PROCEEDINGS OF SCIENCE

Searches for neutrino physics beyond the Standard Model with KM3NeT/ORCA6

V. Carretero[a,*] **for the KM3NeT Collaboration**

[a] *IFIC (UV-CSIC),*
Carrer del Catedràtic José Beltrán Martinez, 2, 46980, Valencia, Spain

E-mail: vcarretero@km3net.de

Upcoming neutrino experiments will not only constrain oscillation parameters with an unprecedented precision, but will also search for physics beyond the Standard Model. ORCA is the atmospheric neutrino detector of the KM3NeT telescope, sensitive to energies from a few GeV to around 100 GeV and with a large potential to explore new physics. A high-purity neutrino sample from data taken with the first six detection units deployed has been selected. The sample has been analysed to probe sub-dominant effects in the oscillation patterns of atmospheric neutrinos propagating through the Earth, as invisible neutrino decay and Non-Standard Interactions. In this contribution, the boundaries obtained for the decay parameter, $\alpha_3 = m_3/\tau_3$, and the flavour violating interaction parameters, $\epsilon_{\alpha\beta}$, are presented together with future sensitivity perspectives after ten years of data taking with the final ORCA configuration of 115 detection units.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

https://pos.sissa.it/

PoS(ICHEP2022)578

1. Introduction

The KM3NeT collaboration is building two next-generation neutrino detectors, which share the same technology but have different physics goals [1]. ARCA (Astroparticle Research with Cosmics in the Abyss), located 80 km off the Sicilian coast near Capo Passero (Italy) at a depth of 3450 m, will be used to search for high energy neutrinos from astrophysical sources. ORCA (Oscillation Research with Cosmics in the Abyss) is being constructed near the French coast of Toulon, 2450 m deep. The main goal of ORCA is to estimate the neutrino mass ordering making use of the matter effects encountered by the atmospheric neutrino flux crossing the Earth. In addition, with ORCA it will be possible to study exotic effects beyond the Standard Model (BSM) in the neutrino sector, such as sterile neutrinos, quantum decoherence, non-standard interactions (NSI), and invisible neutrino decay. In this contribution the focus is on the last two topics.

The Cherenkov photons produced by relativistic charged particles coming from neutrino interactions will be picked up by large arrays of optical sensors. In pressure-resistant glass spheres known as Digital Optical Modules (DOMs) a total of 31 photomultiplier tubes (PMTs) and the corresponding readout boards are housed [2]. The DOMs are positioned along vertical flexible strings known as Detection Units (DUs), which are anchored to the sea floor and held vertical by the buoyancy of the DOMs and a submerged buoy at the top. ORCA will consist of one block of 115 DUs, each one equipped with 18 DOMs. The vertical distance between DOMs is 9 m and the DUs are separated horizontally by 20 m. The instrumented volume of ORCA contains about 7 Mt of sea water. At present, 11 DUs are already deployed and taking data. The results presented in this contribution correspond to the first data taken with the 6-DU configuration, hereafter ORCA6. The estimated sensitivities correspond to the full ORCA configuration, hereafter ORCA115.

The first BSM scenario considered in this contribution refers to Non-Standard Interactions (NSI). Several theories generalise BSM phenomena including hefty TeV-scale bosons that can cause new interactions in addition to the Standard Model matter effects [3]. In this work, the effects of non-standard interactions between atmospheric neutrinos and the Earth fermionic matter are investigated. Effective descriptions of NSI include the following Hamiltonian:

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{\tau e} & \epsilon^*_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix},$$

where the NSI parameters $\epsilon_{\alpha\beta}$, with $\alpha, \beta = (e, \mu, \tau)$, can be expressed as:

$$\epsilon_{\alpha\beta} = \epsilon^e_{\alpha\beta} + \frac{n_u}{n_e}\epsilon^u_{\alpha\beta} + \frac{n_d}{n_e}\epsilon^d_{\alpha\beta}$$

in terms of their coupling strengths to different fermions, $f = e, u, d$. The interactions with u quarks and electrons are neglected for the sake of simplicity. The results reported here can easily be rescaled to derive the NSI coupling strengths to the other fermions on the assumption that the Earth density profile has a stable relation $n_d \approx 3n_e$ and that the matter of the Earth is electrically neutral. Here the focus is on constraining only the $\epsilon_{\mu\tau}$ parameter. In general, the off-diagonal NSI parameters might also have a complex phase, but only their real part is taken into account.

