

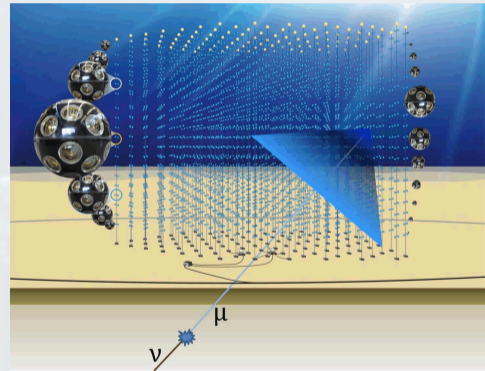


Measurement of atmospheric neutrino oscillations with KM3NeT/ORCA

Alfonso Lazo Pedrajas
on behalf of the KM3NeT Collaboration

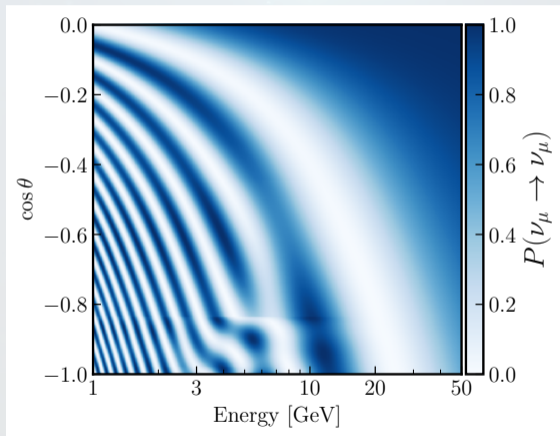


- Water-Cherenkov neutrino telescope under construction in the Mediterranean Sea, 40 km offshore Toulon (Fr)
- 18 Multi-PMT Digital Optical Modules (DOMs) along vertical Detection Units (DUs)
- 23 DUs deployed, 115 foreseen
- $\sim 20\text{m}$ horizontal DU spacing, $\sim 9\text{m}$ vertical DOM spacing
- Detection of Cherenkov light induced by secondary charged particles from neutrino interactions
- Main goal: **Measurement of Neutrino Mass Ordering (NMO) and neutrino oscillation parameters**

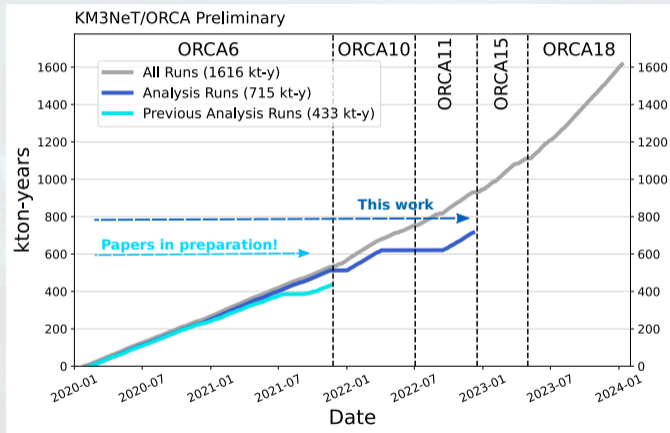


- ORCA optimised to detect atm ν in the 1-100 GeV range coming from multiple arrival directions ($\cos \theta_z$)
- Matter effects modify vacuum oscillations enabling the measurement of Δm_{31}^2 and θ_{23}
- Matter resonance yields asymmetry of $\nu/\bar{\nu}$ at $\sim 3-7$ GeV \rightarrow eventual NMO measurement with larger detector

