Non-standard Neutrino Interactions in with Mediterranean Neutrino Telescopes

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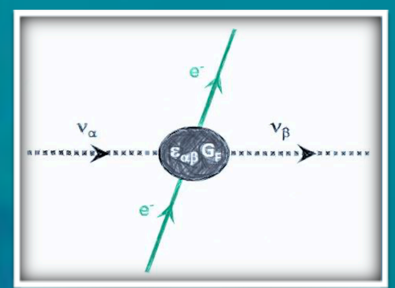
Non-standard Interactions:

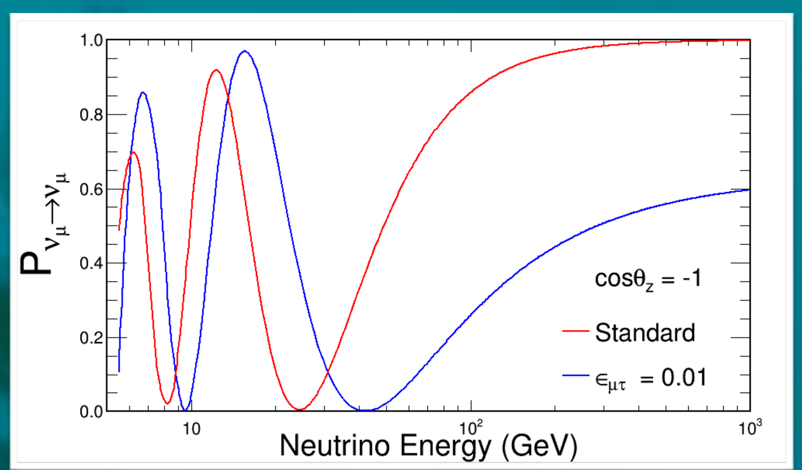
Neutral-current non-standard interactions (NSI) [1] of neutrinos of all flavours with matter fermions (e and u or d-quarks) modify the oscillation probabilities [2] while propagation.

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

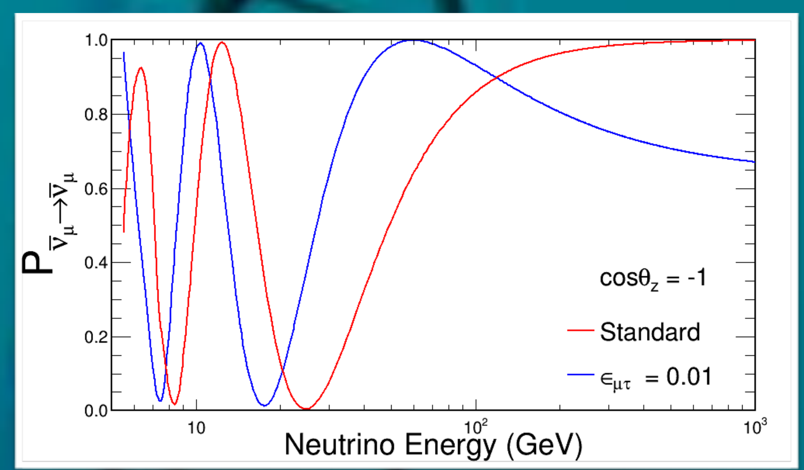


Non-standard flavour transitions distort the standard MSW effects, thereby modifying the atmospheric oscillation signals at detectors w.r.t. Standard Model (SM) predictions.

Neutrinos

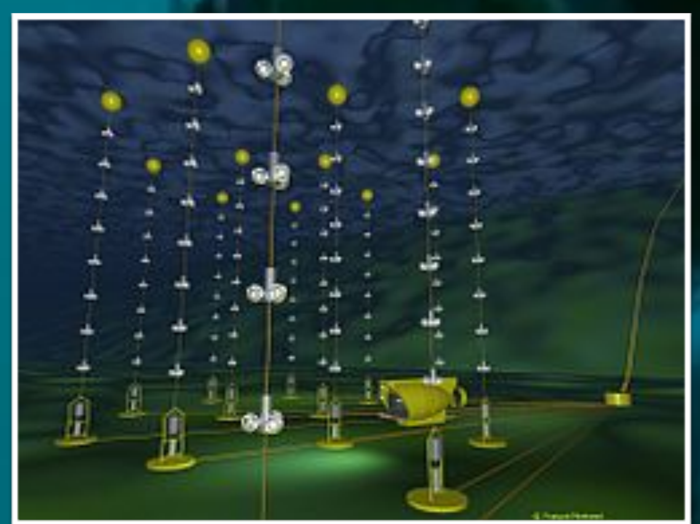


Anti-Neutrinos



Statistical excess/deficit of $\nu + \bar\nu$ events discernible at "iso-scalar charge-blind" Cherenkov detectors gives a handle to constrain NSI model parameters.

