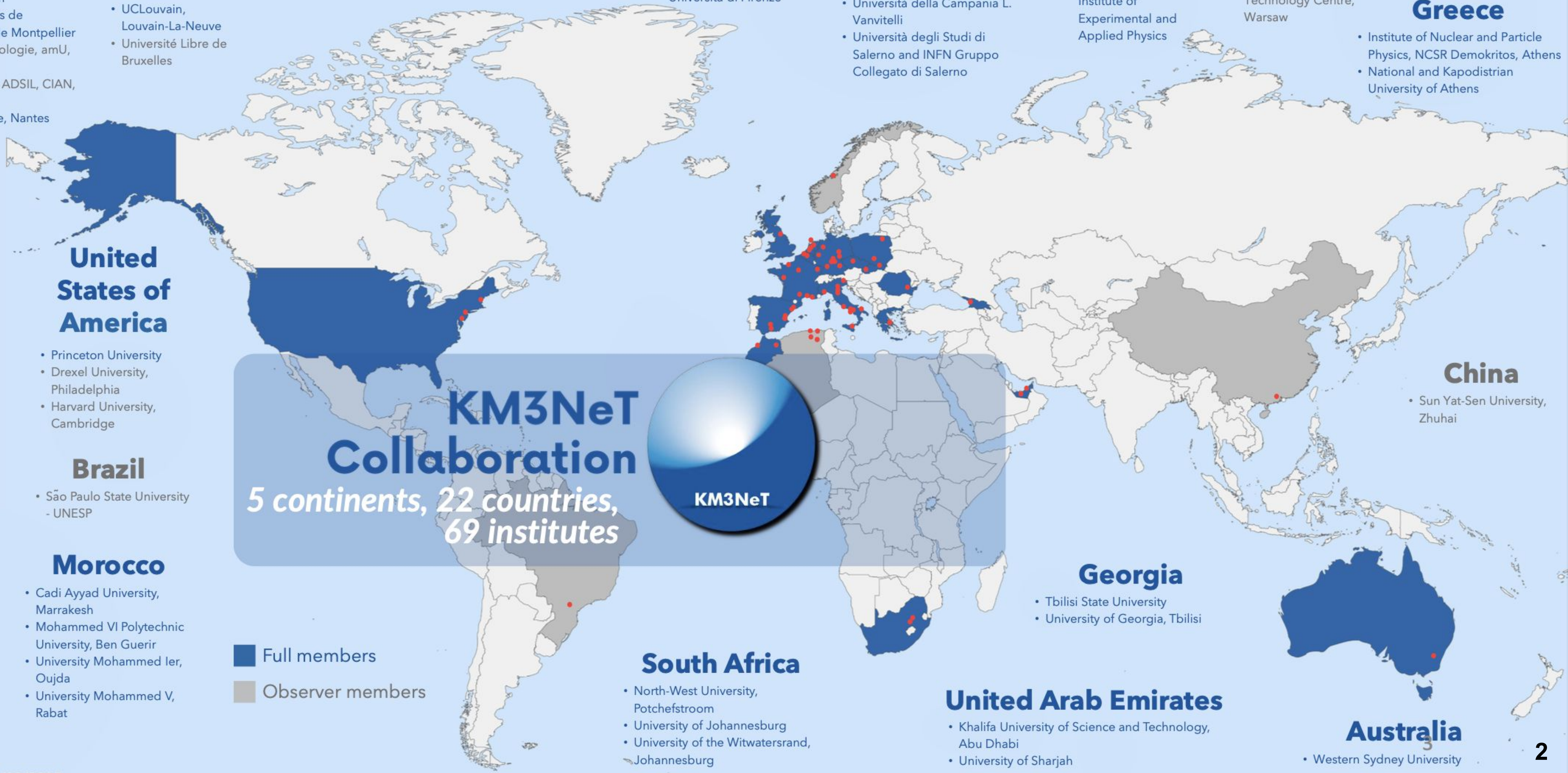
KM3NeT/ORCA – towards the determination of the neutrino mass ordering

Victor Carretero Cuenca (Nikhef)

KM3NeT Collaboration

5 continents, 22 countries, 69 institutes



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- Centre de Physique des Particules de Marseille, Aix-Marseille Université, CNRS
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- Laboratoire Astroparticules et Cosmologie, CNRS, Université Paris Cité
- Laboratoire d'Astrophysique de Marseille, AMU, CNES, CNRS
- Laboratoire de Physique Corpusculaire de Caen, CNRS, Université de Caen
- Laboratoire Univers et Particules de Montpellier, CNRS, Université de Montpellier
- Institut Méditerranéen d'Océanologie, amU, CNRS, IRD, Marseille
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- Università degli Studi di Salerno and INFN Gruppo Collegato di Salerno

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- Nicolaus Copernicus Astronomical Center, Particle Astrophysics Science and Technology Centre, Warsaw

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- Instituto de Física Corpuscular, Universitat de València, CSIC
- Laboratori d'Aplicacions Bioacústiques, Universitat Politècnica de Catalunya, Vilanova i la Geltrú
- Universitat Politècnica de València, IGIC, Gandia, València
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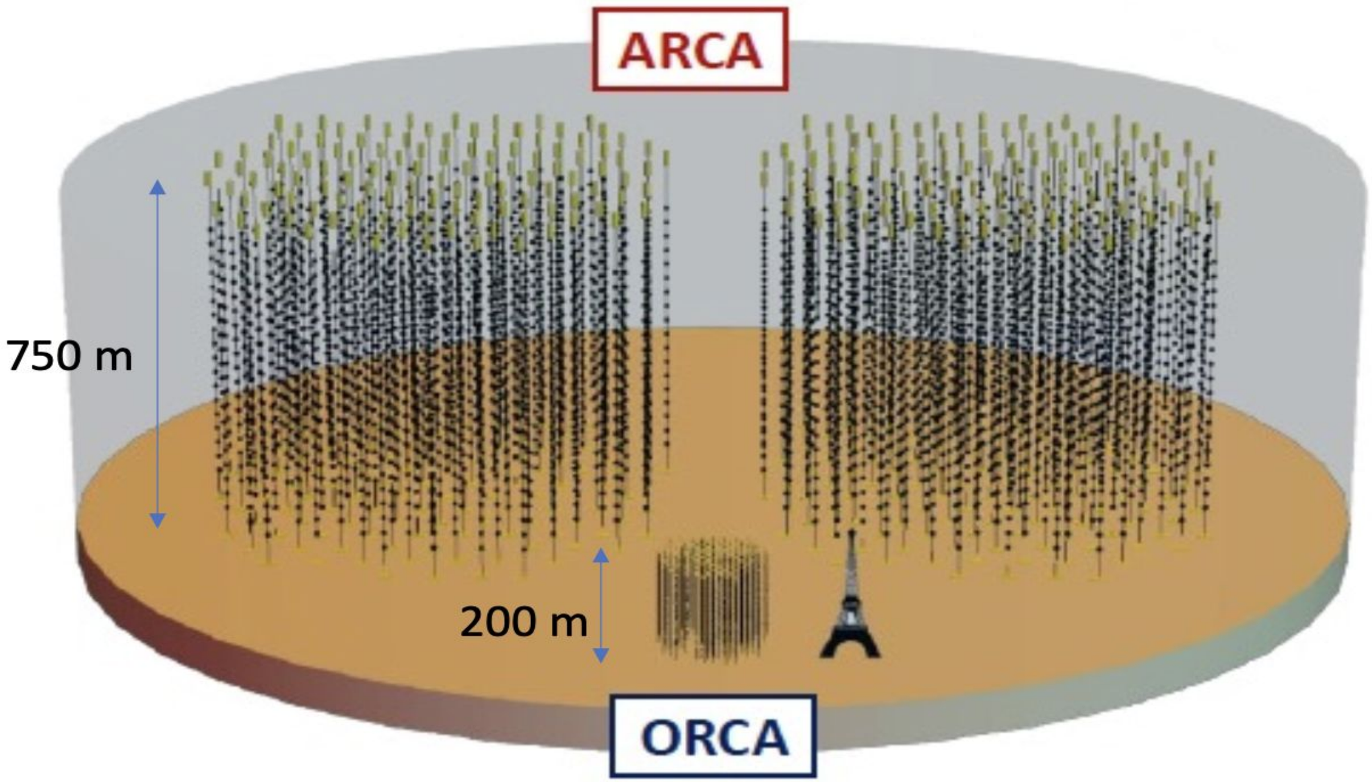
- University of Sharjah

Australia
- Western Sydney University

KM3NeT

KM3NeT = ARCA + ORCA



	Water mass	Lines	Optical Modules	PMTs	vertical	horizontal spacing
ARCA :	1 Gton	230	4140	128k	36m	70m
ORCA :	7 Mtons	108	1944	60k	9m	20m

Multi-PMTs

Design developed by KM3NeT

Applied now for in all next-generation detectors

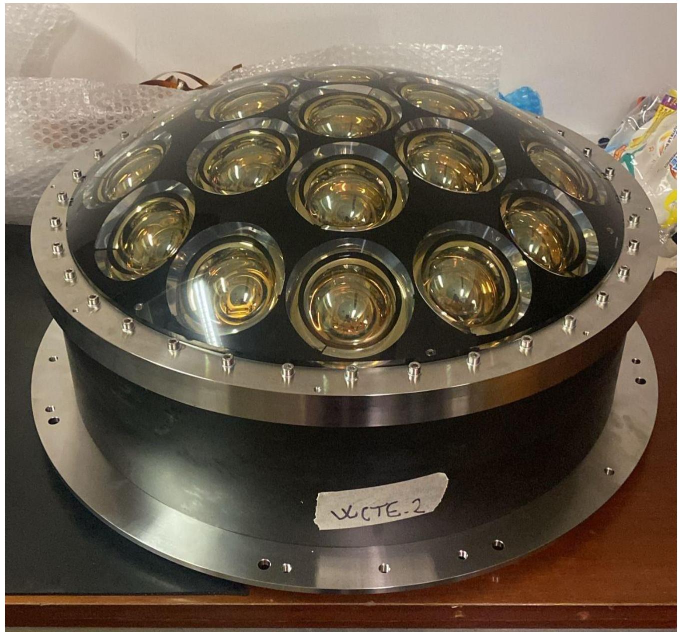
Photon counting, nsec coincidences, directionality

Better calibrations

KM3NeT

IC upgrade

Hyperkamiokande

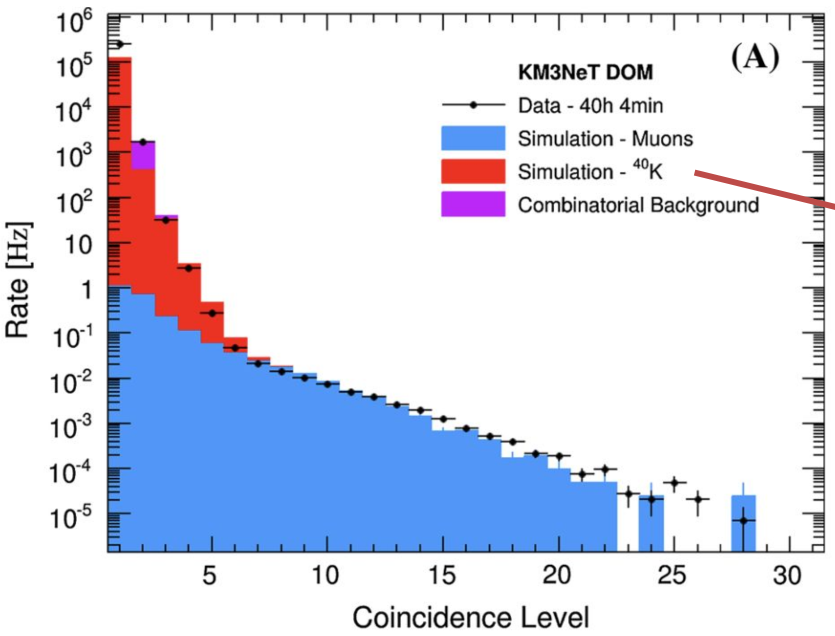


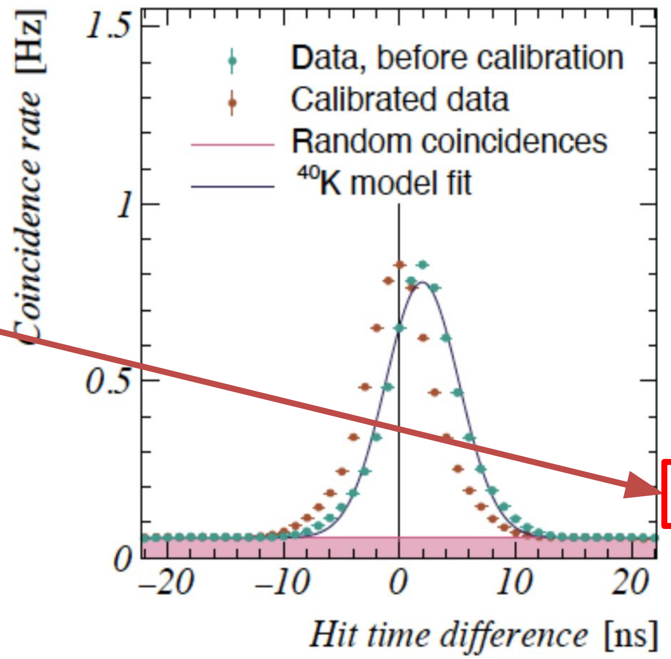
Single DOM signal

Bioluminescence variable but no coincidences

^{40}K – well understood, excellent calibration source

atm. muons – main contribution at higher values





^{40}K decays: correlated photons

Detector Timing

PMT efficiency

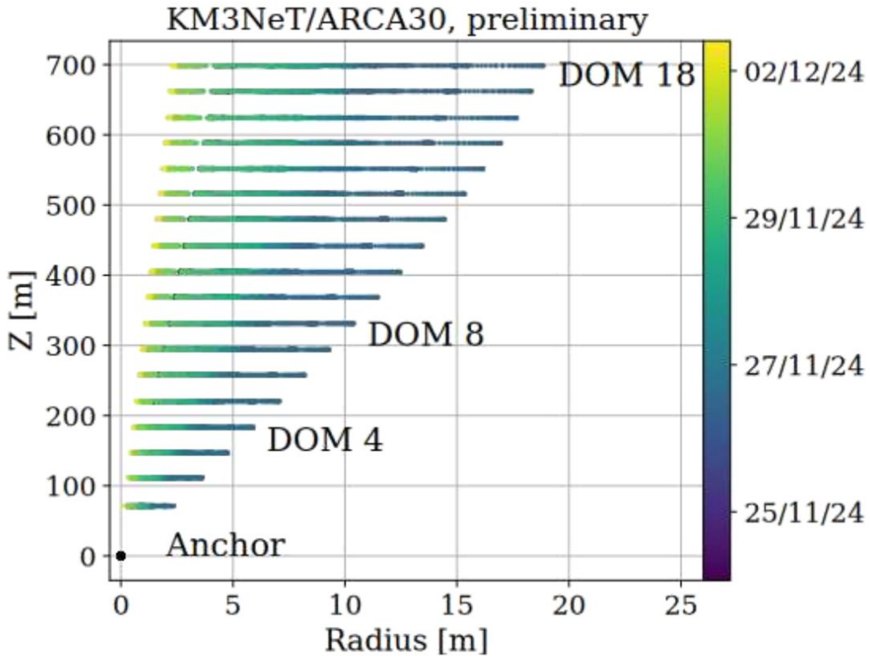
Eur. Phys. J. C (2014) 74: 3056

Relative position calibration

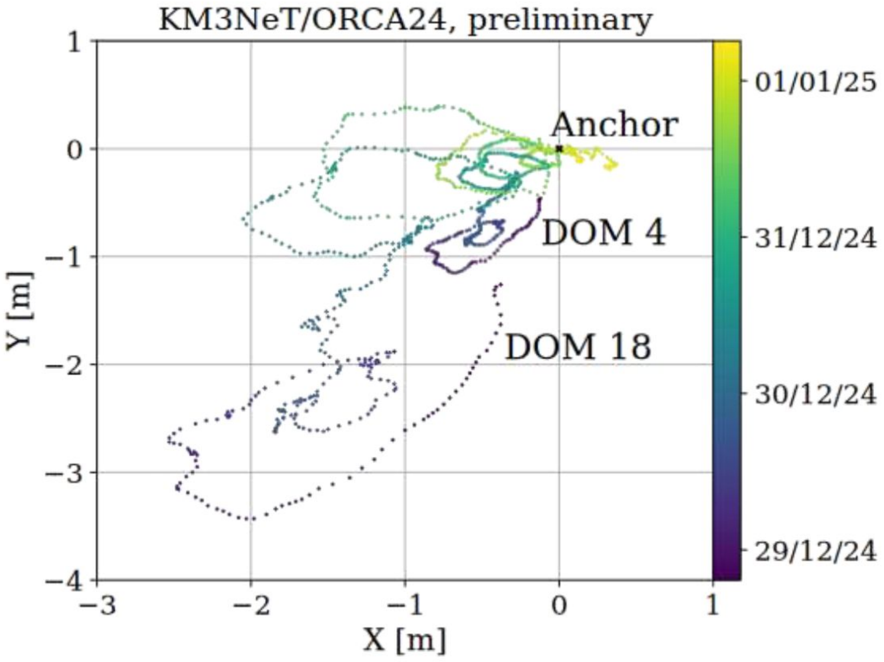
Individual DOMs can be located to ~10cm

orientation precision : few degrees

Reconstructed deviation of a DU in ARCA in 7 days

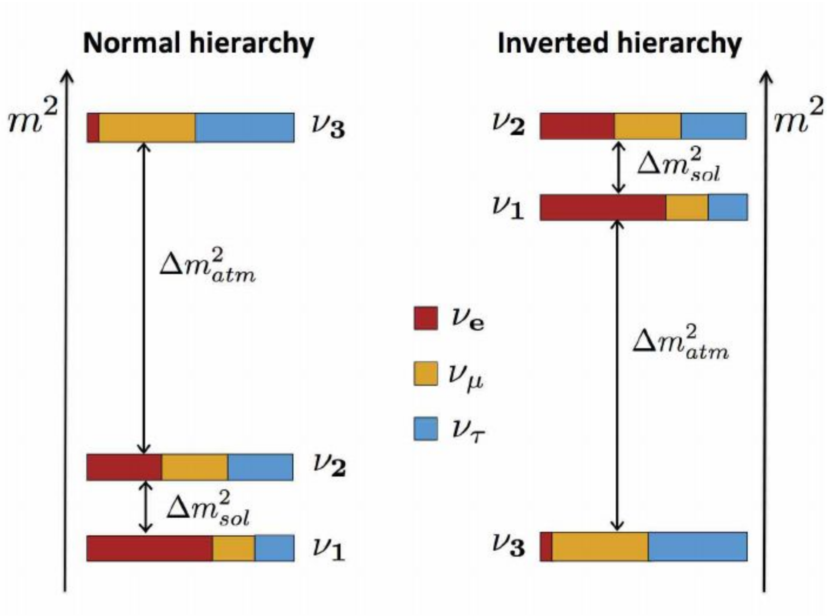


Reconstruction DOM position shifts in ORCA in 4 days



[J. Phys. , G43 , 084001 (2016)]

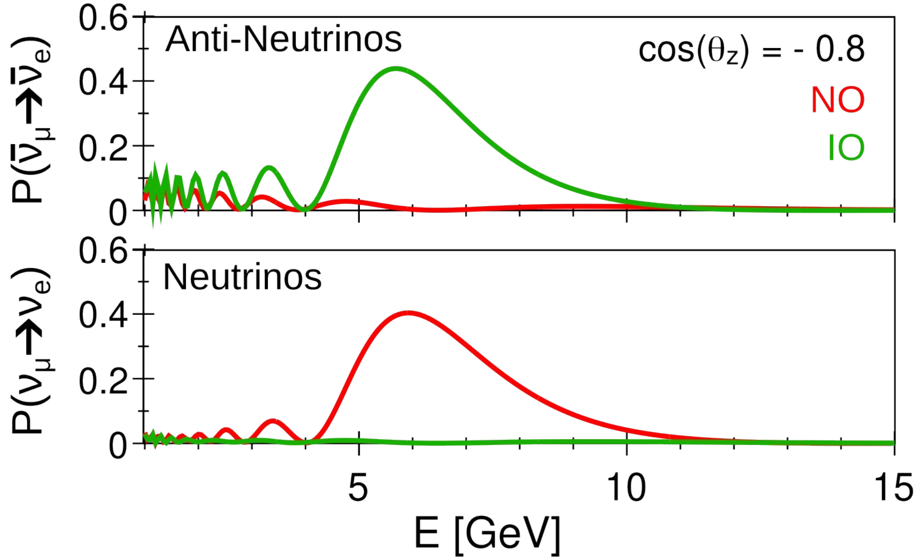
Mass ordering with atmospheric neutrinos



- **NMO:** is ν_3 the heaviest of the lighest of the three neutrino mass eigenstates?
- **Matter** along the neutrino propagation makes the oscillation probability sensitive to NMO

$$P^m_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} 2\sin^2\theta^m_{13} \sin^2\left(\frac{\Delta^m m^2 L}{4E_\nu}\right)$$

$$\sin^2(2\theta^m_{13}) \equiv \frac{(\Delta m^2_{31}\sin 2\theta_{13})^2}{(\Delta m^2_{31}\cos 2\theta_{13} \mp 2E_\nu V_{CC})^2 + (\Delta m^2_{31}\sin 2\theta_{13})^2}$$

