Measurement of atmospheric neutrino oscillations with KM3NeT/ORCA

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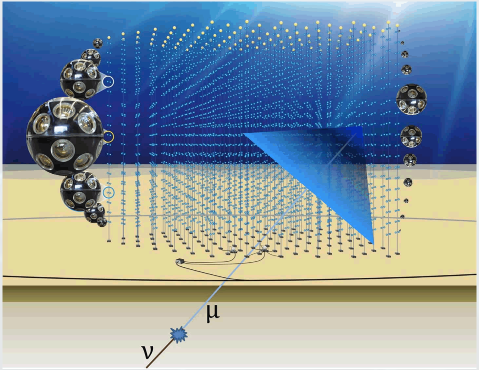
KM3NeT/ORCA

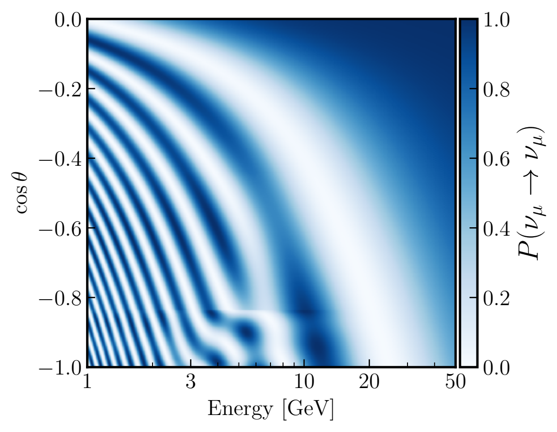
- Water-Cherenkov neutrino telescope under construction in the Mediterranean Sea, 40 km offshore Toulon (Fr)
- 18 Multi-PMT Digital Optical Modules (DOMs) along vertical Detection Units (DUs)
- 23 DUs deployed, 115 foreseen
- $\sim$ 20m horizontal DU spacing, $\sim$ 9m vertical DOM spacing
- Detection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



Oscillation of atmospheric neutrinos

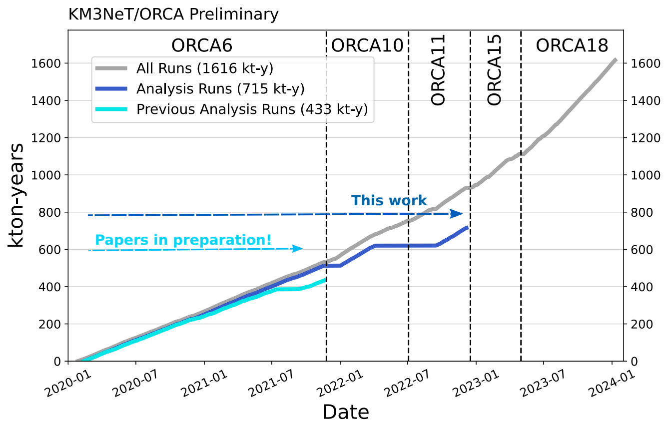
- ORCA optimised to detect atm ν in the 1-100 GeV range coming from multiple arrival directions ($\cos\theta_z$)
- Matter effects modify vacuum oscillations enabling the measurement of Δm^2_{31} and θ_{23}
- Matter resonance yields asymmetry of $\nu/\bar{\nu}$ at $\sim$3-7 GeV $\rightarrow$ eventual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

$$\mathcal{H}_{\rm eff} = \frac{1}{2\mathrm{E}}\mathcal{U}_{PMNS}\mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})\mathcal{U}^{+}_{PMNS} + \mathrm{diag}(\sqrt{2}G_F n_{\rm e}(x), 0, 0)$$



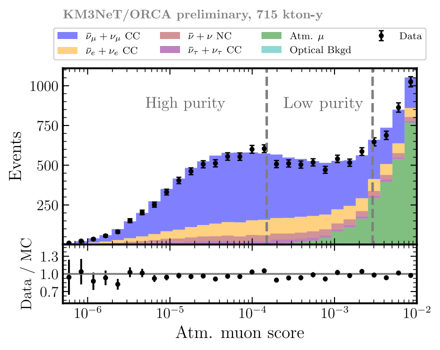
KM3NeT/ORCA dataset

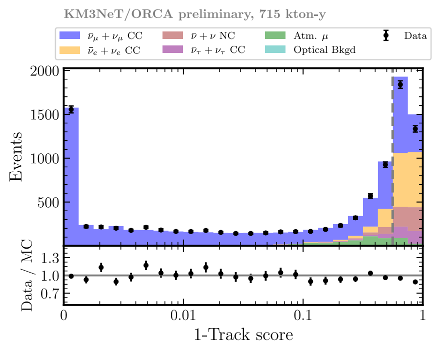
- Three detector configurations analysed:
  - Re-analysis of **ORCA6** with overall reconstruction, simulation and calibration improvements + 20% added exposure
  - **ORCA10**
  - **ORCA11**
- Updated measurement with **715 kton-yr** compared to previous 433 kton-yr
- Similar energy and direction reconstruction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



