Measuring atmospheric neutrino oscillations with KM3NeT/ORCA

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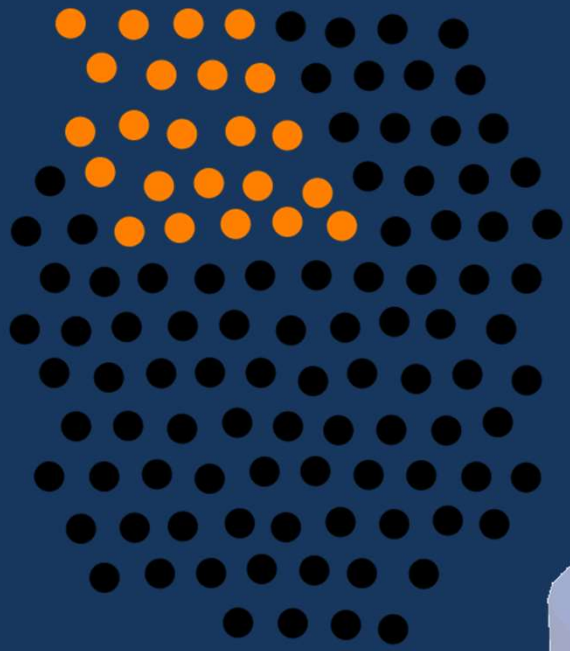
for the KM3NeT Collaboration

26 June 2024

KM3NeT/ORCA

23 DUs Deployed



115 Detection Units
18 DOMs / DU

200 m

7 Mton detector

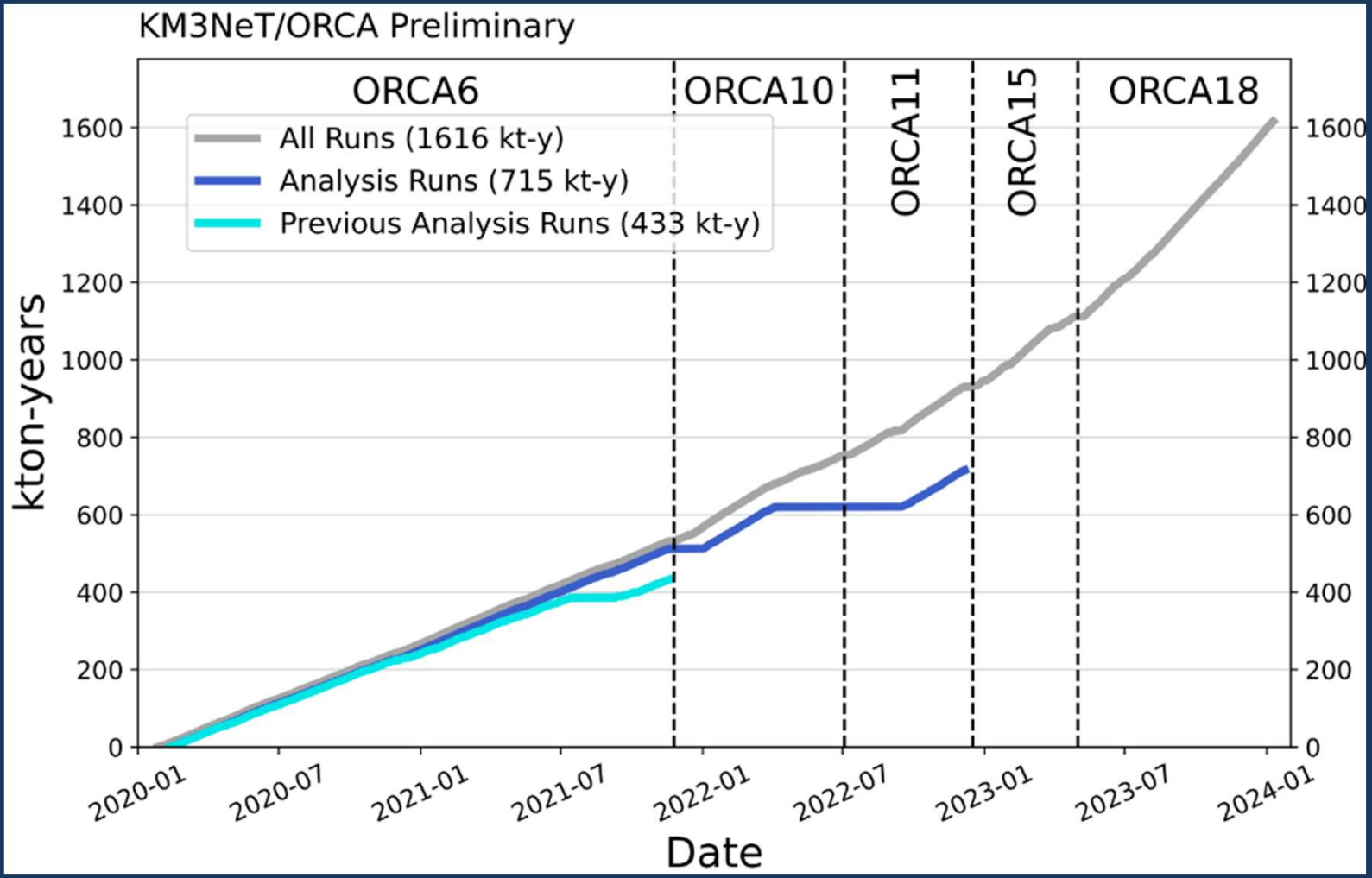
2450 m

31x 3" PMTs

43 cm

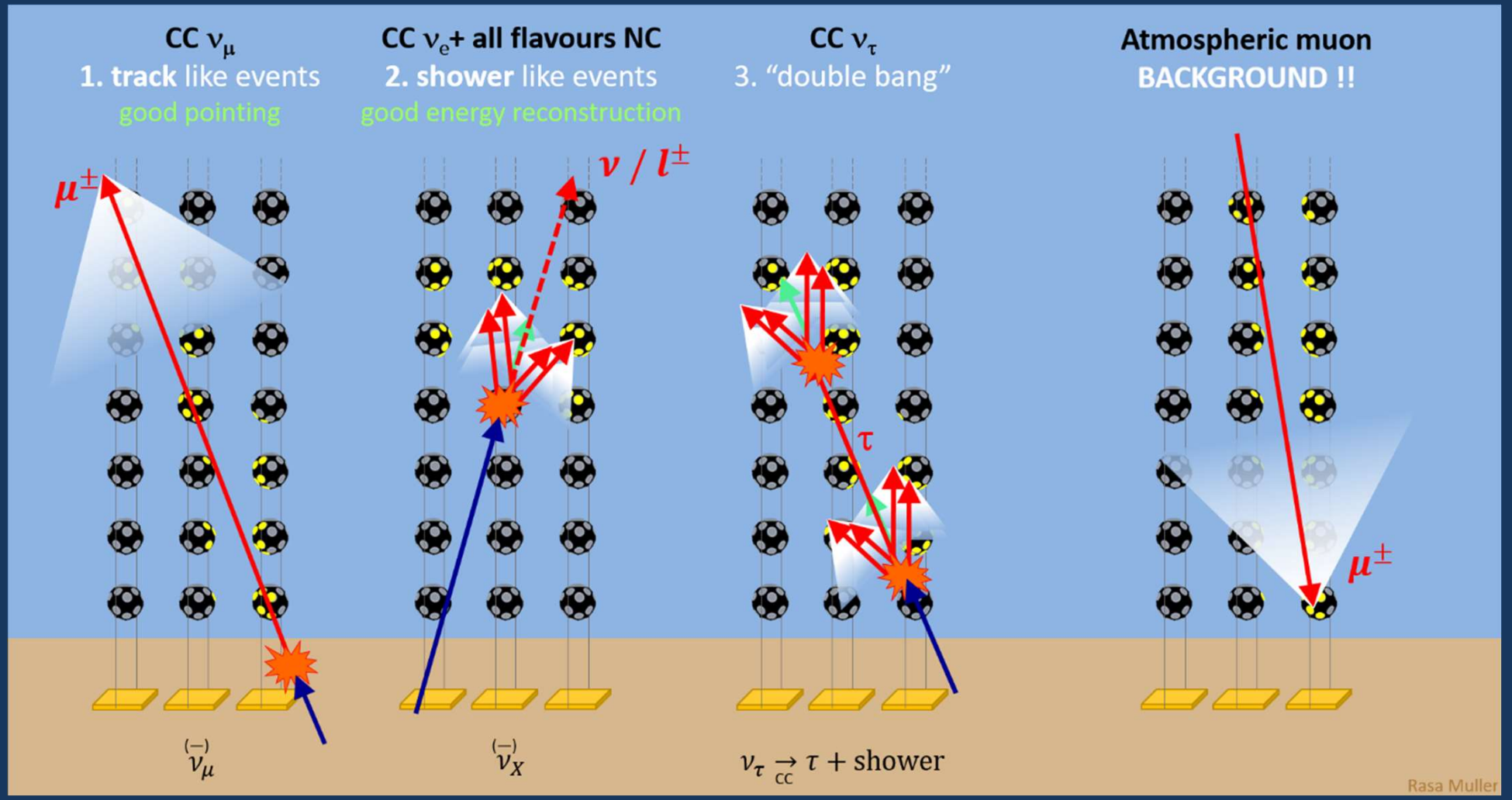
Data

- Already collected and processed more than 1.6 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