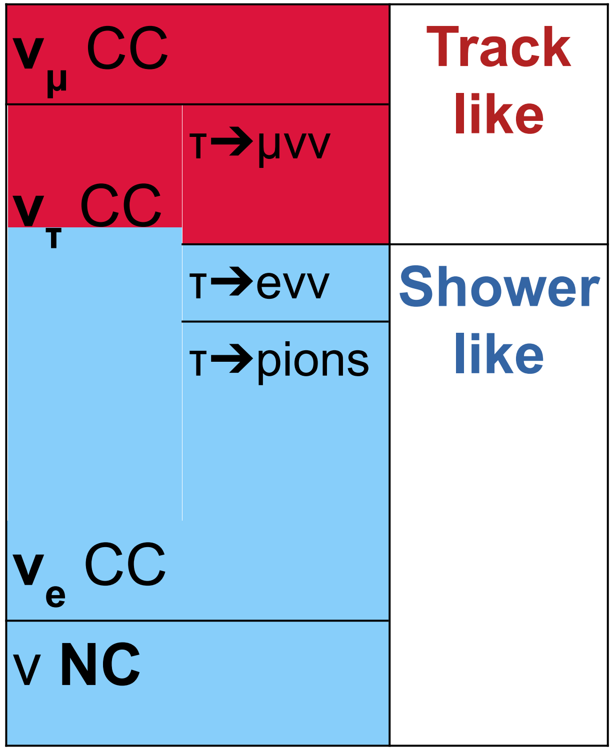


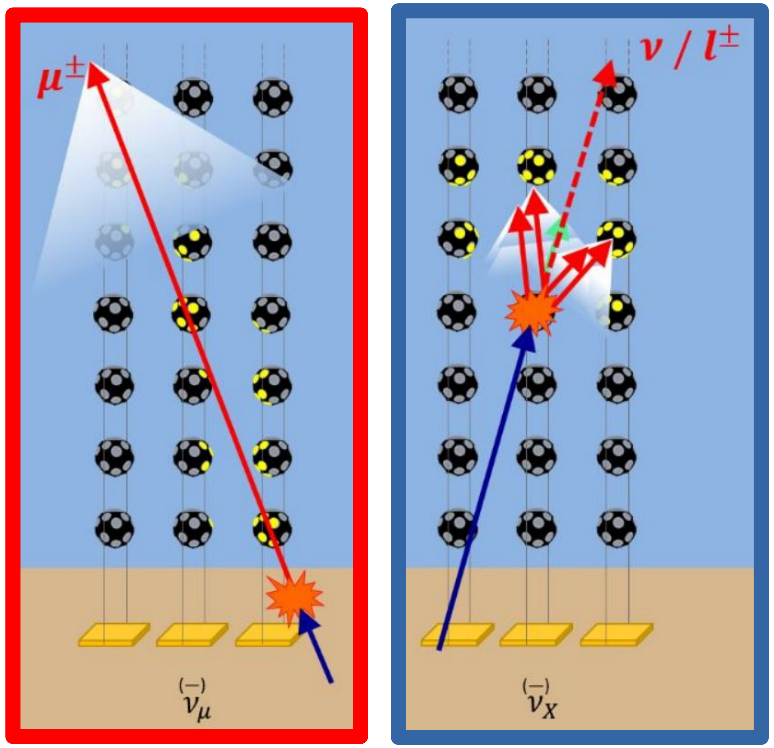
- **Resonance** occurs at E = 7 GeV for
  - **neutrino** and **normal mass ordering**
  - **anti-neutrino** and **inverted mass ordering**

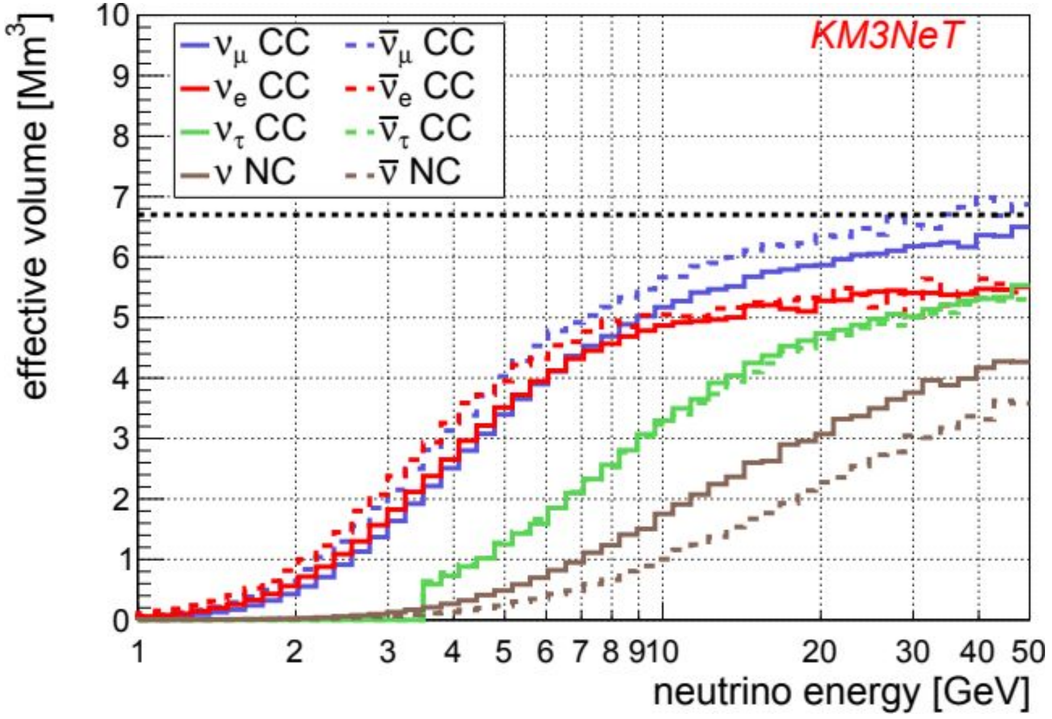
[Eur. Phys. J. C , 82 , 26 (2022)]

Mass ordering at KM3NeT/ORCA

- **ORCA** designed to collect **ν with energies of 1-100 GeV**
- Event topology (track/shower) allows to select **flavour enriched ν samples**



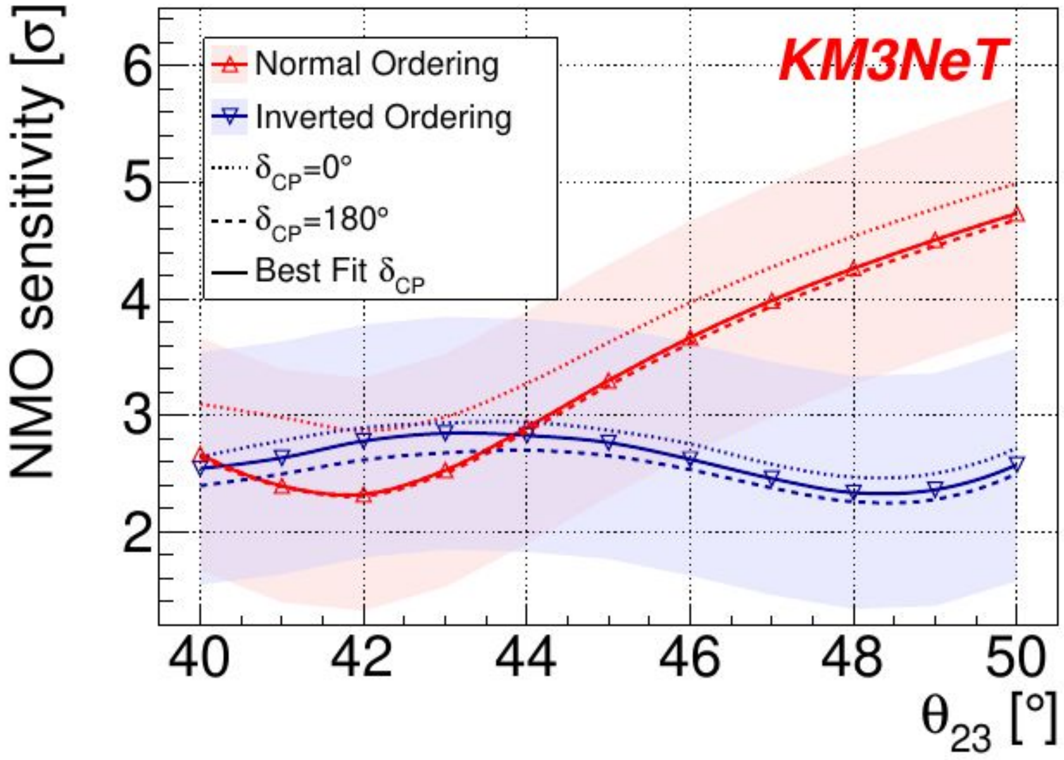


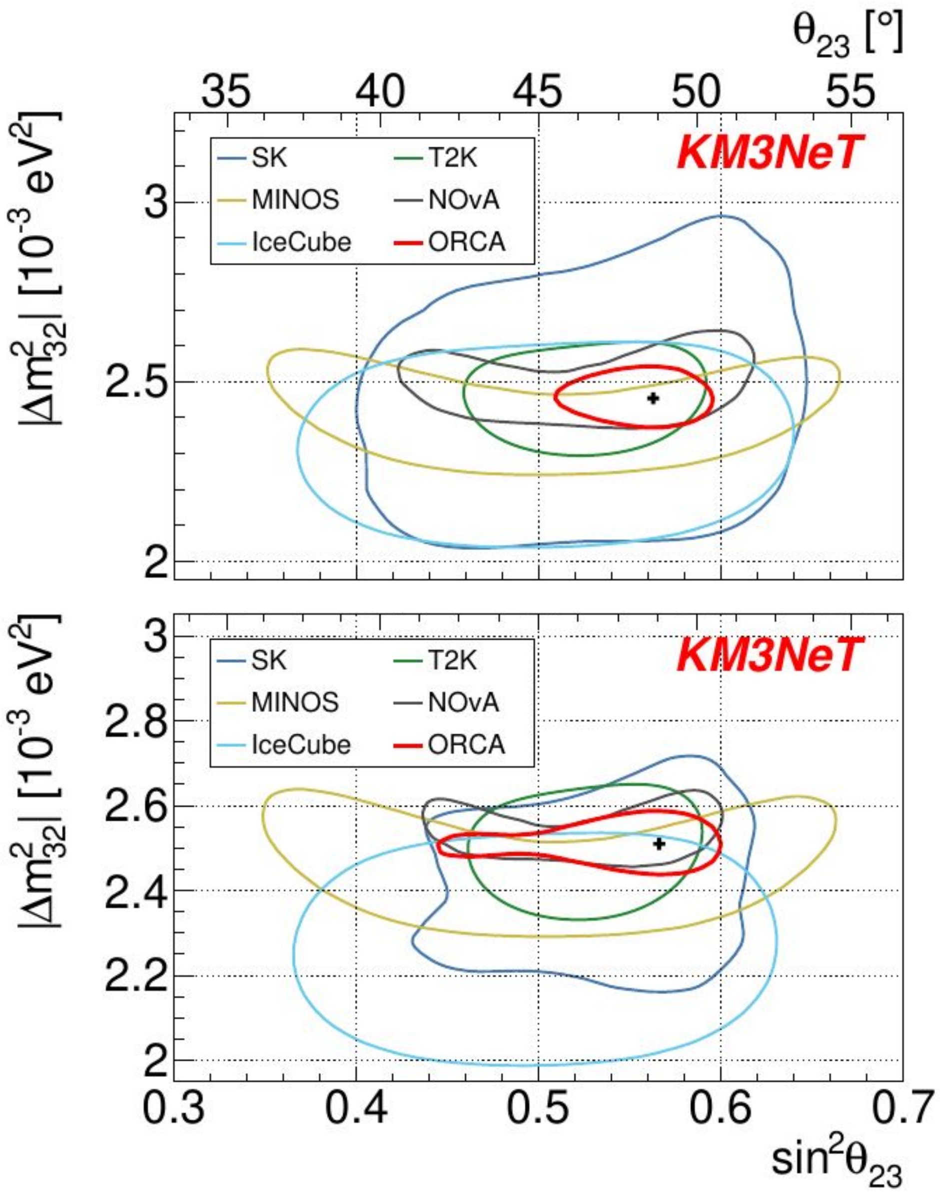


[Eur. Phys. J. C , 82 , 26 (2022)]

Sensitivity with full ORCA (3 years)

- Atmospheric oscillation parameters
- NMO sensitivity
  - strongly depends on θ_{23} for NO
  - band thickness corresponds to stat. fluct. (68% coverage)

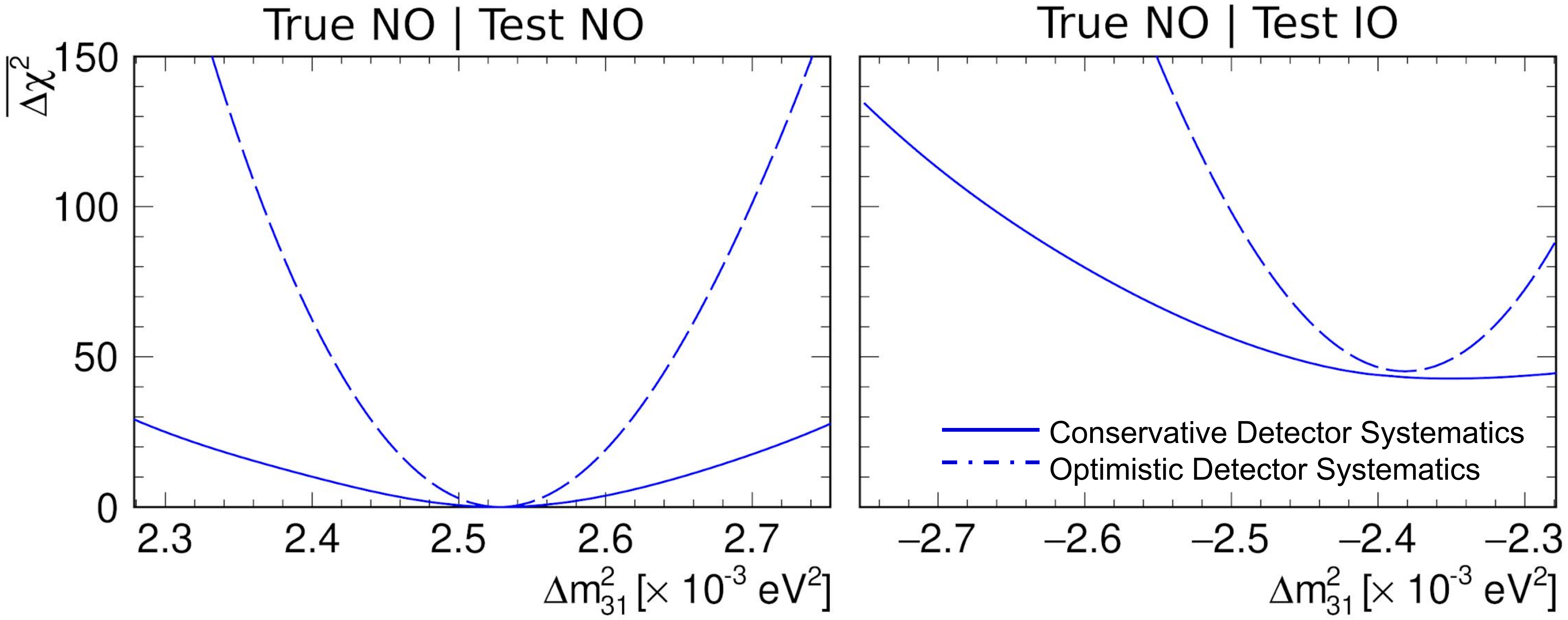




Mass ordering sensitivity with ORCA 115

JHEP03(2022)055

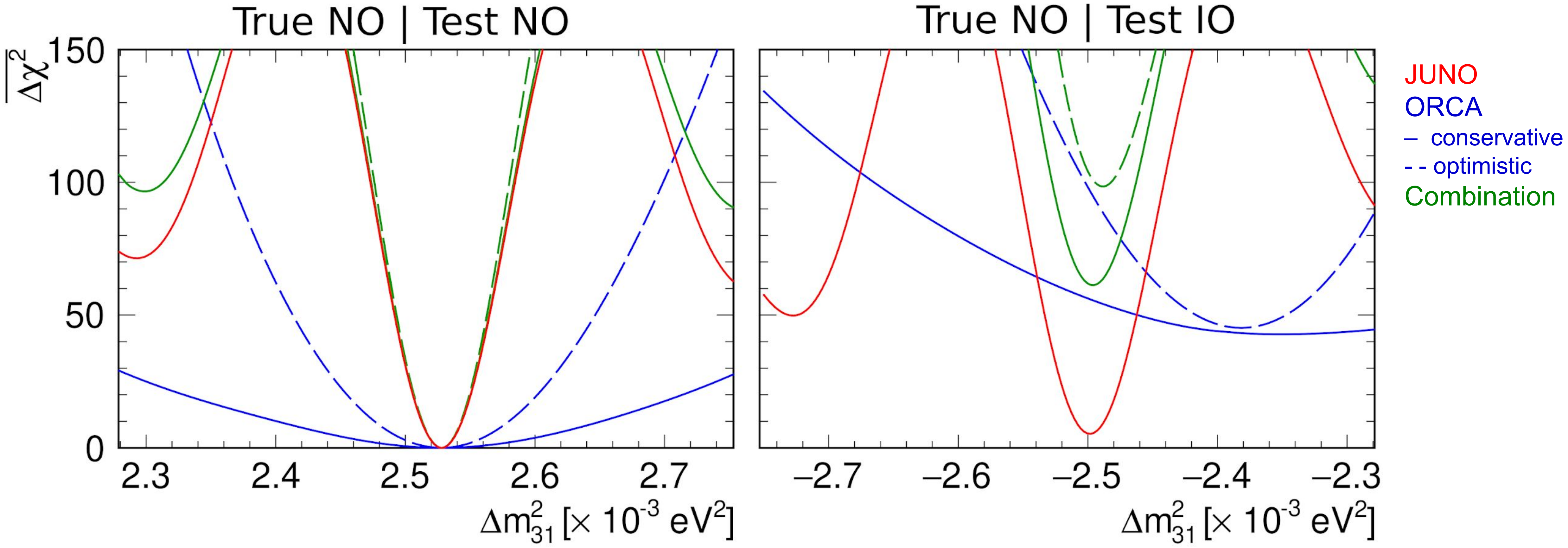
- Degeneracy between NMO and Δm^2_{31}



How to lift the degeneracy

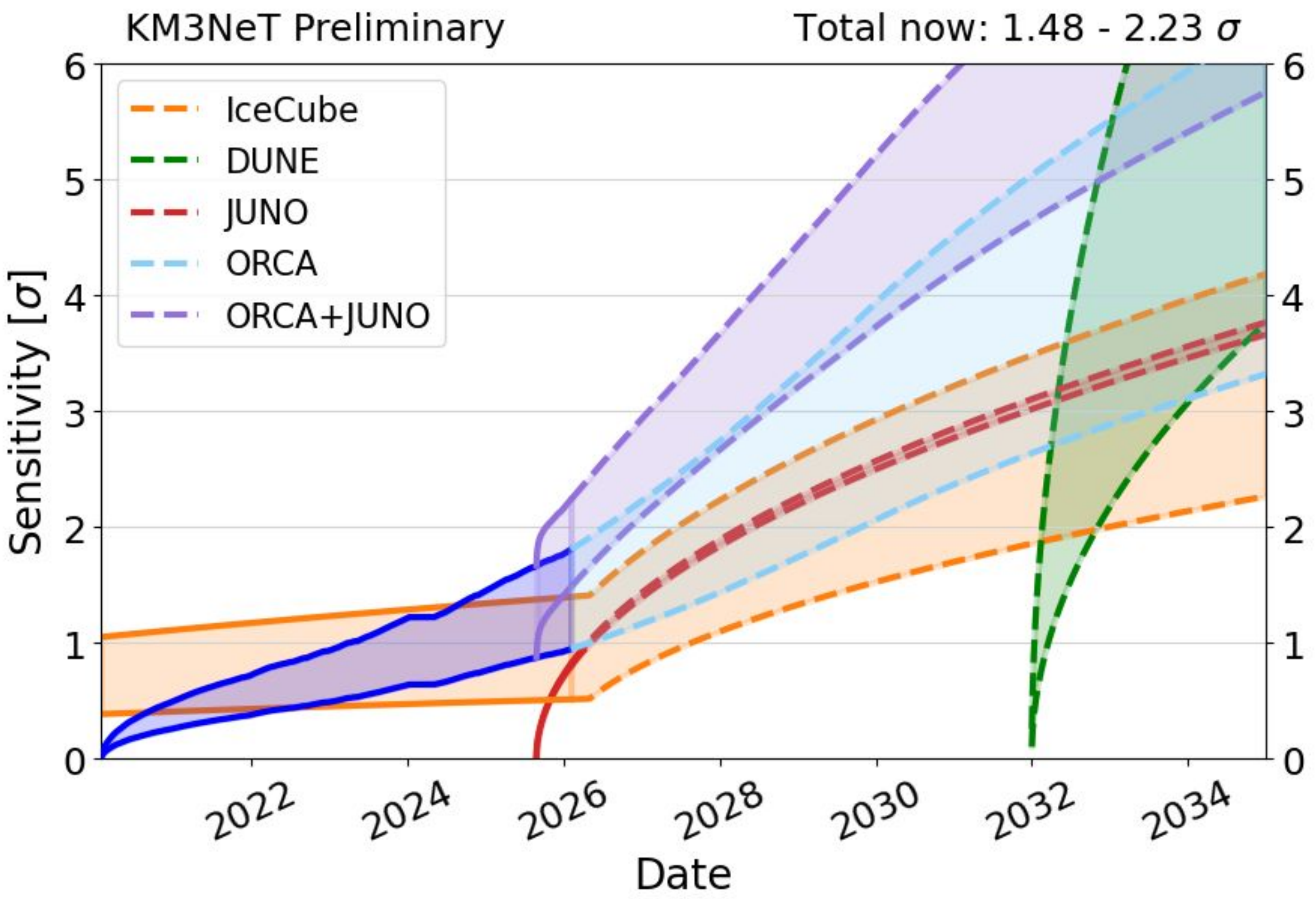
JHEP03(2022)055

- **JUNO** much **less affected** by NMO/Δm^2_{31} degeneracy
- JUNO's Δm^2_{31} measurement strongly **boosts ORCA sensitivity** (even without a full combination)



