Neutrino oscillations and Beyond Standard Model searches with KM3NeT/ORCA

Nadja Lessing

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

Nadja.Lessing@ific.uv.es

KM3NeT

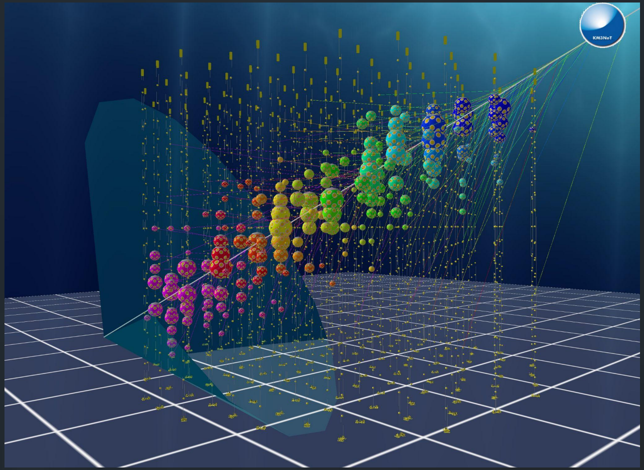
VNIVERSITAT DE VALÈNCIA

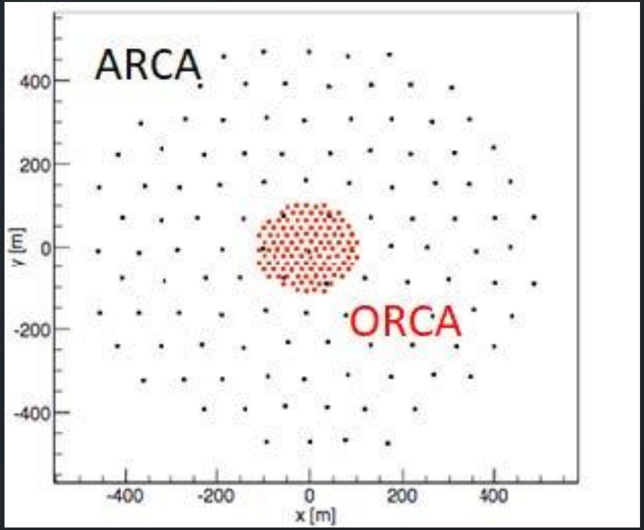
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

KM3NeT detectors

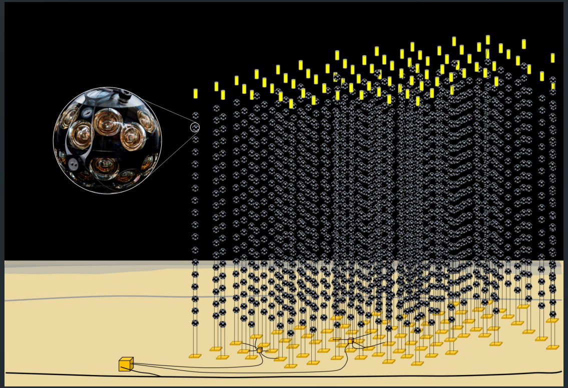
- KM3NeT/ORCA and KM3NeT/ARCA are water Cherenkov detectors in the Mediterranean Sea:
  ARCA in Italy, ORCA in France
- ORCA (*Oscillation Research with Cosmics in the Abyss*) is optimized to measure the neutrino oscillation parameters:

  ORCA is denser than ARCA in order to measure neutrinos down to a few GeV.





KM3NeT/ORCA



- Full ORCA detector:
  - 115 Detection Units.
  - 7 Mton of sea water instrumented volume.
- Currently we have 18 Detection Units deployed for ORCA.
- We have completed the data analysis for a six Detection Unit configuration (results to be shown here).
- We have started analyzing data from larger detector configurations up to ORCA18.

Results related to neutrino oscillation physics presented at ICRC2023

- Standard neutrino oscillations
- ν_τ appearance in atmospheric ν flux
- Non-Standard Interactions (NSI)
- Decoherence in neutrino oscillations
- Neutrino decay

IFIC INSTITUT DE FÍSICA CORPUSCULAR

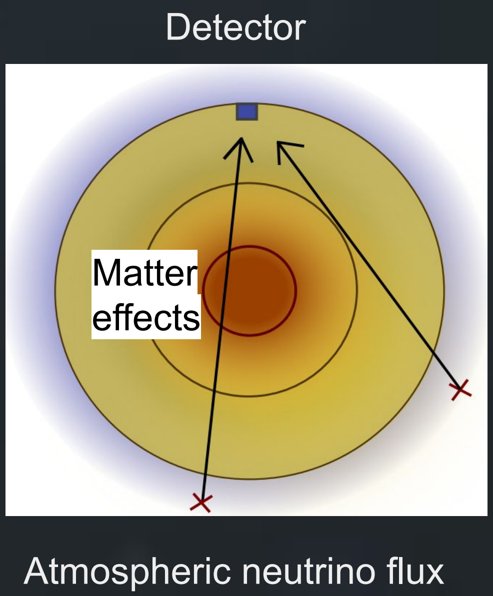
➞ I will give a review of these results here.

Analysis

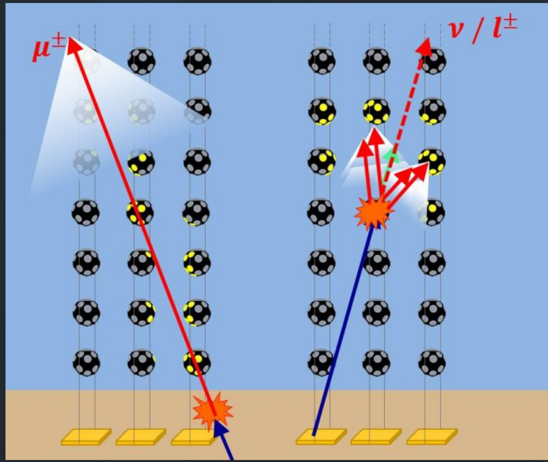
Data set

- Exposure of 433 kton-years.
- This corresponds to 510 days of data-taking time.
- Only up-going events (ν that have traversed the Earth) to avoid atmospheric muon background.
- Cuts to reject badly reconstructed events/noise.

