Neutrino non-standard interactions with the KM3NeT/ORCA detector

J. Mańczak[a], N. R. Khan Chowdhury[a], J.J. Hernández-Rey[a] and S. Navas Concha[b]
on behalf of the KM3NeT Collaboration

[a]Instituto de Física Corpuscular - Universitat de València and CSIC, Paterna, Valencia, Spain
[b] Universidad de Granada, Avda. del Hospicio, s/n C.P. 18010 Granada, Spain

Non-standard interactions

NSI are a subset of possible interactions not present in the Standard Model that involve left-chiral neutrinos and left and right-chiral fermions. Neutral current NSI would influence the neutrino propagation through the Earth according to an effective Hamiltonian[1]:

$$H_{eff} = \frac{1}{2E} U_{PMNS} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix} U^{\dagger}_{PMNS} + V_{CC} \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{bmatrix}, \quad (1)$$

where $V_{CC} = \sqrt{2} G_F N_e$ is the standard MSW (Mikheyev–Smirnov–Wolfenstein) effect electron Earth matter potential [2] and the NSI parameters $\epsilon_{\alpha\beta}$ (with $\alpha, \beta = (e, \mu, \tau)$) can be expressed as

$$\epsilon_{\alpha\beta} = \epsilon^{eC}_{\alpha\beta} + \frac{n_u}{n_e}\epsilon^{uC}_{\alpha\beta} + \frac{n_d}{n_e}\epsilon^{dC}_{\alpha\beta},$$

in terms of their coupling strength ϵ^{fC} to different fermions ($f = e, u, d$). Interactions of neutrinos with d-quarks only are assumed for simplicity and in this case $\epsilon_{\alpha\beta} = \epsilon^d_{\alpha\beta} n_d/n_e$ In this work the sensitivity for $\epsilon_{\mu\tau}$ is studied while other NSI parameters are assumed to be zero. Figure 1 shows the effect of opposite values of $\epsilon_{\mu\tau}$ in comparison to the standard oscillations for the muon neutrinos.