Projections for NMO Sensitivity

- **Projections** based on current construction schedule and conservative detector syst.
- **Band thickness** corresponds to favourable/disfavourable scenarii (NO/IO)
- **ORCA is the most sensitive experiment** (until DUNE starts)
- **JUNO/ORCA** synergy allows for **world's first determination (5σ) of the NMO**

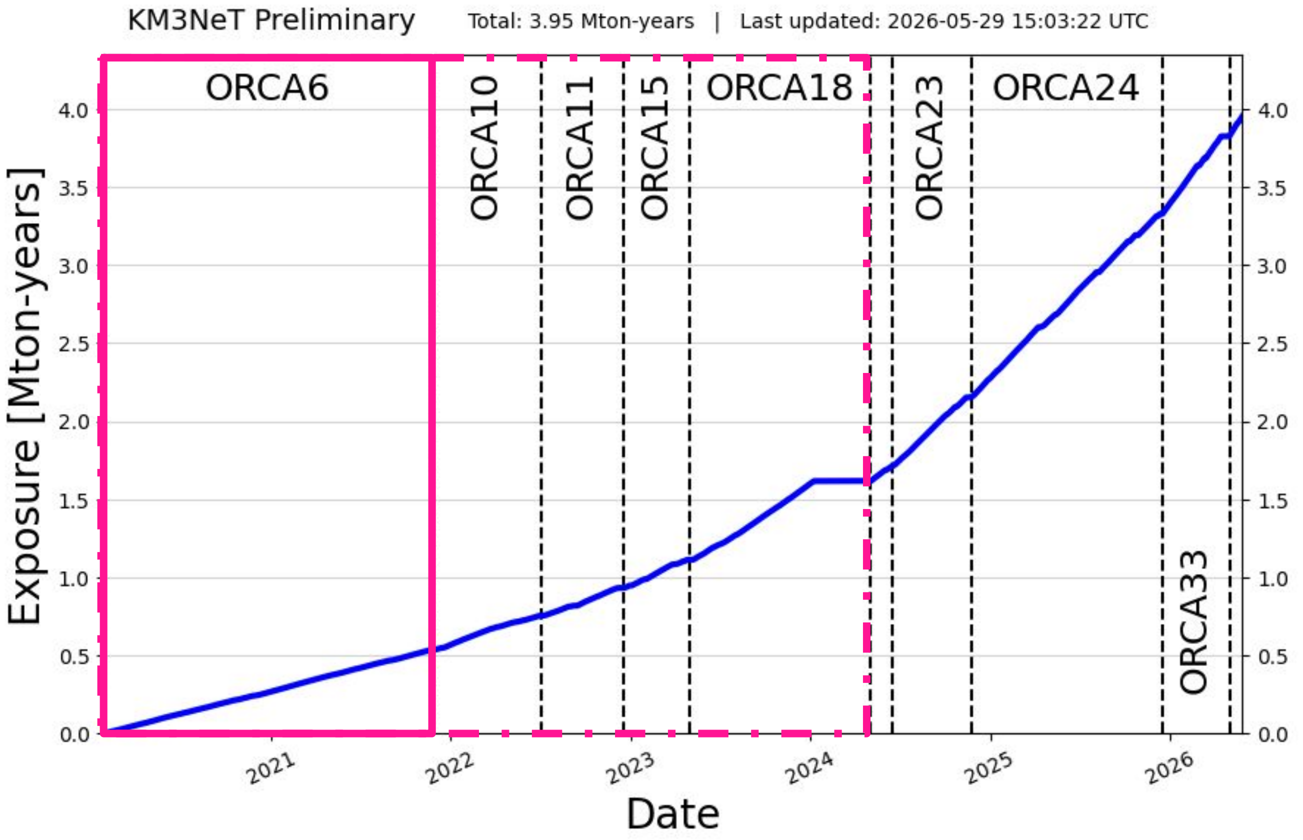


Results on first data

- **Extensive set of analyses** performed on **ORCA6** (433kton.y) using methods similar to those used for full ORCA sensitivity

Standard Oscillations	JHEP10(2024)206
Sterile Neutrinos	JHEP02(2026)080
Lorentz Invariance Violation	arxiv:2603.04264
Quantum Decoherence	JCAP03(2025)039
Neutrino Decay	JHEP04(2025)105
Non Standard Interaction	JCAP02(2025)073
Tau appearance/NUNM	JHEP07(2025)213

- ORCA6 **public data** set released: https://zenodo.org/records/15715220



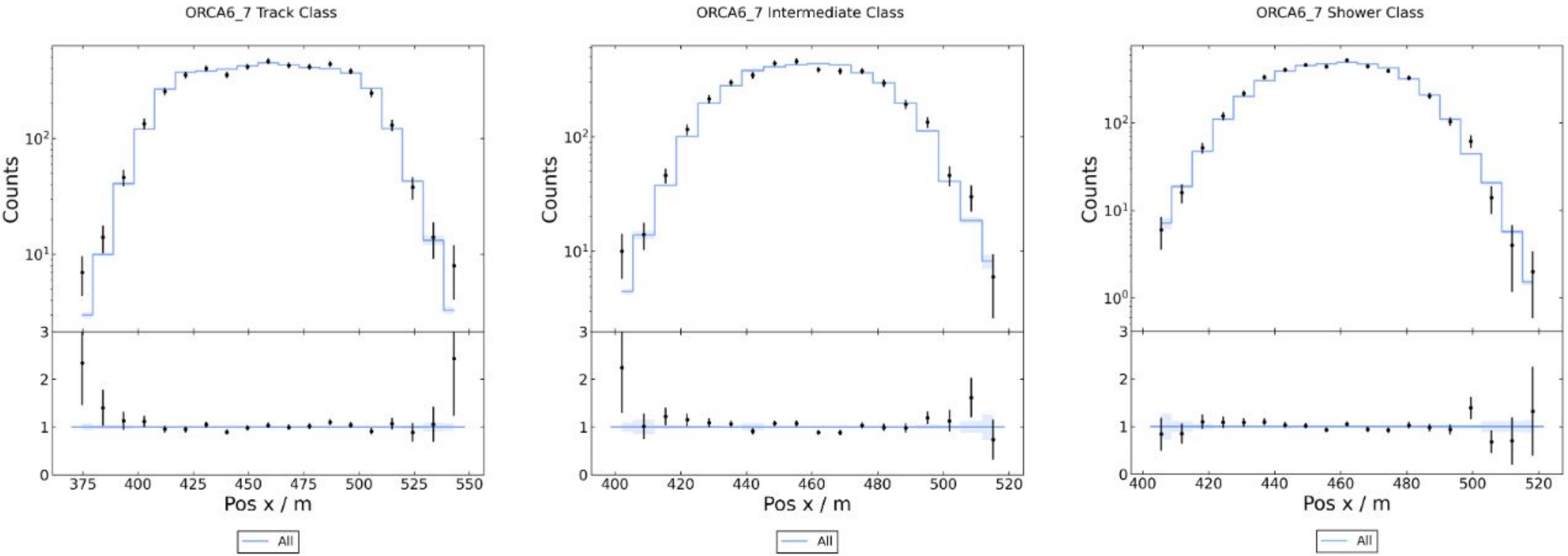
- Update for standard oscillations shown in conference (2023) with **715 kton-yr (ORCA6-11)**
- Preparing next result with twice as much data for next month with 1.5 Mton-yr (ORCA6-18)
- Plan to add up to ORCA24 by the end of the year (3.3 Mton-yr).

Expected events

Sample	N_{sig}	N_{bkg}	P_{ν_e} [%]	P_{ν_μ} [%]	P_{ν_τ} [%]	P_{NC} [%]	C_{atm} [%]
ORCA 6-7 tracks	4793	36	1.2	96.8	0.8	0.5	0.8
ORCA 6-7 intermediates	1634	47	25.8	57.5	5.6	8.3	2.8
ORCA 6-7 showers	2193	53	37.5	34.4	8.4	17.4	2.4
ORCA 6-7 total	**8619**	**136**	15.5	74.4	3.7	6.4	1.6
ORCA 10-18 tracks	6544	44	2.5	94.9	1.1	0.9	0.7
ORCA 10-18 intermediates	2761	43	30.1	53.4	5.5	9.5	1.6
ORCA 10-18 showers	2725	37	40.5	31.4	8.7	18.1	1.3
ORCA 10-18 total	**12030**	**124**	17.7	71.6	3.8	6.9	1.0
Total	**20649**	**260**	16.8	72.8	3.8	6.7	1.2

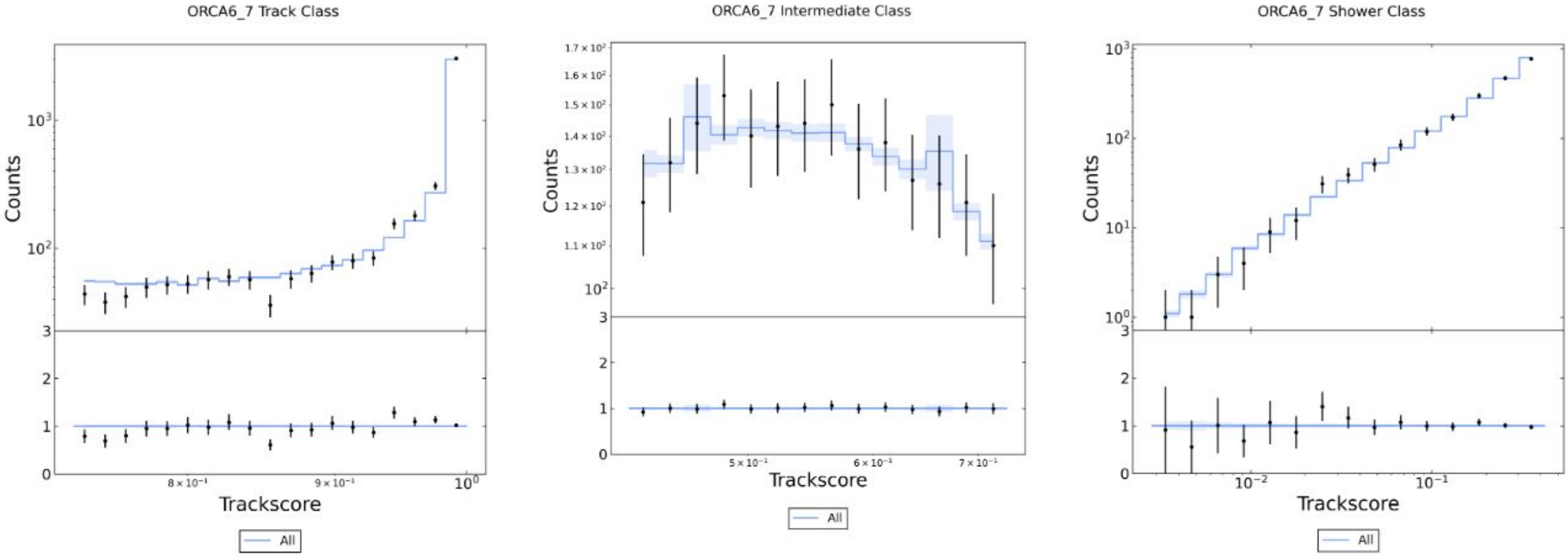
- Expecting 20k neutrinos.
- High purity in the track channel.
- Mixed class to constrain systematics.
- Selection combines:
  - Quality cut to select good reconstructed track and showers.
  - Boosted Decision Trees to reject atmospheric muons and separate tracks and showers.

First peak at Data/MC



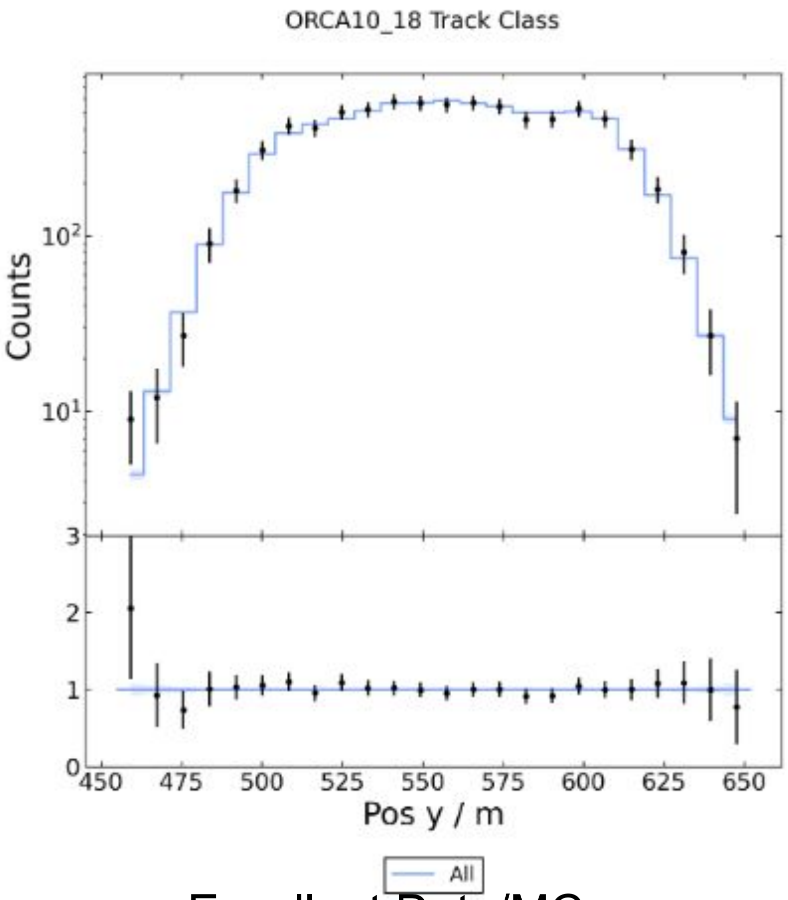
- Excellent Data/MC agreement

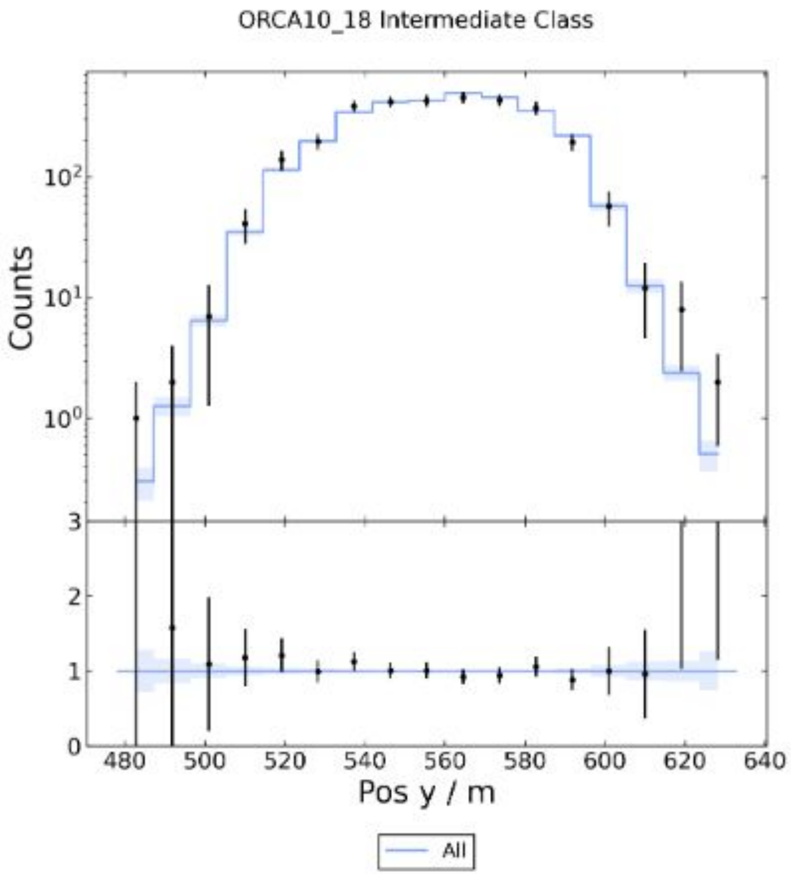
First peak at Data/MC

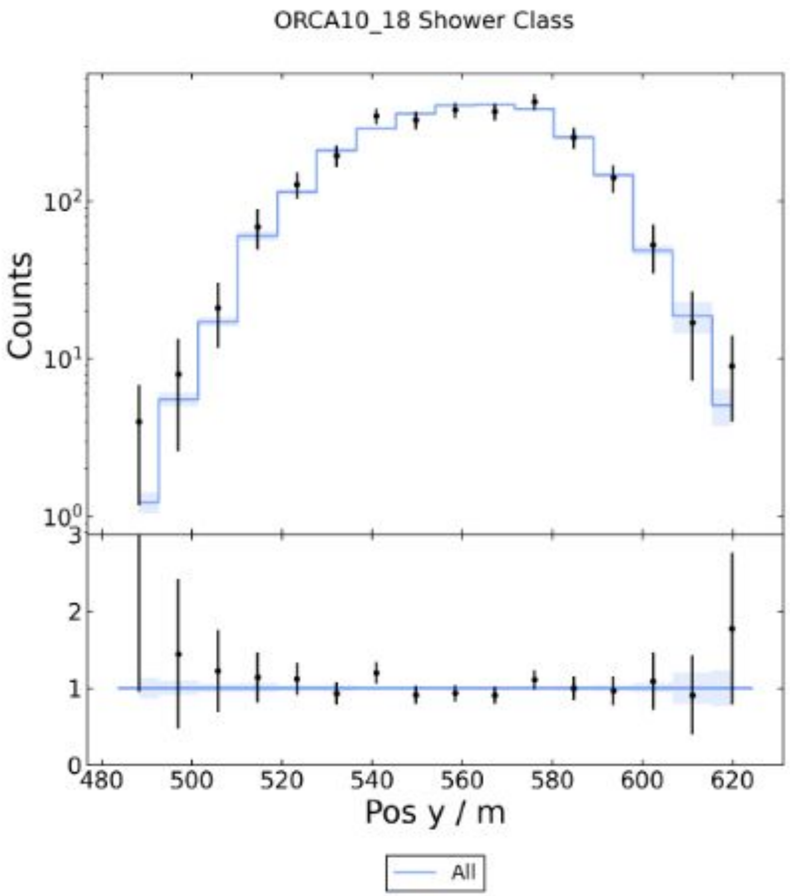


- Excellent Data/MC agreement

First peak at Data/MC







- Excellent Data/MC agreement

Ratio to No oscillations (Pseudo-Experiment)