➡ 5828 events observed.

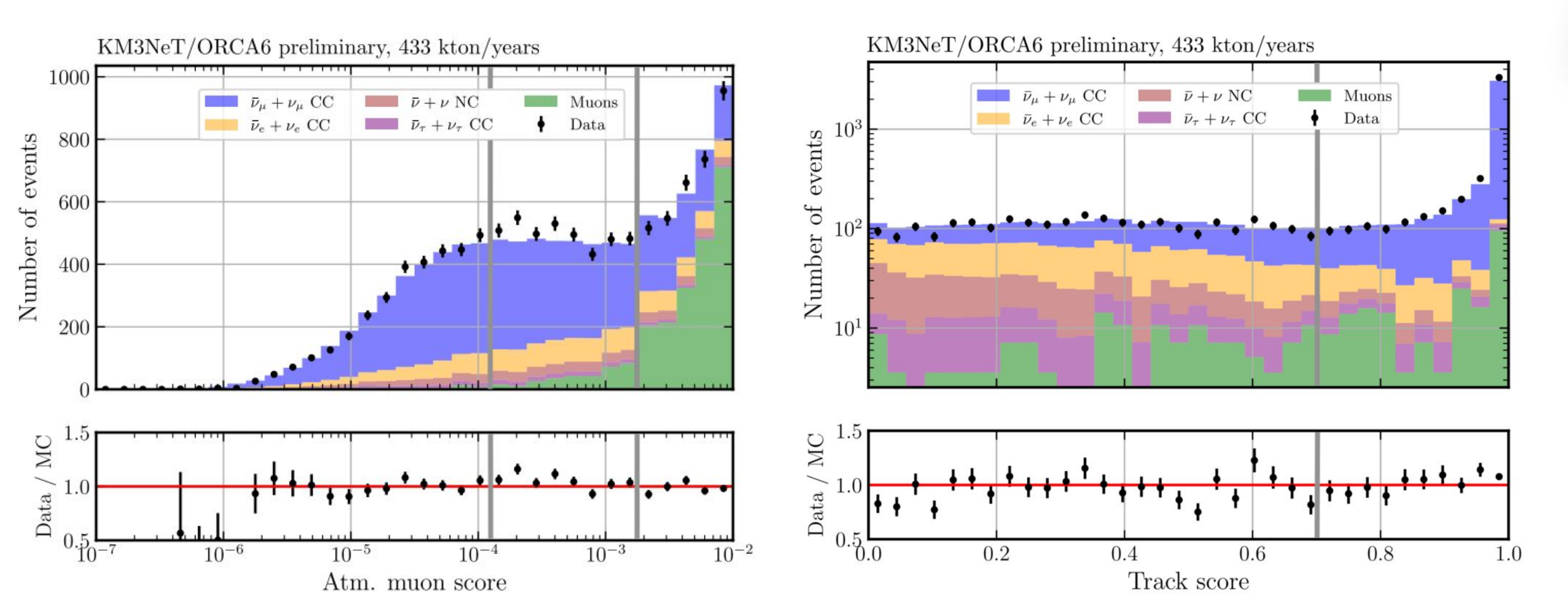


Event classification

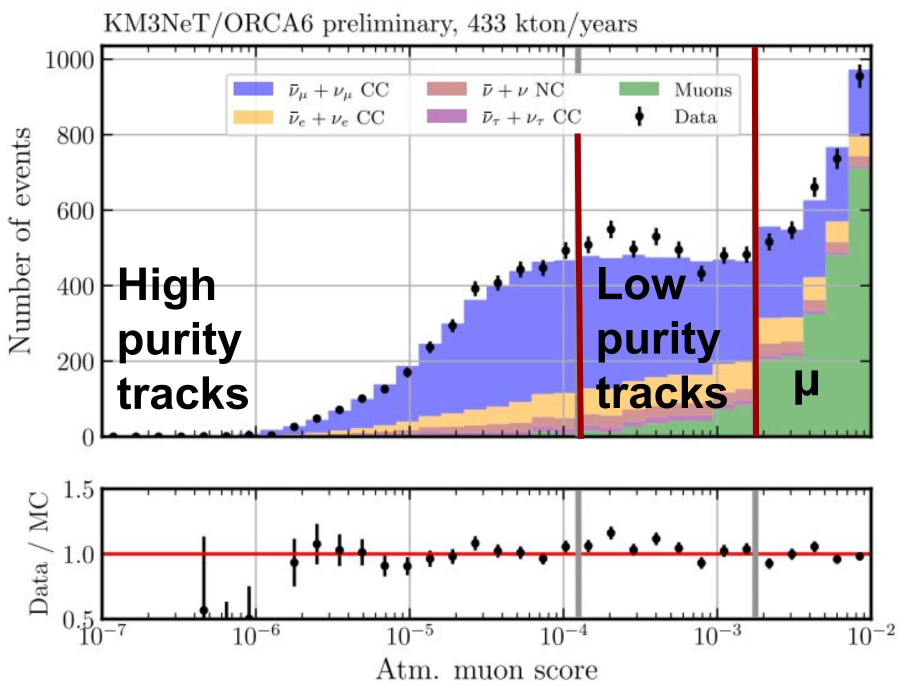


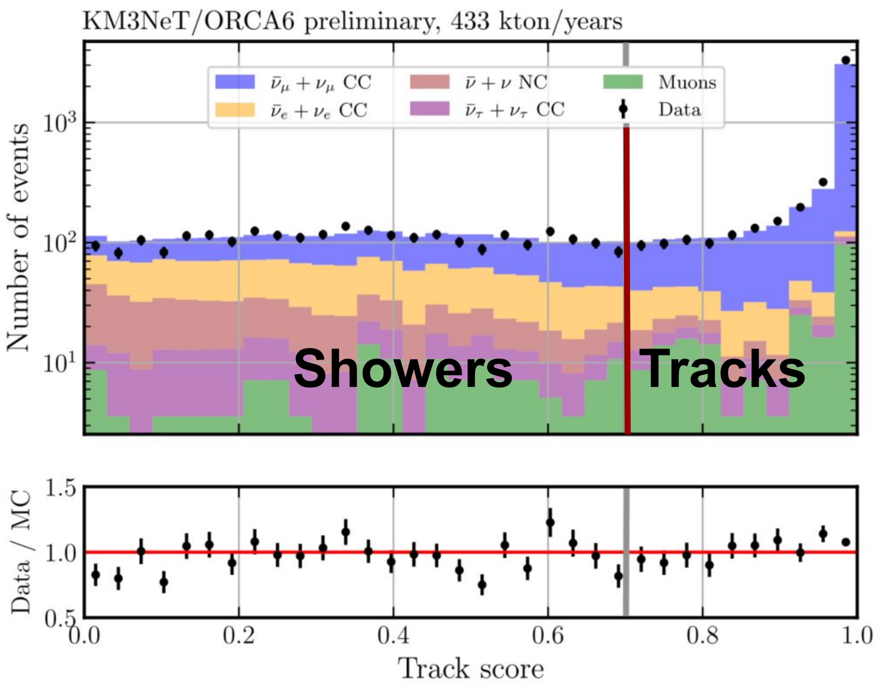
- Boosted Decision Tree (BDT) assigns atmospheric muon score and track score to each event in order to:
    - reject remaining atmospheric muon background.
    - discriminate between track-like and shower-like events.
- Event sample is divided into three classes:
    - High purity tracks (very likely from a neutrino interaction).