In a BSM scenario, neutrinos can decay into a lighter fermion state and a BSM boson according to several theoretical models [4]. The depletion factor, $D = e^{-\frac{m_i L}{\tau_i E}}$, can be used to characterise relativistic neutrino decay, where τ_i is the lifetime in the rest frame of the state with mass m_i. The expression refers to the portion of neutrinos of energy E that decay over a distance L. In this study, the parameter, $\alpha_i = m_i/\tau_i$, is used to describe the neutrino decay. Since the ν_1 and ν_2 decays are well constrained by solar and supernova data [5, 6], in this contribution the focus is on ν_3 decays, which are not so well constrained.

2. Analysis

The events in ORCA are divided into two topologies: $track-like$ (ν_μ CC events and ν_τ CC events in which the produced tau decays into a muon) and $shower-like$ (ν_e CC events, the remaining ν_τ CC event decay channels, and all ν NC events). By applying a maximum likelihood fit and assuming a specific topology (track-like or shower-like), the energy and direction of the events are reconstructed. The analysis was conducted with the first 354.6 days of data taken with the ORCA6 configuration. A total of 1237 high quality track-like events were selected with an expected atmospheric muon contamination of a 3%.

The analyses to constrain the invisible decay parameter, α_3, and the NSI $\epsilon_{\mu\tau}$ parameter, are based on the maximisation of a binned log-likelihood constructed with bins of the two-dimensional distribution of events in $\log_{10}(E_{\text{reco}})$ and $\cos\theta_{\text{reco}}$. The observed data is compared to a model prediction assuming a specific value of the probed parameter, ϕ. Each maximisation is performed four times, assuming both θ_{23} octants and both possible neutrino mass orderings to avoid local maxima. In the absence of actual data (ORCA115), sensitivities are calculated using the Asimov method, which entails assessing the sensitivity from sample datasets. Using NuFit 5.0 [7], the representative Asimov datasets are simulated under the assumption of standard oscillation parameters. Poisson distributions for the expected number of events in each bin and Gaussian distributions linked to the nuisance parameters are used to build the log-likelihood. It is assumed that the negative log-likelihood will follow a chi-square distribution:

$$\chi^2(\phi) = -2\log L = \min_{\vec{\epsilon}} \left\{ 2\sum_{i,j} \left[(N_{ij}^{\text{mod}}(\phi;\vec{\epsilon}) - N_{ij}^{\text{dat}}) + N_{ij}^{\text{dat}} \log\left(\frac{N_{ij}^{\text{dat}}}{N_{ij}^{\text{mod}}(\phi;\vec{\epsilon})} \right) \right] + \sum_k \left(\frac{\epsilon_k - \langle \epsilon_k \rangle}{\sigma_k} \right)^2 \right\}, \tag{1}$$

where N_{ij}^{mod} and N_{ij}^{dat} denote the number of reconstructed events predicted by the model and the number of events actually observed in the bin (i,j), respectively. The parameters of the model that define the distributions are represented by $\vec{\epsilon}$, and they are made up of oscillations parameters and nuisance parameters associated with systematic uncertainties. Some of the parameters are constrained with priors that act as ‘penalties’ preventing the maximisation procedure to find minima with values of the nuisance parameters far from those provided by external experiments (mean value $\langle\epsilon_k\rangle$ and standard deviation σ_k). The systematics included in this analysis can be found in table 1 and are discussed in Ref. [8].