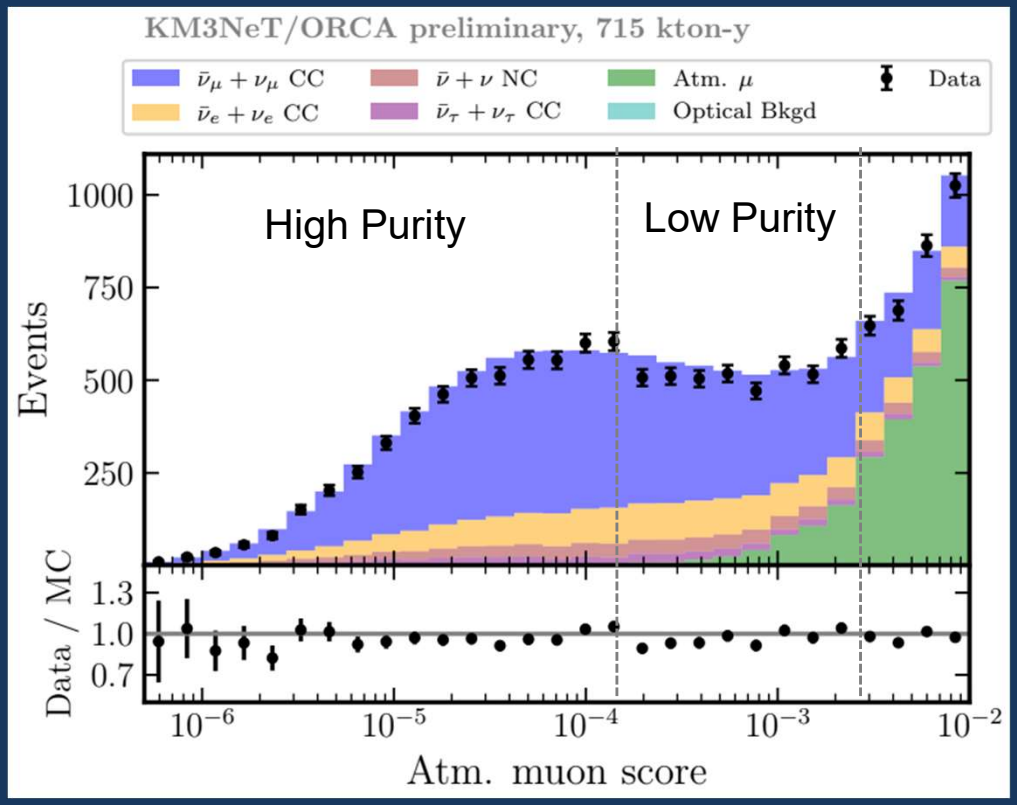
Topologies

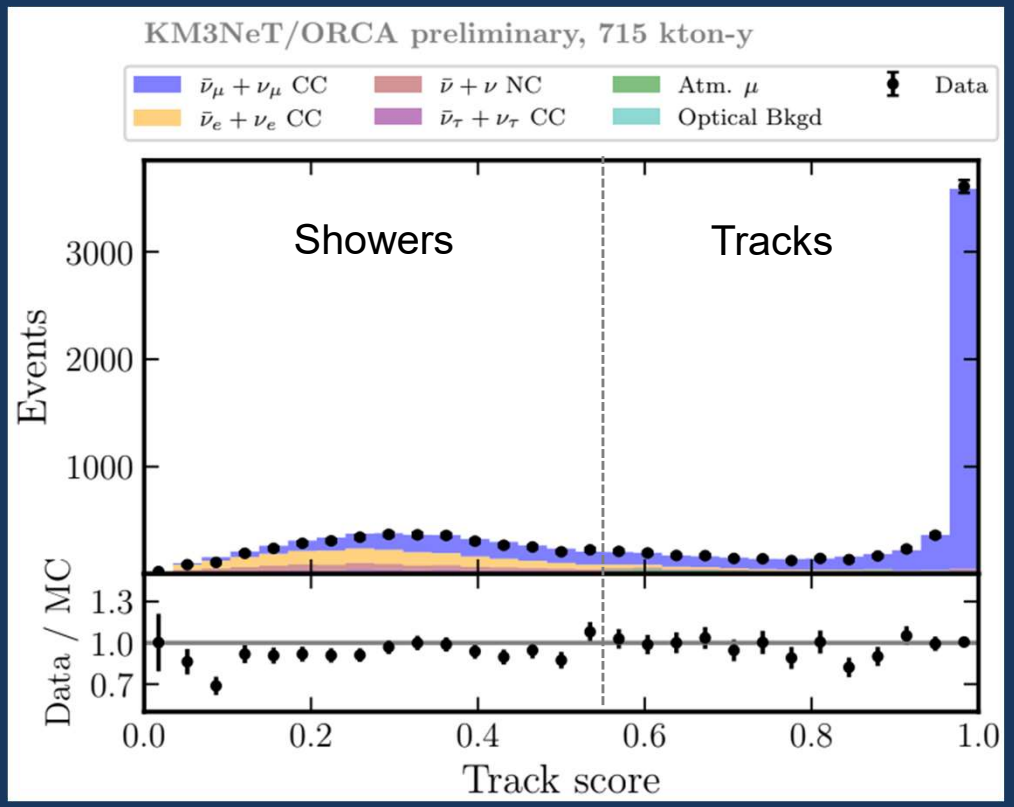
- Neutrinos in the GeV range pass through the Earth while it acts like a shield for atmospheric muons.
- Distinct patterns of light can be used to identify neutrino flavours and background.



Event Selection

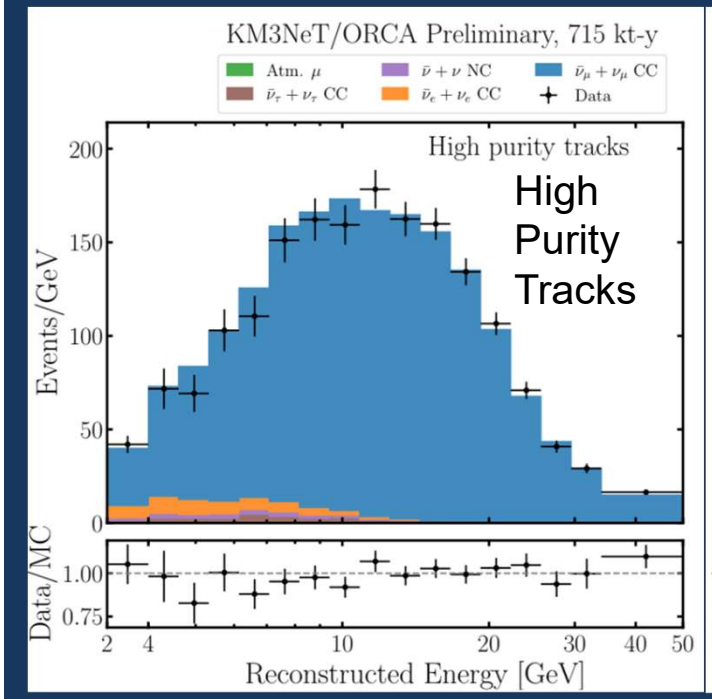
- Events are reconstructed assuming track and shower topologies.
- We employ Boosted Decision Trees (BDTs) to summarize reconstructed quantities into background scores.
- 3 selection regions are defined: High purity tracks, low purity tracks, and showers.
- Excellent agreement between data and simulation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

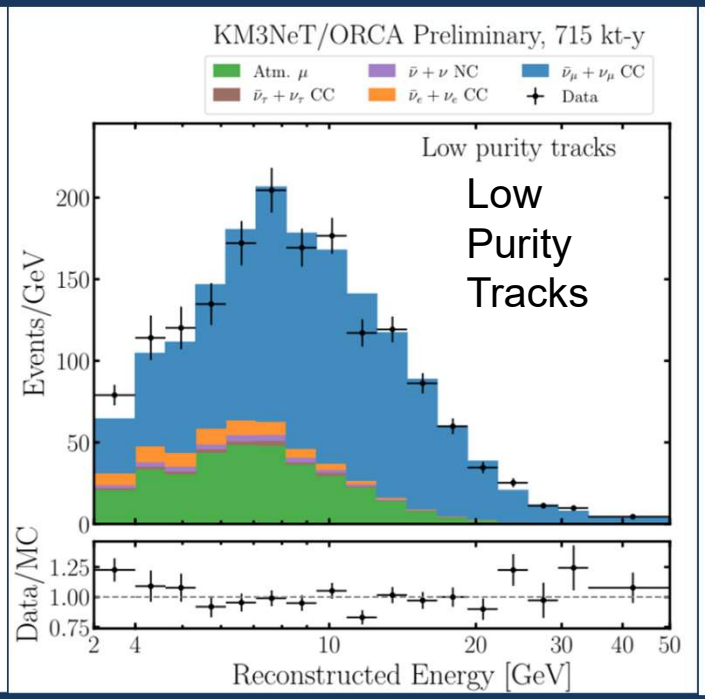


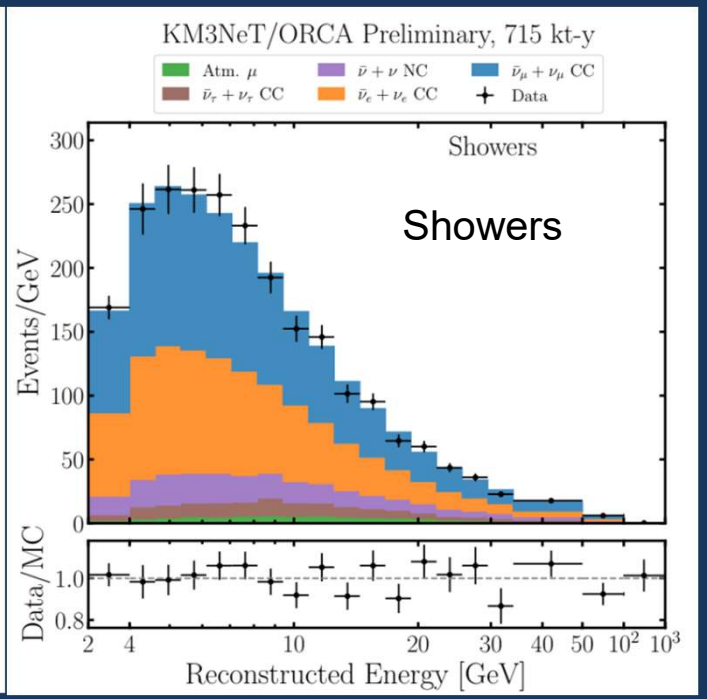


Event Selection

- 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.