    - Low purity tracks (some atm. muon contamination possible).
    - Showers.

Event distributions



Event distributions



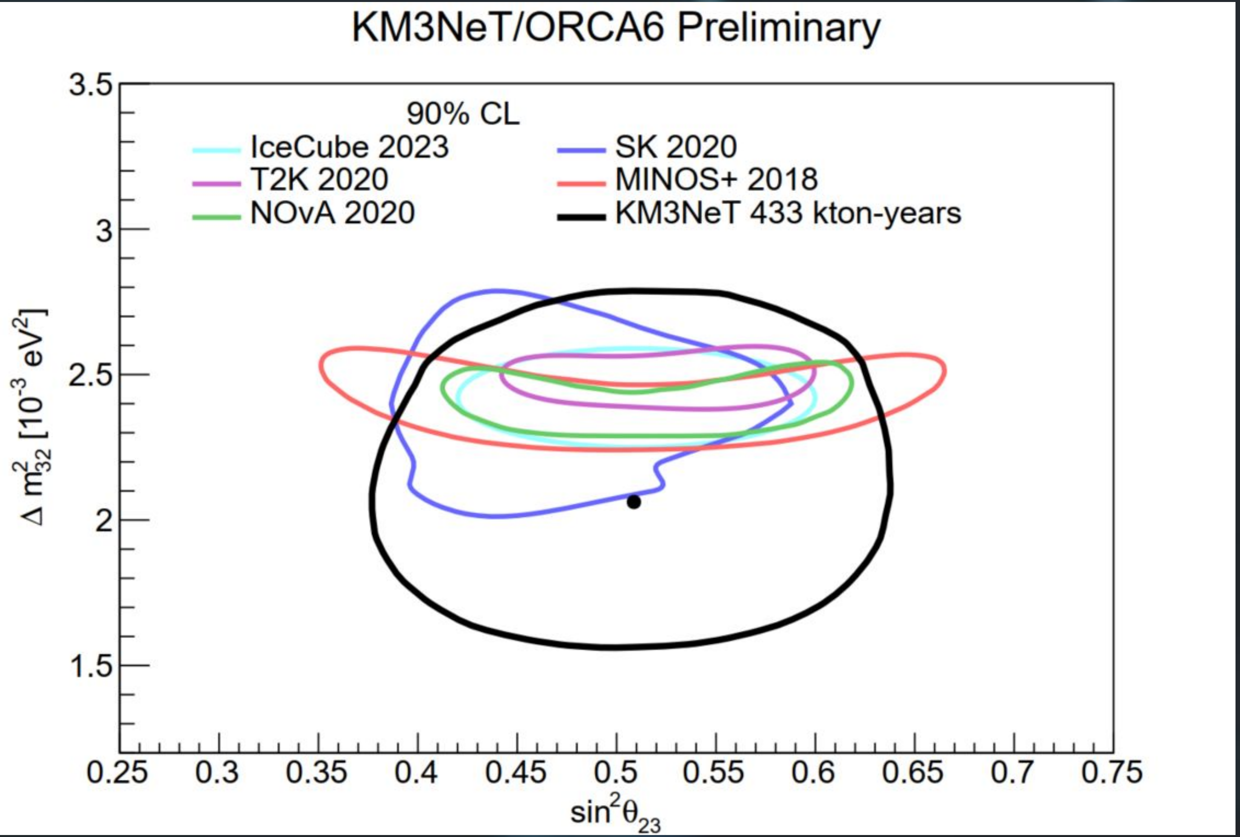


Analysis methods

- Events are reconstructed in 2D histograms of energy vs. $\cos(\theta_z)$.
- Binned log-likelihood is maximized for the 2D distributions.
- Systematics take into account uncertainties about:
  - optical properties of water and PMT efficiencies.
  - spectral index and composition of atmospheric neutrino flux.
  - number of events (normalization) in each class.

