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Measuring neutrino oscillations with KM3NeT/ORCA

3rd year PhD student seminars

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Outlines

1. KM3NeT, ORCA, and the neutrino oscillations
2. Current results
3. Detector systematic uncertainty

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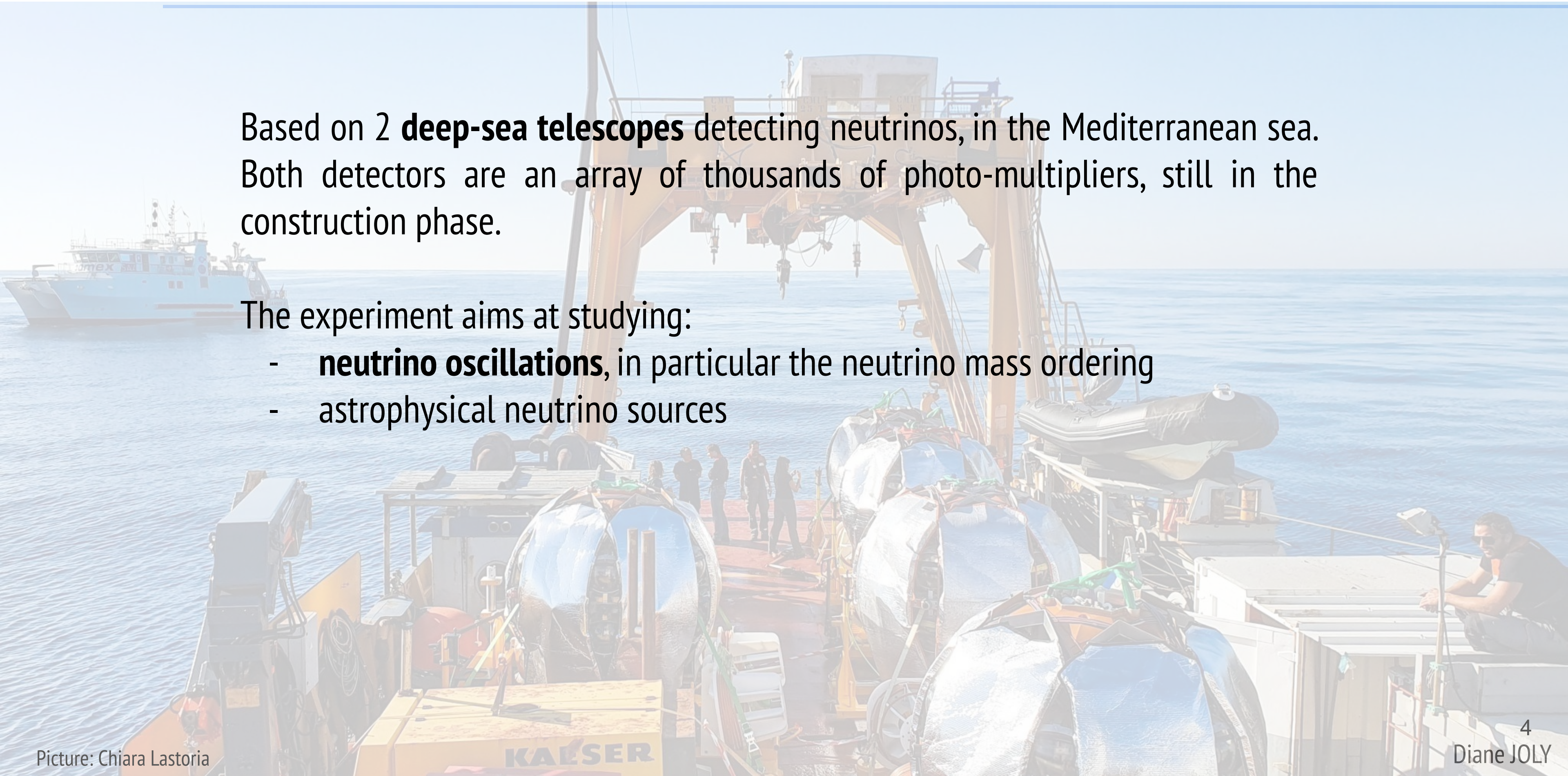
KM3NeT experiment

Based on 2 **deep-sea telescopes** detecting neutrinos, in the Mediterranean sea. Both detectors are an array of thousands of photo-multipliers, still in the construction phase.

The experiment aims at studying:

- **neutrino oscillations**, in particular the neutrino mass ordering
- astrophysical neutrino sources



Picture: Chiara Lastoria

Detection principle

For a charged current interaction, a neutrino interacts into its leptonic partner, close to the detector (in the water or in the ground). Example with a muon neutrino:

