Measuring atmospheric neutrino oscillations with KM3NeT/ORCA

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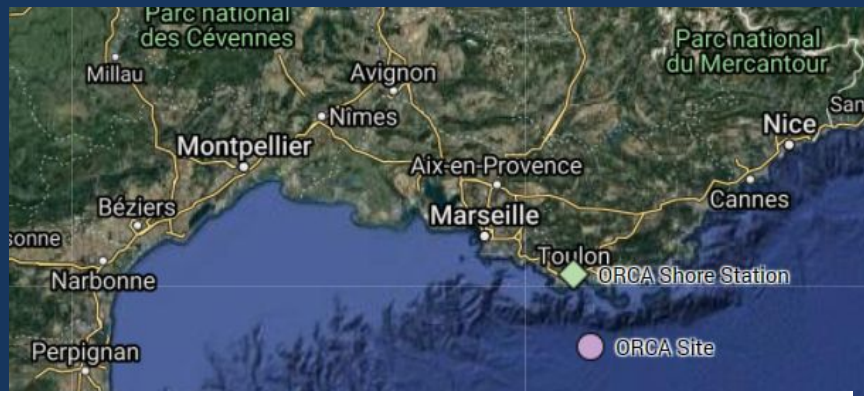
for the KM3NeT Collaboration

