Physics of ν Oscillation with Atmospheric ν Detectors

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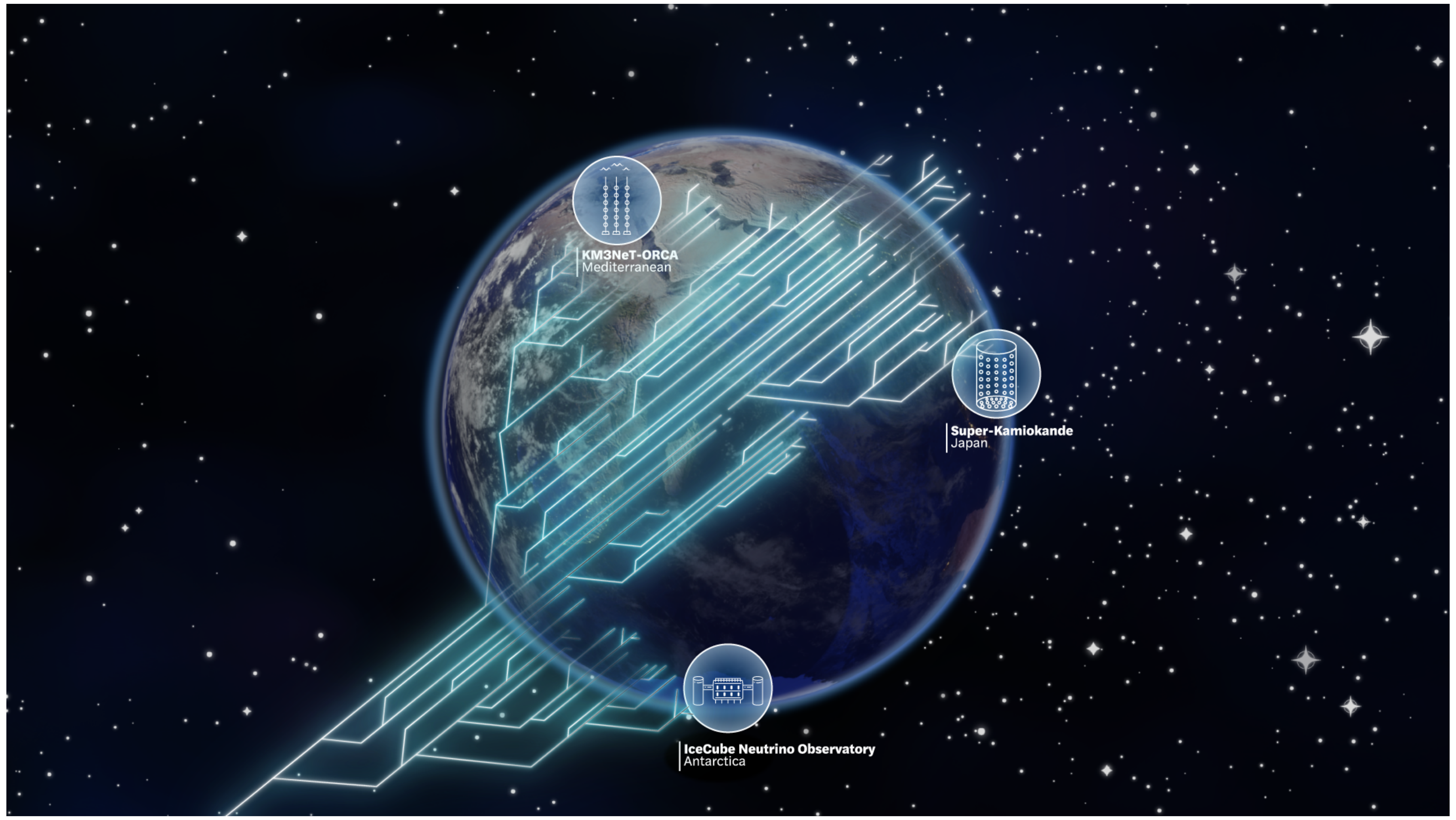