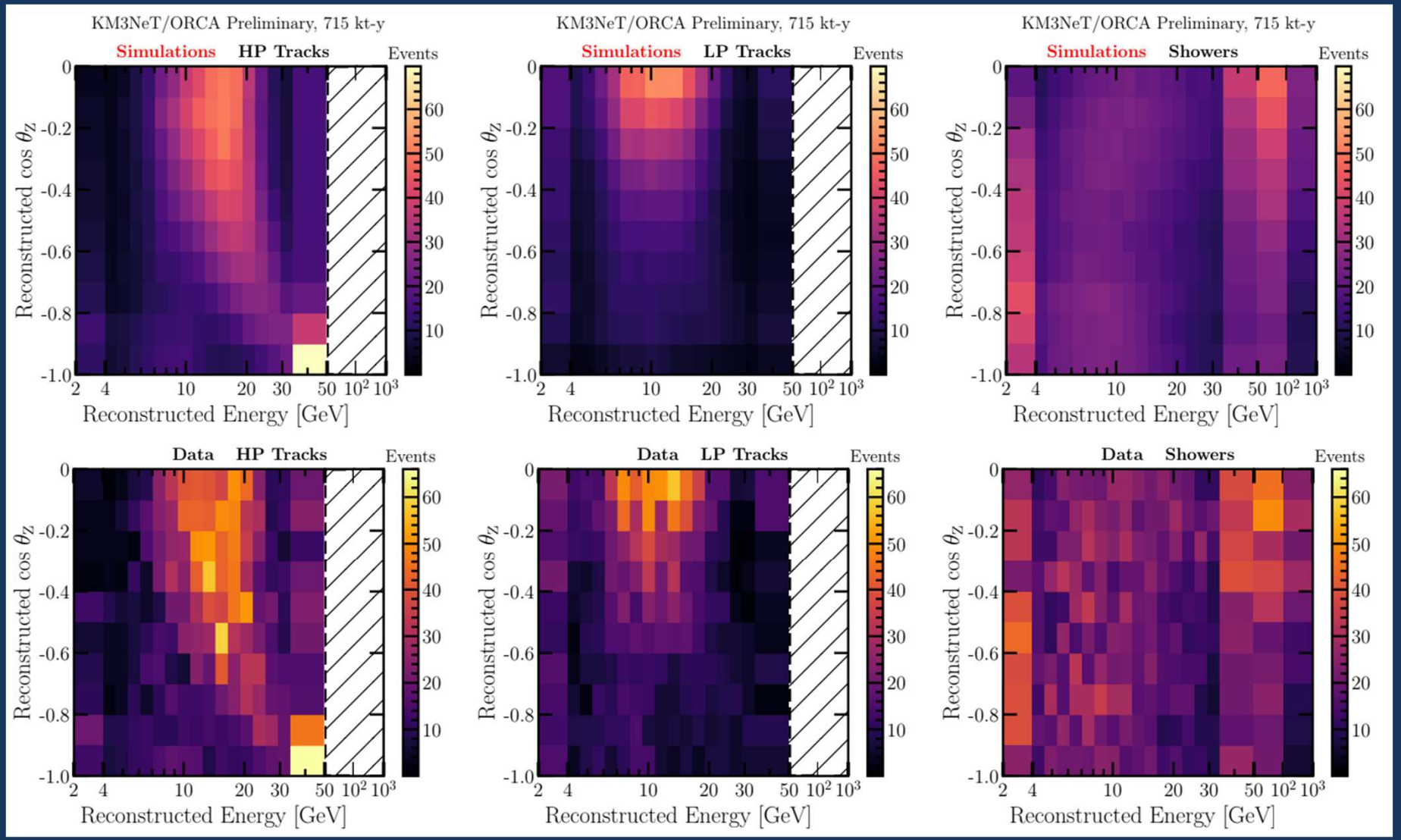






Oscillation Patterns

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



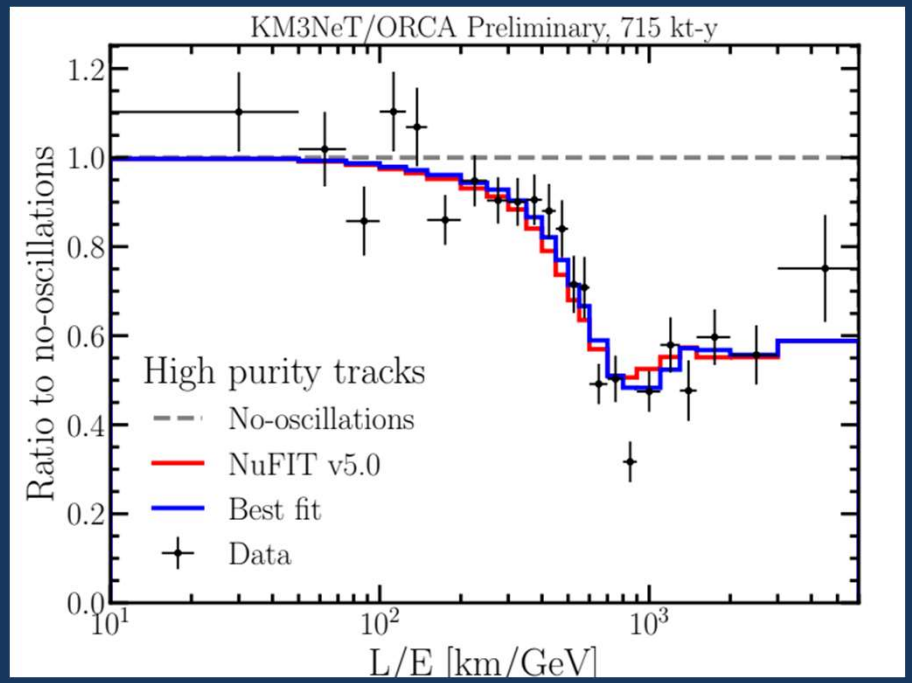
Improved Measurement

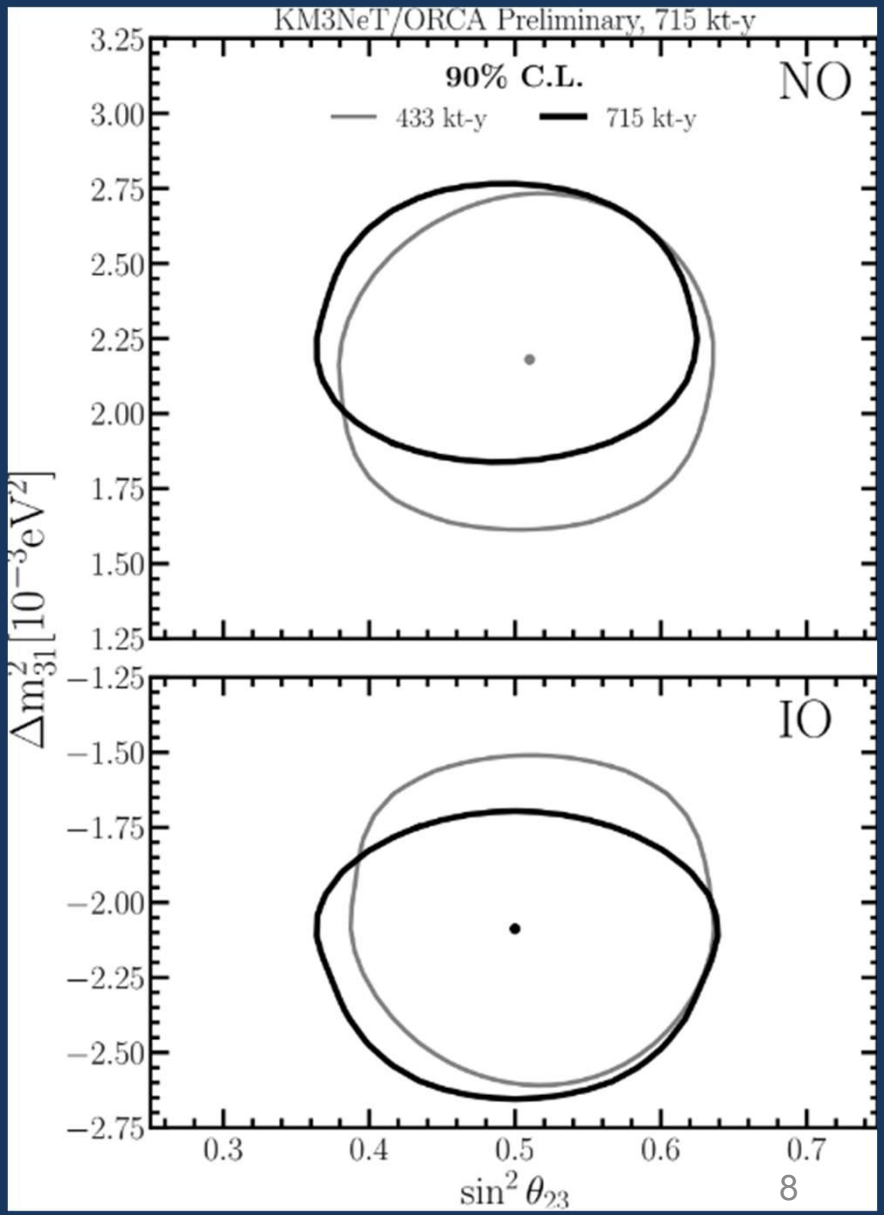
- New measurement uses 715 kt-y of data (65% increase over 2023 dataset)
- Clear oscillation pattern in L/E
- Slight preference for Inverted Ordering (IO)