Neutrino Telescopes in sea:

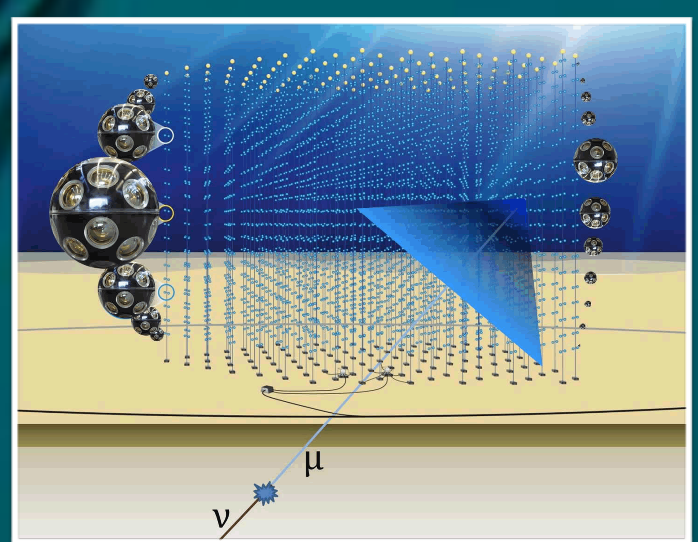


ANTARES

12 strings (~10 Mton) live since 2008.
Strings apart by ~ 65 m horizontal separation.
25 storeys placed at ~14.5 m vertical spacings.
3 10" PMTs per storey amounting to 885 in total.
Median muon angular resolution: 3° at 20 GeV.
Energy resolution: ~ 50% ± 22%.
Energy threshold ~15 GeV.

Denser array [3] of 64k PMTs across 115 strings.
Strings (DUs) placed 20 m apart horizontally.
18 DOMs/string placed 9 m apart vertically.
31 3" PMTs per storey facing multiple directions.
Direction resolution: 10° at 10 GeV.
Energy resolution: ~ 25% ± 5%.
Access to wide range of energies ∈ [3-100] GeV.

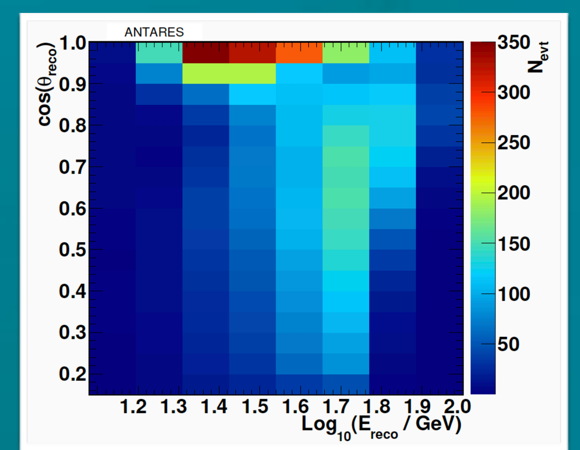
ORCA



Event Spectra at Detectors:

Two event topologies depending on the Cherenkov signature of outgoing lepton: **Tracks** [mostly ν_μ^{CC} and $\bar\nu_\mu^{CC}$] and **Cascades** [$\nu_\alpha^{CC}, \bar\nu_\alpha^{CC}$, ($\alpha = e, \tau$) and, $\nu_\beta^{NC}, \bar\nu_\beta^{NC}$, ($\beta = e, \mu, \tau$)].

