Atmospheric Neutrino Oscillation Results

WCD 2025

17-19 September 2025

Kraków (Poland)

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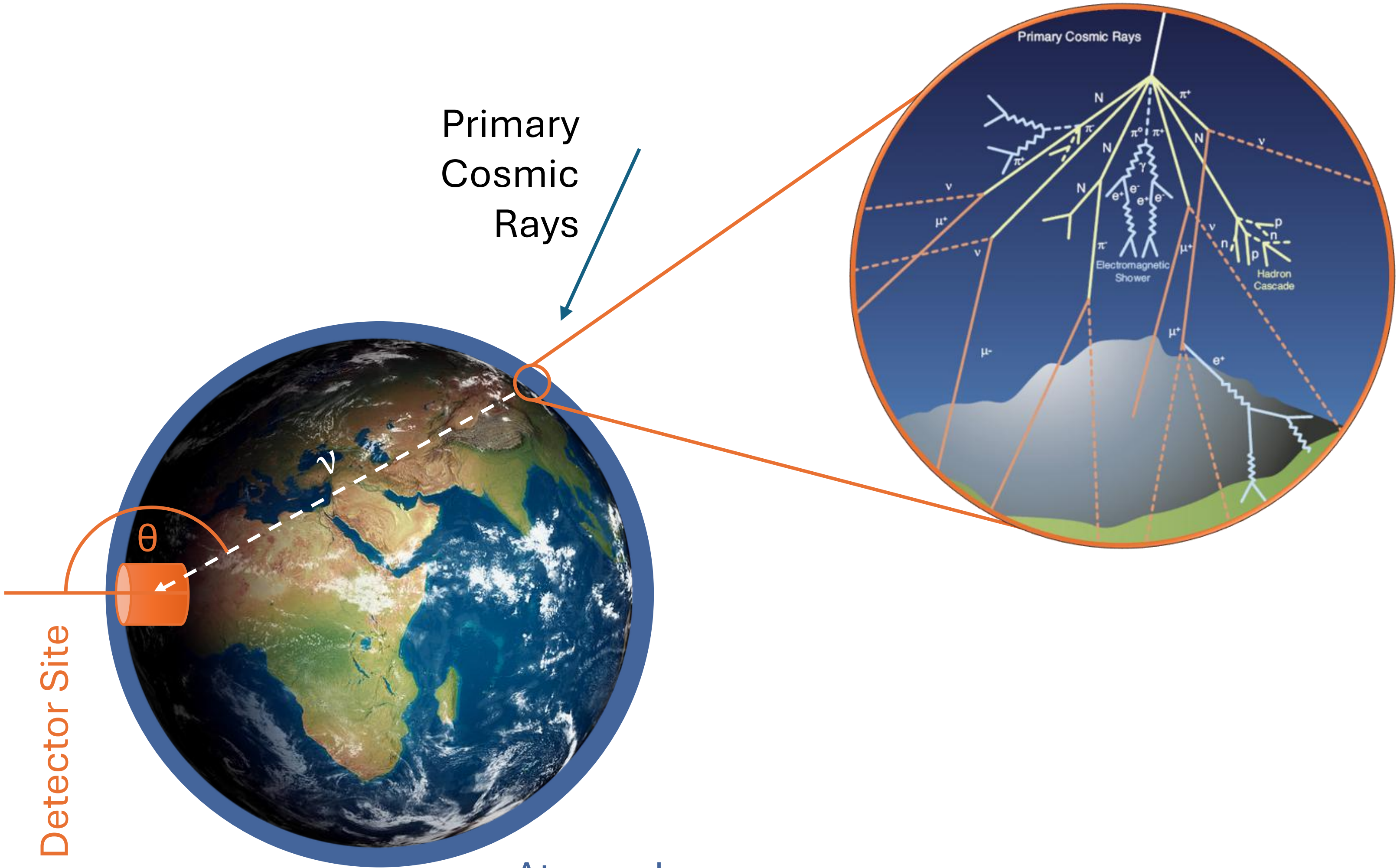
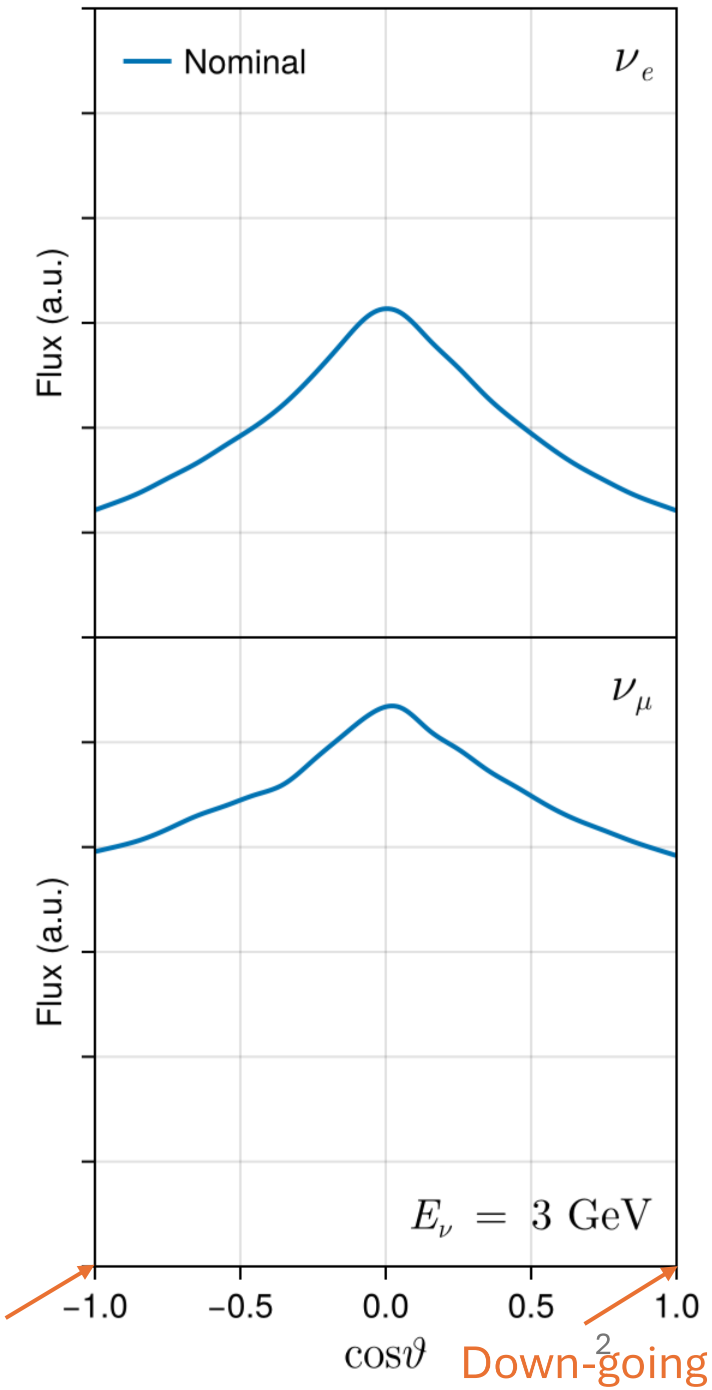
Atmospheric Neutrinos





Neutrino Oscillations

Probability of oscillation: $P_{\alpha\to\beta}(L) = \left|\left(Ue^{-iH\mathbf{L}}U^{\dagger}\right)_{\beta\alpha}\right|^2$

$L \approx 20\ km$ for down-going
$L \approx 12700\ km$ for up-going

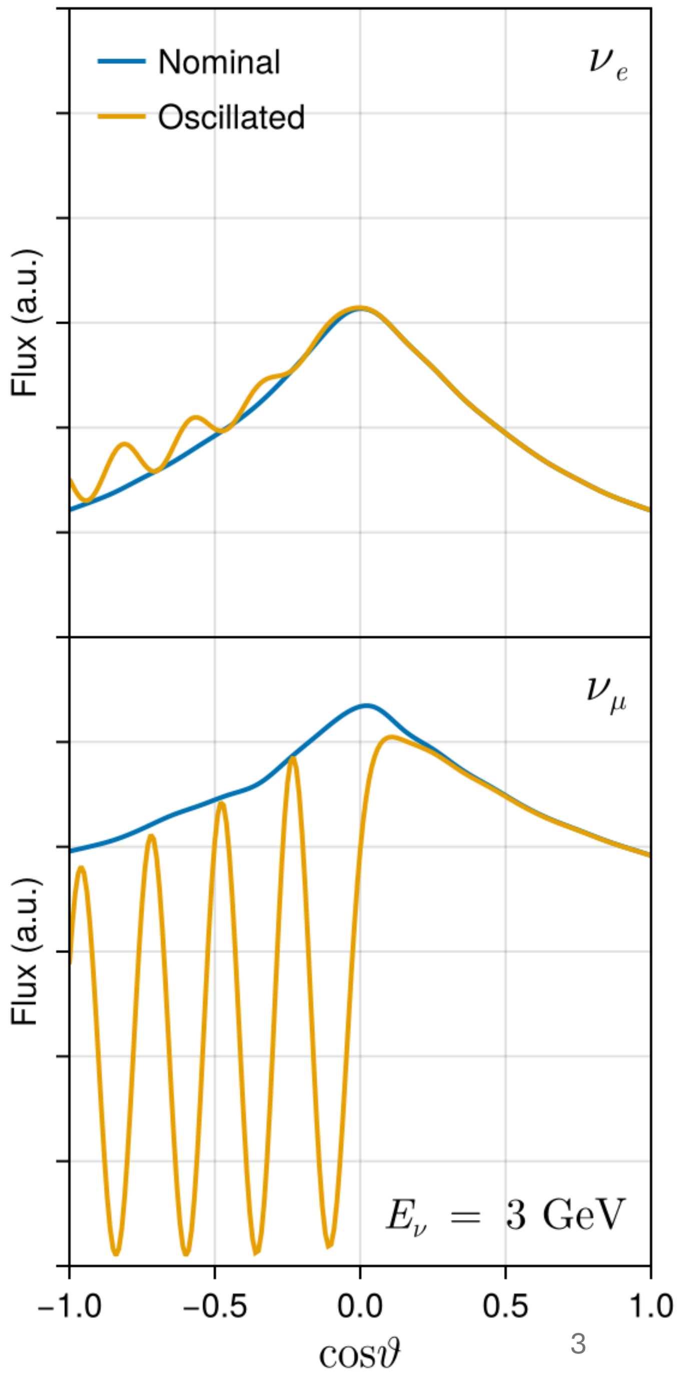
Hamiltonian: $H = \frac{1}{2E}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix}$