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

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

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





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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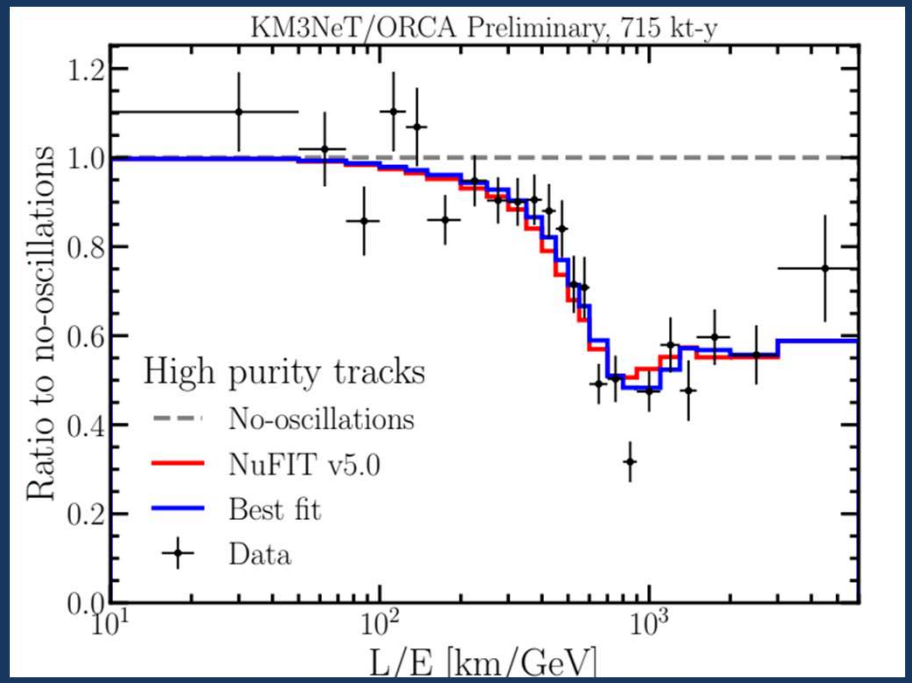
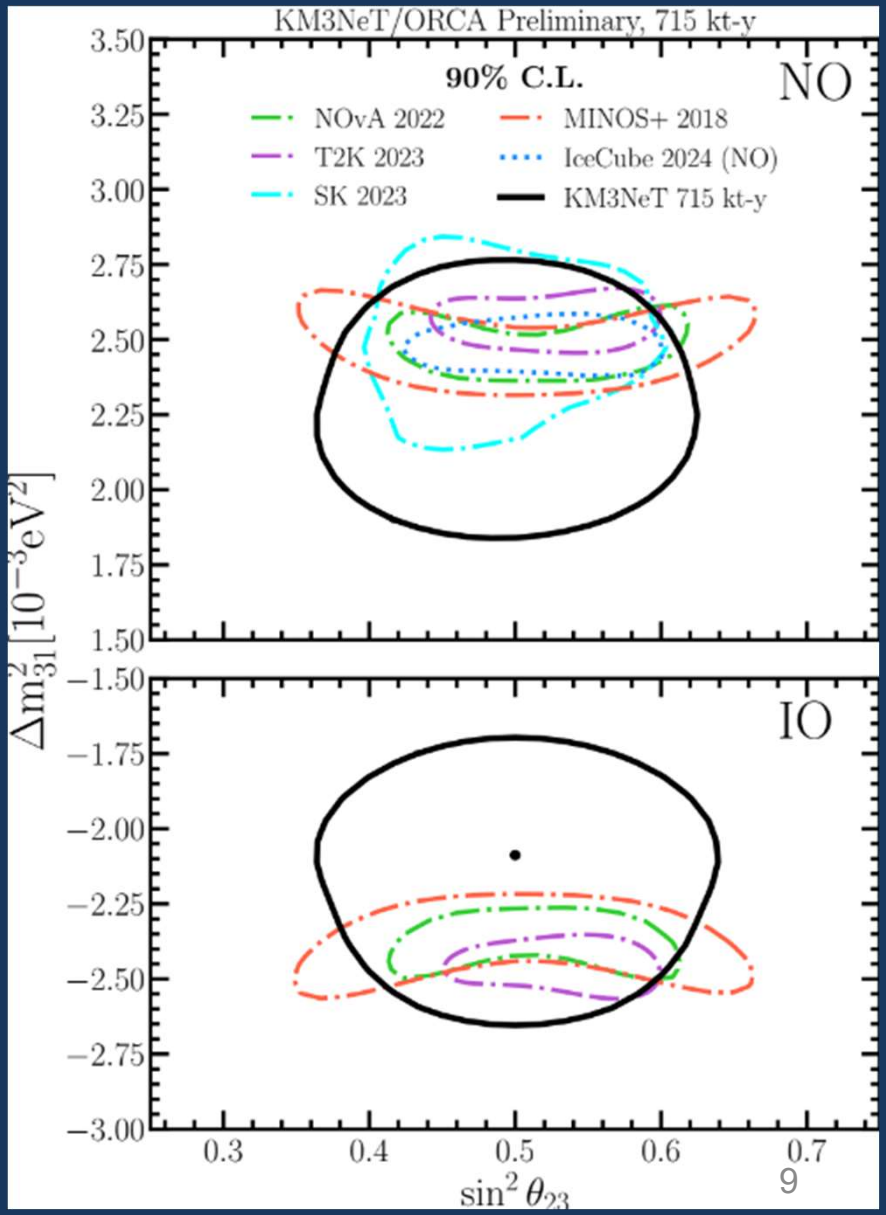
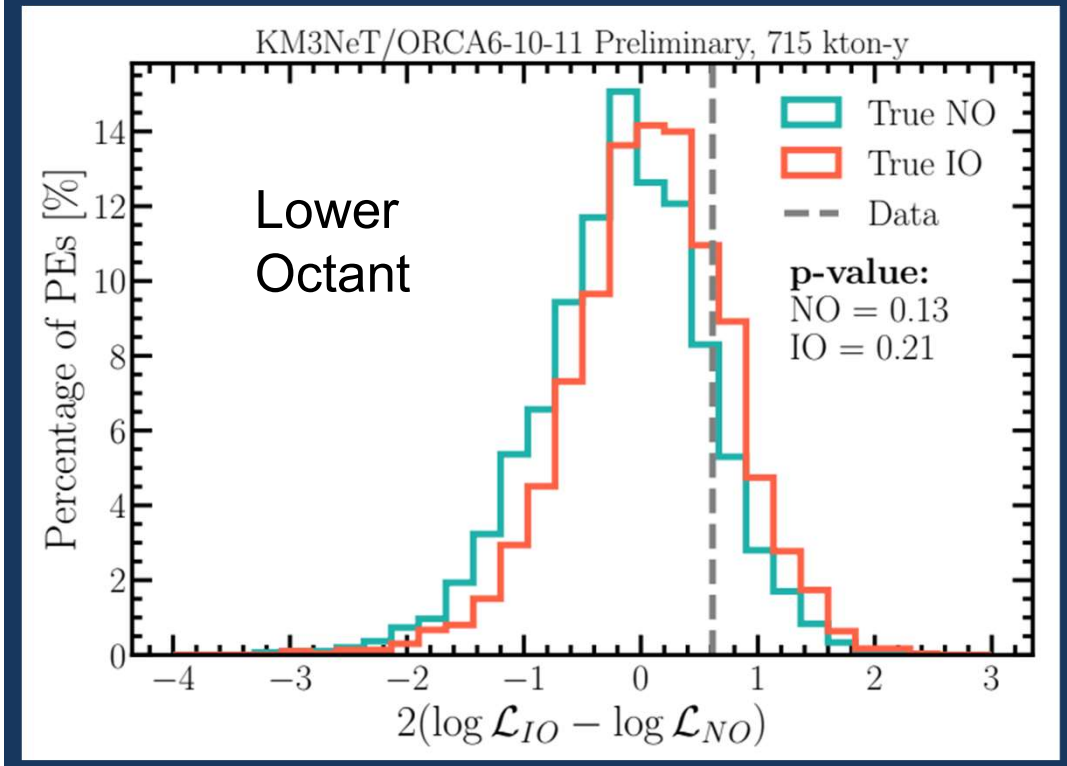