7 July 2025

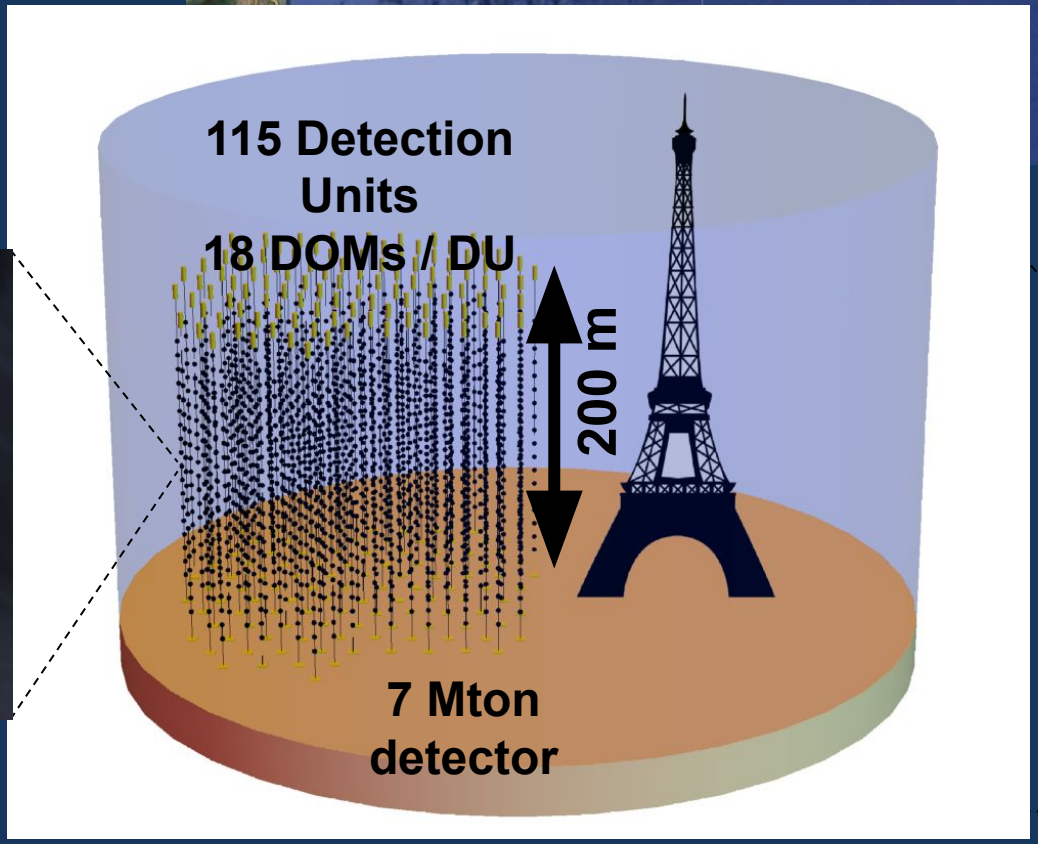
KM3NeT/ORCA

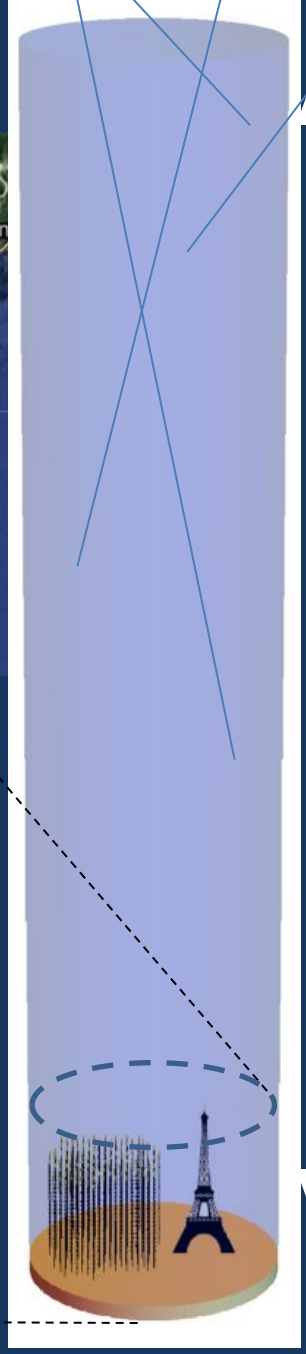
28 DUs Deployed



31x 3” PMTs

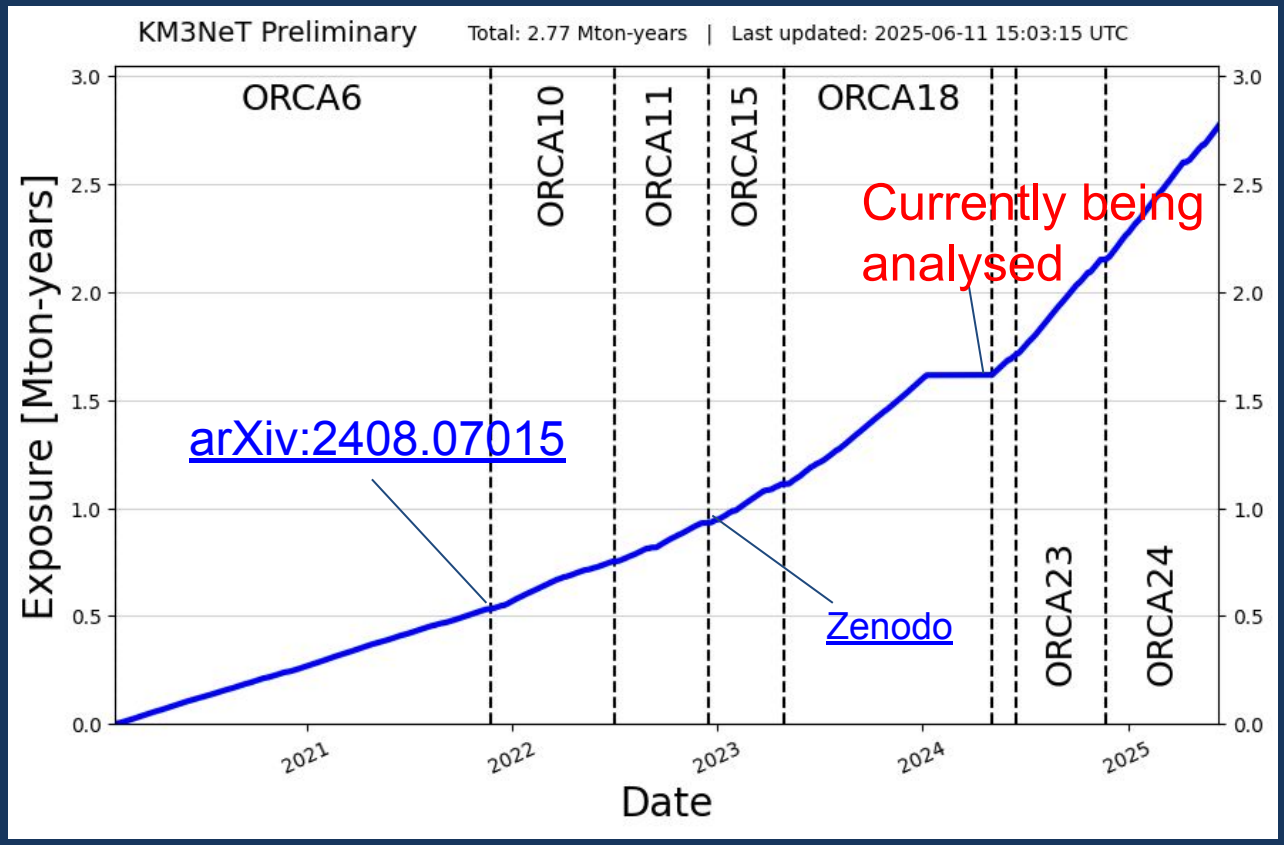
43 cm





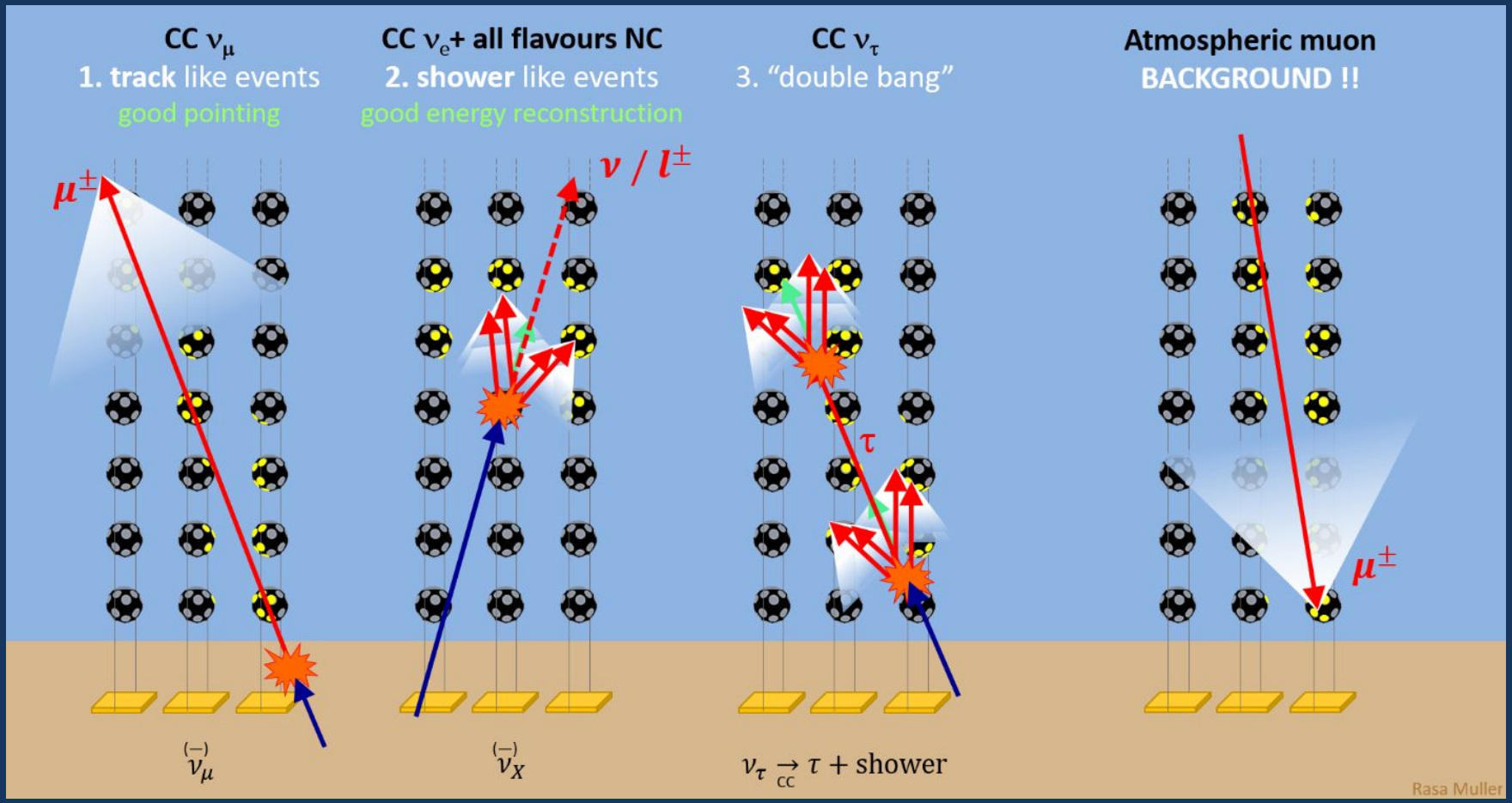
Data

- Already collected and processed more than 2.5 Mt-y of data
- Current analysis only covers the first half of this data, prioritized in data processing
- Expect to update these results very soon with remaining available data
- Competitive measurement by 2030 □ 21 Mt-yr



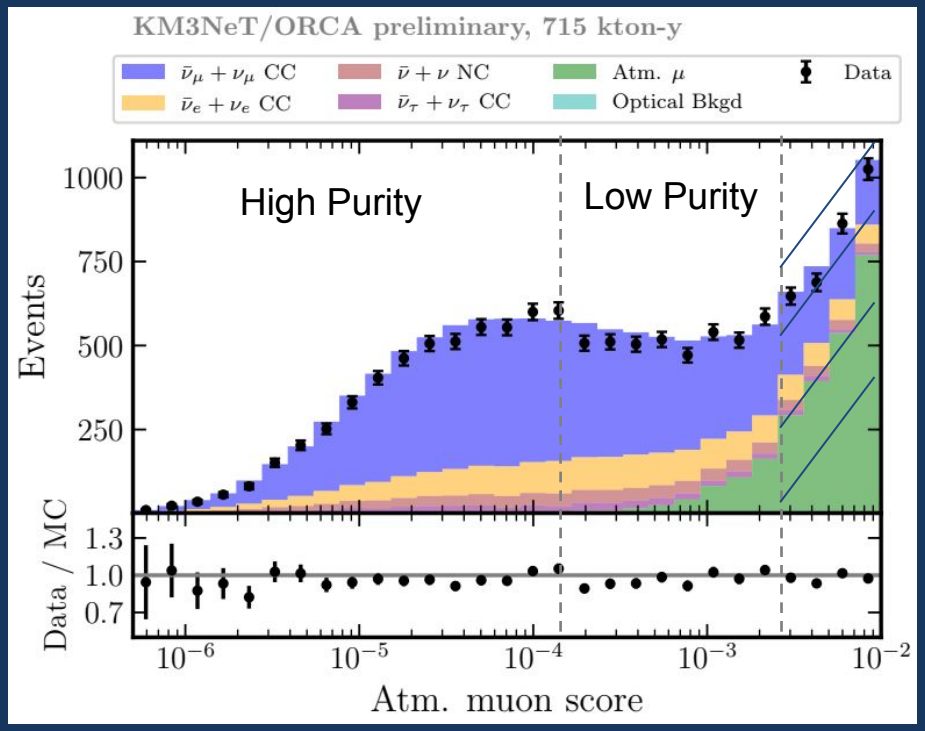
Topologies

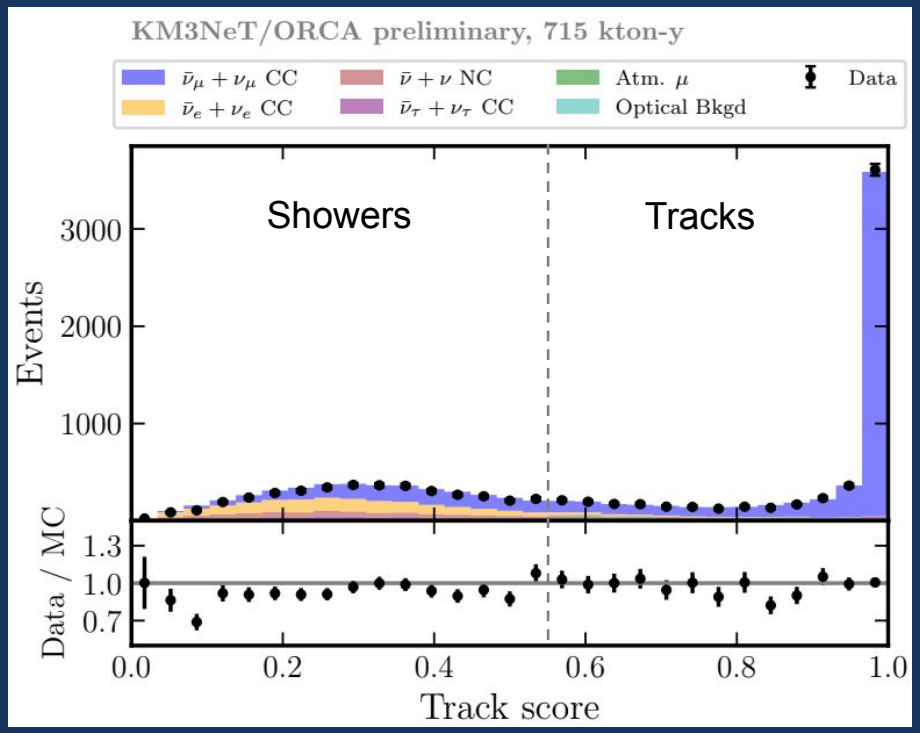
- Neutrinos in the GeV range pass through the Earth while it acts like a shield for atmospheric muons.
- Distinct patterns of light can be used to identify neutrino flavours and background.



Event Selection

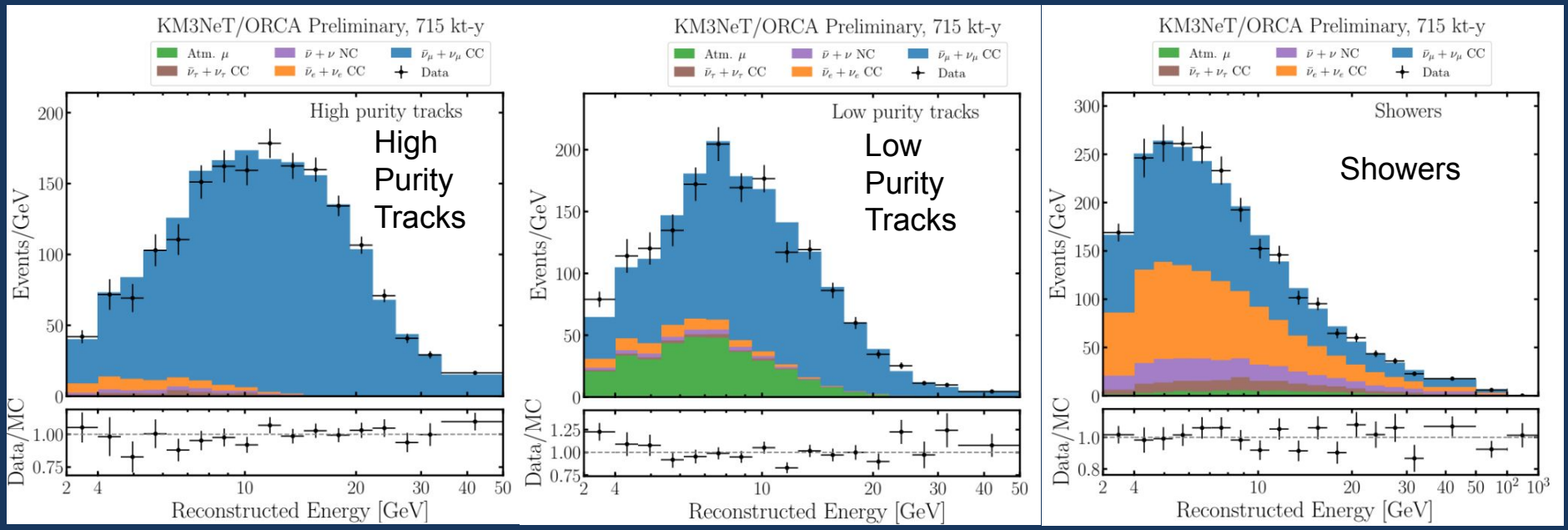
- Events are reconstructed assuming track and shower topologies.
- We employ Boosted Decision Trees (BDTs) to summarize reconstructed quantities into classification scores.
- 3 selection regions are defined: High purity tracks, low purity tracks, and showers.
- Excellent agreement between data and simulation for neutrinos and atm. muons.





