Searches for neutrino physics beyond the standard model with KM3NeT/ORCA6

Víctor Carretero Cuenca (IFIC, Universitat de València - CSIC) on behalf of the KM3NeT Collaboration

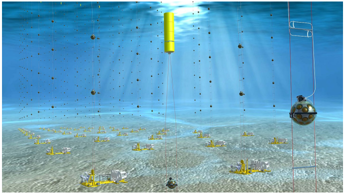
International Conference of High Energy Physics
9/07/2022 (Bologna, Italy)

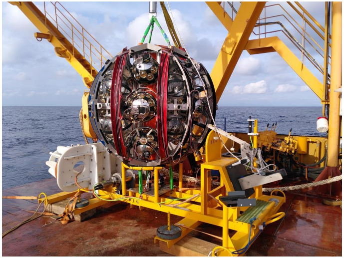
Table of contents

KM3NeT/ORCA

KM3NeT (Kilometre Cube Neutrino Telescope)
ORCA (Oscillation Research with Cosmics in the Abyss)

- Digital Optical Modules (DOMs) and Detection Units (DUs).
- Currently 11 DUs (out of 115) deployed for KM3NeT/ORCA.
- 7 Mtons of instrumented volume (KM3NeT/ORCA115).
- Detection principle: Cherenkov light produced in neutrino interactions.
- See previous presentation by V. Pestel.

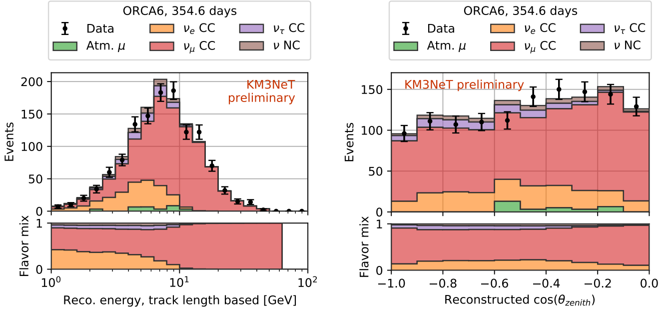




ORCA6 dataset

Same dataset that was described in V. Pestel presentation.

- Only up-going events.
- 1237 neutrino candidates in 354.6 days.
- Only $\sim$30 background events (atmospheric μ) expected.
- Signal dominated by ν_μ - CC interactions.



Invisible Neutrino Decay
Summary

- **Motivation:** Proposed as a solution to neutrino deficit. Ruled out as main contribution (oscillation) but not as a **subdominant** process.
- There are several models that can explain this neutrino decay:
  1. **Majoron** Model: $\nu_i \to \nu_j + J$.
  2. **Dirac** Model: $\nu_i \to \bar{\nu}_j + \xi$
- Visible or **Invisible** Decay.
- Only ν_3 decays are not well constrained by data.
- A **decay constant** is introduced in the Hamiltonian: $\alpha_3 = \frac{m_3}{\tau_3}$

$$H_T = \frac{1}{2E}\left[H_{vacuum} + H_{decay} + H_{matter}\right] = \frac{1}{2E} H$$

$$H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + U \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -i\alpha_3 \end{pmatrix} U^\dagger + \begin{pmatrix} V & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

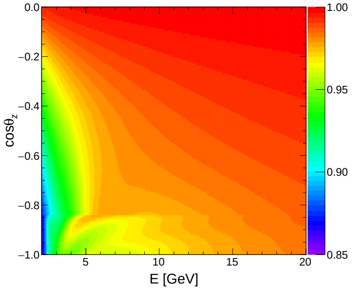
$$\Delta m^2_{31} \to \Delta m^2_{31} - i\alpha_3 \qquad V = \pm 2 E n_e \sqrt{2} G_F$$