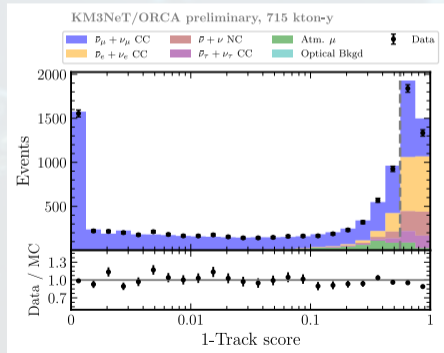
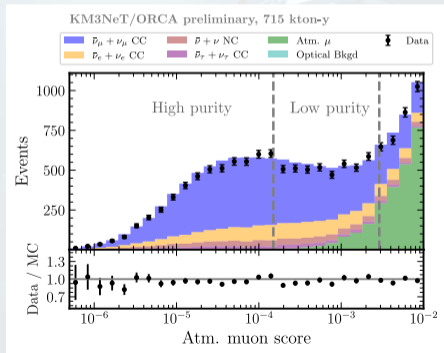
$$\mathcal{H}_{\text{eff}} = \frac{1}{2E} \mathcal{U}_{PMNS} \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) \mathcal{U}_{PMNS}^+ \\ + \text{diag}(\sqrt{2}G_F n_e(x), 0, 0)$$



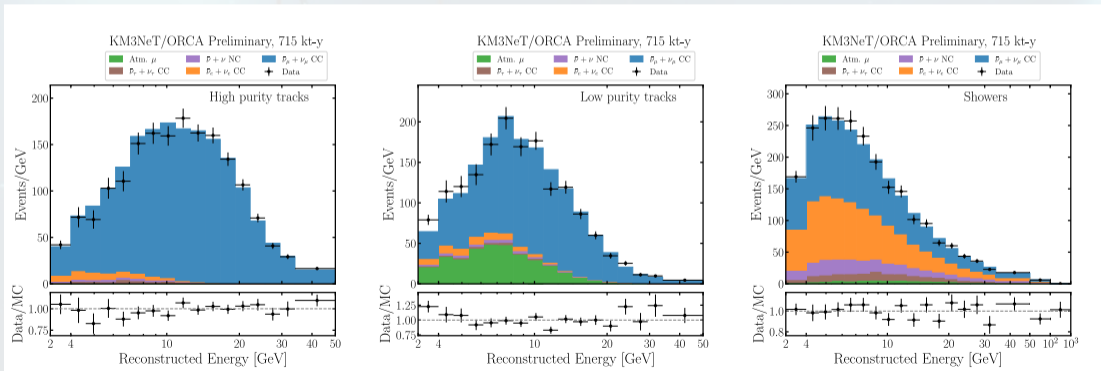
- Three detector configurations analysed:
 - Re-analysis of **ORCA6** with overall reconstruction, simulation and calibration improvements + 20% added exposure
 - **ORCA10**
 - **ORCA11**
- Updated measurement with **715 kton-yr** compared to previous 433 kton-yr
- Similar energy and direction reconstruction performance between detectors



- Data dominated by optical background before selection → dedicated BDTs
- Further BDTs to distinguish atm- ν from misreconstructed μ and track-like from shower-like topologies
- Three event sets: **High-purity (HP) tracks**, **Low-purity (LP) tracks** and **Showers**



- **9751** neutrino candidates in the 715 kton-yr dataset (**+40%** with respect to previous analysis)
- 97% $\nu_\mu + \bar{\nu}_\mu$ purity in HP tracks
- 91% of $\nu_e + \bar{\nu}_e$ in the selection present in the Shower set

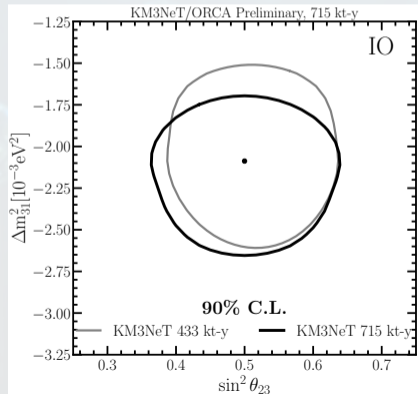
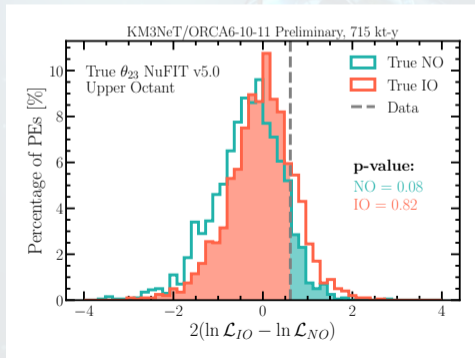