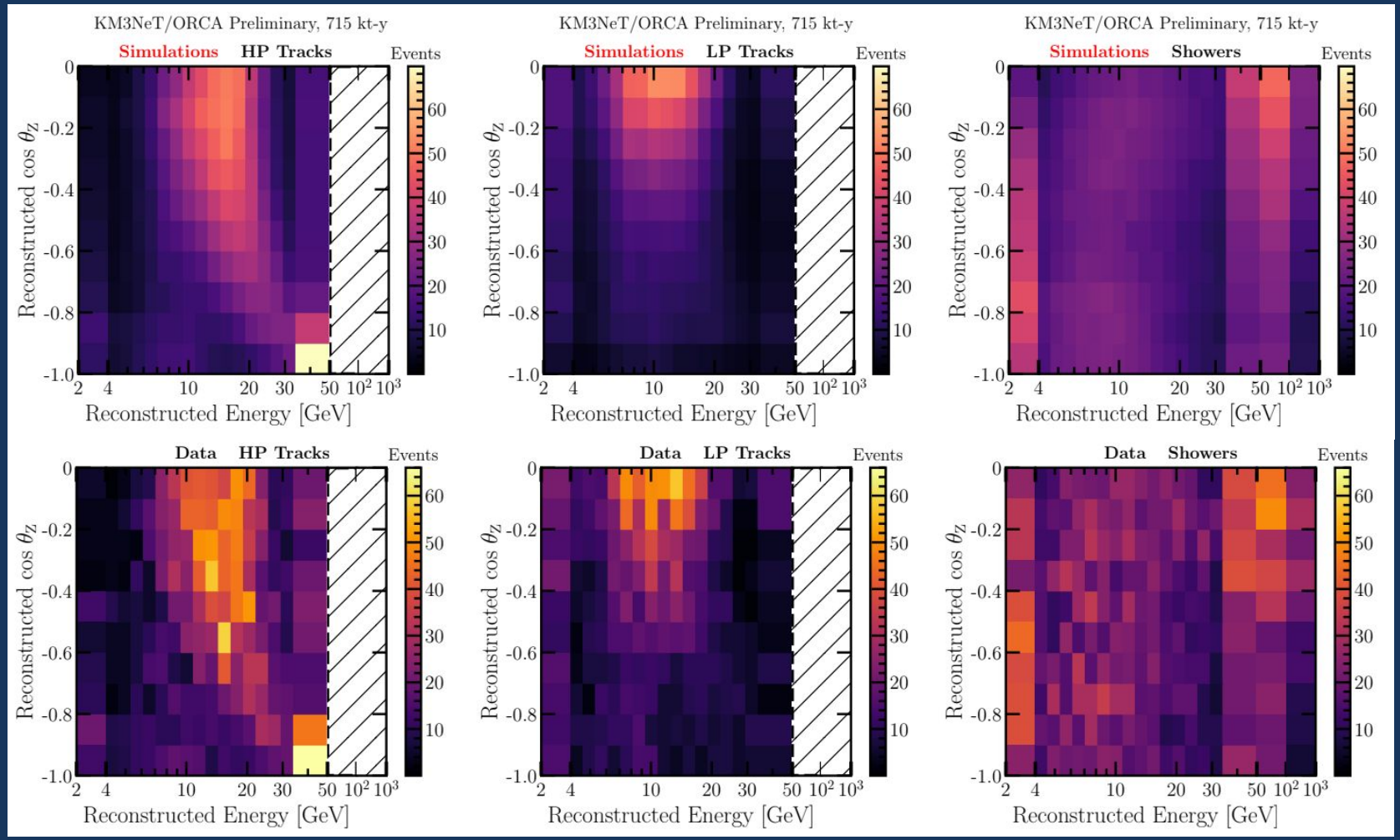
Event Selection

- 9751 neutrino candidates in our selection with similar numbers in each class
- 97% pure ν_μ-CC sample in high purity track-like class
- 91% accuracy in classifying ν_e-CC events as showers
- ~1300 ν_e-CC events expected in shower-like sample
- 0.1% atmospheric muon background contamination in the High Purity Track class and 6% in the whole dataset.



Oscillation Patterns

- Analyze data in 2D space of energy and direction
- Oscillation best fit describes data very well (-2logL p-value: 41%)



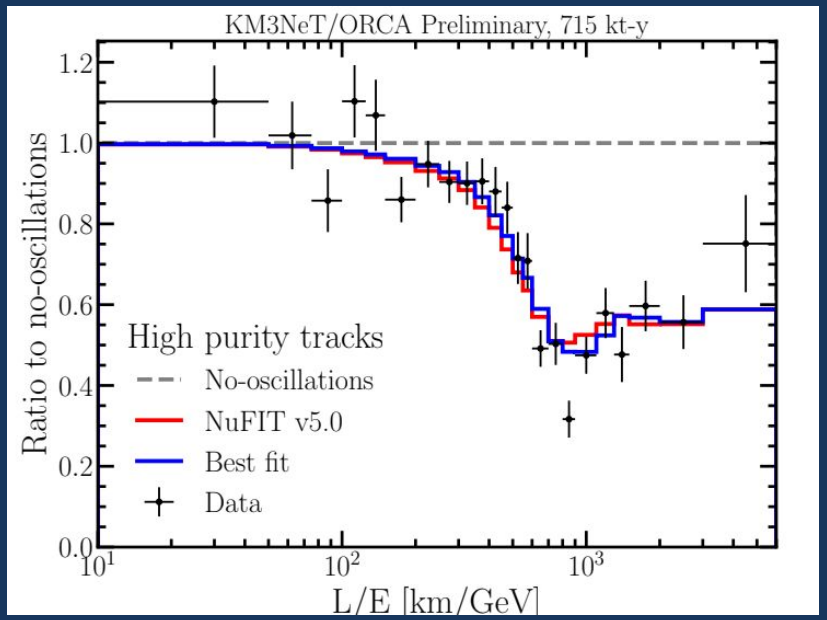
Improved Measurement

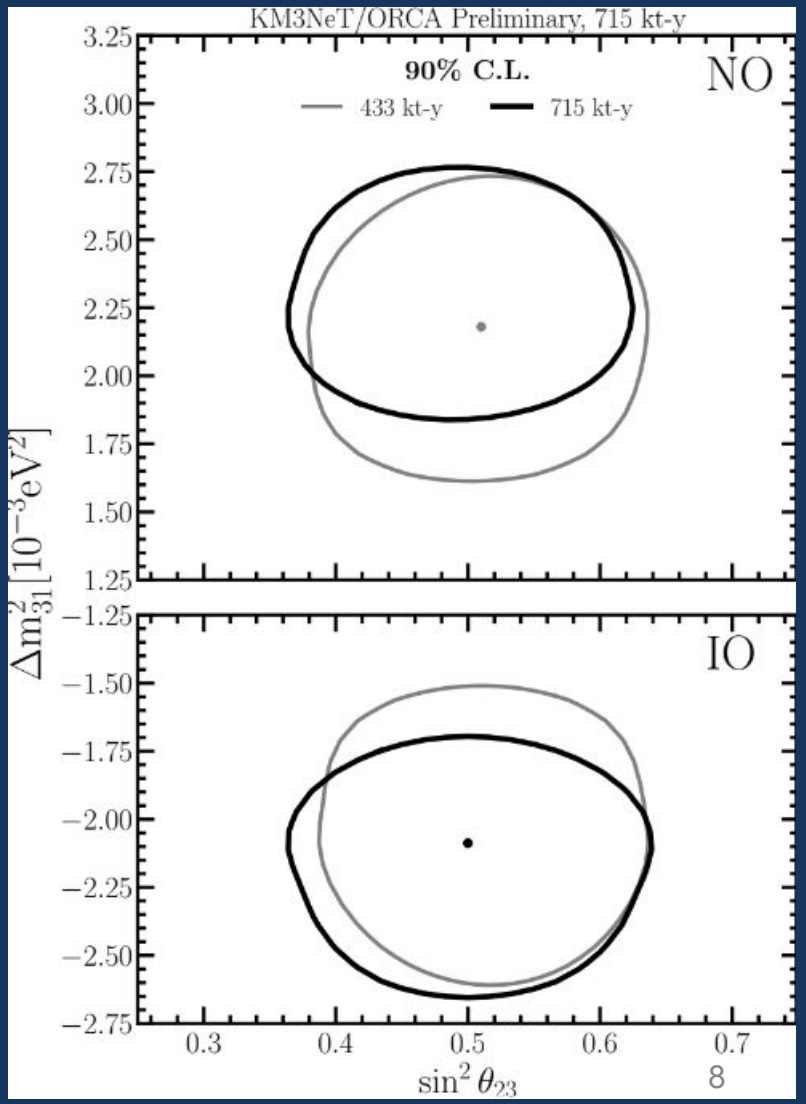
- New measurement uses 715 kt-y of data (65% increase over 2023 dataset)
- Clear oscillation pattern in L/E
- Slight preference for Inverted Ordering (IO)

$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\text{eV}^2, & \text{IO} \\ [2.10, 2.37] \times 10^{-3}\text{eV}^2, & \text{NO} \end{cases}$$

$$\sin^2\theta_{23} = 0.50 \pm 0.07$$

$$2\log(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61$$





Improved Measurement

- Already providing relevant information with exposure equivalent to only 37 days of full ORCA detector
- Fully consistent with world data