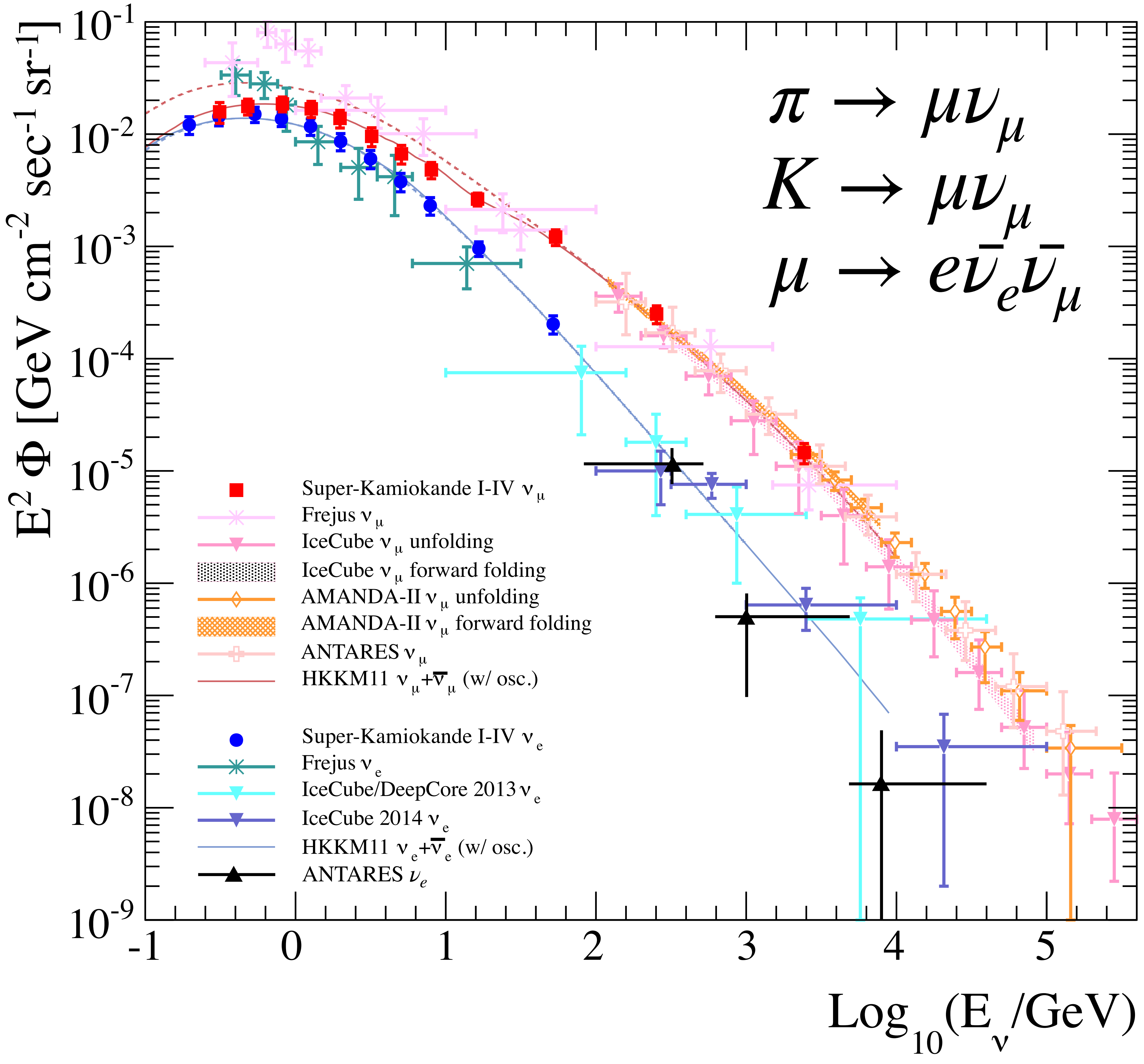
XXXI International Conference on Neutrino Physics and Astrophysics