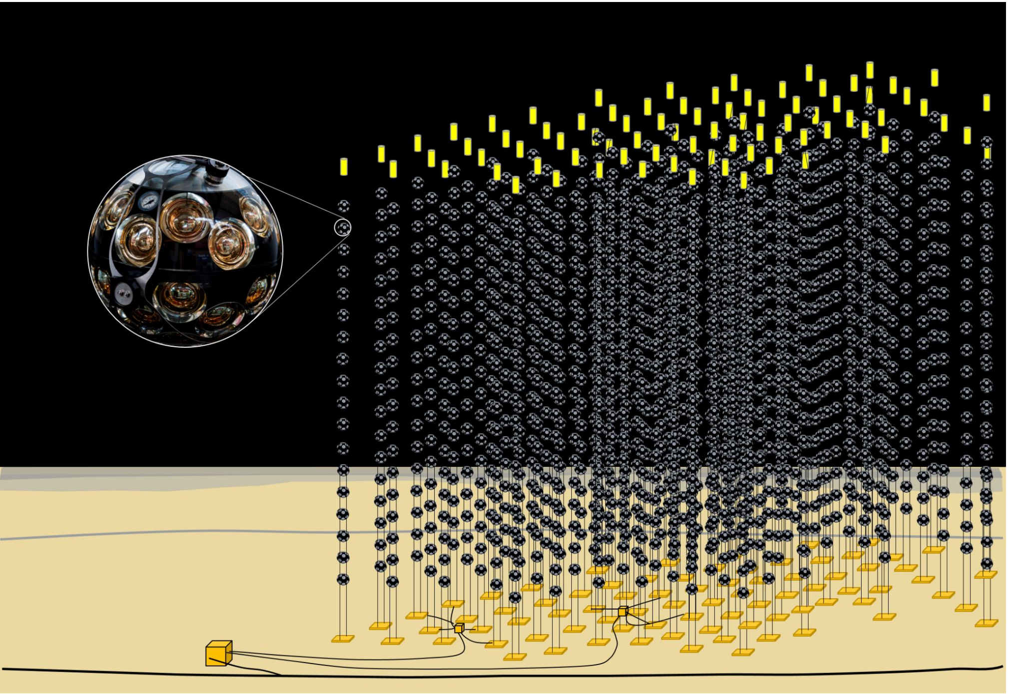
$$\nu_\mu + N \rightarrow \mu^- + X$$

with N a nucleus and X an unspecified hadronic final state

The muon propagates in the water, creating **Cherenkov light**. The optical modules then detects the Cherenkov light emitted on the path of the lepton. We can then reconstruct the energy and the direction of the lepton and the original neutrino.
Neutral current interactions are also detected.

A neutrino has initially a very small interaction probability: that’s why we need such a big detector (200m tall).

ORCA



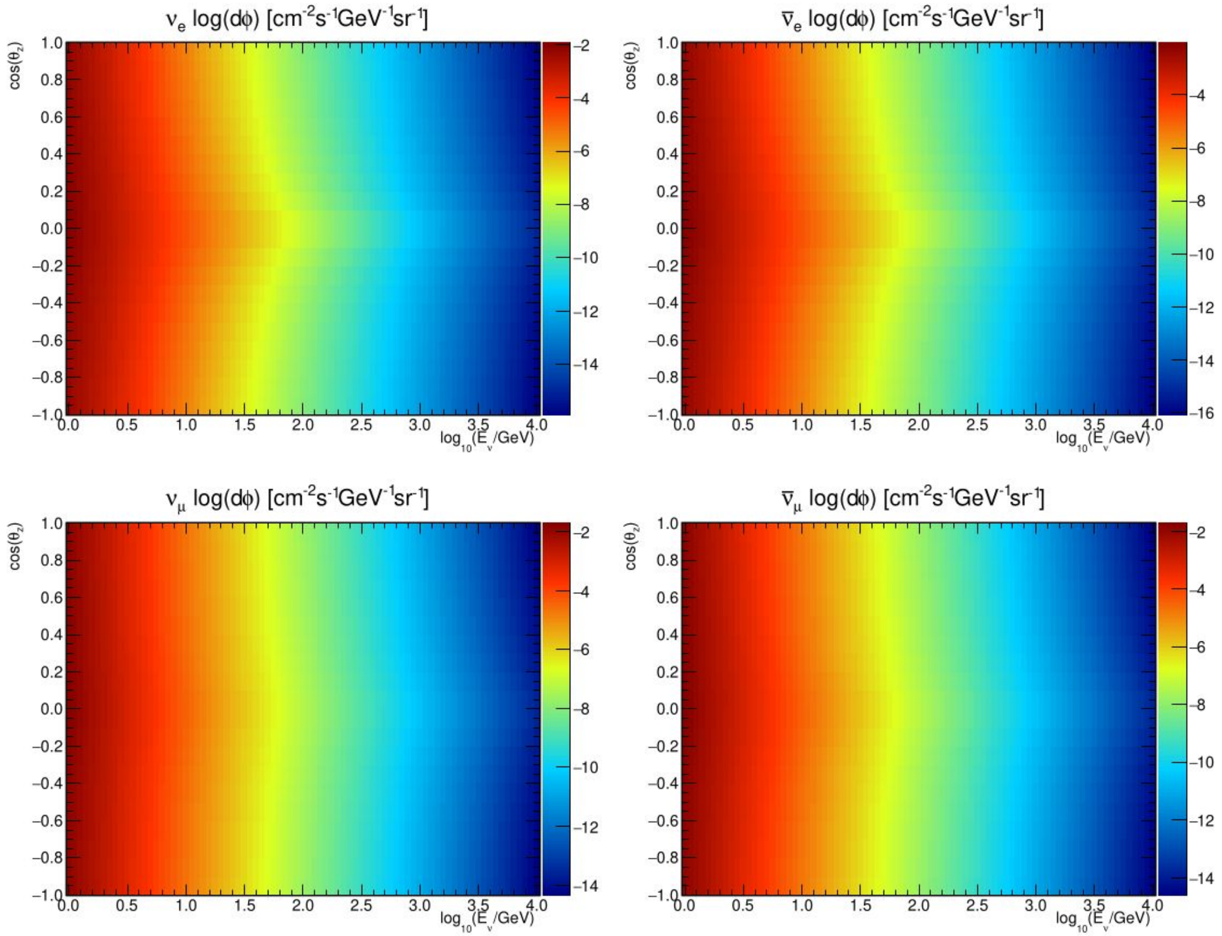
One of the 2 detectors is **ORCA** (Oscillation Research with Cosmics in the Abyss):

- Located **2.5 km below the surface**, 40 km offshore Toulon. 200 meters tall

- Array of **33 lines**, each composed of 18 optical modules. 115 lines are planned in the future. Each optical module contains 31 photo-multipliers

- Designed to detect **atmospheric neutrino** in the GeV energy-range for **mass-hierachy studies**

Neutrino flux



KM3NeT/ORCA detects atmospheric neutrinos in the GeV range. Here is the neutrino flux up to 10 TeV, measured at the Fréjus site (close to ORCA).