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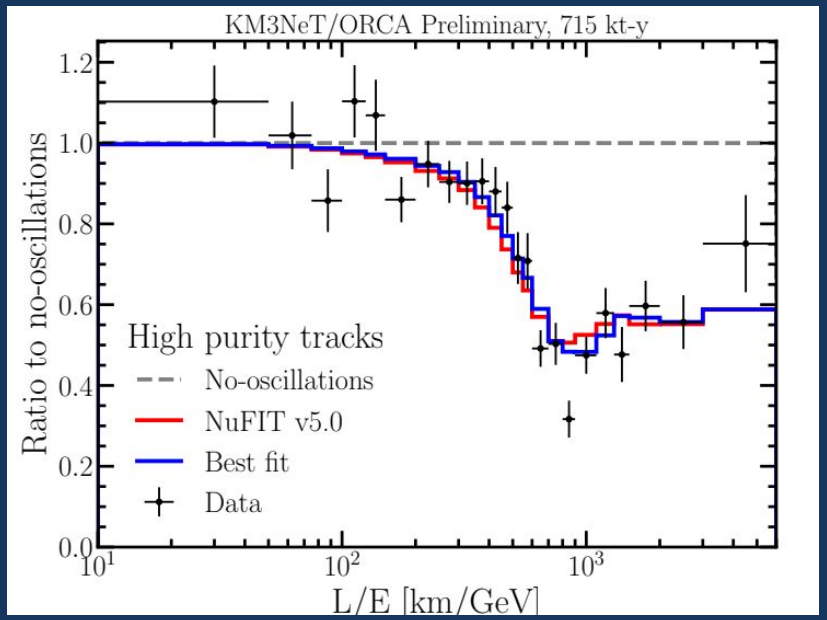
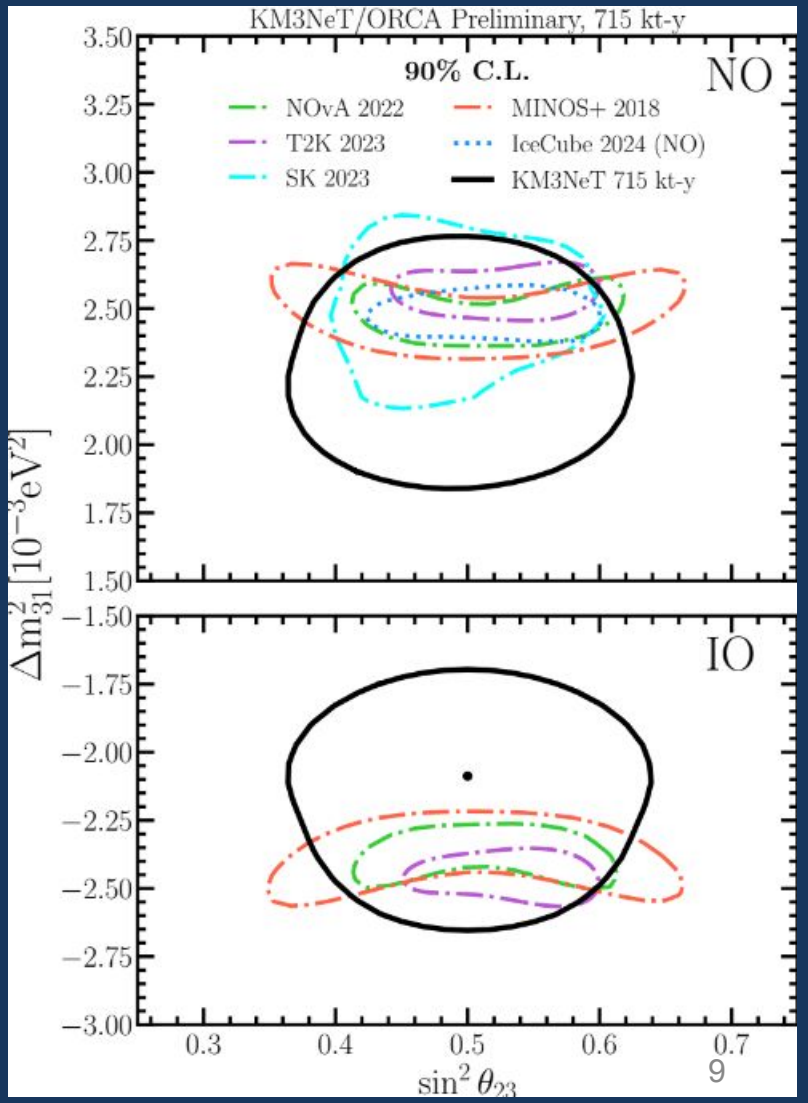
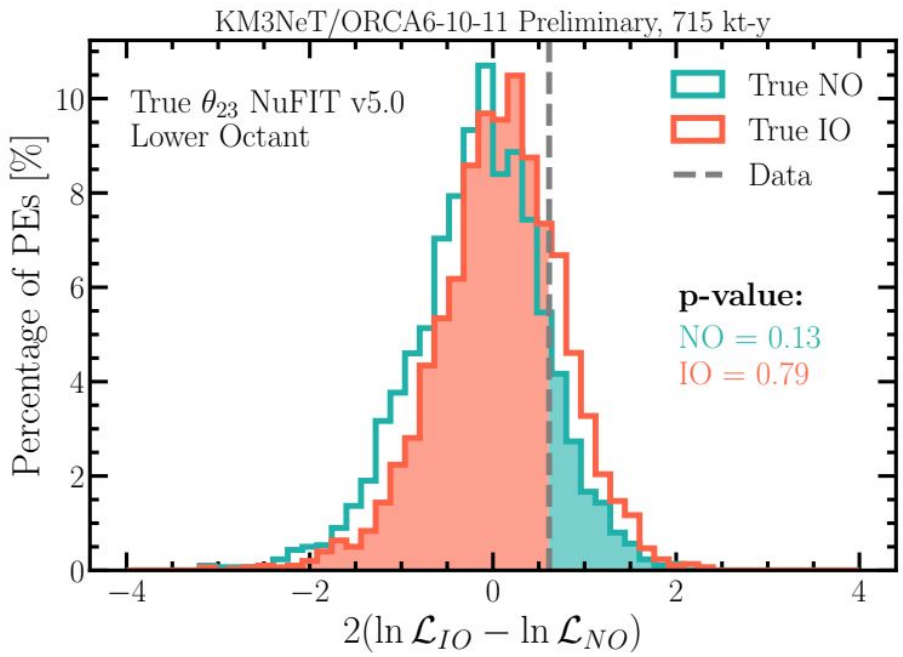
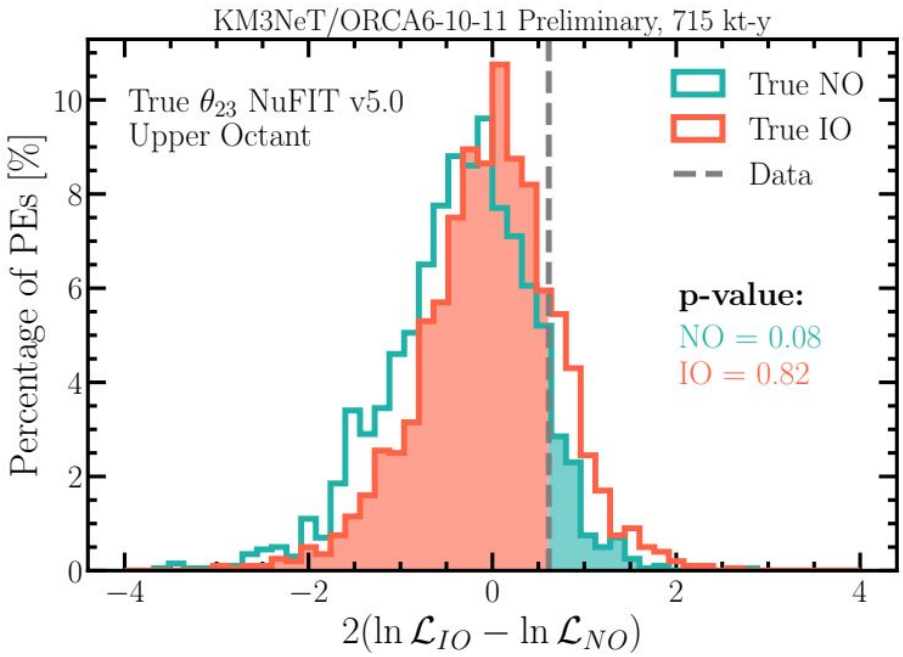




NMO Significance

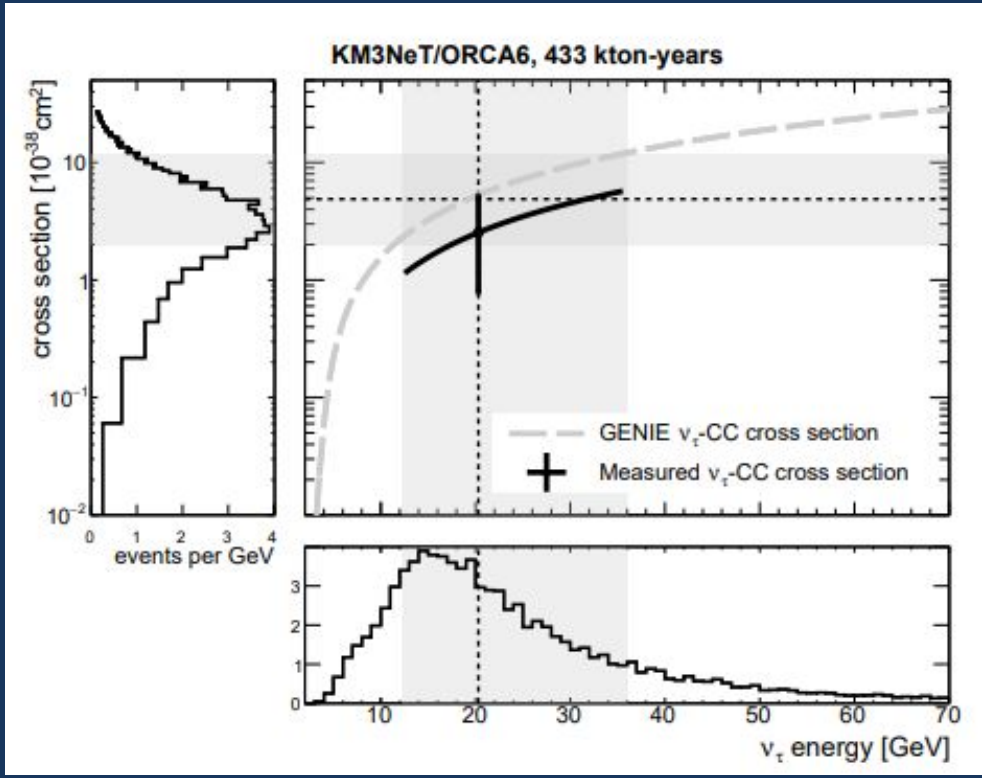
- Conversion from -2logL to p-value depends on choice of nuisance parameters
- At NuFIT 5.0 best fit, NO hypothesis disfavoured at 1.7σ / 1.5σ in (UO/LO)
- IO preference slightly stronger than expected (18%/21% p-value in UO/LO)
- Working towards a more general statement as a function of $\sin^2\theta_{23}$