Durham University

Atmospheric Neutrinos

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



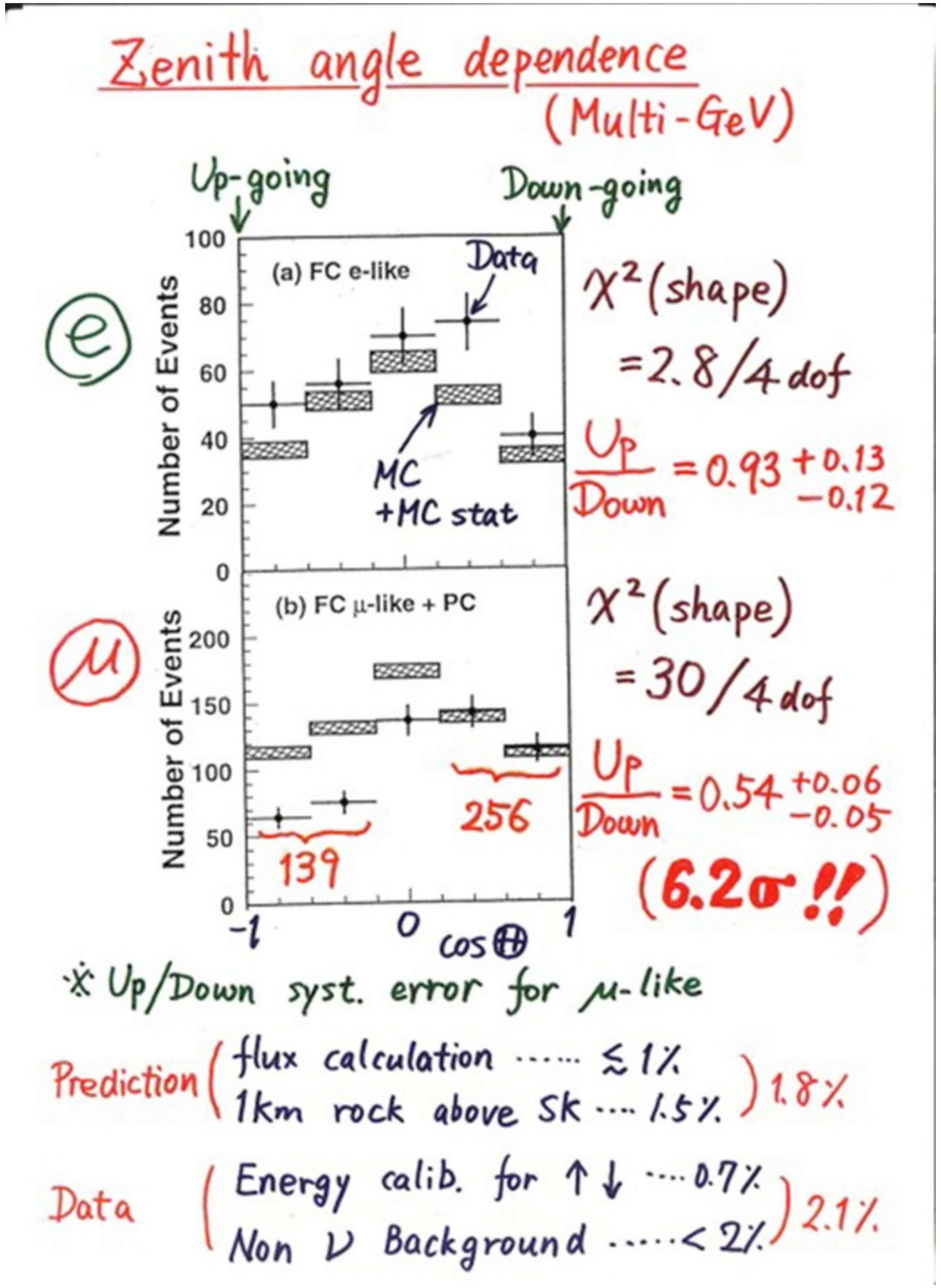


E. Richard et al. (SK), PRD 94 (2016) 5

Evidence for Flavor Oscillation

The measurement of the **atmospheric neutrino** flux provided evidence for neutrino flavor oscillation.