Results from 715 kton-yr dataset



$$\Delta m_{31}^2 = -2.09_{-0.21}^{+0.17} \cdot 10^{-3} \text{eV}^2 \text{ IO}$$
$$([2.10, 2.37] \cdot 10^{-3} \text{eV}^2 \text{ NO})$$
$$\sin^2 \theta_{23} = 0.50 \pm 0.07$$

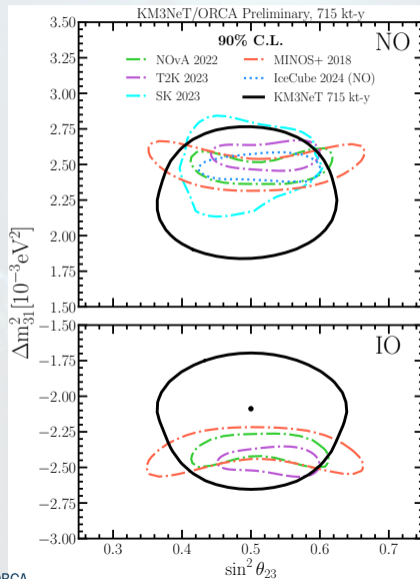
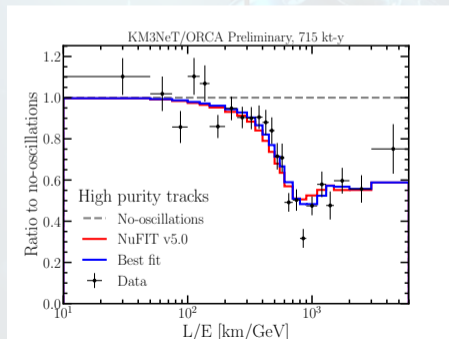
- Goodness of fit p-value 0.41 → excellent data-MC agreement
- Mild preference for IO $2 \ln(\mathcal{L}_{\text{IO}}/\mathcal{L}_{\text{NO}}) = 0.61$ → not significant
- Improved measurement on Δm_{31}^2



Results from 715 kton-yr dataset



- Result consistent with global fits and other experiments
- Approaching competitive measurement of θ_{23} , not yet there in Δm_{31}^2

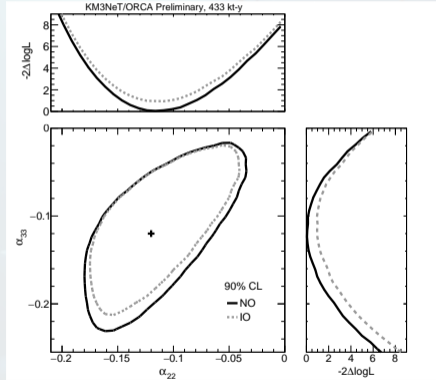


Oscillations and beyond: What if...?



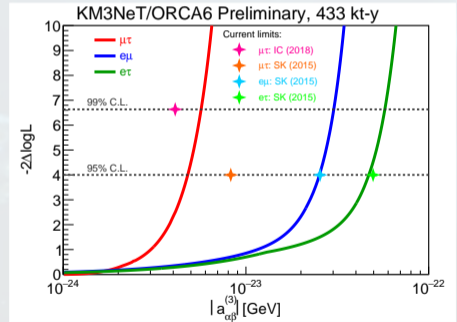
... left-handed neutrino mixing was **non-unitary** due to the presence of heavy sterile states [2]?

$$N = (1 + \alpha)U_{PMNS}$$



... neutrinos manifested time-independent isotropic **Lorentz Invariance Violation** as a consequence of quantum gravity [3]?