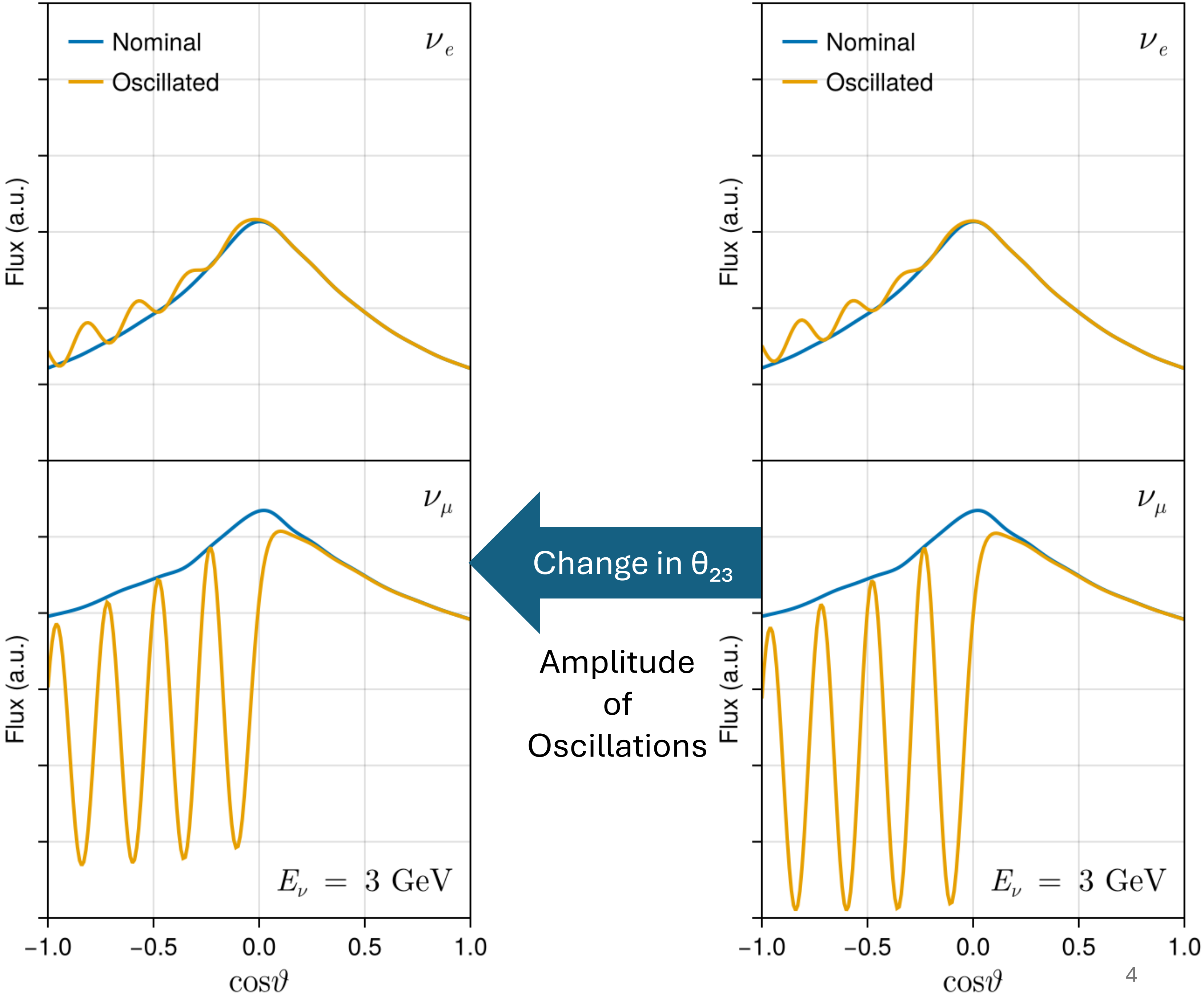
PMNS Mixing Matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ 0 & -s_{13}e^{i\delta_{CP}} & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

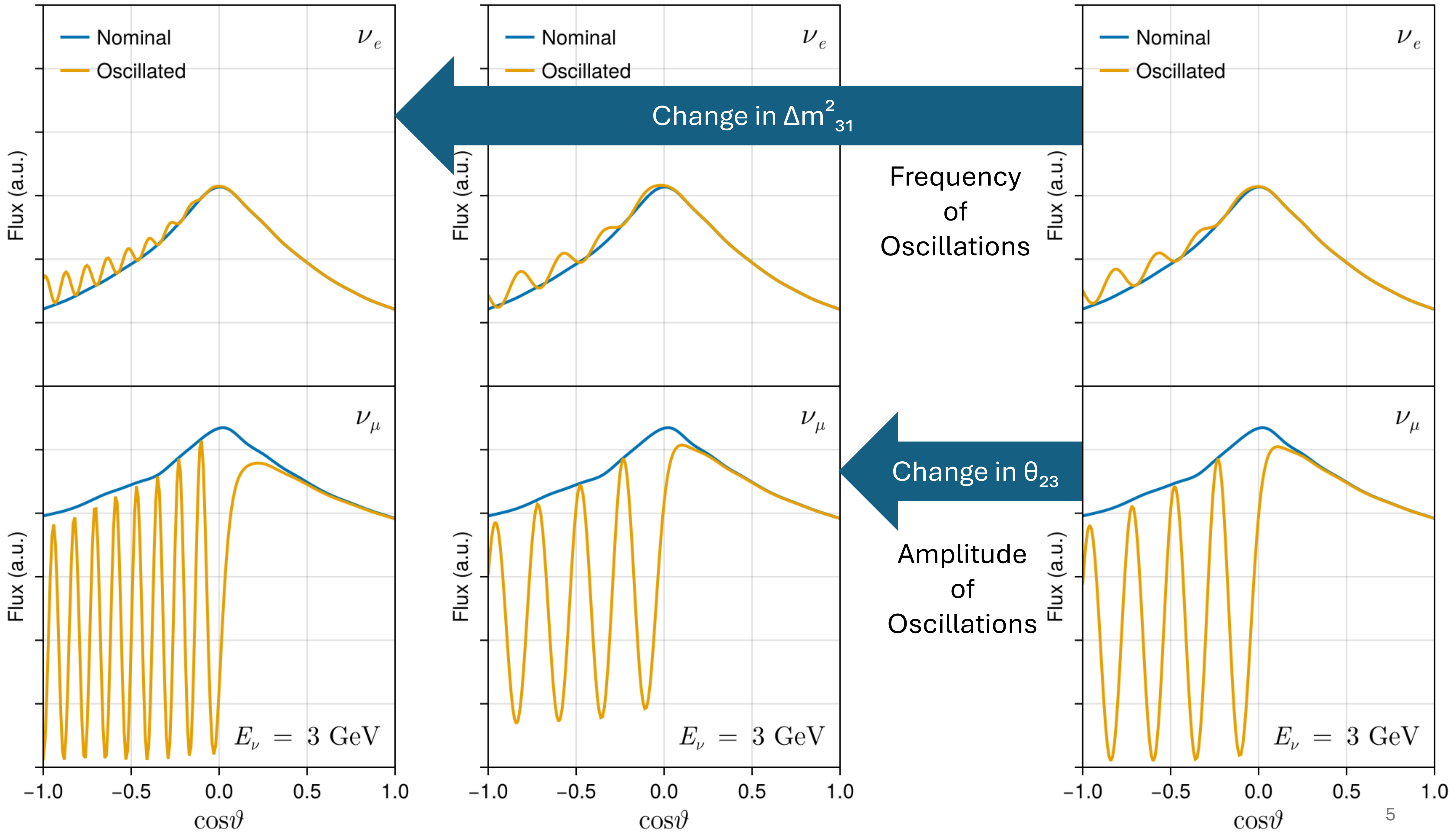
where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

Measurement Parameters





Nominal
Oscillated
ν_e
ν_μ
Flux (a.u.)
$E_\nu = 3$ GeV
−1.0
−0.5
0.0
0.5
1.0
$\cos\vartheta$
Change in θ_{23}
Amplitude of Oscillations



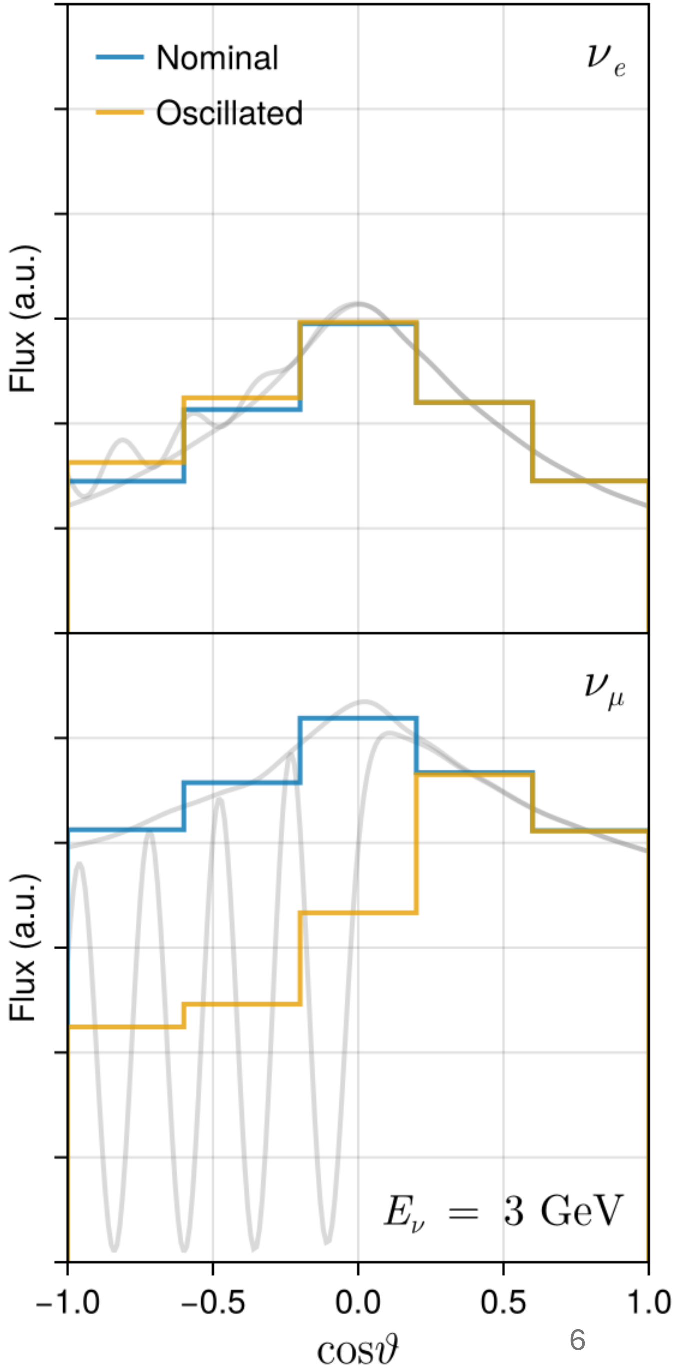
Nominal
Oscillated
ν_e
ν_μ
Flux (a.u.)
$E_\nu = 3$ GeV
$\cos\vartheta$
−1.0
−0.5
0.0
0.5
1.0
Change in Δm^2_{31}
Frequency of Oscillations
Change in θ_{23}
Amplitude of Oscillations

Up-Down Asymmetry

Because of these oscillations:

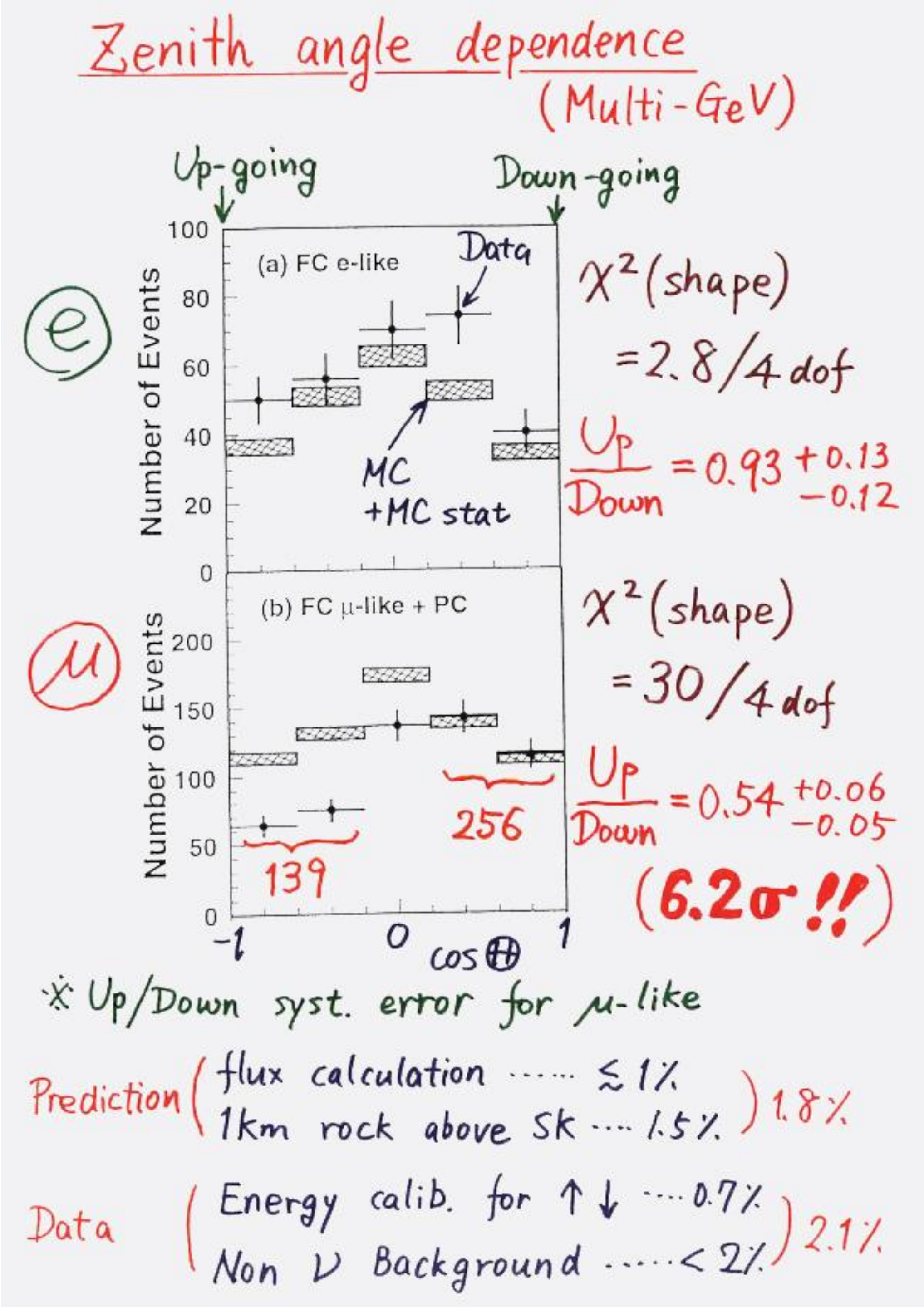
- A clear disappearance of muon neutrinos is expected for Earth crossing (i.e. long) trajectories
- Down-going neutrinos are virtually unoscillated
- Only small effect on electron neutrinos (θ_{13} small)