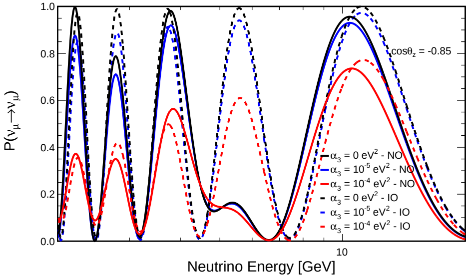
Invisible Neutrino Decay

Oscillation effects

Neutrino invisible decay effects:

- Unitarity breaking.
- Atmospheric oscillation damping.





$$P_{\mu e} + P_{\mu\mu} + P_{\mu\tau} < 1$$

$$\alpha_3 = 10^{-5}\mathrm{eV}^2$$

Oscillation damping
Matter resonance effects play an important role.

Non Standard Interactions

Summary

- **Motivation:** NSI describe the effects at the electro-weak scale of possible new physics at a higher energy scale.
- Additional potential terms in the Hamiltonian.
- The terms have the following **impact**:
  - Diagonal: If different, violation of **leptonic universality**.
  - Off-diagonal: **Flavour-changing neutral currents**.
- Neutrinos could couple to electrons, down quarks or up quarks.
- Not sensitive to the relative coupling strengths. For this analysis, **down quark** coupling is considered.

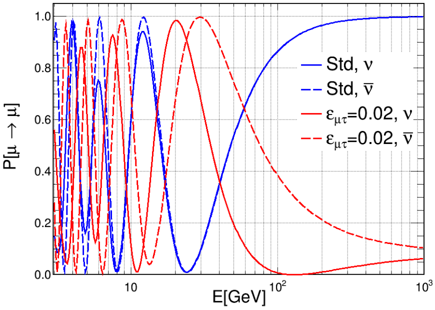
$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{\tau e} &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

$$\epsilon_{\alpha\beta} = \xcancel{\epsilon^{eC}_{\alpha\beta}} + \xcancel{\frac{n_u}{n_e}\epsilon^{uC}_{\alpha\beta}} + \frac{n_d}{n_e}\epsilon^{dC}_{\alpha\beta}$$

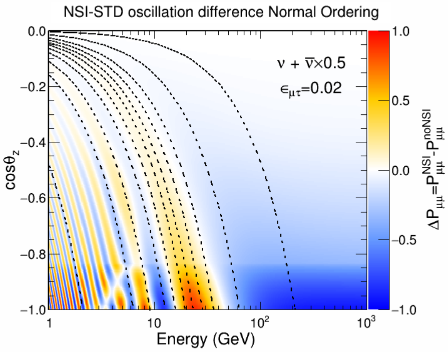
Non Standard Interactions
Oscillation effects

NSI effects most important signature

Main effects are seen near the vertical and for energies > 10 GeV.



NO. $\cos\theta = -1$



Analysis

- 2D binned analysis in E_{reco} and $\cos\theta_{\text{reco}}$.
- Reconstructed events are computed taking into account:
  - **Atmospheric flux**.
  - **Cross-sections**.
  - **Oscillation probabilities**.
  - **Effective mass**.
- A χ^2 analysis is performed: Poisson log-likelihood and gaussian penalties for systematics.

$$\chi^2_{\text{total}} = \chi^2_{\text{Stat}} + \chi^2_{\text{Priors}}$$

$$\chi^2_{\text{total}} = 2\sum_{i,j}\left[(N_{ij}^{\text{mod}} - N_{ij}^{\text{dat}}) + N_{ij}^{\text{dat}}\log\left(\frac{N_{ij}^{\text{dat}}}{N_{ij}^{\text{mod}}}\right)\right] + \sum_k\left(\frac{\epsilon_k - \mu_k}{\sigma_k}\right)^2$$

Systematics and Priors

Nuisance parameters. The **best fit** values correspond to the **standard oscillation** model.

