PROCEEDINGS OF SCIENCE

Non-standard oscillations with KM3NeT

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Several phenomena predicted by theories beyond the Standard Model manifest as modifications in the neutrino oscillation pattern. Large-volume Cherenkov detectors are able to observe atmospheric and cosmic neutrinos over a broad range of energies and baselines, making them powerful instruments for probing a variety of beyond Standard Model effects. KM3NeT is an infrastructure of two water Cherenkov detectors currently under construction in the Mediterranean Sea. The KM3NeT/ORCA detector is optimized for the precise measurement of atmospheric neutrino oscillation parameters at GeV energies, whereas KM3NeT/ARCA aims at the observation of high-energy astrophysical neutrinos. This contribution summarizes the results of several beyond Standard Model searches conducted with data from the partially deployed ORCA detector. Furthermore, future plans for exploring new physics effects at high energies with ARCA are discussed.

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1. The KM3NeT detectors

The KM3NeT research infrastructure comprises two water Cherenkov detectors which are currently under construction in the Mediterranean sea. The detectors, known as KM3NeT/ARCA and KM3NeT/ORCA, are composed of 3D arrays of digital optical modules arranged in vertical detection units. Each of the modules hosts 31 photomultiplier tubes (PMTs) which collect Cherenkov light emitted by relativistic charged particles emerging from neutrino interactions. The distribution and duration of recorded PMT pulses allows to reconstruct the event topology, as well as the direction and energy of the neutrino. The ORCA detector is being build about 40 km offshore from Toulon, France, at a depth of 2450 m. The main purpose of ORCA is the precise measurement of atmospheric neutrino oscillations in the few GeV to 100 GeV energy range, and the determination of the neutrino mass ordering. The detector can also be used to search for deviations from the standard oscillation expectation, which may point to physics beyond the Standard Model. The ARCA detector is situated at a depth of 3500 m, 100 km off the coast of Portopalo di Capo Passero, Sicily, Italy. While ARCA's primary objective is the detection for astrophysical neutrinos in the TeV to PeV energy range, it can also be used to study the properties of atmospheric neutrinos.

2. Beyond Standard Model physics from GeV to PeV energies

In order to reject the atmospheric muon background, only up-going events enter the selection. This means that atmospheric neutrinos detected in KM3NeT travel long baselines up to $\sim$ 12 700 km which corresponds to the diameter of the Earth. For these baselines neutrino oscillations are visible at energies below 100 GeV as shown in Figure 1 on the left-hand side. The plot displays the survival probability of an up-going muon neutrino for standard oscillations as well as for several beyond Standard Model (BSM) phenomena including neutrino decoherence ($\Gamma \propto E_\nu^{-1}$, $\Gamma_{21} = \Gamma_{31} = 10^{-22}$ GeV), invisible neutrino decay ($\alpha_3 = 10^{-4}\,\mathrm{eV}^2$), non-standard interactions ($\epsilon_{\tau\tau} - \epsilon_{\mu\mu} = 0.025$), and a sterile neutrino scenario ($\Delta m^2_{41} = 10^{-3}\,\mathrm{eV}^2$, $\sin^2(\theta_{24}) = 0.1$). The parameter values chosen here are close to current experimental bounds but mainly serve the purpose of illustration. At energies above 100 GeV standard oscillations are suppressed and the expected survival probability for all neutrino flavours is 100 %, independent of the energy. Consequently, any deviation from $\mathrm{P}(\nu_\alpha \rightarrow \nu_\alpha) = 1$ is a clear signal for physics beyond the standard oscillation framework. This can be seen in Figure 1 on the right hand-side which shows the survival probability of an up-going muon antineutrino as a function of the neutrino energy for standard oscillations as well as neutrino decoherence ($\Gamma \propto E_\nu^2$, $\Gamma_{31} = 10^{-31}$ GeV) and sterile neutrinos ($\Delta m^2_{41} = 1\,\mathrm{eV}^2$, $\sin^2(2\theta_{24}) = 0.04$). For sterile neutrinos the matter resonance at TeV energies occurs only for anti neutrinos (and not for neutrinos) when normal ordering is assumed.

3. BSM searches with KM3NeT

Some BSM phenomena involve only very high energy neutrinos that cannot be produced in artificial sources. In the future, these models will be constrained with ARCA using atmospheric neutrinos, which are the dominant contribution to the flux below 100 TeV. At higher energies, the astrophysical neutrino flux becomes relevant and might also be used to test certain models.

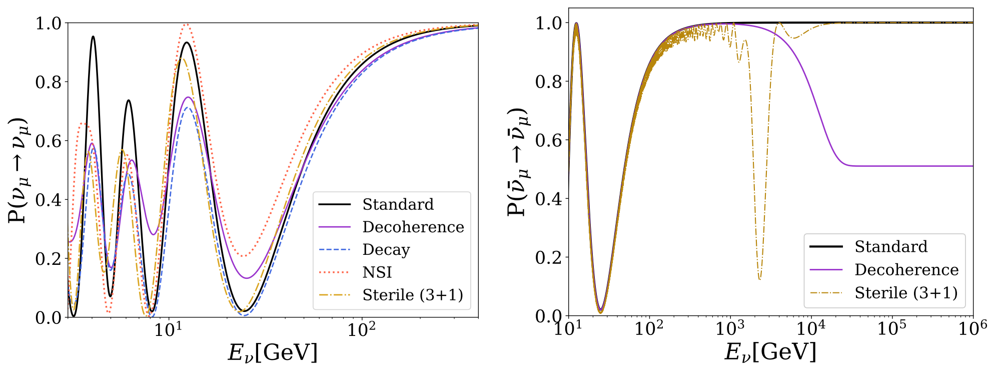

Figure 1: Survival probability for a muon (anti) neutrino with a baseline of ~ 12 700 km as a function of the neutrino energy E_ν for standard oscillations and various BSM phenomena including neutrino decoherence, invisible neutrino decay, non-standard interactions, and a 3+1 sterile neutrino model [2].