Results

Standard Oscillations with ORCA6



Standard Oscillations with ORCA6

PoS (ICRC2023) 996

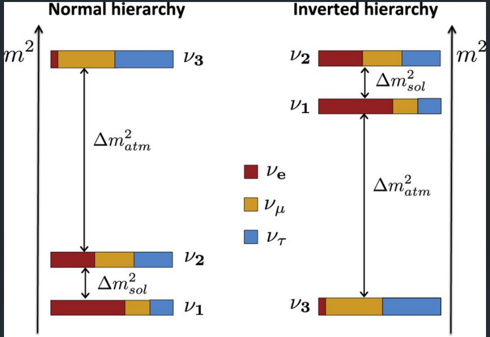
Results of the fit:

$$\sin^2(\Theta_{23}) = 0.51^{+0.06}_{-0.07}$$

Difference in the LLR for the best fit of each mass ordering:

$$\Delta m^2_{31} = (2.14^{+0.25}_{-0.36} \cdot 10^{-3})\ \mathrm{eV}^2$$

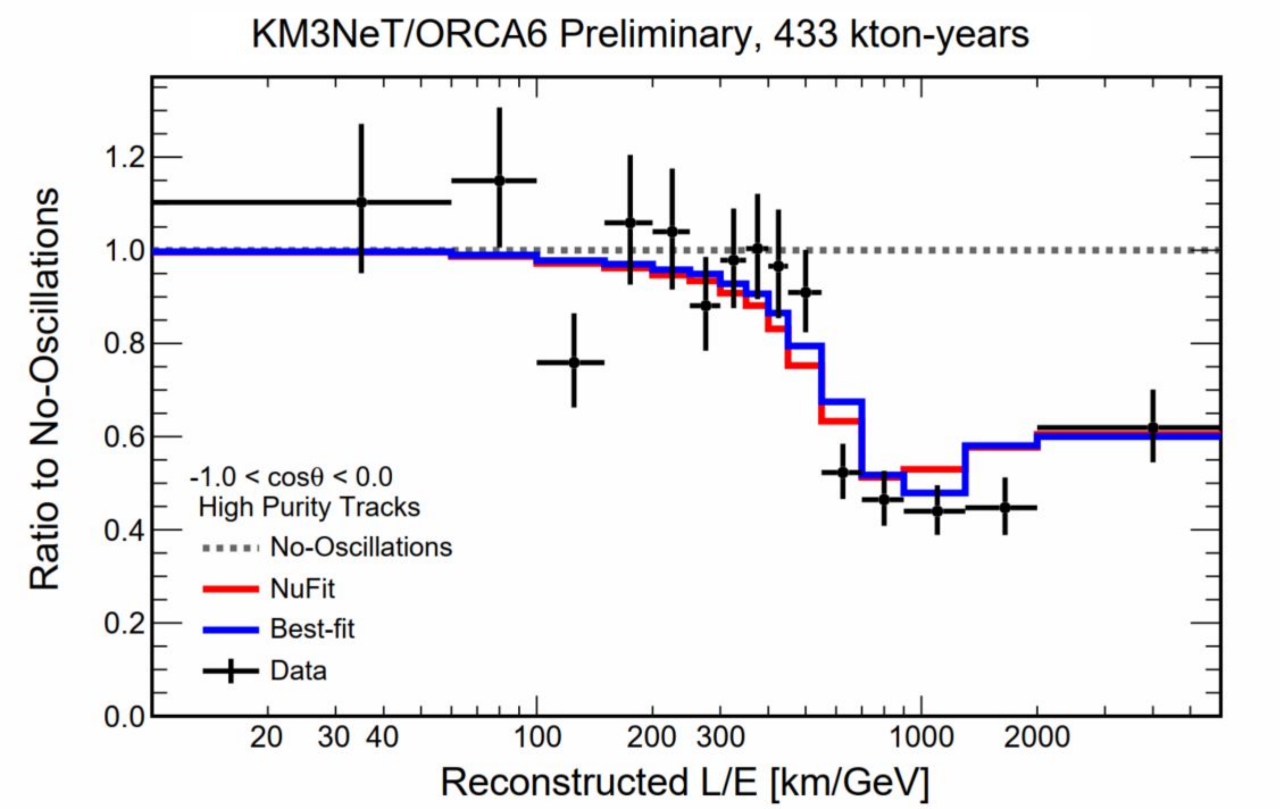
$$-2\log(L_{NO} / L_{IO}) = 0.9$$



Small preference for normal ordering.

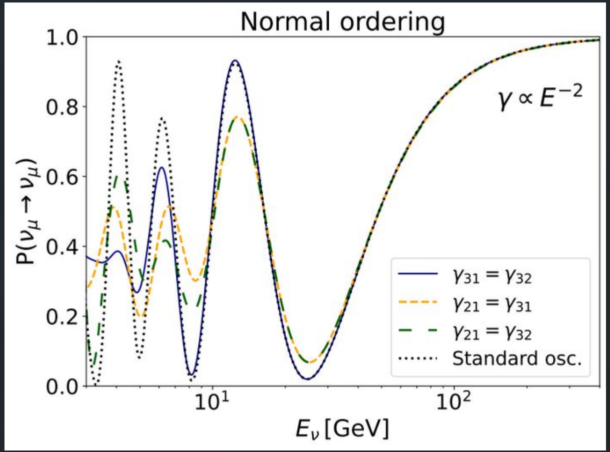
Author: Víctor Carretero, vcarretero@km3net.de