$$\mathcal{H}_{LIV} \approx \dot{a}^{(3)} - 4E/3\dot{c}^{(4)} + E^2\dot{a}^{(5)} - E^3\dot{c}^{(6)} \dots$$



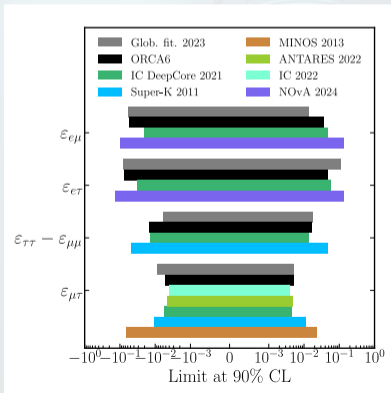
- Atm- ν oscillations observed consistent with SM prediction, but **strong bounds** were placed on BSM models (results from 433 kton-yr dataset)

Oscillations and beyond: What if...?

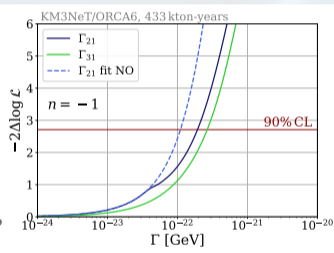
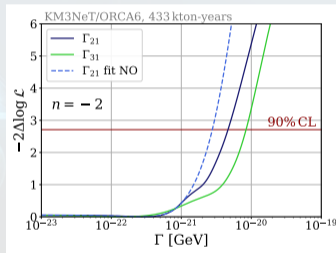


... neutrinos experienced NC **Non-Standard Interactions** in the coherent forward scattering [4]?

$$\mathcal{H}_{\text{nsi}} = \sqrt{2}G_F n_e(x) \begin{bmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{bmatrix}$$



... neutrino mass eigenstates interacted with the environment and lost their coherent superposition (**Quantum Decoherence**) [5]?



- Atm- ν oscillations observed consistent with SM prediction, but **strong bounds** were placed on BSM models (results from 433 kton-yr dataset)

- KM3NeT/ORCA provides valuable data already during construction
- Growing detector improves its own measurements very rapidly
- Excellent understanding of the data and simulations with still plenty of room for innovation in systematics modelling
- KM3NeT carries out an extensive research program of BSM physics with neutrino oscillations resulting in competitive bounds
- KM3NeT/ORCA offers bright prospects for the near future
 - **23 detection units** currently deployed
 - Up to **1.6 Mton-yr** with expanded detector in the pipeline about to be analysed!



Backup

- Maximum Likelihood Estimation of the parameters:

$$-2 \ln \mathcal{L} = \left\{ 2 \sum_{i,j}^{N_{\text{bin}}} \left[N_{ij}^m(\vec{\omega}, \vec{\eta}) - N_{ij}^{\text{dat}} + N_{ij}^{\text{dat}} \ln \left(\frac{N_{ij}^{\text{dat}}}{N_{ij}^m(\vec{\omega}, \vec{\eta})} \right) \right] + \sum_{i,j}^{N_{\text{bin}}} \frac{(\beta_{ij} - 1)^2}{\sigma_{ij}^2} + \sum_k^{\text{syst}} \left(\frac{\eta_k - \langle \eta_k \rangle}{\sigma_k} \right)^2 \right\}.$$

- 2D-profiled likelihood scans of the Δm_{31}^2 and $\sin^2 \theta_{23}$:
 $-2 \ln(\mathcal{L}_{\Delta m_{31}^2, \theta_{23}} / \mathcal{L}_{bf}) = -2 \Delta \ln \mathcal{L}.$
- 530 bins in total: 3 PID bins (17 HP-track, 17 LP-track and 19 showers in reco energy) x10 $\cos \theta_z$ bins