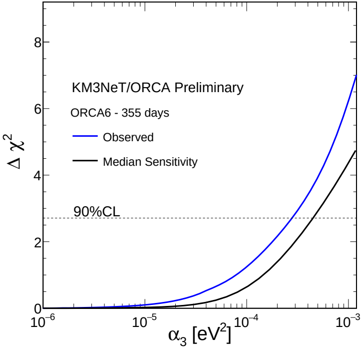
Systematic	Pull (σ)	Best Fit	Post-fit error	C. V.	Prior
Normalisation	**1.2**	0.88	0.10	1	None
ν_τ-CC normalisation	0.15	0.97	0.20	1	0.20
Cosmic muon normalisation	0.3	1.3	0.9	1	None
NC normalisation	0.2	0.9	0.5	1	0.5
$\nu_\mu/\bar{\nu}_\mu$ ratio	0.0	0.00	0.05	0	0.05
$\nu_e/\bar{\nu}_e$ ratio	0.0	0.00	0.07	0	0.07
ν_μ/ν_e ratio	0.0	0.000	0.020	0	0.020
Energy scale	0.0	1.00	0.05	1	0.05
Spectral index	**1.2**	0.05	0.04	0	0.3
$\nu_{\text{up}}/\nu_{\text{horiz}}$ ratio	0.1	0.002	0.020	0	0.020
$\Delta m^2_{31}\,[10^{-3}\text{eV}^2]$	**2.2**	1.98	0.24	2.517	None
$\theta_{23}\,[^\circ]$	0.8	45	5	49.2	None

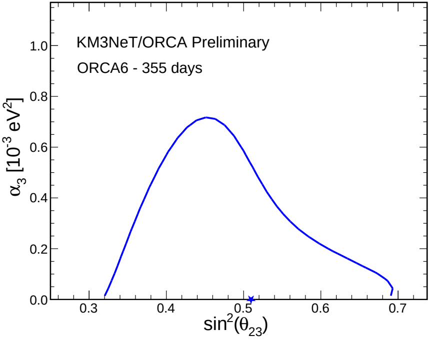
The most important systematics effects for both analyses are in **bold**, in blue for neutrino invisible decay and in red for NSI.

Neutrino Invisible Decay

Results

θ_{23} dependency was accounted for, so a 90% contour plot to constrain both of them is computed.





Neutrino Invisible Decay

Lower Limit comparison.

Lower limits for the **inverse of the decay constant** $1/\alpha_3 = \tau_3/m_3$ in ps/eV at 90% CL.

Experiment	L.L.(90%CL) (ps/eV)	Reference
ORCA6	2.4	Data analysis
ORCA115 (10y)	180	Sensitivity
T2K, NOvA	2.3	[1]
T2K, MINOS	2.8	[2]
K2K, MINOS, SK I+II	290	[3]

- Official results from experiments on this topic are **scarce**.
- Ref [3] was derived under the two flavour approximation and without matter effects.

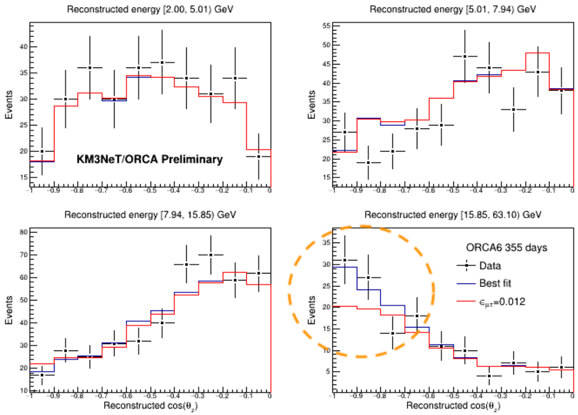
[1] S. Choubey et al. *Invisible neutrino decay in the light of NOvA and T2K data*, Journal of High Energy Physics 2018 (2018).

[2] R. Gomes et al. Constraints on neutrino decay lifetime using long-baseline charged and neutral current data, Physics Letters B (2015) 345–352.