Electron (top) and muon (bottom) neutrino (left) and antineutrino (right)
logarithm of the differential flux in cm^{-2}.s^{-1}.GeV^{-1}.sr^{-1} as a function of the cosine of the zenith angle and logarithm of the neutrino energy

Neutrino oscillations

3 flavour eigenstates $\nu_e \quad \nu_\mu \quad \nu_\tau$
3 mass eigenstates $\nu_1 \quad \nu_2 \quad \nu_3$

A neutrino oscillates from one flavour eigenstate to another during its propagation with a certain probability, due to the different propagation speeds of the mass eigenstates.

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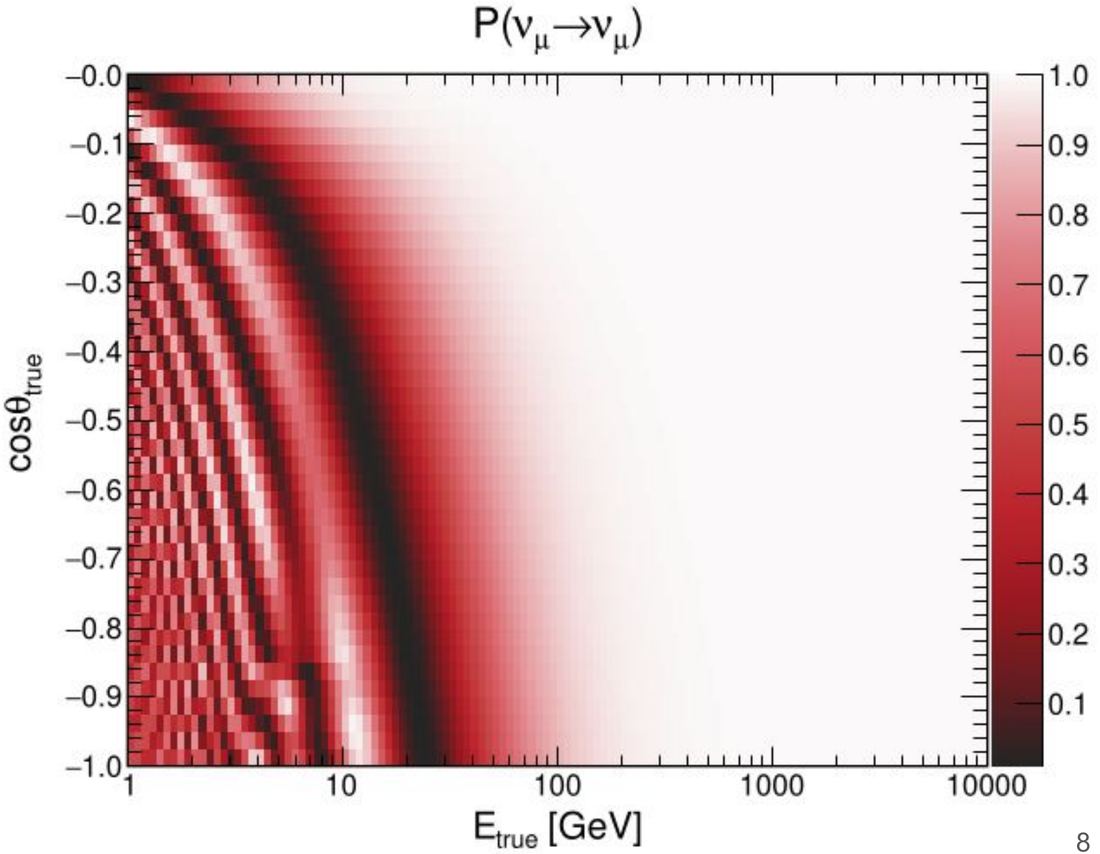
Survival rate of muon neutrino as a function of the cosine of the zenith angle and the neutrino energy

$\cos(\theta_{true})$ is linked to distance traveled by the neutrino: the oscillation pattern depends on L/E (distance/energy)

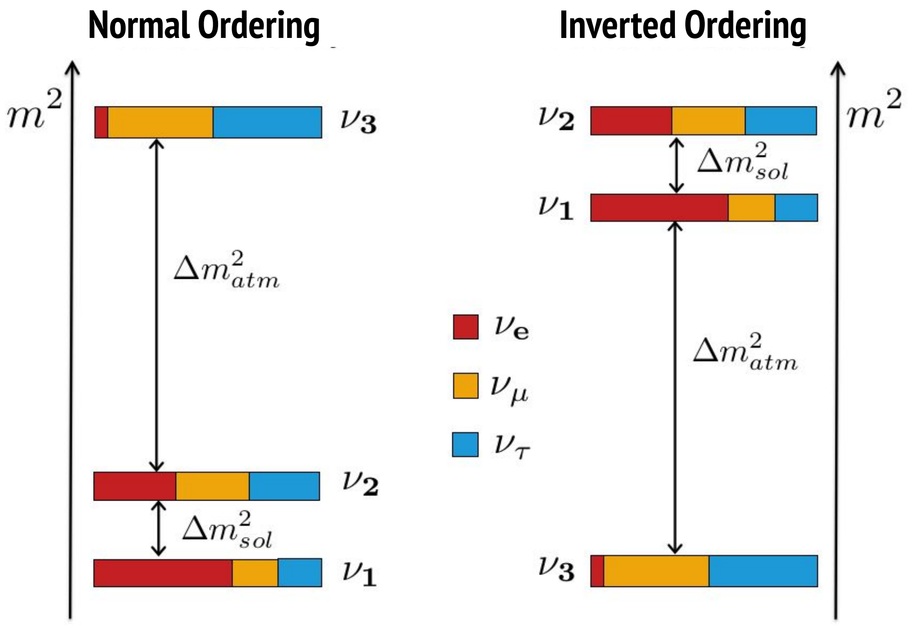


NMO and the oscillation parameters

The oscillation pattern depends on the **mass differences between the eigenstates**. Two scenarios are possible: Normal Ordering or Inverted Ordering, depending on the sign of $\mathbf{\Delta m_{31}^2} = \Delta m_{atm}^2$. This is the **Neutrino Mass Ordering** (NMO) problem.