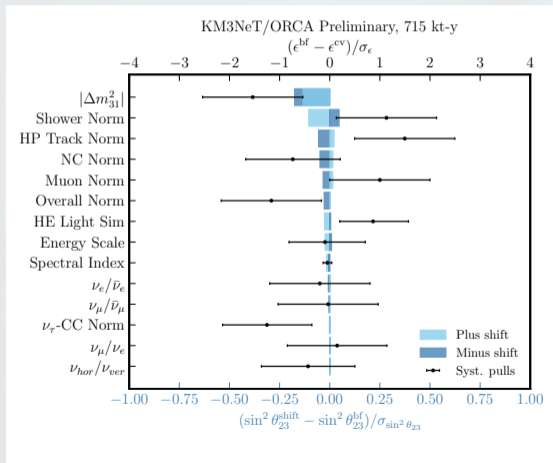
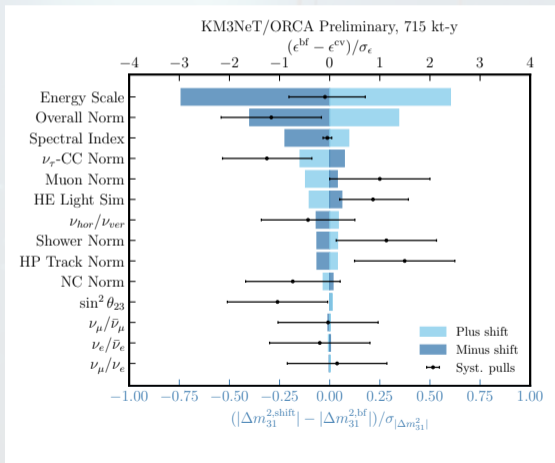
- Uncertainties in flux, detector, cross section and background modelling






	Nominal value	Syst. unc.
$\Delta m_{31}^2 \cdot 10^{-3} [\text{eV}^2]$	2.517 (NO) / -2.424 (IO)	free
$\Delta m_{21}^2 \cdot 10^{-5} [\text{eV}^2]$	7.42	fixed
$\theta_{23} [^\circ]$	49.2 (NO) / 49.3 (IO)	free
$\theta_{21} [^\circ]$	33.44	fixed
$\theta_{31} [^\circ]$	8.57 (NO) / 8.60 (IO)	fixed
High purity Normalisation	1.0	free
Overall Normalisation	1.0	free
Shower Normalisation	1.0	free
Atm. Muon Normalisation	1.0	free
HE Light Sim	1.0	20%
Energy Scale	1.0	9%
Flux energy slope	0.0	10%
Flux zenith slope	0.0	2%
ν_τ Normalisation	1.0	20%
ν NC Normalisation	1.0	20%
$\nu_\mu / \bar{\nu}_\mu$	0.0	5%
$\nu_e / \bar{\nu}_e$	0.0	7%
ν_μ / ν_e	0.0	2%

Impact of systematics 715 kton-yr dataset



- Shift each systematic by $\pm 1\sigma$ respect to its best fit, fit all remaining systematics and Δm_{31}^2 or θ_{23}
- Evaluate deviation in Δm_{31}^2 or θ_{23} respect to the best fit divided by observed uncertainty
- Black dots are pulls and error bars are ratio post-fit uncertainty to prior



-  S. Peña Martínez. *Updated measurement of atmospheric neutrino oscillation parameters with KM3NeT/ORCA*. <https://agenda.infn.it/event/37867/contributions/227962/>.
-  L. Cerisy. *Non unitary neutrino mixing with KM3NeT/ORCA*. <https://agenda.infn.it/event/37867/contributions/228303/>.
-  L. Hennig. *Search for Lorentz invariance violation with ANTARES and KM3NeT/ORCA6*. <https://agenda.infn.it/event/37867/contributions/228296/>.
-  A. Lazo. *Updated results on neutrino Non-Standard Interactions with KM3NeT/ORCA6*. <https://pos.sissa.it/444/998>.
-  N. Lessing. *Search for Quantum Decoherence in Neutrino Oscillations with KM3NeT/ORCA6*. <https://pos.sissa.it/444/1025/>.