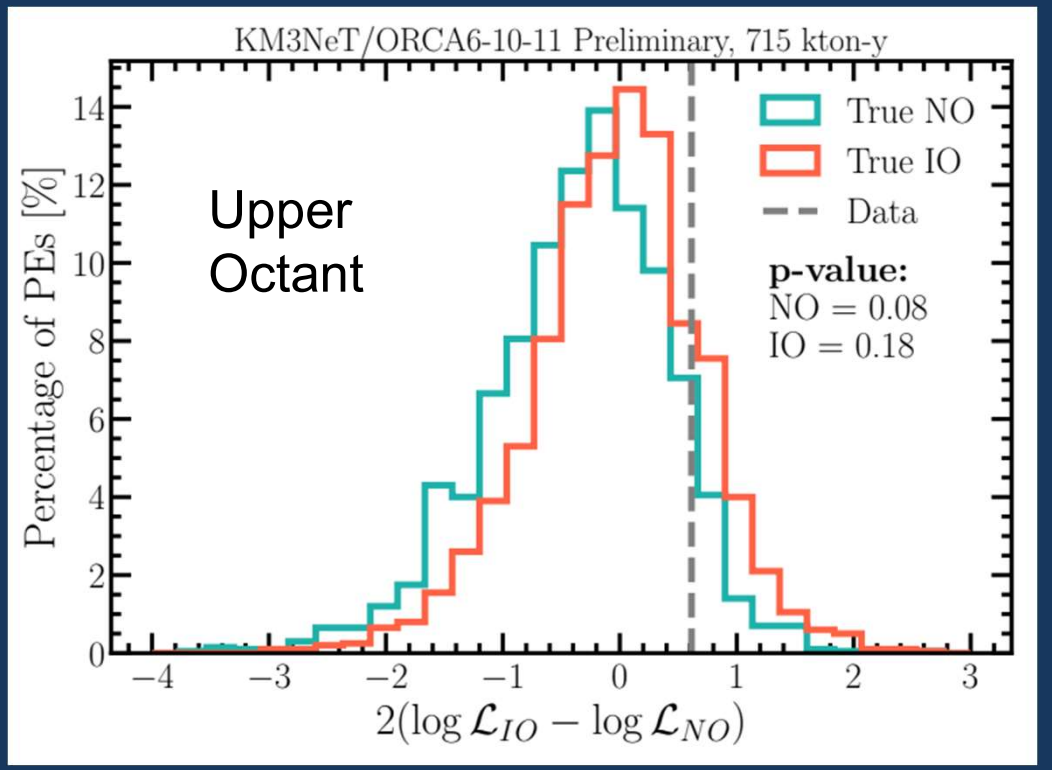


See poster 358

NMO Significance

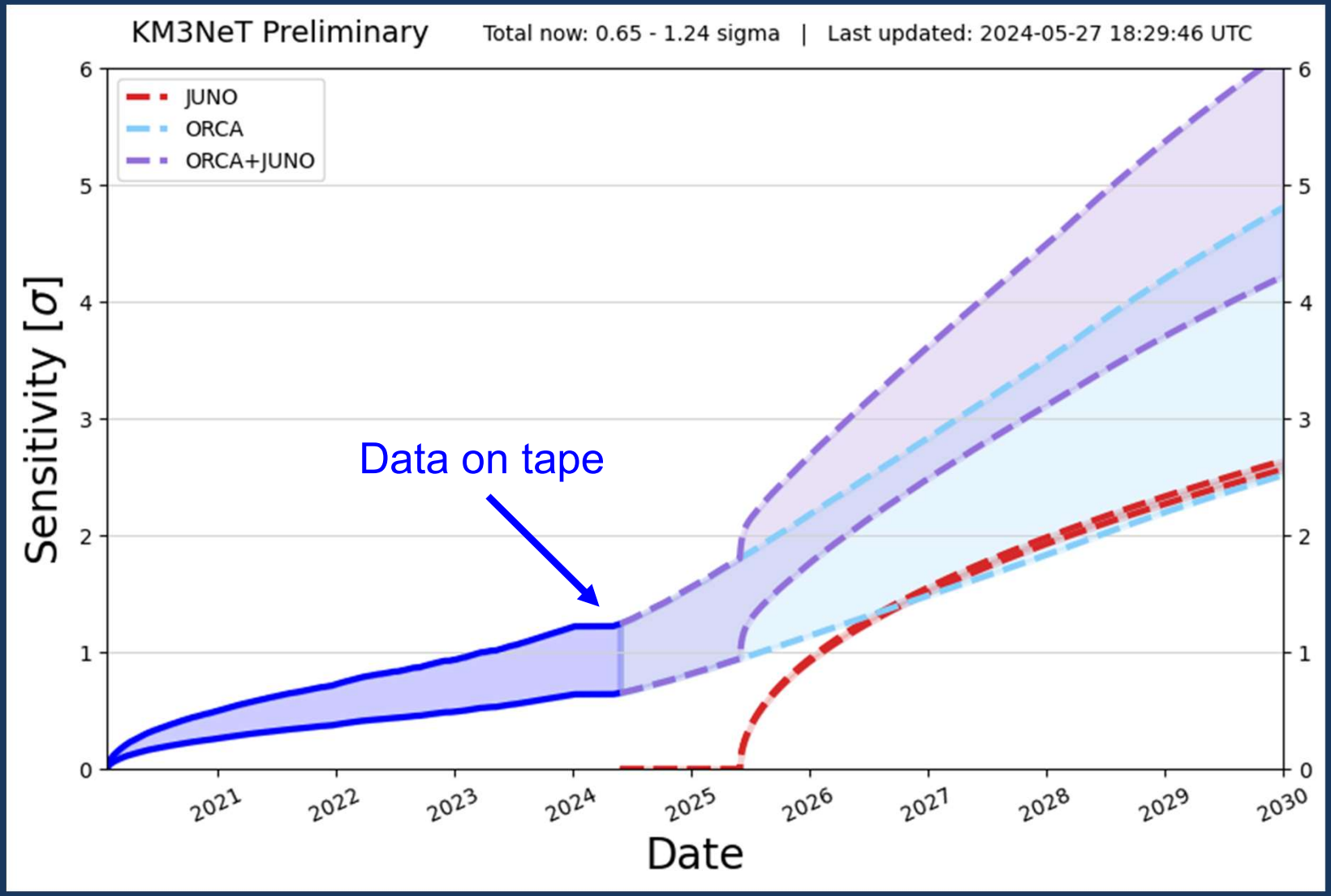
- Conversion from -2logL to p-value depends on choice of nuisance parameters
- At NuFIT 5.0 best fit, NO hypothesis disfavoured at 1.7σ / 1.5σ in (UO/LO)
- IO preference slightly stronger than expected (18%/21% p-value in UO/LO)
- Working towards a more general statement as a function of $\sin^2\theta_{23}$





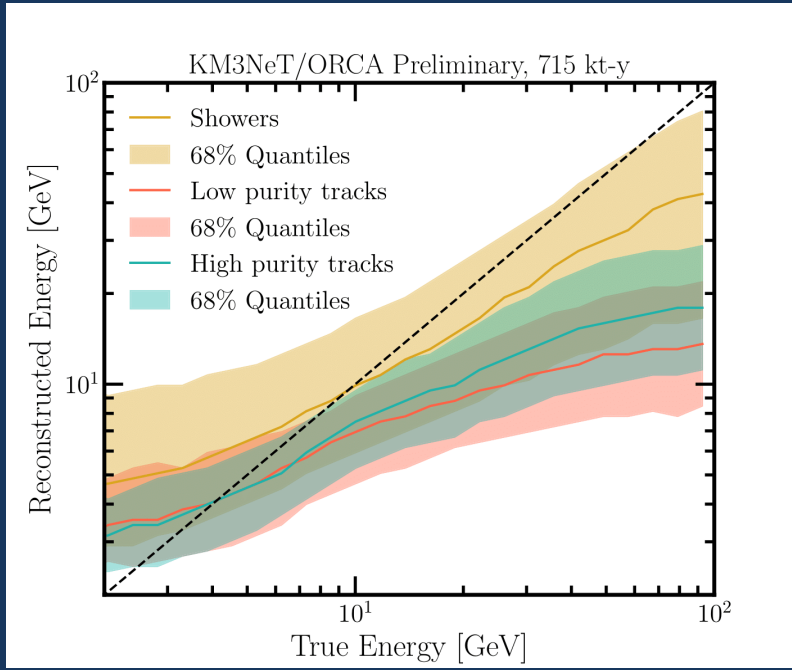
And More Data is Coming

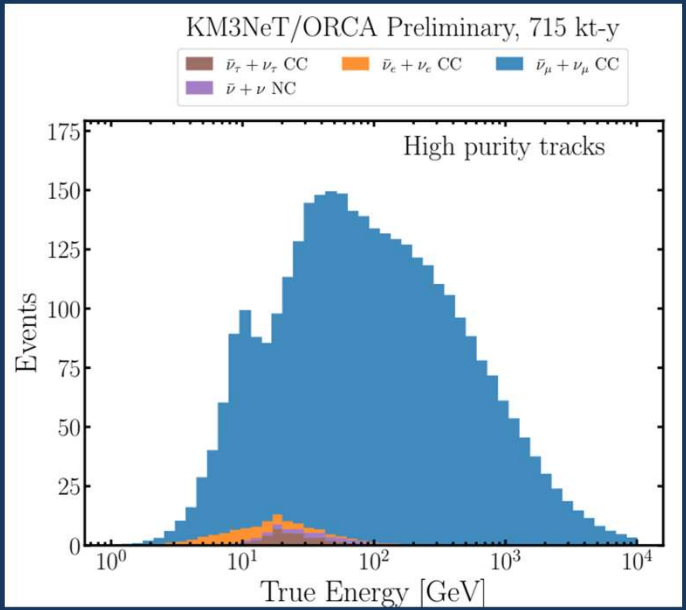
- Current projections including detector construction schedule show 5σ NMO determination in reach within this decade when combined with JUNO