Systematic	**Expectation value, μ_k**	**Standard deviation, σ_k**
Track normalisation	1	No prior
τ CC normalisation	1	0.2
NC normalisation	1	0.5
Cosmic muon normalisation	1	No prior
$\nu_\mu/\bar{\nu}_\mu$ ratio	0	0.05
$\nu_e/\bar{\nu}_e$ ratio	0	0.07
ν_μ/ν_e ratio	0	0.02
Spectral index	0	0.3
$\nu_{\text{up}}/\nu_{\text{hor}}$ ratio	0	0.02
Energy scale	1	0.05
Δm^2_{31} (NO/IO) [10^{-3} eV^2]	2.528/−2.424	No prior
θ_{23} (NO/IO) [°]	49.2/49.3	No prior

Table 1: List of systematic parameters used in the fitted model with their corresponding priors.

3. Non-Standard Interactions

In figure 1, the reconstructed zenith angle distribution is shown for four energy ranges. The blue line shows the expected number of events for the best-fit parameter values, while the red line is for $\epsilon_{\mu\tau} = 0.012$ and the rest of parameters fitted. This proves that vertical medium energy events are the most contributing to the measurement of $\epsilon_{\mu\tau}$ in ORCA6. In figure 2, the 90% CL limit in $\epsilon_{\mu\tau}$ is shown alongside current experiment limits. The 90% CL interval is $-8.7\times10^{-3} < \epsilon_{\mu\tau} < 9.0\times10^{-3}$, which is of the same order of magnitude as those measured by current experiments as shown in the figure.

After three years of data taking with ORCA115 the confidence interval will improve up to $-1.7\times10^{-3} < \epsilon_{\mu\tau} < 1.7\times10^{-3}$. This sensitivity is preliminary and is expected to get updated in the near future. On the other hand, the parameter $\epsilon_{\mu\tau}$ is degenerated with neutrino mass ordering [3], so the sensitivity to this parameter will increase even more once the true ordering is determined.

4. Invisible neutrino decay

The 90% CL upper limit obtained for the decay constant, α_3, with 355 days of data taking with ORCA6 is reported in figure 3 left. The black curve represents the expected median sensitivity derived from the Asimov dataset and the blue curve is the result obtained with the observed data. The 90% upper limit is 2.4×10^{-4}eV^2. The 90% CL contour (see figure 3 right) constraining both θ_{23} and α_3 at the same time shows how the sensitivity to α_3 is degraded by lacking proper sensitivity to θ_{23} octant. Increasing θ_{23} precision as the detector grows will greatly enhance the sensitivity to the invisible decay parameter.

In figure 4 left, the expected sensitivity for KM3NeT/ORCA115, including shower events and particle identification algorithms to separate topologies, is reported for both true orderings and 3 and 10 years of data taking. In the case of true IO, the θ_{23} degeneracy shows how the sensitivity

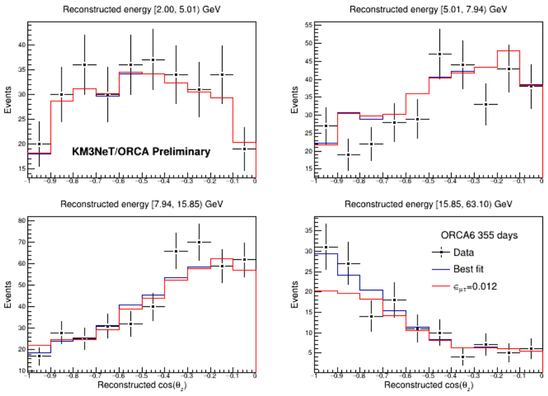

Figure 1: Distributions of the reconstructed cosine of the zenith angle for four energy ranges and 355 days of ORCA6 data taking, best fit (blue) and fixing $\epsilon_{\mu\tau}$ to 0.012 (red).