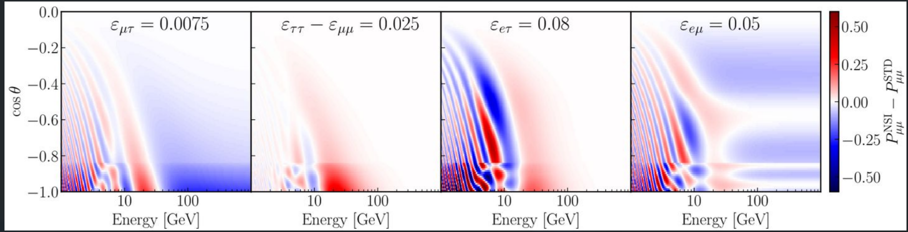
Standard Oscillations with ORCA6



Beyond Standard Model searches

- Several Beyond Standard Model effects are expected to alter the neutrino oscillation probabilities.
- We have searched for various BSM effects with the same dataset as for the standard oscillation analysis:
  - Non-Standard Interactions
  - Neutrino Decoherence
  - Invisible Neutrino Decay



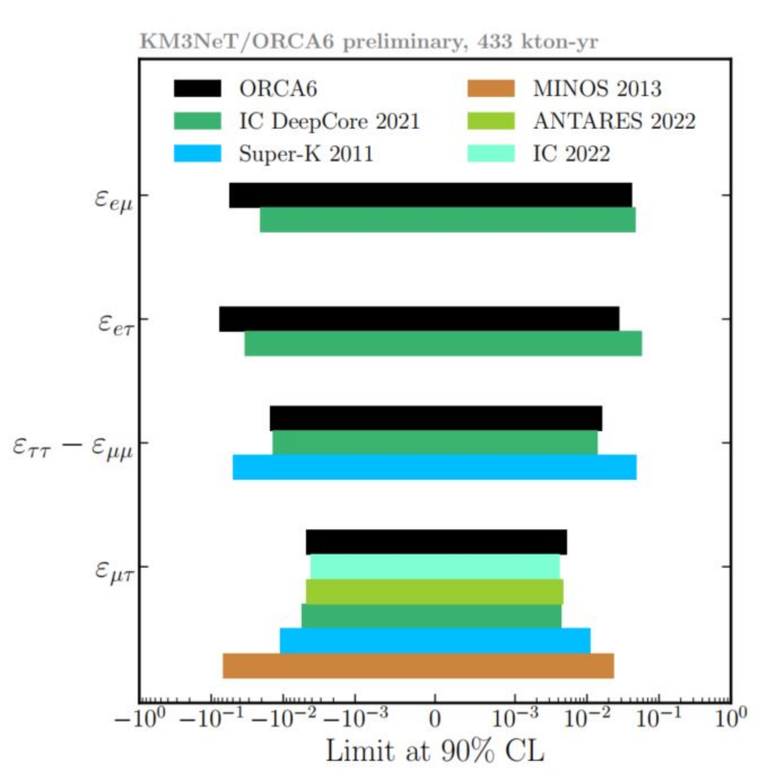


Non-Standard Interactions PoS (ICRC2023) 998

- Coherent forward scattering of neutrinos on fermions in matter is modified.

$$\mathcal{H}_{\text{eff}} = \frac{1}{2E}\mathcal{U}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix}\mathcal{U}^{+} + A(x)\begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}$$

- No deviation with respect to standard interactions found.
- ORCA6 gives bounds to four NSI parameters. The bounds are of the same order of magnitude as current leading limits.

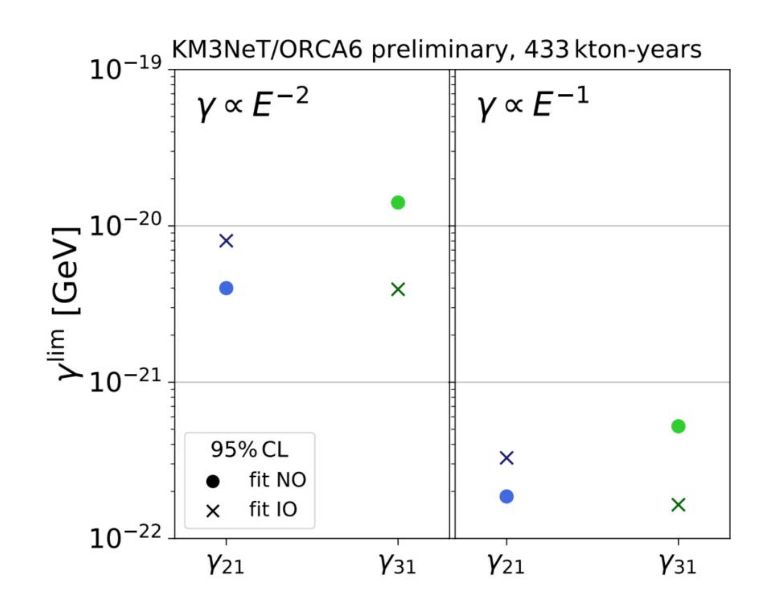


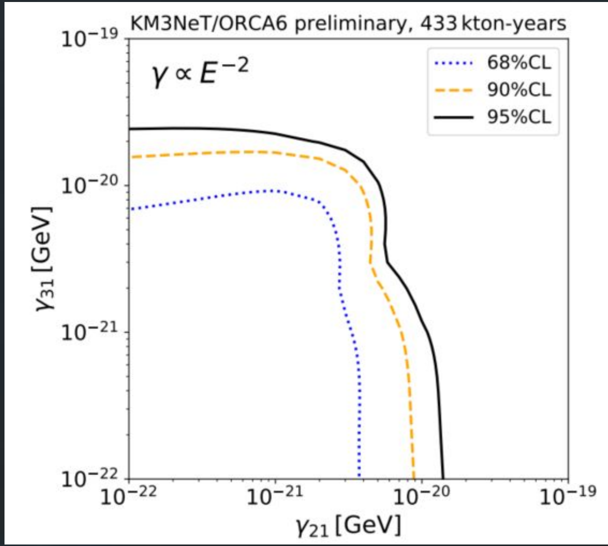
Author: Alfonso Lazo, Alfonso.Lazo@ific.uv.es

Neutrino Decoherence [PoS (ICRC2023) 1025]

- Neutrino mass states as an open quantum system interact with the environment and lose their coherent superposition.

