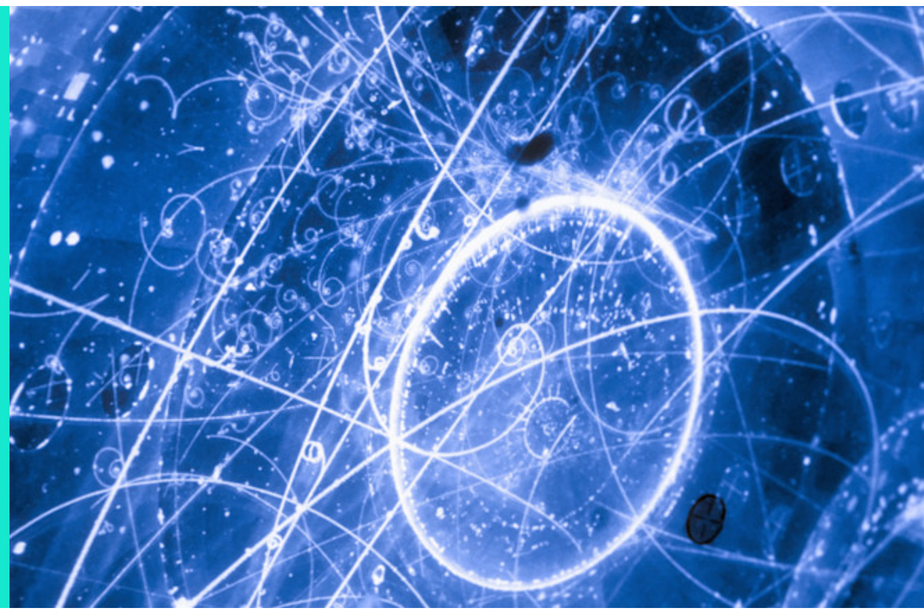
Global Update on Three-Flavor Neutrino Oscillation Parameters



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XXIst Rencontres du Vietnam
Neutrino Physics

Durham University

July 22, 2025

IP3

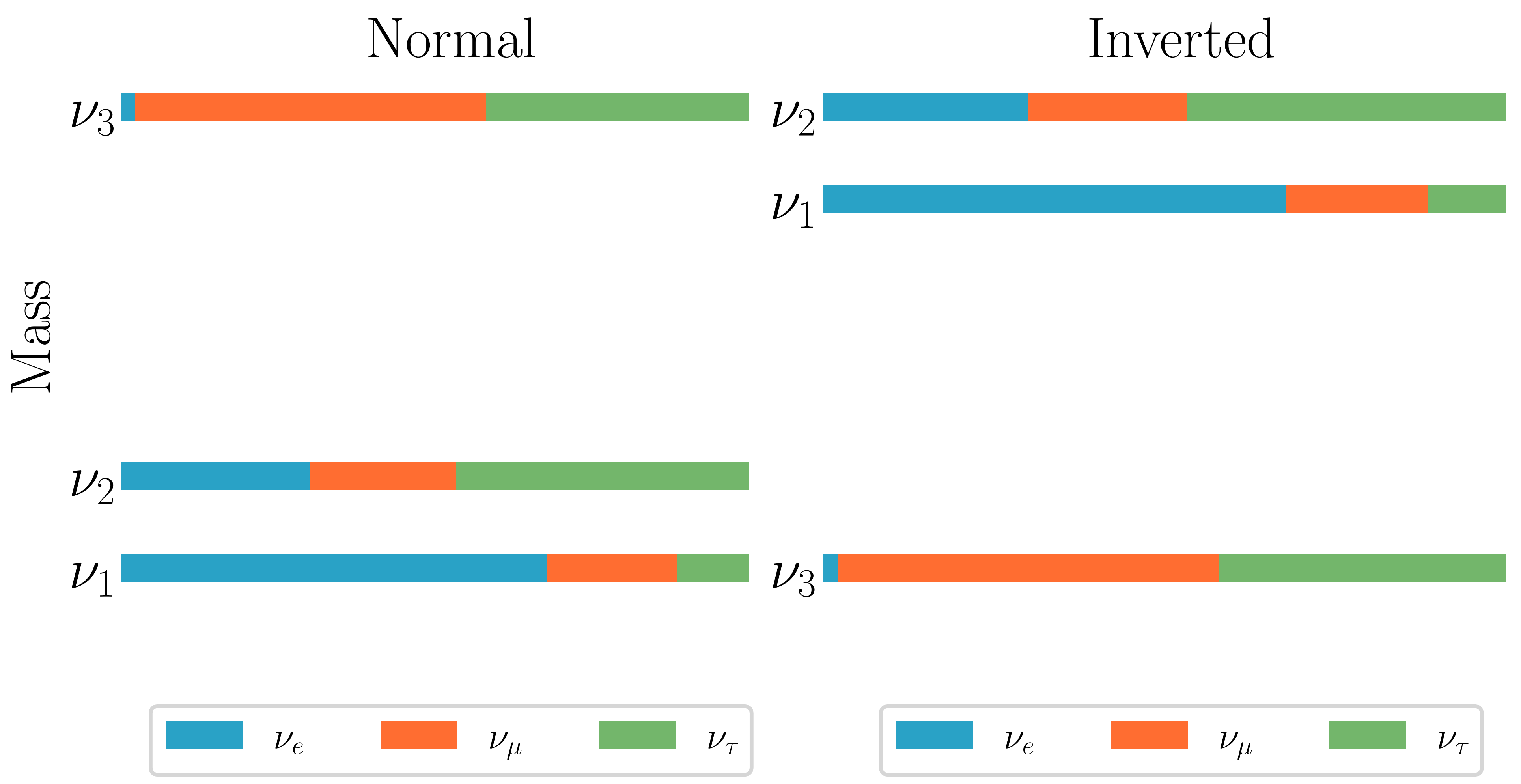
3ν mixing

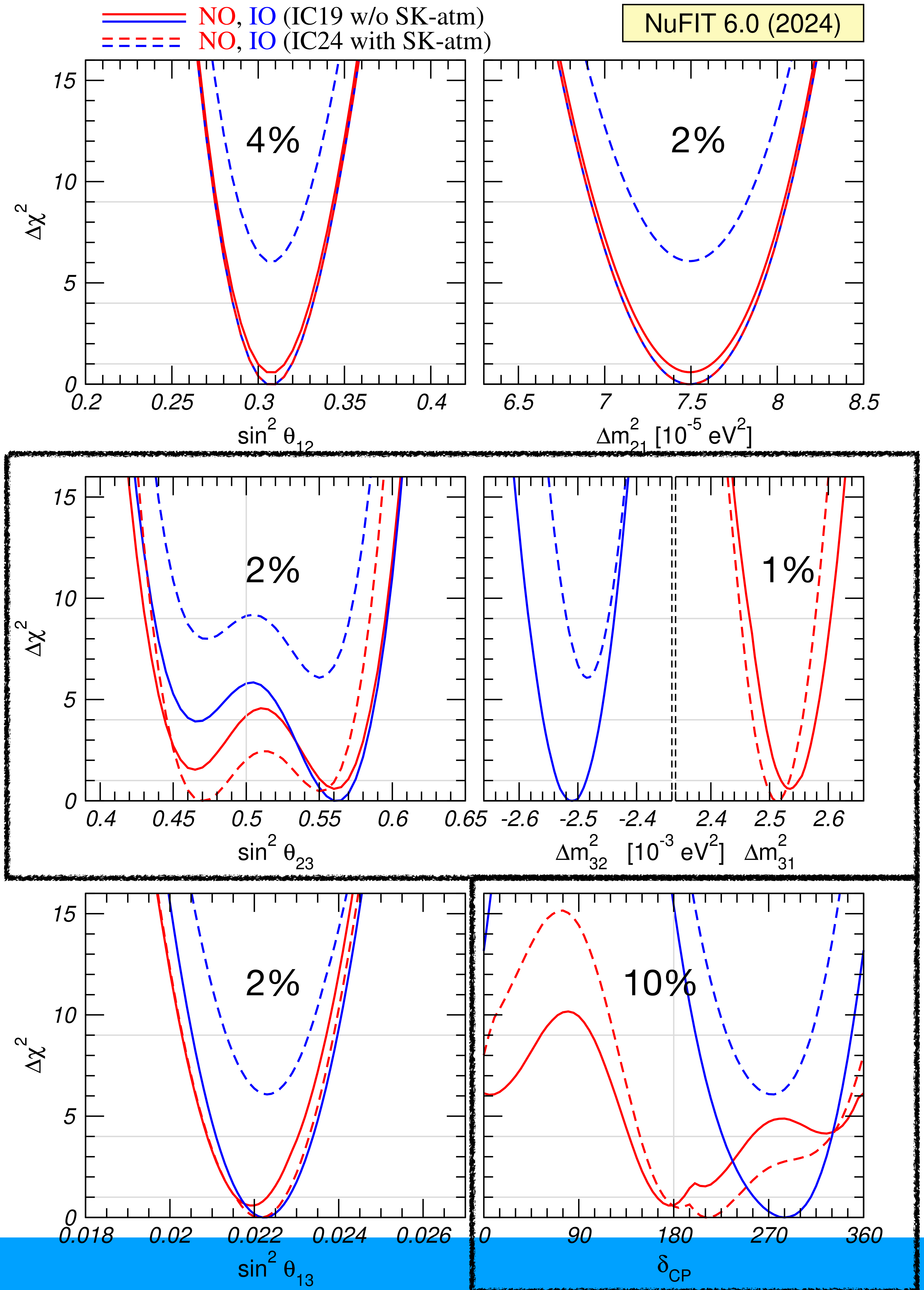
In the 3ν **scenario**, neutrino evolution is described by six parameters

$$i\frac{d\nu}{dE} = \frac{1}{2E}\left(U^\dagger \text{diag}(0,\Delta m^2_{21},\Delta m^2_{31})U\right)\nu$$

$$\nu_\alpha = \sum U_{\alpha i}\nu_i \qquad U = U(\theta_{23})U(\theta_{13},\delta_{cp})U(\theta_{12})$$

Mass ordering





3ν mixing

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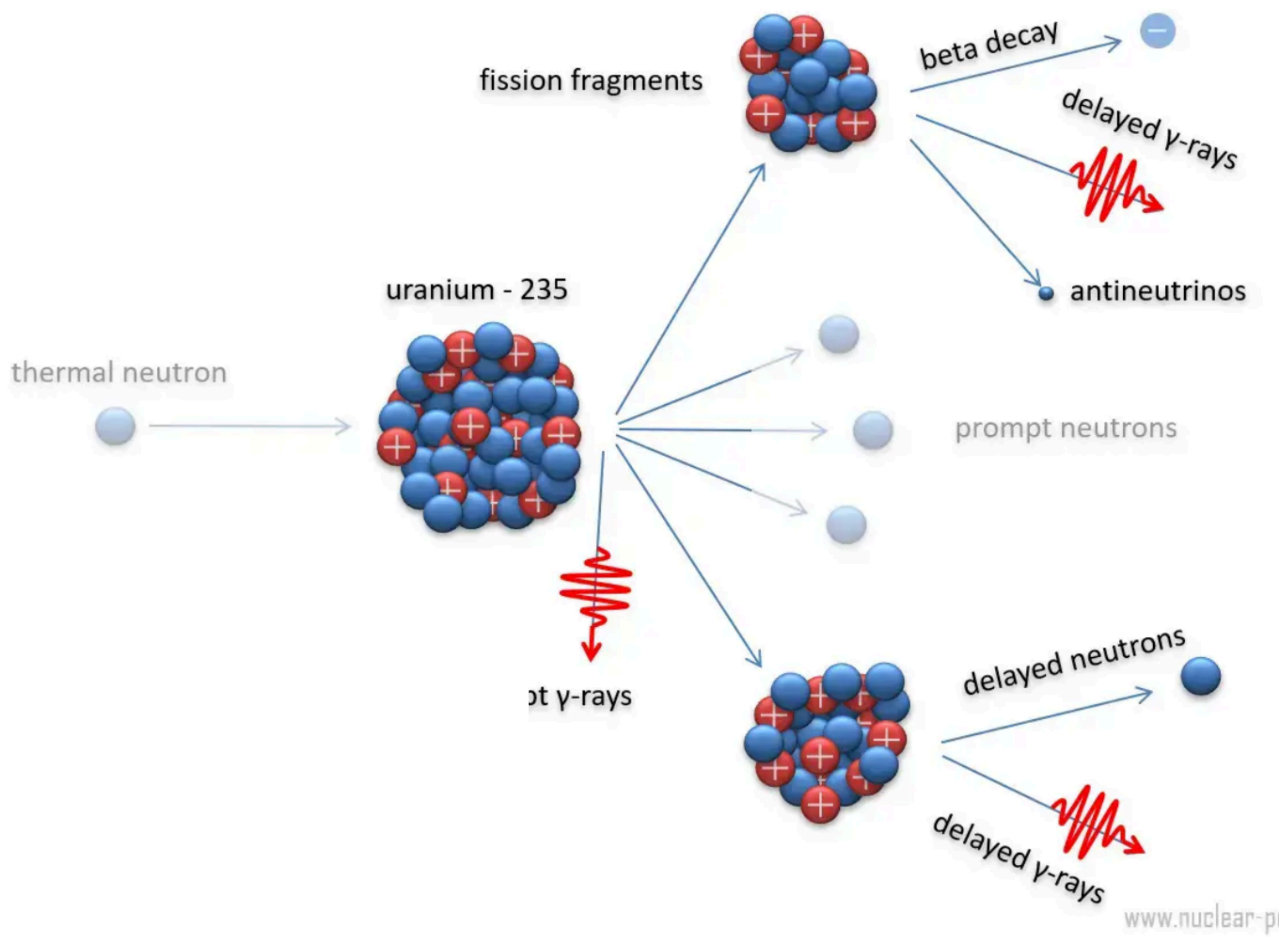
Experiment	Dominant	Important
Solar	$\sin^2\theta_{12}$	Δm^2_{21}
Reactor LBL	Δm^2_{21}	$\sin^2\theta_{12}$
Reactor MBL	$\sin^2\theta_{13}$	$\vert\Delta m^2_{31}\vert$
Atmospheric	$\vert\Delta m^2_{31}\vert$ $\sin^2\theta_{23}$	$\sin^2\theta_{13}$ δ_{cp}
Accelerator Disapp	$\vert\Delta m^2_{31}\vert$ $\sin^2\theta_{23}$	
Accelerator App	δ_{cp}	$sign(\Delta m^2_{31})$ $\sin^2\theta_{23}$ $\sin^2\theta_{13}$

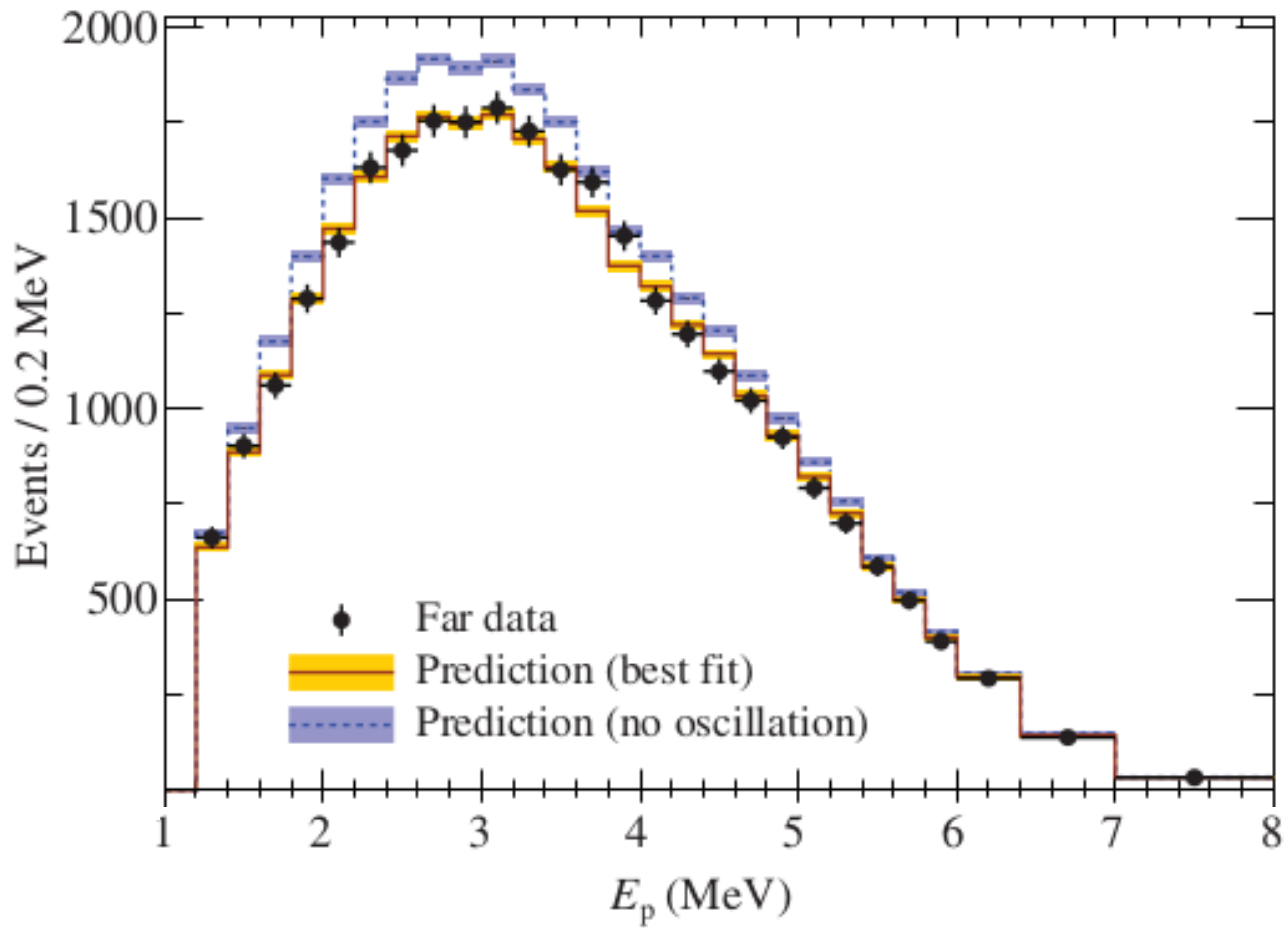
Reactor Neutrinos



In reactor experiments, a **flux of** $\bar{\nu}_e$ is created with energies around the ~ MeV

The neutrino flux is created due to the **fission** of four different isotopes:

$$^{235}\mathrm{U}(\sim 56\%),^{238}\mathrm{U}(\sim 8\%),^{238}\mathrm{Pu}(\sim 30\%),^{241}\mathrm{Pu}(\sim 6\%)$$



Double-Chooz, RENO, and Daya Bay established that $\theta_{13} \neq 0$

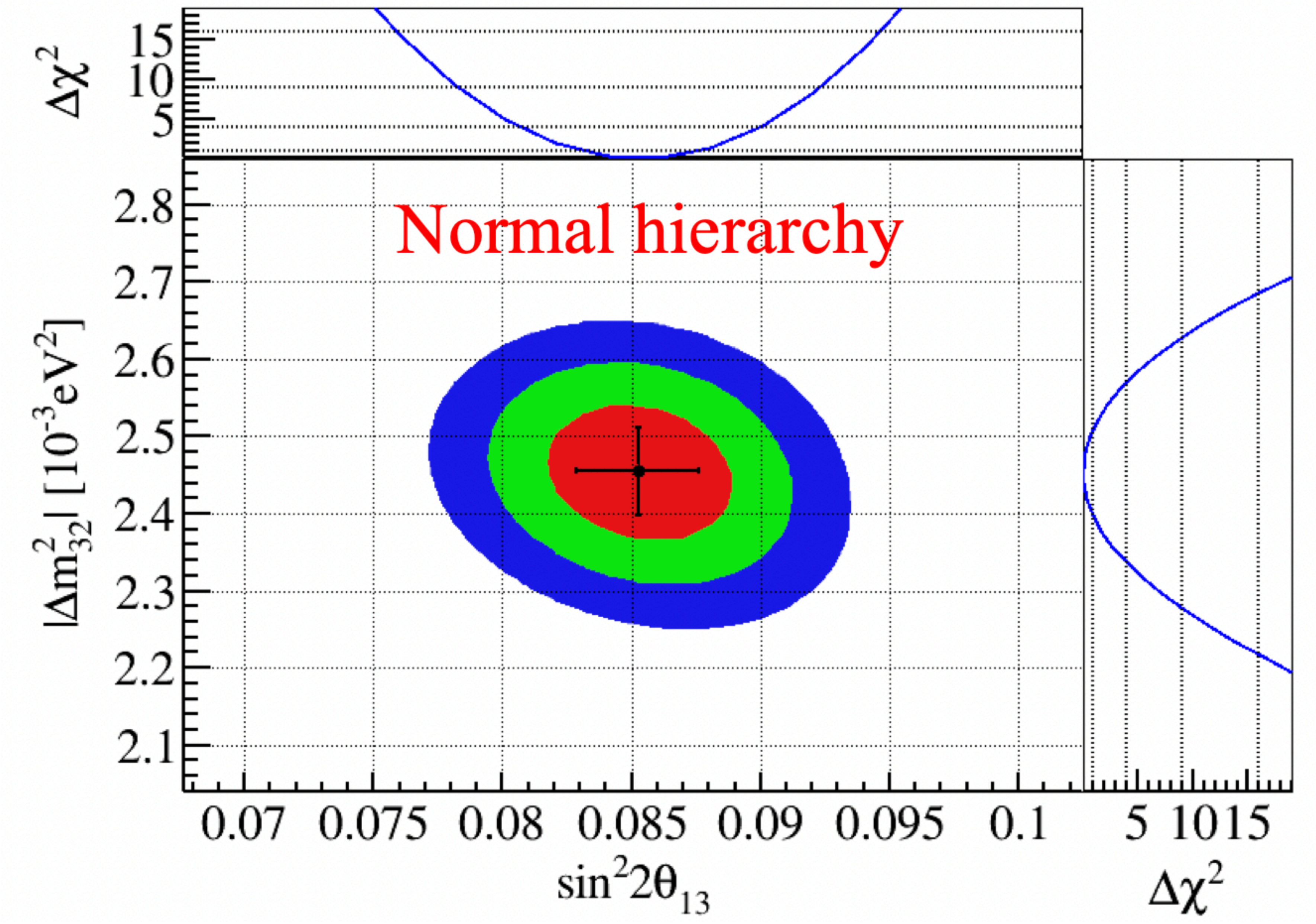
S.H. Seo et al. (RENO) PRD 98 (2018) arXiv:1610.04326