Flavor oscillations are the only evidence that **neutrinos are massive particles**



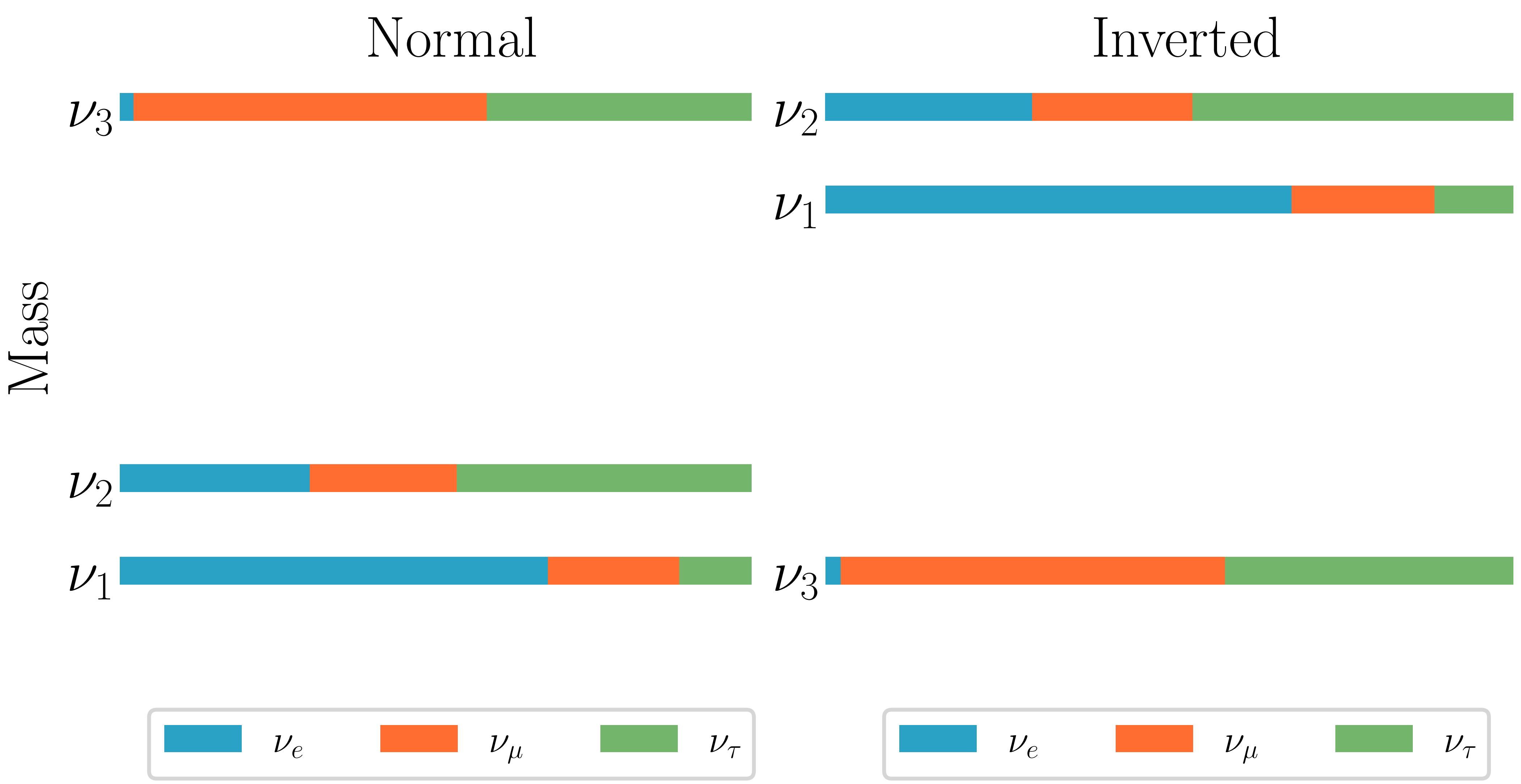
Takaaki Kajita (Super-kamiokande) Neutrino 98