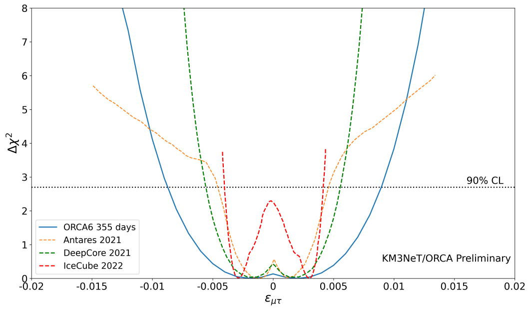

Figure 2: $\Delta\chi^2$ as a function of $\epsilon_{\mu\tau}$ for 355 days of ORCA6 data taking. The results from current experiments are also shown.

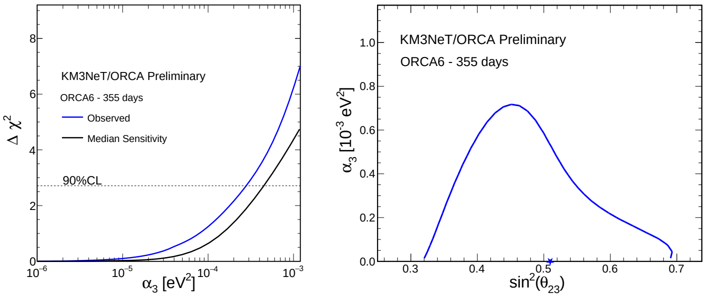

Figure 3: Left: $\Delta\chi^2$ as a function of α_3 for 355 days of data taking with ORCA6 (blue) and median Asimov sensitivity (black). Right: $\theta_{23} - \alpha_3$ 90% CL contour for 355 days of data taking with ORCA6.

gets degraded beyond the 90% CL. The effect happens also for NO but for higher values of α_3. The sensitivity to θ_{23} for the ORCA115 configuration is high enough to prevent the degradation in the desired CL, as can be seen in the contour in figure 4 right.

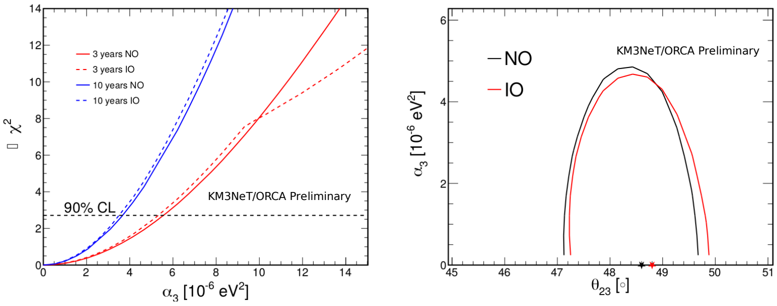

Figure 4: Left: Sensitivity as a function of α_3 assuming true NO (solid) or IO (dashed) for 3 (red) and 10 (blue) years of KM3NeT/ORCA115 data taking. Right: $\theta_{23} - \alpha_3$ 90% CL contour for true NO (black) and IO (red) for 10 years of KM3NeT/ORCA115 data taking.

5. Conclusions

With only the 5% of its final configuration, the ORCA detector is able to probe BSM effects in atmospheric neutrino oscillations. The 90% CL upper limits in neutrino invisible decay α_3 (2.4×10^{-4} eV^2) and NSI $\epsilon_{\mu\tau}$ interval ($-8.7 \times 10^{-3} < \epsilon_{\mu\tau} < 9.0 \times 10^{-3}$) are of the order of magnitude of current experiments. The detector deployment is progressing steadily and these measurements will improve as the detector volume gets larger.

6. Acknowledgements

This research was supported by an FPU grant (Formación de Profesorado Universitario) from the Spanish Ministry of Science, Innovation and Universities.

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