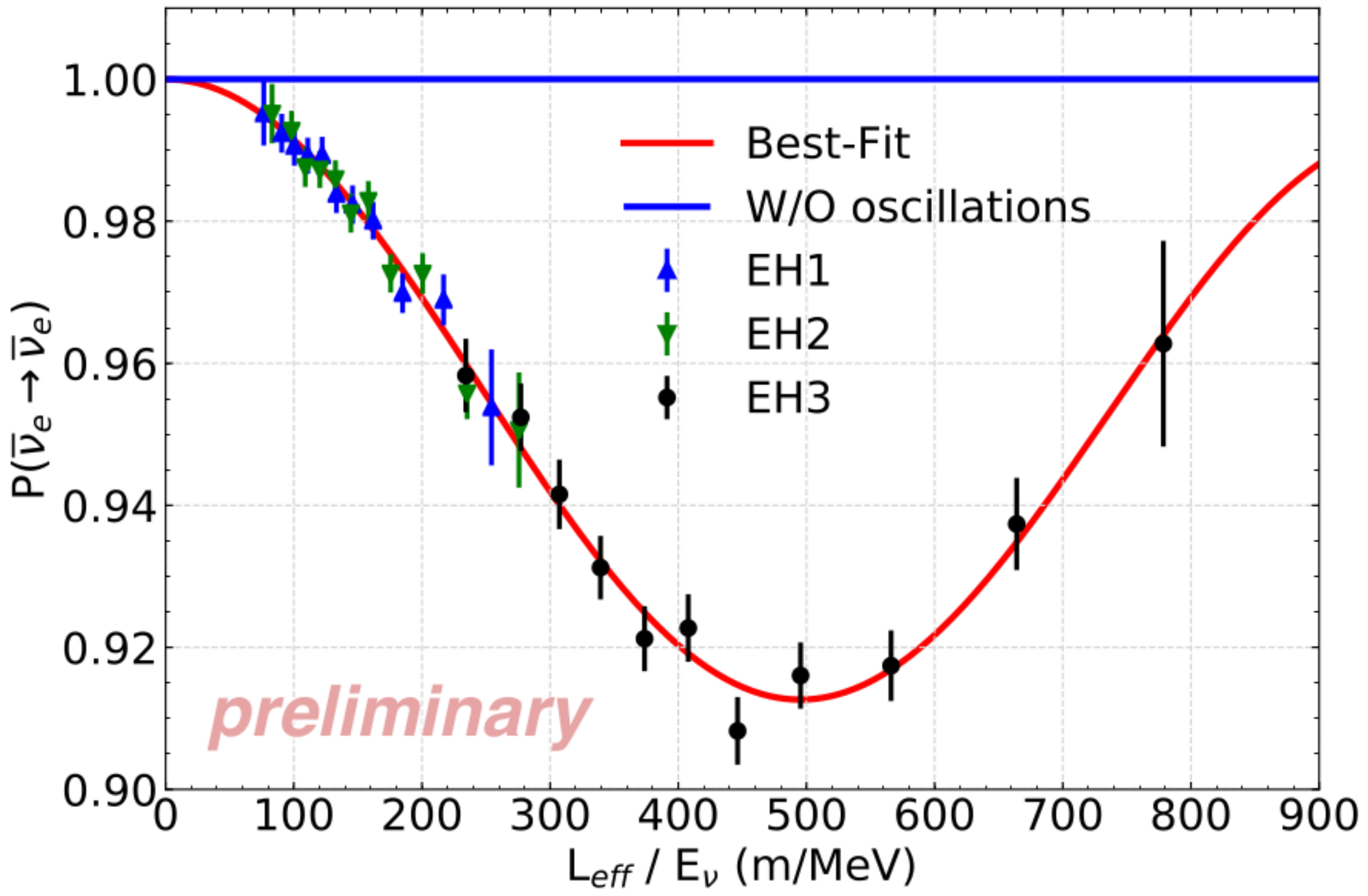
Reactor neutrinos: θ_{13} and Δm^2_{ee}

The **spectral information** from reactor experiments determines θ_{13} and Δm^2_{31}

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee}$$

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

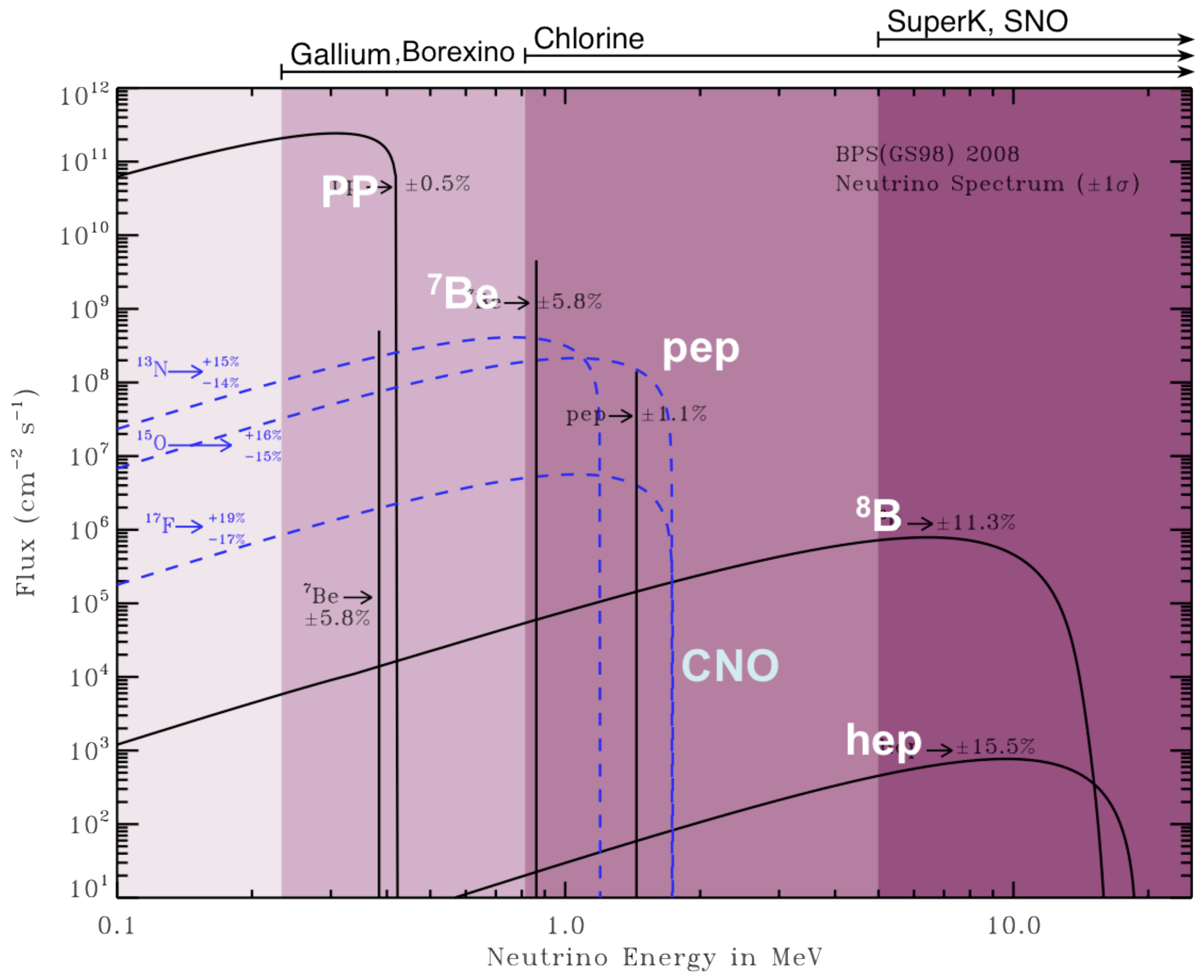




K. Luk (DayaBay) Neutrino 2022

- Near detector imposes an upper bound over Δm^2_{31}
- The oscillation measured at the far detector imposes a lower bound on θ_{13} and Δm^2_{31}

Solar Sector: θ_{12} and Δm^2_{21}

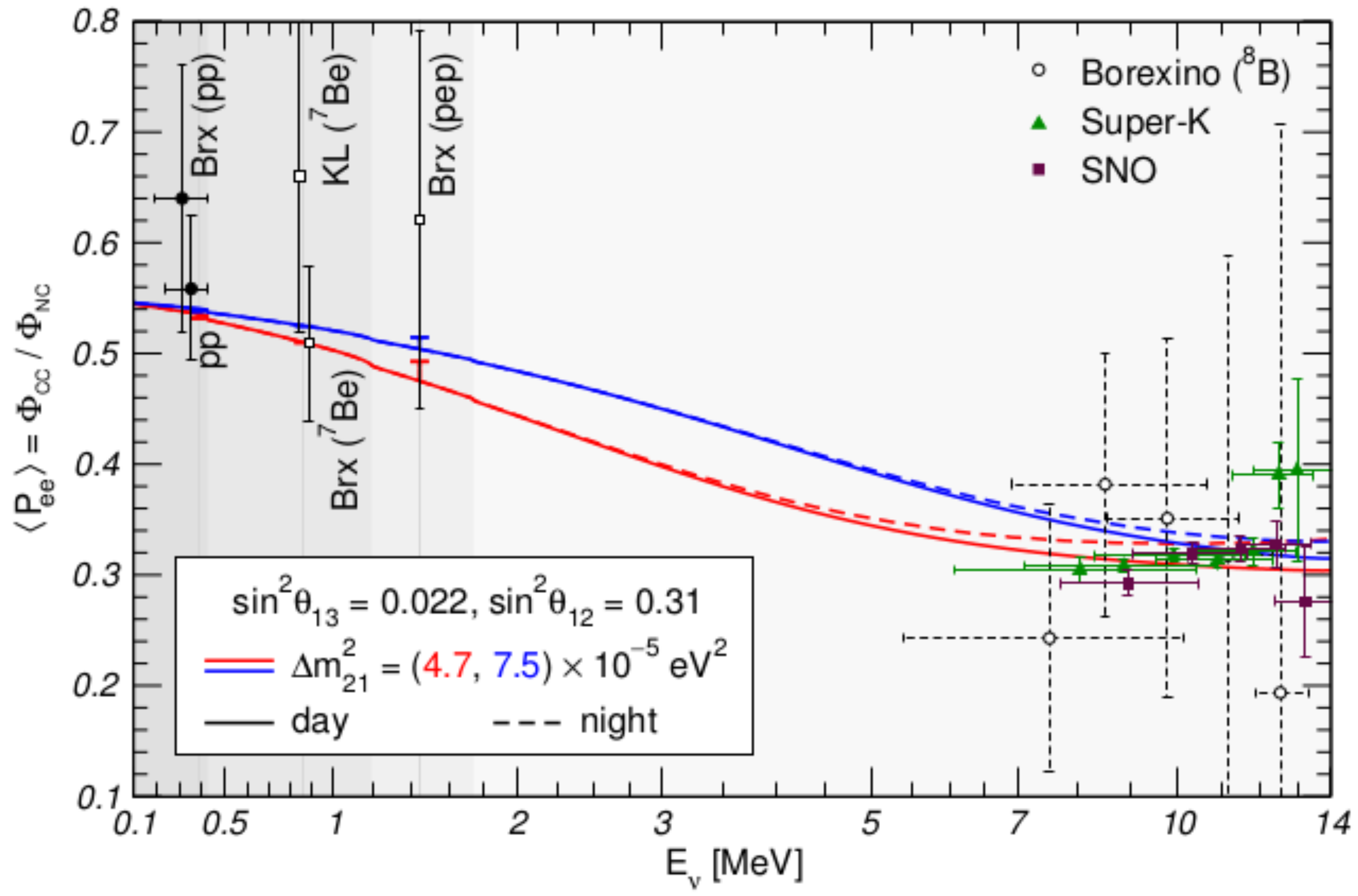


Solar neutrinos are produced by **nuclear fusions** reactions

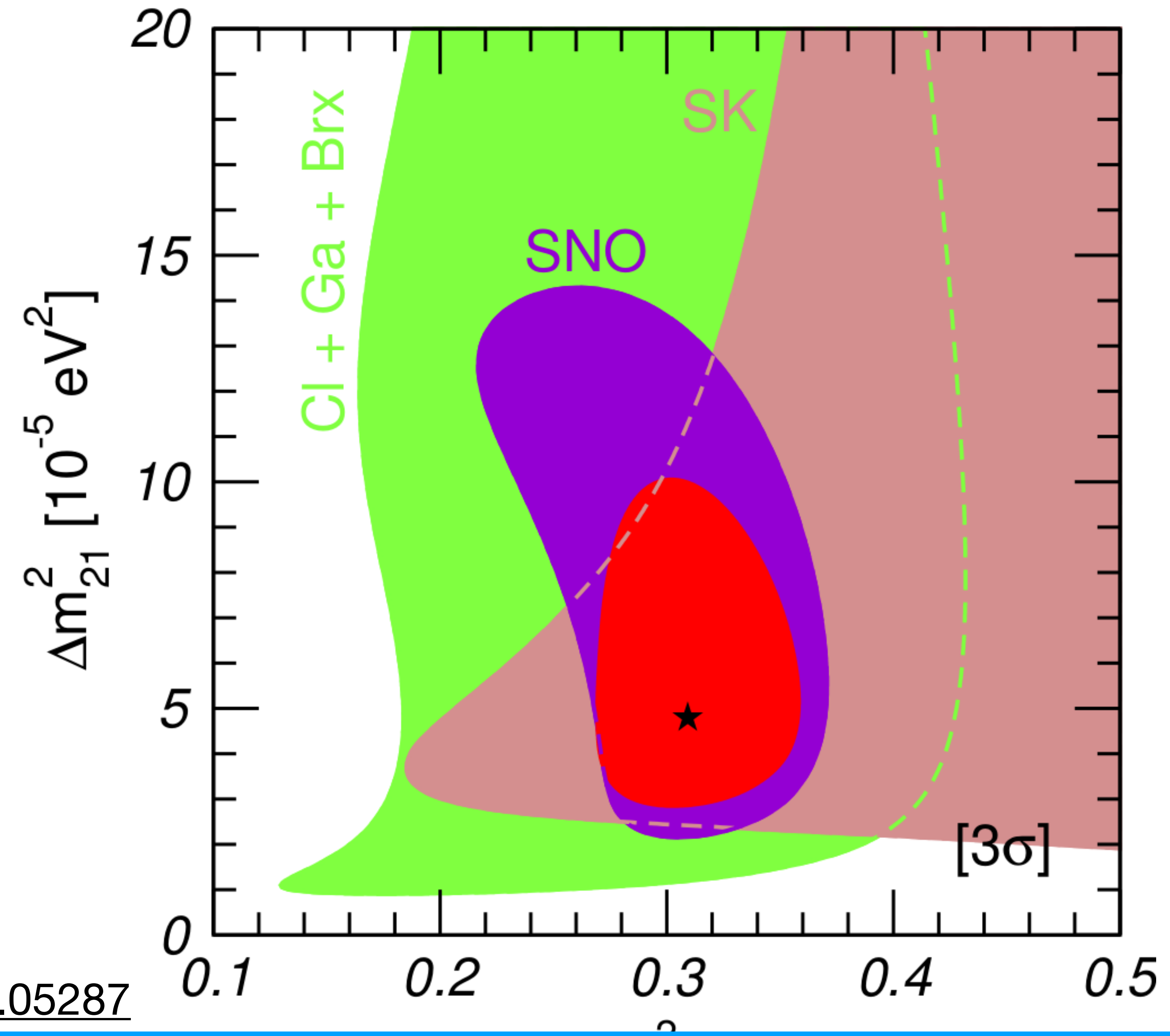
Survival probability for neutrinos from dense solar regions

$$P^{2\nu}_{eff}(\Delta m^2_{21}, \theta_{12}) = \frac{1}{2}(1 + \cos\theta^m_{12}\cos\theta_{12})$$

Sensitivity to θ_{12} is dominant, while Δm^2_{21} is probe throught matter effects



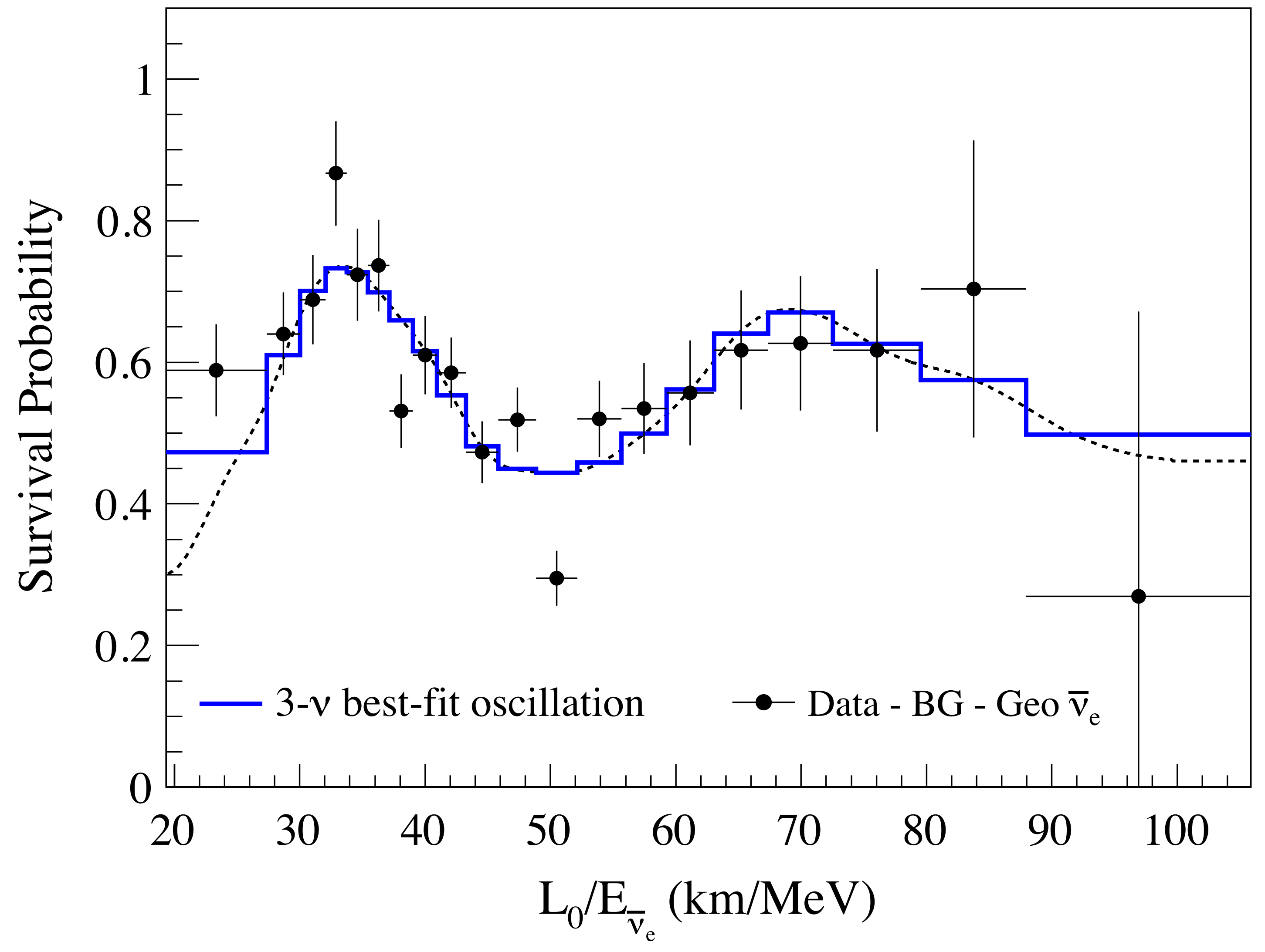
The constraint over θ_{12} are mainly driven by **SK+SNO**