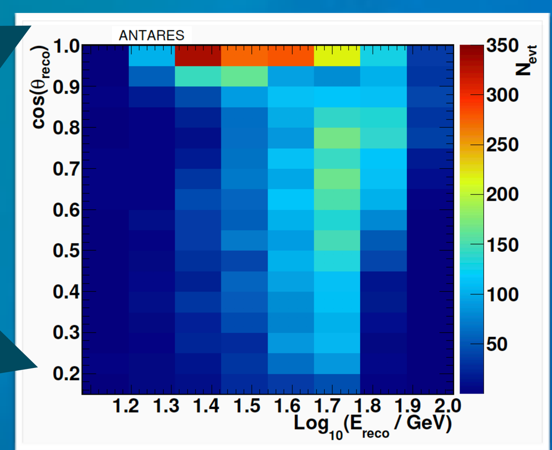
Un-oscillated MC



Up-going neutrinos

(Near) horizontal neutrinos

Data



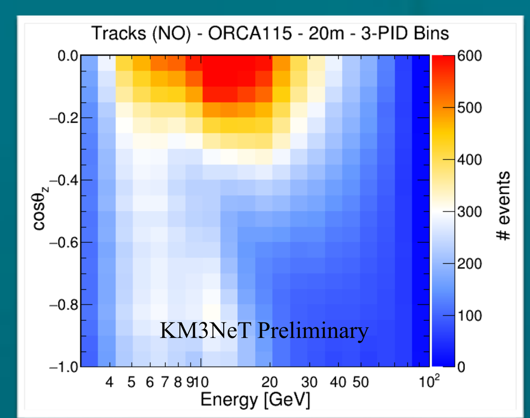
ANTARES dataset of 7710 (track-like) events corresponding to data acquisition time from 2007 to 2016. Live time of 2830 days. ν_μ-disappearance results published in [4].

1 log bin in reconstructed $E_\nu \in$ [$10^{-0.5}$, $10^{1.2}$] GeV & 7 for $E_\nu \in$ [$10^{1.2}$, 10^{2}]. 17 bins in $\cos\theta_z$.

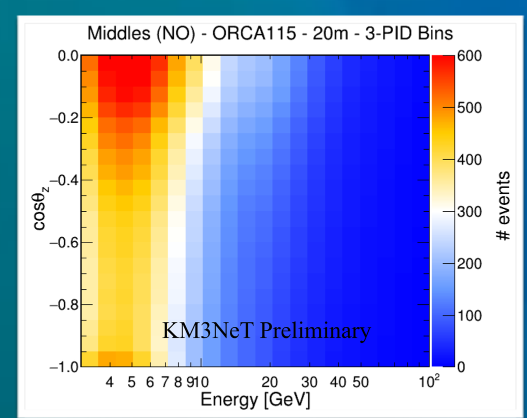
True E_ν spans a few TeV. Reco. E_ν till 100 GeV based on reconstructed muon track length.

Partially contained high energy neutrinos brings enhanced sensitivity to NSI effects.

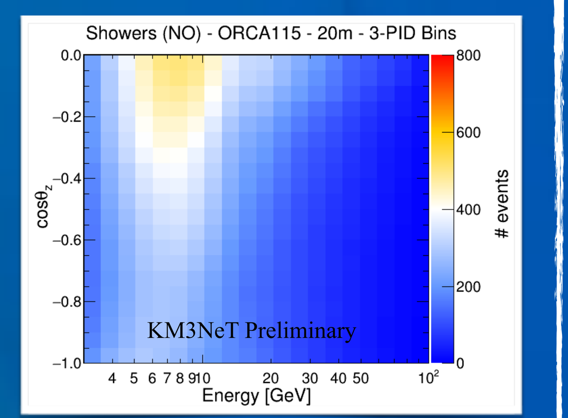
Tracks



Middles



Cascades



Simulated event rates at **KM3NeT-ORCA** with atmospheric HKKM flux for 3 years runtime.

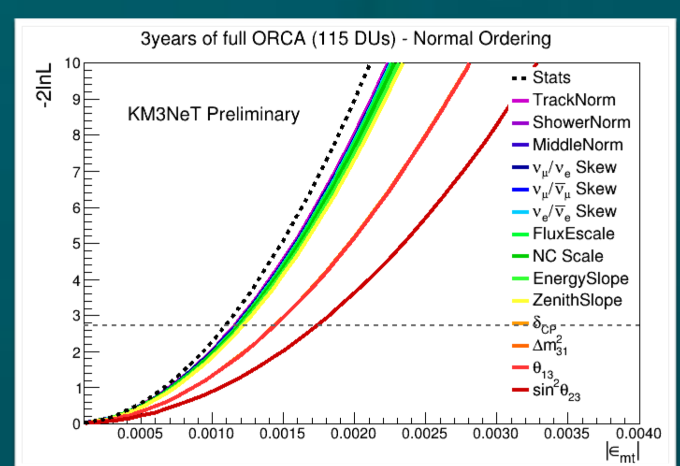
20×20 binning in reconstructed $\log_{10}(E_\nu)$ and $\cos\theta_z$ to fold in detector response.

Three event classes based on track probability (PID) estimated with Random Decision Forest of reconstructed heuristics.