3ν Mixing

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

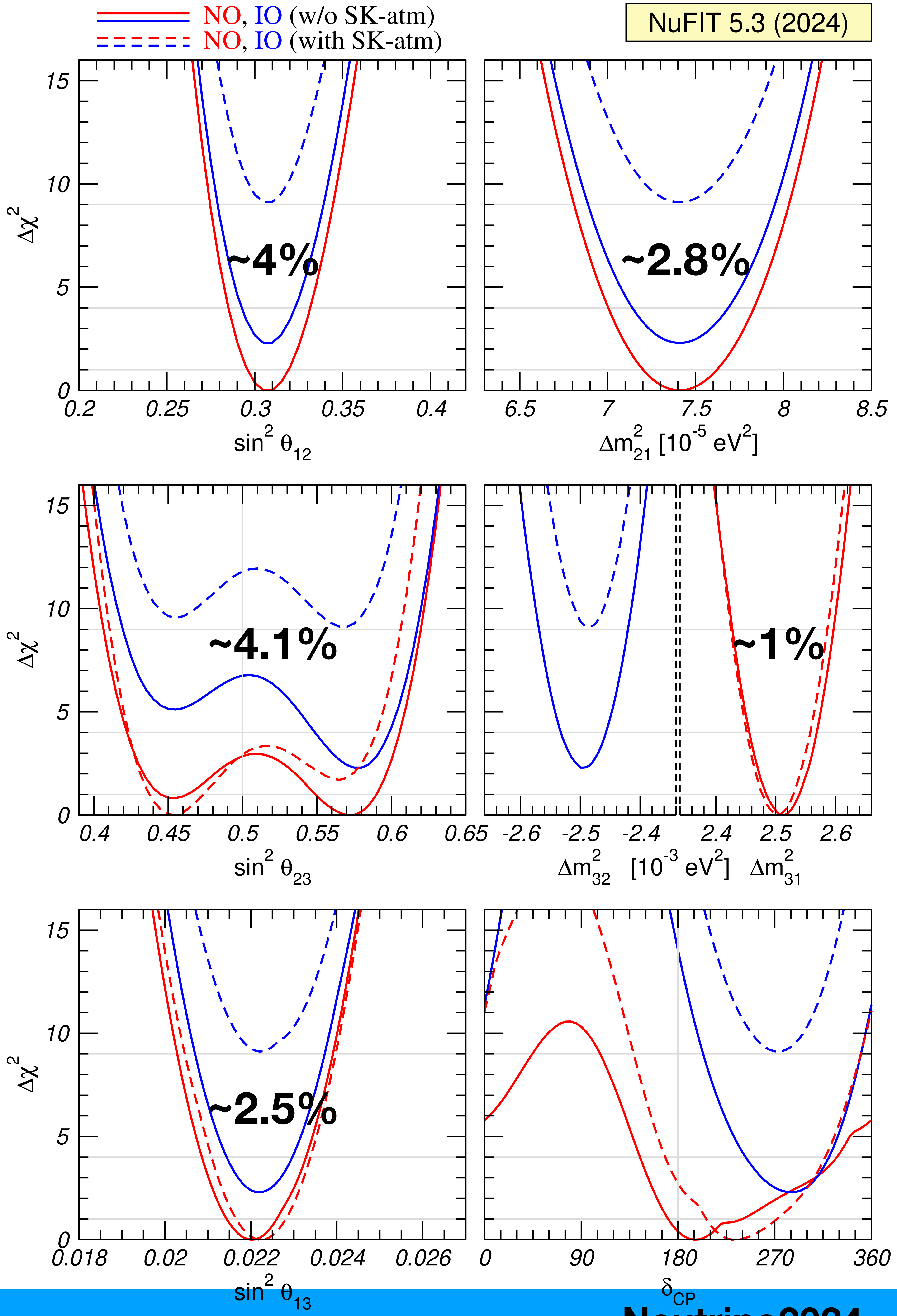
$$i\frac{d\nu}{dE} = \frac{1}{2E}\left(U^\dagger \mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) U\right)\nu \qquad \nu_\alpha = \sum U_{\alpha i}\nu_i$$

Present sensitivity to the **3ν scenario** reaches ~1-4% for most of the parameters.