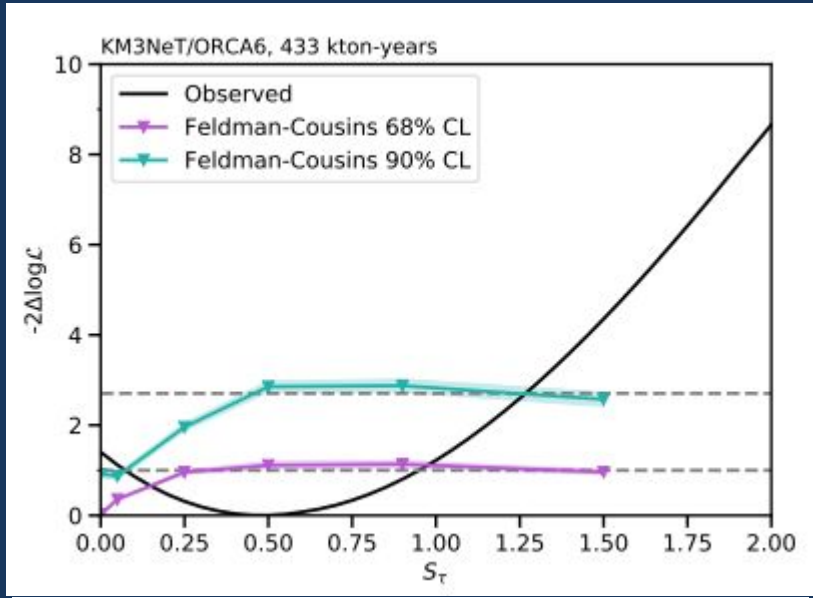


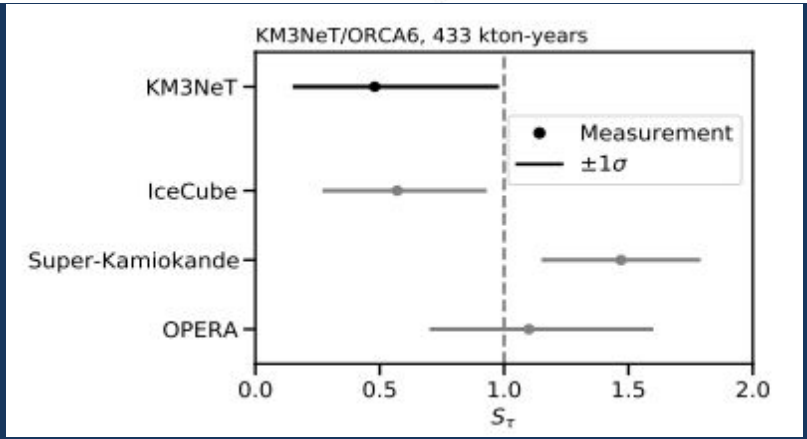


Tau appearance

- Measurement of the tau cross section as a single normalisation.
- Consistent with other experiments.
- 93 measured tau events.





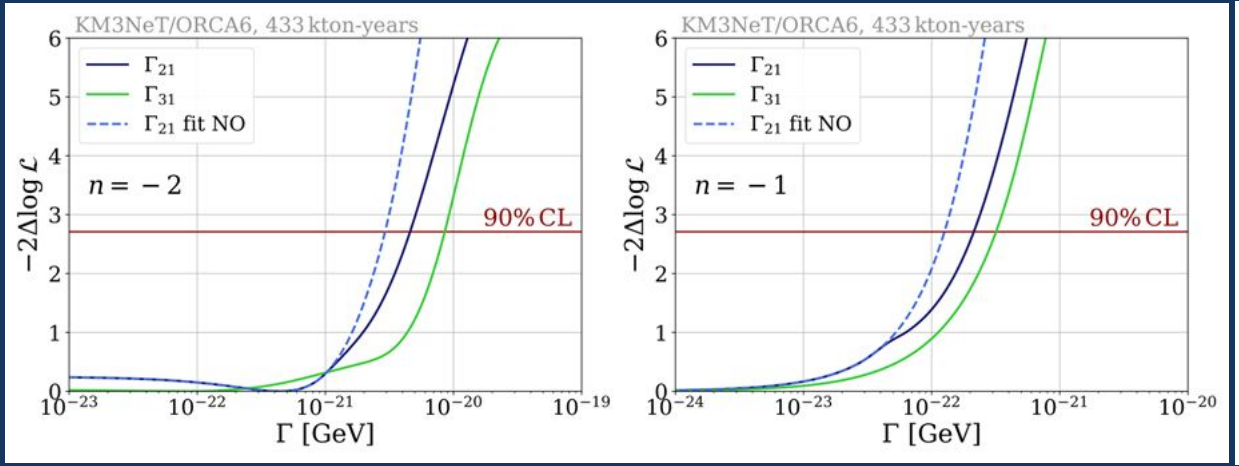


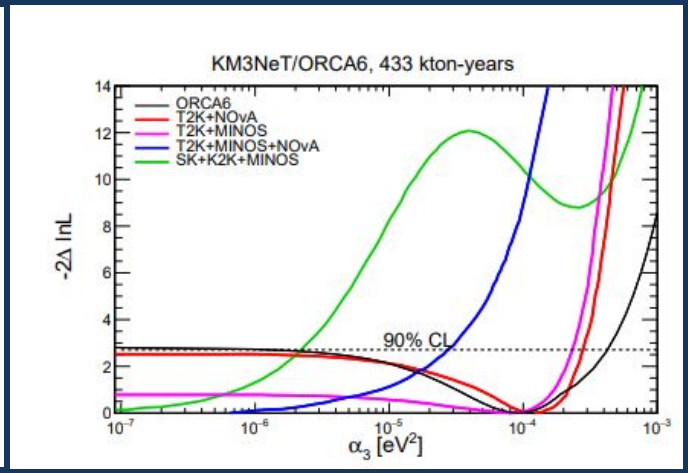
arXiv:2502.01443

New Physics Models

- While determining the upper limit the other decoherence parameter is left as free parameter in the fit
- Effects depend on mass ordering

- Since neutrinos have masses can decay into lighter particles.
- Decays of the third mass state are not strongly constrained.
- In agreement with current experiments.





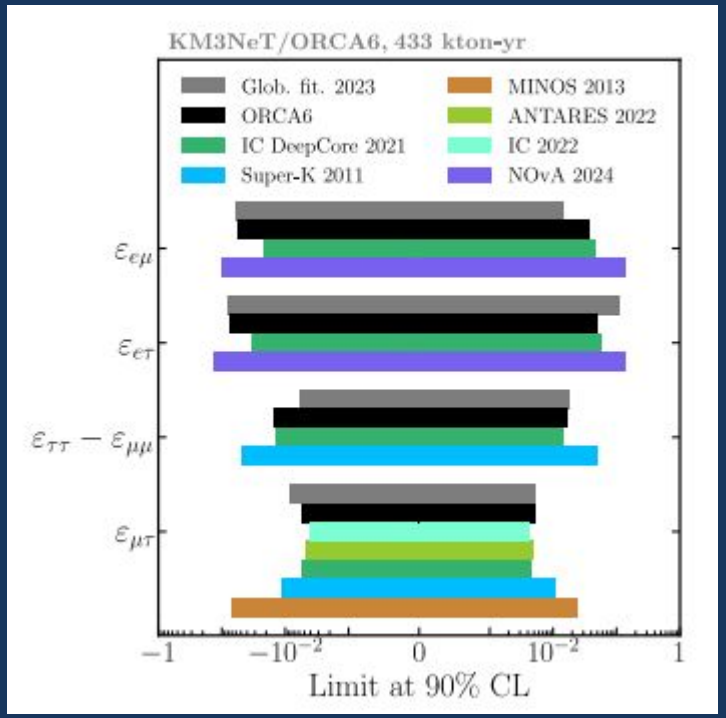
Quantum decoherence
arXiv:2410.01388

Invisible decay
arXiv:2501.11336

New Physics Models

- No significant deviation from the SM.
- In agreement with other experiments.