KM3NeT/ORCA dataset

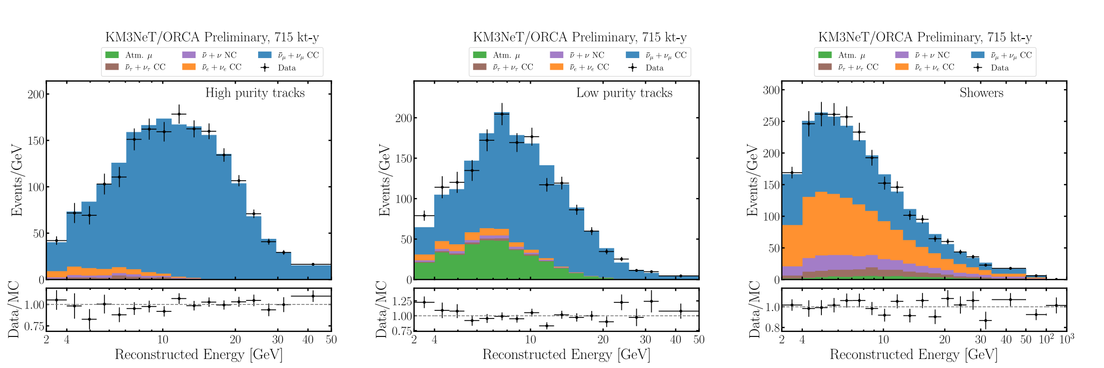
- Data dominated by optical background before selection $\rightarrow$ dedicated BDTs
- Further BDTs to distinguish atm-ν from misreconstructed μ and track-like from shower-like topologies
- Three event sets: **High-purity (HP) tracks**, **Low-purity (LP) tracks** and **Showers**





KM3NeT/ORCA dataset

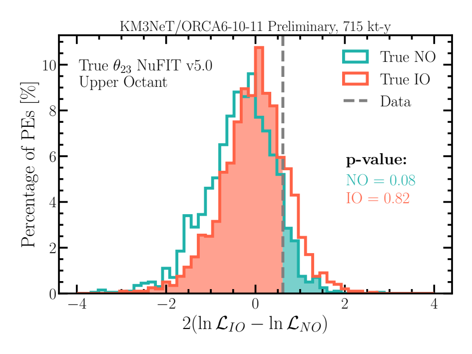
- **9751** neutrino candidates in the 715 kton-yr dataset (**+40%** with respect to previous analysis)
- 97% ν_μ+$\bar{\nu}_\mu$ purity in HP tracks
- 91% of ν_e+$\bar{\nu}_e$ in the selection present in the Shower set

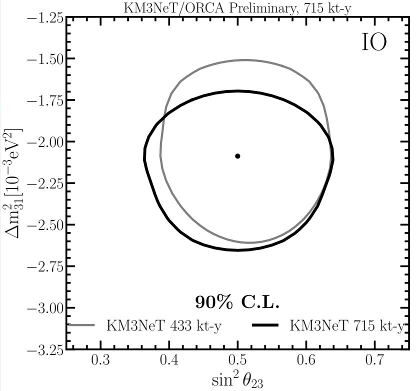


Results from 715 kton-yr dataset

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

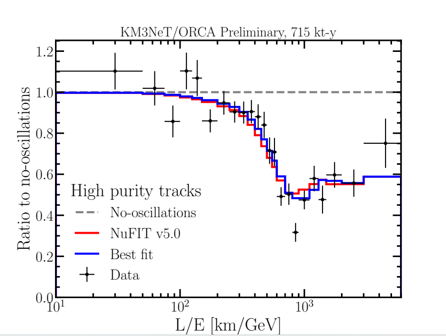
- Goodness of fit p-value 0.41 $\rightarrow$ excellent data-MC agreement
- Mild preference for IO $2\ln(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61 \rightarrow$ not significant
- Improved measurement on Δm^2_{31}

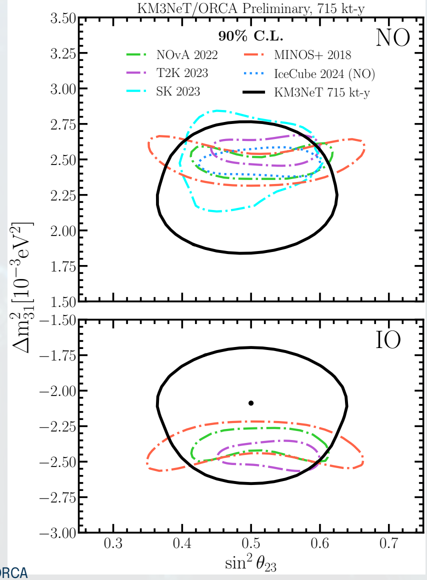




Results from 715 kton-yr dataset

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

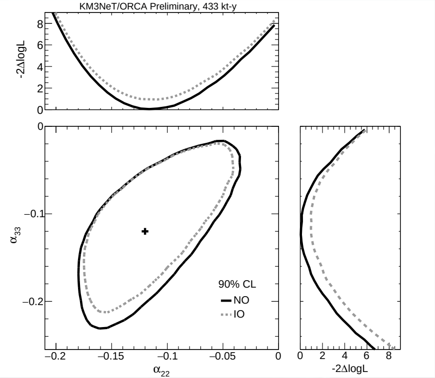




Oscillations and beyond: What if...?