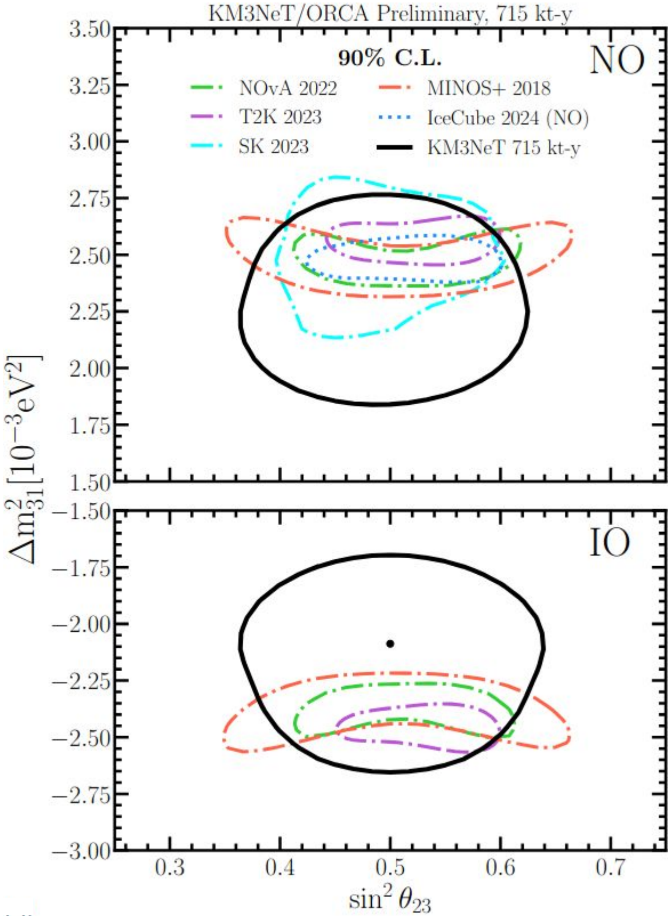
The oscillation probability depends also on the angle mixing, in particular $\boldsymbol{\theta_{23}}$.

The KM3NeT collaboration works on the {$\mathbf{\Delta m_{31}^2}$, $\boldsymbol{\theta_{23}}$} estimation.

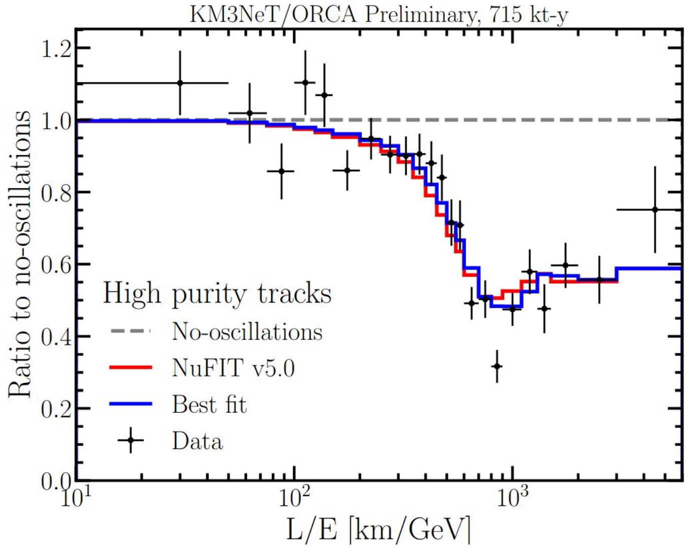


Outlines

Current oscillation results



For this contribution, data from **715 kt-y of exposure** were analysed, accounting for **9751 neutrinos**.

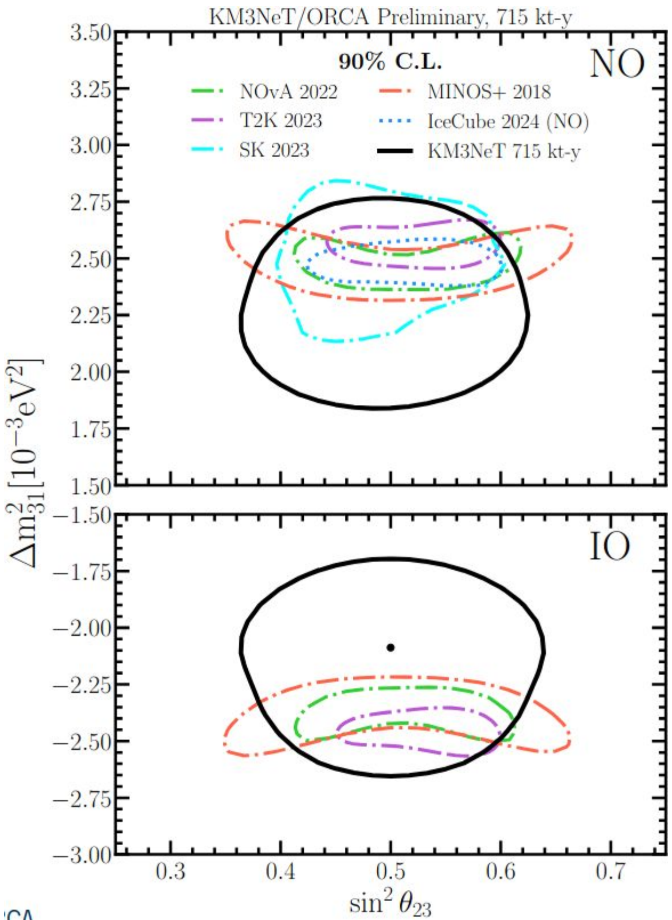


Data comes from 3 configurations: 6, 10 and 11 lines, between early 2020 and late 2022. High quality data has been taken during this construction phase.