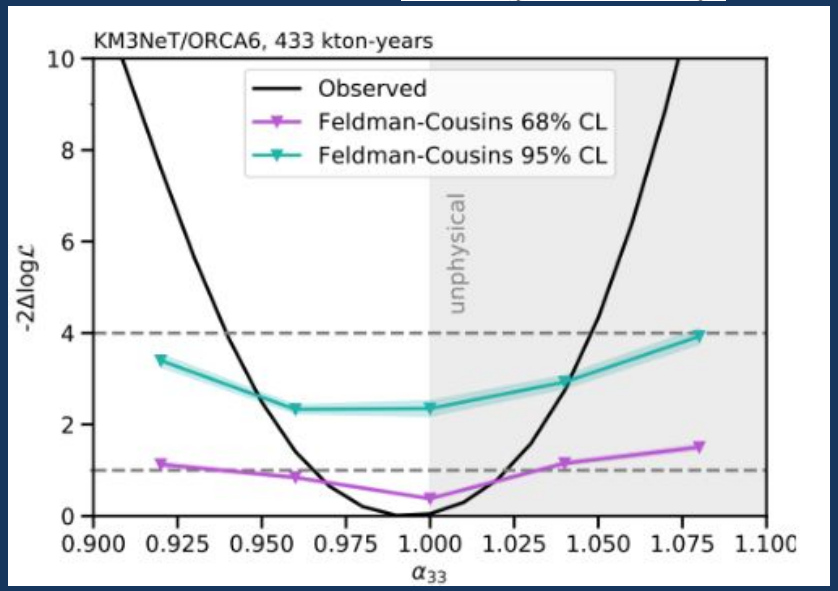
$$\mathcal{H}_{\text{eff}} = \frac{1}{2E}\mathcal{U}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix}\mathcal{U}^{+} + A(x)\begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}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



Non-Standard-Interactions
arXiv:2411.19078

- The unitarity of the neutrino mixing matrix was probed.
- The current limit on the non-unitarity parameter affecting the τ -row of the mixing matrix was improved.

$$N = \alpha\, U_{\text{PMNS}}. \qquad \alpha = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}$$

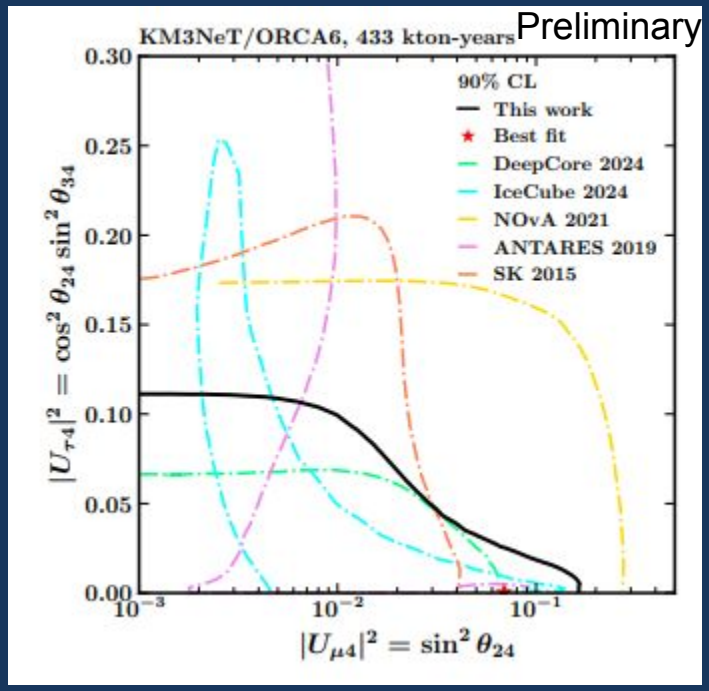


Non-Unitary Mixing
arXiv:2502.01443

New Physics Models

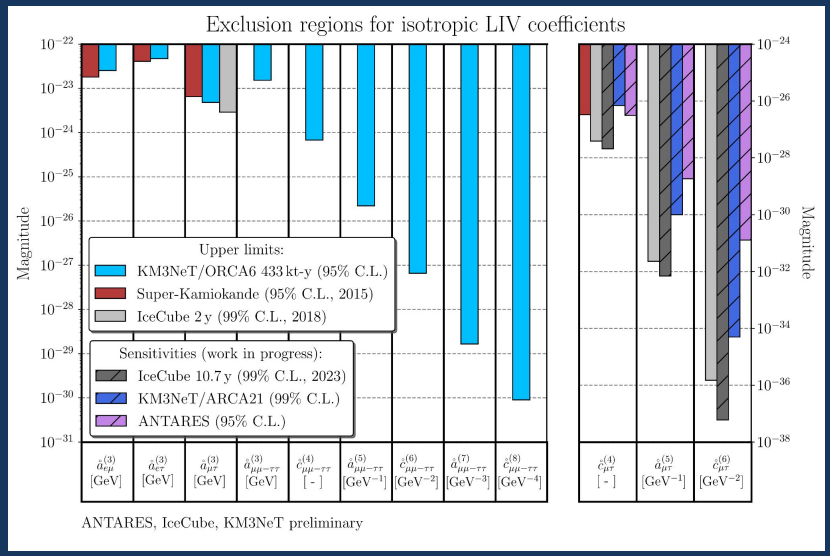
- Search for light sterile neutrinos in the eV scale.
- Consistent with other experiments.
- Paper in preparation

Sterile Neutrinos
https://pos.sissa.it/476/155



- Lorentz invariance violation probes for dimension 3 coefficients and higher dimensions off-diagonal terms.
- Paper in preparation.

$$H_{LIV} = \begin{pmatrix} \mathring{a}^{(3)}_{ee} & \mathring{a}^{(3)}_{e\mu} & \mathring{a}^{(3)}_{e\tau} \\ \mathring{a}^{(3)*}_{e\mu} & \mathring{a}^{(3)}_{\mu\mu} & \mathring{a}^{(3)}_{\mu\tau} \\ \mathring{a}^{(3)*}_{e\tau} & \mathring{a}^{(3)*}_{\mu\tau} & \mathring{a}^{(3)}_{\tau\tau} \end{pmatrix} - \frac{4}{3}E \begin{pmatrix} \mathring{c}^{(4)}_{ee} & \mathring{c}^{(4)}_{e\mu} & \mathring{c}^{(4)}_{e\tau} \\ \mathring{c}^{(4)*}_{e\mu} & \mathring{c}^{(4)}_{\mu\mu} & \mathring{c}^{(4)}_{\mu\tau} \\ \mathring{c}^{(4)*}_{e\tau} & \mathring{c}^{(4)*}_{\mu\tau} & \mathring{c}^{(4)}_{\tau\tau} \end{pmatrix} + E^2\mathring{a}^{(5)} - E^3\mathring{c}^{(6)} + \ldots$$



Lorentz Invariance Violation
Poster Neutrino2024

Conclusions

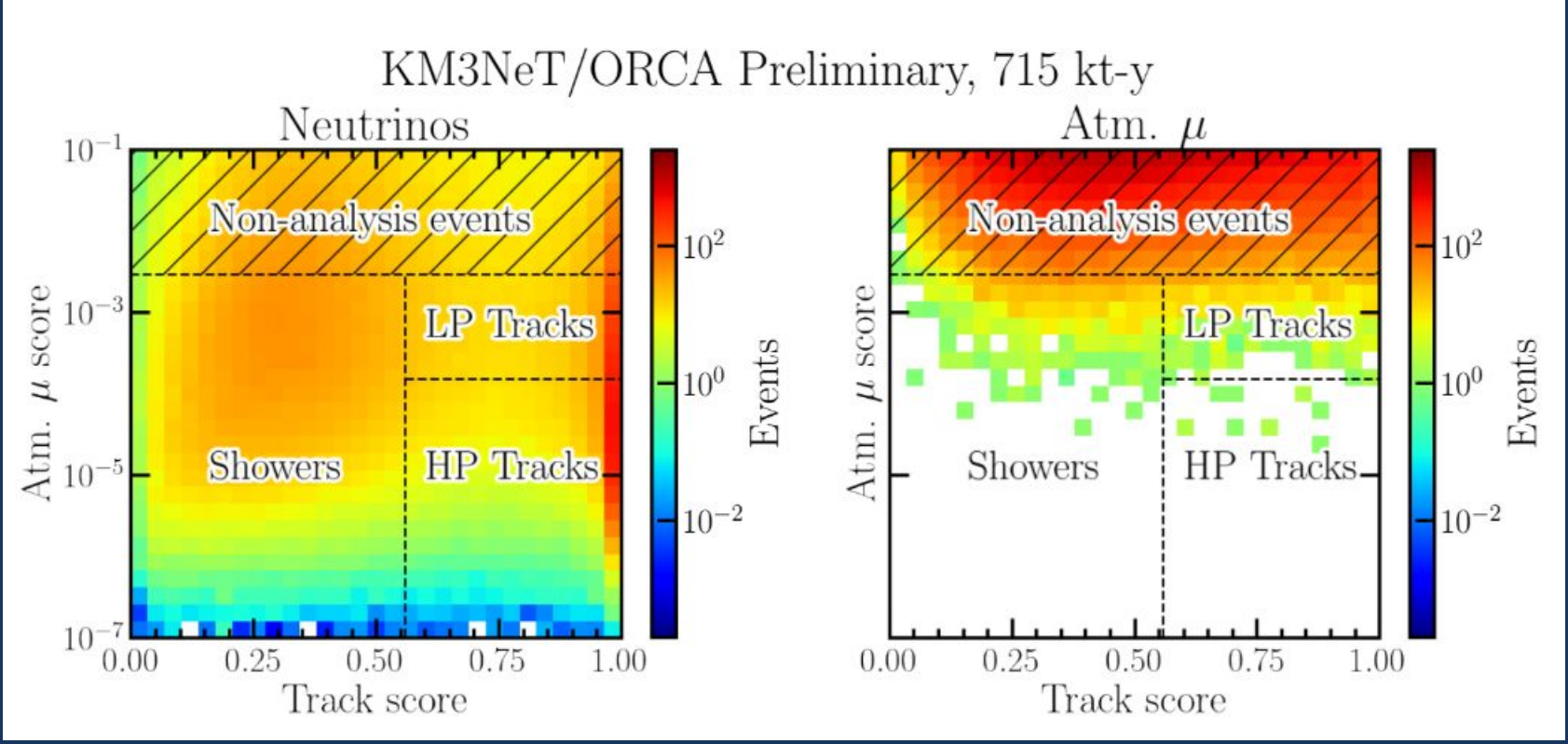
- High quality data has been taken during construction phase
- New improved oscillation results and much more data to come
- Strong matter effects open a window to exciting new physics models
- Competitive results with 5% of planned exposure
- Next analysis with 2.5 times more exposure
- Before end of decade competitive results also on NMO
  - Exposure ~20 Mt-yr
  - More realistic systematics
- Stay tuned!