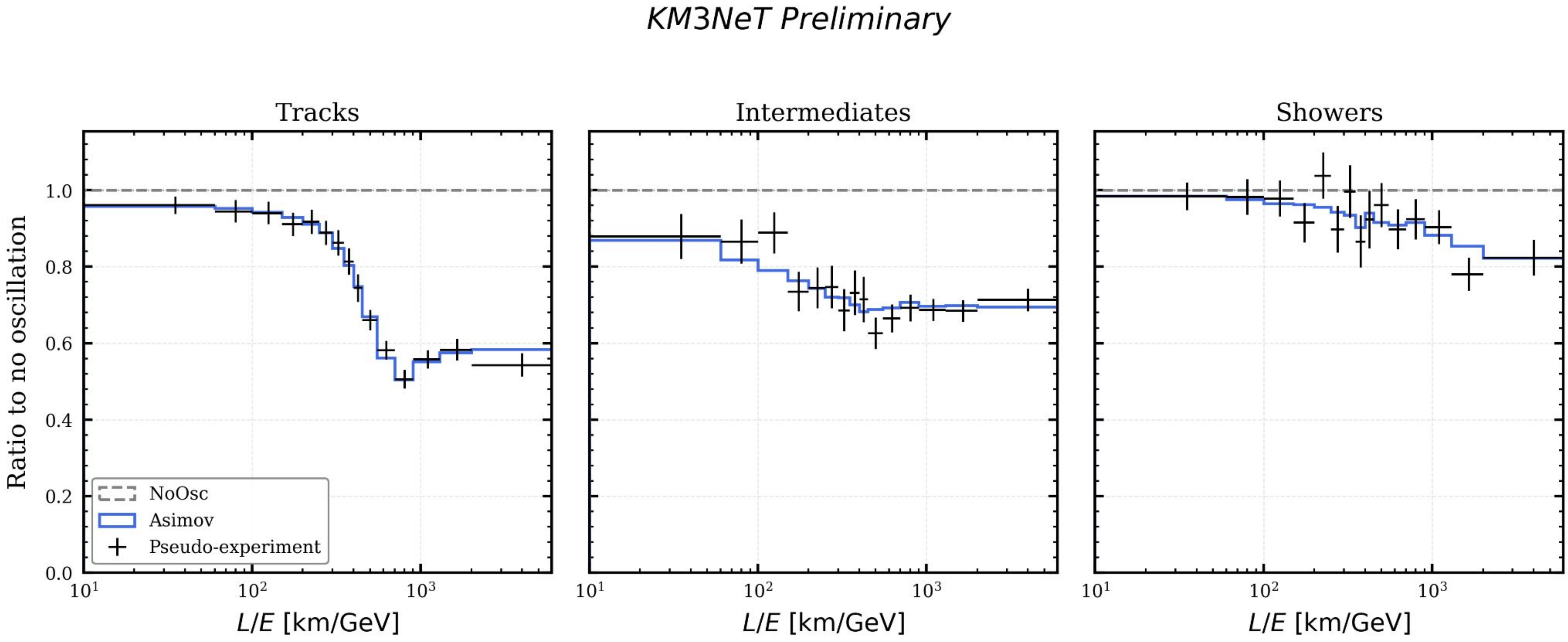
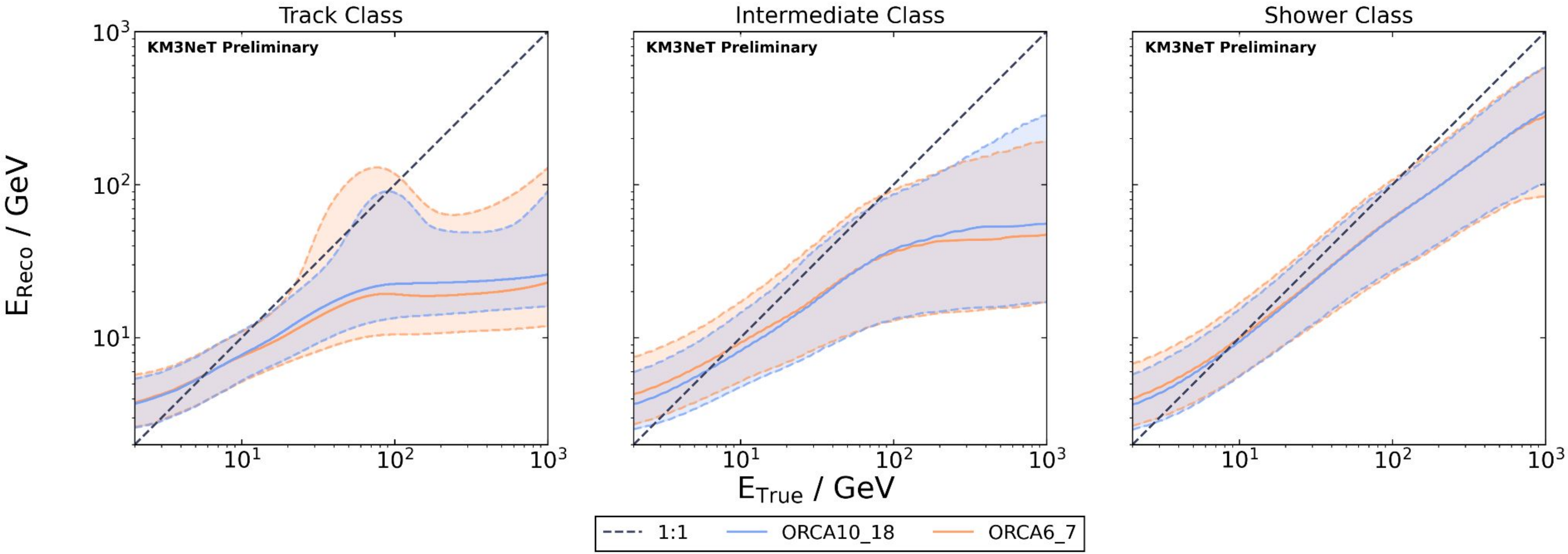


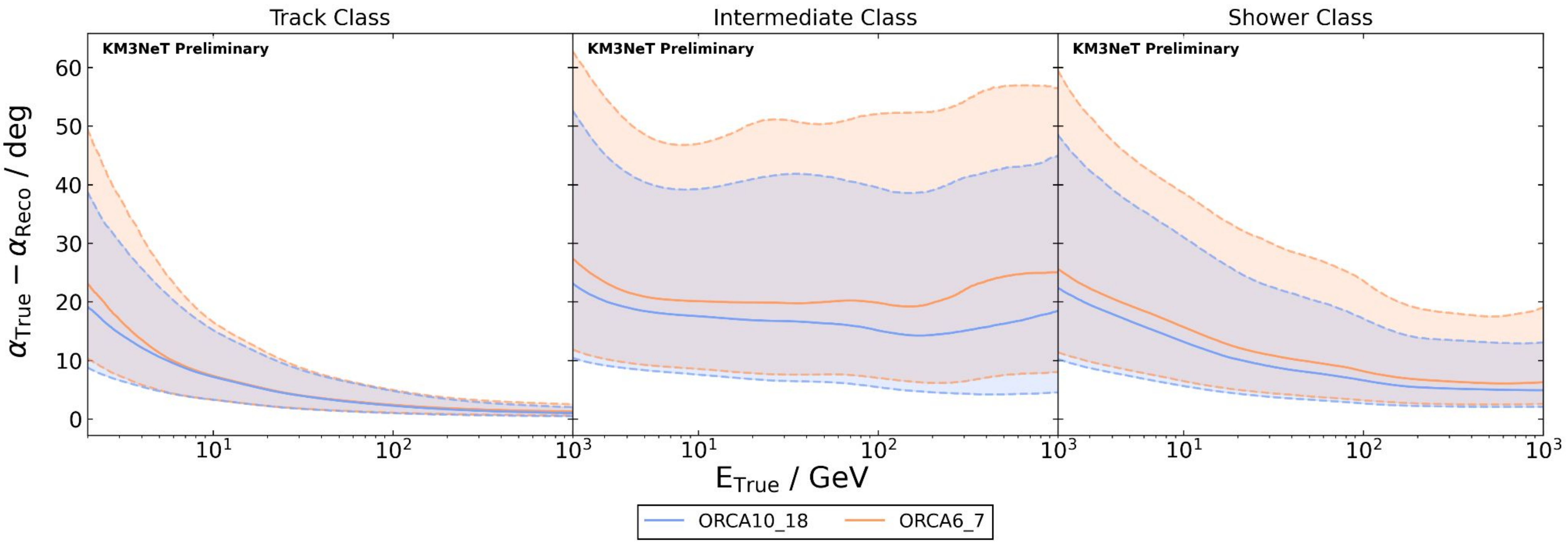
Illustration of how the distributions may look like with a PseudoExperiment.

Energy resolution



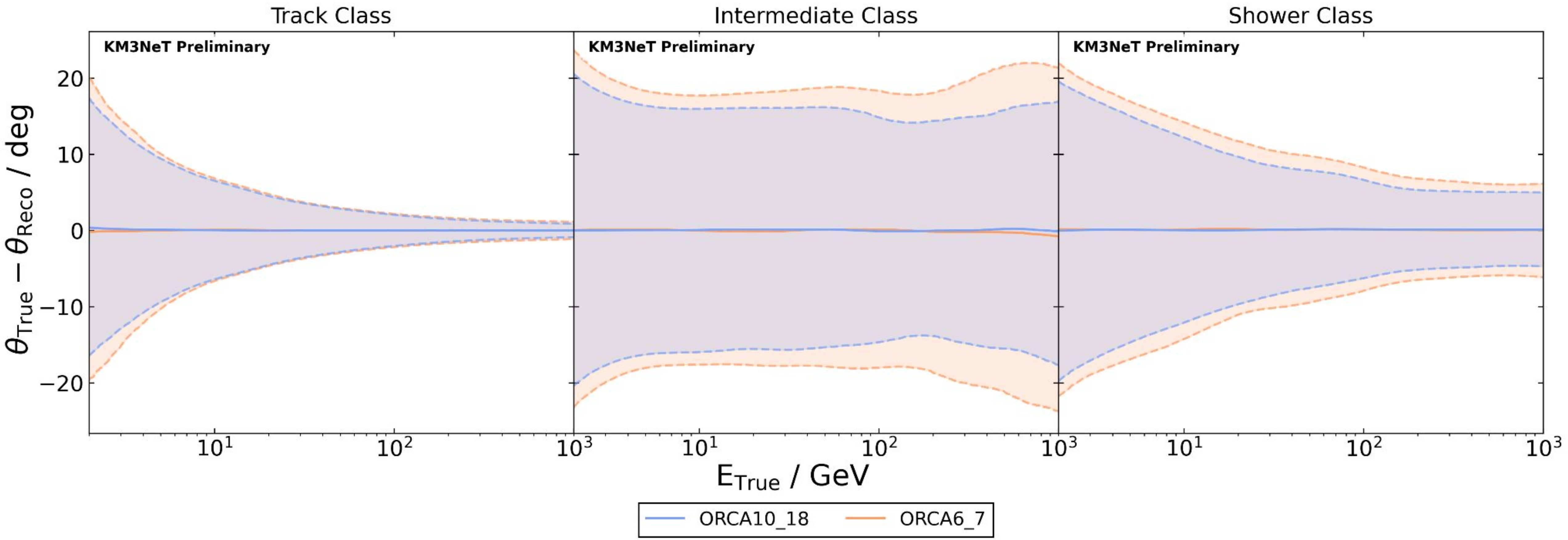
- Improved energy resolution as we add more lines.
- Most track events are uncontained, saturation at high neutrino energies.

Angular resolution



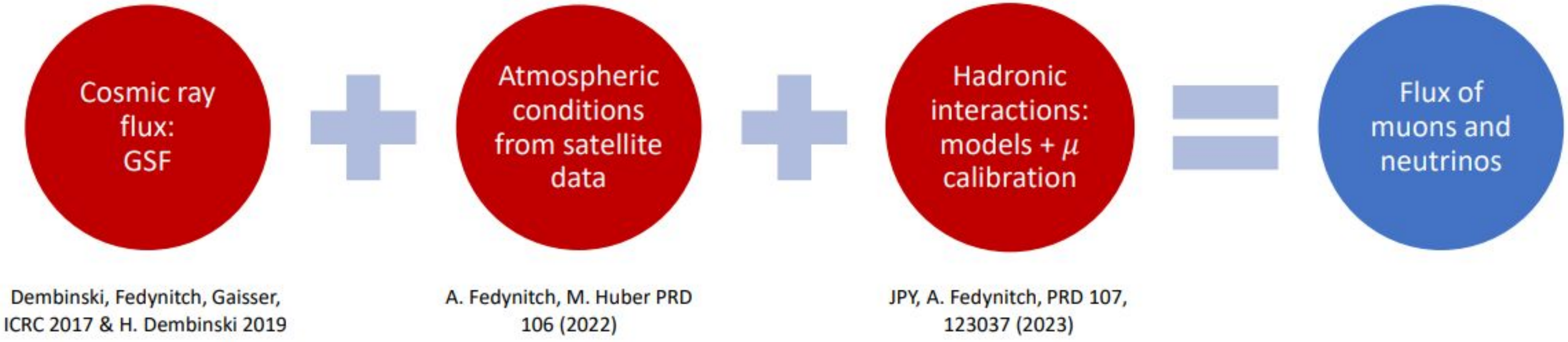
- 10 degrees at 10 GeV for track events and 15 degrees for shower-like events.
- Intermediate class is comprised of a mix of lesser quality events that are challenging to reconstruct, poorer angular and energy resolution.

Zenith angle resolution



Analysis

- **Neutrino flux**
  - We replaced Honda flux by **Daemonflux** (data driven model, physics driven uncertainties, coherent ν and μ fluxes description)
  - Daemonflux does not include right now geomagnetic corrections at a few GeV. Temporal solution to interpolate between HONDA2014 and Daemonflux at the transition region (5GeV).



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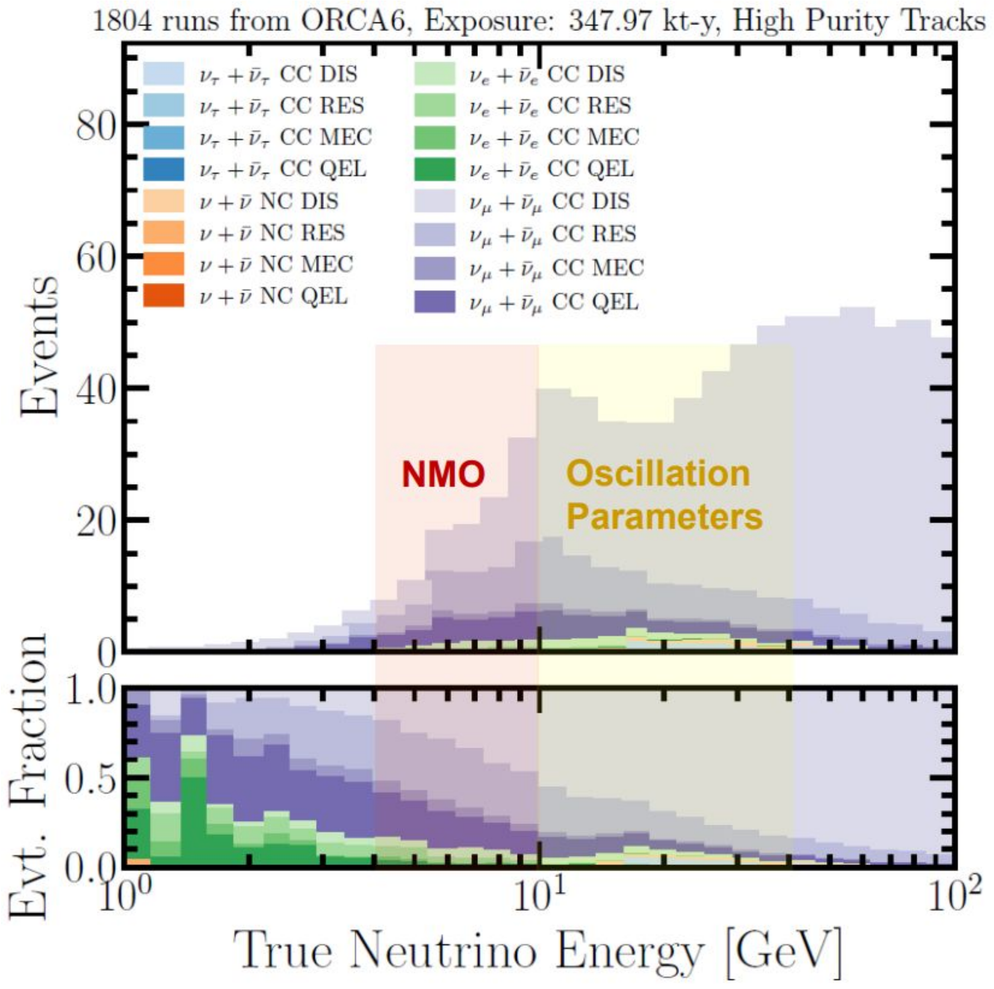
Analysis

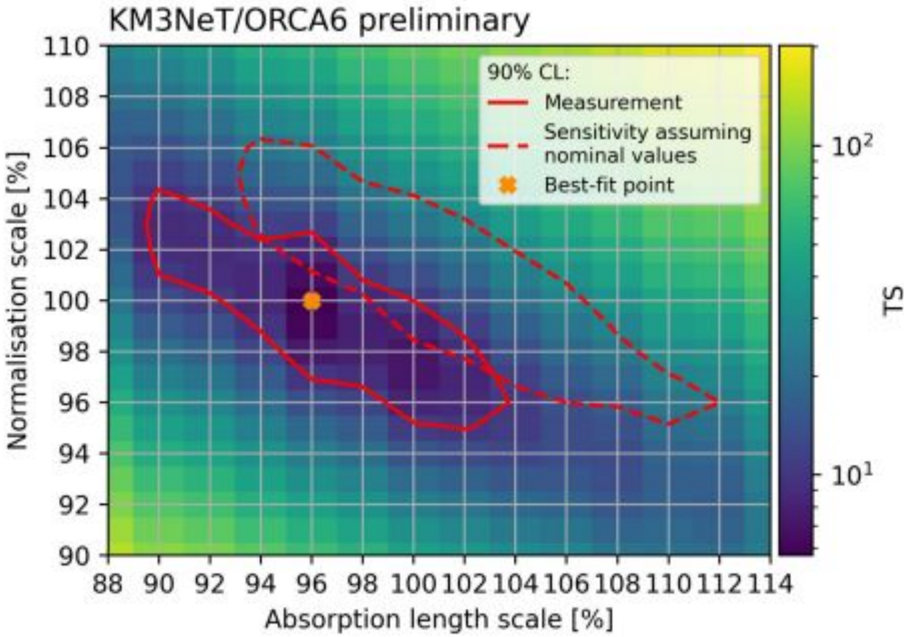
- **Neutrino flux**
- **Neutrino-cross section**
  - **short term:**
    scaling of different x-section processes (RES, DIS, QE, v_τ, NC)
  - **long term:**
    replace simple scaling factors with event reweighting using GENIE with modified parameters and possibly other generators (Nuisance framework)



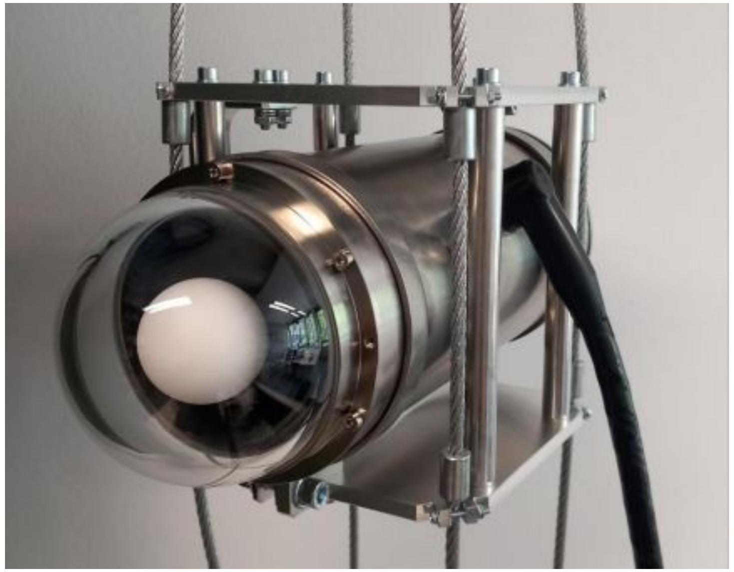
Analysis

Next round of analyses on-going with **ORCA18**
Major improvement of the treatment of **systematics**

- **Neutrino flux**
- **Neutrino-cross section**
- **Detector response**
  - improve **detector modelling** by **physics driven effects** decoupling the effects in the triggering from the effects in the reconstruction.
  - **simulate** MC for different **DOM efficiencies & water absorption length**
  - **measure** abs. length and DOM efficiency with stopping μ (time dependent meas.) and/or other sources (^{40}K, POCAM, T-REX)