[3] M. Gonzalez-Garcia et al. *Status of oscillation plus decay of atmospheric and long-baseline neutrinos*, Physics Letters B (2008) 405–409.

Non Standard Interactions
Energy slices distributions.

$\epsilon_{\mu\tau}$ effects are more pronounced for **up-going** neutrino directions.

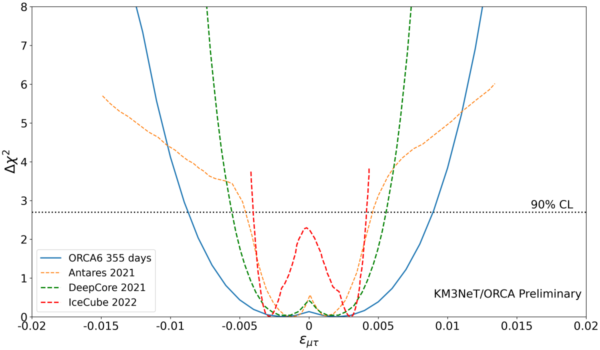


Non Standard Interactions

Results.

$\epsilon_{\mu\tau}$

KM3NeT/ORCA6 results not far away from the **world-leading** NSI measurements.



KM3NeT/ORCA6 limit: $-8.7 \times 10^{-3} < \epsilon_{\mu\tau} < 9.0 \times 10^{-3}$

KM3NeT/ORCA115 3-year sensitivity: $-1.7 \times 10^{-3} < \epsilon_{\mu\tau} < 1.7 \times 10^{-3}$ (TBU)

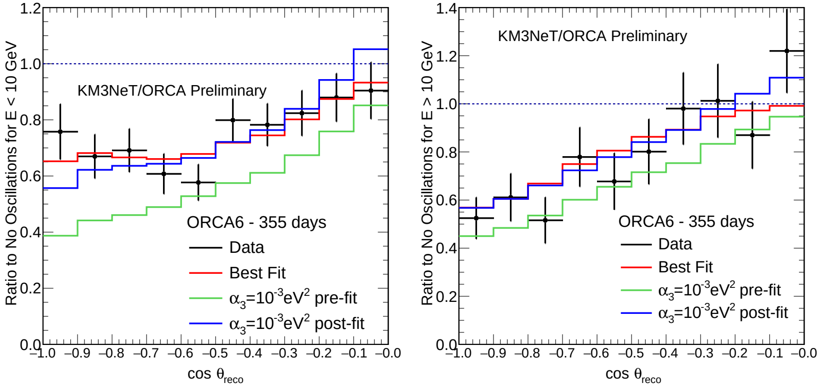
Conclusions

- Preliminary studies of **one year of data** with only a **5%** of the detector yields promising BSM results.
- Neutrino invisible decay constant constrained at 90% CL: $1/\alpha_3 = \tau_3/m_3 > 2.4$ ps/eV
- NSI $\epsilon_{\mu\tau}$ parameter constrained at 90% CL: $[-8.7, 9.0] \times 10^{-3}$
- Several **forthcoming** improvements:
  - Analysis of additional half year of data.
  - Shower reconstruction.
  - Particle Identification classification.
- KM3NeT/ORCA keeps growing and the increase in statistics and resolution will enhance our sensitivity and potential to BSM physics.