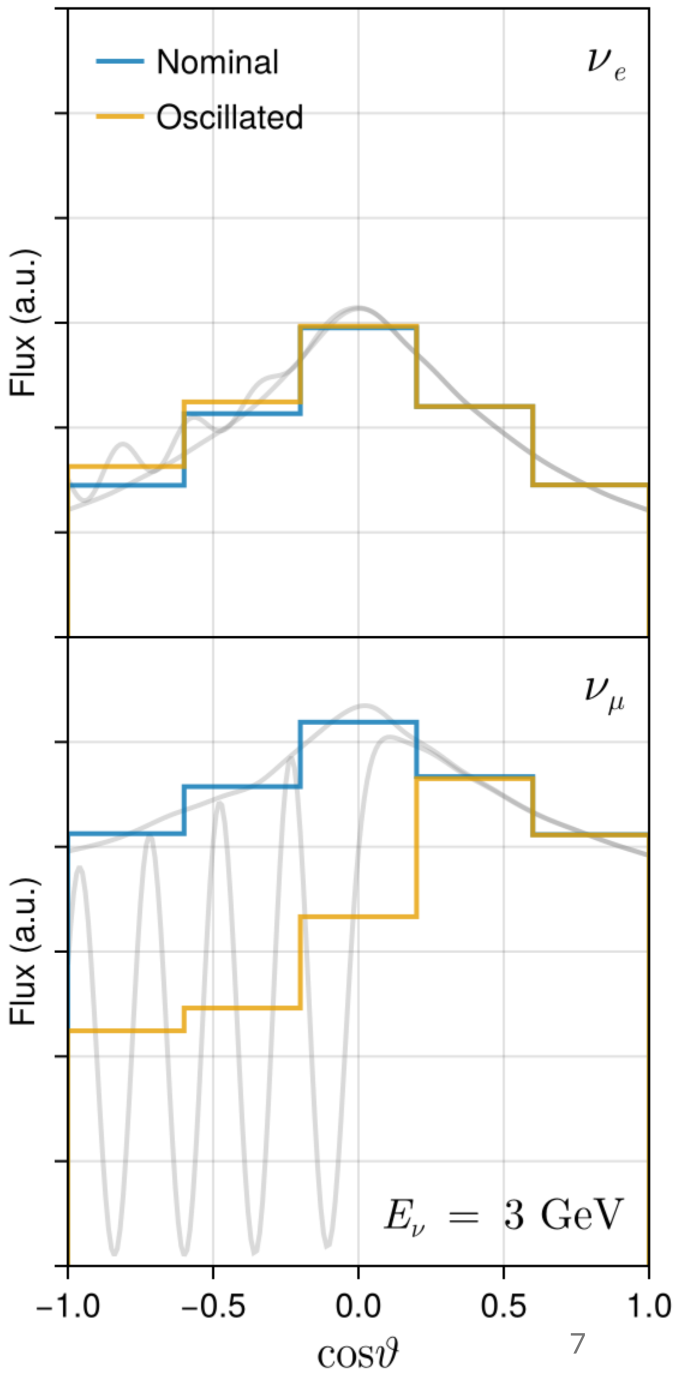
→ **With limited resolution, expect a large up-down asymmetry for muon neutrinos, but not for electron neutrinos**



Discovery at Super-K

Takaaki Kajita, for the Kamiokande and Super-Kamiokande collaborations, talk pre sented at the 18th International Conference in Neutrino Physics and Astrophysics (Neutrino ’98)



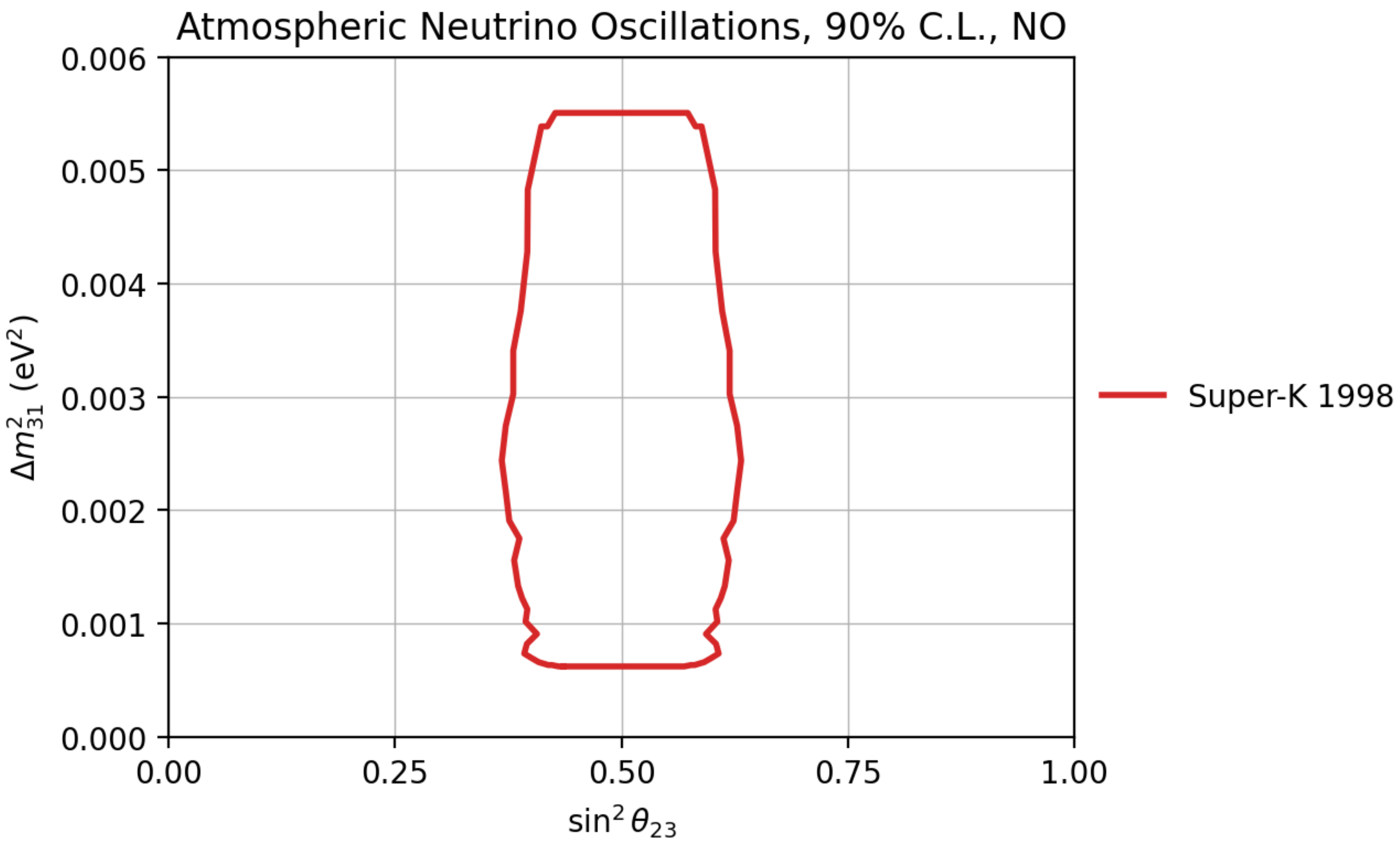


Super-K First Results

Atmospheric neutrinos are most sensitive to:

- Δm^2_{31}
- $\sin^2\theta_{23}$

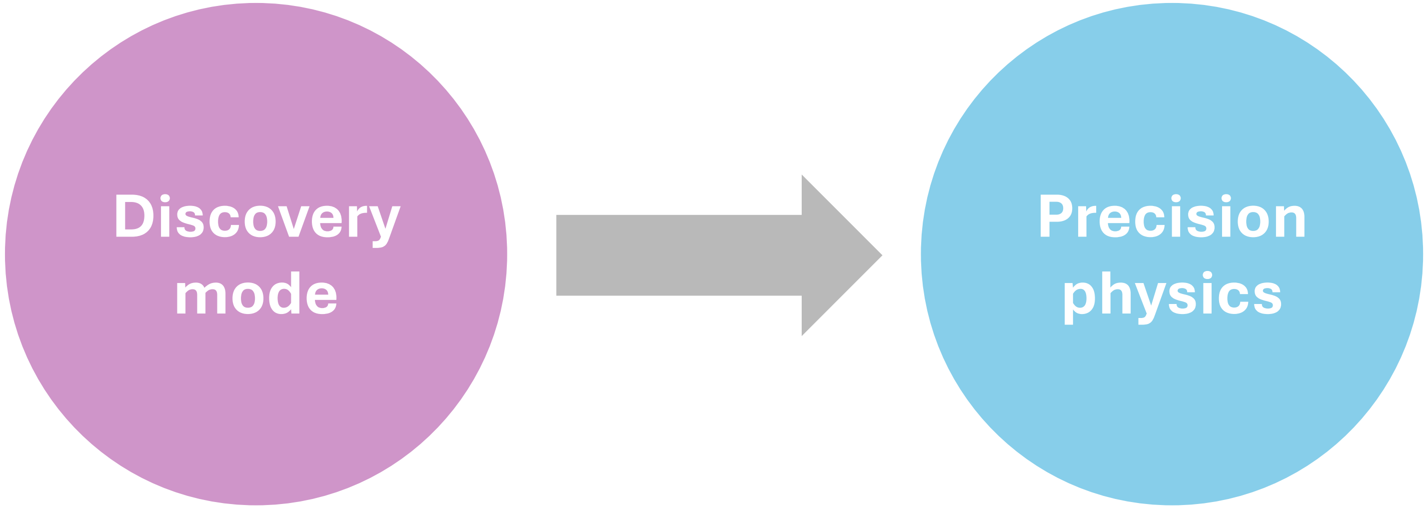
- Clear effect of oscillations, large (maximal) mixing angle, significantly different from zero
- Constraints on Δm^2_{31} is relatively weak



(* converted from 2-flavour osc)

From 1998 to 2025

What happened since the landmark discovery of oscillations in Super-K?