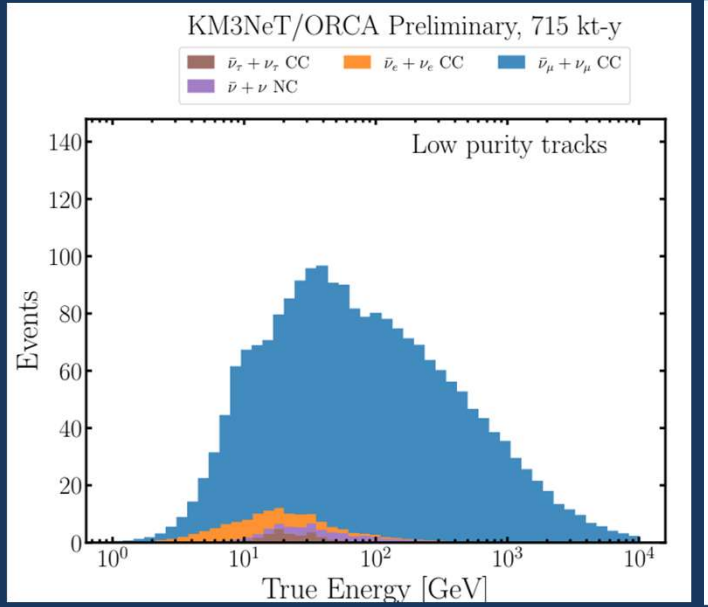


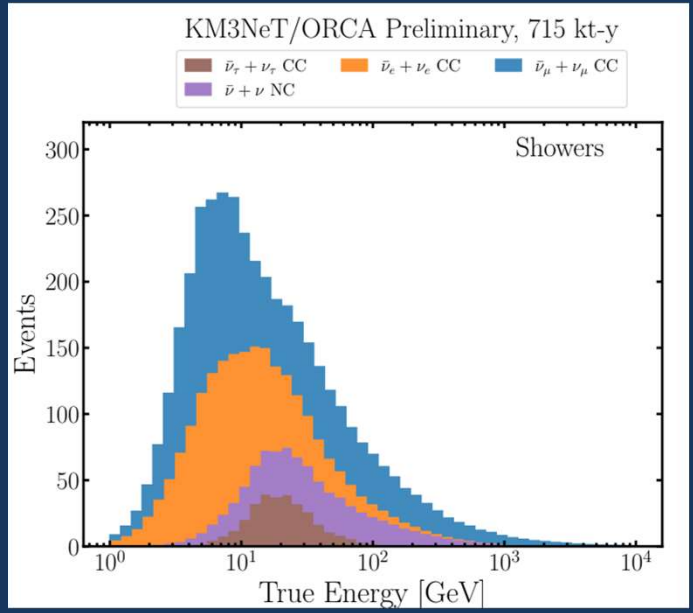
Challenges

- 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.





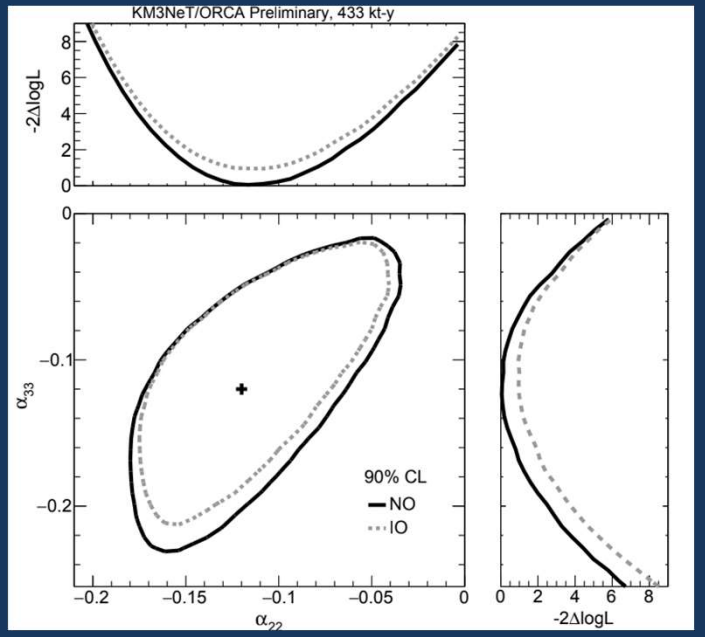




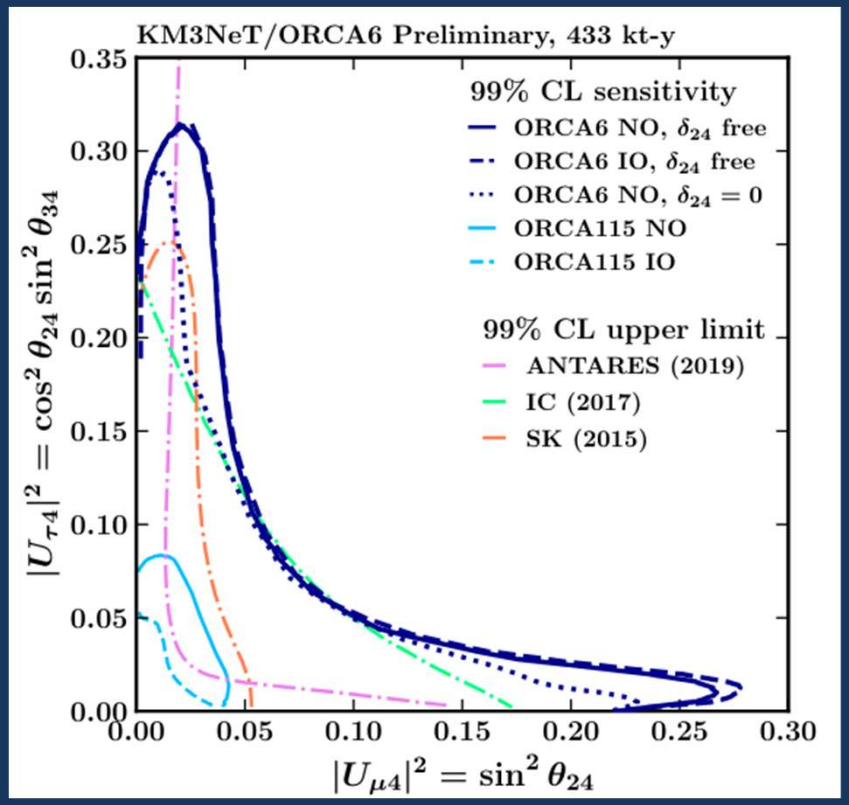
New Physics Models

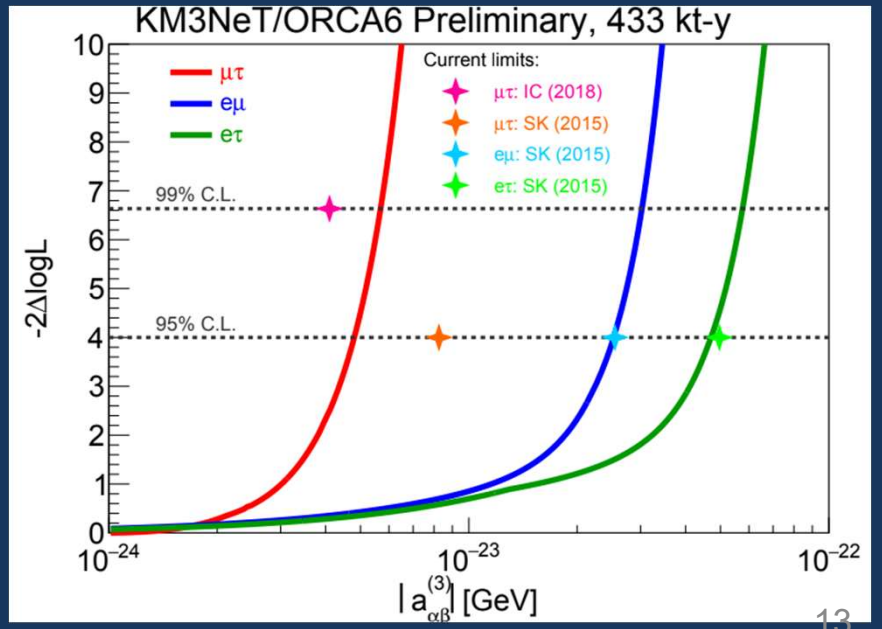
- Many other alternative models have been probed with the previous dataset, 433 kton-years.