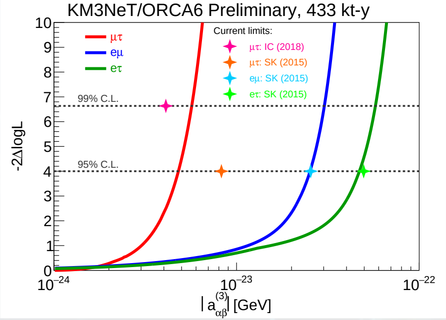
... left-handed neutrino mixing was **non-unitary** due to the presence of heavy sterile states [2]?

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



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

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

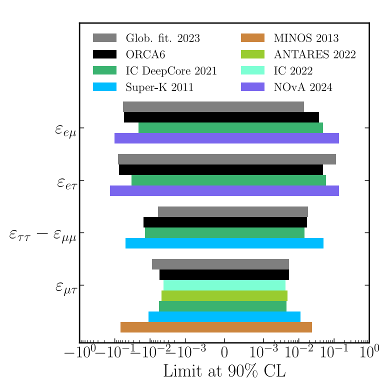


- Atm-ν oscillations observed consistent with SM prediction, but **strong bounds** were placed on BSM models (results from 433 kton-yr dataset)

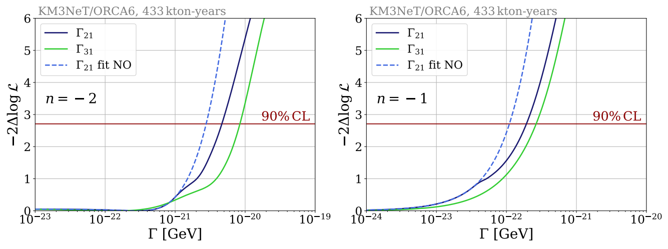
Oscillations and beyond: What if...?

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

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



... 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)

Conclusions

- 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

Analysis method

- Maximum Likelihood Estimation of the parameters:

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

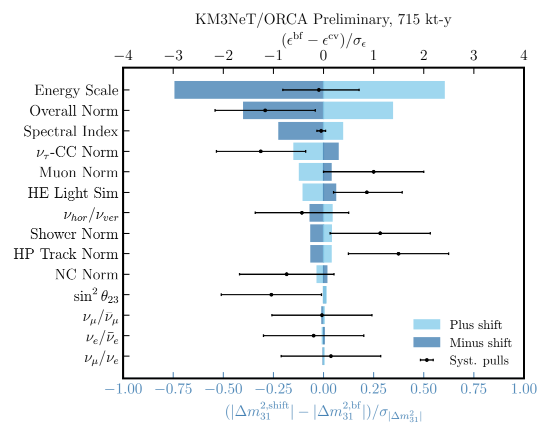
- 2D-profiled likelihood scans of the Δm^2_{31} and $\sin^2\theta_{23}$: $-2\ln(\mathcal{L}_{\Delta m^2_{31},\theta_{23}}/\mathcal{L}_{bf}) = -2\Delta\ln\mathcal{L}$.
- 530 bins in total: 3 PID bins (17 HP-track, 17 LP-track and 19 showers in reco energy) x10 $\cos\theta_z$ bins

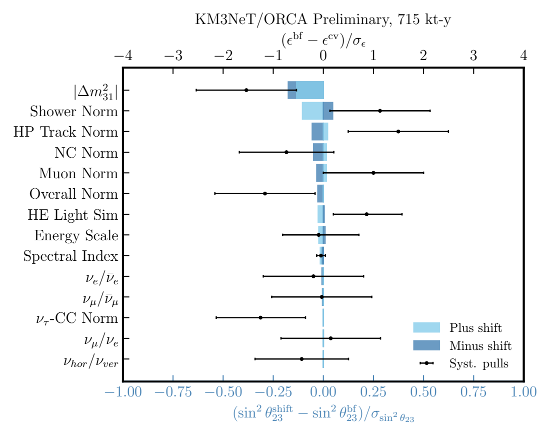
- Uncertainties in flux, detector, cross section and background modelling

	Nominal value	Syst. unc.
$\Delta m^2_{31}\cdot 10^{-3}$ [eV^2]	2.517 (NO) /-2.424 (IO)	free
$\Delta m^2_{21}\cdot 10^{-5}$ [eV^2]	7.42	fixed
θ_{23} [°]	49.2 (NO) / 49.3 (IO)	free
θ_{21} [°]	33.44	fixed
θ_{31} [°]	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^2_{31} or θ_{23}
- Evaluate deviation in Δm^2_{31} 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





References

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