Maltoni and Smirnov, EPJA 52 (2016) arXiv:1507.05287

Solar Sector: θ_{12} and Δm^2_{21}

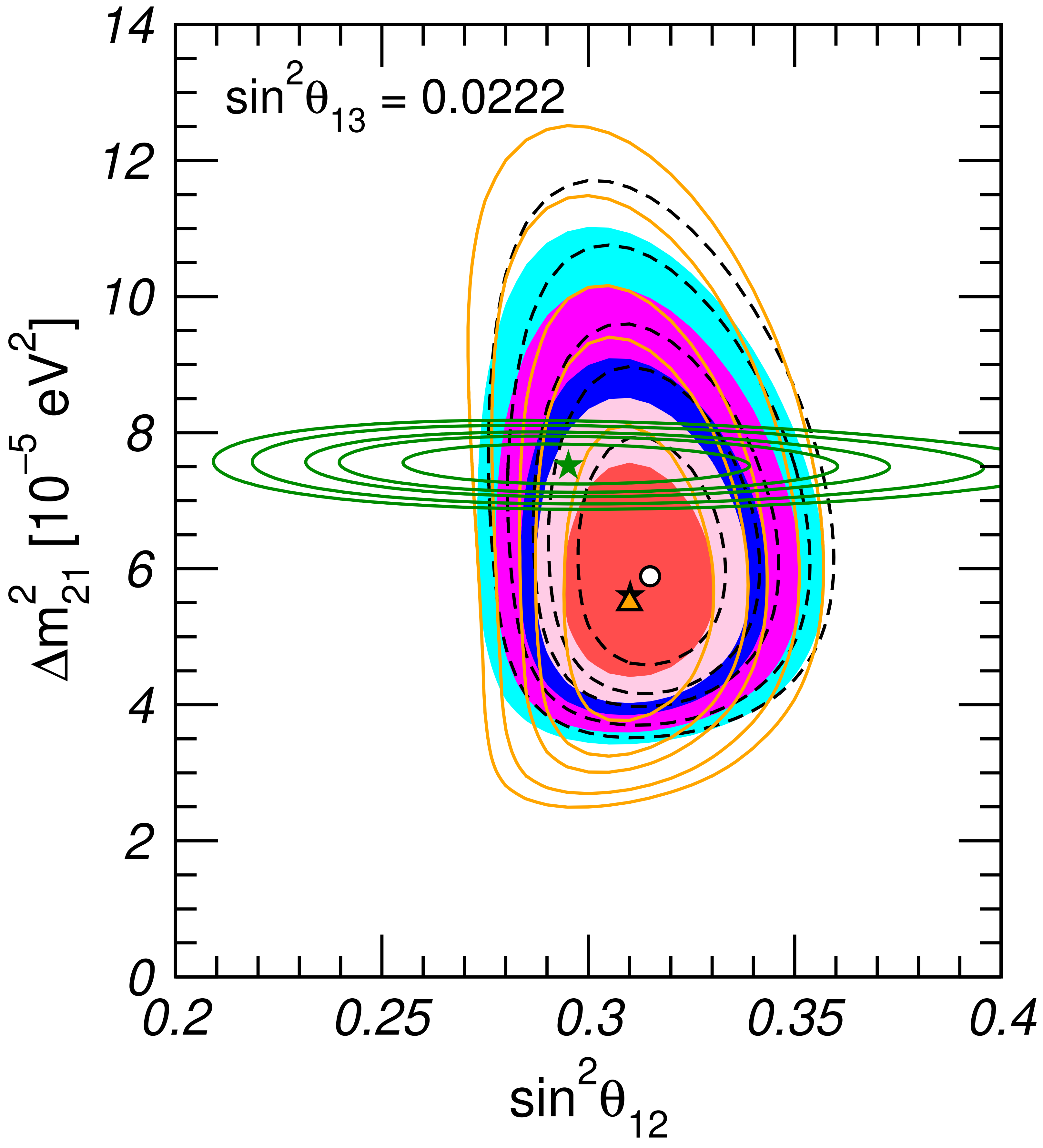
Δm^2_{21} is determined by **long-baseline reactor** experiments

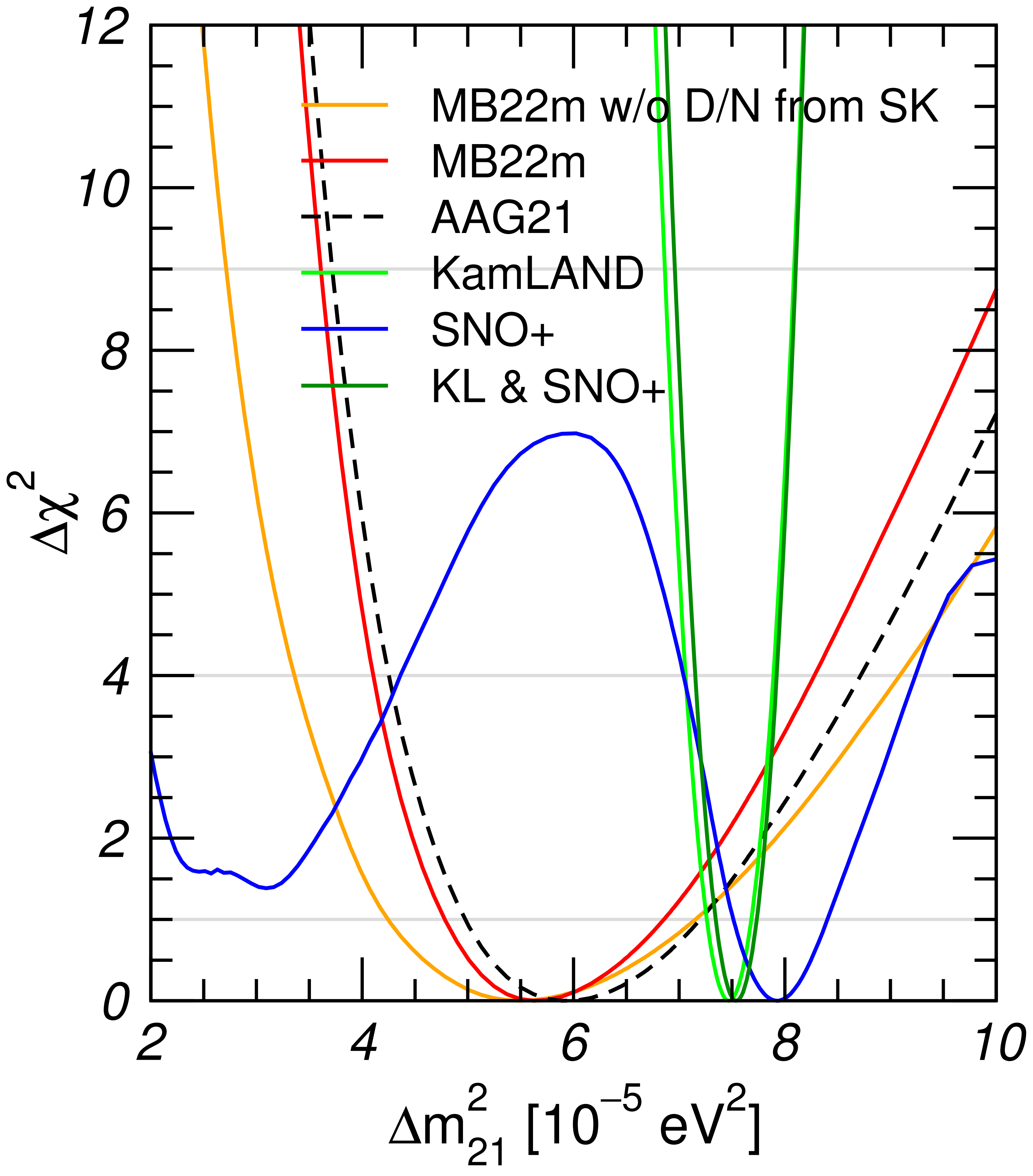


A. Gando et al. (KamLAND) PRD 88 (2013)

Tension in the determination of Δm^2_{21} between reactor and solar experiments

NuFIT 6.0 (2024)



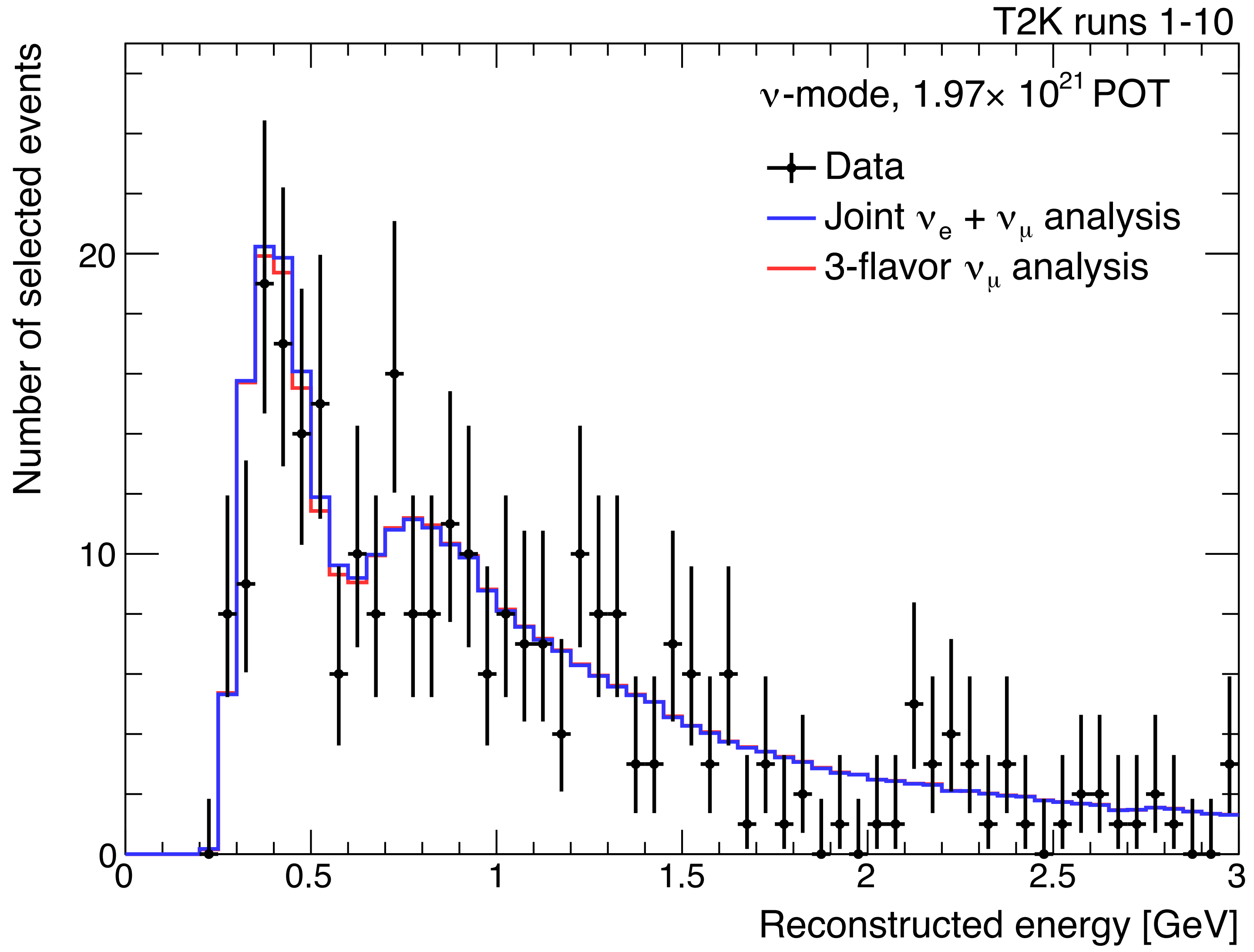


I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

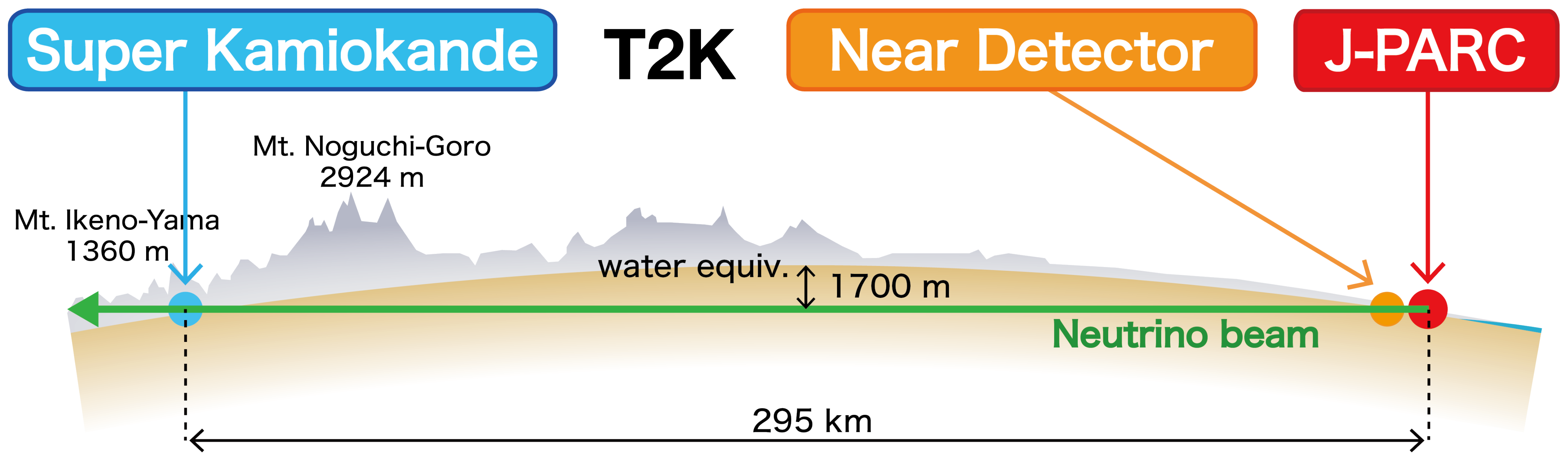
Long-Baseline Accelerators

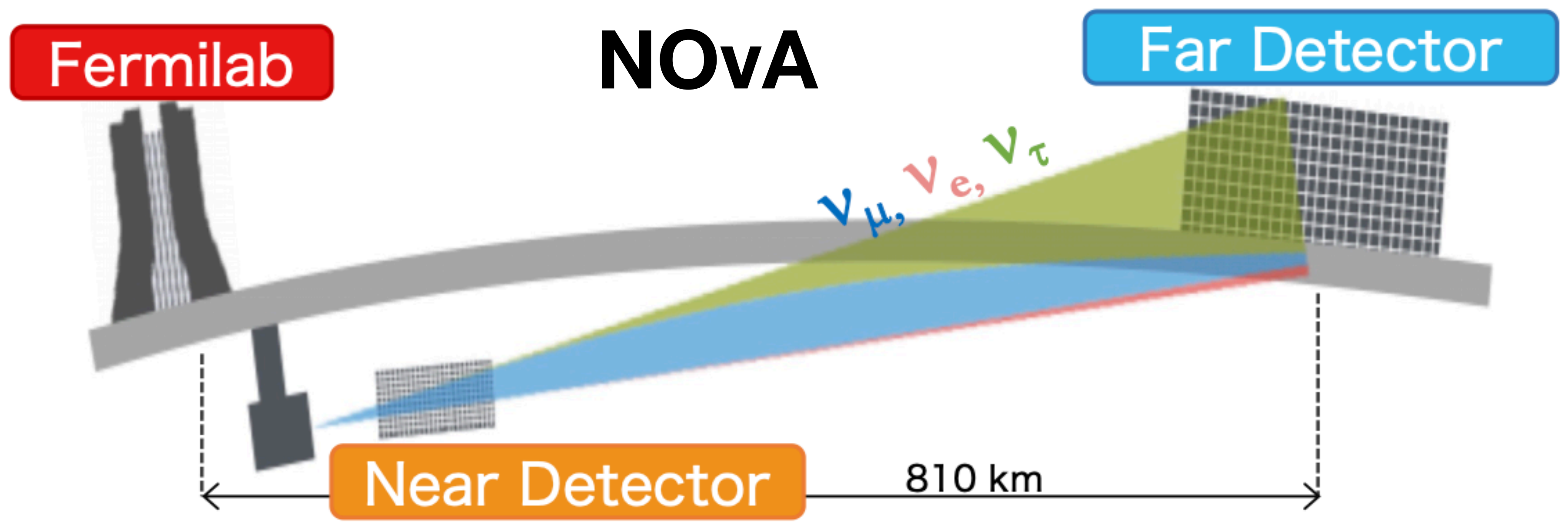
Neutrinos are generated from **pion/kaon decays** caused by an accelerated proton beam hitting a target.

Neutrinos travel ~ 100 Km and have energies $E \sim 1$ GeV, making these experiments **sensitive to** $\Delta m^2_{31}, \sin\theta_{23}, \delta_{CP}$



Abe et al., (T2K) PRD 108 (2023) arXiv:2305.09916





LBL: Δm^2_{31} and $\sin 2\theta_{23}$

Accelerator experiments are sensitive to Δm^2_{31} and $\sin^2 2\theta_{23}$, searching for ν_μ-**disappearance**

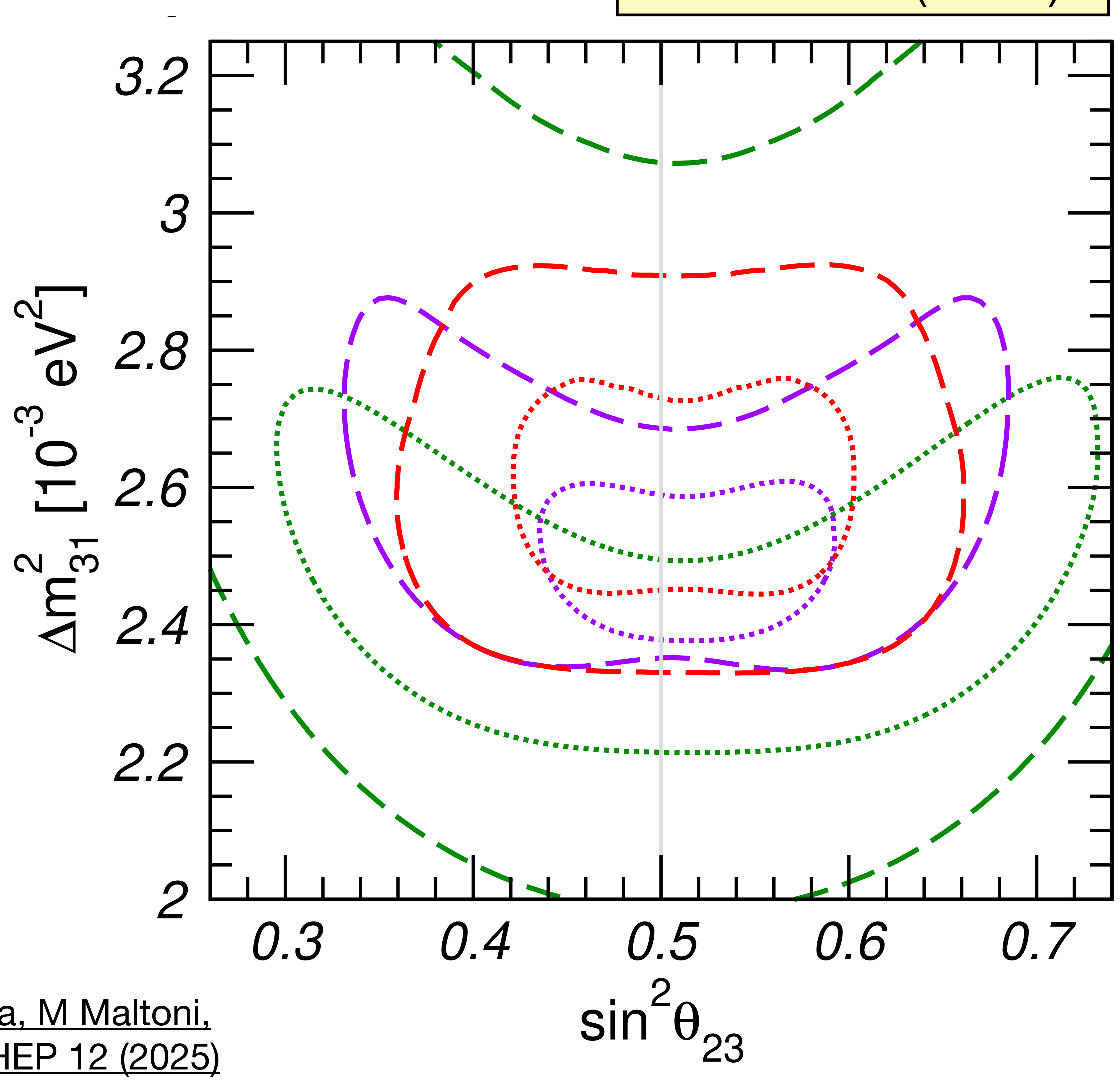
$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E}$$

$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32}$$
$$+\cos\delta_{cp}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}$$

$$\sin^2\theta_{\mu\mu} = \cos^2\theta_{13}\sin^2\theta_{23}$$

It can discriminate whether θ_{23} is maximal or not

NuFIT 6.0 (2024)



I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

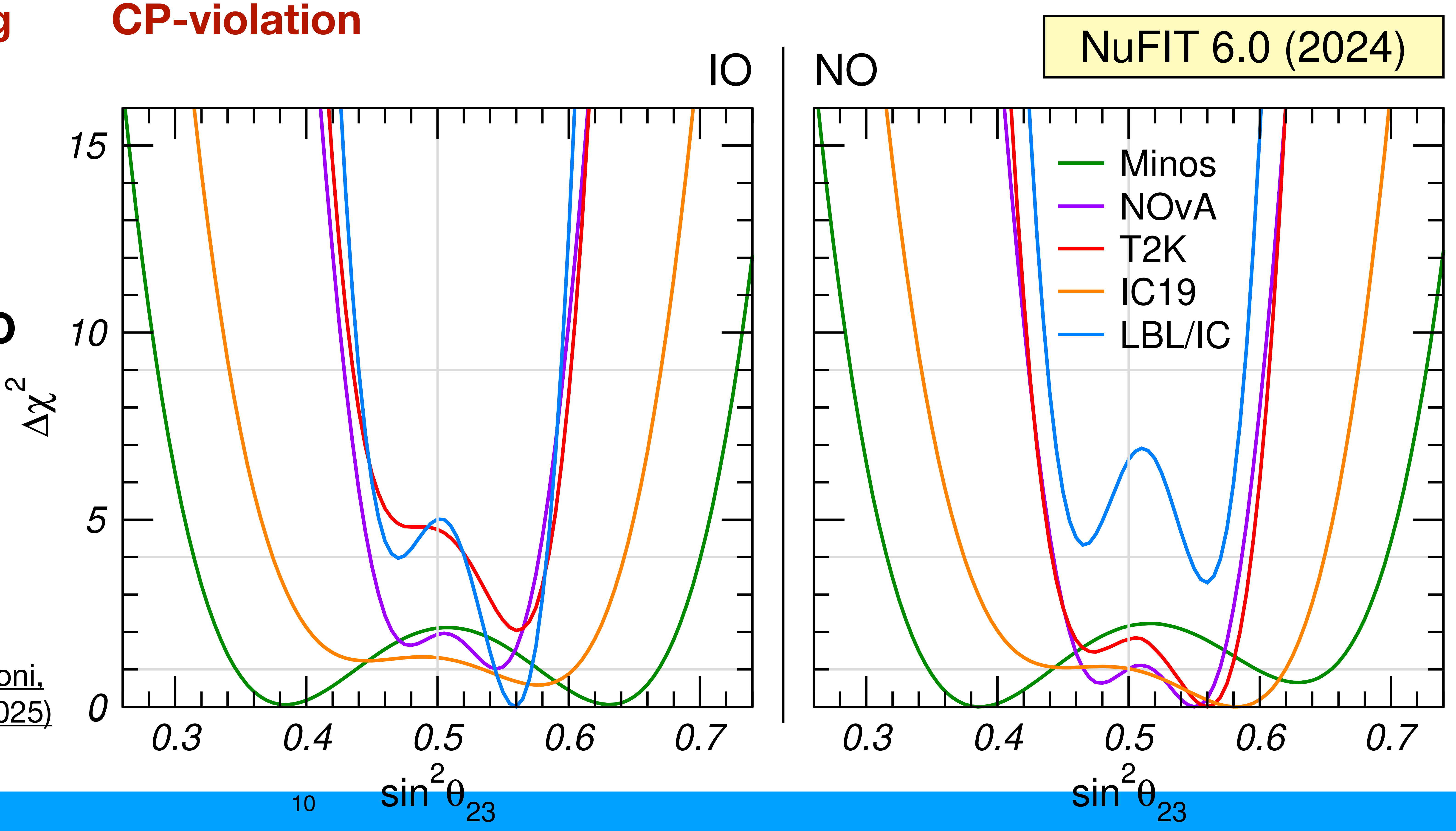
LBL: δ_{CP} , $\sin\theta_{23}$ and Ordering