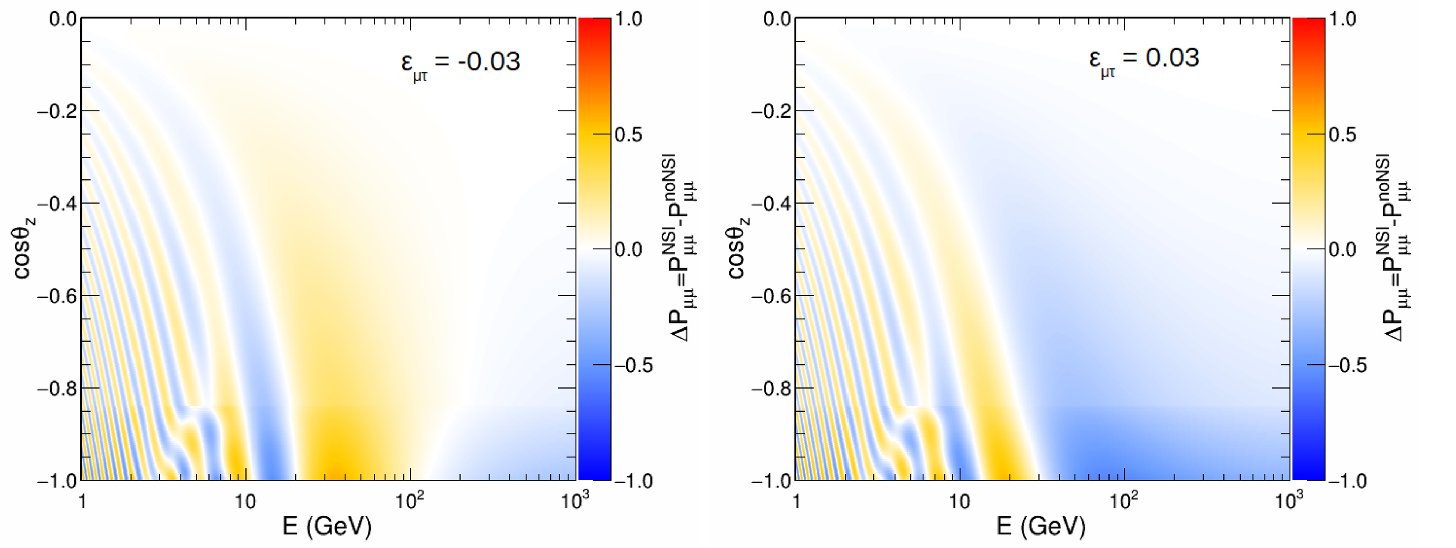


Fig. 1: Distributions of the difference between the summed survival probabilities of the atmospheric muon neutrinos $\nu_\mu + \bar{\nu}_\mu$ arriving at the KM3NeT/ORCA detector from NSI and no-NSI models as a function of $\cos(\theta_{\text{zenith}})$ and neutrino energy for opposite values of $\epsilon_{\mu\tau}$.

KM3NeT/ORCA detector

- ORCA (Oscillations Research with Cosmics in the Abyss) is the low-energy node of KM3NeT, the next generation underwater neutrino detector in the Mediterranean sea. The finalKM3NeT/ORCA detector block will consist of 115 DUs (Detection Units or "strings")
- Each DU comprises 18 DOMs (Digital-Optical Modules) each equipped with 31 3-inch photomultipliers (PMTs) and sensitive to the Cerenkov light induced by the charged products of the neutrino interactions with the seawater.
- The present configuration of ORCA has six DUs deployed and operating. With an energy threshold of a few GeV and an effective mass of several Mtons, KM3NeT/ORCA can also make precision measurements of atmospheric neutrino oscillation parameters.
- Its access to a wide range of energies and baselines makes it optimal to discover exotic physics beyond the Standard Model such as NSI.

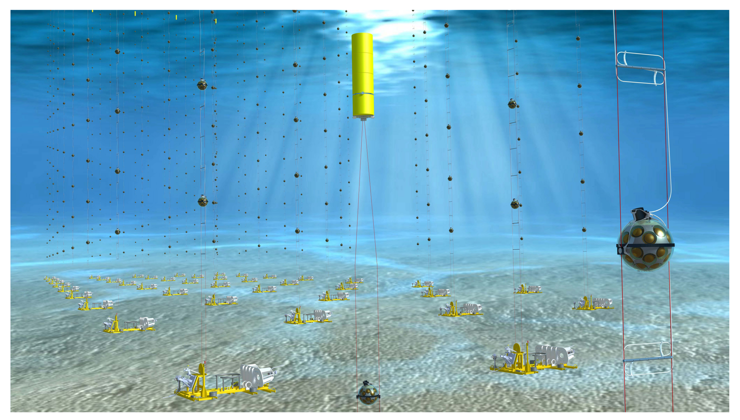


Fig. 2: KM3NeT/ORCA detector, an artistic vision

Analysis method

To study the ORCA115 sensitivity for $\epsilon_{\mu\tau}$, a profile Poisson likelihood ratio is calculated with respect to the non-NSI pseudo-data nominal parameters:

$$-2\ln\left(\frac{L(\epsilon_{\mu\tau},\eta)}{L(0,\hat{\hat{\eta}})}\right) = 2\sum_{bins}\left(N_{NSI}(\epsilon_{\mu\tau},\eta) - N_{STD}(0,\hat{\hat{\eta}}) + N_{STD}(0,\hat{\hat{\eta}})\ln\frac{N_{STD}(0,\hat{\hat{\eta}})}{N_{NSI}(\epsilon_{\mu\tau},\eta}\right) + \sum_{syst}\frac{\eta-\bar{\eta}}{2\sigma^2_\eta}, \quad (2)$$

where $\hat{\hat{\eta}}$ here indicates the nominal values of the nuisance parameters. For each point scanned in $\epsilon_{\mu\tau}$, the sum of the likelihood ratio (Eq. 2) from all the separate PID classes is minimized over the set of the nuisance parameters $\{\eta\}$.
For ORCA6 no fits are performed and the likelihood profiling for each scanned value of $\epsilon_{\mu\tau}$ is done only over the mass ordering with NuFit best fit values for NO (Normal ordering) and IO (Inverted Ordering) [3].

