Search for neutrino non-standard interactions with ANTARES and KM3NeT-ORCA

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ABSTRACT: Non-standard interactions (NSIs) in the propagation of neutrinos in matter can lead to significant deviations in neutrino oscillations expected within the standard 3-neutrino framework. These additional interactions would result in an anomalous flux of neutrinos observable at neutrino telescopes. The ANTARES detector and its next-generation successor, KM3NeT, located in the abyss of the Mediterranean Sea, have the potential to measure sub-dominant effects in neutrino oscillations, coming from non-standard neutrino interactions. In this contribution, a likelihood-based search for NSIs with 10 years of atmospheric muon-neutrino data recorded with ANTARES is reported and sensitivity projections for KM3NeT/ORCA, based on realistic detector simulations, are shown. The bounds obtained with ANTARES in the NSI $\mu - \tau$ sector constitute the most stringent limits up to date.

KEYWORDS: Analysis and statistical methods; Cherenkov detectors

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1 Neutrino propagation in presence of NSI

When neutrinos propagate in matter, their evolution is affected by interactions with the medium, that result in the coherent forward elastic scattering of neutrinos. The overall effect can be described by effective potentials associated to the charged (CC) and neutral (NC) currents. In the case of neutrinos travelling through Earth, the only relevant potential is the one stemming from the electron neutrino components interacting with electrons in matter [1]:

\[ V_{CC} = \sqrt{2} G_F n_e, \]

where \( G_F \) is the Fermi coupling constant and \( n_e \) is the electron number density along the neutrino path.

The presence of NSI in neutrino propagation can be described as an additional potential that will translate into an additional term in the neutrino propagation Hamiltonian:

\[ H^{NSI} = \frac{1}{2 E_\nu} U M^2 U^\dagger + V_{CC} \text{diag}(1,0,0) V_{CC} \frac{n_f}{n_e} \epsilon, \]

where \( U \), the PMNS mixing matrix, performs the rotation of the relevant mass matrix \( M^2 = \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) \) in the neutrino flavour space. \( n_f \) and \( n_e \) are the fermion and electron number density along the neutrino path and neutrinos are assumed to interact with down quarks which are roughly three times as abundant as electrons, \( n_f = n_d \approx 3 n_e \). The matrix \( \epsilon (\epsilon_{\alpha\beta}, \alpha, \beta = e, \mu, \tau) \) gives the strength of the NSI. The diagonal terms of this matrix, if different from each other, can give rise to the violation of leptonic universality, while the off-diagonal terms can induce flavour-changing neutral currents, which are highly suppressed in the Standard Model (SM) [2].

NSI are expected to have sub-dominant effects and therefore they would be observed as deviations from the distributions of the energy and arrival direction expected for standard oscillations. Figure 1 depicts the variation of the oscillation pattern in the muon disappearance channel due to NSIs.

2 The ANTARES and KM3NeT detector

ANTARES [3] is a 0.01 km\(^3\) deep-water water Cherenkov detector located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore of Toulon (France). The basic detection component is a 17"-diameter pressure resistant sphere called Optical Module (OM), housing a 10" photomultiplier tube (PMT). Starting about 100 m from the sea floor, the OMs are arranged in triplets vertically...
separated by about 15 m. The average horizontal separation between strings is \( \sim 65 \text{ m} \) and 12 such strings are anchored on the seabed to form an octagon with an effective mass of \( \sim 10 \text{ Mtons} \).

KM3NeT\(^4\) is then the next-generation upgrade of ANTARES, currently under construction in the Mediterranean Sea. Based on the granularity of the optical modules (to target different neutrino energy regimes), KM3NeT will house two detectors at different locations: ORCA (for measuring neutrino properties) and ARCA (for doing neutrino astronomy). ORCA represents a three-dimensional array of \( \sim 64,000 \) PMTs distributed among 115 detection strings with 18 spherical Digital Optical Modules (DOMs) per line. Starting about 40 m from the sea floor, the strings of ORCA are 200 m high, horizontally separated by about 20 m, with 18 DOMs spaced 9 m apart in the vertical direction.