Accelerator experiments can search for ν_e-**appearance**

$$P_{\nu_\mu\to\nu_e} \approx 4\sin^2\theta_{13}\sin^2\theta_{23}(1+2oA) - C\sin\delta_{cp}(1+oA)$$

Octant θ_{23} **Ordering** **CP-violation**

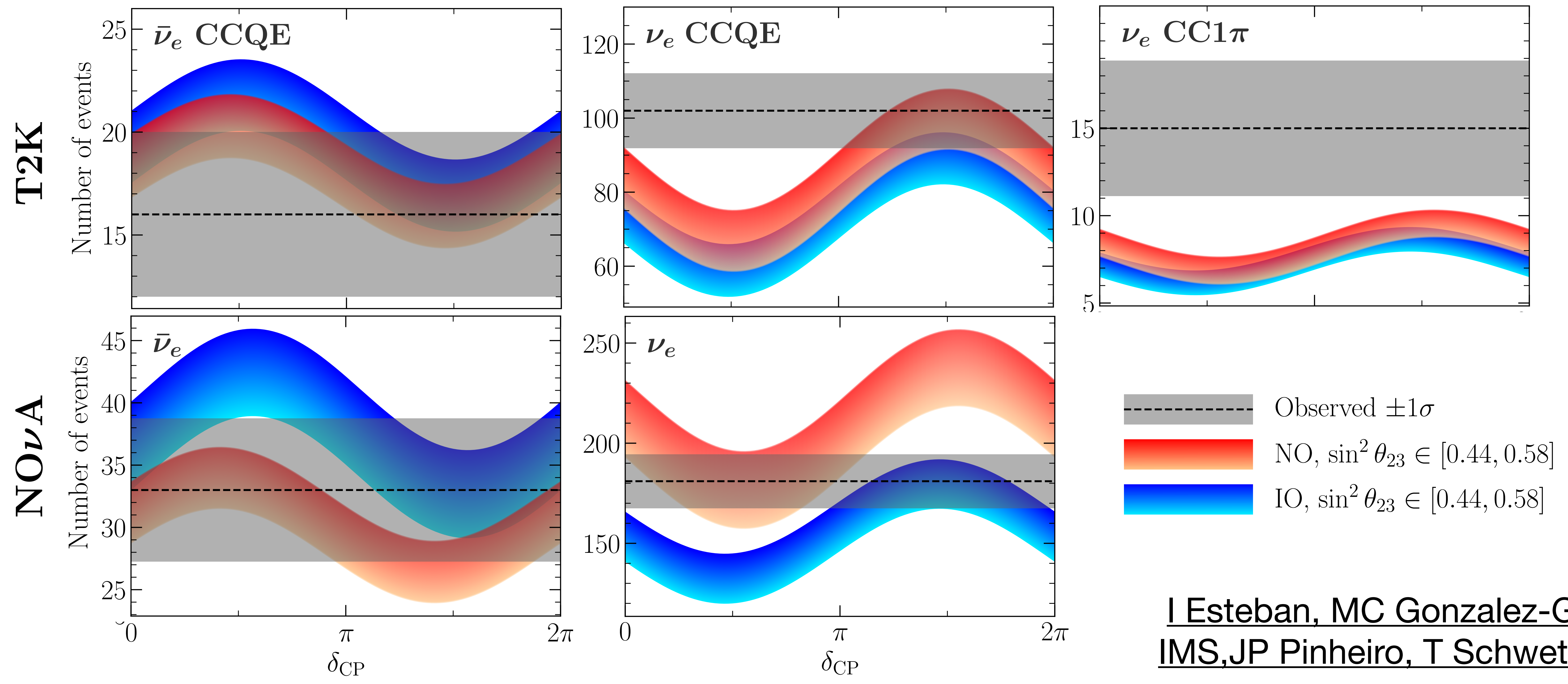
Preference for the **higher-octant and IO**

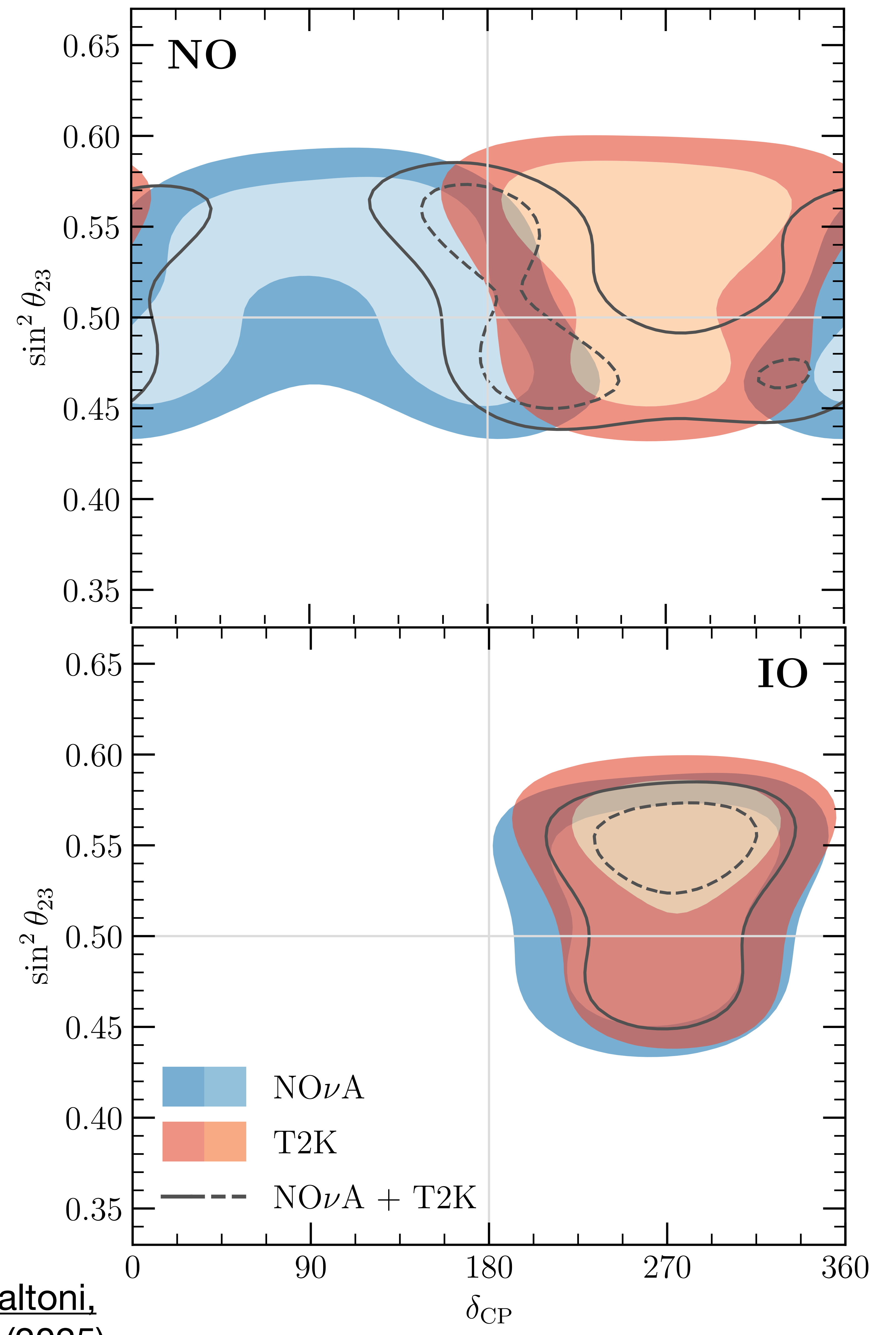


I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

Long-Baseline Accelerators

The **tension** between **T2K** and **NOvA** over δ_{CP} and NO shifts the LBL preference toward **IO**

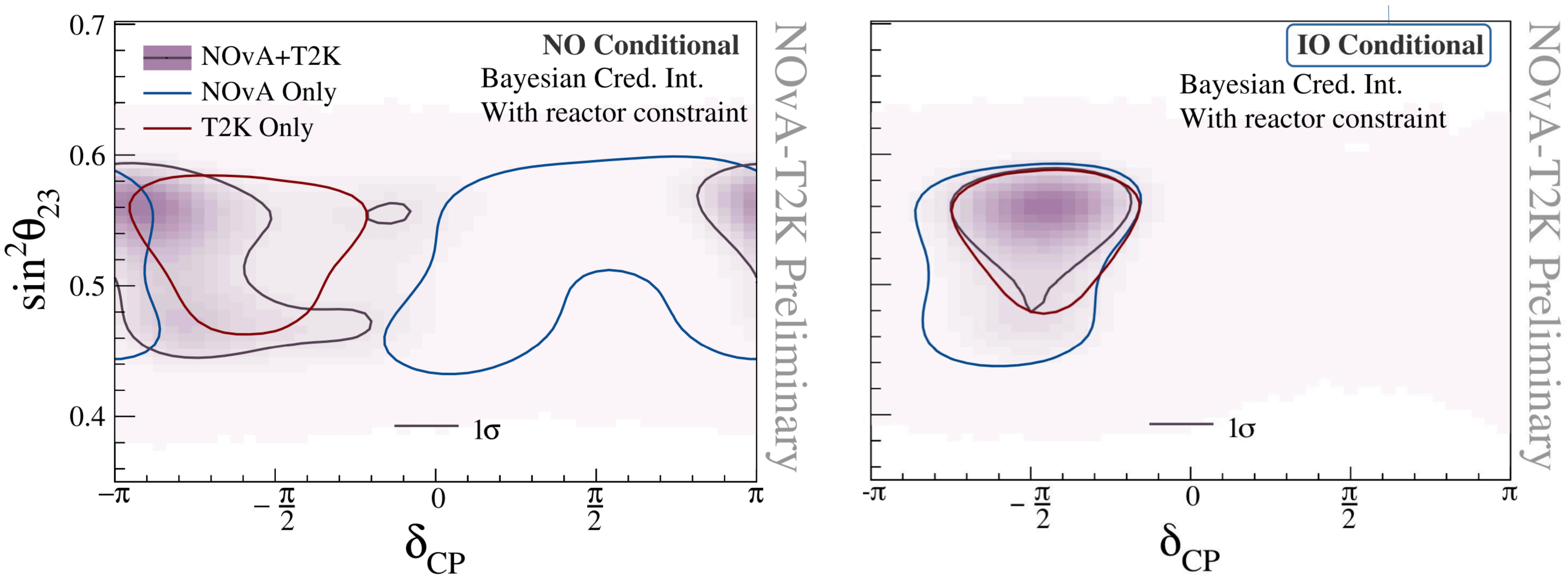




I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

NOvA-T2K joint fit

NOvA and T2K have performed a joint fit, showing **good agreement with global analysis**



No correlation between the flux, detector and cross-section

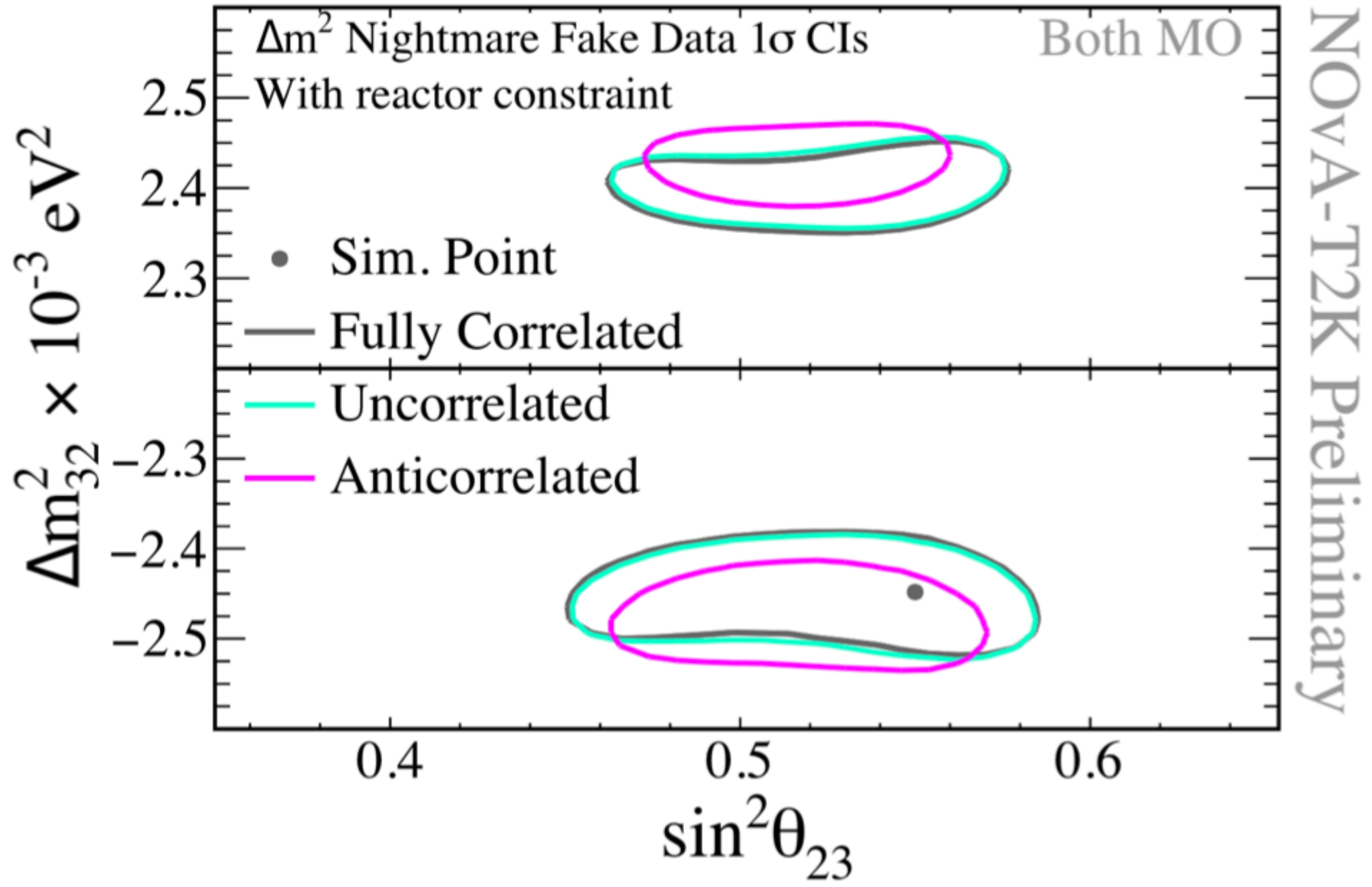
Jeremy Wolcott (Neutrino 2024)

Zoya Vallari (Joint Experimental-Theoretical Physics Seminar, Fermilab, 2024)

NOvA-T2K joint fit

- **Several cross-section models** were explored, along with their impact on **potential correlations**

- The **uncorrelated and correlated** models **agree** with negligible differences.

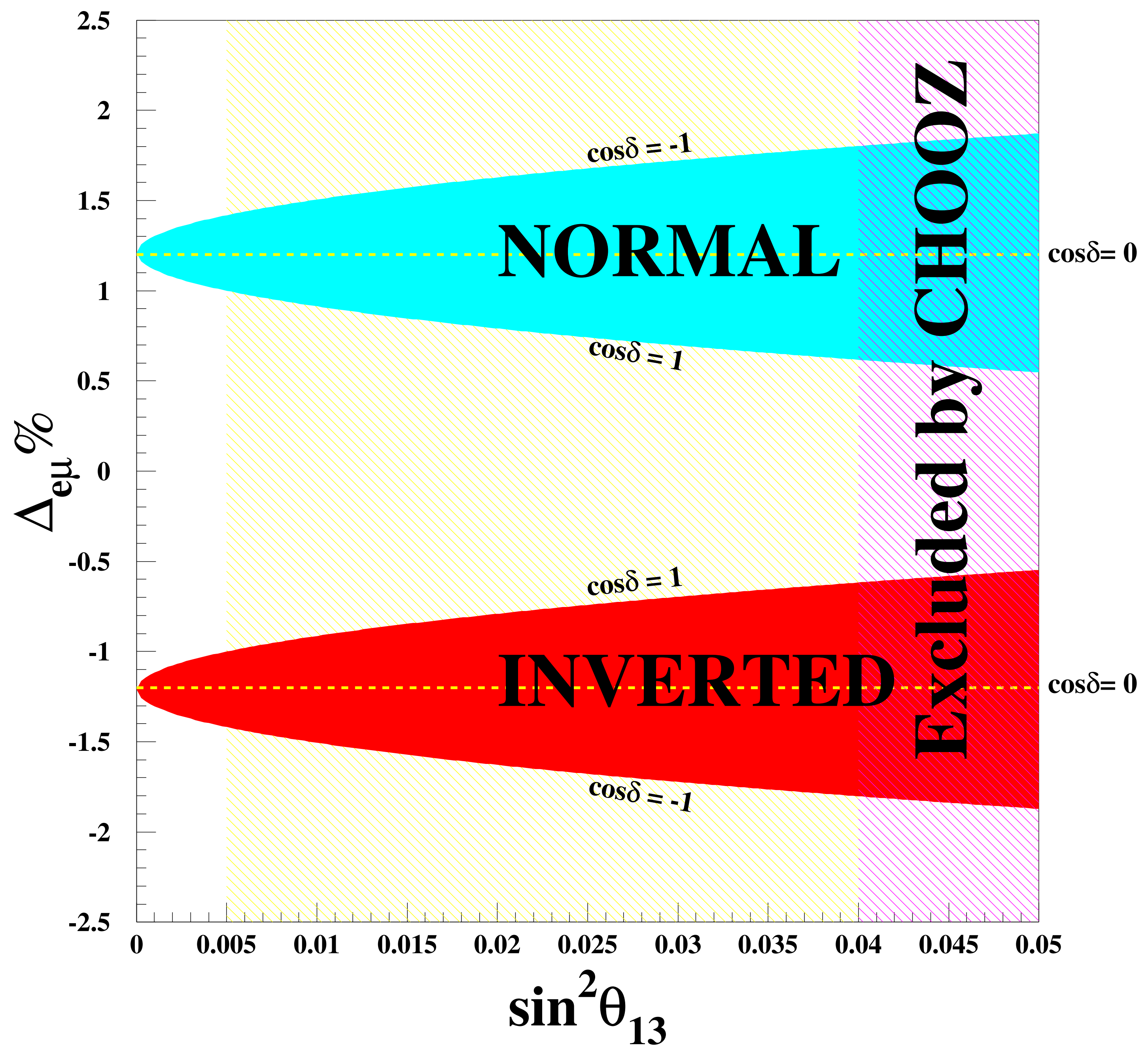


Zoya Vallari (Joint Experimental-Theoretical Physics Seminar, Fermilab, 2024)