Backup Slides

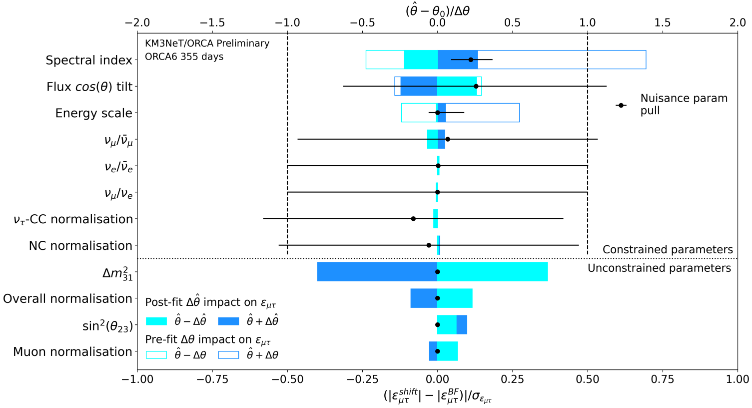
Invisible neutrino decay event distribution

Invisible neutrino decay produces a depletion of events that is increased for vertical low energy events.



Systematics rank for $\epsilon_{\mu\tau}$

Most important systematics are Δm^2_{31} and spectral index, which yields the biggest pull.



Neutrino Invisible Decay Limits

KM3NeT/ORCA115 will improve the current bounds on the invisible neutrino decay by two orders of magnitude, and it will be at least as competitive as future experiments.

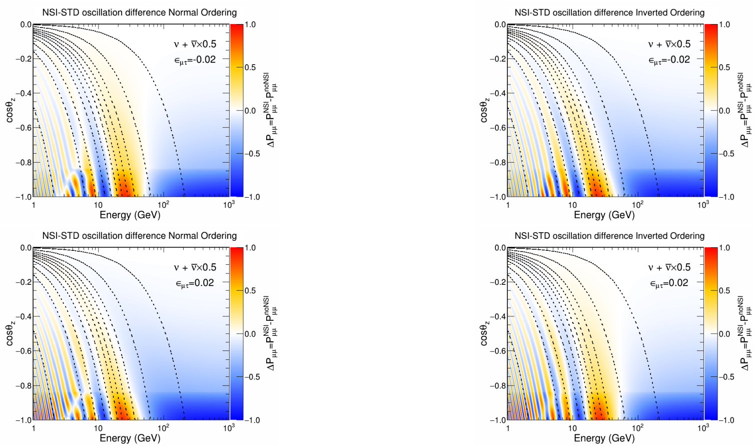
Experiment	UL (90% CL) $[10^{-6}\mathrm{eV}^2]$	LL (90% CL) [ps/eV]
KM3NeT/ORCA6	280	2.4
KM3NeT/ORCA115 (10 y)	3.7	180
T2K, NOvA	290	2.3
T2K, MINOS	240	2.8
K2K, MINOS, SK I+II	2.3	290
MOMENT (10 y)	24	28
ESSnuSB (5ν+$5\bar{\nu}$) y	16 – 13	42 – 50
DUNE (5ν+$5\bar{\nu}$) y	13	51
JUNO (5 y)	7	93
INO-ICAL (10 y)	4.4	151

Non Standard Interactions

Oscillation effects

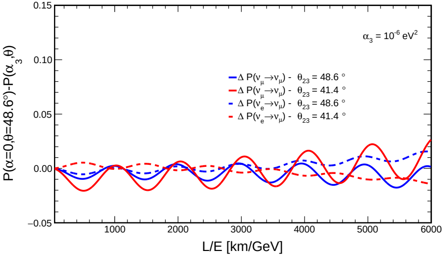
NSI effects most important signature

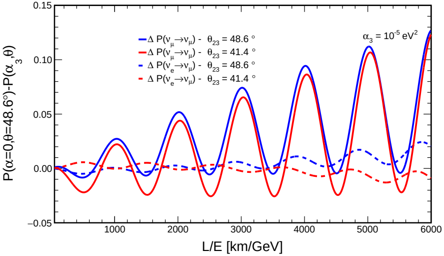
Mainly effects are seen at very vertical directions.



θ_{23} interplay with α_3

Flipping θ_{23} octant for high values of α_3 in the model reduces the difference with respect to standard oscillations.





This effect implies that as long as θ_{23} octant is not constrained with precision, sensitivity to α_3 could be affected.