### 3 Analysis

A first step is to compute the number of events corresponding to a specific oscillation hypothesis with or without NSI. The total number of charged current muon neutrino events (similar calculations hold for other flavours) expected at the detector for a certain runtime \( t \) is given by:

\[
\frac{d^2N_{\mu}^{CC}}{dE\,d\cos\theta} = \left( \frac{d^2\phi_{\nu_{\mu}}}{dE\,d\cos\theta} P_{\mu\mu} + \frac{d^2\phi_{\nu_e}}{dE\,d\cos\theta} P_{e\nu} \right) \times \sigma_{\nu_{\mu}}^{CC} A_{\nu_{\mu}}^{CC} \times t + \left( \frac{d^2\phi_{\bar{\nu}_{\mu}}}{dE\,d\cos\theta} P_{\mu\bar{\mu}} + \frac{d^2\phi_{\bar{\nu}_e}}{dE\,d\cos\theta} P_{e\bar{\nu}} \right) \times \sigma_{\bar{\nu}_{\mu}}^{CC} A_{\bar{\nu}_{\mu}}^{CC} \times t.
\]

\( N_{\mu} \) is the number of detected muon events within the range of energy \( dE \) and cosine of zenith angle \( d\cos\theta \); \( \phi_{\nu_{\alpha}} \) (\( \phi_{\bar{\nu}_{\alpha}} \)) is the atmospheric flux of neutrinos (antineutrinos) of flavour \( \alpha \) at the detector site; \( P_{\alpha\beta} \) is the probability of oscillation of a neutrino flavour \( \nu_{\alpha} \) to a neutrino flavour \( \nu_{\beta} \); \( \sigma_{\nu_{\alpha}}^{CC} \) is the charged current cross-section of muon neutrino with nucleons in sea water; \( A_{\nu_{\alpha}}^{CC} \) is the energy and zenith angle dependent effective area of the detector corresponding to muon neutrinos undergoing CC interaction within the detector.

Depending on the Cherenkov signatures of the outgoing lepton from the \( \nu_e-, \nu_{\mu}-\) and \( \nu_{\tau}-\) CC and NC interactions, two distinct event topologies are observed at the detector: track-like and shower-like events. \( \nu_{\mu} \) CC and \( \nu_{\tau} \) CC interactions with muonic \( \tau \) decays mostly account for the
The list of systematics encountered in this analysis. Each colour coded curve corresponds to the effect of that particular systematic plus (+) the ones appearing on top of it being fitted simultaneously. The systematics are added incrementally in the sequence as they appear in the legends from violet to red.

track-like topology. The shower-like topology corresponds to events from $\nu_e$ CC, $\nu_\tau$ CC interactions with non-muonic $\tau$ decays and NC interactions of all flavours. The eight distributions indexed by interaction type $X \in \{(\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau \rightarrow $ CC and ( $\nu, \bar{\nu} \rightarrow $ NC) are merged and split into two distributions corresponding to the two event topologies: tracks and showers. (For effective areas of individual channels, vide [5]).

Assuming a Poissonian distribution of event numbers, the test statistic to estimate the sensitivity to a test parameter in the NSI model hypothesis is based on a binned likelihood approach [6]:

$$-2LLR(\lambda, n) = 2 \cdot \sum_{i \in \text{bins}} \left[ \lambda_i(\bar{o}, \bar{s}) - n_i + n_i \ln \left( \frac{n_i}{\lambda_i(\bar{o}, \bar{s})} \right) \right] + \sum_{j \in \text{syst}} \frac{(s_j - \bar{s}_j)^2}{2 \sigma_j^2}. $$

where the number of predicted events $\lambda_i$ in the $i^{th}$ bin is a function of the set of oscillation parameters, $\bar{o}$, as well as on the set of parameters related to systematic uncertainties, $\bar{s}$. The second term runs over penalty terms of the number, $j$, of nuisance parameters, $\bar{s}_j$ and $\sigma_j^2$ being the assumed prior and Gaussian standard deviation of the parameter $j$, respectively. The exhaustive list is shown in figure 2 and can be found in [5].

4 Results

A total ANTARES livetime of 2830 days between years [2007, 2016] has been used [7, 8]. The data was found consistent with standard oscillation hypothesis at 1.8$\sigma$. Figure 3 shows the 90\% C.L. upper limit obtained with 10 years of ANTARES. Limits on NSI matrix elements are extracted by profiling over the other variable:

$$-4.2 \times 10^{-3} < \epsilon_{\mu\tau} < 2.7 \times 10^{-3} \quad \text{(at 90\% C.L.)},$$

$$-6.1 \times 10^{-2} < \epsilon_{\tau\tau} < -2.1 \times 10^{-2} \quad \text{and} \quad 2.1 \times 10^{-2} < \epsilon_{\tau\tau} < 7.3 \times 10^{-2} \quad \text{(at 90\% C.L.)}.$$
Figure 3. Left: 90% C.L. upper limits allowed after 10 years of ANTARES livetime obtained in this work are shown. The cross depicts the best-fit point obtained. Right: bounds on NSI couplings at 90% C.L. for two assumed mass orderings, for a runtime of 3 years of full ORCA comprising 115 DUs with 20 m horizontal DU spacing. Only one NSI parameter is considered at a time.

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