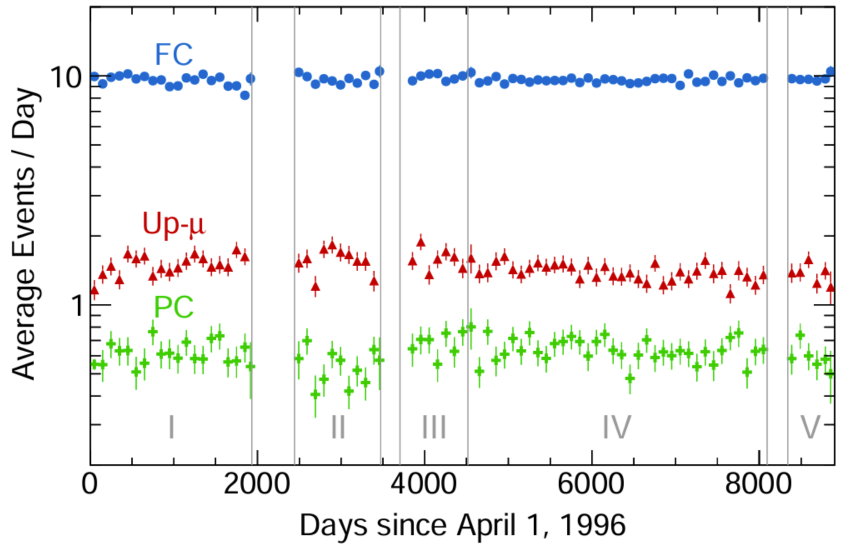


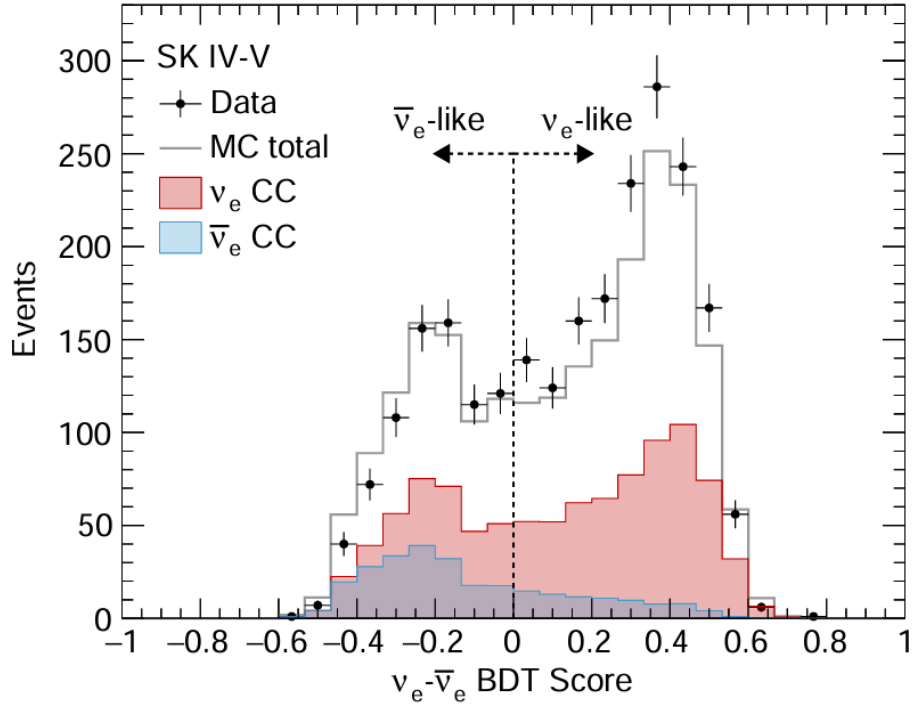
→ Collect more data

→ Improve the detector, the calibration, and the analysis!

Newest Analysis

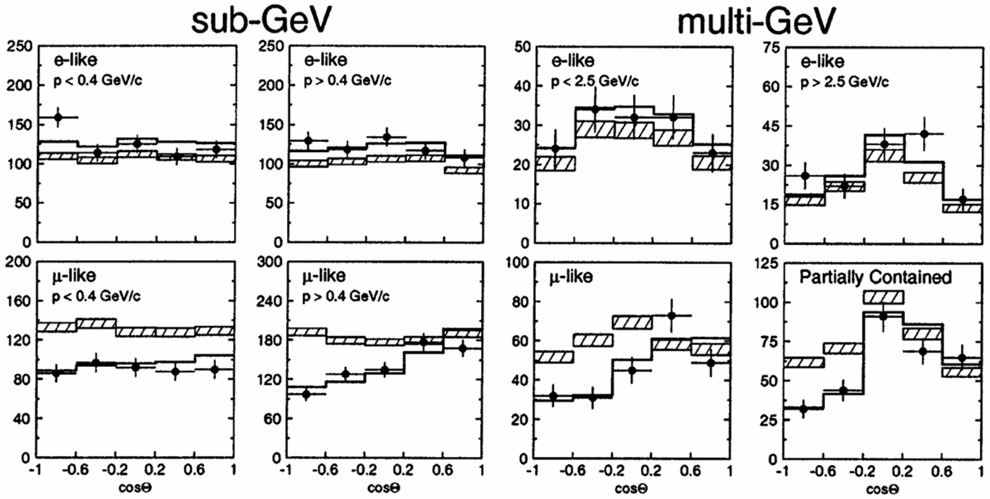
- Increased fiducial Volume & Lifetime (SK I–V)
  → from ~4k in 1998 to now ~66k neutrino events
- Detector upgrades for SK IV-V
  → Higher efficiency in detecting decay electrons
  → Capability to tag neutron captures on hydrogen
- Nu-nubar separation techniques
- Large suite of systematic uncertainties
  - from originally 8 → 193 parameters in fit



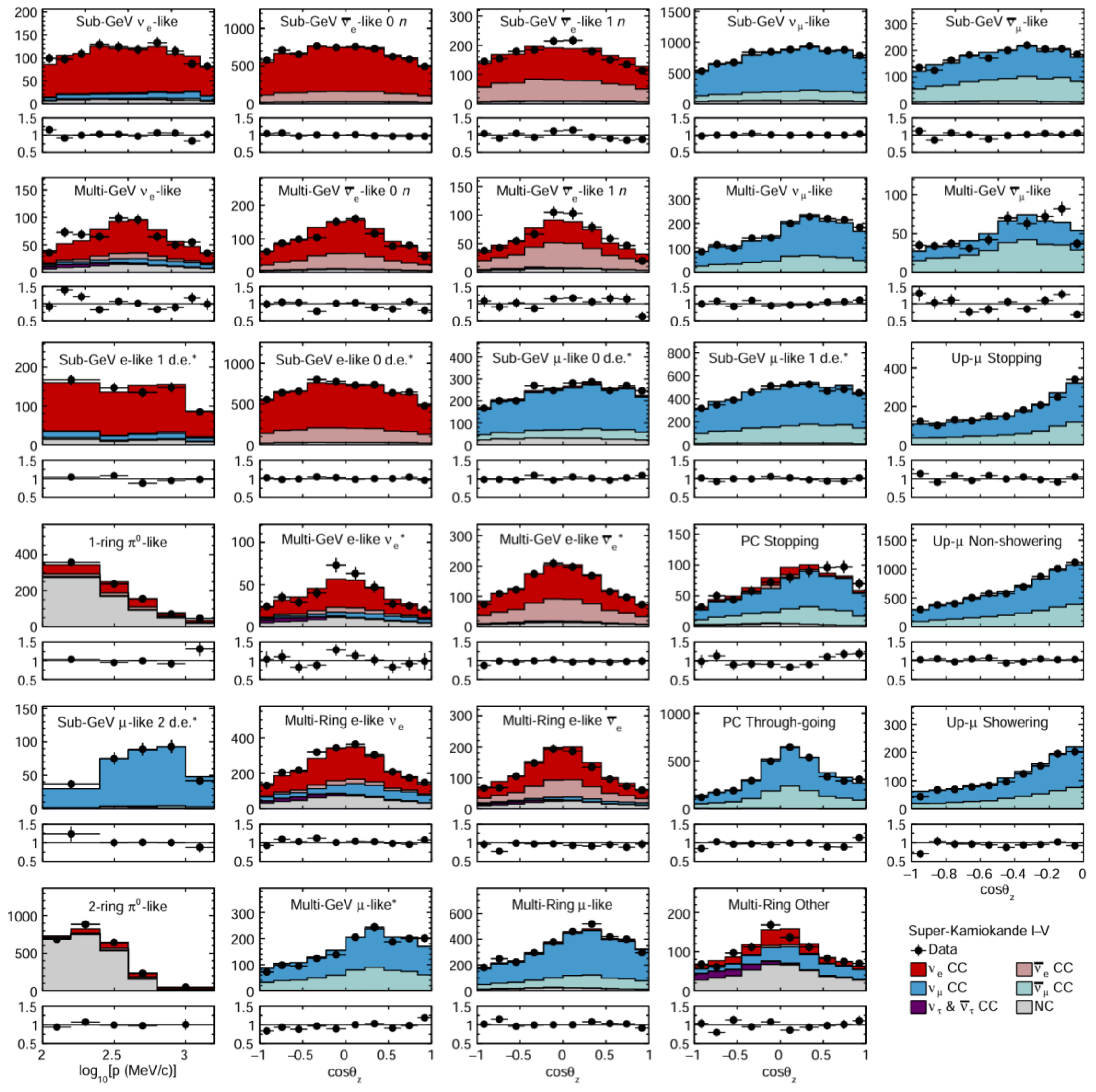


New Event Classes

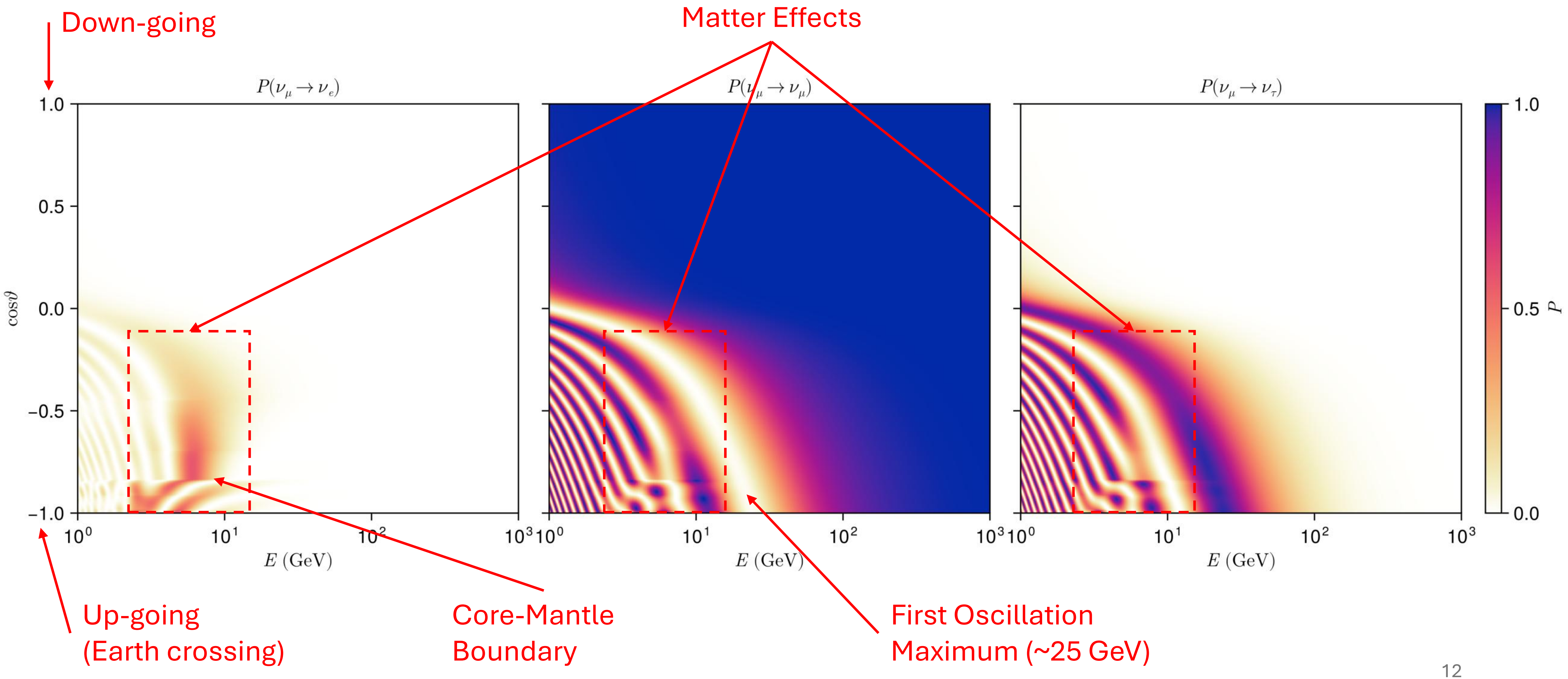
1998: (8 classes)



