physical sciences forum

MDPI

Proceeding Paper

Neutrino Oscillation Measurements with KM3NeT/ORCA †

Johannes Schumann on behalf of the KM3NeT Collaboration

Erlangen Centre for Astroparticle Physics, Universität Erlangen-Nürnberg, Nikolaus-Fiebiger-Straße 2, 91058 Erlangen, Germany; johannes.schumann@fau.de

† Presented at the 23rd International Workshop on Neutrinos from Accelerators, Salt Lake City, UT, USA, 30–31 July 2022.

Abstract: KM3NeT/ORCA is an underwater neutrino telescope which is currently being deployed in the Mediterranean Sea. Its geometry has been optimized for the study of neutrino oscillations using atmospheric neutrinos (within an energy range of 1–100 GeV). In particular, this will allow to measure the neutrino mass hierarchy as well as the oscillation parameters θ_{23} and Δm^2_{31}. The data from the ORCA detector with a six string configuration and one year of exposure has already allowed to exclude the non-oscillation hypothesis with more than $5\,\sigma$. In this contribution an overview of current results will be presented and the sensitivity of a fully deployed ORCA detector will be discussed.

Keywords: neutrino oscillations; detector; KM3NeT

1. Introduction

The KM3NeT Collaboration is building a water Cherenkov detector infrastructure in the Mediterranean Sea. KM3NeT consists of two detectors, ARCA and ORCA, which share photo detection technology but differ in the density of the arrangement. In general the detectors are a combination of so-called building blocks, each containing 115 vertical lines, the so-called detection units (DU). A single DU holds 18 digital optical modules (DOM), which have a segmented photosensitive area provided by 31 3″ photomultiplier tubes housed in a 17″ glass sphere.

ARCA consists of two building blocks with its geometry optimised for the detection of neutrinos in the energy range between TeV and PeV in order to study neutrinos from astrophysical sources. It is located off the coast of Sicily at a depth of 3.5 km and it will cover an instrumented volume of about 1 km^3 [1].

The ORCA detector consists of one building block with its geometry optimised for the detection of atmospheric neutrinos, which dominate the flux for energies between 1 GeV and 100 GeV. It will cover an effective detection target mass of about 7 Mt. It is designed to determine the neutrino mass hierarchy (NMH) and measure the oscillation parameters Δm^2_{31} and θ_{23}. ORCA is deployed off the coast of southern France near the city of Toulon at a depth of 2.5 km [2].

2. Data Taking

The data taking of the ORCA detector has been on-going in different sub-configurations since 2017 as the detector grows. In 2020, the first important intermediate step was achieved by the first six DUs deployed, which allowed for the first oscillation measurements to be performed.

Within this data collection period, the detector had an uptime of approximately 96%. After an additional run selection in order to remove, e.g., calibration or data runs with high impact from signal background, the first dataset was presented in 2021 with 355 days of livetime recorded. This was extended until 2022 to 540 days.

The average trigger rate for ORCA6 is 8.5 Hz, where the contribution of atmospheric muons is 7.2 Hz, atmospheric neutrinos is about 0.2 mHz and the rest is related to pure

Citation: Schumann J., on behalf of the KM3NeT Collaboration. Neutrino Oscillation Measurements with KM3NeT/ORCA. *Phys. Sci. Forum* **2023**, *8*, 35. https://doi.org/10.3390/psf2023008035

Academic Editor: Yue Zhao

Published: 9 August 2023

noise, i.e., potassium 40 decay and bioluminescence [3]. In the final 115 DU configuration, the expected trigger rate is 50 Hz for background events, e.g., atmospheric muons, and 8 mHz for atmospheric neutrinos [2]. In order to filter the overall triggered events for atmospheric neutrino events selection cuts are applied, which are based on the number of hits and track quality parameters, position and direction information provided by the reconstruction algorithms [4,5].

The previously published results are based on a reconstruction using a track-like event hypothesis. The small number of DUs causes larger systematic uncertainties due to track-like events induced by muons at higher energies, which are often partially contained and their energies are underestimated.This problem will be solved in future by deploying a lager number of DUs.