Symulations and event selection

- **ORCA115** sample is divided by a PID score (Particle Identciation) generated with machine-learning RDF-based algorithm (Random Decision Forest) in 3 separate classes: **tracks**, **showers** and **intermediate** (ambiguous event topology). The MC sample corresponds to **3 years** of data taking, which is the minimum time necessary for resolving the mass hierarchy[5].
- For **ORCA6** no particle identification is used yet. Shower reconstruction is still not optimised for the limited size of ORCA6, so that only track reconstruction is taken into account in this study. For this reason, even without PID, the fraction of ν_μ in the ORCA6 MC reconstructed neutrino sample reaches roughly 70%. For the detailed explanation of event selection for ORCA6 see the presentation in this conference *First neutrino oscillation measurement with KM3NeT/ORCA* (Presenter-Forum Number: 345).

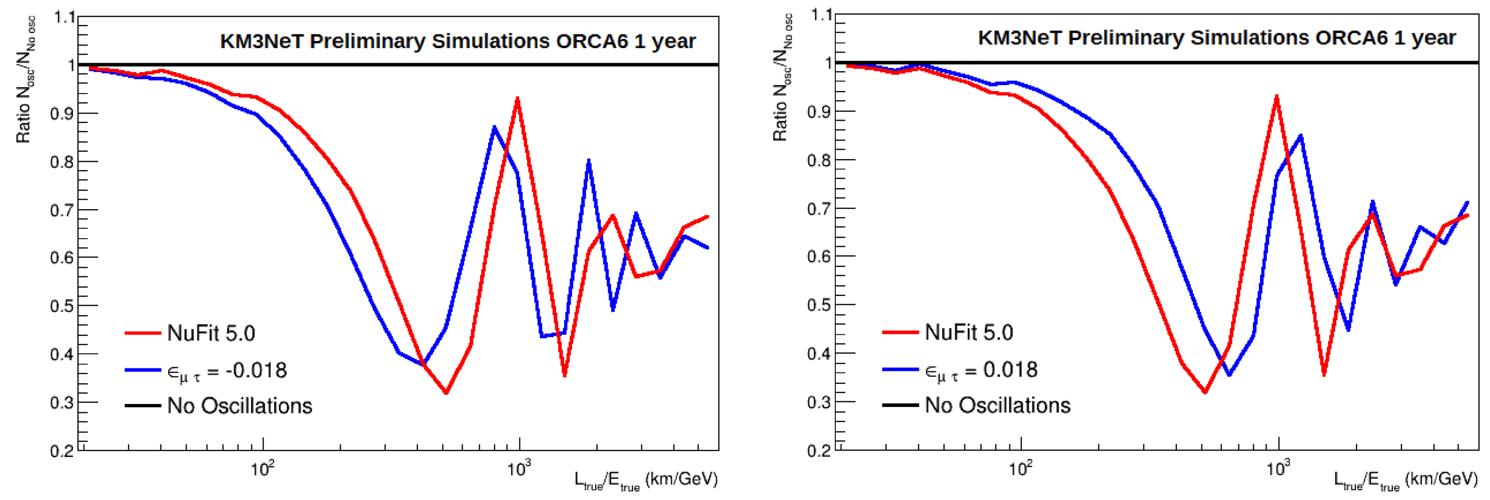
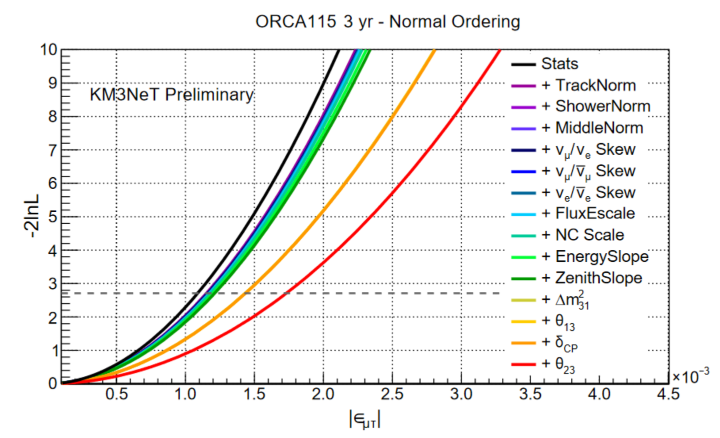


Fig. 3: One-year ORCA6 distributions of the ratio of event rates for oscillated to unoscillated MC as a function of the true oscillation length divided by the true neutrino energy for the selected events.