→ Oscillation probabilities are modified by a damping term.



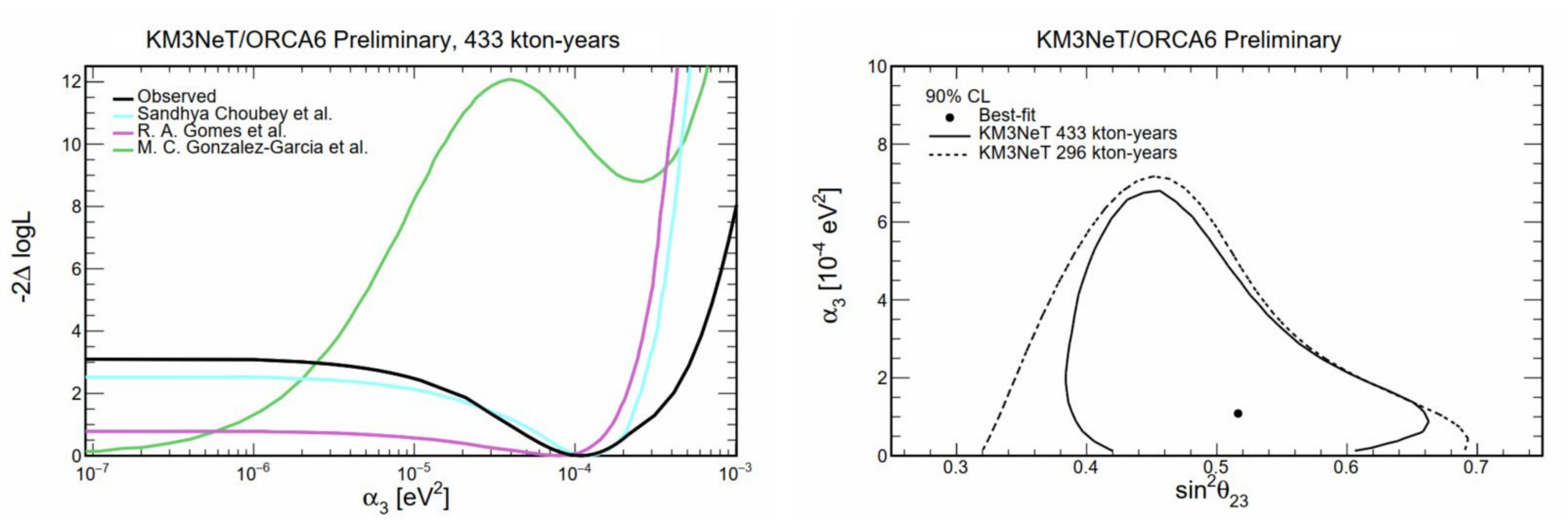


We give limits on the decoherence parameters for two dependencies of the neutrino energies and both mass orderings.

Author: Nadja Lessing (me), Nadja.Lessing@ific.uv.es

Invisible Neutrino Decay PoS (ICRC2023) 997

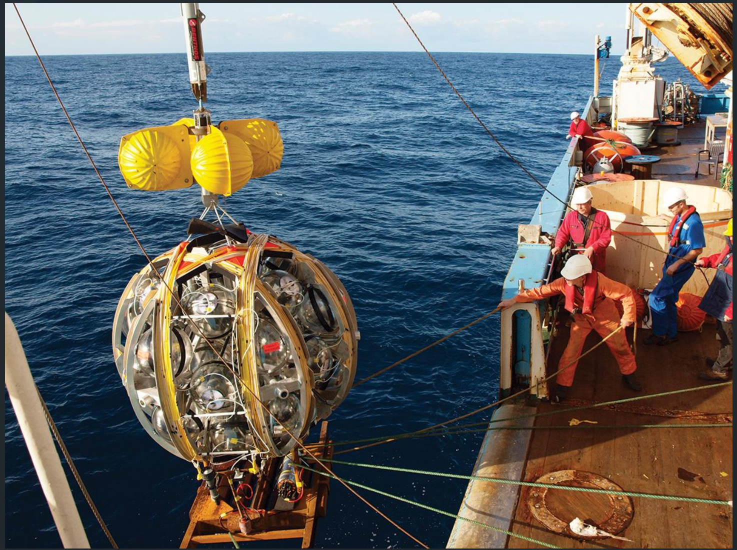
- Third neutrino mass state decays into an undetectable state.
- Best fit of the decay parameter $\alpha_3 = 1.08 \cdot 10^{-4} \mathrm{eV}^2$, preference $1.8\ \sigma$.