For upcoming studies and measurements, reconstructions based on a shower-like hypothesis are also incorporated. In combination with an improved event selection, the sample size will increase by a factor of four for the dataset with 540 days of livetime.

3. Oscillation Parameters and Neutrino Mass Hierarchy Measurements

In order to measure Δm^2_{31} and θ_{23} with KM3NeT/ORCA, a log-likelihood is minimized with respect to the distribution of reconstructed neutrino events over energy and the zenith angle. The atmospheric neutrino flux is assumed to be HKKM15 [6], and the remaining oscillation parameters required to setup the PMNS matrix and calculate the oscillation behaviour is set to NuFit v5.0 values. The L/E distribution fitted to the ORCA6 data points yields a significance to exclude the non-oscillation hypothesis at a level of $5.9\,\sigma$ [7].

The measurement of the individual oscillation parameters using the dataset containing 355 days of livetime yielded $\Delta m^2_{31} = 1.95^{+0.24}_{-0.22}$ (stat. + syst.) and $\sin^2\theta_{23} = 0.50^{+0.10}_{-0.10}$ (stat. + syst.) [3]. A sensitivity estimate for the updated extended livetime dataset and refined analysis was created based on the previous measurement, which is shown in Figure 1.

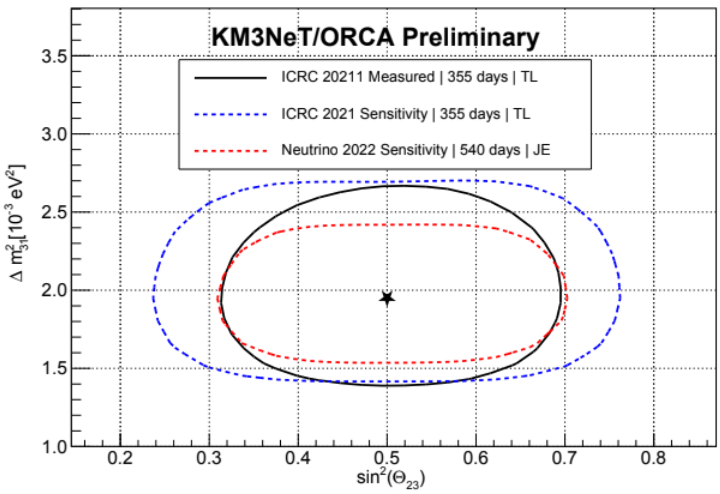


Figure 1. Measured oscillation parameters $\sin^2\theta_{23}$ and Δm^2_{31} with an ORCA6 livetime of 355 days (black) and the expected sensitivity at 90% CL for the increased livetime of 540 days and refined analysis (red). Taken from [3].

We assume the measured value at the 90% confidence level will shrink the value from $\pm 6\times 10^{-4}\,\text{eV}^2$ to $\pm 4\times 10^{-4}\,\text{eV}^2$ for Δm^2_{31} and from ± 0.25 to ± 0.2 for $\sin^2(\Theta_{23})$. A new analysis with an even larger dataset is currently in progress, and results from that analysis will be published soon. In Figure 1, the expected improvement in the 90% confidence region is shown given the last measured values.

The estimated NMO sensitivity of ORCA in its full configuration is shown in Figure 2. According to the best fit from NuFIT v5.1 of $\theta_{23} \approx 49^\circ$, the NMO sensitivity is expected to be 4.5 σ for a normal hierarchy and 2.5 σ for an inverted hierarchy after two years of data collection [2].