Figure 3 shows the event distribution obtained for ORCA6 with an oscillated, 1-year equivalent Monte Carlo simulated sample, in the true L/E (oscillation length divided by energy) space, after the selection is applied. Despite all the limitations mentioned above, ORCA6 is capable of observing the effect of $\epsilon_{\mu\tau}$ on neutrino oscillations at a significant level.

Systematics

Figure 4 (left hand side) shows that the systematics with the strongest impact for NSI study with ORCA115 are the unconstrained standard oscillation parameters [4]. The nominal values and the priors from the table in Fig 4 (right hand side) are used in the second term log-likelihood ratio formula (Eq. 2) as the mean $\bar{\eta}$ and standard deviation σ_η representing Gaussian external constraints on the systematic parameters.



Nuisance parameters	Treatment	Nominal values	Priors
Oscillation			
$\theta_{12}(^\circ)$	fixed	33.82	-
$\theta_{13}(^\circ)$	fitted	8.60	0.13
$\theta_{23}(^\circ)$	fitted	48.6	free
$\delta_{CP}(^\circ)$	fitted	221	free
$\Delta m^2_{21}(\times 10^{-5}\text{eV}^2)$	fixed	7.39	-
$\Delta m^2_{31}(\times 10^{-3}\text{eV}^2)$	fitted	2.528	free
Flux			
Track norm.	fitted	1	free
Shower norm.	fitted	1	free
Middle norm.	fitted	1	free
ν_μ/ν_e skew	fitted	0	5%
$\nu_\mu/\overline{\nu}_\mu$ skew	fitted	0	5%
$\nu_e/\overline{\nu}_e$ skew	fitted	0	5%
Energy slope ($\Delta\gamma$)	fitted	0	5%
Zenith slope	fitted	0	2%
Cross-section			
NC scale	fitted	1	5%
Detector			
Energy scale	fitted	1	10%

Fig. 4: Incremental impact on $\epsilon_{\mu\tau}$ sensitivity of all the systematic parameters used for ORCA115 (left) and the table of systematic parameters used with ORCA115 (right).

The impact of the systematic uncertainties in the KM3NeT/ORCA6 sample is still being investigated. So far it was found that the nuisance parameter with the largest influence for the $\epsilon_{\mu\tau}$ study is Δm^2_{31}. Changing the sign of $\epsilon_{\mu\tau}$ flips the preferred mass ordering, which introduces degeneracy. In Fig 5 contours with 90% CL allowed regions in Δm^2_{31} versus $\epsilon_{\mu\tau}$ are shown to portrait the correlation between these parameters.