Author: Víctor Carretero, vcarretero@km3net.de

Conclusion

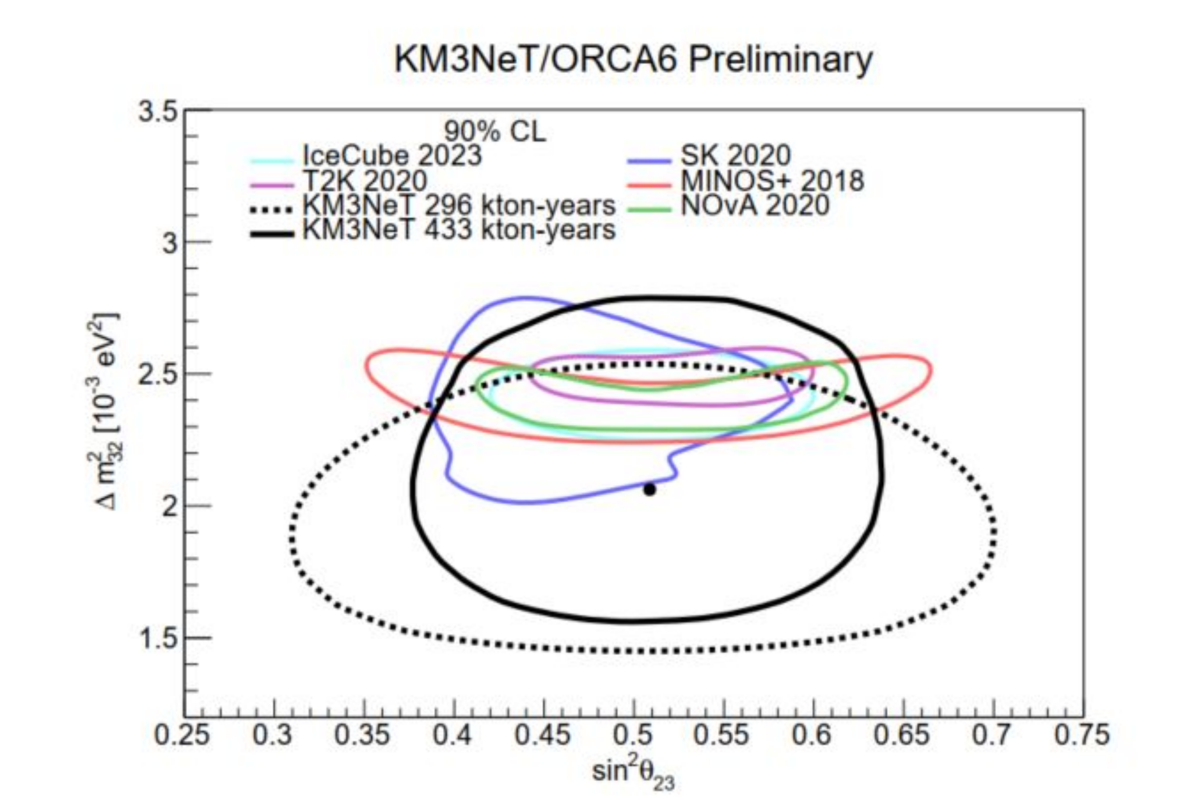
- We are able to measure the neutrino oscillation parameters even with only six detection units of the ORCA detector.
- At the same time we are searching for various Beyond Standard Model physics.
- We gave constraints for the effects of Non-Standard Interactions, Neutrino Decay and Neutrino Decoherence.



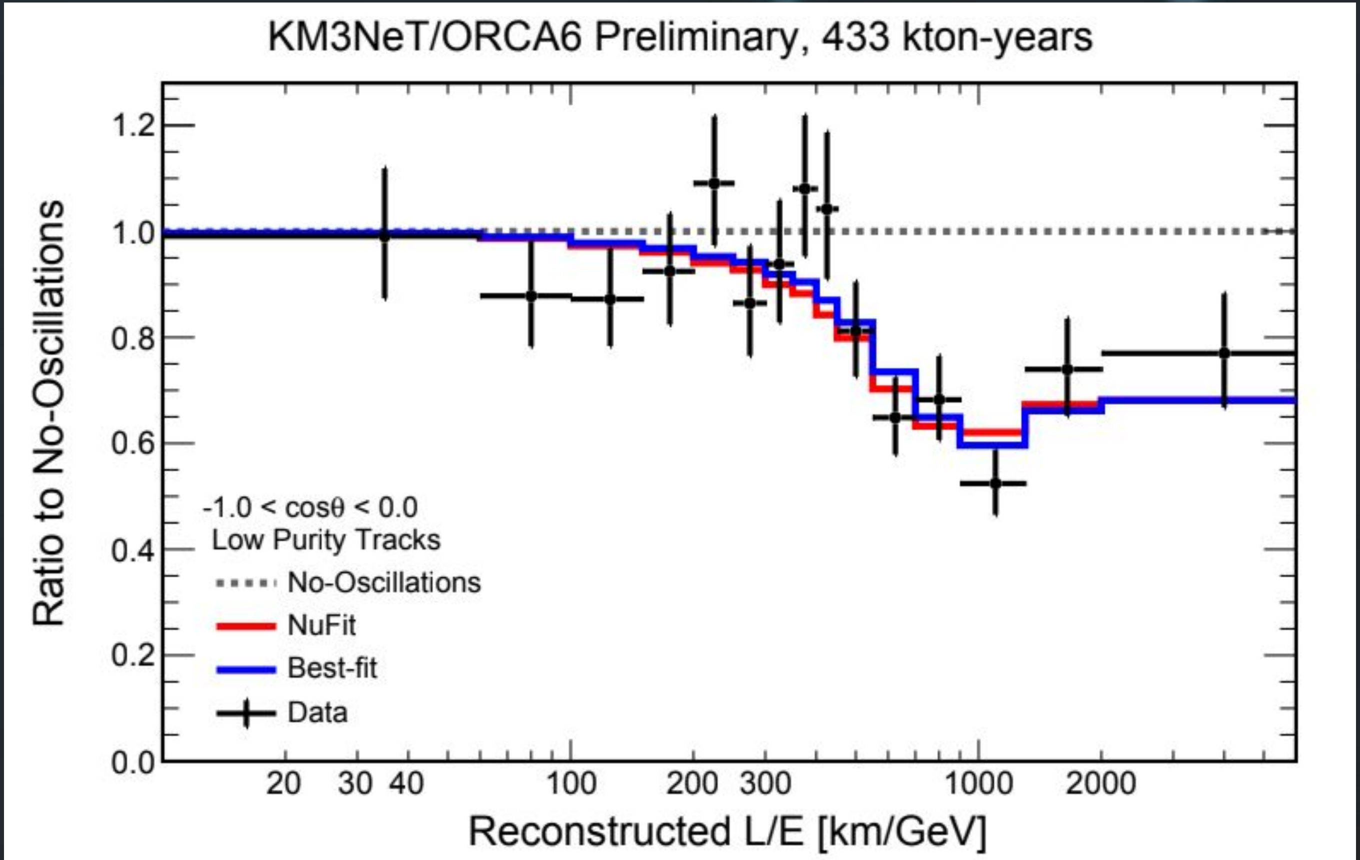
ORCA is continuously growing (we now have 18 detection units!) so we will be able to improve all our results in the near future.