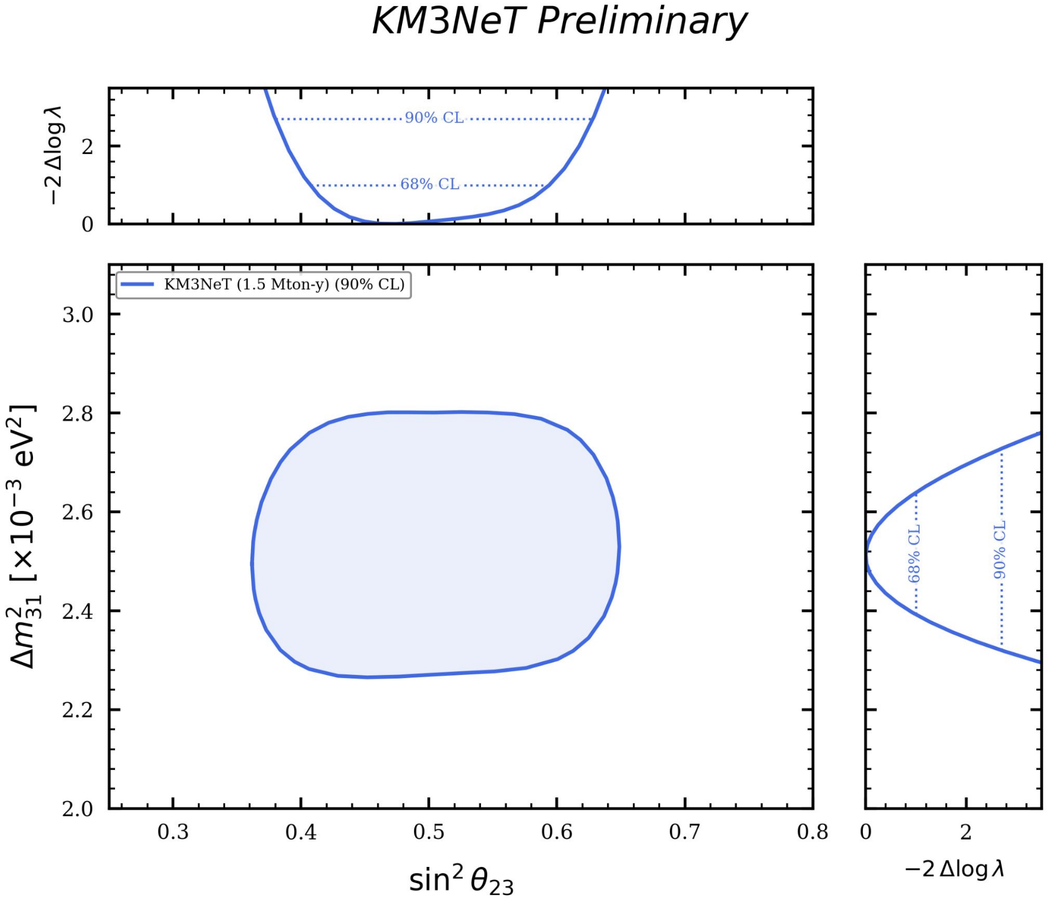


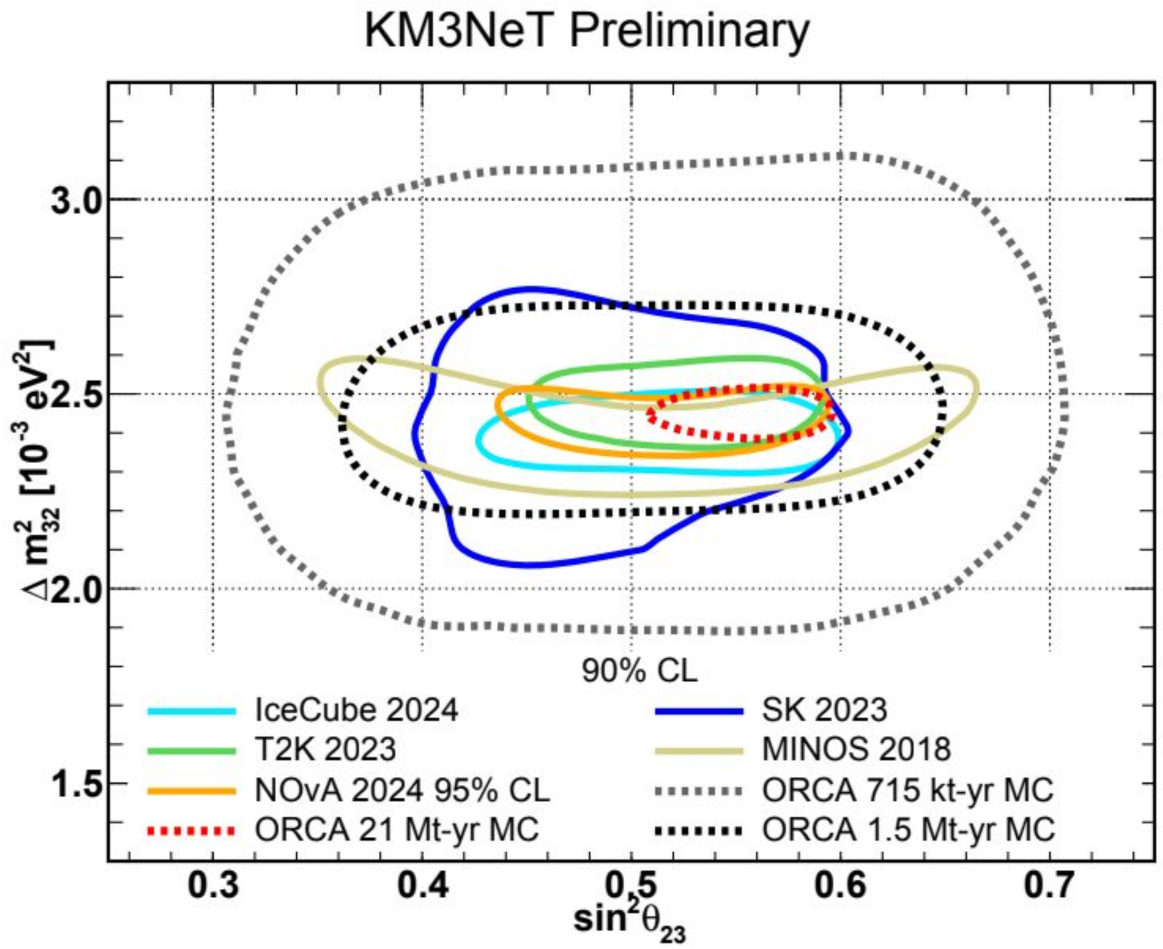
[Stopping Muon, ICRC 2025]



https://doi.org/10.5281/zenodo.13234815

Standard Oscillations



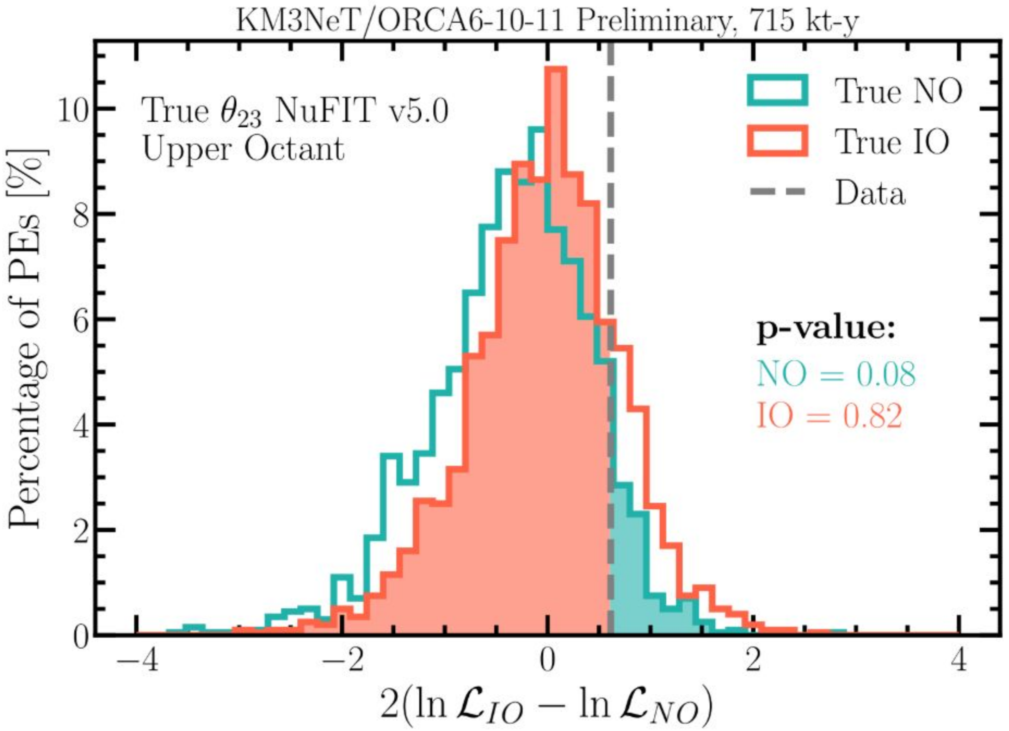


- Reaching competitive values with the sensitivities of this dataset.
- Improved precision not only from statistics but from the modelling of our uncertainties.

https://doi.org/10.5281/zenodo.13234815

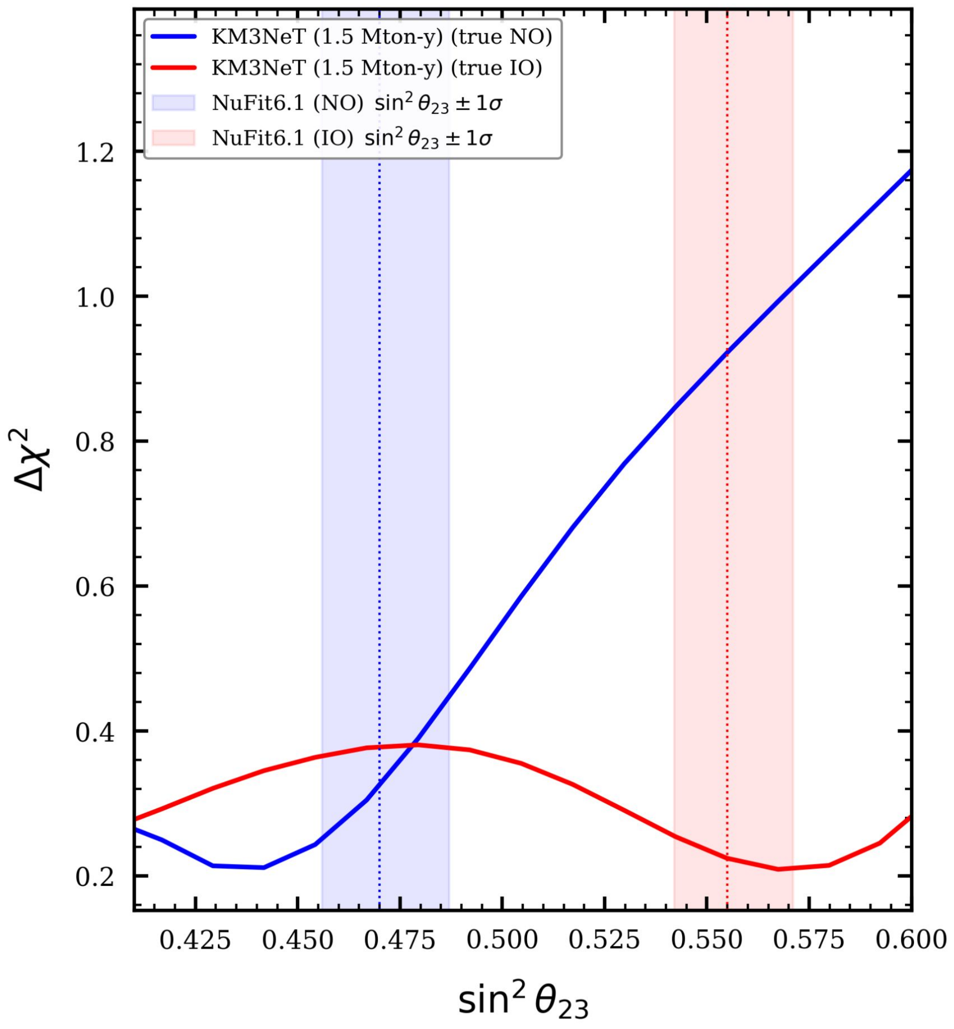
NMO

Previous result



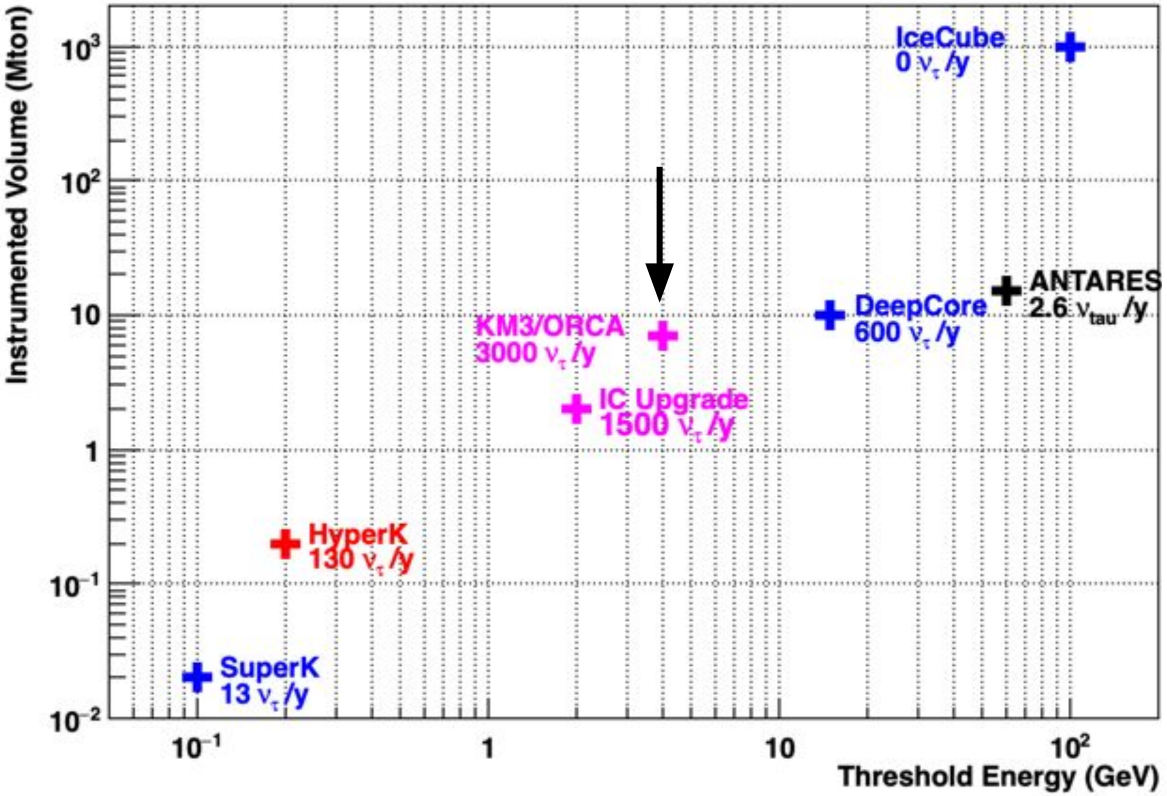
Preparing a p-value as a function of the mixing angle for the unblinding.

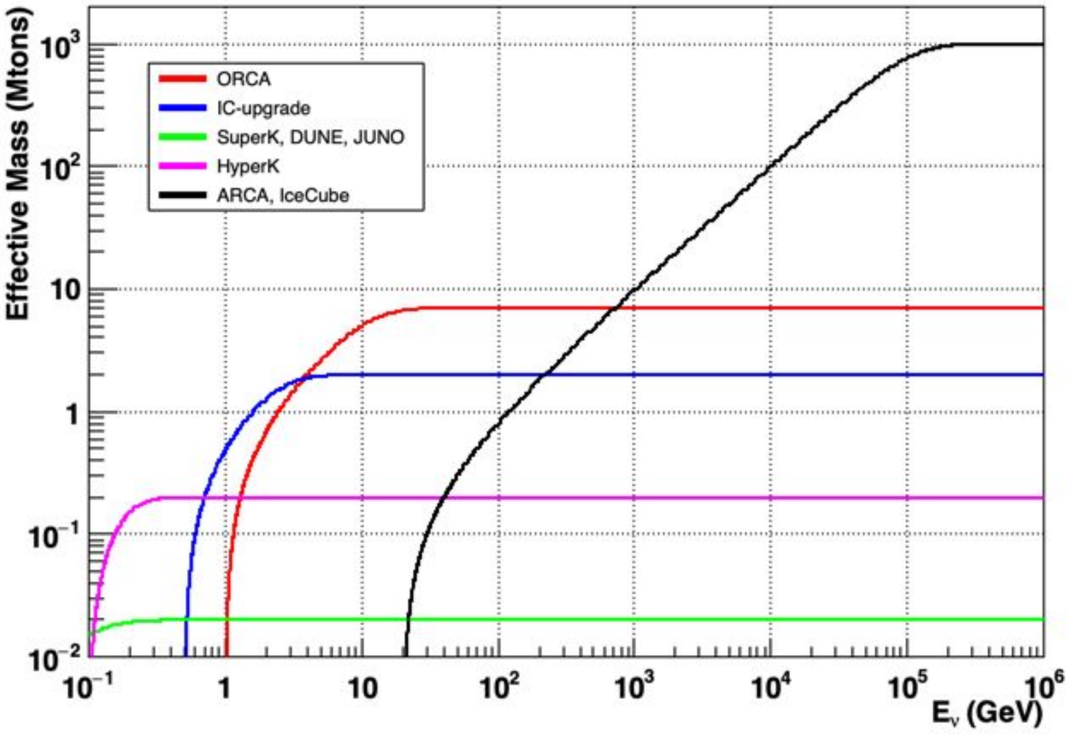
KM3NeT Preliminary



Tau Neutrinos

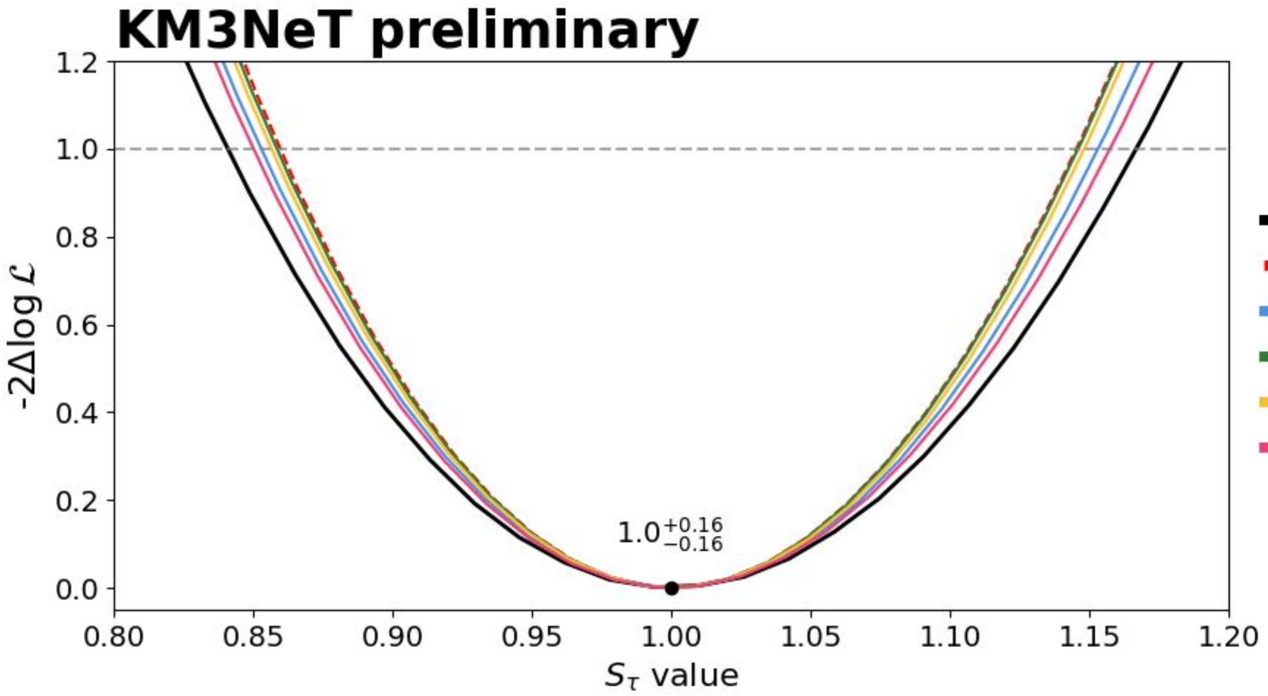
- ORCA accesses **one of the world's largest ν_τ sample**

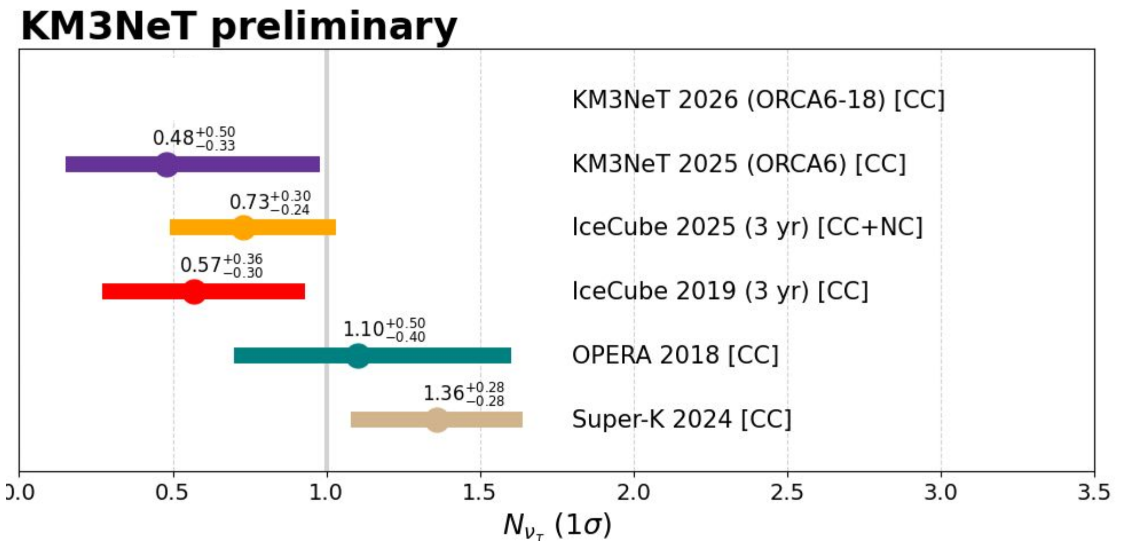




Based on:
[1] arXiv:1711.09436. [2] arXiv:1901.05366. [3] arXiv:2502.01443. [4] arXiv:1805.04163. [5] arXiv:2307.15295. [6] arXiv:2103.09885.