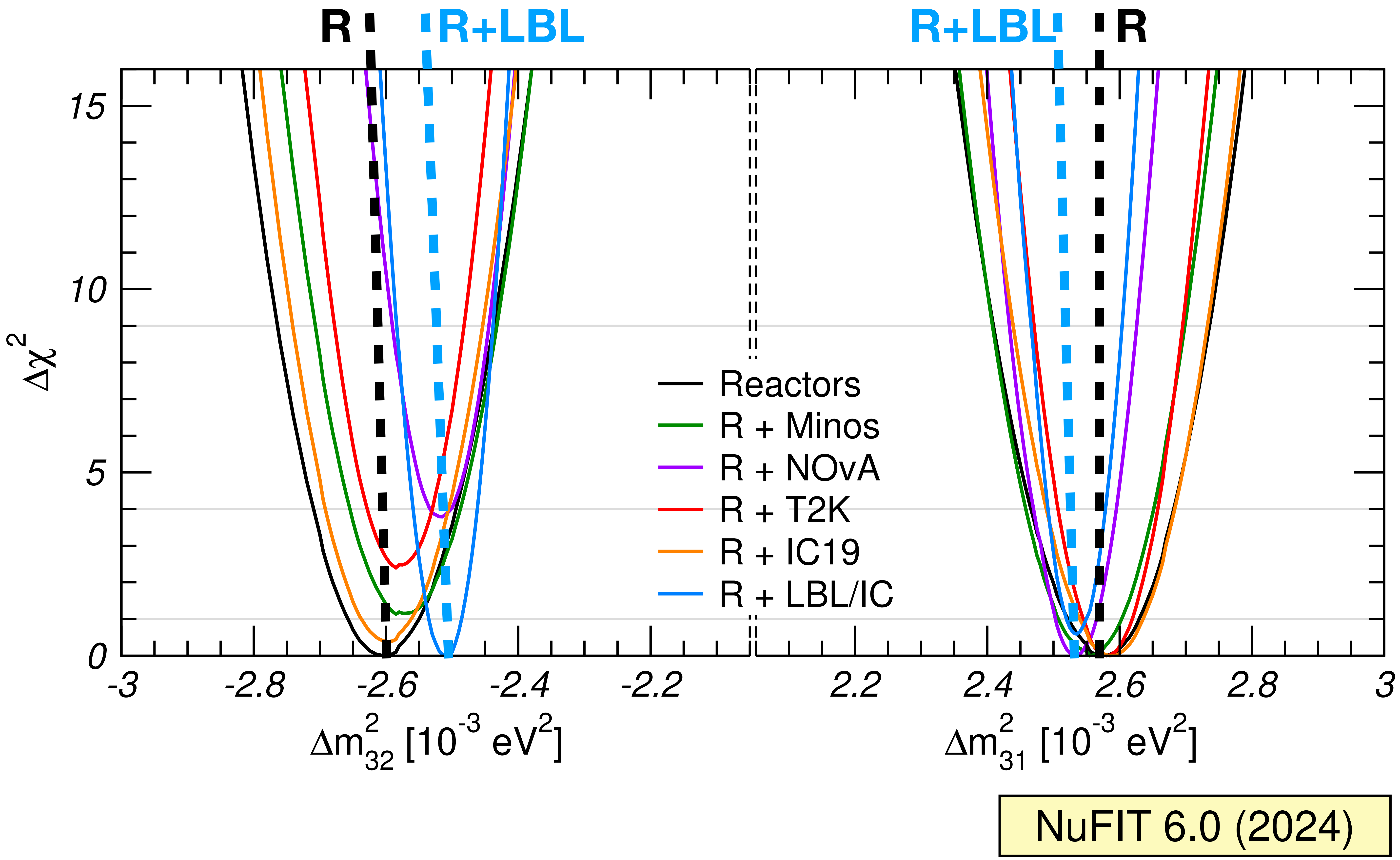
LBL+Reactors

Full LBL-reactor combo eases T2K-NOvA tension

- Combining LBL($\Delta m^2_{\mu\mu}$) and reactors (Δm^2_{ee}) **strengthens NO preference**



Nunokawa, Parke, Funchal, PRD 72(2005) arXiv: hep-ph/0503283



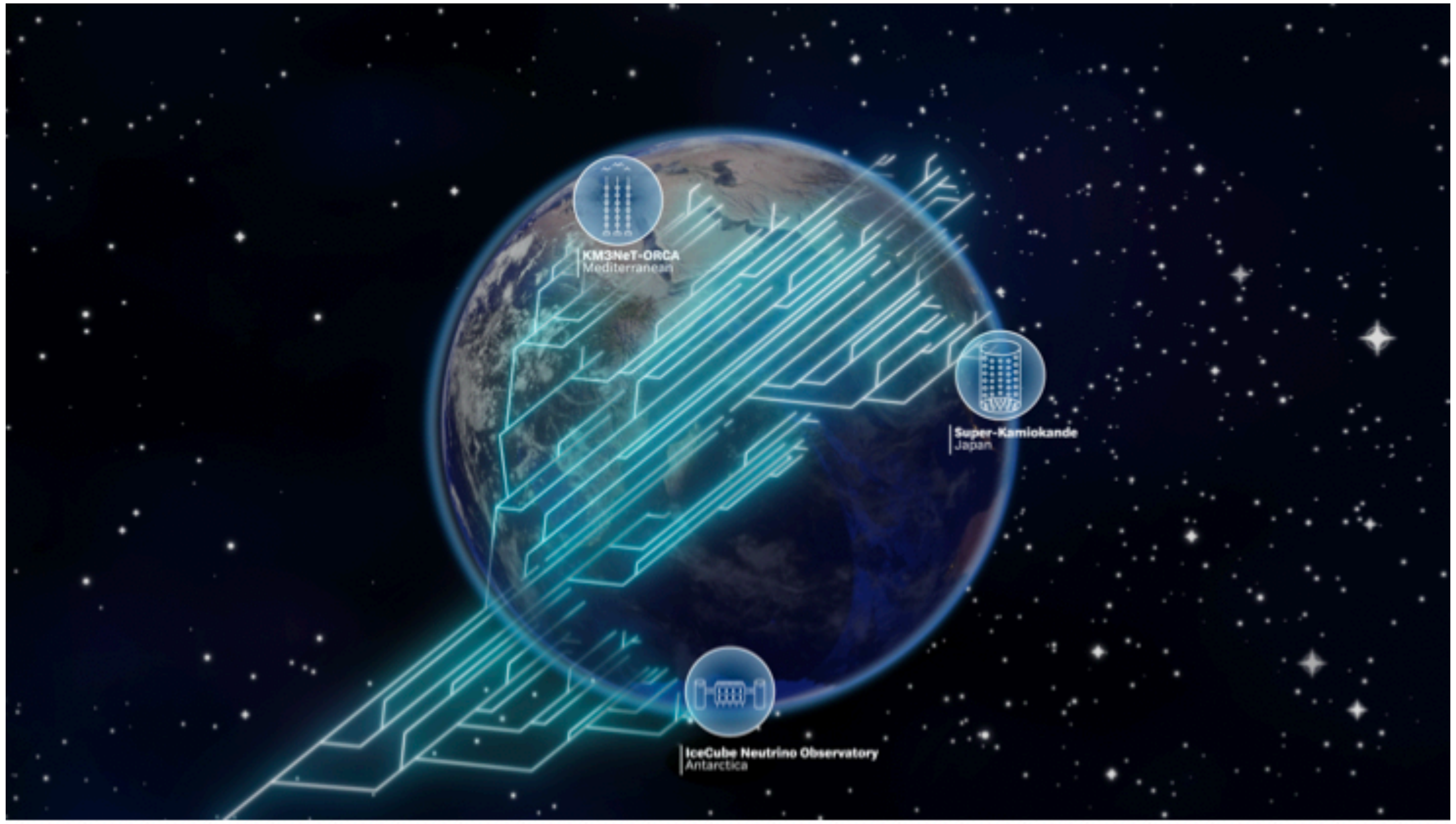
$$\Delta_{e\mu} = (\Delta m^2_{ee} - \Delta m^2_{\mu\mu})/\Delta m^2$$

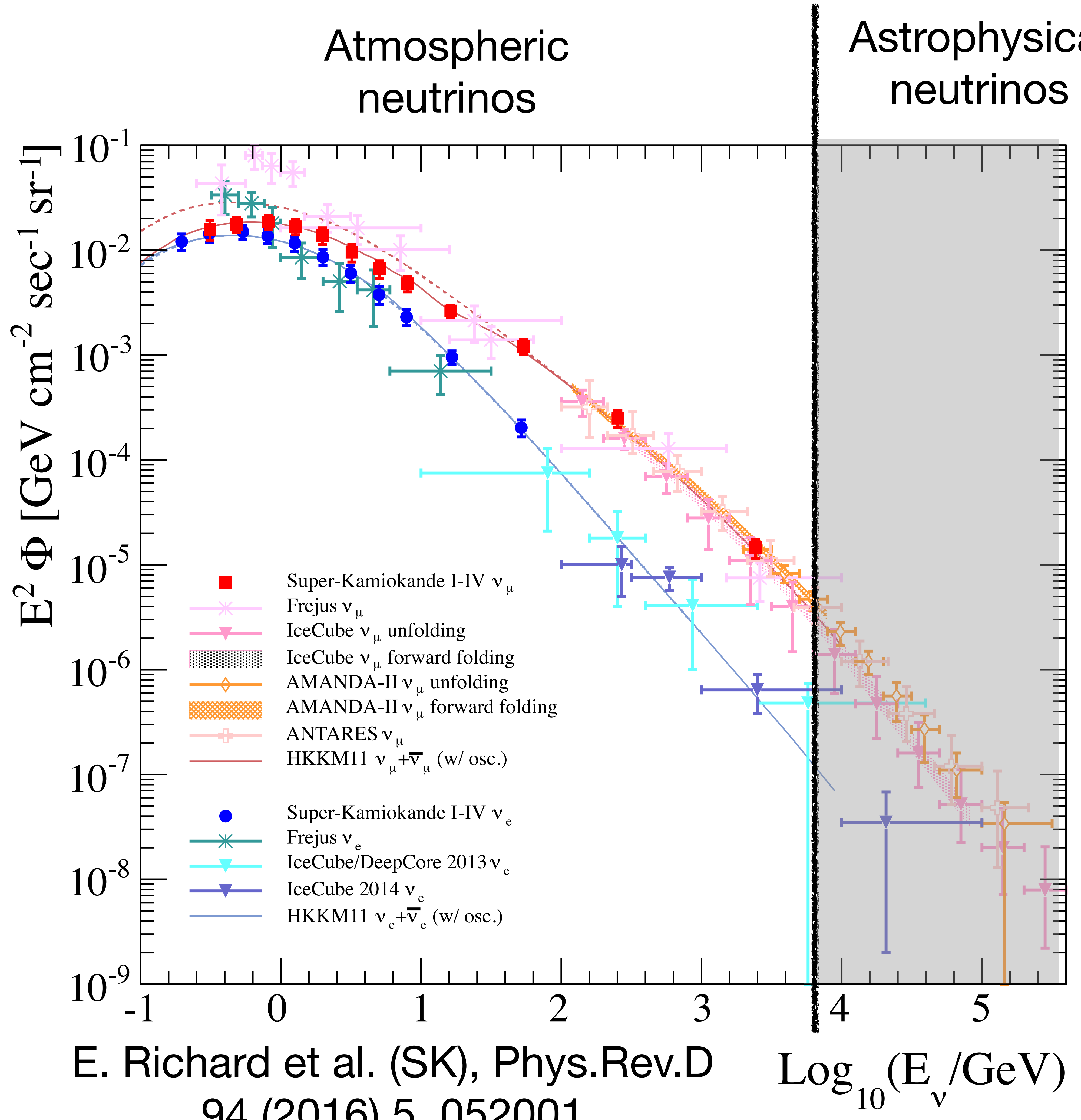
I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

How can atmospheric neutrinos contribute?

Atmospheric Neutrinos

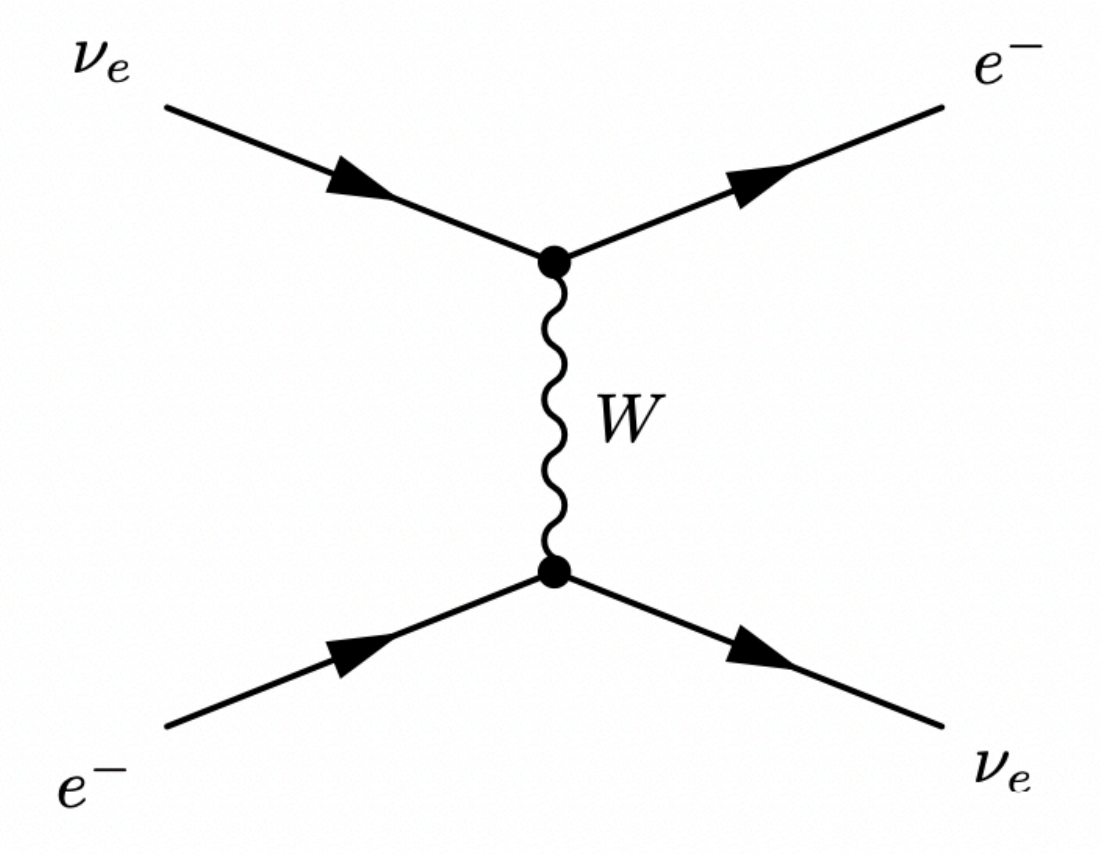
Atmospheric neutrinos are created in the **collision of cosmic rays** with the atmospheric nuclei





E. Richard et al. (SK), Phys.Rev.D 94 (2016) 5, 052001

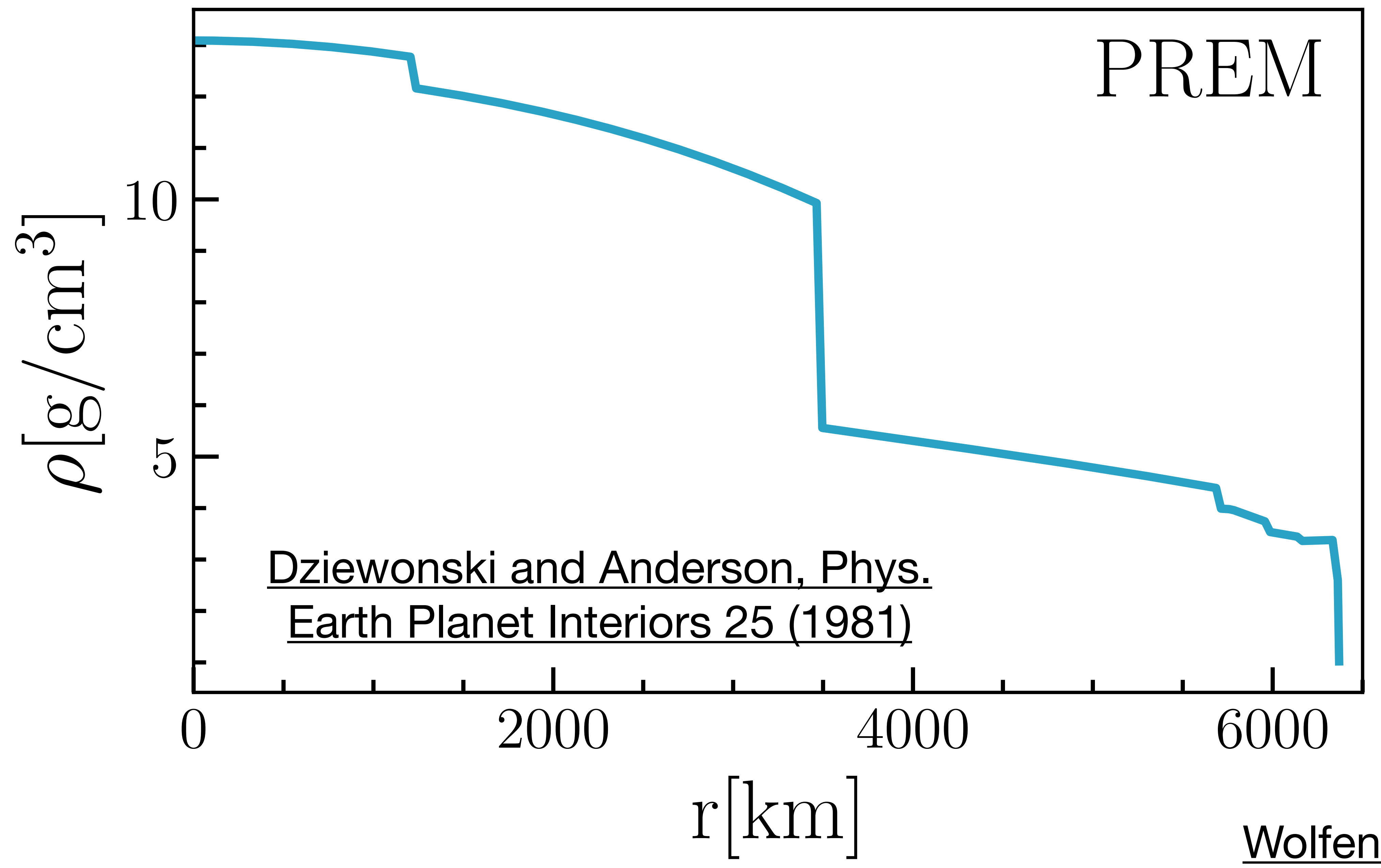
Neutrino Evolution in Matter



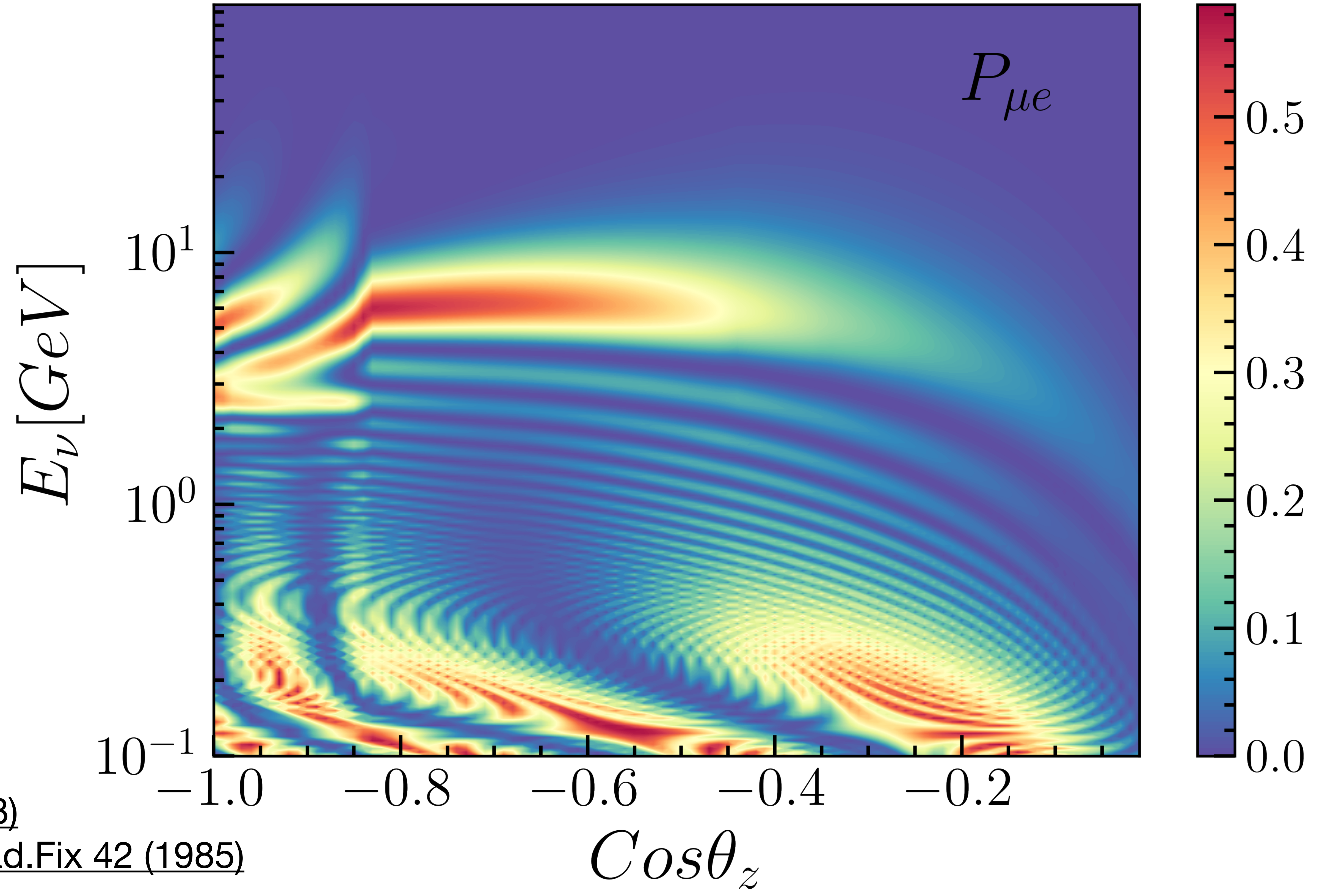
Matter effects play a crucial role in the evolution of atmospheric neutrinos

$$i\frac{d\nu}{dE} = \frac{1}{2E_\nu}\left(U^\dagger \text{diag}(0,\Delta m^2_{21}, \Delta m^2_{31})U \pm V_{mat}\right)\nu$$

$$V_{mat} = 2\sqrt{2}G_F N_e E_\nu \text{diag}(1,0,0)$$



Dziewonski and Anderson, Phys. Earth Planet Interiors 25 (1981)