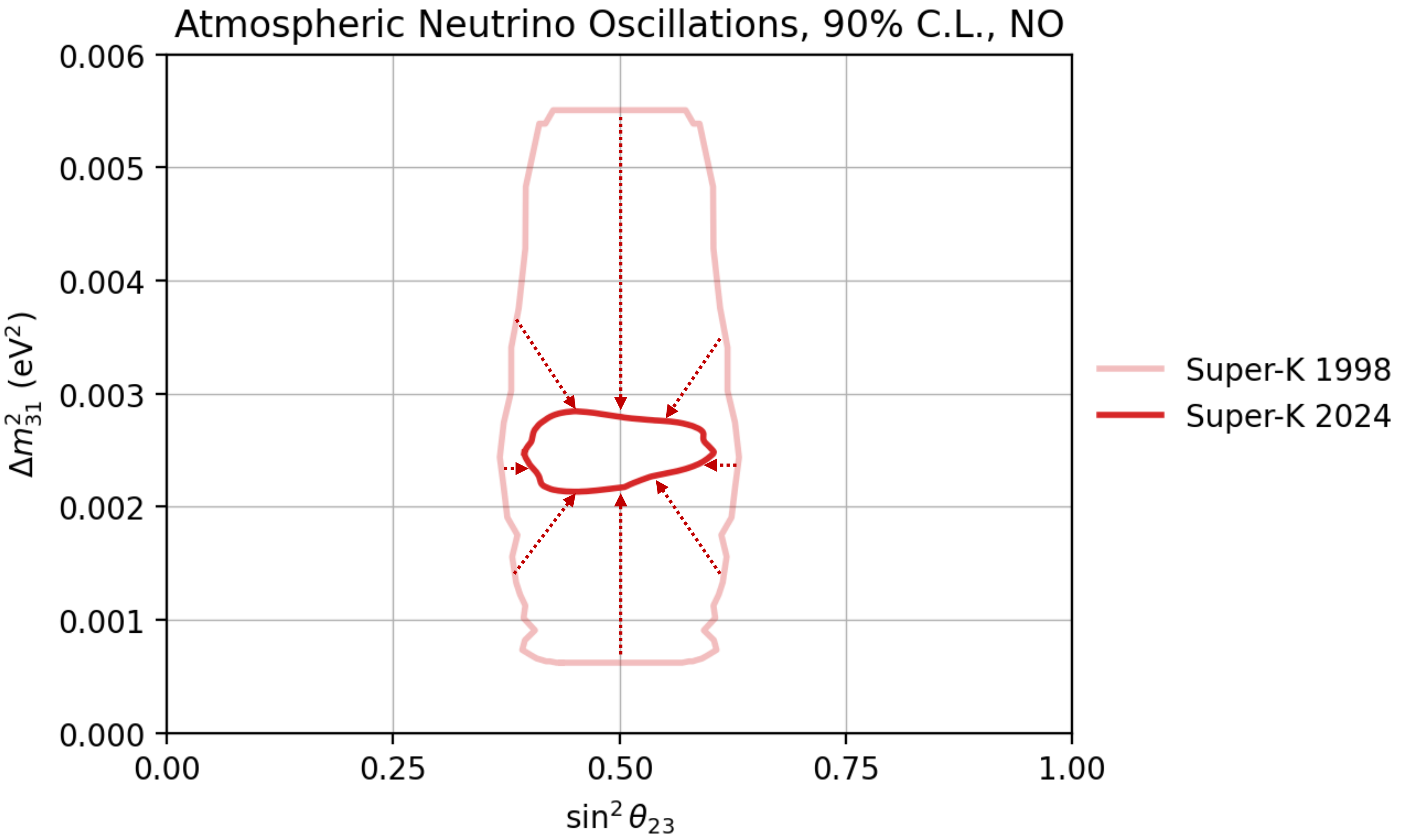
Now: (29 classes)



3-flavour Oscillations & Matter Effects



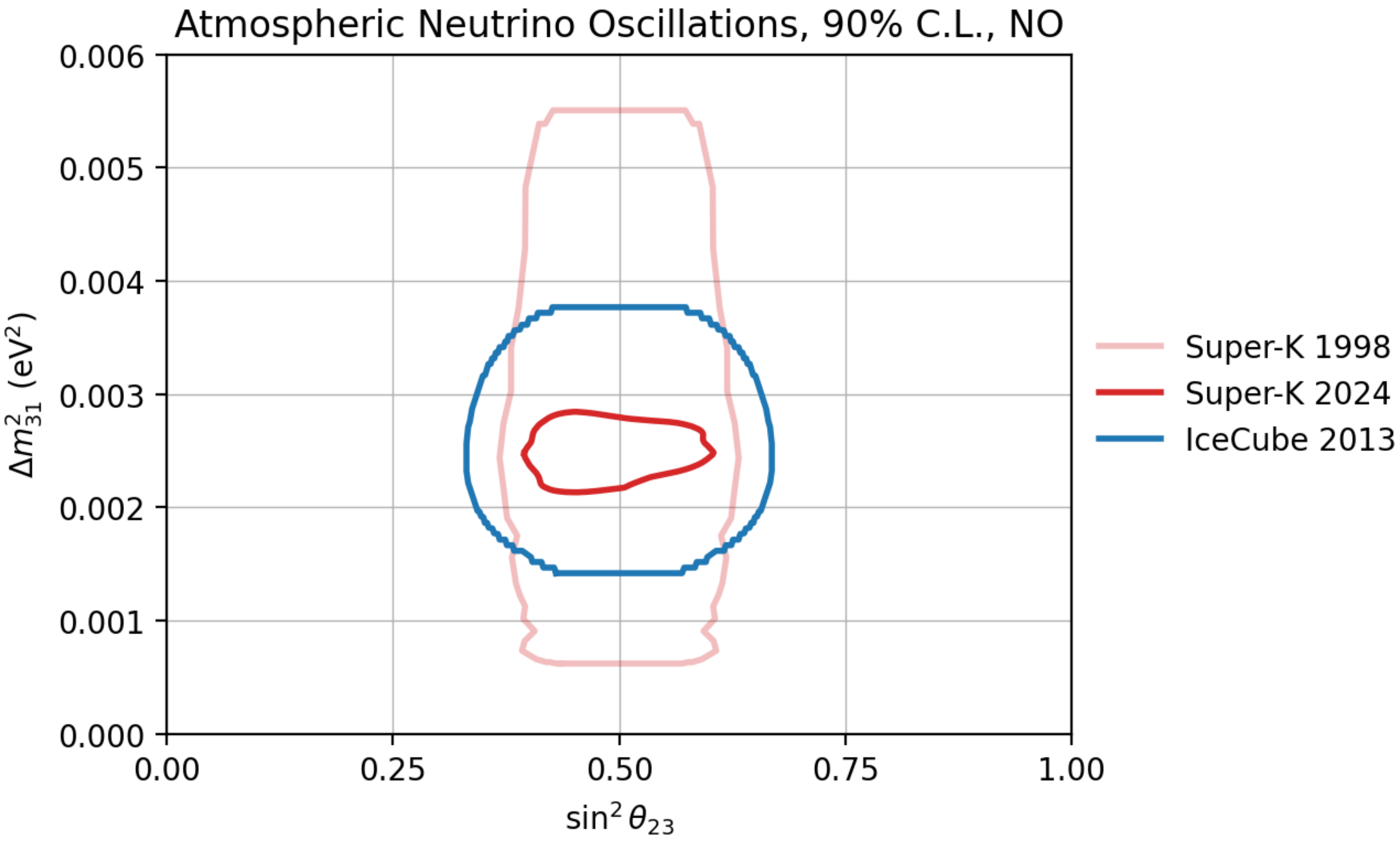
Super-K Latest Results



IceCube

Similar historic progression for IceCube / DeepCore

The first result was published in 2013 after seeing a ***„hole in the sky“***



Newest IceCube Results

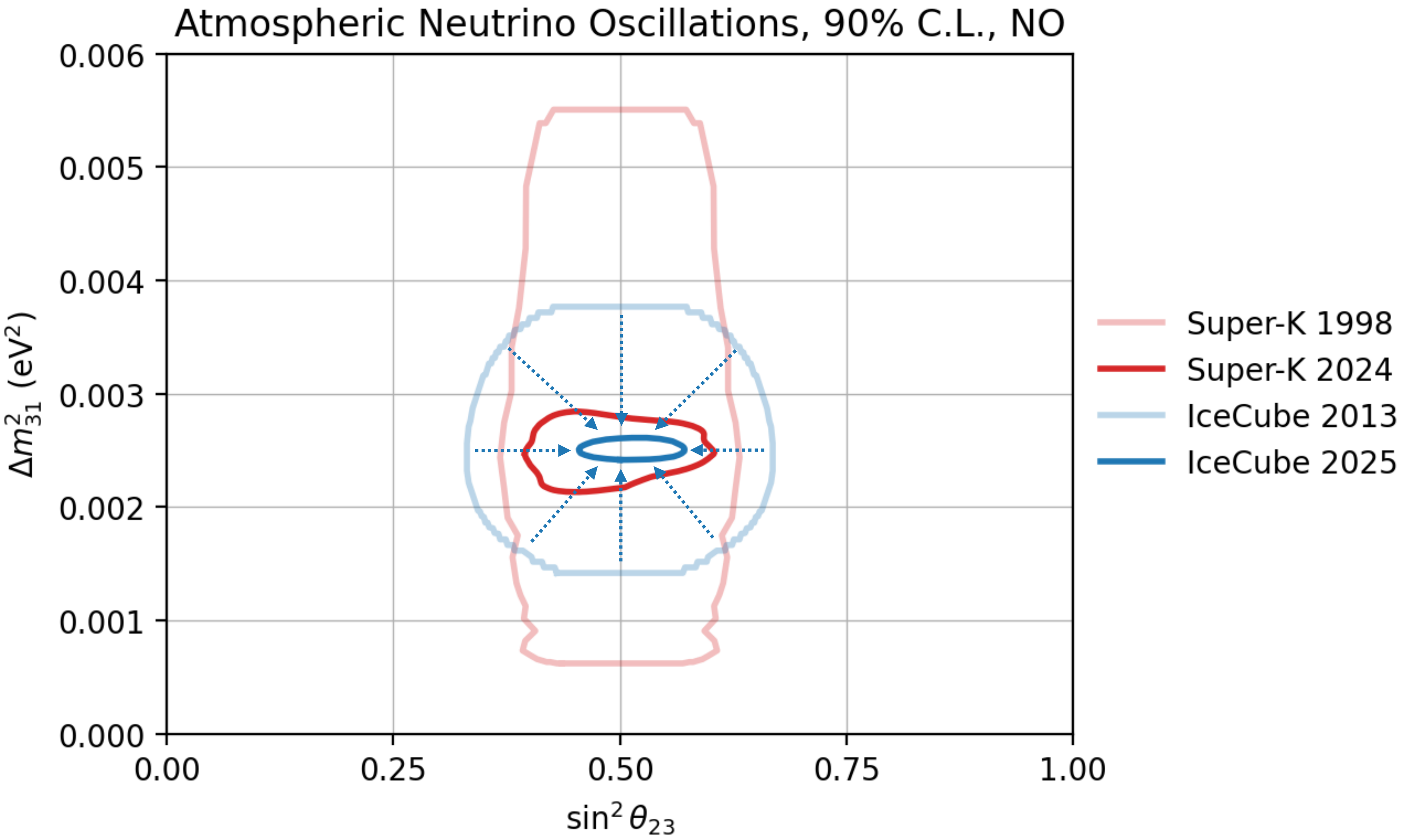
New result from 2025 with 11 years of DC data **(First presented two weeks ago @ NuFact!!)**

- This represents the ~6th iteration of oscillation results for IceCube (2013 – 2015 – 2018/2019 – 2023 - 2024 - 2025)

Changes since 2013:

- Much larger sample: 719 neutrino events → > 100k events
- From 7 systematics → 20 systematics (>40 systematics checked)
- Simple reconstruction → GNN-based ML reconstruction
- Improved calibration, simulation, ice modelling, etc.