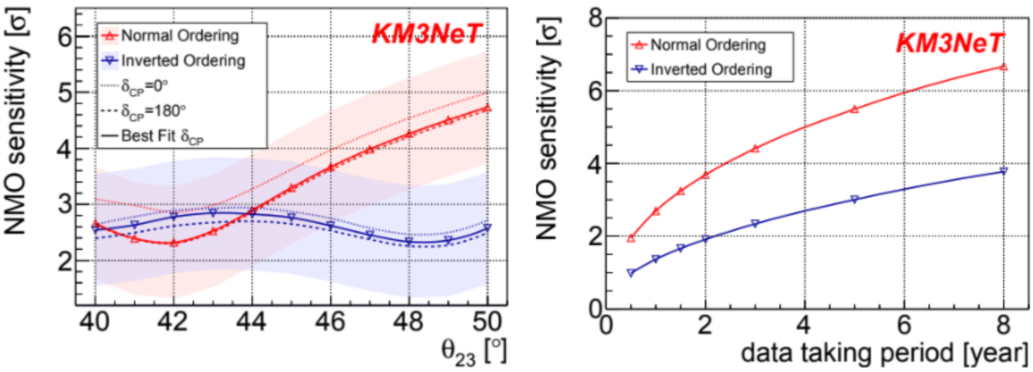


Figure 2. Estimated neutrino mass hierarchy sensitivity for a normal and inverted hierarchy of ORCA115 over the atmospheric mixing angle θ_{23} for three years of livetime (**left**) and over the data collection period for fixed $\theta_{23} = 48^{\circ}$ (**right**). Taken from [2].

The significance of the measurements can also be improved by performing combined studies with other experiments. The combination of ORCA and JUNO was studied with a combined likelihood for both experiments being minimized. The parameters to which each experiment is sensitive to are left free for minimization where Δm^2_{31} and θ_{23} are scanned. The estimated combined sensitivity yields about 6 σ (4 σ) for a normal (inverted) hierarchy after three years of livetime, as shown in Figure 3 [8].

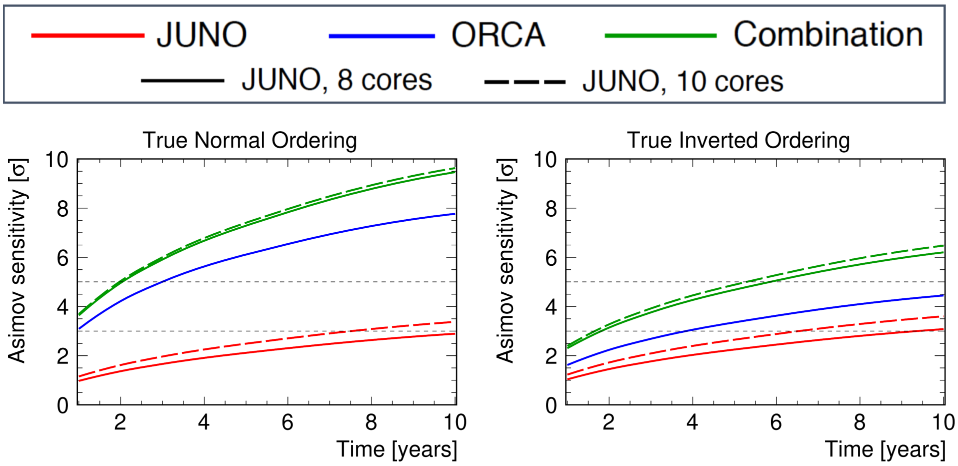


Figure 3. Estimated neutrino mass hierarchy sensitivity for a normal (**left**) and inverted hierarchy (**right**) of ORCA115, JUNO, and both in a combined study. Taken from [8].

4. Beyond the Standard Model Physics

The sensitivity of ORCA beyond the standard model physics (BSM) is studied with respect to multiple models. The BSM interaction in the three flavour case can be phenomenologically described via the interaction term in the Hamiltonian following the definition in [9] for the NSI parameters:

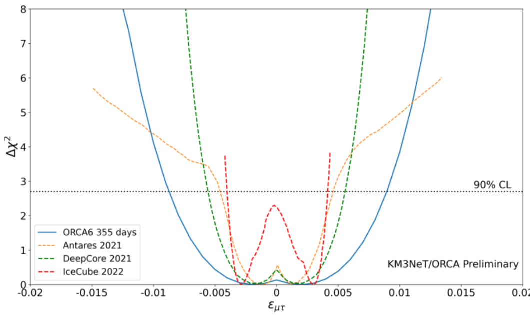
$$\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}. \quad (1)$$