Non-Unitary Mixing



Sterile Neutrinos



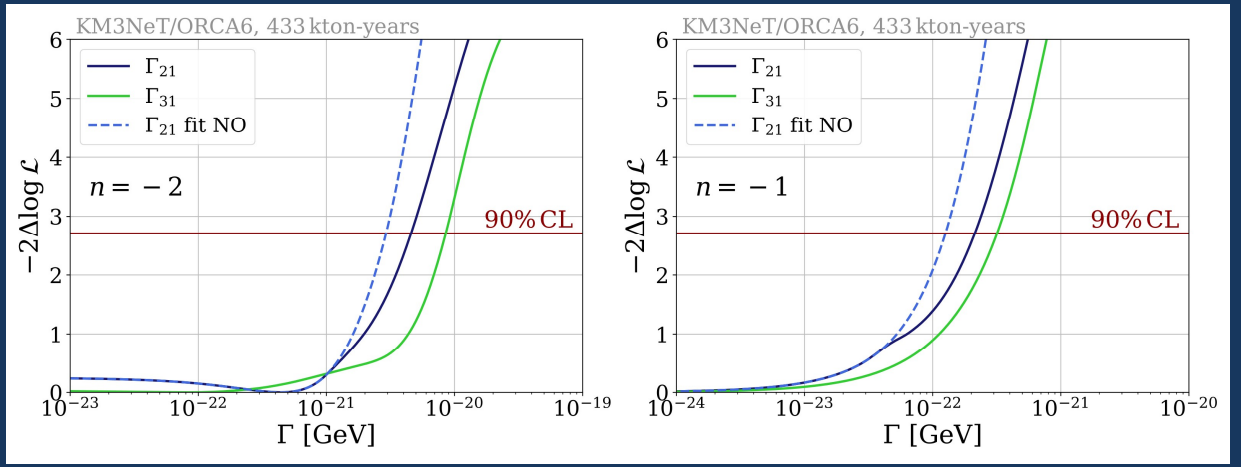


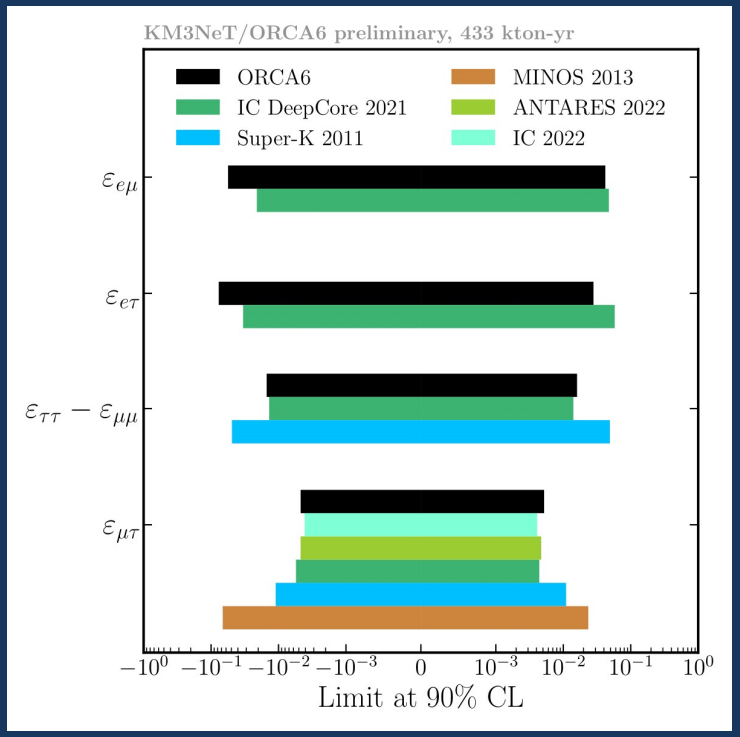
Lorentz Invariance Violation

New Physics Models

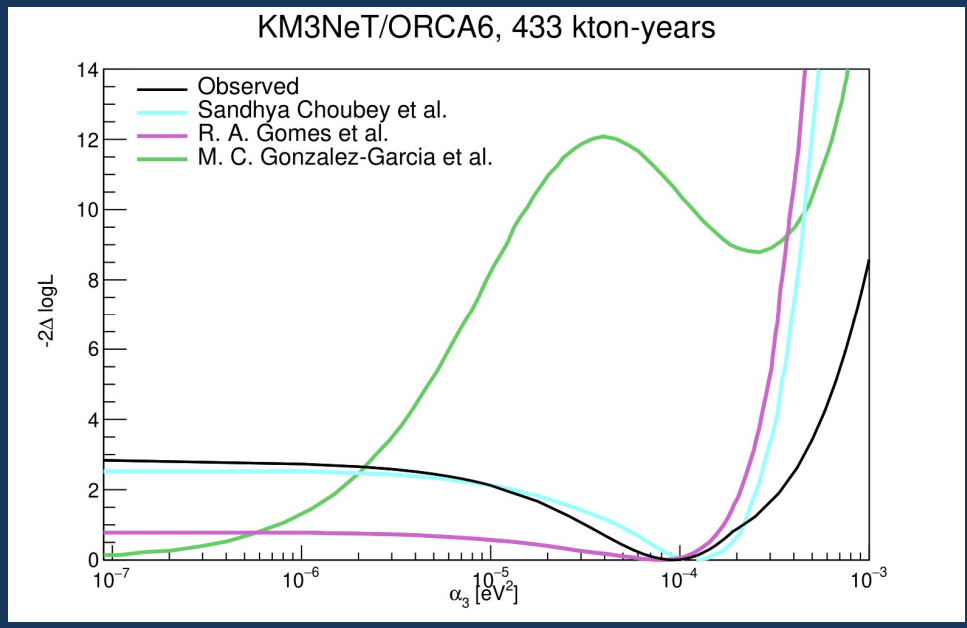
- Many other alternative models have been probed with the previous dataset, 433 kton-years.
- Papers in preparation for these results.

Quantum decoherence





Non-Standard-Interactions



Invisible decay

Conclusion

- 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:
  - Invisible neutrino decay
  - Non standard interactions
  - Decoherence
  - Lorentz invariance
  - Sterile neutrinos
  - Non-unitarity mixing
- Major challenges to overcome in the coming analyses:
  - Water properties uncertainties
  - Shower performance and classification
- Stay tuned!

Thank you!