Newest IceCube Results

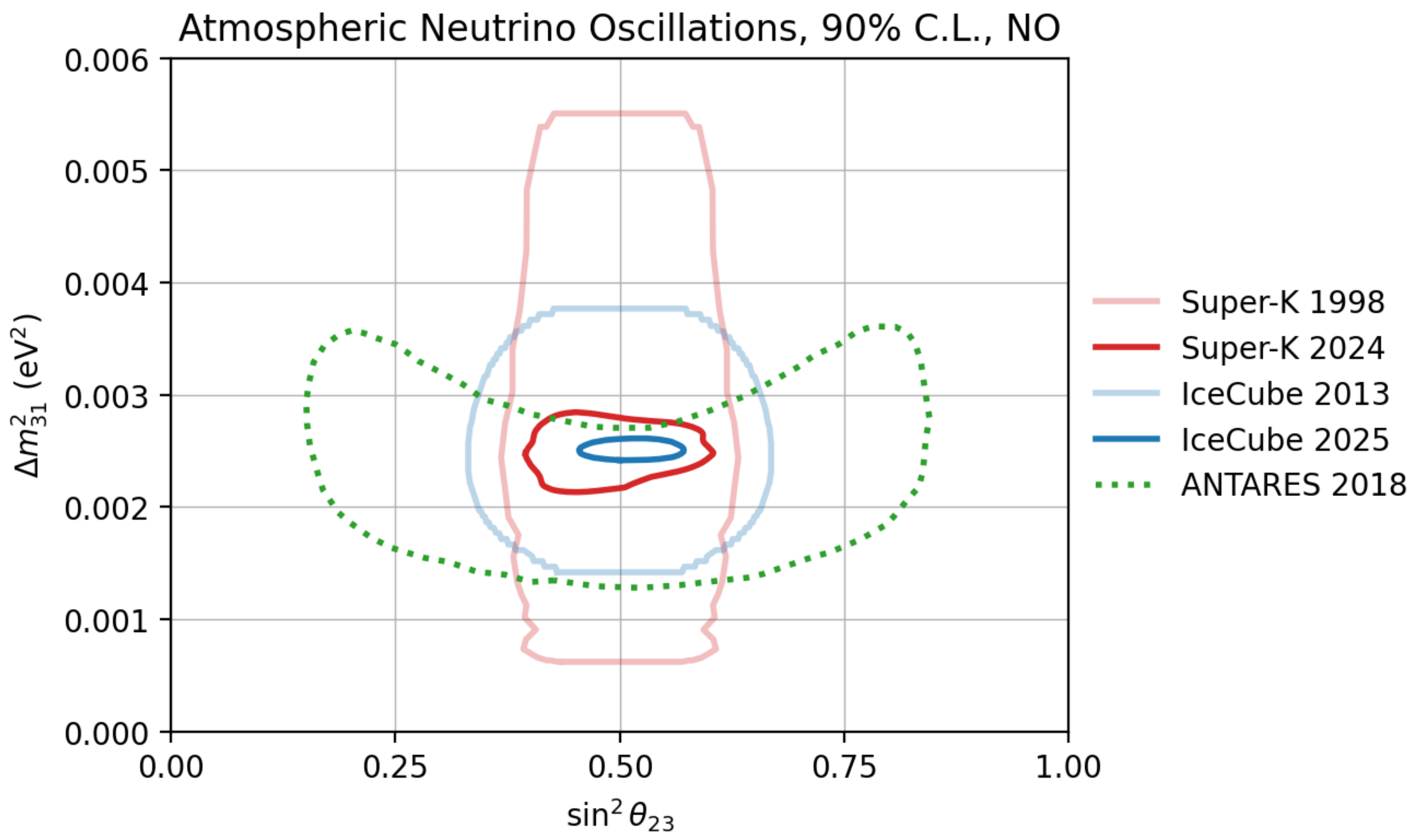


Meanwhile in the Mediterranean...

ANTARES has put out oscillation measurements in 2012 and in 2018

- Limited sensitivity because first oscillation peak is right at the energy threshold of the detector

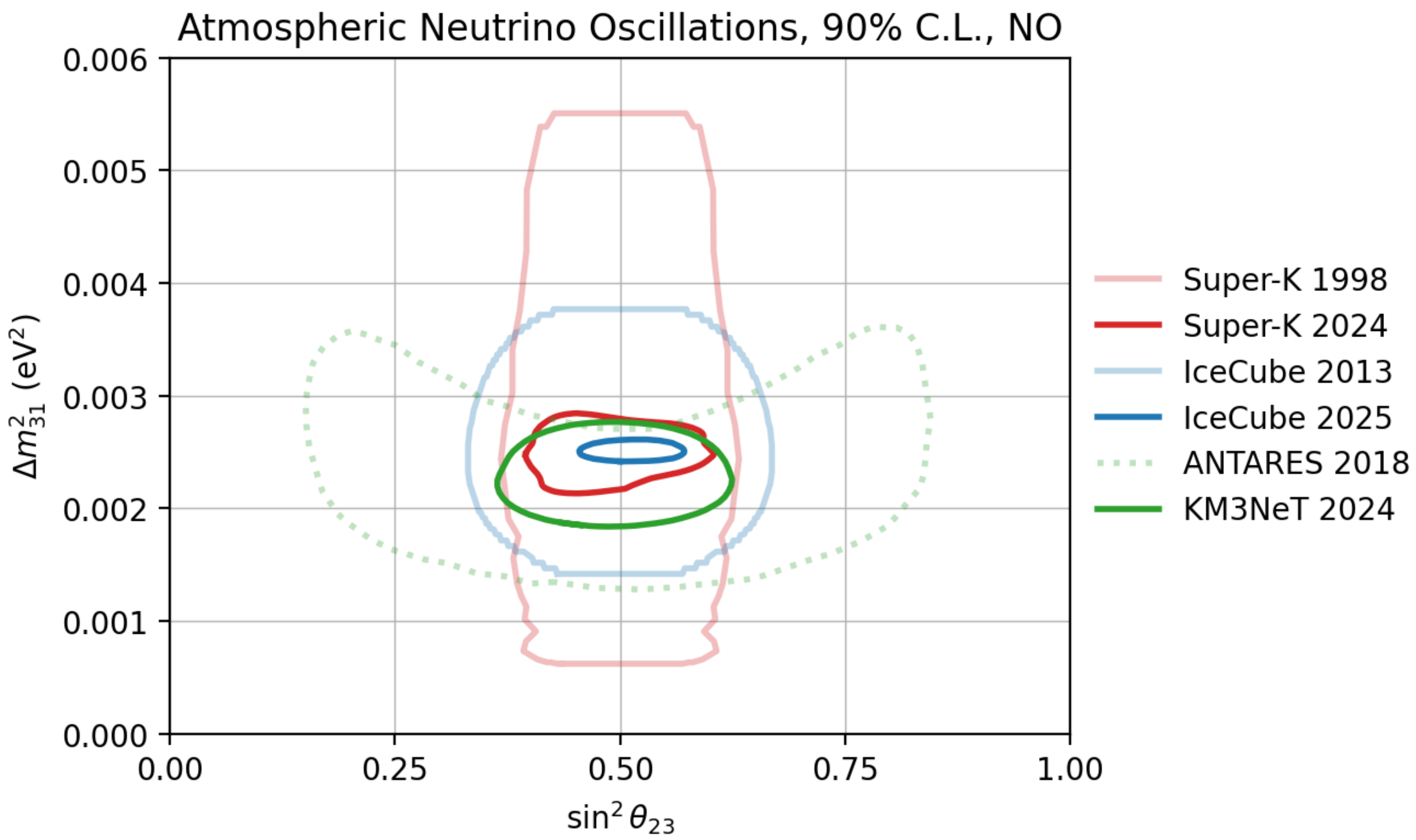
→ **ORCA**, however, is optimized for oscillations (see next slide)



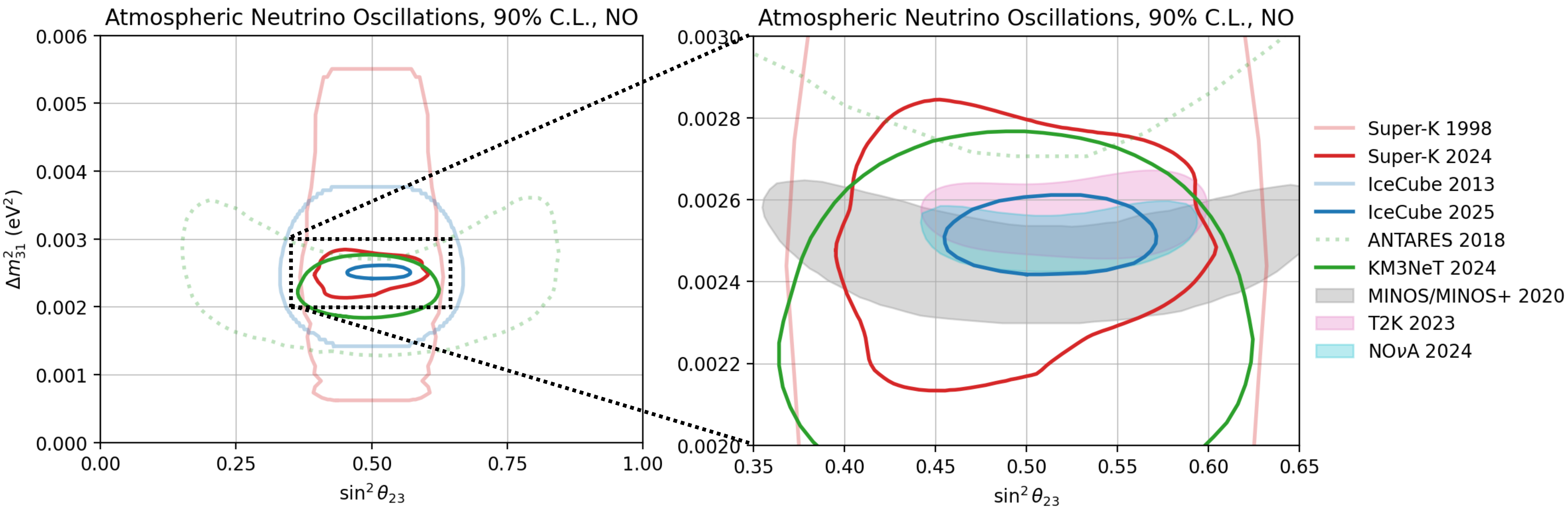
ORCA First Results

- **First ORCA results** based on a six-string detector configuration from **2024**
- Based on 510 days / 433 kton-year, and updated already to 715 kton-year
- 13 systematics in the fit

→ Much more is expected to come after these initial results



Global Landscape



Precision in oscillation parameters is at the same level as T2K and NOvA!

Neutrino Mass Ordering

Neutrino Mass Ordering (NMO)

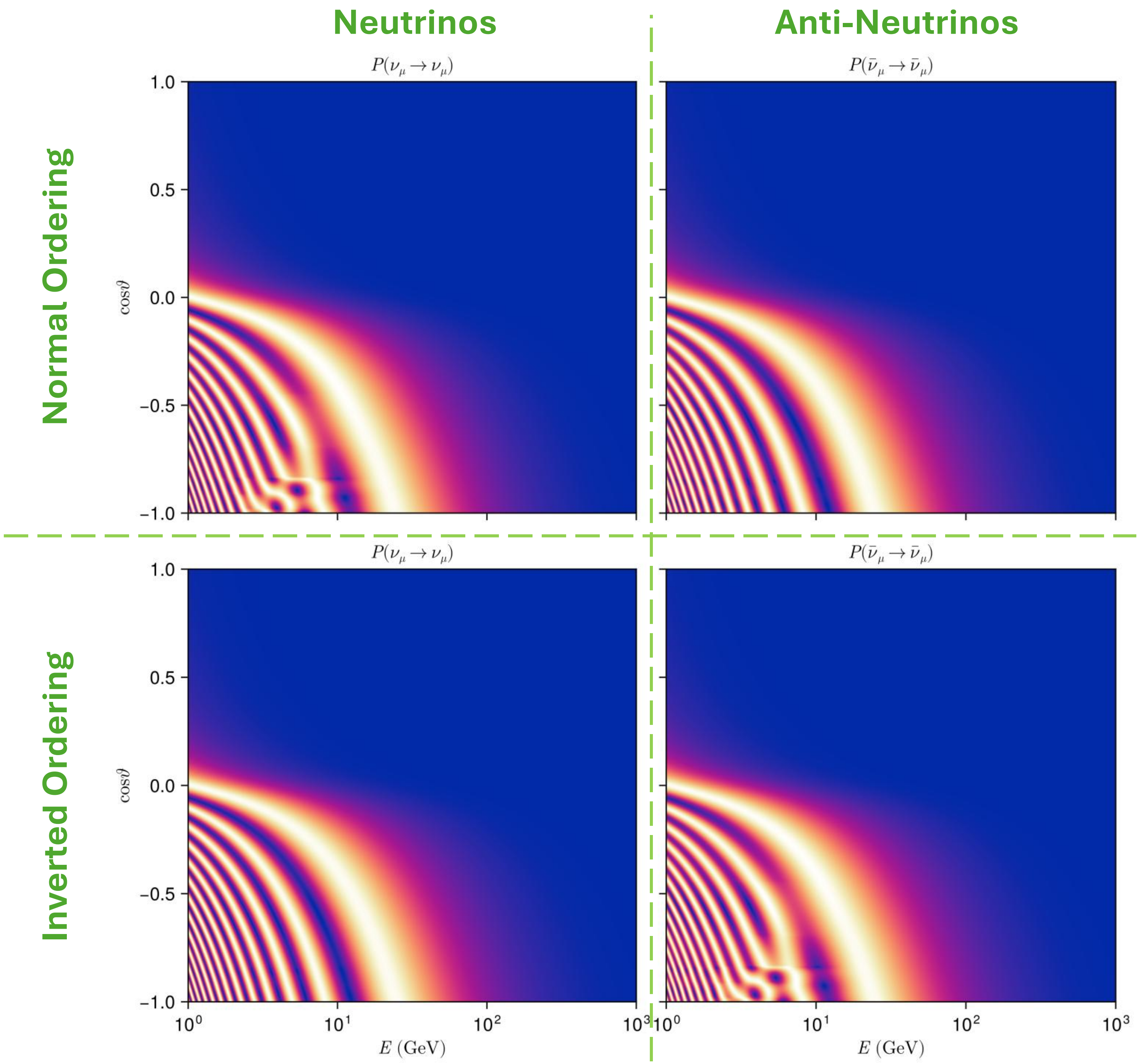
The Question: Is $\Delta m^2_{31} > 0$ („normal“) or $\Delta m^2_{31} < 0$ („inverted“) ?