Wolfenstein, PRD 17 (1978)
Mikheyev and Smirnov, Yad.Fix 42 (1985)

Ivan Martinez-Soler (IPPP)

Sub-GeV

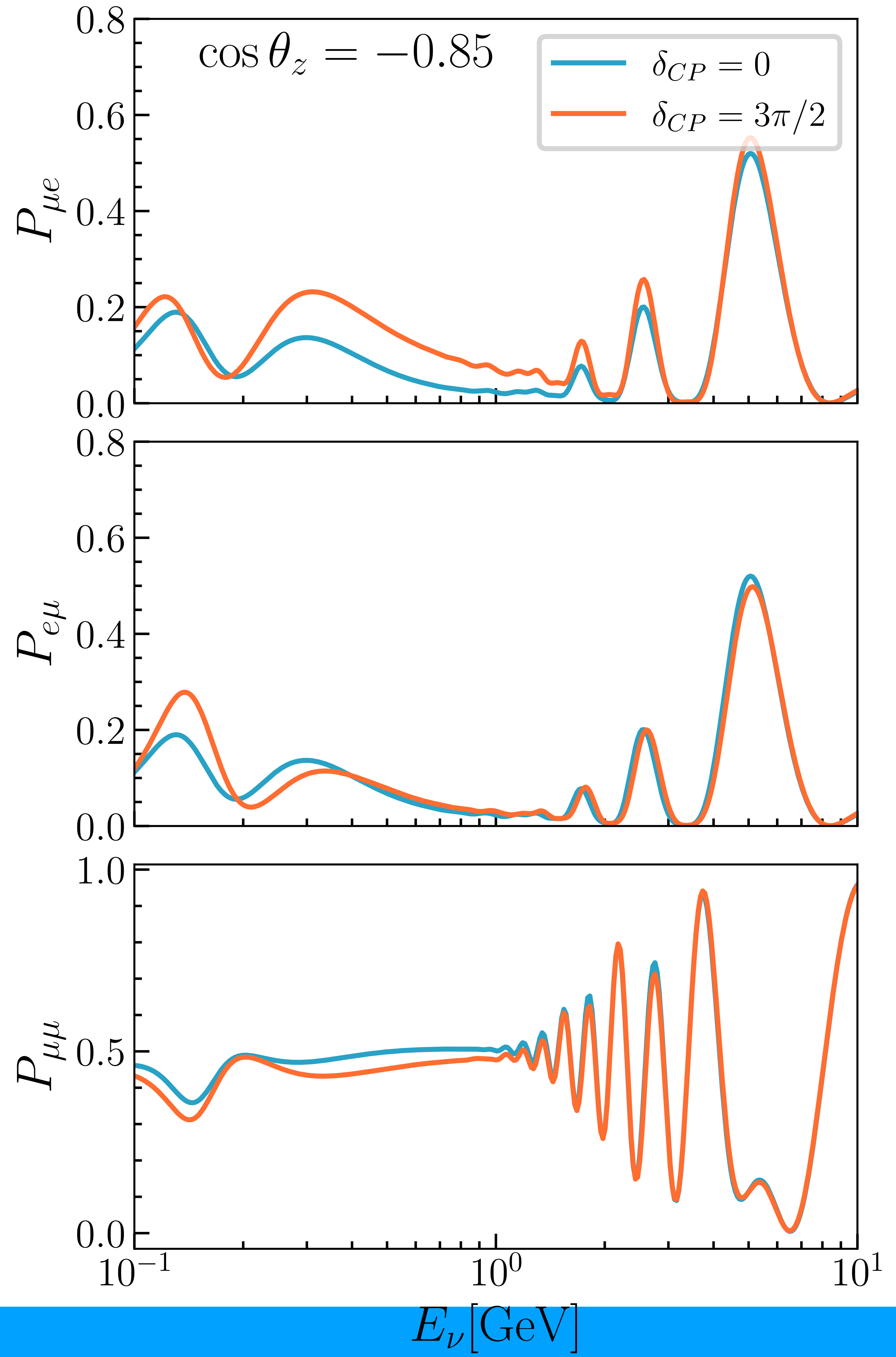
For atmospheric neutrinos, both fluxes are sensitive to δ_{CP}

- In the case of $\delta_{cp} \neq 0$, **the CPT conservation** implies

$$P(\nu_\mu \to \nu_e) \neq P(\nu_e \to \nu_\mu)$$

- The impact of δ_{cp} depends mainly on the neutrino direction

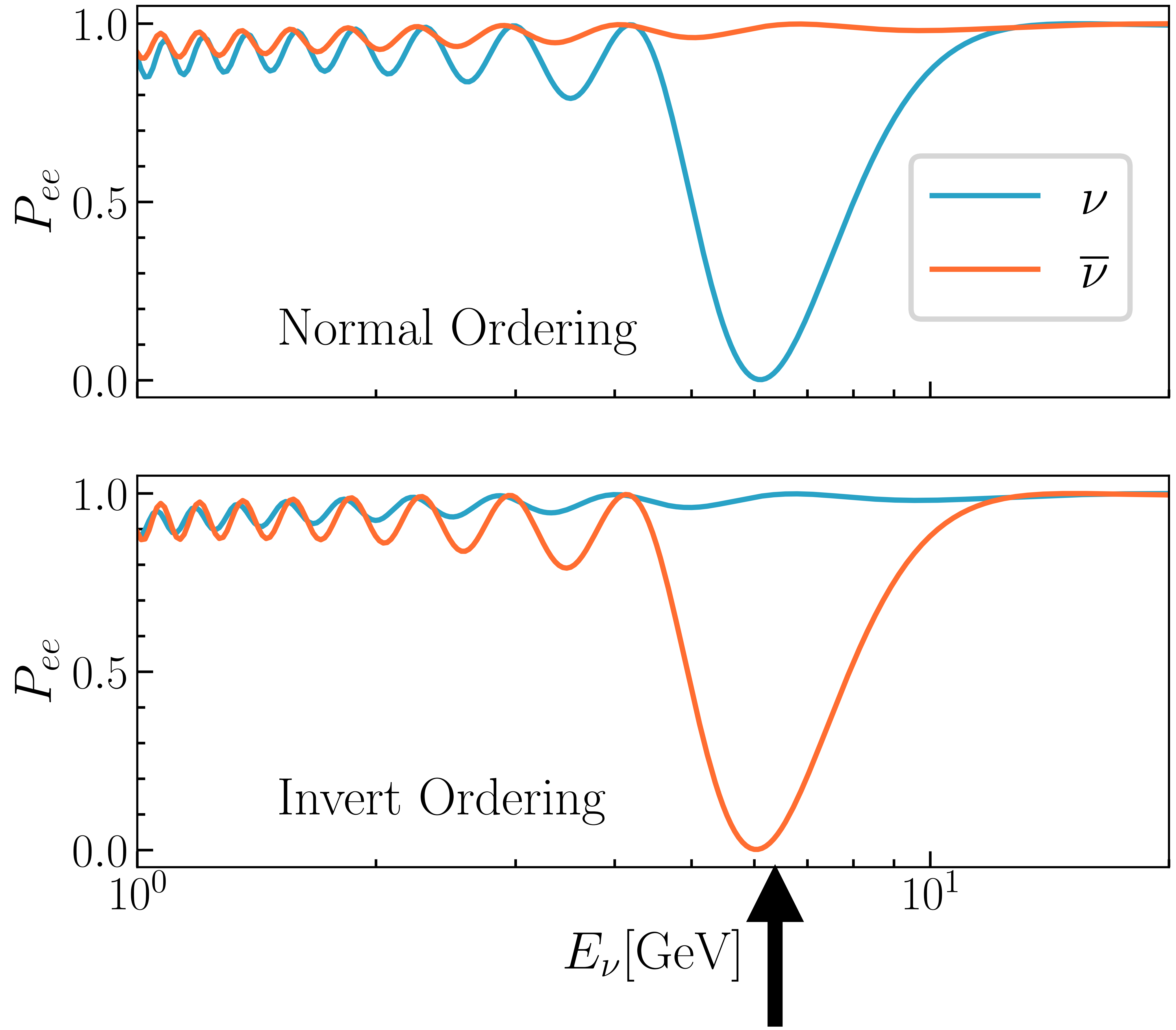
- $P_{\mu\mu}$ contribute to measuring the phase via $\cos \delta_{CP}$



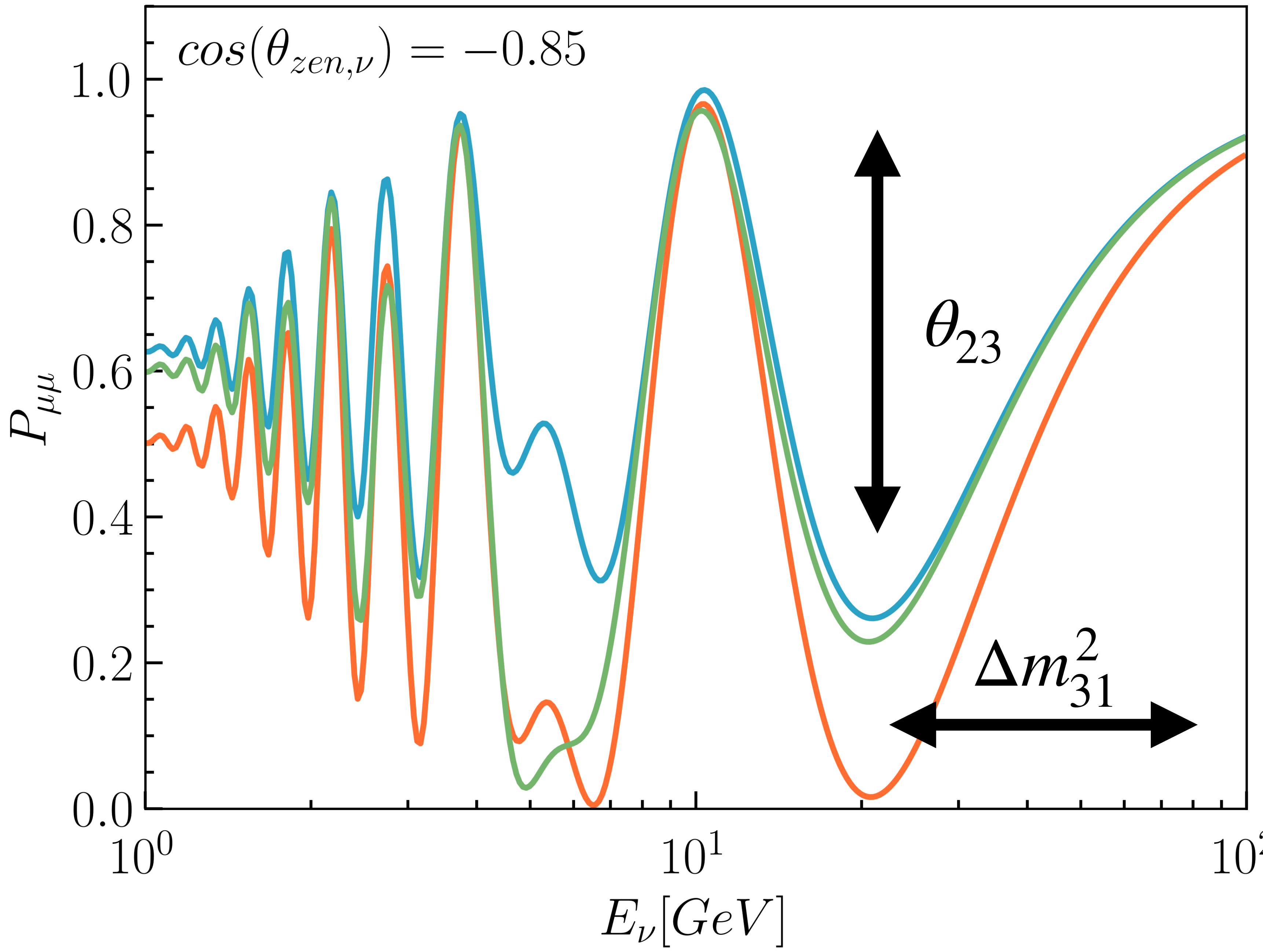
Minakata, Nunokawa, Parke, PLB 537 (2002) Minakata, Nunokawa, Parke, PRD 66 (2002)
Denton and Parke, PRD 109 (2024)

Multi-GeV

At the **GeV scale**, trajectories crossing the mantle experience a resonance, making neutrinos sensitive to the **mass ordering**:



In the multi-GeV region, neutrino evolution is dominated by Δm^2_{31} and $\sin^2\theta_{23}$



The enhancement of θ^{eff}_{13} lead to a deep in P_{ee} for ν ($\overline{\nu}$) for NO (IO)

Palomares-Ruiz and Petcov, NPB 712 (2005)

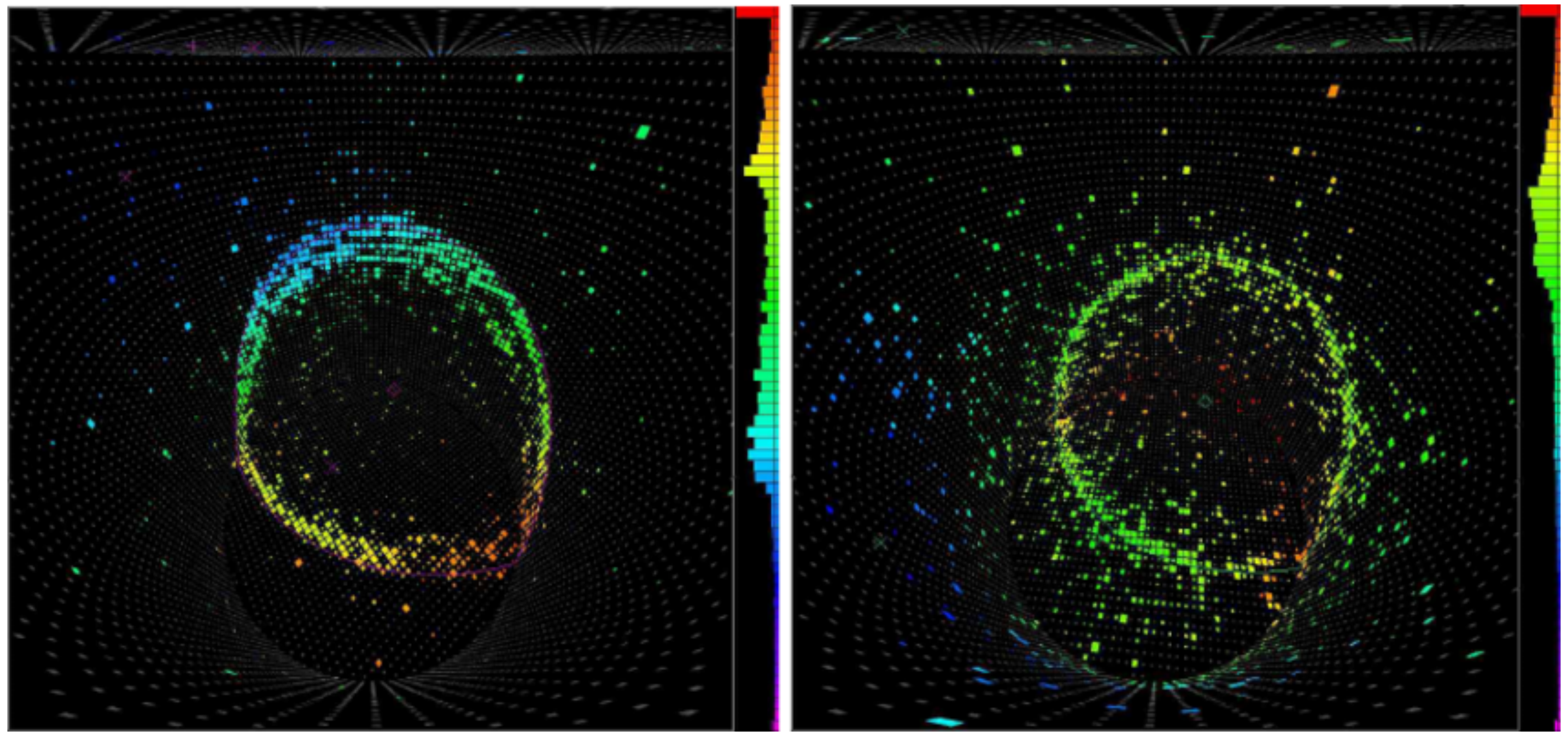
Akhmedov, Maltoni and Smirnov, JHEP 05 (2007)

Super-Kamiokande

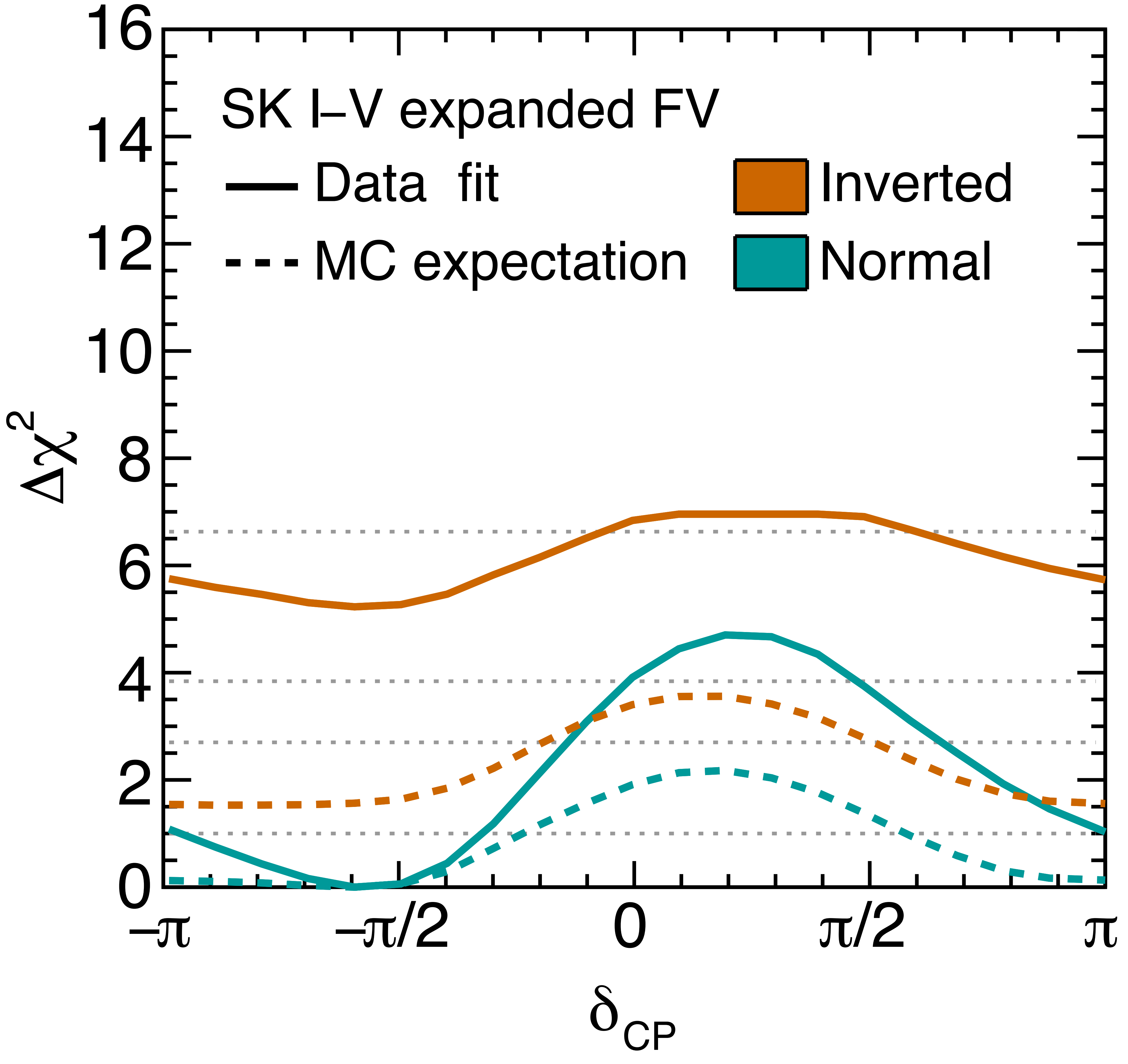
Several experiments have measured the atmospheric neutrino flux, with **SK** starting from the **sub-GeV scale**.