Event Breakdown

Selection	HP Tracks	LP Tracks	Showers	Total
ν_μ CC	2166	1232	1266	4664
$\bar{\nu}_\mu$ CC	1103	618	495	2216
$\nu_\mu + \bar{\nu}_\mu$ CC	3269	1850	1761	6880
ν_e CC	38	49	907	994
$\bar{\nu}_e$ CC	19	23	415	457
$\nu_e + \bar{\nu}_e$ CC	57	72	1322	1451
ν_τ CC	19	13	155	187
$\bar{\nu}_\tau$ CC	10	6	63	79
$\nu_\tau + \bar{\nu}_\tau$ CC	29	19	218	266
ν NC	16	23	367	406
$\bar{\nu}$ NC	5	7	108	120
$\nu + \bar{\nu}$ NC	21	30	475	526
Background	2	421	205	628
Best fit MC	3378	2392	3981	9751
Total Data	3378	2390	3983	9751

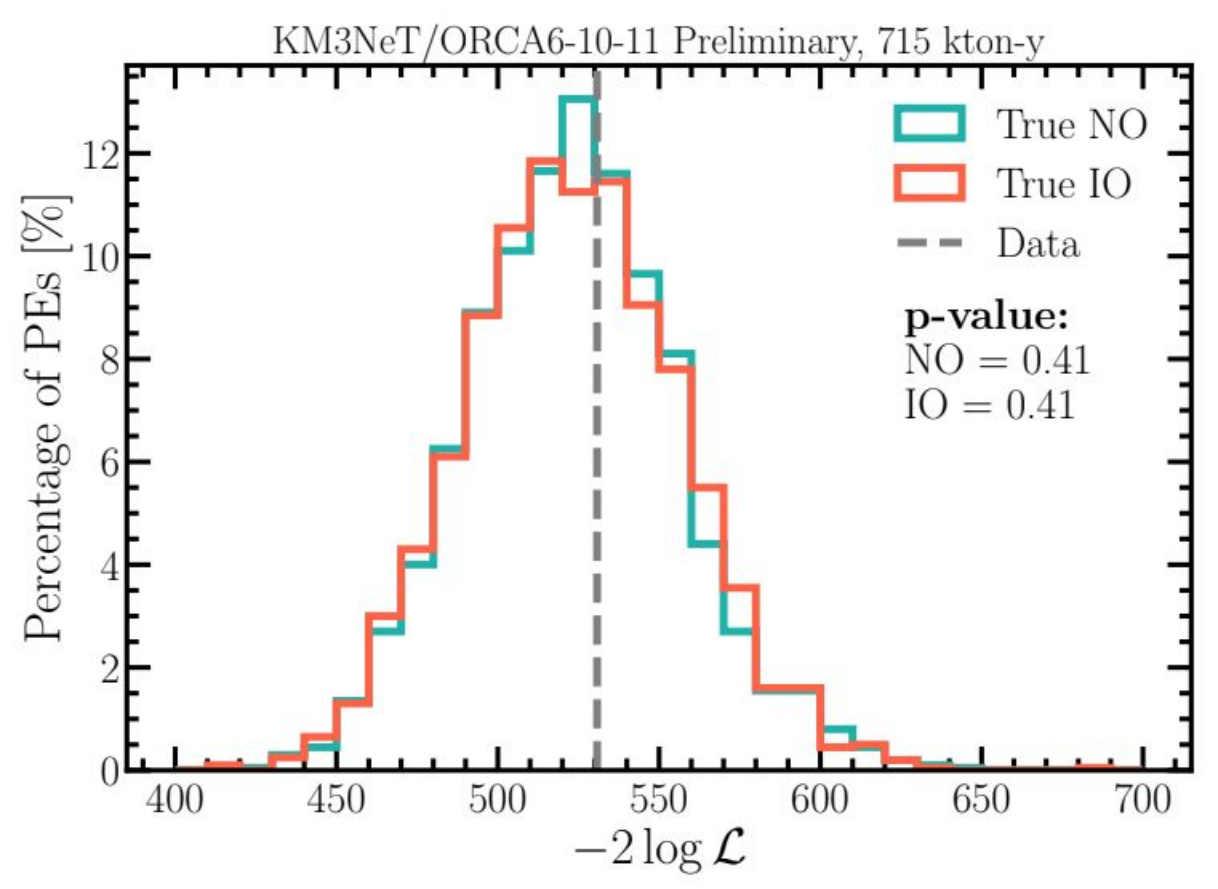
Class Definitions

- Tile the 2D space of track and atm. Muon BDT scores
- Prioritized a very pure track-like sample