Already providing relevant information, with exposure equivalent to only 37 days of full ORCA detector

Competitive for θ_{23} but not for $\Delta m_{31}{}^2$, because of the systematic uncertainties

Sensitivity



KM3NeT/ORCA is competitive with other experiments, demonstrating strong sensitivity to neutrino oscillation parameters. However, these measurements remain limited by several sources of **systematic uncertainty**, particularly in modeling the **detector response**.

By developing more accurate models of the detector response, I aim to reduce the dominant systematic errors and enhance the precision of future ORCA analyses.

In addition, for the next analysis, more data will be analysed: 1.7 Mt-y.

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Detector systematic uncertainties

The detector systematics used to be taken into account via the **energy scale E_s** parameter. $E_{true}{}^{*}E_s \rightarrow E_{true}$

The energy-dependent parameters were then computed with this new E_{true}.

Issue: the energy scale is widely over-estimated, even though it is a key factor to constrain Δm^2_{31}.

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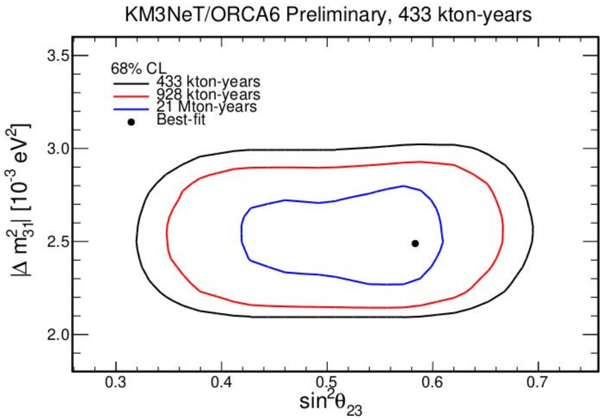
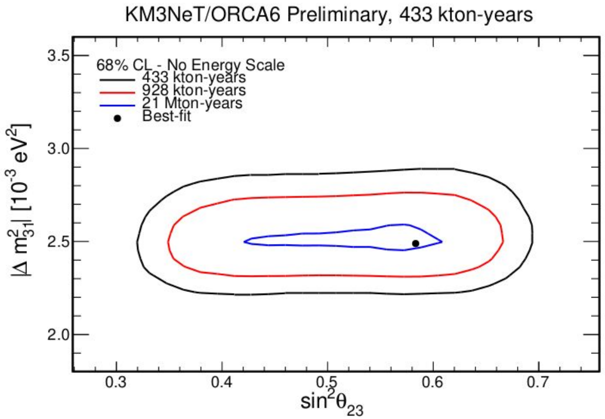
Comparing the contour fitting all systematics (*left*) and removing energy scale (*right*)





Solution: replace E_s by 2 detector systematic parameters:

- the **quantum efficiency of the optical modules** QE
- the **water absorption length** Abs

Improving detector systematics modelling

We want to quantify the influence of these detector systematics on the event distribution. The method is

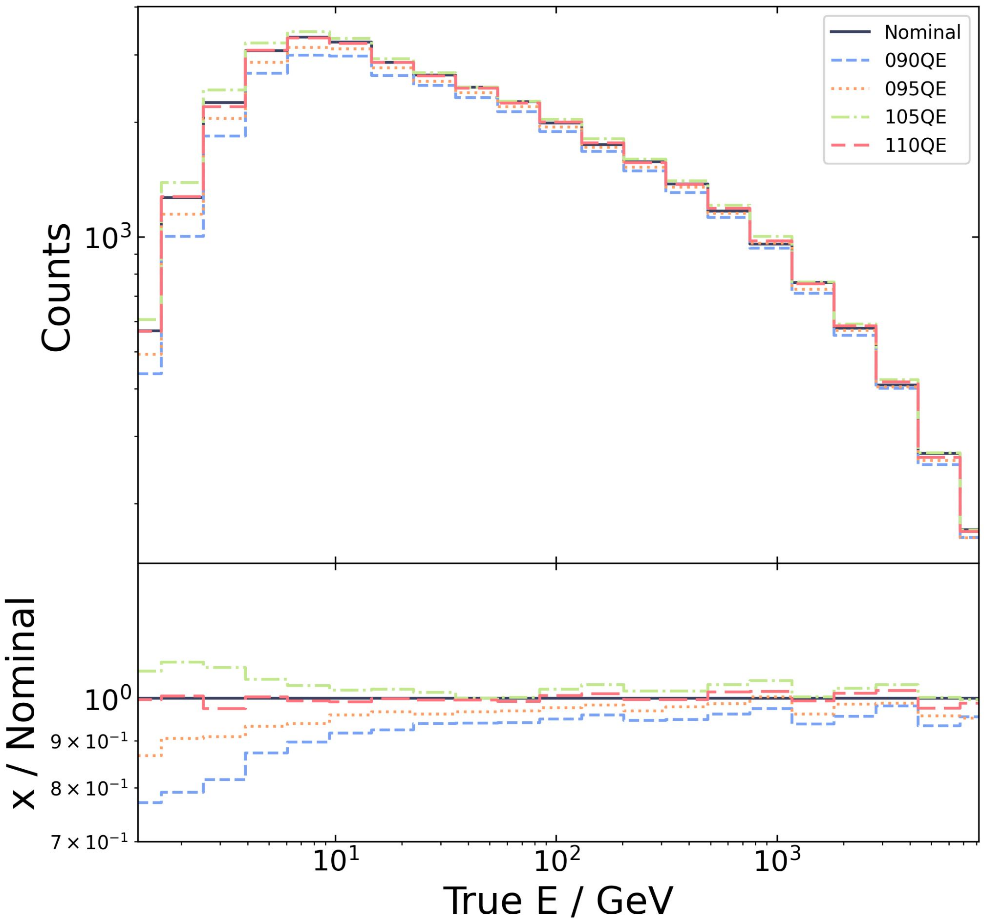
1. To **calculate the response matrix** of the detector for *different values of the detector systematics*