Backup

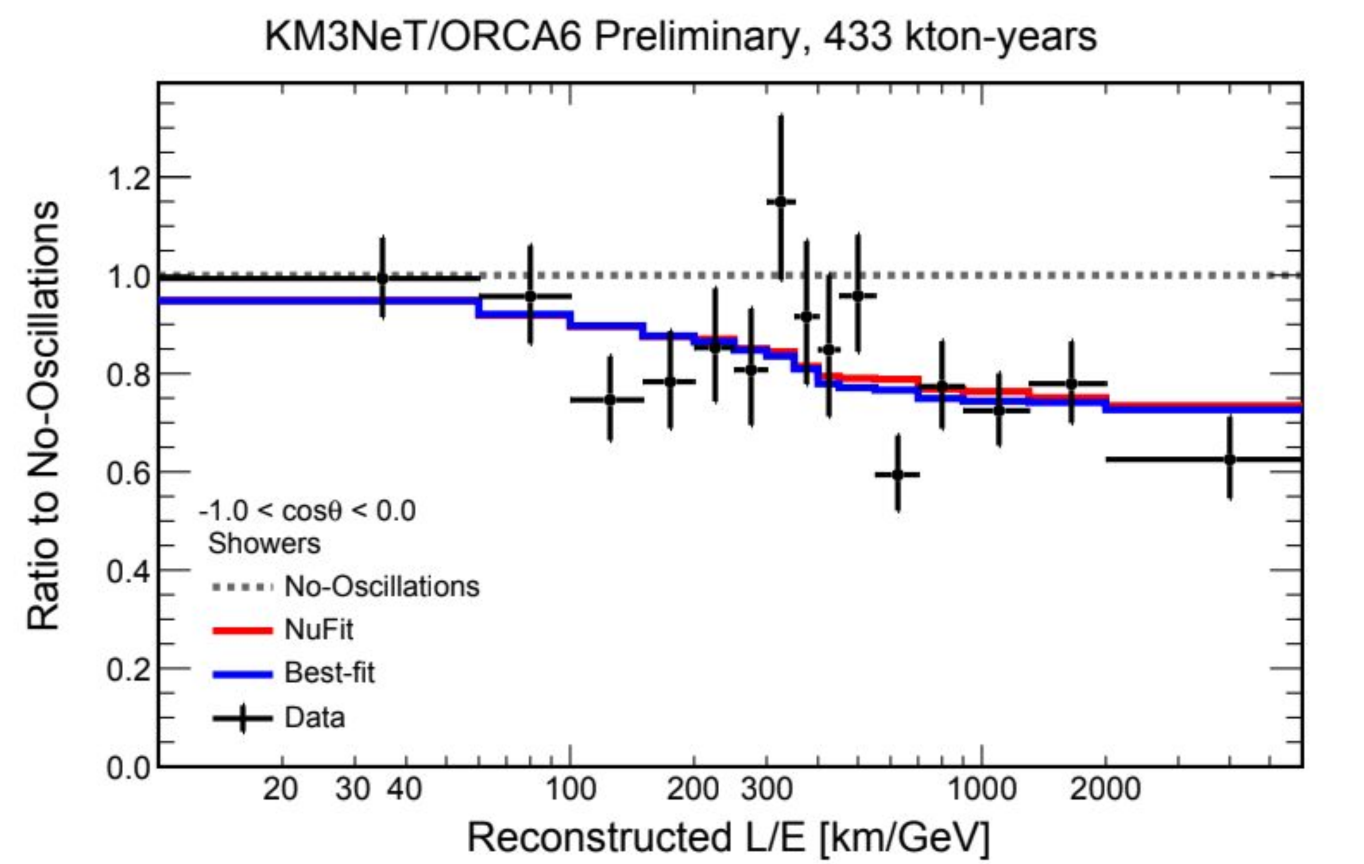
Standard Oscillations and previous result



Standard Oscillations with ORCA6



Standard Oscillations with ORCA6



Parameters and systematics

Parameter	Nominal value NO	Nominal value IO	Treatment
Δm^2_{31} [eV^2]	$2.517 \cdot 10^{-3}$	$-2.424 \cdot 10^{-3}$	free
Δm^2_{21} [eV^2]	$7.42 \cdot 10^{-5}$	$7.42 \cdot 10^{-5}$	fixed
θ_{12} [°]	33.44	33.45	fixed
θ_{13} [°]	8.57	8.60	fixed
θ_{23} [°]	49.2	49.3	free
δ_{CP} [°]	197	282	fixed

Parameter	Prior
Spectral index	±0.3
Energy scale	±9 %
ν_{hor}/ν_{ver} ratio	±2 %
$\nu_e/\bar{\nu}_e$ ratio	±7 %
$\nu_\mu/\bar{\nu}_\mu$ ratio	±5 %
$(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ ratio	±2 %
High-energy light simulation	±50 %
NC normalization	±20 %
τ-CC normalization	±20 %
Muon normalization	free
Track normalization	free
Shower normalization	free
Overall normalization	free

Table 2: Nuisance parameters along with their prior uncertainties.

Result and expectation from Pseudo-data