Tracks: [1, 0.7); Middles: [0.7, 0.3); Cascades: [0.3, 0].

Systematic Uncertainties:

Effect of cumulative addition of nuisance parameters (from violet to red, as in legends) in the fit for a test NSI hypothesis at **ORCA**.



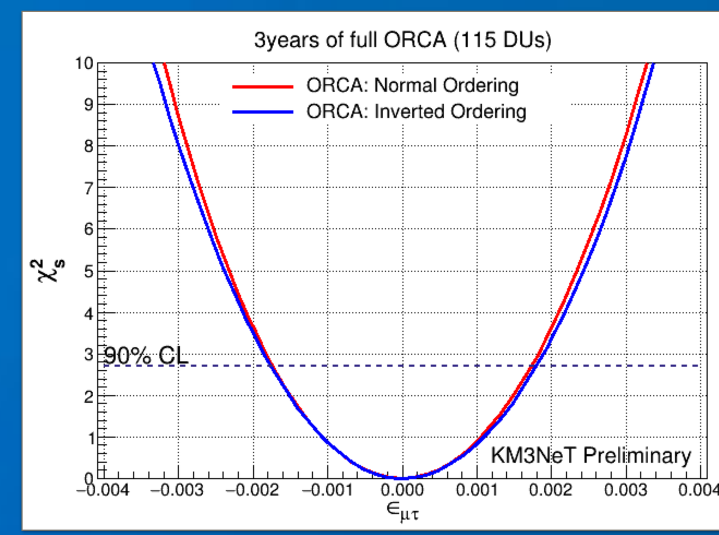
Asimov approach to calculate final sensitivities/limits including systematics.

List of nuisance parameters along with their injected central values and prior (if any) for **ANTARES**.

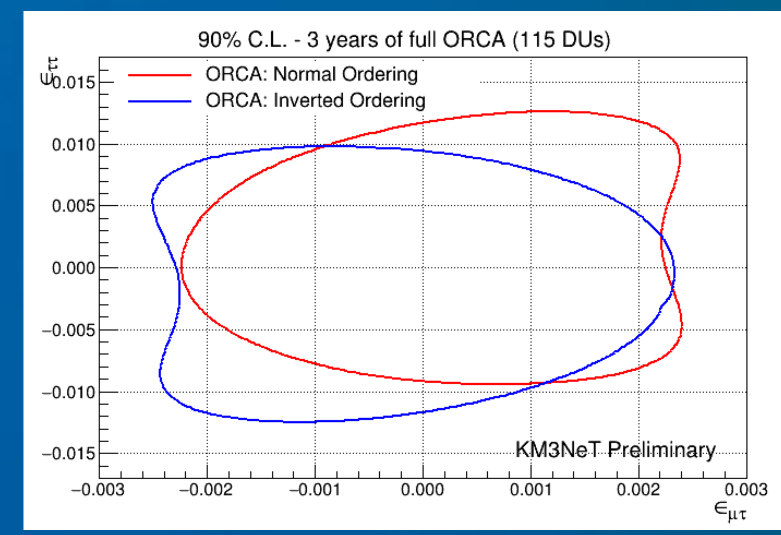
Parameter	Central value	Prior
Oscillation		
$\Delta m^2_{31}/10^{-3}(\mathrm{eV}^2)$	2.494	none
$\theta_{23}(°)$	47.2	none
$\theta_{13}(°)$	8.54	0.28
$\delta_{CP}(°)$	234	none
Flux		
N_ν	1	none
$\Delta\gamma$	0	0.05
$\nu/\bar\nu\ (\sigma)$	0	1.0
Cross section		
$\Delta M_A(\sigma)$	0	1

Results:

ORCA Sensitivities

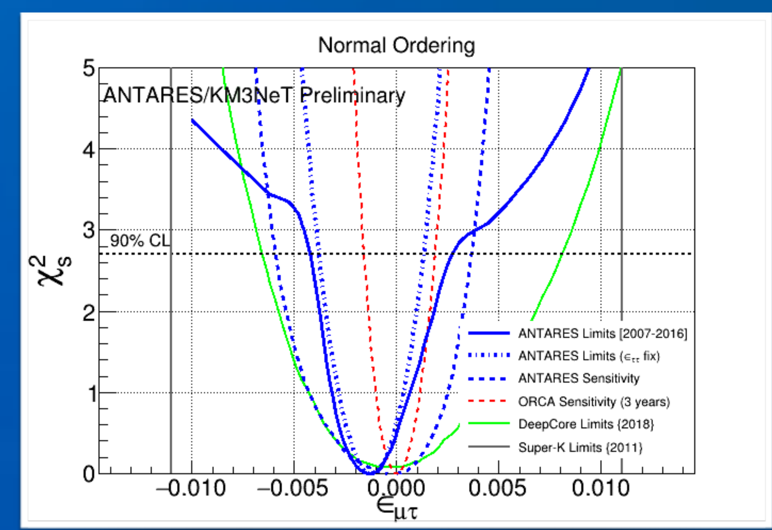


Projected sensitivity (left) for **ORCA** towards $\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau}$ after 3 years.