The parameter $\epsilon_{\mu\tau}$ is fitted together with the oscillation parameters. The sensitivity for $\epsilon_{\mu\tau}$ for one year of livetime is within

$$-8.7 \times 10^{-3} < \epsilon_{\mu\tau} < 9.0 \times 10^{-3} \quad (2)$$

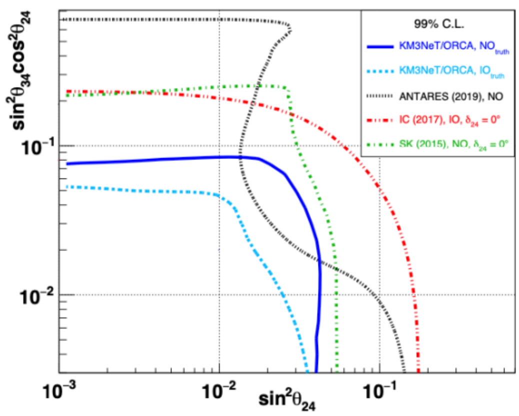
at a 90% CL, which is also shown in Figure 4. This shows ORCA in the six DU configuration to be competitive with other experiments tackling neutrino oscillation measurements with atmospheric neutrinos. The $\Delta\chi^2$ is optimized with respect to the parameters listed to the right in Figure 4, where the rest of the oscillation parameters are fixed to NuFit values.

For BSM models including a fourth sterile neutrino, six additional oscillation parameters yield more combinations which need to be addressed. The 4×4 mixing matrix U is given by $U = U^{4\nu}U^{3\nu}$, where $U^{3\nu}$ is the standard three flavour PMNS matrix and $U^{4\nu} = R_{34}\tilde{R}_{24}\tilde{R}_{14}$ holds the mixing to the fourth flavour. The CP phase δ_{24} is kept free in the fit, whereas δ_{14} and θ_{14} showed to be negligible and fixed to 0 [10]. The sensitivity with respect to the oscillation angles at $\Delta m^2_{41} = 1\,\text{eV}^2$ for a potential fourth neutrino flavour as well as the optimized parameters are shown in Figure 5.



Parameter	Fitted value	Gaussian prior width
$\epsilon_{\mu\tau}$	$0.002^{+0.0065}_{-0.0064}$	free
$sin^2(\theta_{23})$	$0.51^{+0.10}_{-0.11}$	free
Δm^2_{31}	$(1.92^{+0.25}_{-0.23}) \cdot 10^{-3}$	free
Overall Normalisation	$0.8^{+0.12}_{-0.10}$	free
Muon Normalisation	2.0 ± 1.48	free
Flux: Spectral index tilt	$0.07^{+0.044}_{-0.040}$	0.3
Flux: cos(θ) tilt	$0.018^{+0.061}_{-0.062}$	0.07
Flux: skew mu/amu	0.007 ± 0.1	0.1
Flux: skew e/ae	0.0004 ± 0.1	0.1
Flux: mu/e	0.0 ± 0.03	0.03
Cross-section: NC norm	0.99 ± 0.1	0.1
Cross-section: tau norm	0.97 ± 0.2	0.2
Detector: Energy scale	$0.0^{+0.018}_{-0.006}$	0.1

Figure 4. Plot of $\Delta\chi^2$ over the parameters $\varepsilon_{\mu\tau}$ with a 90% confidence level for ORCA in the six DU configuration, ANTARES [11] and IceCube [12,13] (**left**); the list of optimised parameters of the ORCA6 result including their fitted values and Gaussian prior width (**right**).Taken from [14].