The response matrix:

- is a **(4+2)D**-matrix: E_{true}, E_{reco}, $\cos(\theta_{true})$, $\cos(\theta_{reco})$ + type + PID
- calculated from a Monte-Carlo (MC)
- characterises the **reconstruction of the true parameters** and the **detection efficiency**
- used to compute the event distribution

2. To **interpolate** them for intermediate values. The KM3NeT software will navigate the interpolated response matrices to find the best one. As the response matrix is computed from a MC, we need to generate new Monte-Carlos with shifted values of QE and Abs.

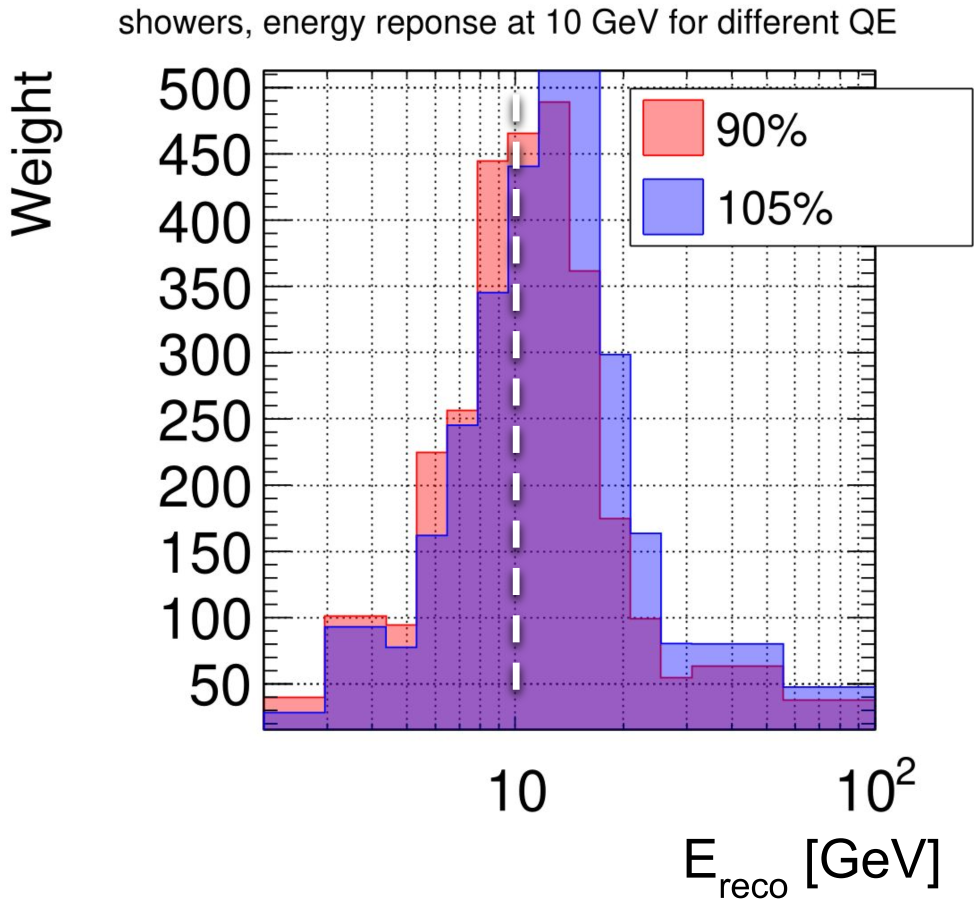
Response matrix for different values of QE



110% QE is the wrong MC (excluded from the next slides)

As QE decreases → less light is detected for the same events → the number of events decreases, especially at low energies (threshold).

Shift in the response matrix



Response at 10 GeV

QE increase → E_{reco} increase, for a given E_{true}

If the quantum efficiency of the optical modules is better, the neutrino are reconstructed with a higher energy

Conclusion & Prospects

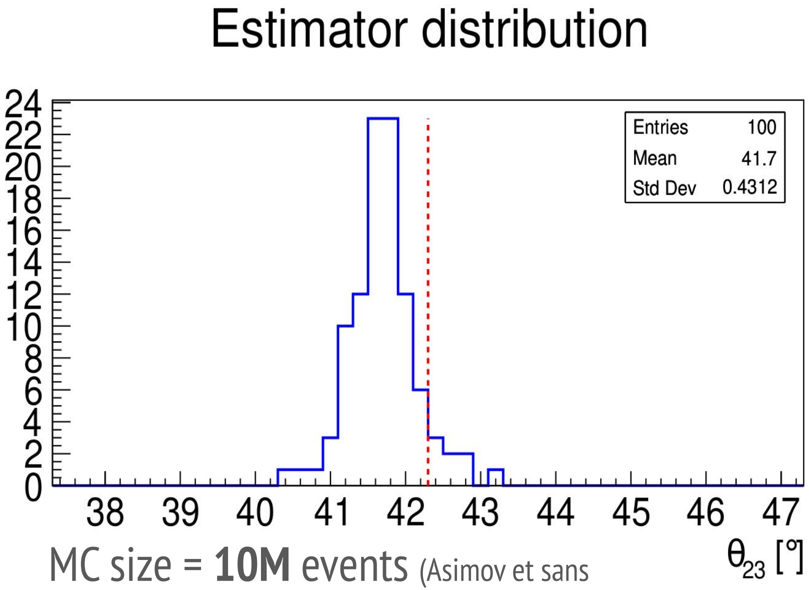
Competitive results with 5% of planned exposure