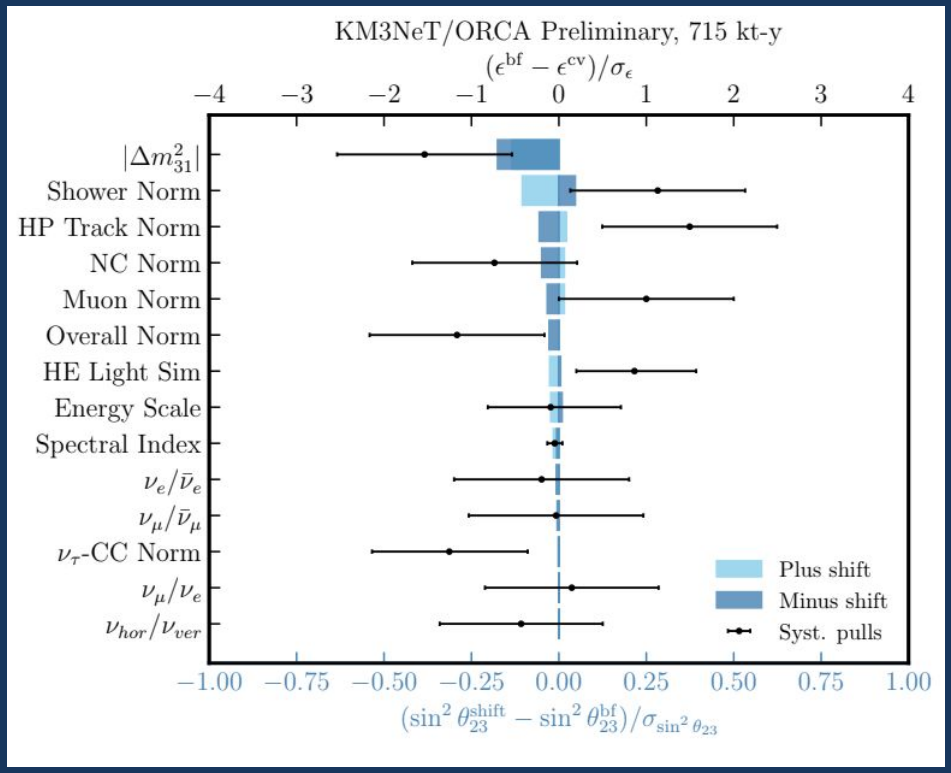


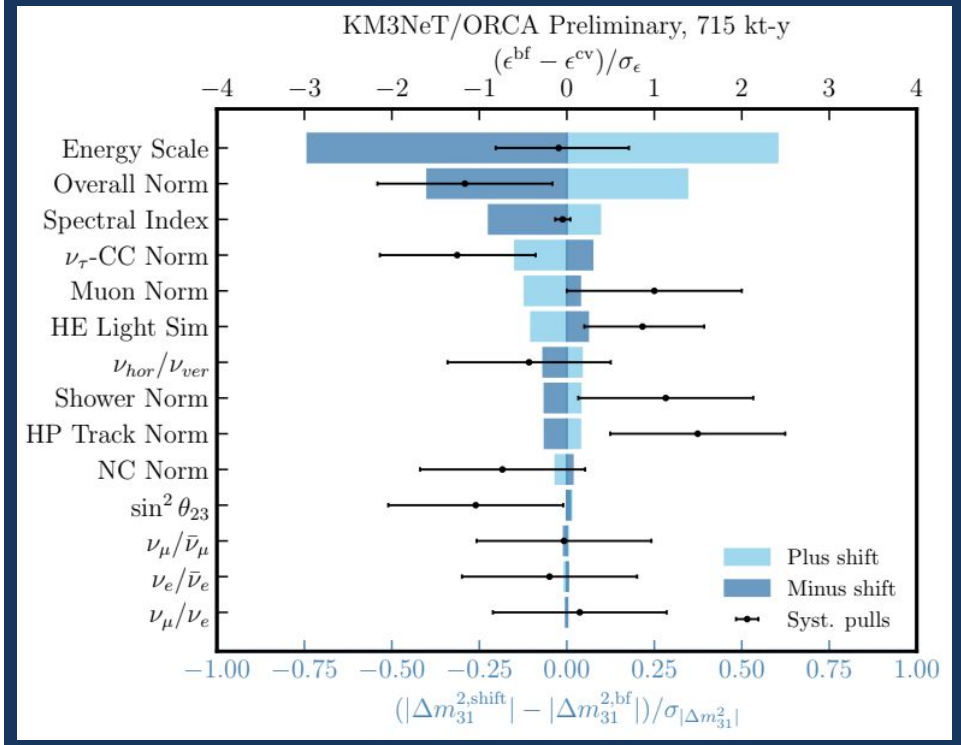
Goodness-of-Fit

- Data total likelihood value consistent with toy simulations



Systematic Uncertainties



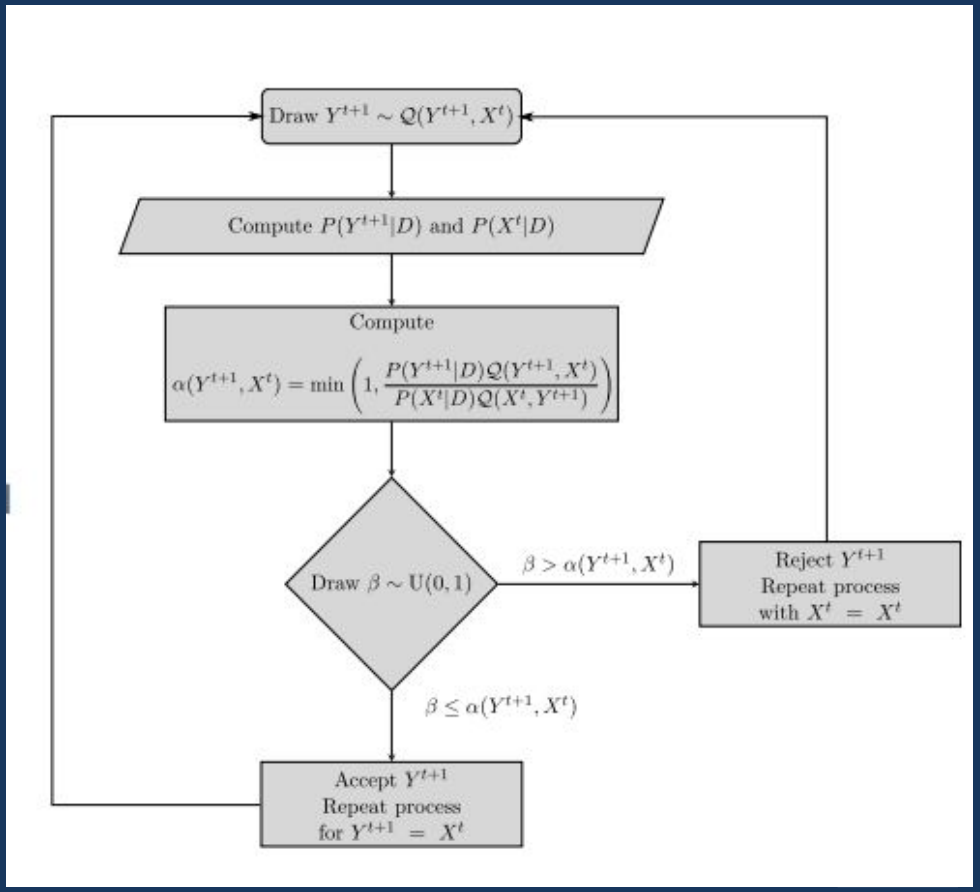


$\sin^2\theta_{23}$ dominated by statistics

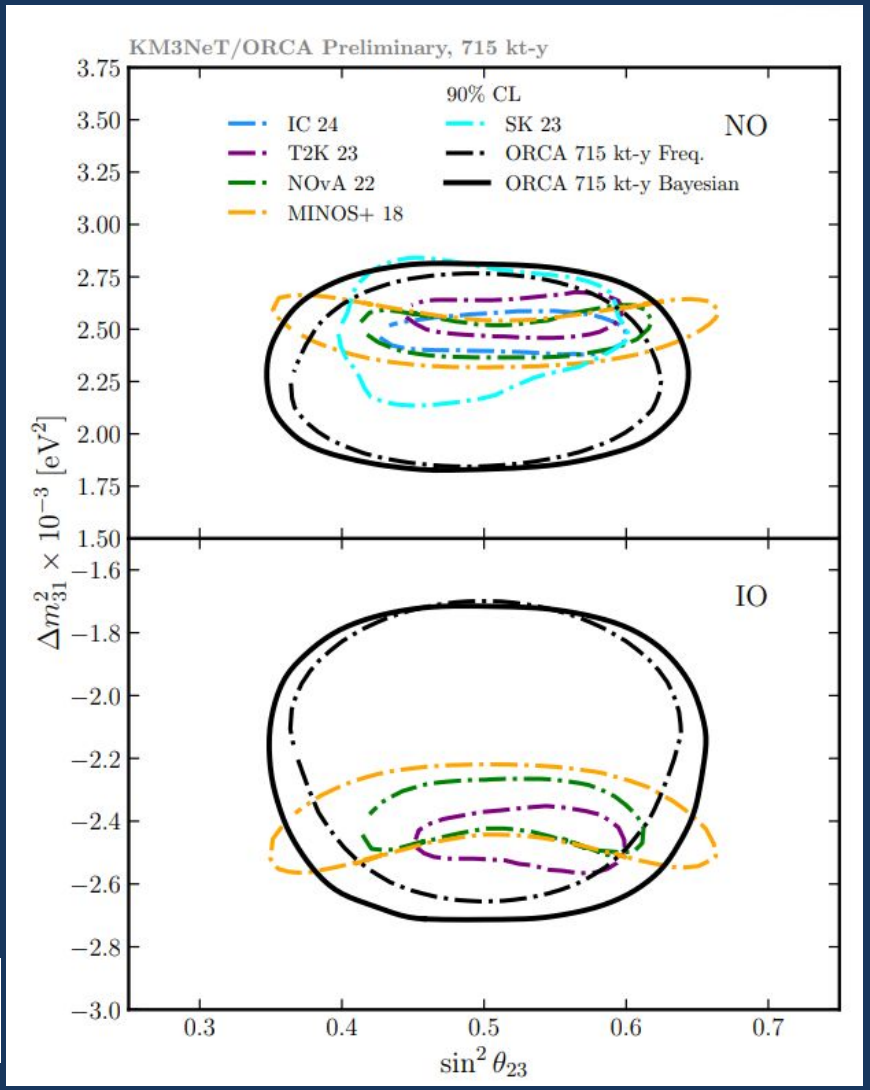
Δm^2_{31} impacted mostly by uncertainty on energy scale

Dominated by uncertainties on water properties

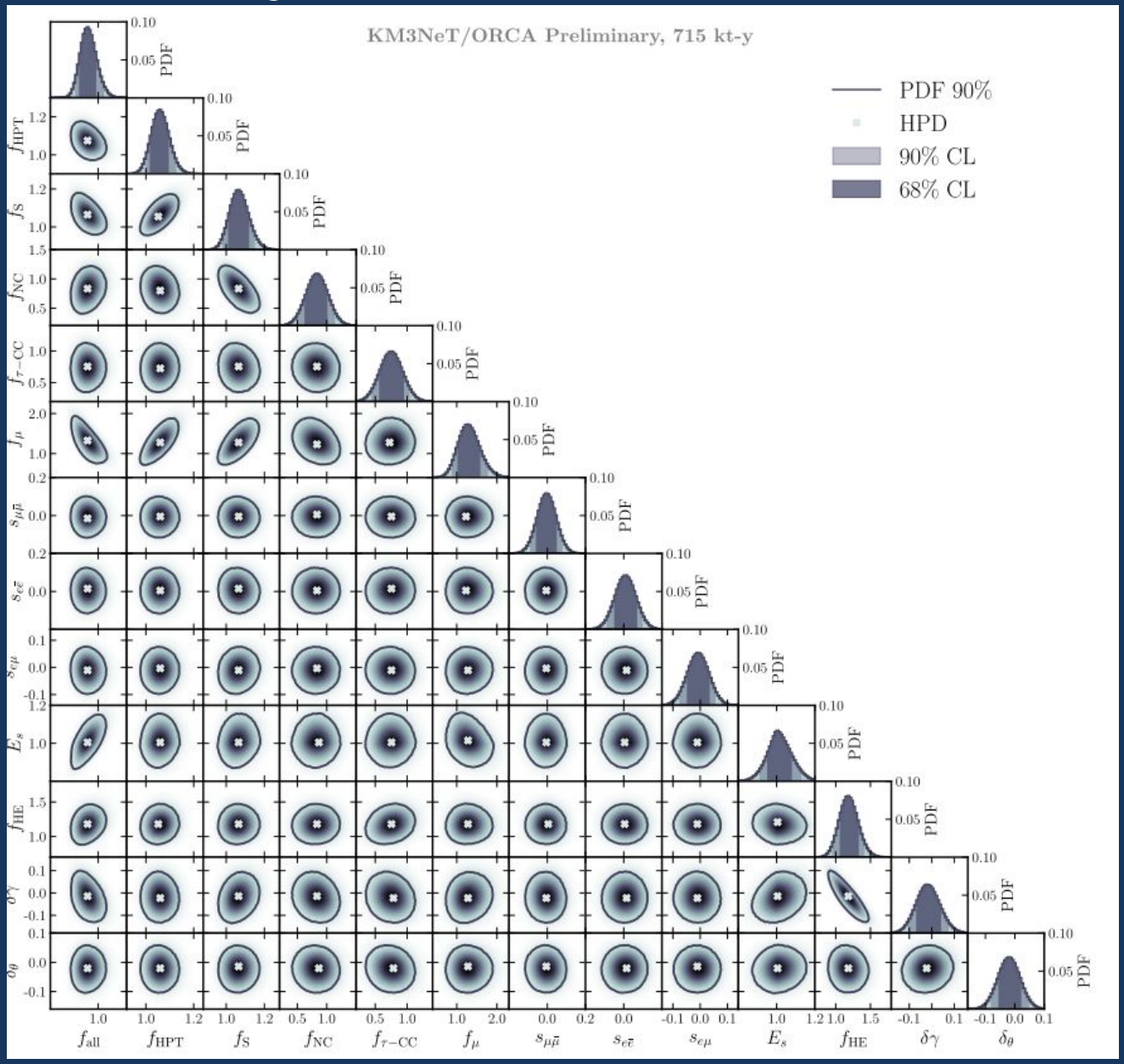
Bayesian approach



$$\mathcal{L}_{\mathrm{BB}}(k|\vec{\theta}) = \max_{\{\bar{n}_j\}} \frac{\lambda(\vec{\theta})^k e^{-\lambda(\vec{\theta})}}{k!} \prod_{j=1}^{s} \frac{\bar{n}_j^{n_j} e^{-\bar{n}_j}}{n_j!} \qquad \mathcal{L}_{\mathrm{eff}}(k|\vec{\theta}) = \int_0^\infty \frac{\lambda^k e^{-\lambda}}{k!} \mathcal{P}(\lambda|\vec{w}(\vec{\theta}))d\lambda$$



Bayesian correlations



Challenges

- Long tail of high energy events in track-like samples (not contained tracks)
- Peak of distribution at a few tens of GeV
- Shower classification for low energy is challenging due to the short length of the tracks.
- Shower purity is the key to the mixing angle sensitivity and mass ordering determination.