Parameter	Gaussian Prior ($\mu \pm \sigma$)
$\nu_e/\bar{\nu}_e$	0 ± 0.07
$\nu_\mu/\bar{\nu}_\mu$	0 ± 0.05
ν_e/ν_μ	0 ± 0.02
NC Scale	No prior
Energy Scale	1 ± 0.05
Energy Slope	No prior
Zenith Angle Slope	0 ± 0.02
Track Normalisation	No Prior
Intermediate Normalisation	No Prior
Shower Normalisation	No Prior
Δm^2_{31}	No prior
θ_{13}	$\theta_{13} \pm 0.13°$
θ_{23}	No prior

Figure 5. The mixing angle sensitivity estimate 99% confidence level for a fourth sterile neutrino at $\Delta m^2_{41} = 1\,\text{eV}^2$ for ORCA115, ANTARES [11], IceCube(DeepCore) [15] and Super-Kamiokande [16]. Taken from [10].

5. Discussion

At the time of the conference (August 2022), the data taking of KM3NeT/ORCA was on-going with 10 DUs available. Up until now (July 2023) the data taking continues at a high uptime fraction including additional eight DUs, which were deployed during sea operations in the end of 2022 and in mid 2023. The first oscillation results have been published based on a one-year dataset of ORCA in a partial configuration with six DUs.

These results are about to be updated based on a refined analysis and an overall 540 days of data collection, for which the expected improvement was shown by the sensitivity estimate.

The measurement of the oscillation parameters in the three-flavour case already out-performs the ANTARES result with 10 years of exposure [17]. Compared to other experiments, ORCA with six DUs is not on the same sensitivity level, which will be the case upon completion. The competitive sensitivity estimated with respect to the BSM models is already shown in the case of $\epsilon_{\mu\tau}$.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ARCA	Astro-particle Research with Cosmics in the Abyss
ORCA	Oscillation Research with Cosmics in the Abyss
DOM	Digital optical module
DU	Detection unit
BB	Building block
NMH	Neutrino mass hierarchy
BSM	Beyond the standard model of physics

References

1. Adrián-Martínez, S.; Ageron, M.; Aharonian, F.; Aiello, S.; Albert, A.; Ameli, F.; Anassontzis, E.; Andre, M.; Androulakis, G.; Anghinolfi, M.; et al. Letter of Intent for KM3NeT 2.0. *J. Phys. G Nucl. Part. Phys.* **2016**, *43*, 084001. [CrossRef]
2. Aiello, S.; Albert, A.; Alves Garre, S.; Aly, Z.; Ambrosone, A.; Ameli, F.; Andre, M.; Androulakis, G.; Anghinolfi, M.; Anguita, M.; et al. Determining the Neutrino Mass Ordering and Oscillation Parameters with KM3NeT/ORCA. *Eur. Phys. J. C* **2022**, *82*, 26. [CrossRef]
3. Pestel, V.; Nauta, L.; Aly, Z.; KM3NeT Collaboration. First Neutrino Oscillation Measurement with KM3NeT/ORCA. In *Proceedings of the 22nd International Workshop on Neutrinos from Accelerators—PoS(NuFact2021)*; Sissa Medialab: Cagliari, Italy, 2022; p. 64. [CrossRef]
4. Quinn, L. Determining the Neutrino Mass Hierarchy with KM3NeT/ORCA. Ph.D. Thesis, Aix-Marseille Université, Marseille, France, 2018.
5. Domi, A. Shower Reconstruction and Sterile Neutrino Analysis with KM3NeT/ORCA and ANTARES. 2020. Available online: https://iris.unige.it//handle/11567/985989 (accessed on 3 August 2023).
6. Honda, M.; Athar, M.S.; Kajita, T.; Kasahara, K.; Midorikawa, S. Atmospheric Neutrino Flux Calculation Using the NRLMSISE-00 Atmospheric Model. *Phys. Rev. D* **2015**, *92*, 023004. [CrossRef]
7. Nauta, L.; Pestel, V.; Manczak, J.; Stavropoulos, D.; Carretero, V.; Chau, N.; Aly, Z.; de Jong, P.; KM3NeT; Ageron, M.; et al. First Neutrino Oscillation Measurement in KM3NeT/ORCA. In *Proceedings of the 37th International Cosmic Ray Conference—PoS(ICRC2021)*; Sissa Medialab: Berlin, Germany, 2021; p. 1123. [CrossRef]
8. KM3NeT Collaboration; Aiello, S.; Albert, A.; Alshamsi, M.; Alves Garre, S.; Aly, Z.; Ambrosone, A.; Ameli, F.; Andre, M.; Androulakis, G.; et al. Combined Sensitivity of JUNO and KM3NeT/ORCA to the Neutrino Mass Ordering. *J. High Energy Phys.* **2022**, *2022*, 55. [CrossRef]
9. Ohlsson, T. Status of Non-Standard Neutrino Interactions. *Rep. Prog. Phys.* **2013**, *76*, 044201. [CrossRef] [PubMed]
10. The KM3NeT Collaboration; Aiello, S.; Albert, A.; Alshamsi, M.; Alves Garre, S.; Aly, Z.; Ambrosone, A.; Ameli, F.; Andre, M.; Androulakis, G.; et al. Sensitivity to Light Sterile Neutrino Mixing Parameters with KM3NeT/ORCA. *J. High Energy Phys.* **2021**, *2021*, 180. [CrossRef]
11. The ANTARES Collaboration; Albert, A.; Alves, S.; André, M.; Anghinolfi, M.; Anton, G.; Ardid, M.; Ardid, S.; Aubert, J.J.; Aublin, J.; et al. Search for Non-Standard Neutrino Interactions with 10 Years of ANTARES Data. *J. High Energy Phys.* **2022**, *2022*, 48. [CrossRef]
12. Aartsen, M.G.; Ackermann, M.; Adams, J.; Aguilar, J.A.; Ahlers, M.; Ahrens, M.; Al Samarai, I.; Altmann, D.; Andeen, K.; Anderson, T.; et al. Search for Nonstandard Neutrino Interactions with IceCube DeepCore. *Phys. Rev. D* **2018**, *97*, 072009. [CrossRef]