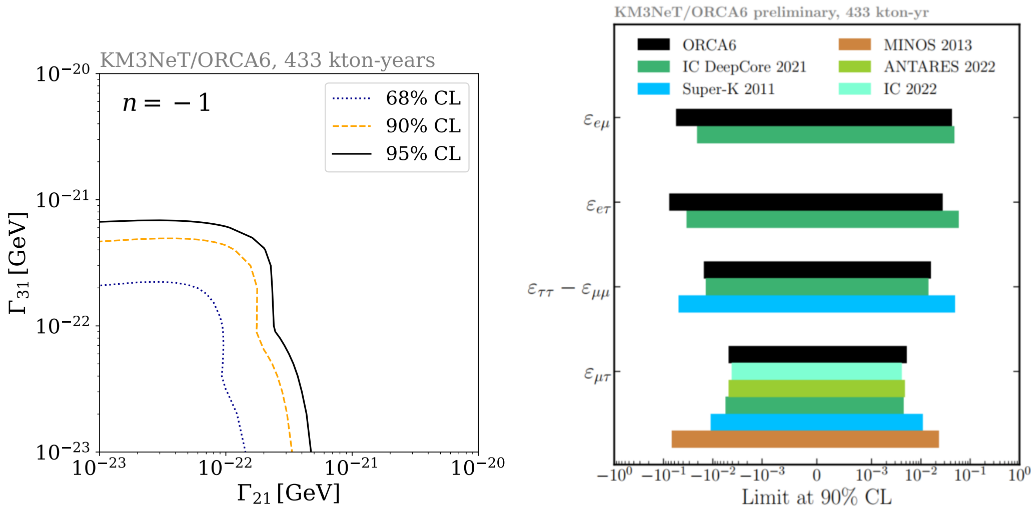

Figure 2: Left: Confidence level contours of the quantum decoherence parameters considering both neutrino mass orderings [4]. Right: Allowed region of the NSI parameters at the 90% CL in comparison with bounds from current experimental results and the global fit [5].

So far, searches for BSM effects have been conducted at energies below 100 GeV using a partial configuration of ORCA with six detection units, referred to as ORCA6. The data was recorded between February 2020 and November 2021 yielding an exposure of 433 kton-years. A measurement of the standard oscillation has been performed with this same dataset [3].

The first BSM effect considered here is quantum decoherence, which refers to a loss of coherence of the neutrino mass eigenstates due to interactions with a stochastic background. The strength of decoherence is characterized by the parameters Γ_{21} and Γ_{31}, where $\Gamma_{ij} \propto E_\nu^n$ and the cases $n = -2, -1$ were studied. The result can be seen on the left-hand side of Figure 2 which shows confidence level contours obtained for Γ_{21} and Γ_{31} for the $n = -1$ model.

Very promising constrains were obtained for non-standard neutrino interactions as can be seen in Figure 2 on the right-hand side. Neutral current NSIs affect the propagation of neutrinos in matter and are described with a set of ϵ parameters which are added to the standard matter potential. The bounds obtained with ORCA6 are in the same order of magnitude as leading limits on NSI.

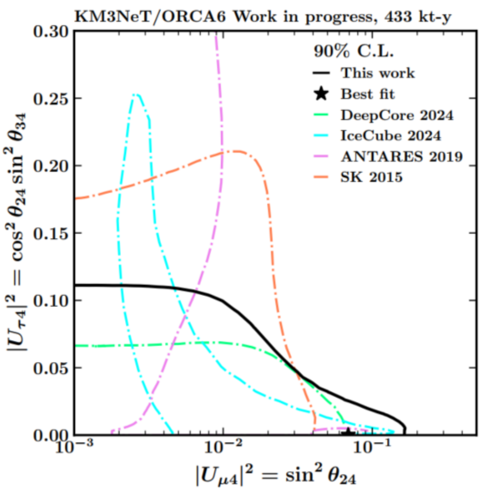

Figure 3: Bound on the mixing elements in a 3+1 sterile neutrino model [6].

Finally, a first measurement of light sterile neutrino mixing parameters was performed using a 3+1 model. Including light sterile neutrinos, oscillations are described by a 4x4 unitary mixing matrix. Bounds on matrix elements which involve the mixing angles θ_{24} and θ_{34} are shown in Figure 3 (ORCA6 has no sensitivity to θ_{14}). To obtain the limits, a mass splitting of Δm^2_{41} =1 eV^2 was assumed, where this value is motivated as a possible explanation for short-baseline anomalies. The limits obtained with ORCA6 are very competitive, especially when considering the small exposure of the data-set. Sensitivities on the mixing angles θ_{24} and θ_{34} in dependence of Δm^2_{41} have also been provided and results on this are expected soon.

4. Conclusion

Besides a first measurement of the standard oscillation parameters, several BSM searches have been performed with the ORCA6 433 kton-year data set. Constraints given on neutrino decoherence, non-standard interactions and light sterile neutrinos have been summarized here. Other analyses that have not been included here have searched for Lorentz-invariance violation, invisible neutrino decay, and non-unitary mixing. For most of the studies, updated results will be given for a larger detector configuration and longer data taking time. Enhanced sensitivities are expected not only from larger statistics but also from a better energy resolution of the detector as well as improvements in the event reconstruction.

References

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