Allowed region in the $\epsilon_{\mu\tau}$ - $\epsilon_{\tau\tau}$ space for both assumed orderings at 90% CL.

ANTARES Sensitivities & Limits



$\epsilon_{\mu\tau}$ & Δm^2_{32} strongly anti-correlated.

In one-NSI approximation (only $\epsilon_{\mu\tau} \neq 0$), **ANTARES puts world's best limits on $\epsilon_{\mu\tau}$.**

When $\epsilon_{\tau\tau}$ is fitted, at 90% C.L

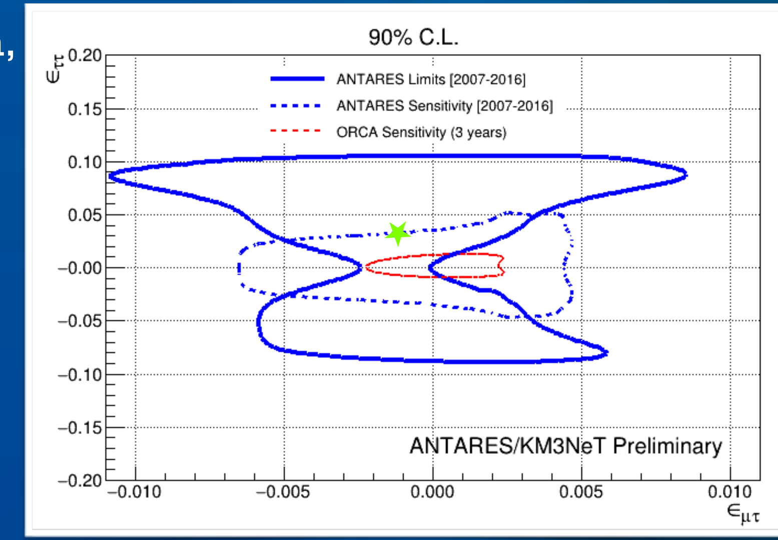
$-4.0 \times 10^{-3} \leq \epsilon_{\mu\tau} \leq 3.0 \times 10^{-3}$.

With 10 years of atmospheric neutrino data, **ANTARES finds mild hint for non-standard interactions** at 90% CL.

The **SM hypothesis (0,0) is discarded at χ^2 = 4.75,** away from best fit (**BF**) point.

NSI BF (✱) in the μ - τ sector:

$\epsilon_{\mu\tau} = -1.3 \times 10^{-3}$; $\epsilon_{\tau\tau} = 3.2 \times 10^{-1}$.



For joint estimation, contours using **Wilks'** theorem resulted in limits at 90% (99%)C.L.

-4.0×10^{-3} (-7.0×10^{-3}) $\leq \epsilon_{\mu\tau} \leq 2.5 \times 10^{-3}$ (3.5×10^{-3});

-0.6×10^{-1} (-1.2×10^{-1}) $\leq \epsilon_{\tau\tau} \leq 0.6 \times 10^{-1}$ (1.2×10^{-1}).

References:

1) Front.in Phys. 6 (2018), Y. Farzan and M. Tortola.
2) https://github.com/joaoabcoelho/OscProb, J. Coelho
3) J.Phys.G 43 (2016) 8, 084001 Letter of Intent for KM3NeT 2.0 [KM3NeT Coll.]
4) JHEP 06 (2019) 113, A. Albert et. al [ANTARES Coll.].
5) Phys.Rev.D 84 (2011) 113008, G. Mitsuka et. al.[Super Kamiokande I and II]
6) Phys.Rev.D 97 (2018) 7, 072009, M. G. Aartsen et. al. [IceCube Coll.]

Acknowledgements:

We thank M. Tortola for useful discussions and acknowledge the financial support of Programa Estatal de Generación de Conocmiento (ref. PGC2018-096663-B-C41, Spanish MCIU and FEDER).