Esteban, et al., JHEP 09 (2020)

Similar results were found by:
Capozzi, et al., PRD 104 (2021)
de Salas, et al., JHEP 02 (2021)

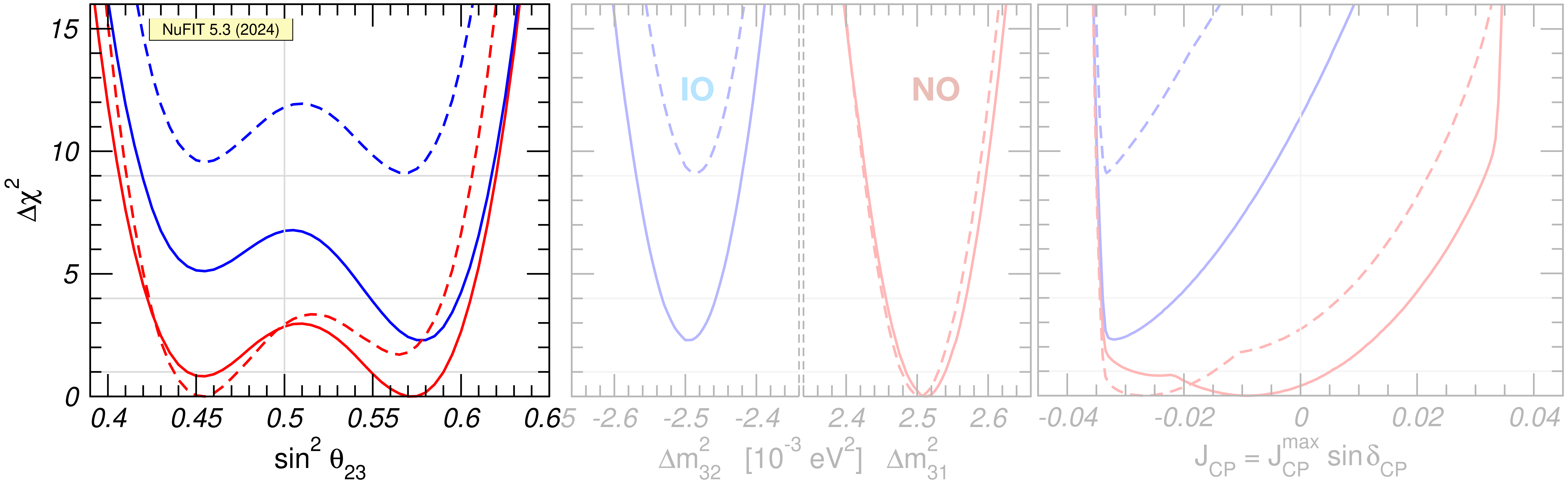


3ν Mixing

The **less constrained parameters** are:

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP 09 (2020)

Preference for $\theta_{23} < 45$ | Preference for NO at 2σ | Preference for CP-violation



In this talk, we aim to investigate the insights that **atmospheric neutrinos** can provide on these **uncertainties**