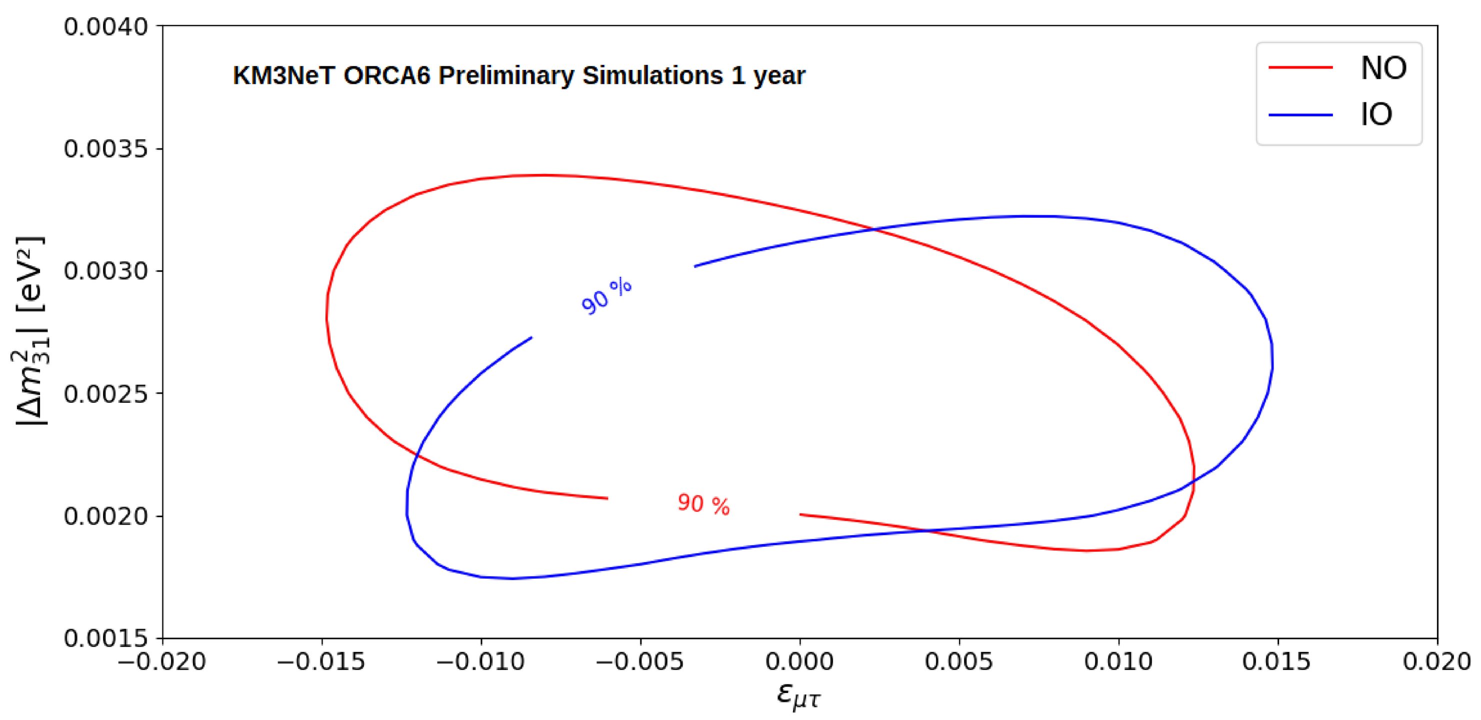


Fig. 5: 90% CL sensitivity contours in $\epsilon_{\mu\tau}$ and Δm^2_{31} with ORCA6 1 year MC sample for both mass hierarchies assuming true NO.

Despite the correlation between $\epsilon_{\mu\tau}$ and Δm^2_{31} which is visible regardless of the ordering, for the current detector exposure of approx. 1 year, ORCA6 sensitivity is expected to be dominated by the sample statistics.

KM3NeT/ORCA sensitivity for $\epsilon_{\mu\tau}$

Almost all the sensitivity for $\epsilon_{\mu\tau}$ with KM3NeT/ORCA comes from the track events populated mainly by atmospheric $\nu_\mu(\bar{\nu}_\mu)$ oscillating to $\nu_\tau(\bar{\nu}_\tau)$. It means that even without the shower reconstruction, ORCA6 can already give a good estimation of its final capability to measure $\epsilon_{\mu\tau}$.

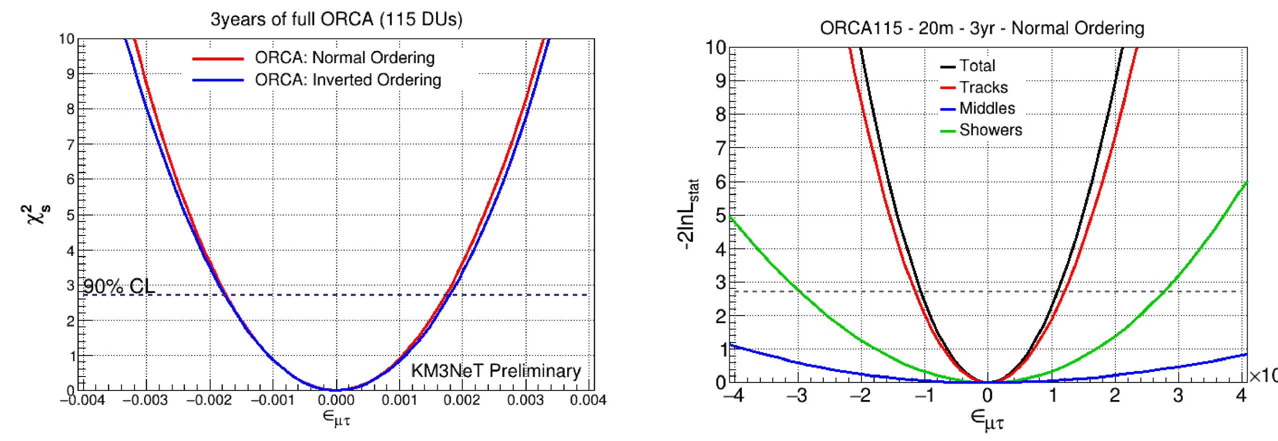


Fig. 6: Caption of the figure

As can be seen in Figure 6 (left), neutrino mass ordering does not affect KM3NeT/ORCA sensitivity to $\epsilon_{\mu\tau}$. It is the case due to the anti-correlation between the sign $\epsilon_{\mu\tau}$ and Δm^2_{31}. Taking this into account, the final analysis was performed only with NO as the pseudo-data generation input.