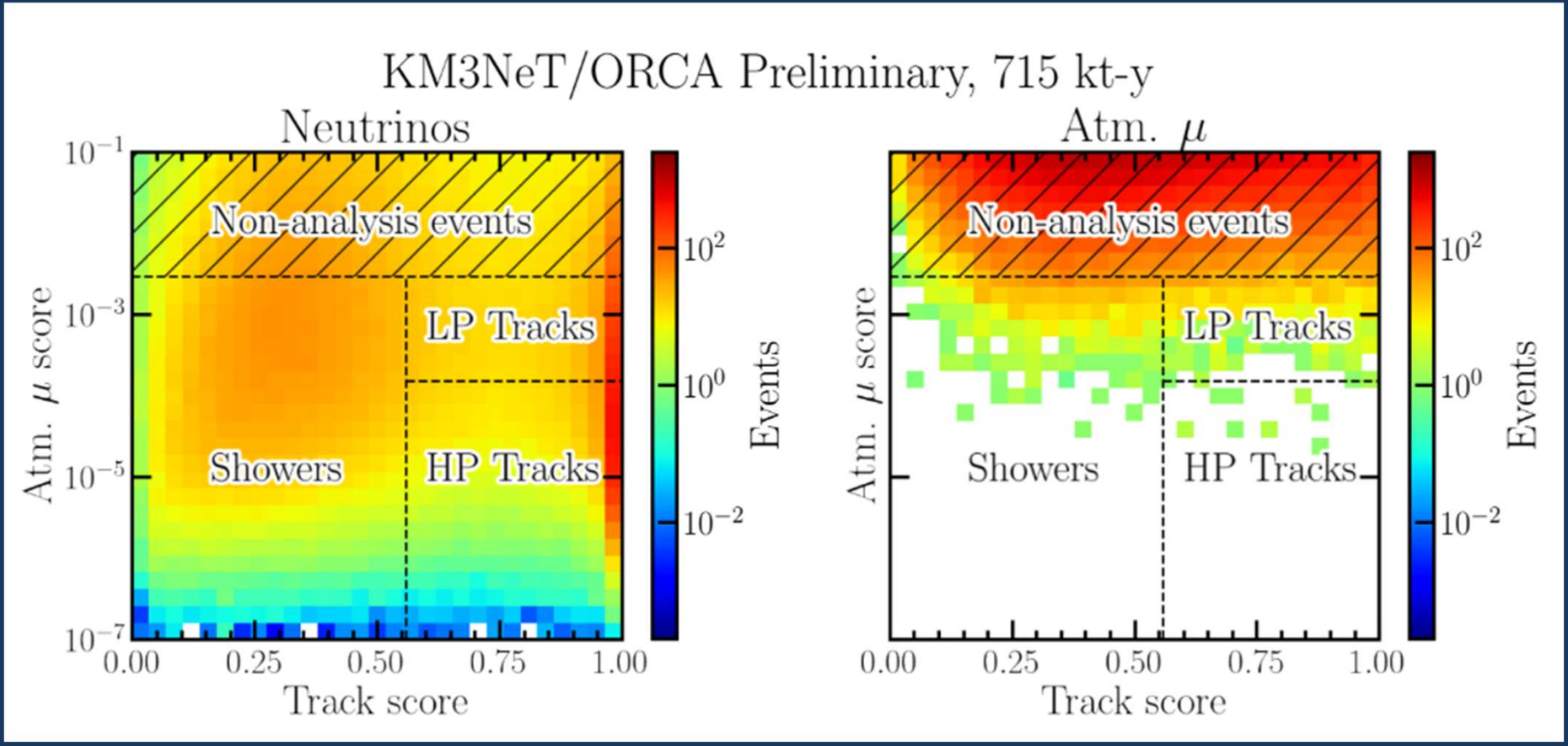

NIOZ
Koninklijk Nederlands Instituut
voor Onderzoek der Zee

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

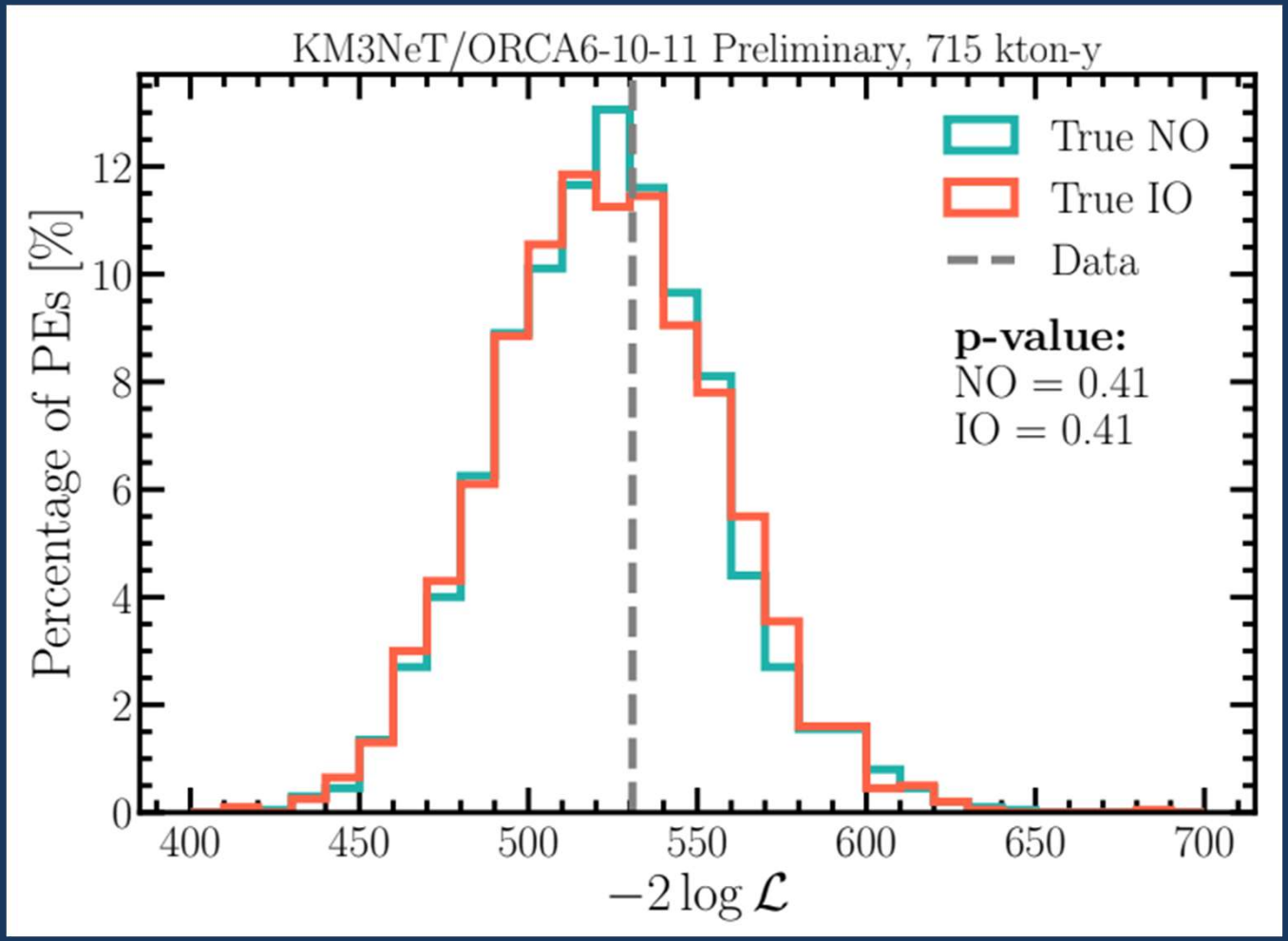
Class Definitions

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

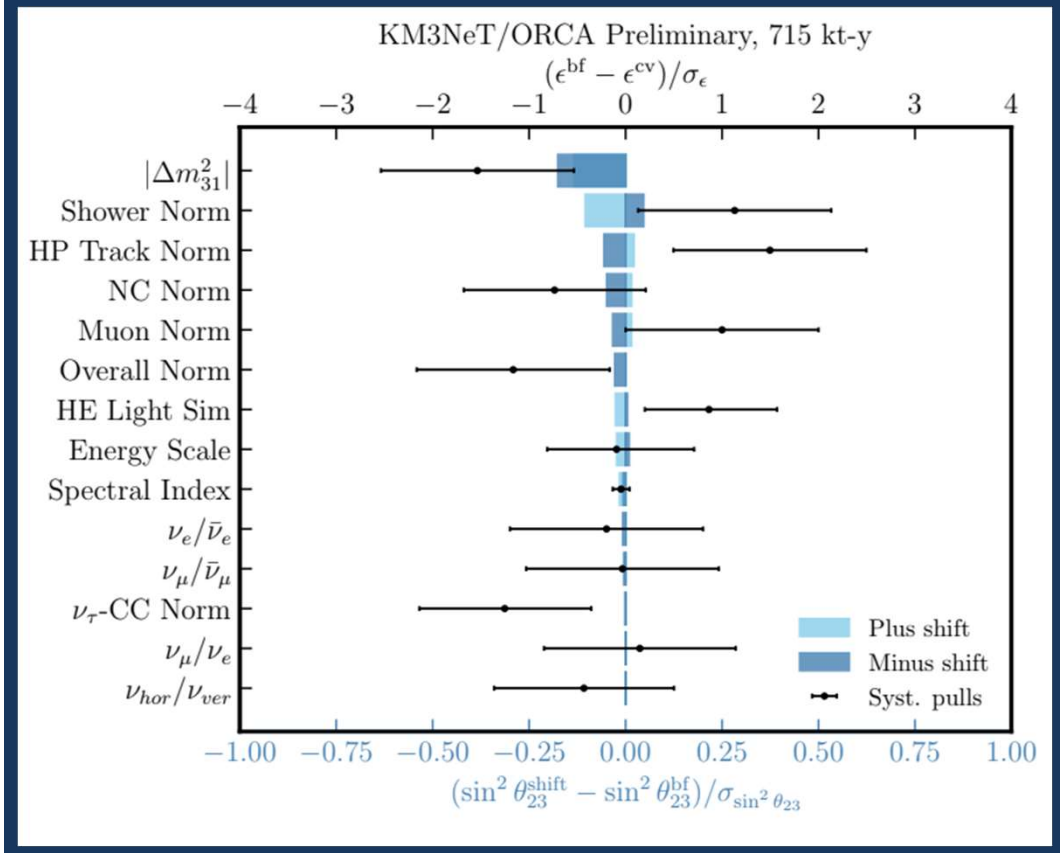


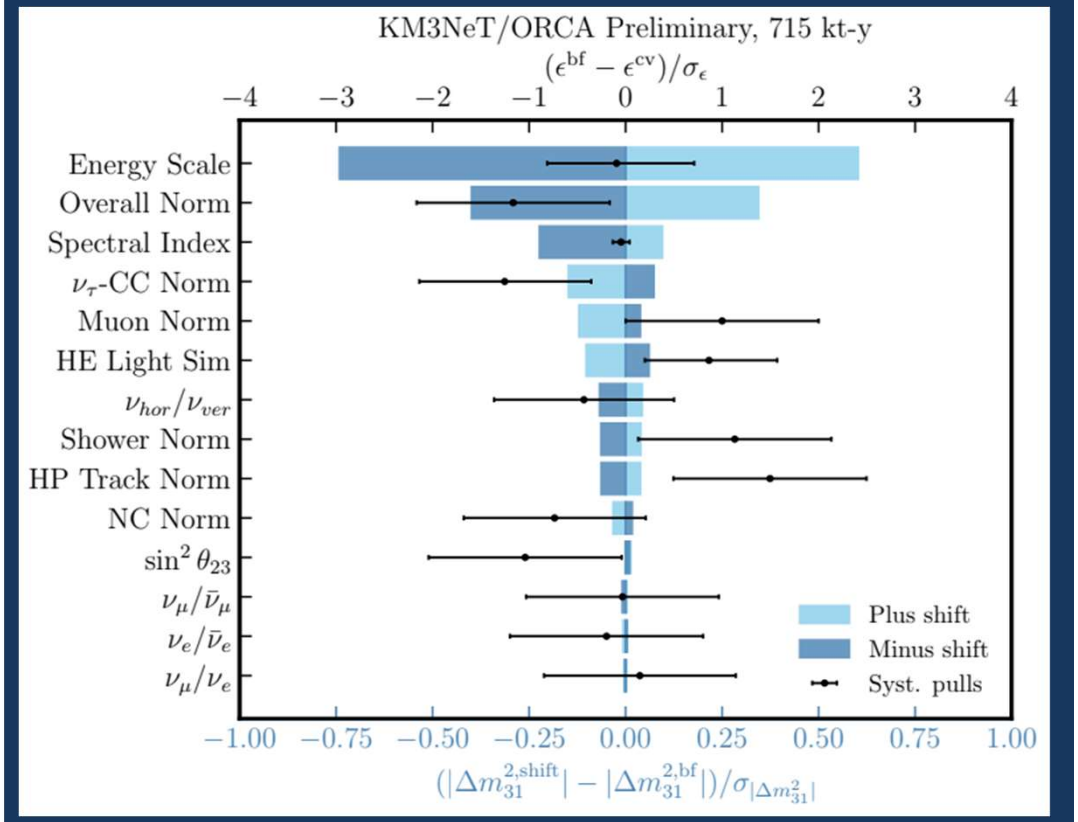
Goodness-of-Fit

- 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