3ν Mixing

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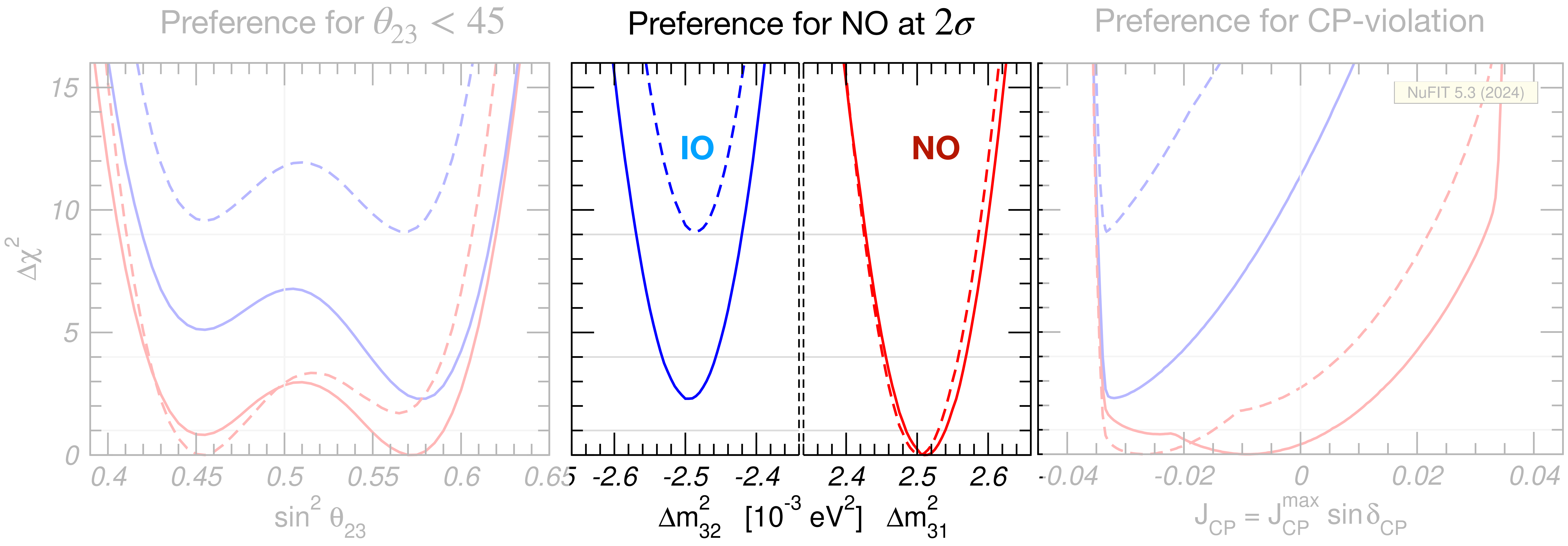
Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP 09 (2020)



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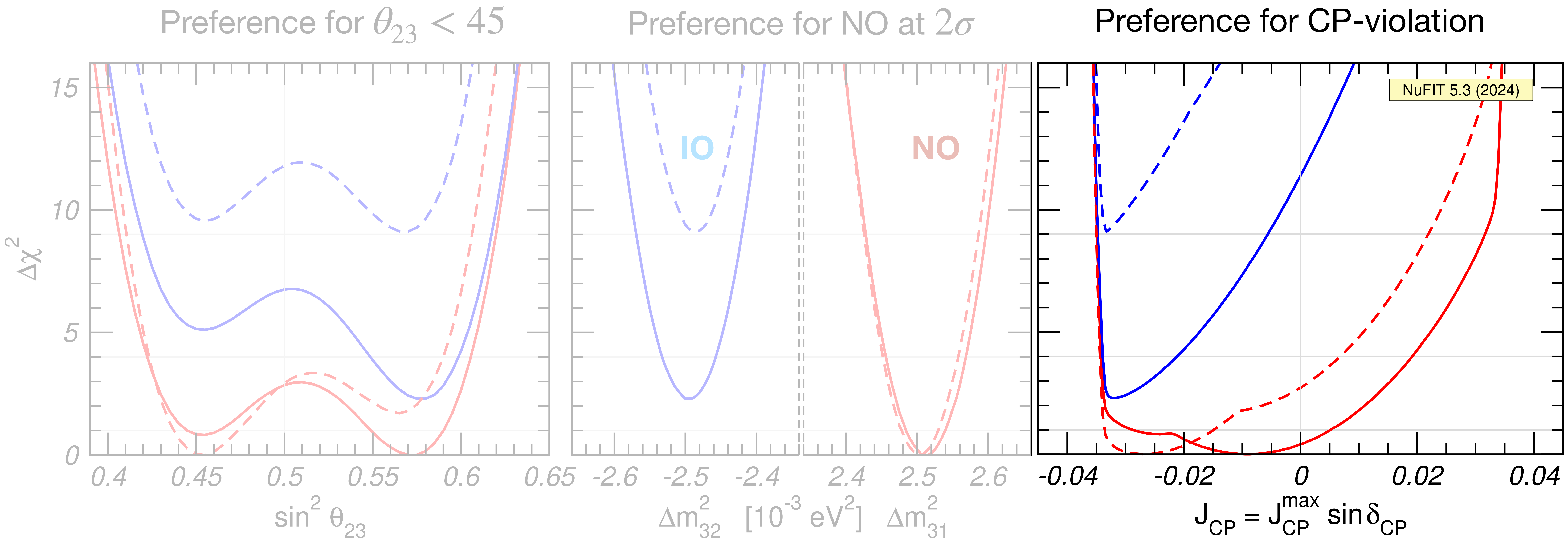
3ν Mixing