13. Abbasi, R.; Ackermann, M.; Adams, J.; Aguilar, J.A.; Ahlers, M.; Ahrens, M.; Alameddine, J.M.; Alispach, C.; Alves, A.A.; Amin, N.M.; et al. Strong Constraints on Neutrino Nonstandard Interactions from TeV-Scale $\nu\ \mu$ Disappearance at IceCube. *Phys. Rev. Lett.* **2022**, *129*, 011804. [CrossRef] [PubMed]
14. Manczak, J. First Limits on Neutrino Non-Standard Interactions with KM3NeT/ORCA6. 2022. Available online: https://zenodo.org/record/6785232 (accessed on 3 August 2023).
15. Aartsen, M.G.; Ackermann, M.; Adams, J.; Aguilar, J.A.; Ahlers, M.; Ahrens, M.; Al Samarai, I.; Altmann, D.; Andeen, K.; Anderson, T.; et al. Search for Sterile Neutrino Mixing Using Three Years of IceCube DeepCore Data. *Phys. Rev. D* **2017**, *95*, 112002. [CrossRef]
16. Abe, K.; Haga, Y.; Hayato, Y.; Ikeda, M.; Iyogi, K.; Kameda, J.; Kishimoto, Y.; Miura, M.; Moriyama, S.; Nakahata, M.; et al. Limits on Sterile Neutrino Mixing Using Atmospheric Neutrinos in Super-Kamiokande. *Phys. Rev. D* **2015**, *91*, 052019. [CrossRef]
17. The ANTARES Collaboration; Albert, A.; André, M.; Anghinolfi, M.; Anton, G.; Ardid, M.; Aubert, J.J.; Aublin, J.; Avgitas, T.; Baret, B.; et al. Measuring the Atmospheric Neutrino Oscillation Parameters and Constraining the 3+1 Neutrino Model with Ten Years of ANTARES Data. *J. High Energy Phys.* **2019**, *2019*, 113. [CrossRef]