Using neutrino oscillations, NMO can be measured in two ways:

- Relative phase between fast (Δm^2_{31}) and slow (Δm^2_{21}) oscillations:
  → **JUNO**

- Via matter effects (see next slide):
  → **LBL (T2K, NOvA, DUNE, ...):** separate nu and nubar modes ✅, but degeneracy with CP phase ❌, low-statistics ❌

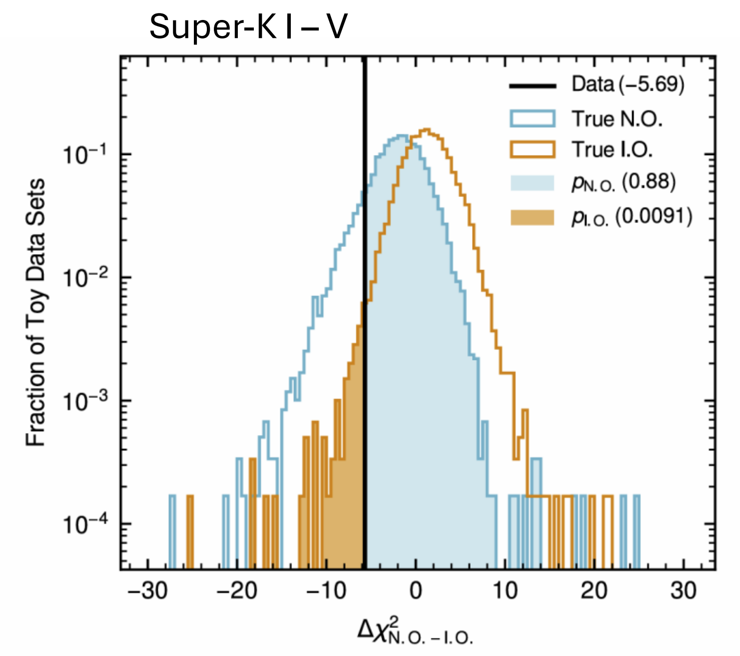
  → **Atmospheric Neutrinos:** large baselines/matter effects ✅, no clean nu-nubar separation ❌, high statistics ✅

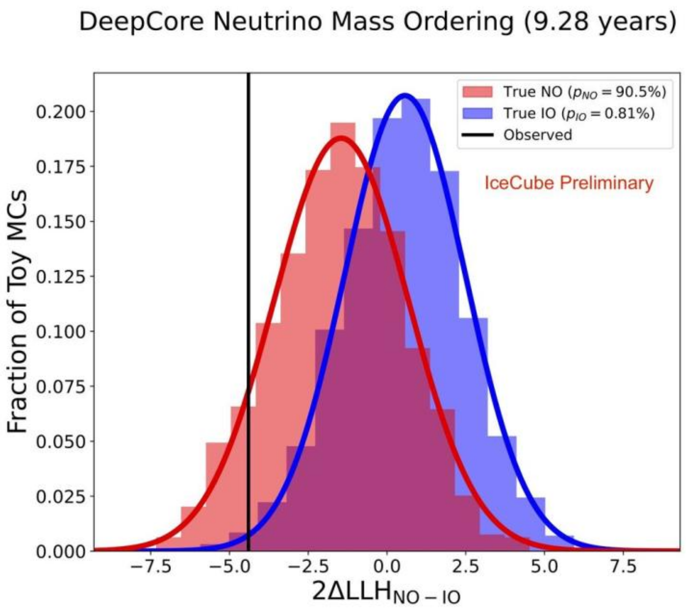


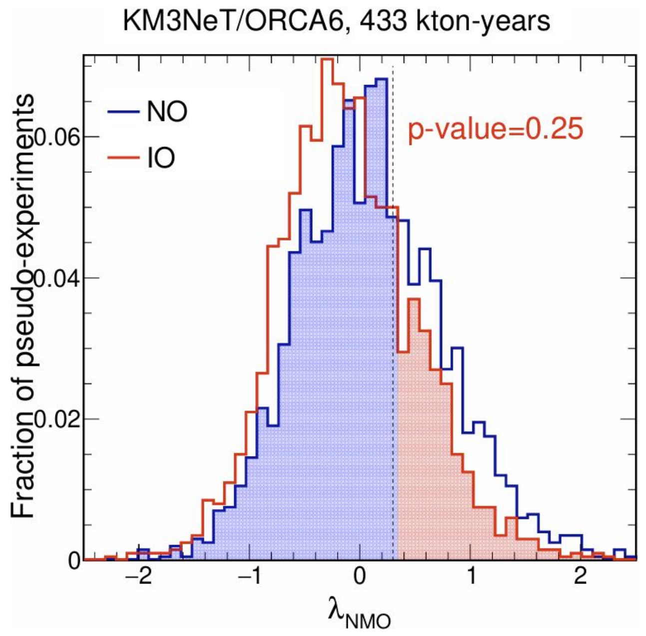
Neutrinos
Anti-Neutrinos
Normal Ordering
Inverted Ordering
$P(\nu_\mu \to \nu_\mu)$
$P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$
$P(\nu_\mu \to \nu_\mu)$
$P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$
$\cos\vartheta$
1.0
0.5
0.0
−0.5
−1.0
10^0
10^1
10^2
10^3
E (GeV)

(*) CLs = $p_0/(1-p_1)$

Current NMO results







p_{IO} = 0.0091
P_{NO} = 0.88
CLs of 0.076

p_{IO} = 0.0081
P_{NO} = 0.905
CLs of 0.085

p_{IO} = 0.25
P_{NO} = 0.65
CLs of 0.71

Observed p-value in Super-K and IceCube is more significant than expected.
Using CLs to somewhat account for this:
→ very slight preference for NO over IO, but nothing yet conclusive

Beyond Standard Oscillations

PMNS unitarity studies

A test for the **unitarity conditions**, i.e. whether basic assumptions hold / probabilities are conserved

$$U^\dagger U = UU^\dagger = 1$$

For example, additional right-handed neutrinos could break this unitarity

→ The 3x3 PMNS matrix would only be a **sub-matrix N** of a larger Unitary matrix

$$\begin{pmatrix} N_{e1} & N_{e2} & N_{e3} & & \\ N_{\mu 1} & N_{\mu 2} & N_{\mu 3} & \cdots & ? \\ N_{\tau 1} & N_{\tau 2} & N_{\tau 3} & & \\ & \vdots & & \ddots & \\ & ? & & & ? \end{pmatrix}$$

Studies had been performed based on **reactor**, **solar**, and **accelerator** neutrinos, but typically omitted atmospheric neutrinos

→But **atmospheric neutrinos** offer a unique opportunity to probe the ν_τ sector

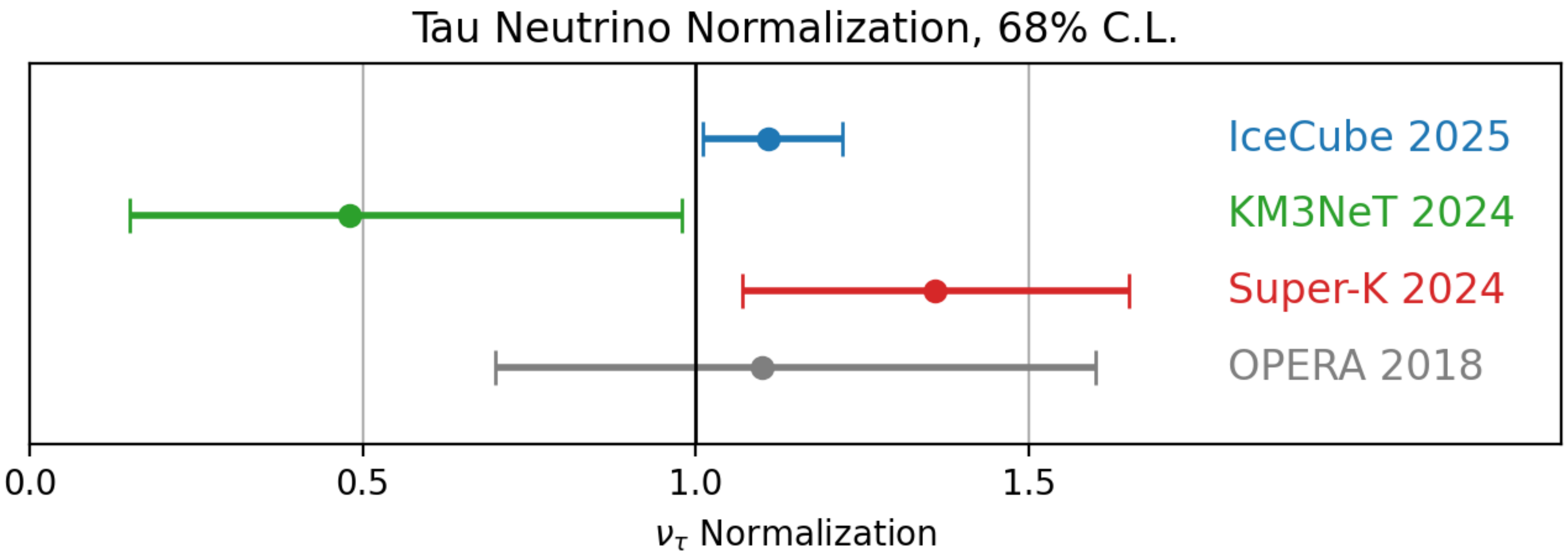
→since ν_τ CC interactions only accessible for E > 3.5 GeV

Option 1: Nutau Normalization

Introducing a parameter to break the unitarity of the mixing

→Scale the ν_τ appearance signal with a „ν_τ Normalization“ parameter rel. to the ν_μ disappearance

- ν_τ Normalization = 1 → Unitarity
- ν_τ Normalization = 0 → Absence of ν_τ



Option 2: PMNS Perturbation

Assume a non-unitry mixing matrix N in place of U

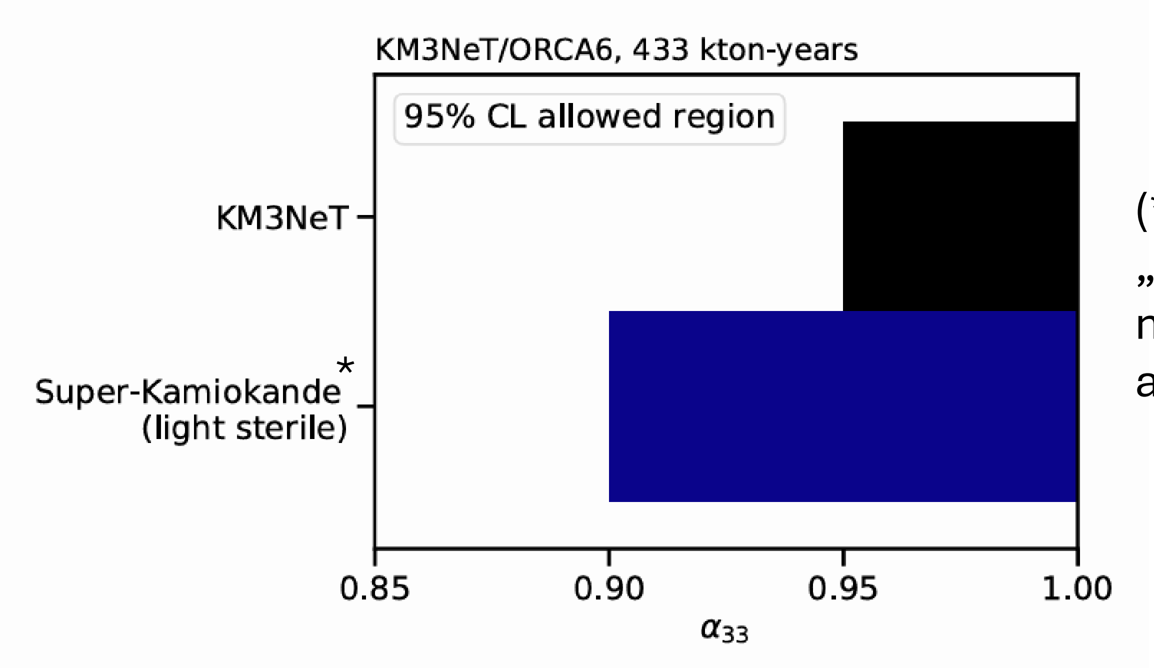
How much can the PMNS Matrix be perturbed with non-unitarity?

