in comparison to the bounds reported by IC-DeepCore [5], IceCube [6], Super-Kamiokande [7] and MINOS [8]. For ORCA6, the off-diagonal parameters are assumed real-valued for consistency with the other experiments. Both DeepCore and MINOS did not assume down-quark NSIs coupling, for which reason their limits have been rescaled following [5]. ANTARES placed bounds on $\varepsilon_{\mu\tau}$ close to the currently leading IceCube limits, and is followed closely by ORCA6. For the remaining coupling strengths, the 90% CL range is of the same order and compatible between ORCA6 and DeepCore.

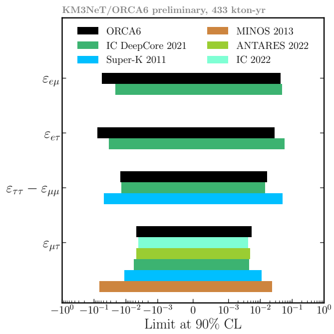

Figure 2: Comparison of the 90% CL limits reported in this work and DeepCore [5], IceCube [6], Super-K [7] and MINOS [8].

4. Conclusions

This work reports on the results from the NSIs search with 433 kton-year of ORCA6 and 10 years of ANTARES. No significant deviation from standard interactions was found by measuring atmospheric neutrino oscillations up to 100 GeV of reconstructed energies. The resulting bounds are of the order of the current most stringent limits, and in the case of ORCA they still offer room for improvement coming from extended instrumented volume.

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References

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