Tau Neutrinos

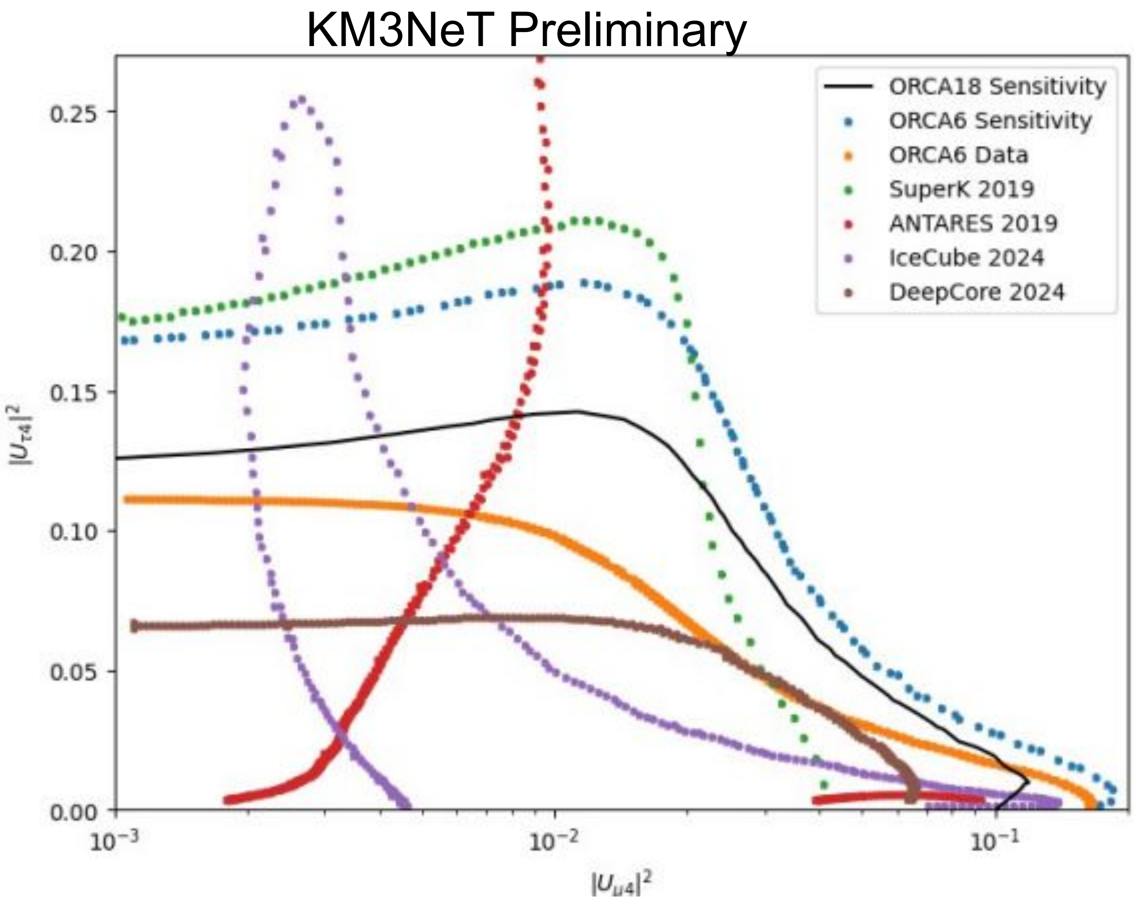


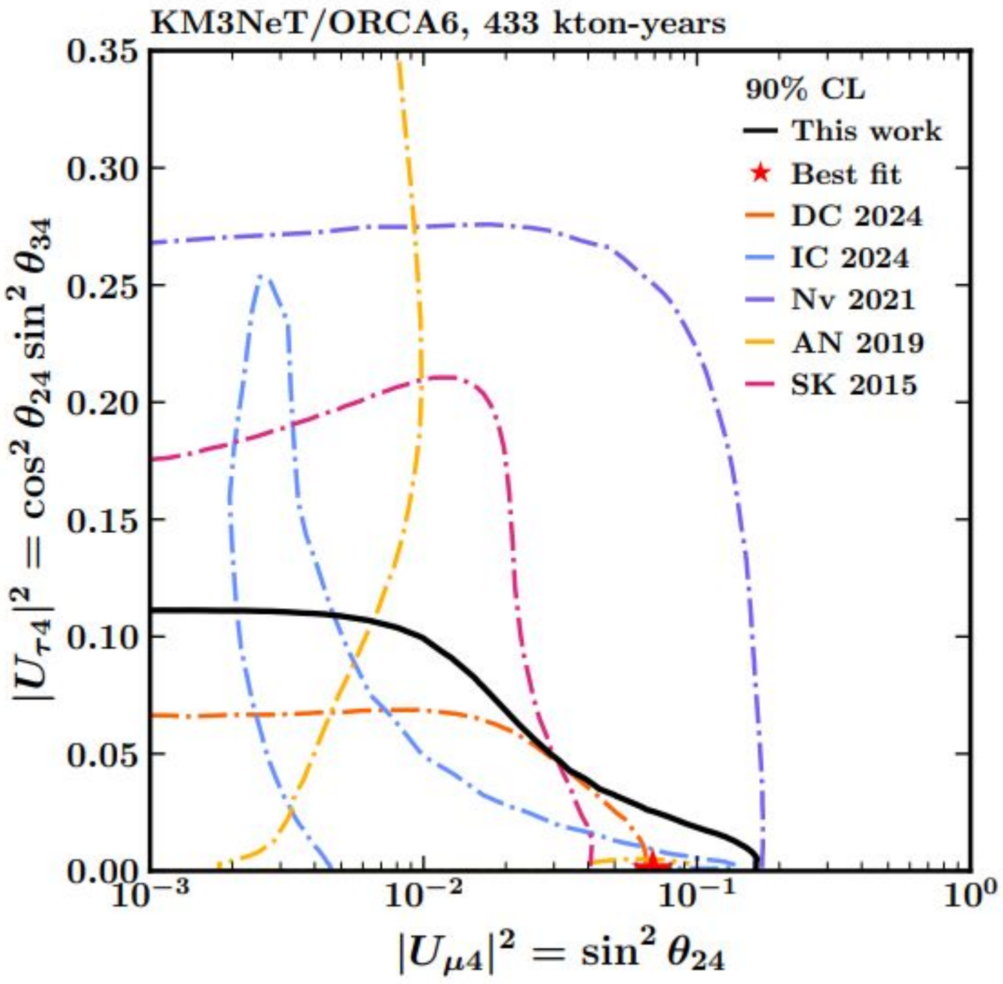


- Excepted high precision with ORCA6-18 sample.
- Dominated by the uncertainties in the oscillation parameters and the flux uncertainties.

Search for sterile neutrinos

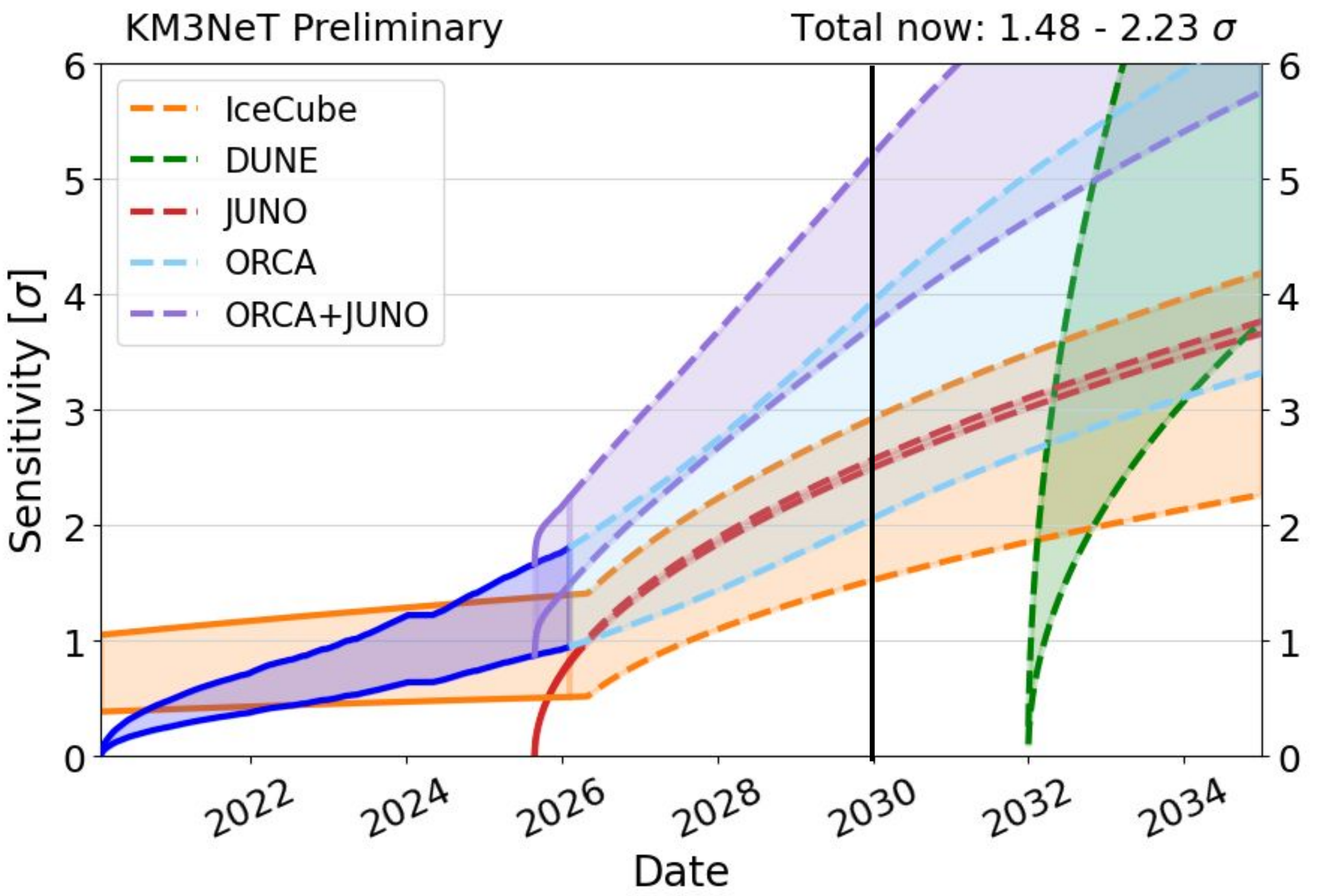
- ORCA6 search for **sterile neutrino above 1eV^2** already gives **competitive results**
- **Expected significant improvement with 1.5Mt-yr**





Prospects by 2030

- **NMO:**
  - 2 – 4σ ORCA alone
  - 3.5 – 5σ ORCA/JUNO
- **θ_{23}**
  - 4-7% relative precision
- **ν_τ x-section**
  - 5% relative precision
- **BSM**
  - improvement x4 wrt ORCA6



Conclusions

- KM3NeT has a **unique potential to determine the NMO**
- Neutrino **physics program extends well beyond NMO**
- **First results** with 5% of the total detectors (ORCA6) are already **competitive**
- New result with **4x more data** and updated modelling of the systematic uncertainties soon to be unblinded.