Super-Kamiokande (SK)

- 22.5 kton water Cherenkov
- Small sample at multi-GeV due to the volume
- The event sample is divided in FC, PC and Up-μ



Abe et al. (Super-Kamiokande), PRD 97 (2018)

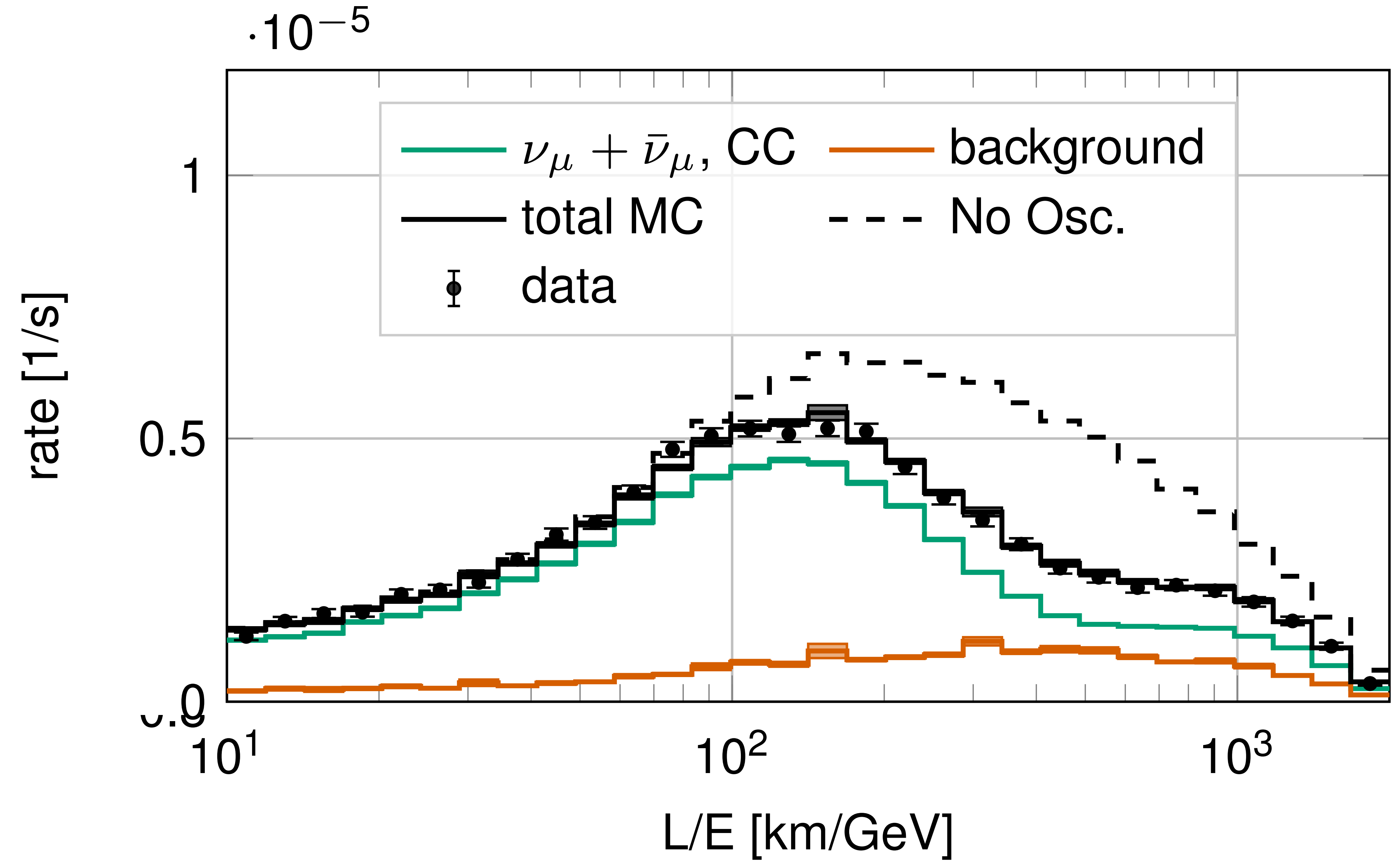


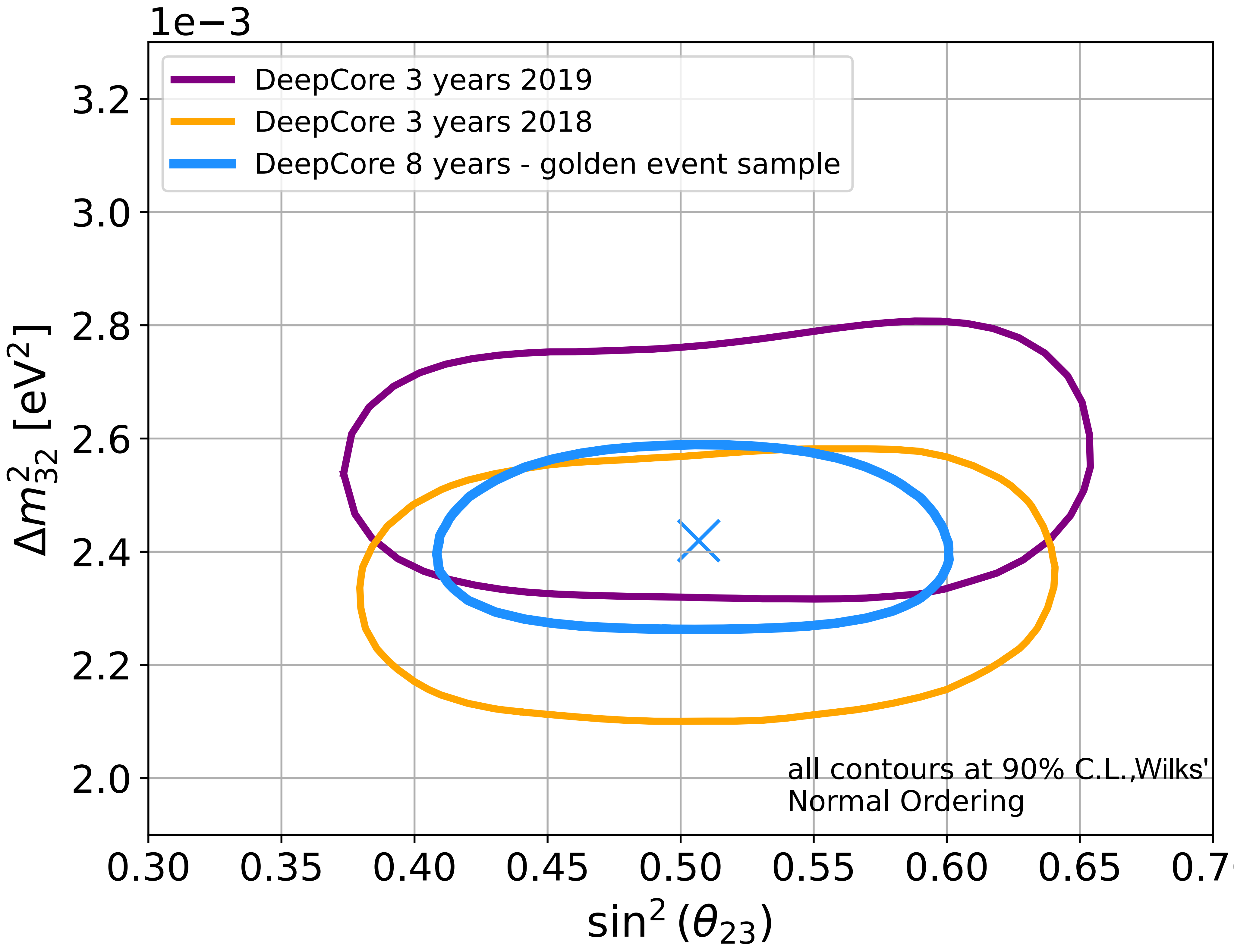
Wester et al. (Super-Kamiokande), arXiv: 2311.05105

IceCube

The **neutrino telescopes** measure the atmospheric neutrino flux from the **multi-GeV** scale

- $\sim 1\text{km}^3$ ice Cherenkov
- The sample is divided into tracks and cascades



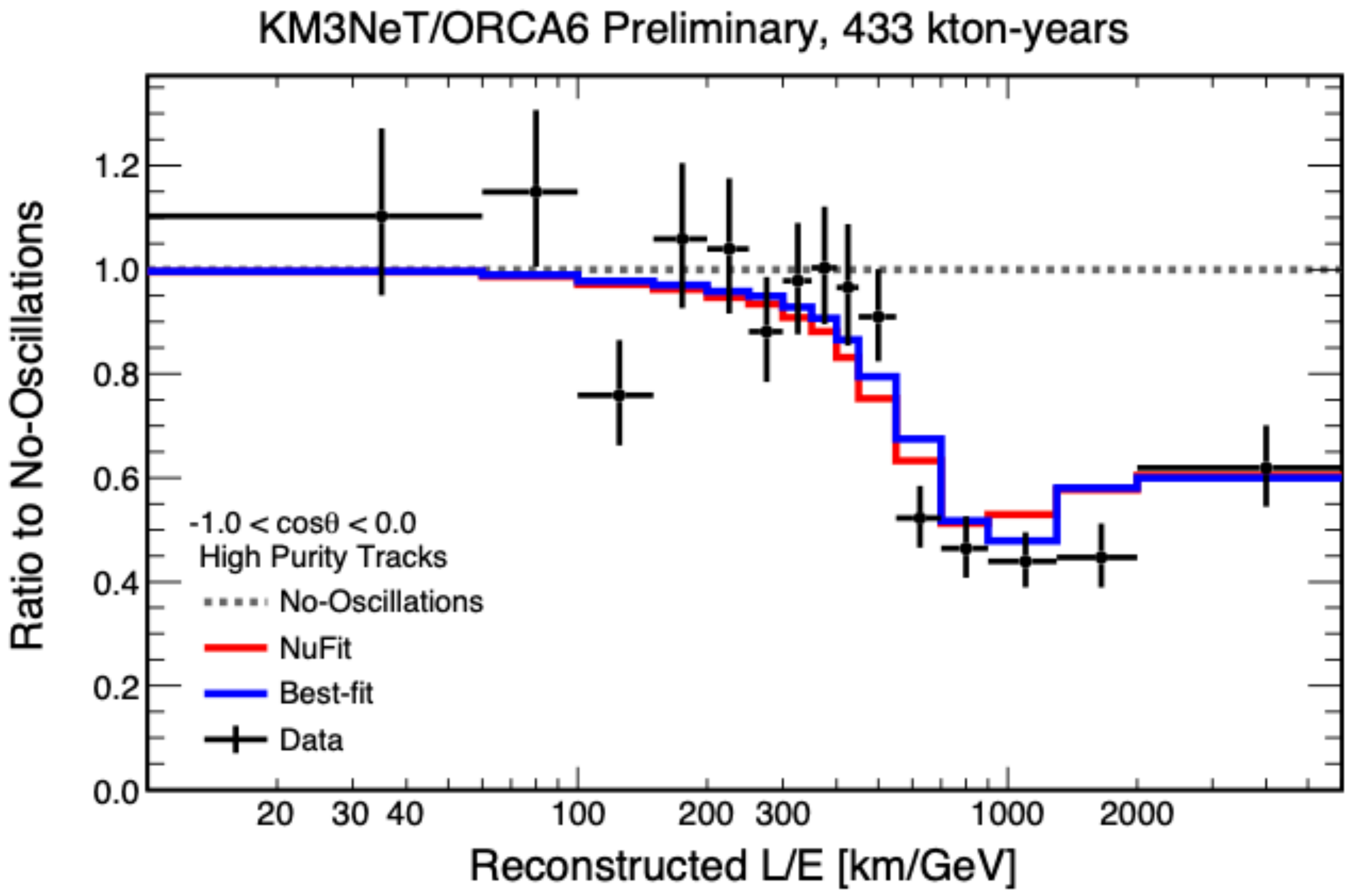


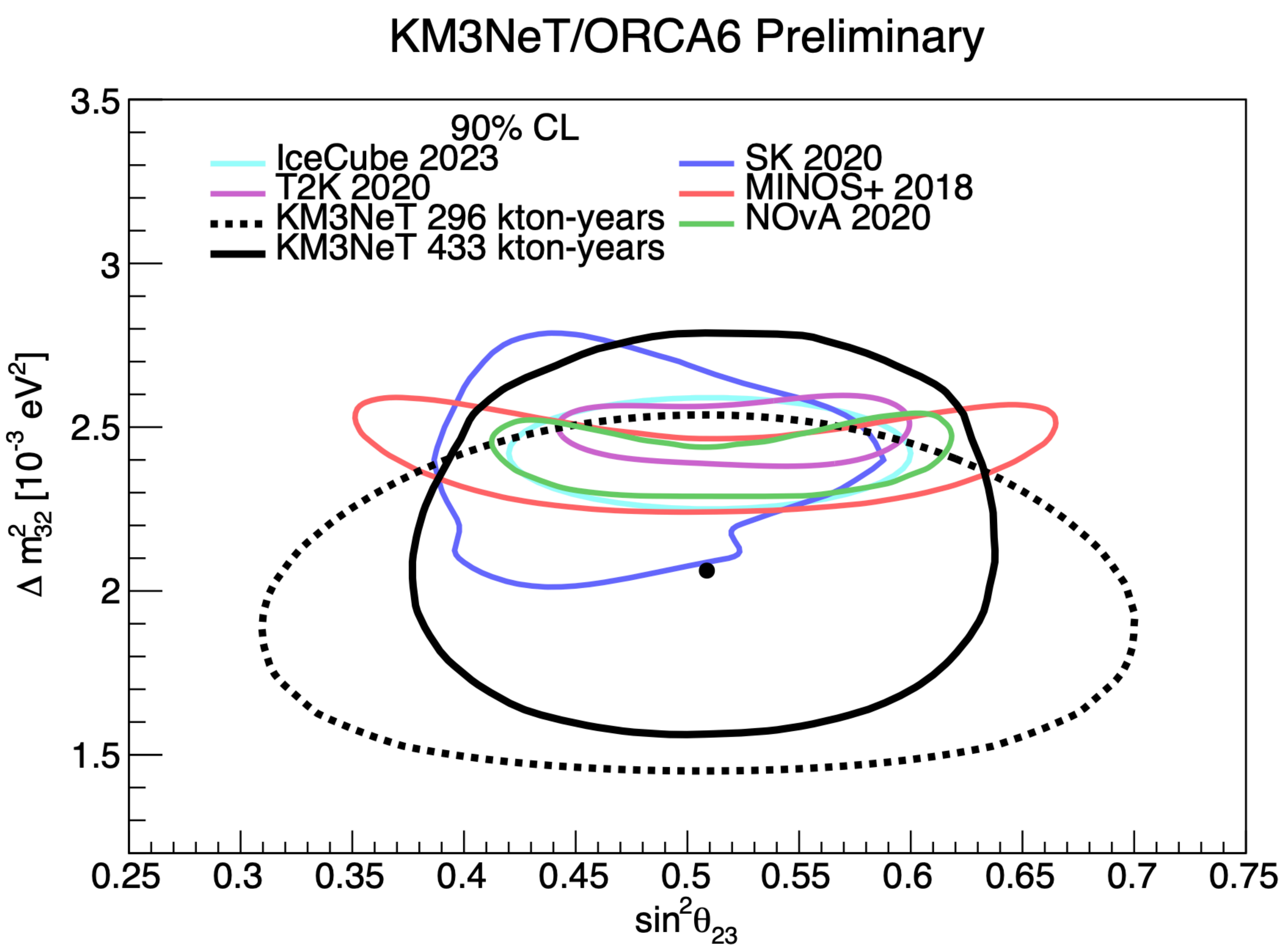
Abbasi et al. (IceCube), PRD 108 (2023)
Abbasi et al. (IceCube), arXiv: 2405.02163

ORCA

ORCA measures the multi-GeV component of the atmospheric neutrino flux from **~2GeV**

The total expected volume is 7 Mt, with events classified into high-purity tracks, low-purity tracks, and showers





Carretero et al. (KM3NeT), PoS ICRC2023
Aiello (KM3NeT), EPJC 82, 26 (2022)

Atmospheric Mass-Squared Splitting

Combining different datasets results in significant **synergy**, as the global **regions are smaller** than the individual ones.

- Colored regions: LBL+IC19
- Black-dashed: LBL+IC24+SK
- Good agreement with **reactor** experiments
- Preference for the higher octant ($\sin^2\theta_{23} = 0.561$)

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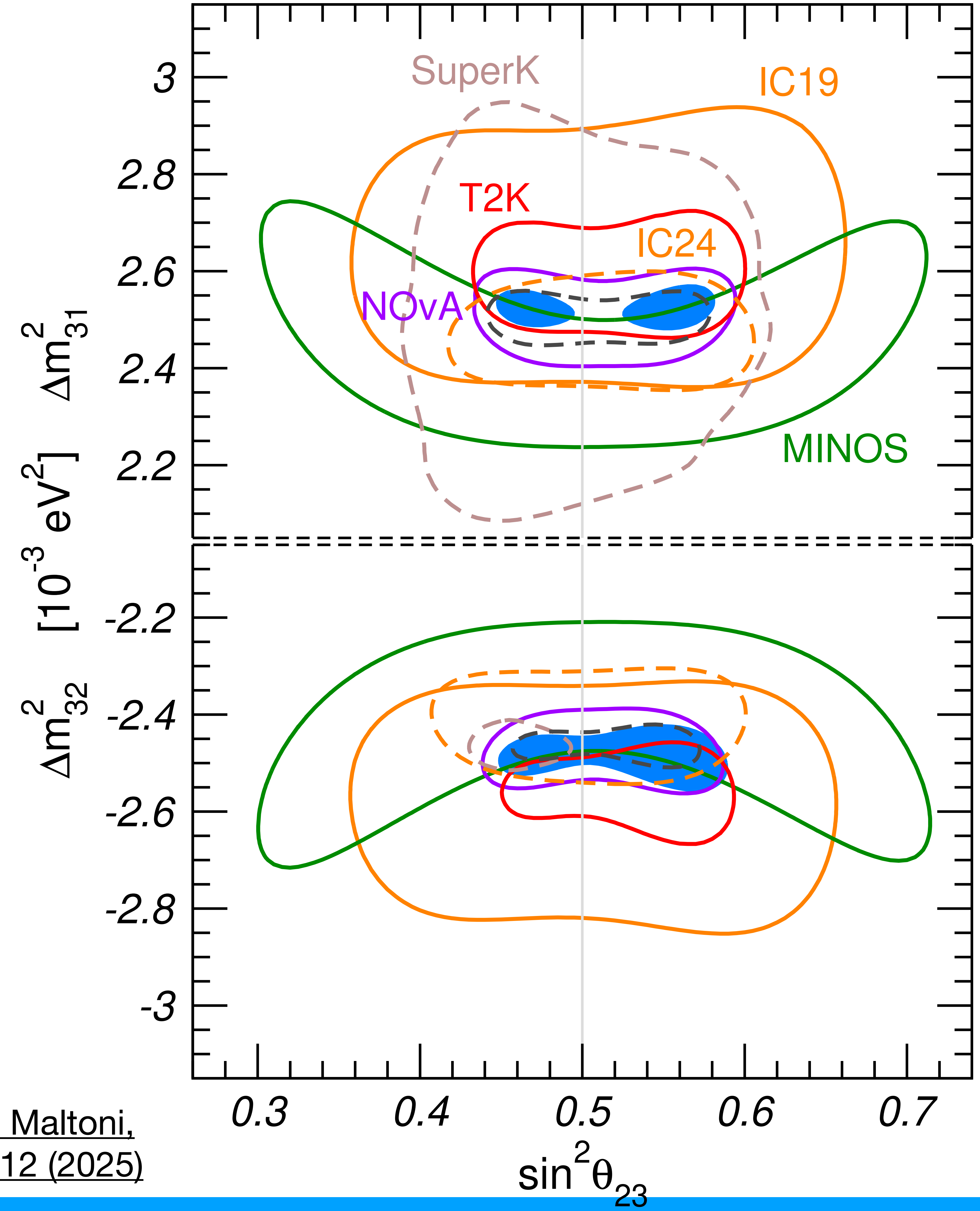
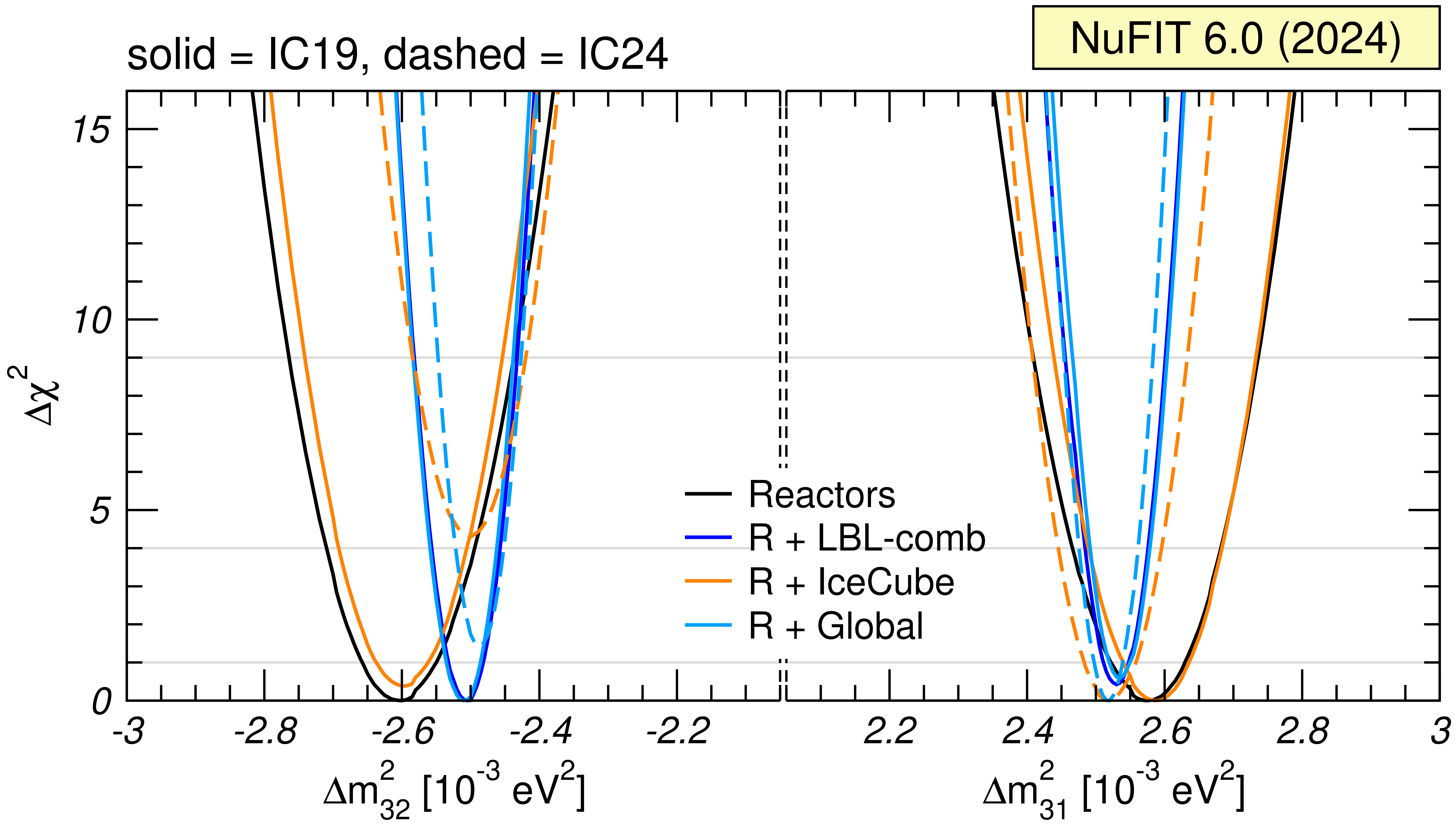