→ Multiplication of U by a lower-triangular matrix:

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

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

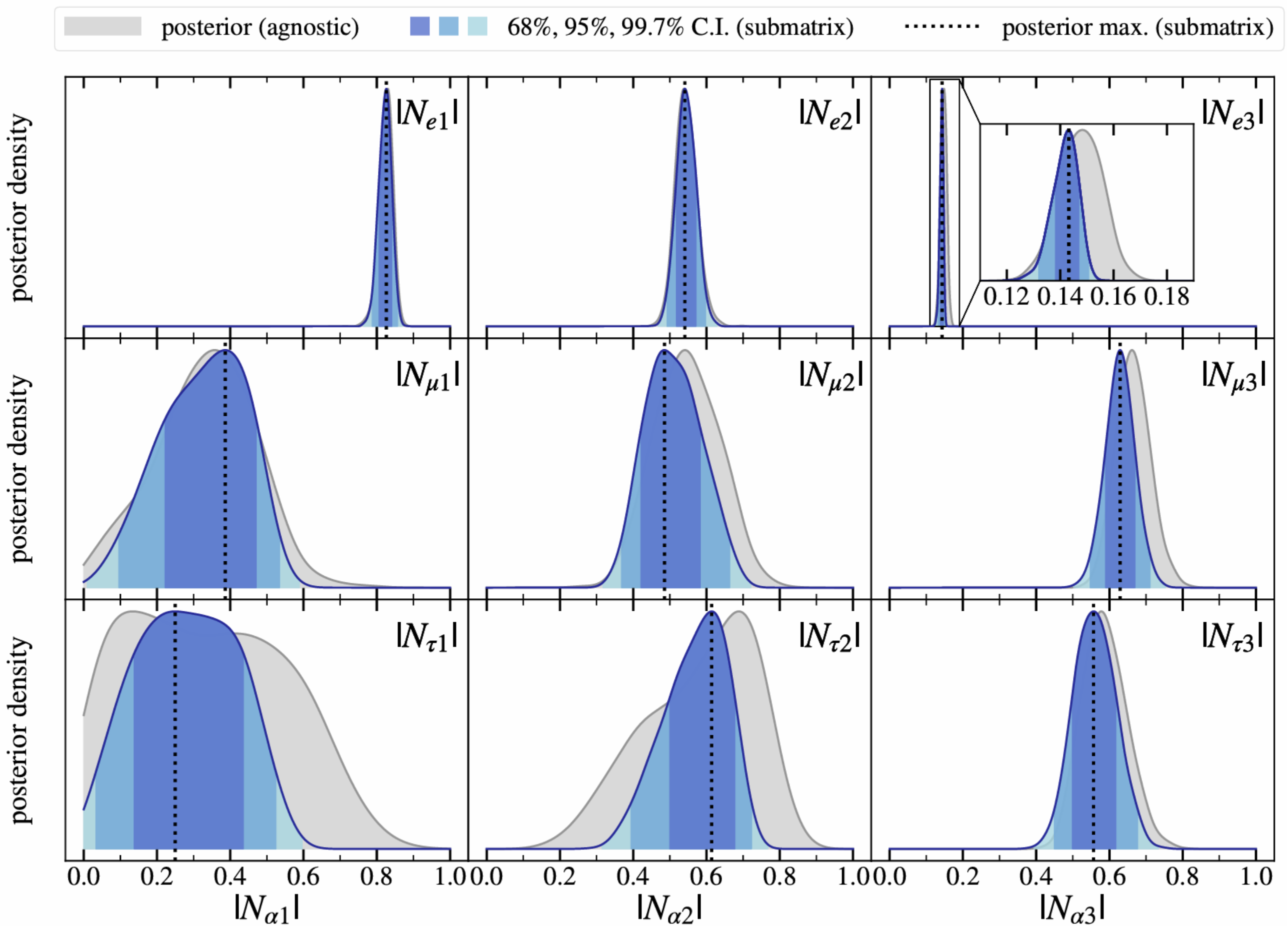
First ORCA6 results:



(*) derived from „multiple sterile neutrino analysis“

Option 3: Arbitrary Mixing Matrix

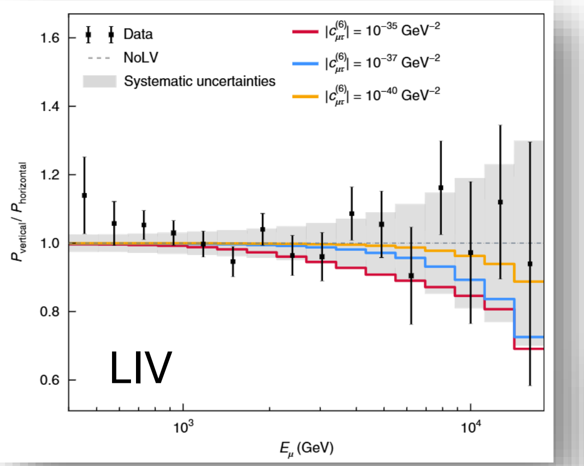
- Fitting an arbitrary 3x3 N mixing matrix (agnostic case), or a 3x3 submatrix N of a larger unitary matrix
- Fit including DayaBay, KamLAND, and **IceCube**
- Atmospheric neutrinos relevant in the $\nu_\mu \leftrightarrow \nu_\tau$ sector
- Everything compatible with unitary mixing



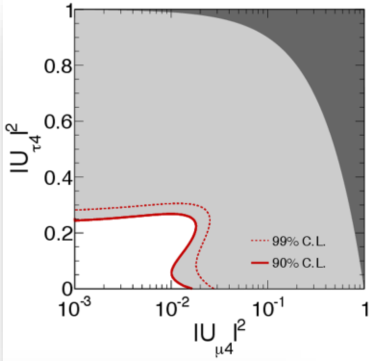
More BSM physics

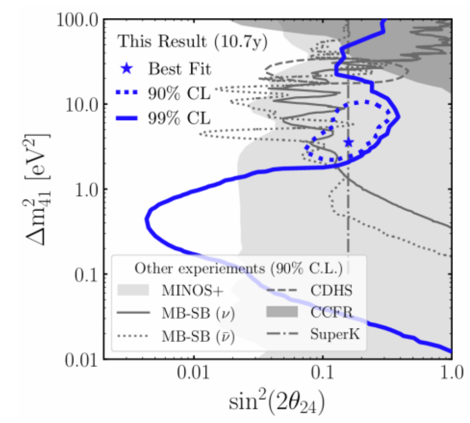
In WCDs, we have a wide range of model-dependent BSM searches based on atm. Neutrinos (incomplete list):

- **3+1 eV-scale sterile neutrinos**
  → MSW resonance at TeV energies
- **Non-standard interactions (NSIs)**
  → Altered matter effects
- **Lorentz Invariance Violation**
  → Spectral Distortion, e.g. depending on angle
- **Quantum Decoherence**
  → Damping of oscillations
- **Extra Dimensions**
  → Multiple MSW resonances from Kaluza-Klein excitations

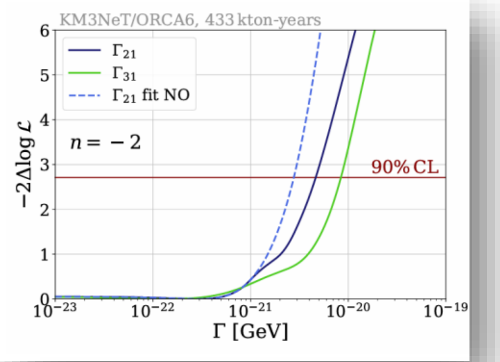


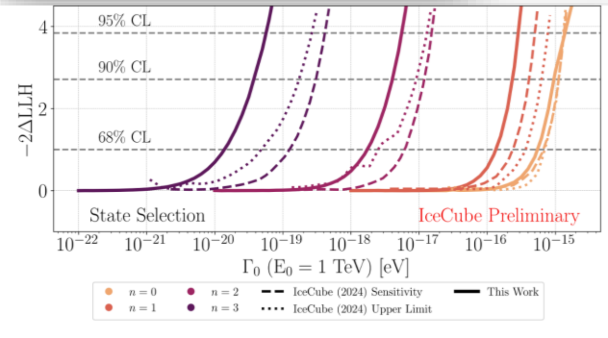
Steriles:



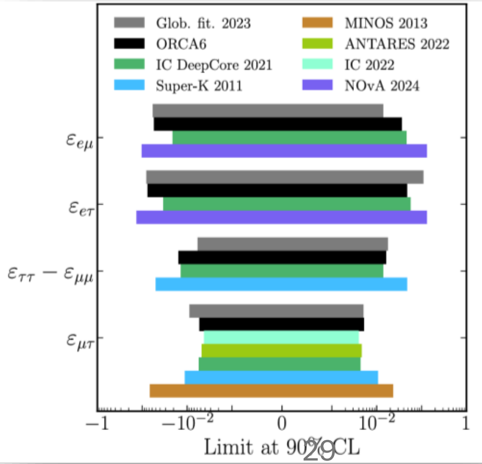


Decoherence:





NSIs:



What does the Future Hold?

New / Upgraded Detectors:

- Super-K Gadolinium / Hyper-K
- IceCube Upgrade
- Full KM3NeT ORCA

Exciting new results / new precision era projected!

Joint Analyses:

- Super-K + T2K joint fit (2025!)
- ORCA + IceCube-Upgrade joint fit (active working group)
- Global fits

Huge benefits from combining data!

Conclusions

- Atmospheric neutrinos have been a main driver in oscillation measurements since right from the beginning
  - Analyses were refined over many years and iterations, and large datasets collected
    - Today, the latest results from WCDs are among the most precise
      - Offers unique opportunities to measure:
        - Neutrino Mass Ordering via Matter Effects
        - Oscillation into tau sector (→ non-unitarity)
        - Rich program of BSM physics
          - Exciting future ahead with ongoing detector upgrades and new experiments being built

References Super-K

Based on Super-K I-V:

- Atmospheric neutrino oscillation analysis with neutron tagging and an expanded fiducial volume in Super-Kamiokande I–V

Based on Super-K IV:

- First Joint Oscillation Analysis of Super-Kamiokande Atmospheric

Based on Super-K I-IV:

- Limits on sterile neutrino mixing using atmospheric neutrinos in Super-Kamiokande

References IceCube

Based on 9.3 years (previous result):

- Measurement of atmospheric neutrino oscillation parameters using convolutional neural networks with 9.3 years of data in IceCube DeepCore

Based on 3 years:

- Constraints on non-unitary neutrino mixing in light of atmospheric and reactor neutrino data
- Measurement of Atmospheric Tau Neutrino Appearance with IceCube DeepCore

References KM3NeT

Based on ORCA6 433 kt-yr:

- Measurement of neutrino oscillation parameters with the first six detection units of KM3NeT/ORCA
- Study of tau neutrinos and non-unitary neutrino mixing with the first six detection units of KM3NeT/ORCA

Based on ORCA 715 kt-yr

- Updated measurement of atmospheric neutrino oscillation parameters with KM3NeT/ORCA

(**ANTARES 10 year:** Measuring the atmospheric neutrino oscillation parameters and constraining the 3+1 neutrino model with ten years of ANTARES data)