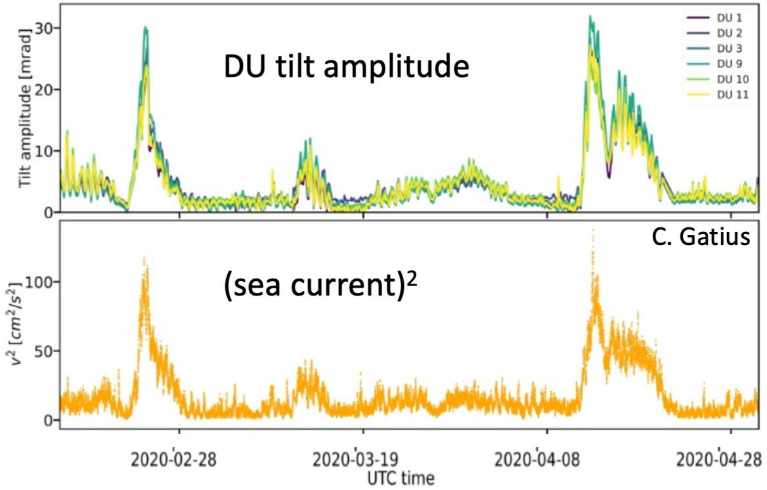
Thank you for your attention

BACKUP

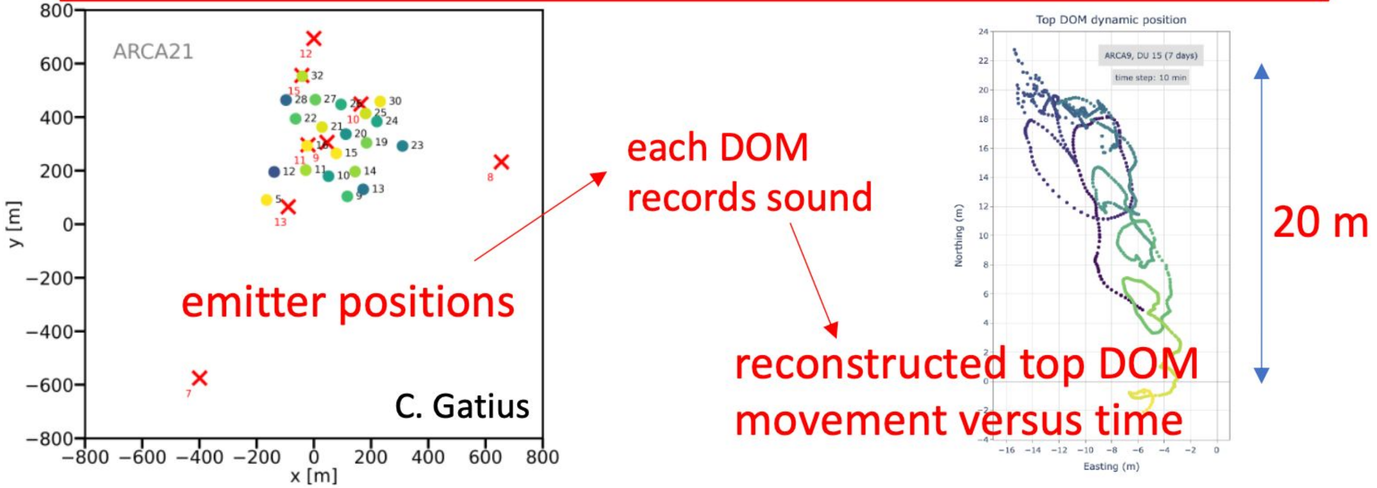
Position Calibration

Individual DOMs can be located to ~10cm

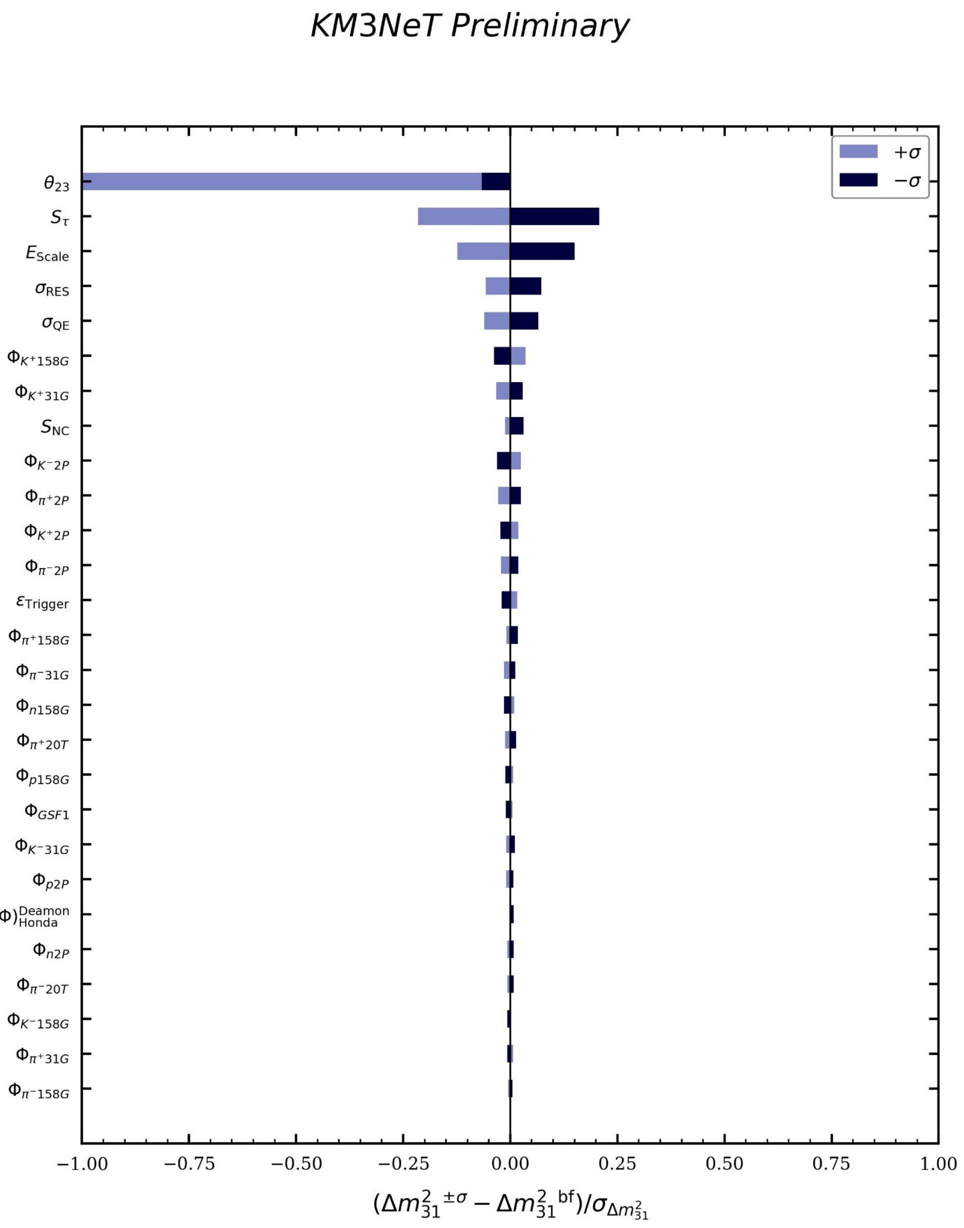
orientation few deg

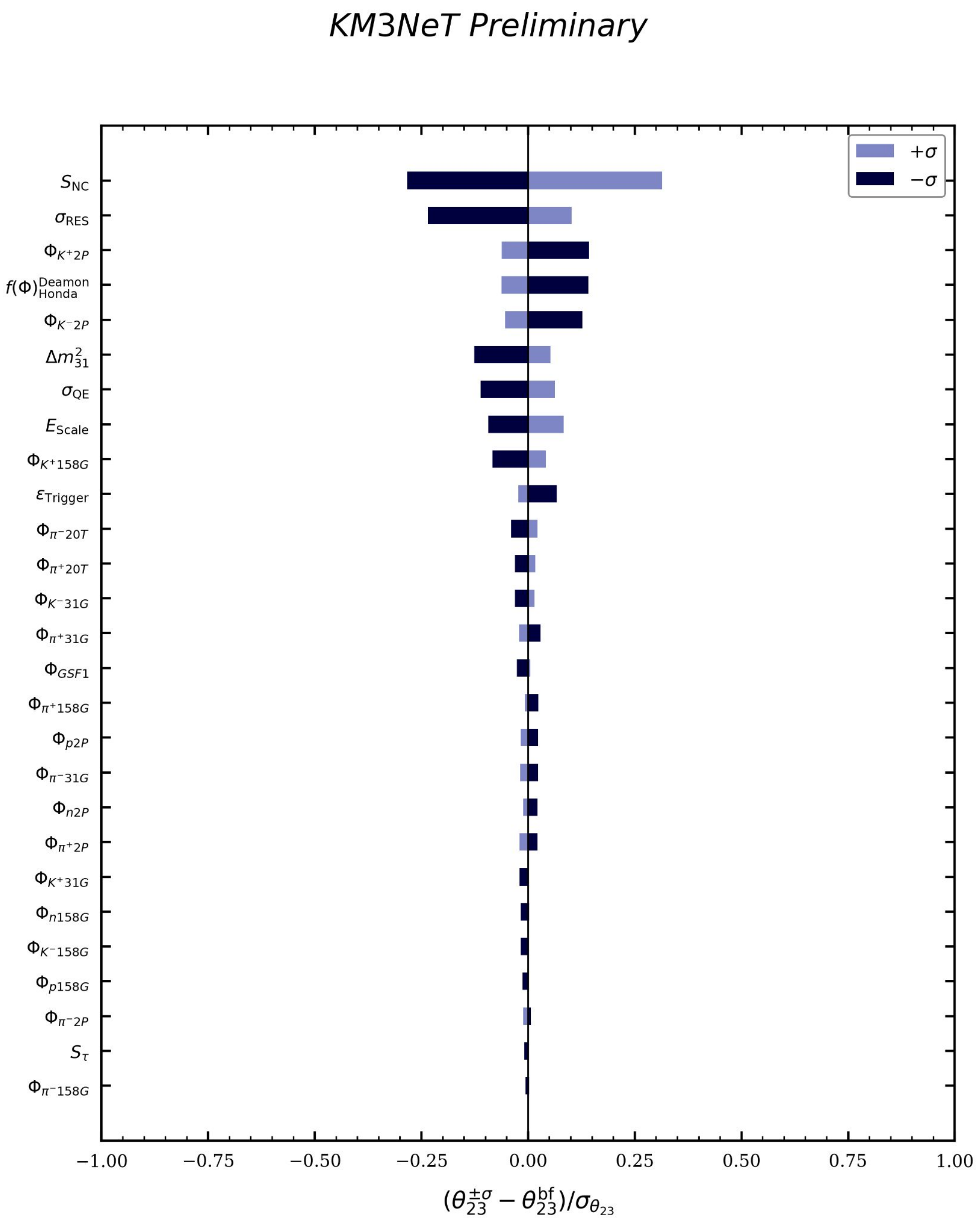


Positioning: acoustic triangulation using autonomous emitters



Impact of systematics Std Osc

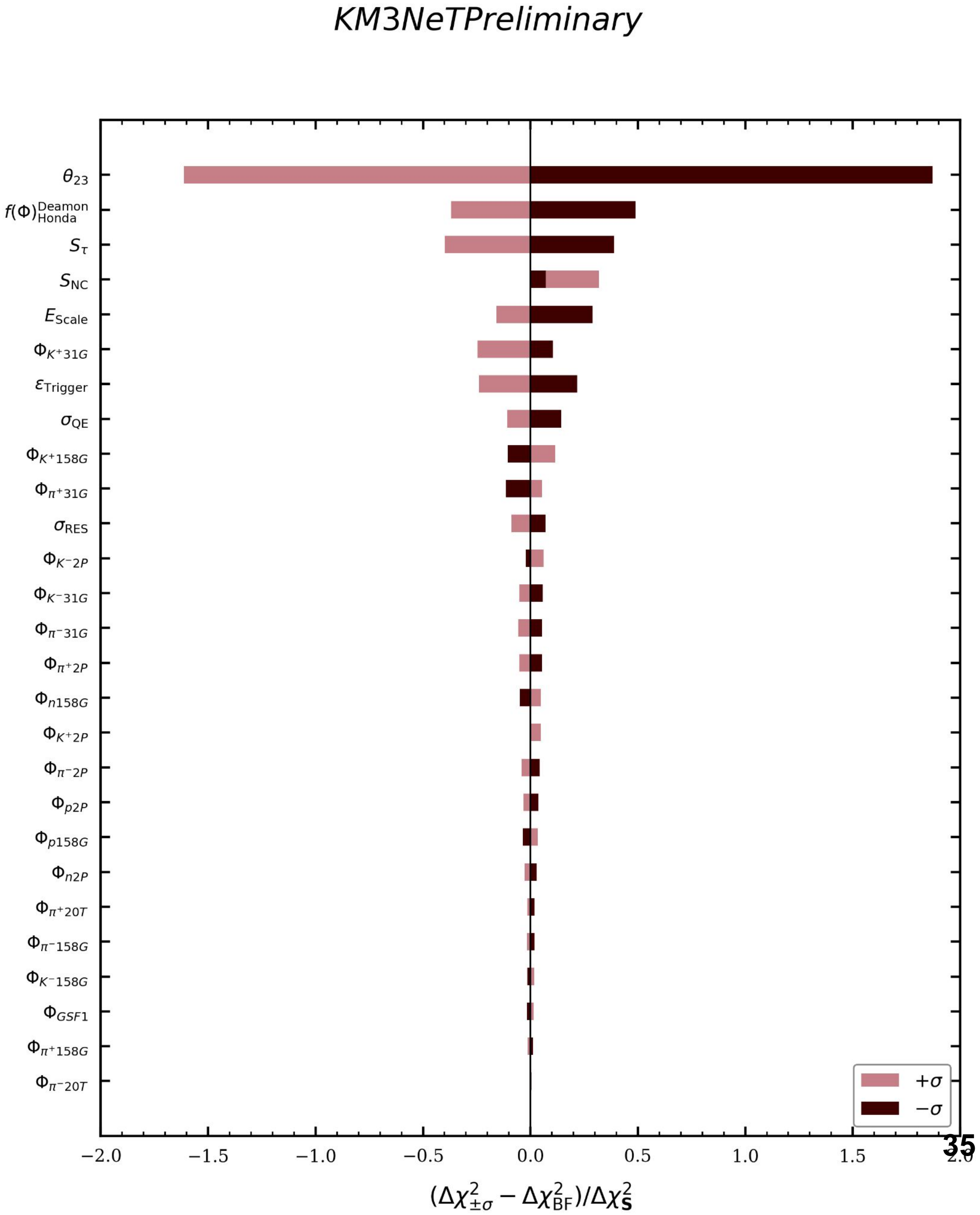




- Most important source of uncertainties are our cross section systematics and our energy scale.
- Flipping mass ordering when shifting the mixing angle and fitting for the mass splitting.

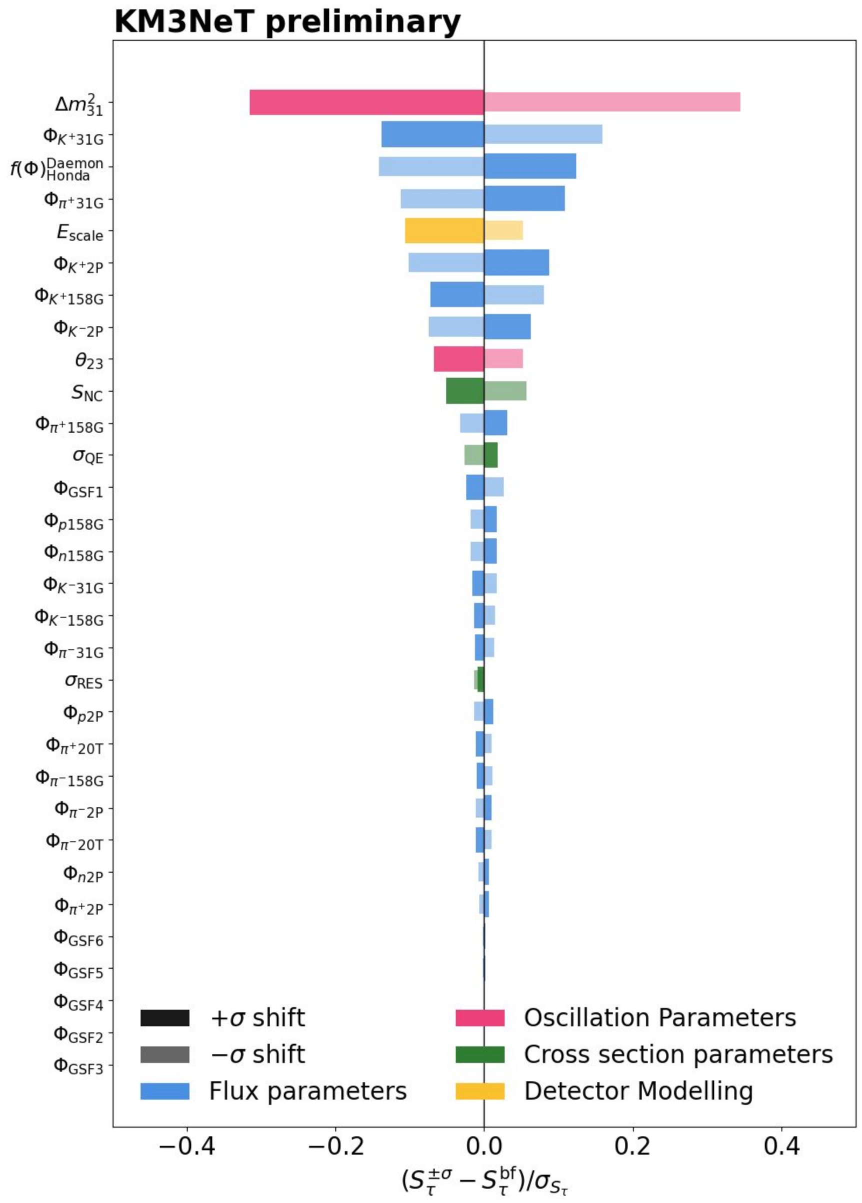
Impact of systematics NMO

- Impact on the NMO dominated by the mixing angle (expected)
- Most important systematic right now is our HONDA-Daemon interpolation <5 GeV, which is a temporal solution for the absence of geomagnetic effects in Daemonflux.



Impact of systematics Tau

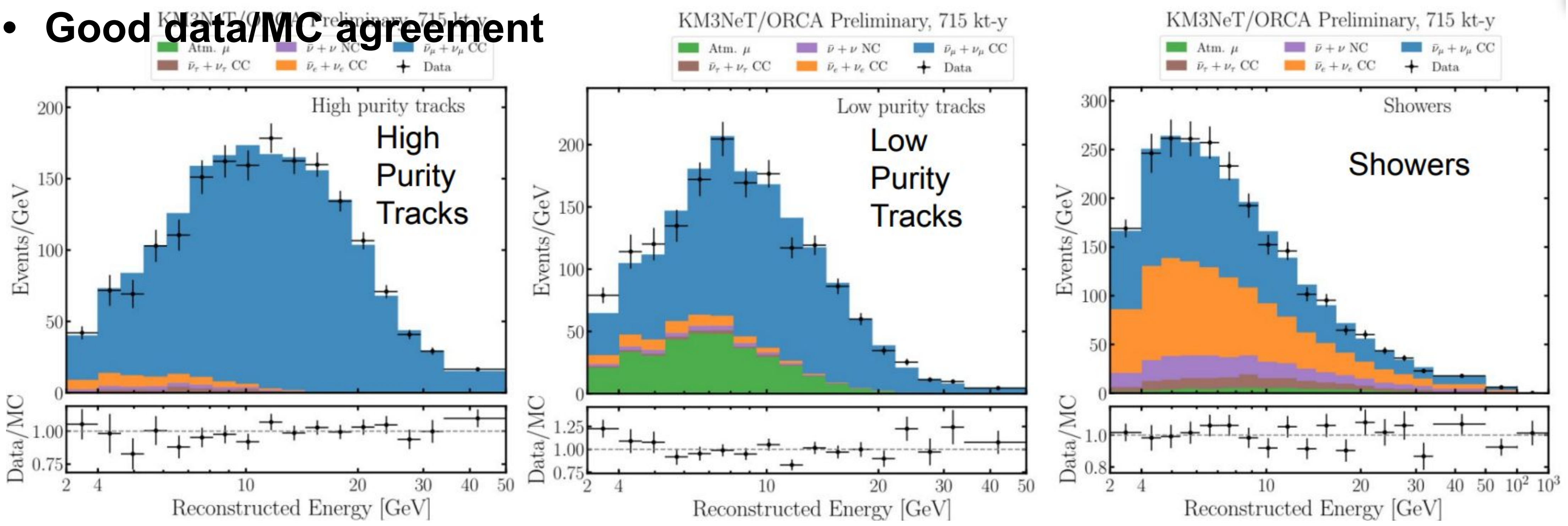
- Impact on the tau appearance dominated by the mass splitting.
- Quite important flux uncertainties and our energy scale.



https://doi.org/10.5281/zenodo.13234815

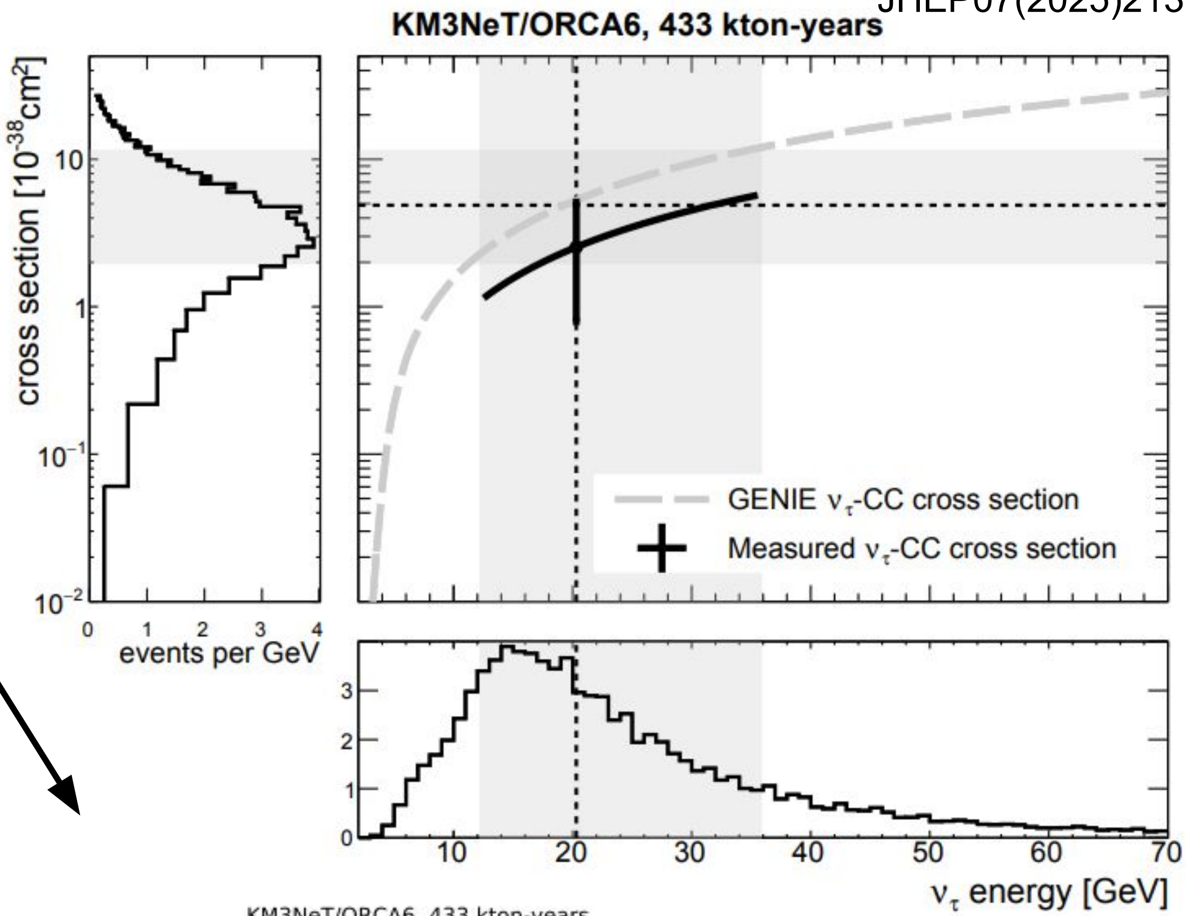
The previous dataset

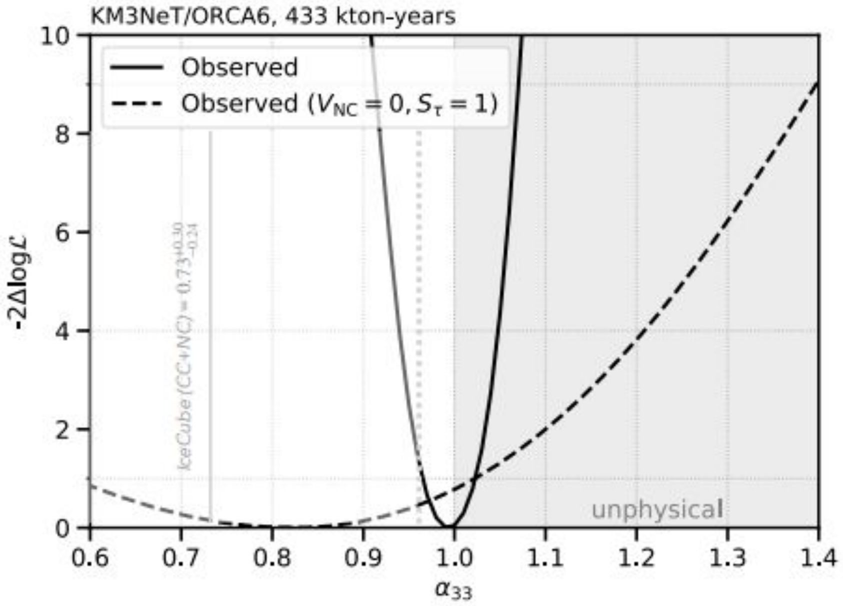
- After selection: **9751 neutrino candidates** (715 kton.y)
- Separated in **three classes**:
  - high purity-tracks (i.e. with minimal muon contamintion)
  - low purity tracks
  - showers
- **Good data/MC agreement**



Tau Neutrinos

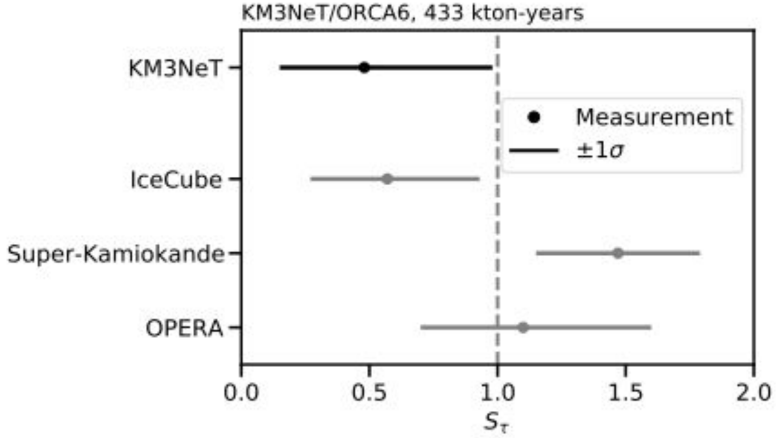
- **ORCA6 ν_τ sample** exploited to
  - measure ν_τ **cross section**
  - constrain ν_τ **normalisation**
  - constrain **non-unitarity mixing**





$$N = \alpha \, U_{\mathrm{PMNS}}$$

$$\alpha = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}$$



Best limit on α_{33}: [0.95, 1.04] at 95% CL

https://doi.org/10.22323/1.501.1058

Lorentz Invariance Violation

- **Lorentz invariance*** can be violated in models trying to unify QFT&GR

- Model independent search using **EFT** (SME)

PMNS

Std Osc. Hamiltonian

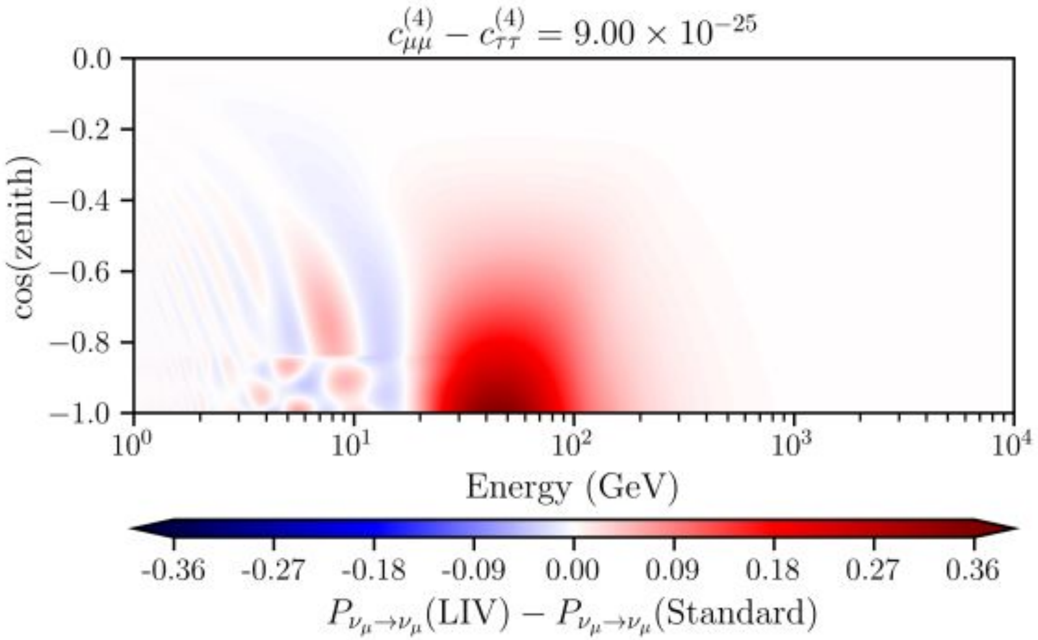
$$H = U H_0 U^\dagger + H_I + H_{LIV}$$

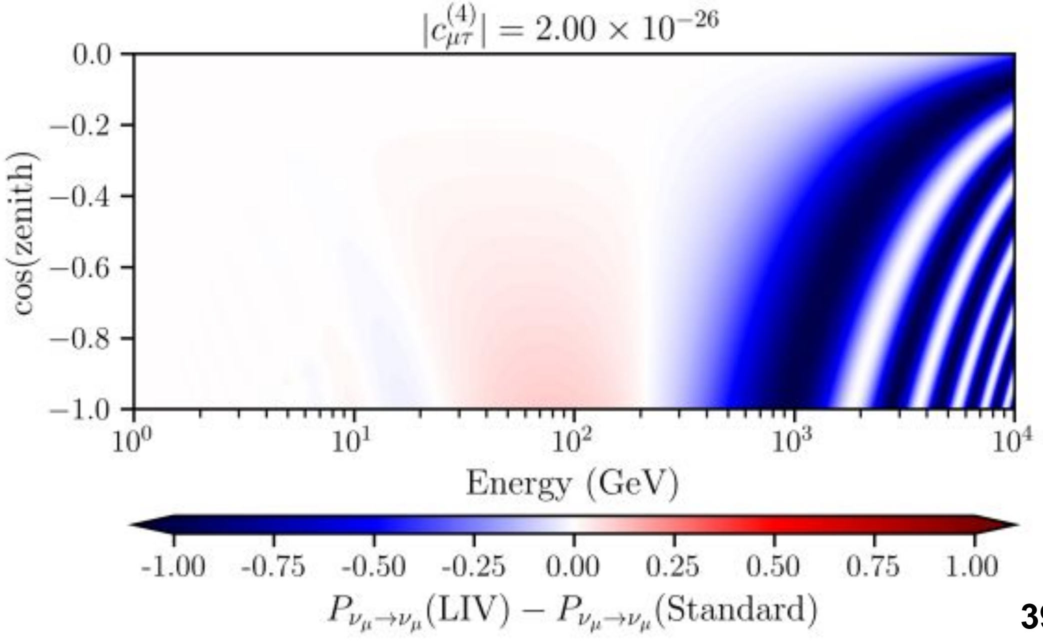
Matter Effect Hamiltonian

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

- **Complementarity ORCA/ARCA** to test the H_{LIV} terms in different energy regimes