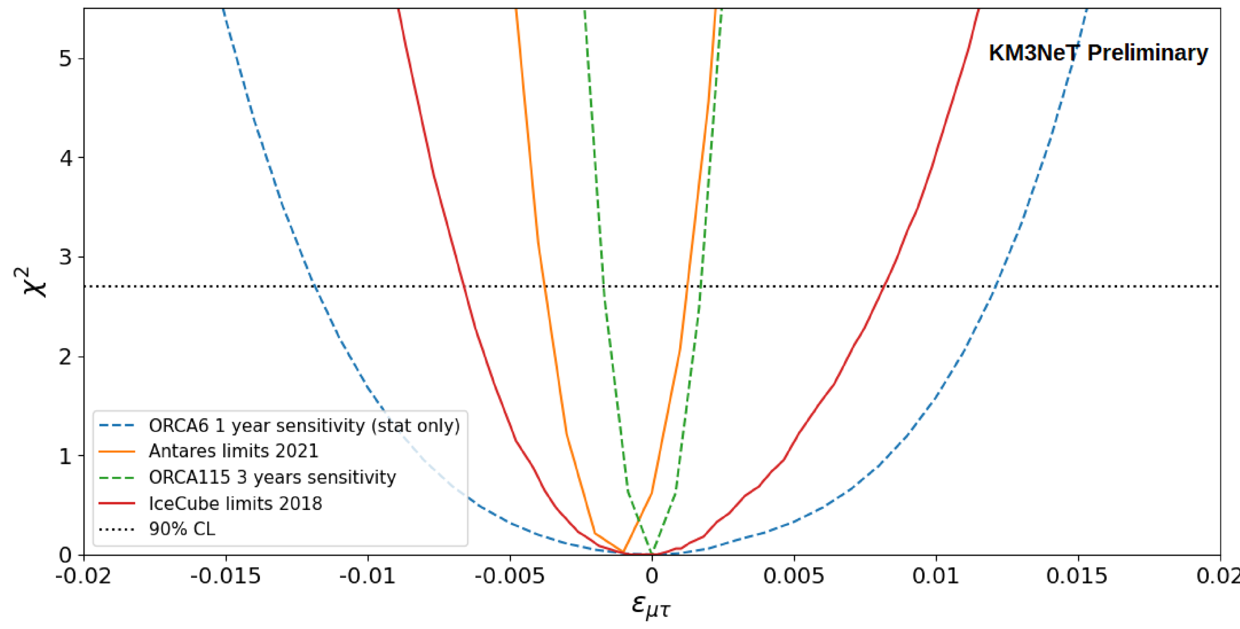


Fig. 7: KM3NeT/ORCA sensitivities compared with the best worldwide limits from IceCube and ANTARES

Figure 7 shows the sensitivities of ORCA6 and ORCA115 for $\epsilon_{\mu\tau}$ compared with limits from other experiments. The 90% CL sensitivities assuming NO are:

- for 1 year of ORCA6 (statistics only):

$$-12 \times 10^{-3} < \epsilon_{\mu\tau} < 12 \times 10^{-3},$$

- for 3 years of ORCA115 (full set of systematics):

$$-1.7 \times 10^{-3} < \epsilon_{\mu\tau} < 1.7 \times 10^{-3}.$$

Conclusions

- Using only one year of data-taking, the ORCA6 configuration, which constitutes about 5% of the full detector, is able to reach a measurement precision of $\epsilon_{\mu\tau}$ only two to three times worse than the current limit.
- Moreover, as ORCA grows in size, not only the event statistics per running time will increase, but also the energy resolution and the highest measurable muon energy, which will improve significantly the sensitivity to the $\epsilon_{\mu\tau}$ parameter.
- When completed, the KM3NeT/ORCA detector will potentially become the world's best tool for probing neutrino non-standard interactions with atmospheric neutrinos.

References

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