Next analysis with 2.5 times more exposure for Neutrino 2026

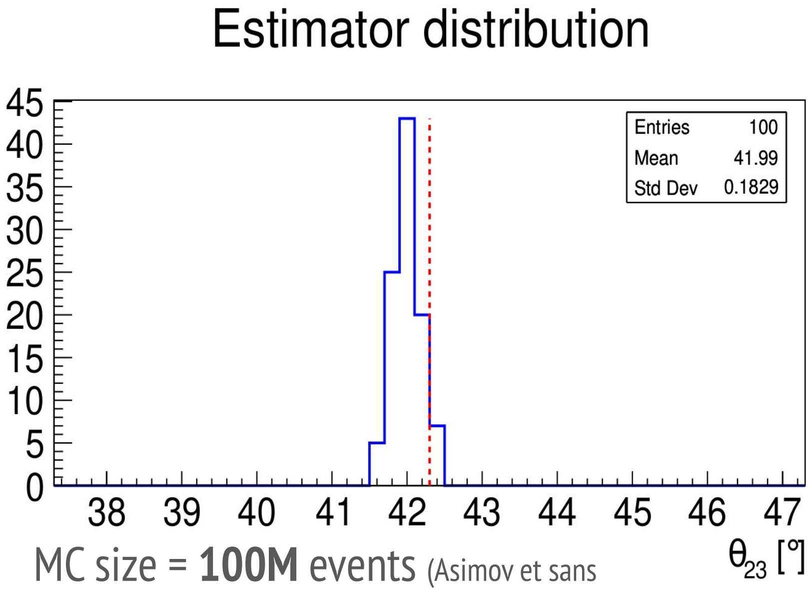
Before end of decade, competitive results also on NMO

- Exposure ~20 Mt-yr
- More realistic systematics

Back-up



MC size = **10M** events (Asimov et sans systématique)



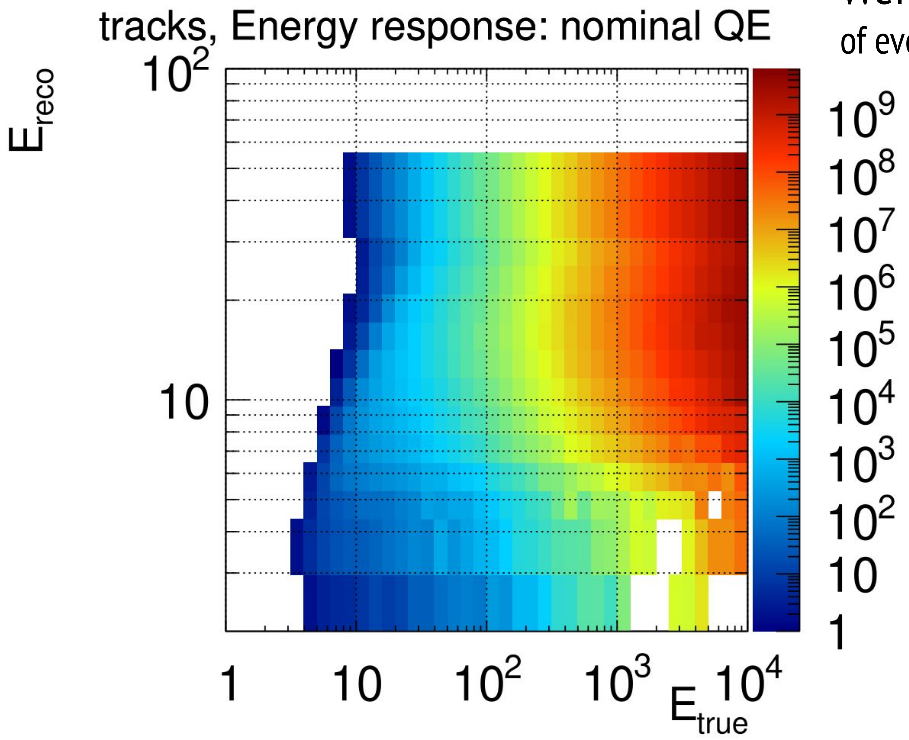
MC size = **100M** events (Asimov et sans sytématique)

With MC size:

- Bias decreases: 0.6° → 0.3°
- Std dev decreases: 0.43° → 0.18°

This bias should be compared to the expected accuracy of ORCA115, for which systematic parameters have been taken into account: 5°.