I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

Mass Ordering

- Combining **IC24+Reactors**, we get a preference for NO of $\Delta\chi^2 \sim 4.5$
- **Super-Kamiokande** alone shows a preference for NO of $\Delta\chi^2 \sim 4.5$
- **Combining IC+SK+global fit** results in a preference for NO of $\Delta\chi^2 \sim 6.1$



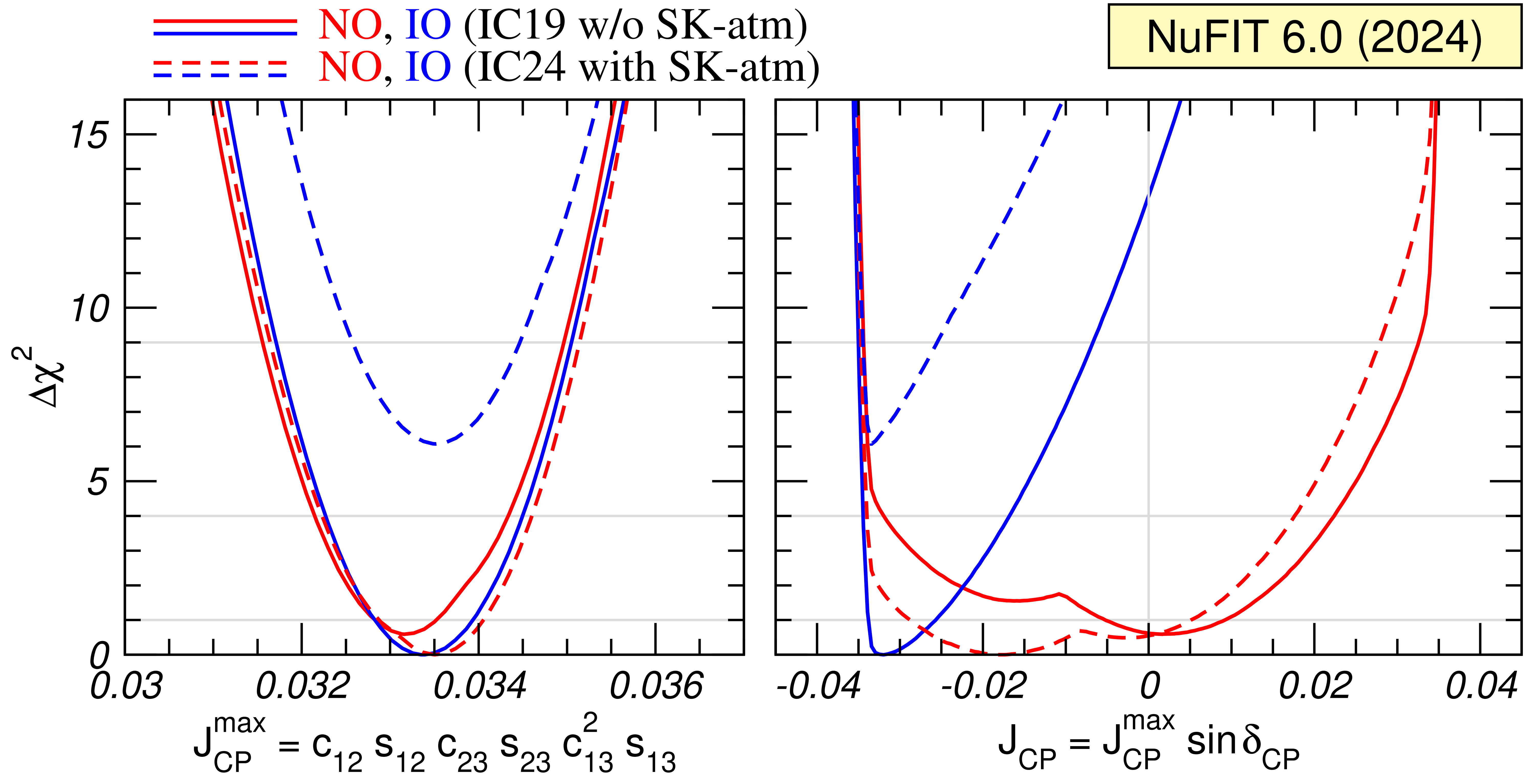
I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

CP-violation

The Jarlskog Invariant provides a convention-independent measurement of the violation of the CP symmetry

CP-conservation is margnizaly disfavored

$$J_{CP} = \text{Im}[U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j}]$$
$$= J_{CP}^{\max} \sin \delta_{CP}$$

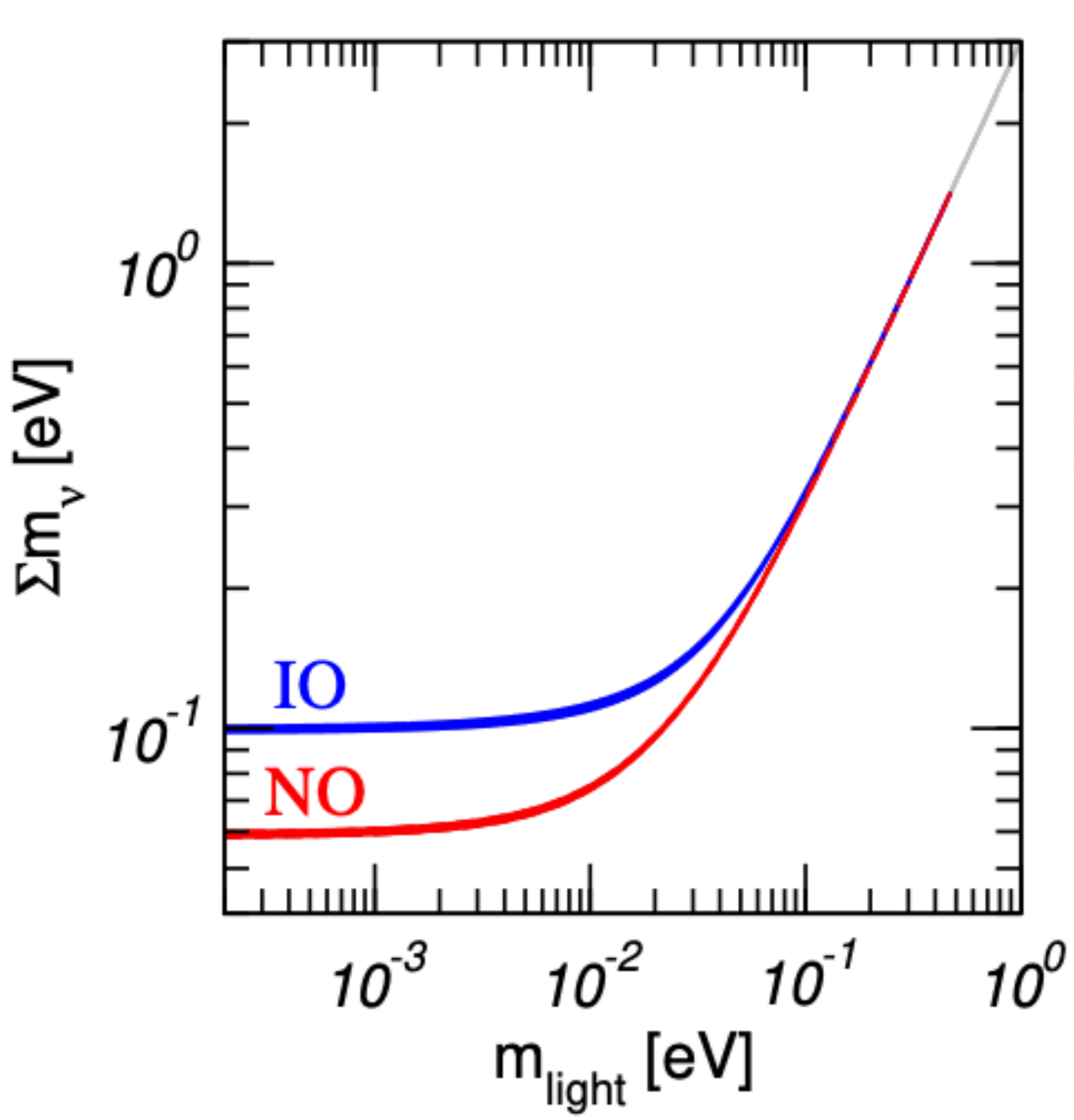


I Esteban, MC Gonzalez-Garcia, M Maltoni,
IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

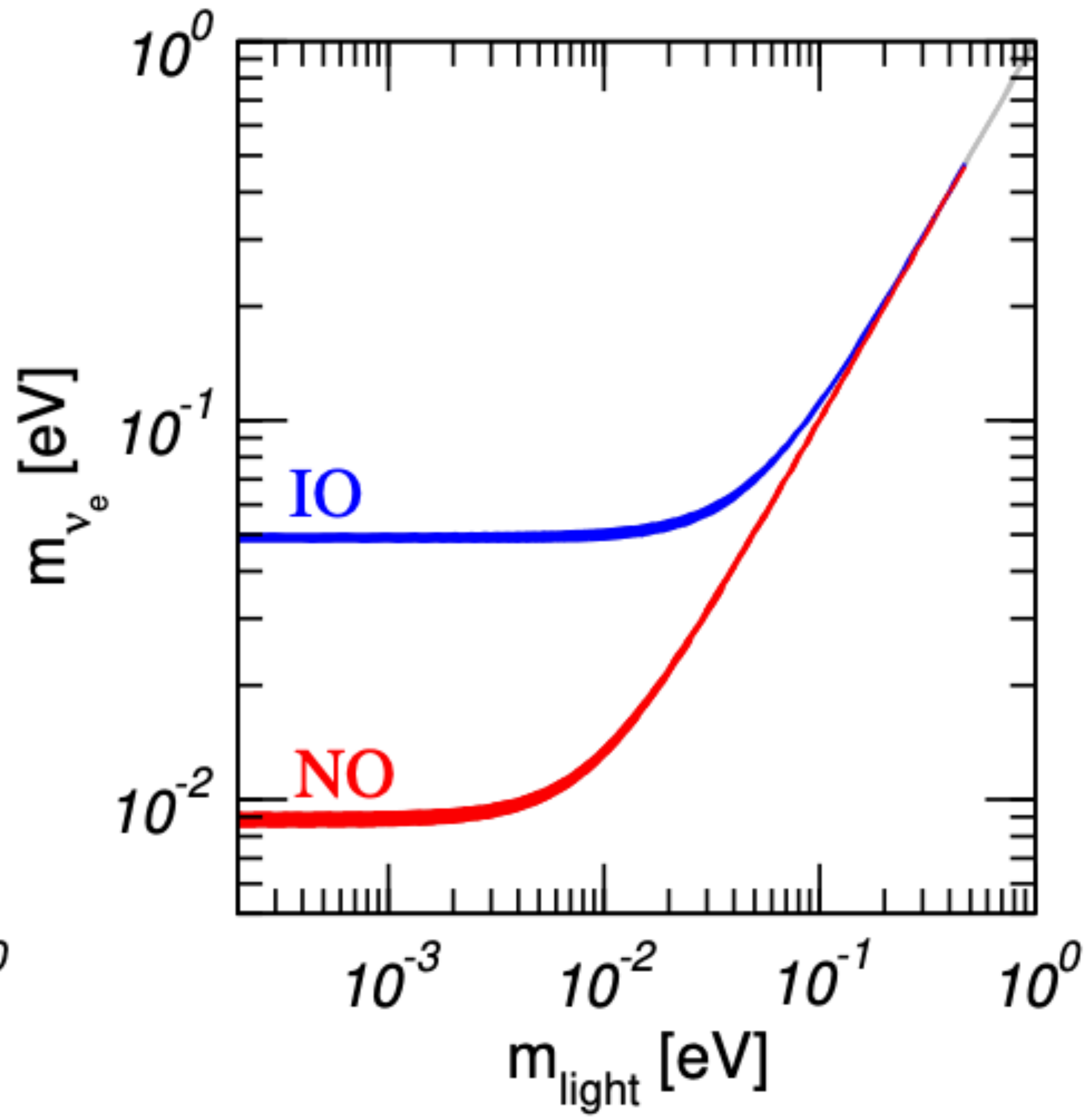
Neutrino Mass Scale

Additional information is needed to measure the absolute neutrino mass scale

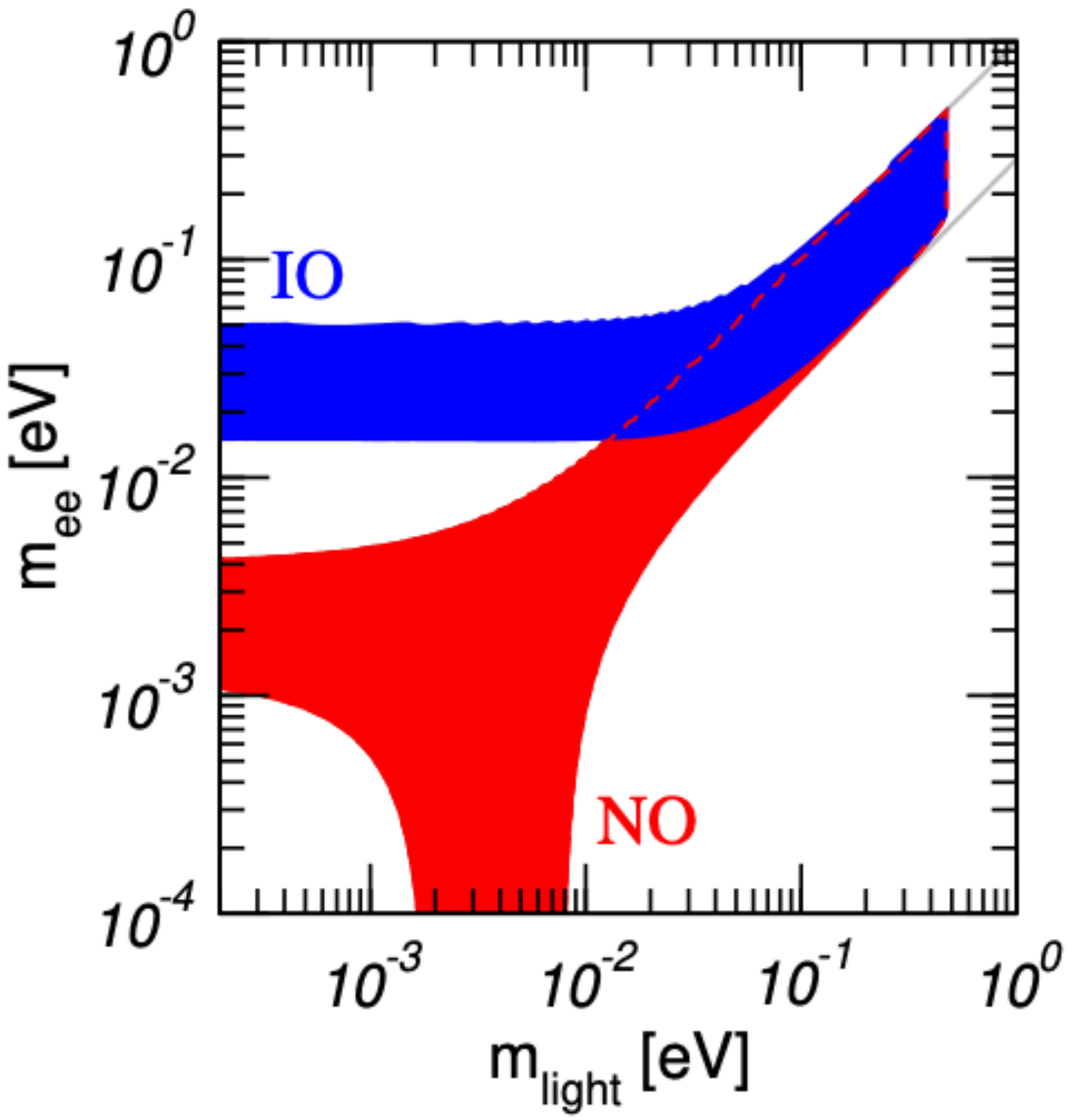
Cosmology



Beta decay (KATRIN)



$0\nu\beta\beta$



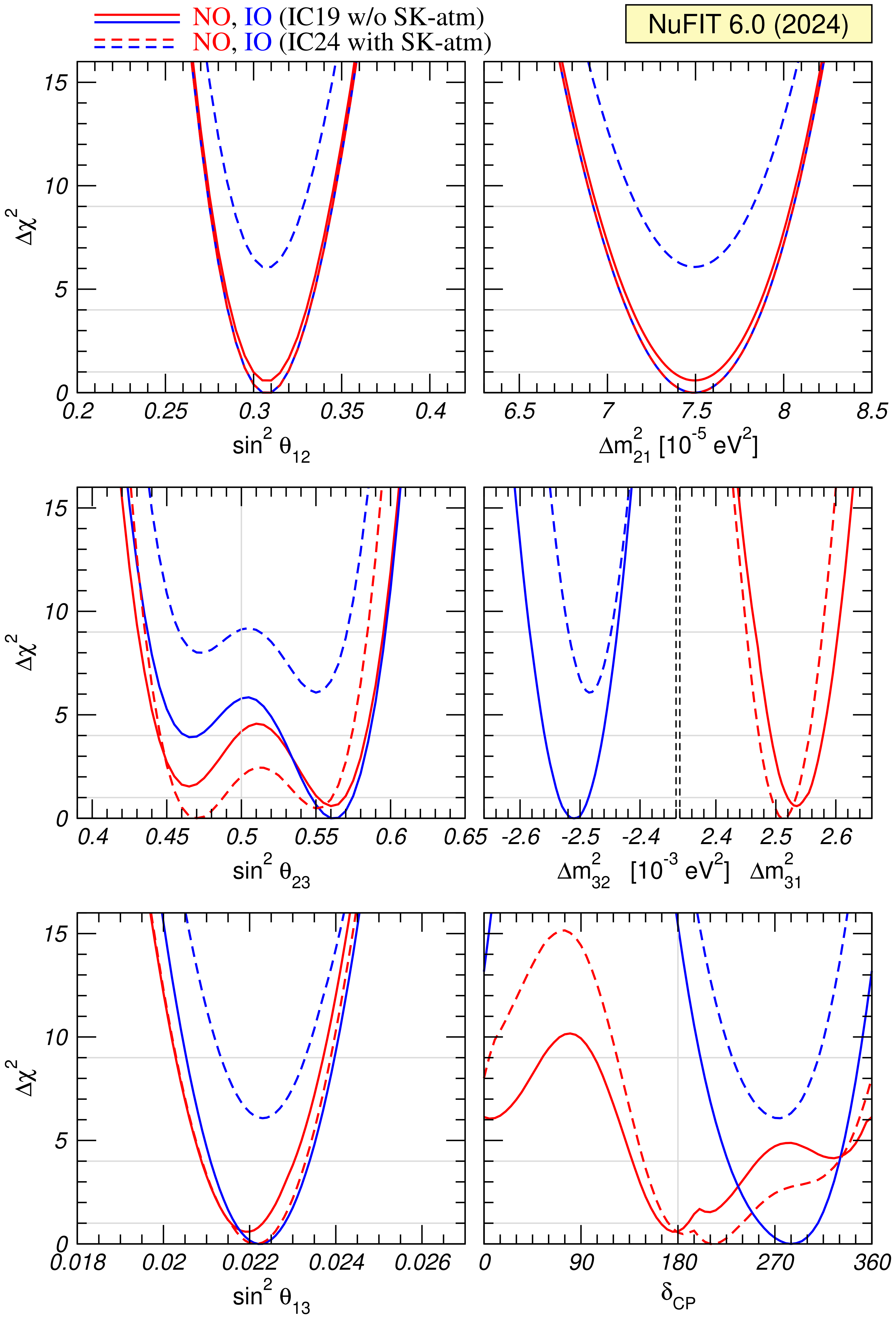
NuFIT 6.0 (2024)

I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

Conclusions

The 3ν mixing provide a consistent description of the results

- For θ_{23}, the precision is $20\,\%$ at 3σ with a small preference for **lower octant** (higher octant) combining IC24+SK+global fit (global)
- For δ_{cp}, almost the **entire region is allowed** to 3σ, with a preference close to CP-conservation for NO and maximal CP-violation for IO.
- For the **mass ordering**, there is almost no preference for ordering until the combination with IC24 and SK, which shows a preference for NO.
- **No indication** of the neutrio mass scale




Thanks!

Conclusions

	NuFit [1]	**Valencia** [2]	**Bari** [3]
$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.012}$	$0.318^{+0.016}_{-0.016}$	$0.303^{+0.01}_{-0.013}$
$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.574^{+0.14}_{-0.14}$	$0.455^{+0.018}_{-0.015}$
$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.022^{+0.00069}_{-0.00069}$	$0.023^{+0.0007}_{-0.0006}$
δ_{CP}	212^{+26}_{-41}	218^{+38}_{-27}	234^{+41}_{-32}
$\Delta m^2_{21}/10^{-5}$	$7.49^{+0.19}_{-0.19}$	$7.50^{+0.22}_{-0.20}$	$7.36^{+0.16}_{-0.15}$
$\Delta m^2_{31}/10^{-5}$	$2.513^{+0.021}_{-0.019}$	$2.55^{+0.02}_{-0.03}$	$2.458^{+0.023}_{-0.029}$

[1] Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Pinheiro, Schwetz, arXiv:2410.05380
[2] Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortola, Valle, JHEP 02 (2021) 071
[3] Capozzi, Di Valetino, Lisi, Marrone, Melchorri, Palazzo, PRD 104 (2021) 8