*Lorentz Invariance: physics is identical for all interial observers

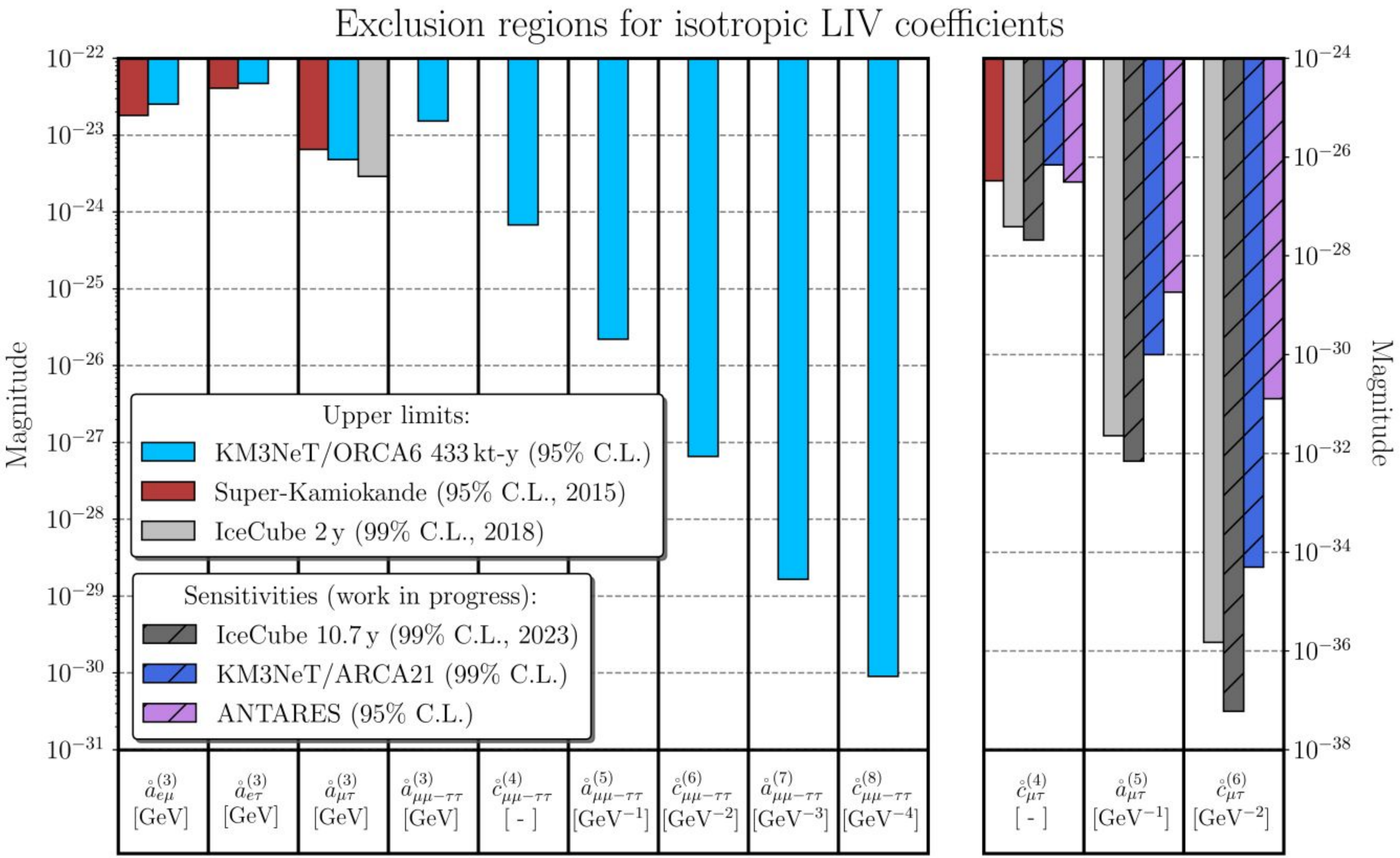




https://doi.org/10.22323/1.501.1058

Lorentz Invariance Violation

- **ORCA6 and ARCA21** data set already put **very competitive constraints**



Non Standard Neutrino Interactions

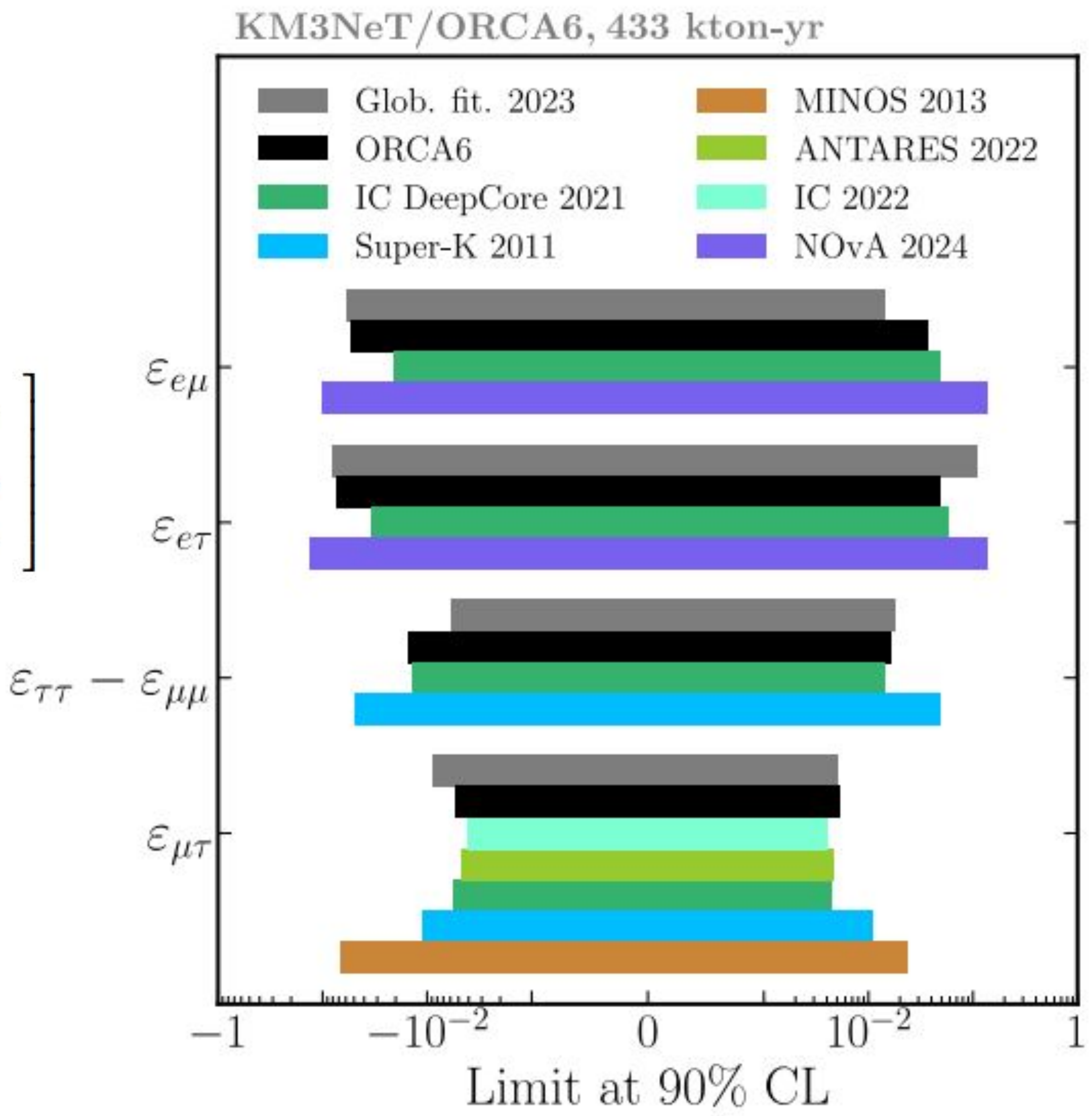
- **NSI** typically arise in models providing mechanisms to explain the **origin of ν masses**

- Model independent search with **EFT**:

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

- **NC-NSI** affect ν oscillations in matter by modifying coherent forward scattering

- ORCA6 data provide **competitive results**



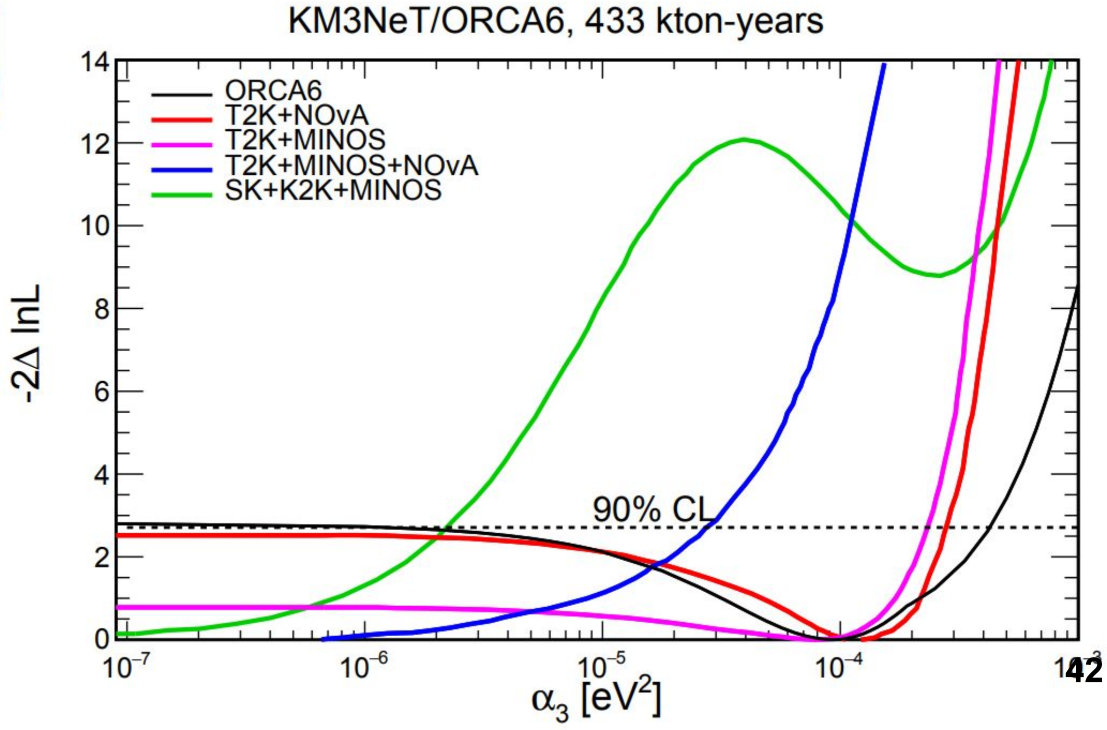
Neutrino Decay

- Hypothesis: neutrino decay to invisible products
- Analysis focuses on ν_3 decay (others constrained by solar and Super Novae)
- Model independent search with EFT

$$H_{\text{Total}} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + U\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & -i\alpha_3\end{pmatrix}U^\dagger\right] + \begin{pmatrix}V & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

- ORCA6 measured $\alpha_3 = 0.92^{+1.08}_{-0.57} \times 10^{-4}\ \text{eV}^2$ compatible with 0 (SM) at 2.1σ

Experiment	UL (90% CL) $[10^{-6}\text{eV}^2]$
ORCA6 (433 kton-year)	[10, 380]
ORCA (70 Mton-year)	3.7
T2K, NOνA	290
T2K, MINOS	240
T2K, NOνA, MINOS	27
K2K, MINOS, SK I+II	2.3
DUNE $(5\nu+5\bar{\nu})$ yr	13
MOMENT (10 yr)	24
ESSnuSB $(5\nu+5\bar{\nu})$ yr	16 – 13
JUNO (5 yr)	7
INO-ICAL (10 yr)	4.4



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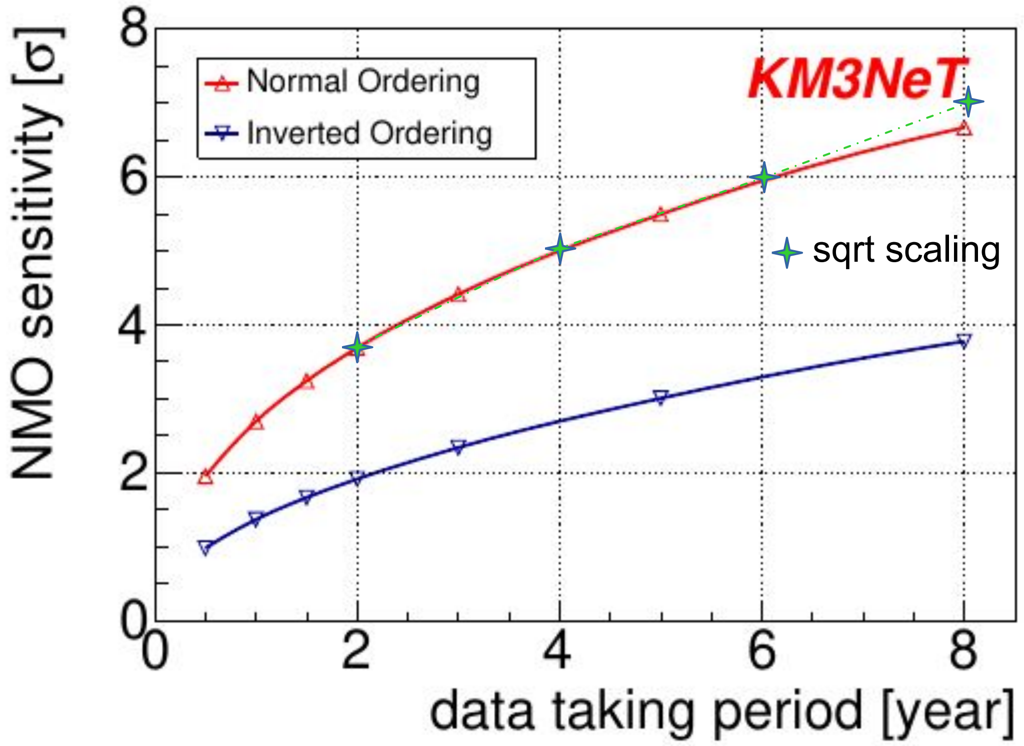
Stats vs Syst

- ORCA is dominated for a long time by statistical uncertainties



Quantum Decoherence

- Oscillations affected by **decoherence**, described by a damping term

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} \tilde{U}_{\alpha i}\tilde{U}^*_{\beta i}\tilde{U}^*_{\alpha j}\tilde{U}_{\beta j} e^{-i\Delta\tilde{E}_{ij}t-\gamma_{ij}t}$$

$$\gamma_{ij} = \gamma^0_{ij}\left(\frac{E}{\text{GeV}}\right)^n$$

- **ORCA** well suited to study **n = -2, -1**
- **ARCA** well suited to study **n = 0, 1, 2, 3**

- **ORCA6** data allows to set limits comparable to **DeepCore** but other exp. at **lower energy** (RENO, KamLAND, T2K) put stronger bounds for n<0.

	Upper Limits on γ31 [GeV]	
	n=-2	**n=-1**
ORCA6 NO, **90%CL**	$8.4\cdot10^{-21}$	$2.7\cdot10^{-22}$
arXiv:2306.14699 γ31=γ32 NO/IO, 90%CL	$6.9\cdot10^{-25}$ **RENO**	$2.1\cdot10^{-23}$ **T2K**
ORCA6 NO, **95%CL**	$11.7\cdot10^{-21}$	$4.2\cdot10^{-22}$
DeepCore γ31=γ32 NO, 95%CL	$4.3\cdot10^{-20}$	$2.0\cdot10^{-21}$

Quantum Decoherence

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	Upper limits [GeV]			
	$n=-2$		$n=-1$	
ORCA6, 90 %CL	NO	IO	NO	IO
Γ_{21}	$2.8 \cdot 10^{-21}$	$\mathbf{4.6 \cdot 10^{-21}}$	$1.1 \cdot 10^{-22}$	$\mathbf{1.9 \cdot 10^{-22}}$
Γ_{31}	$\mathbf{8.4 \cdot 10^{-21}}$	$2.2 \cdot 10^{-21}$	$\mathbf{2.7 \cdot 10^{-22}}$	$0.8 \cdot 10^{-22}$
$\Gamma_{21} = \Gamma_{31}$	$\mathbf{4.1 \cdot 10^{-21}}$	$2.9 \cdot 10^{-21}$	$\mathbf{1.8 \cdot 10^{-22}}$	$1.1 \cdot 10^{-22}$
ORCA6, 95 %CL	NO	IO	NO	IO
Γ_{21}	$3.7 \cdot 10^{-21}$	$\mathbf{6.9 \cdot 10^{-21}}$	$1.6 \cdot 10^{-22}$	$\mathbf{3.0 \cdot 10^{-22}}$
Γ_{31}	$\mathbf{11.7 \cdot 10^{-21}}$	$3.2 \cdot 10^{-21}$	$\mathbf{4.2 \cdot 10^{-22}}$	$1.3 \cdot 10^{-22}$
$\Gamma_{21} = \Gamma_{31}$	$\mathbf{5.2 \cdot 10^{-21}}$	$3.6 \cdot 10^{-21}$	$\mathbf{2.3 \cdot 10^{-22}}$	$1.4 \cdot 10^{-22}$

	Upper limits [GeV]			
	$n=-2$		$n=-1$	
Reported in [14], 90 % CL				
$\Gamma_{21} = \Gamma_{32}$	$7.9 \cdot 10^{-27}$ (KL)		$1.8 \cdot 10^{-24}$ (KL)	
$\Gamma_{31} = \Gamma_{32}$	$6.9 \cdot 10^{-25}$ (R)		$2.1 \cdot 10^{-23}$ (T2K)	
$\Gamma_{21} = \Gamma_{31}$	$7.9 \cdot 10^{-27}$ (KL)		$1.8 \cdot 10^{-24}$ (KL)	
Reported in [18], 95 %CL	NO	IO	NO	IO
$\Gamma_{21} = \Gamma_{32}$	$7.5 \cdot 10^{-21}$	$\mathbf{5.0 \cdot 10^{-20}}$	$3.5 \cdot 10^{-22}$	$\mathbf{2.3 \cdot 10^{-21}}$
$\Gamma_{31} = \Gamma_{32}$	$\mathbf{4.3 \cdot 10^{-20}}$	$1.4 \cdot 10^{-20}$	$\mathbf{2.0 \cdot 10^{-21}}$	$5.8 \cdot 10^{-22}$
$\Gamma_{21} = \Gamma_{31}$	$\mathbf{1.2 \cdot 10^{-20}}$	$8.3 \cdot 10^{-21}$	$\mathbf{5.4 \cdot 10^{-22}}$	$3.6 \cdot 10^{-22}$

[J. Phys. , G43 , 084001 (2016)]

NMO Net Effect

- **Degeneracy between NMO and chirality** is broken by cross-section (and flux) difference between neutrinos and anti-neutrinos
- **Strong net effect** even without chirality measurement