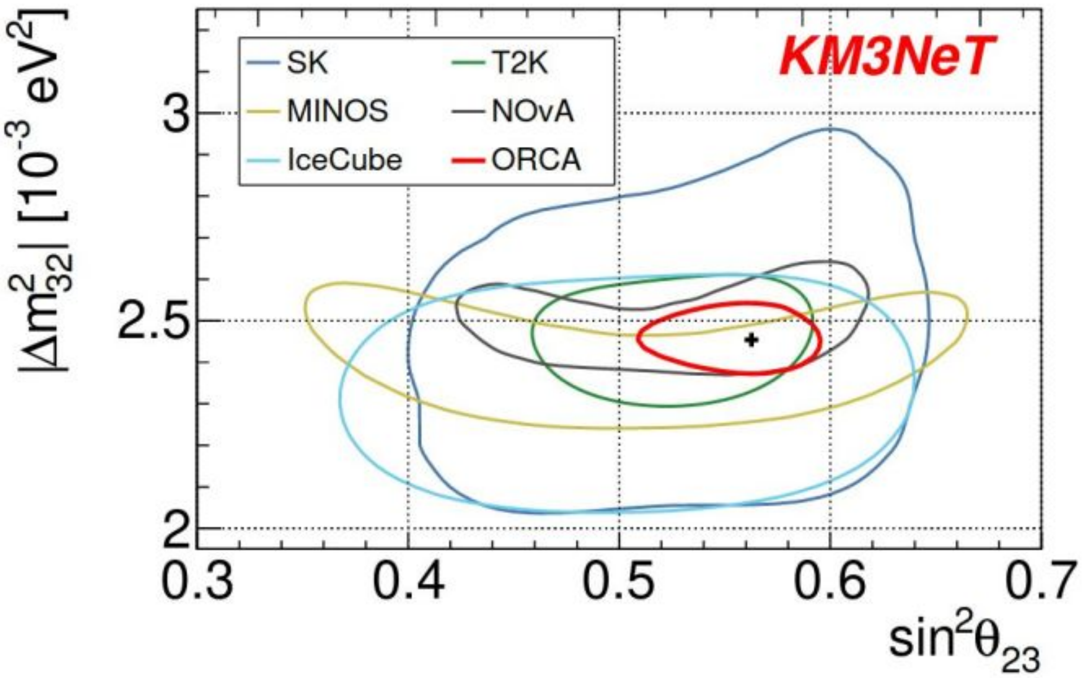
Response matrix



Weight (number of events /unit flux)

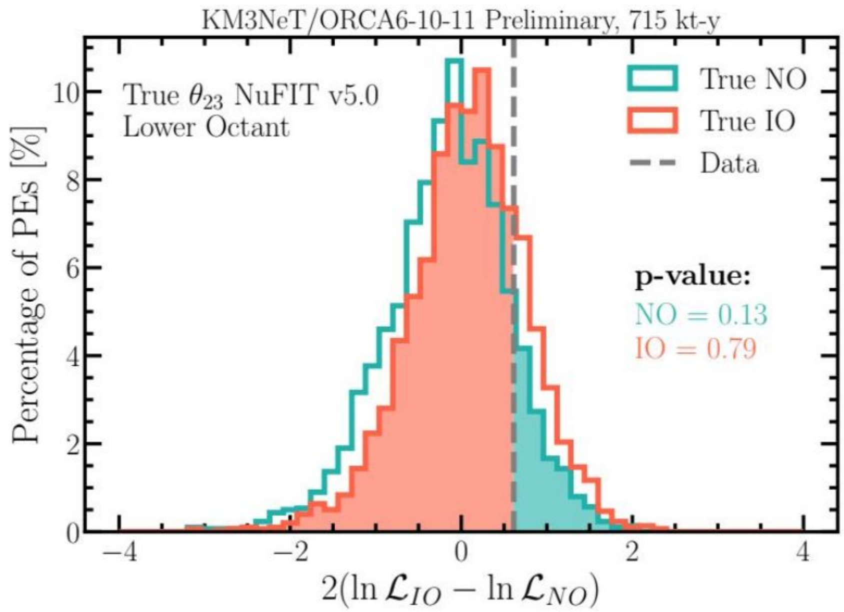
Response matrix for track events, projected on the energy space

Sensitivity

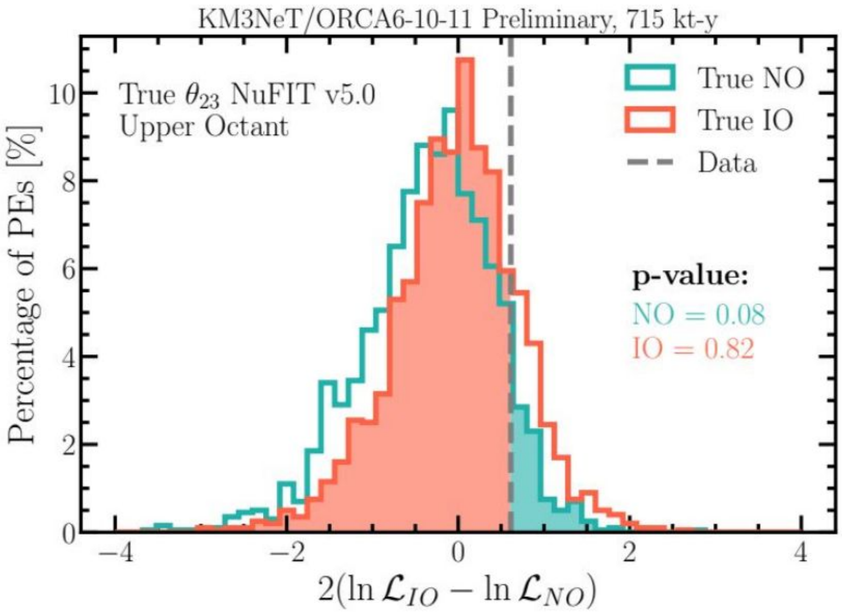


Sensitivity (ORCA) VS measurements (other experiments)
(Expected sensitivity for 3 years exposure, full detector)

NMO



KM3NeT/ORCA6-10-11 Preliminary, 715 kt-y
True θ_{23} NuFIT v5.0
Lower Octant
True NO
True IO
Data
p-value:
NO = 0.13
IO = 0.79
Percentage of PEs [%]
$2(\ln \mathcal{L}_{IO} - \ln \mathcal{L}_{NO})$



KM3NeT/ORCA6-10-11 Preliminary, 715 kt-y
True θ_{23} NuFIT v5.0
Upper Octant
True NO
True IO
Data
p-value:
NO = 0.08
IO = 0.82
Percentage of PEs [%]
$2(\ln \mathcal{L}_{IO} - \ln \mathcal{L}_{NO})$