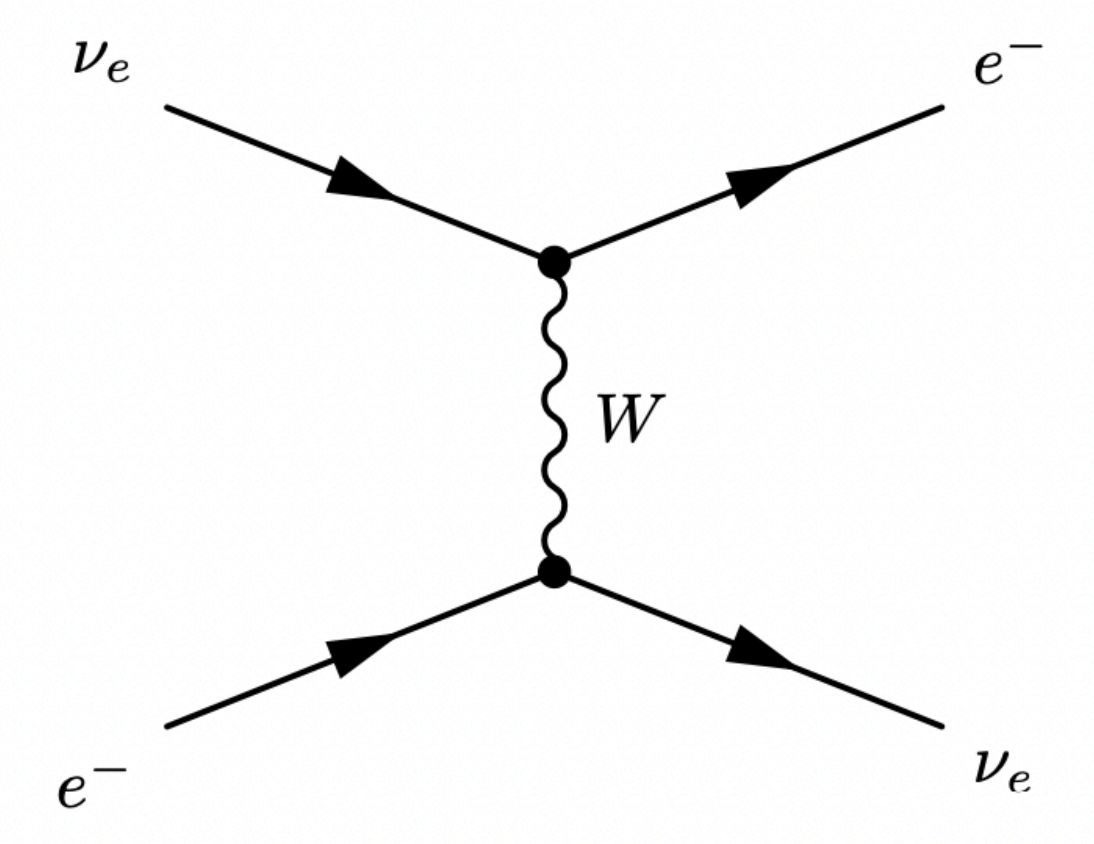
The **less constrained parameters** are:

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP 09 (2020)



In this talk, we aim to investigate the insights that **atmospheric neutrinos** can provide on these **uncertainties**

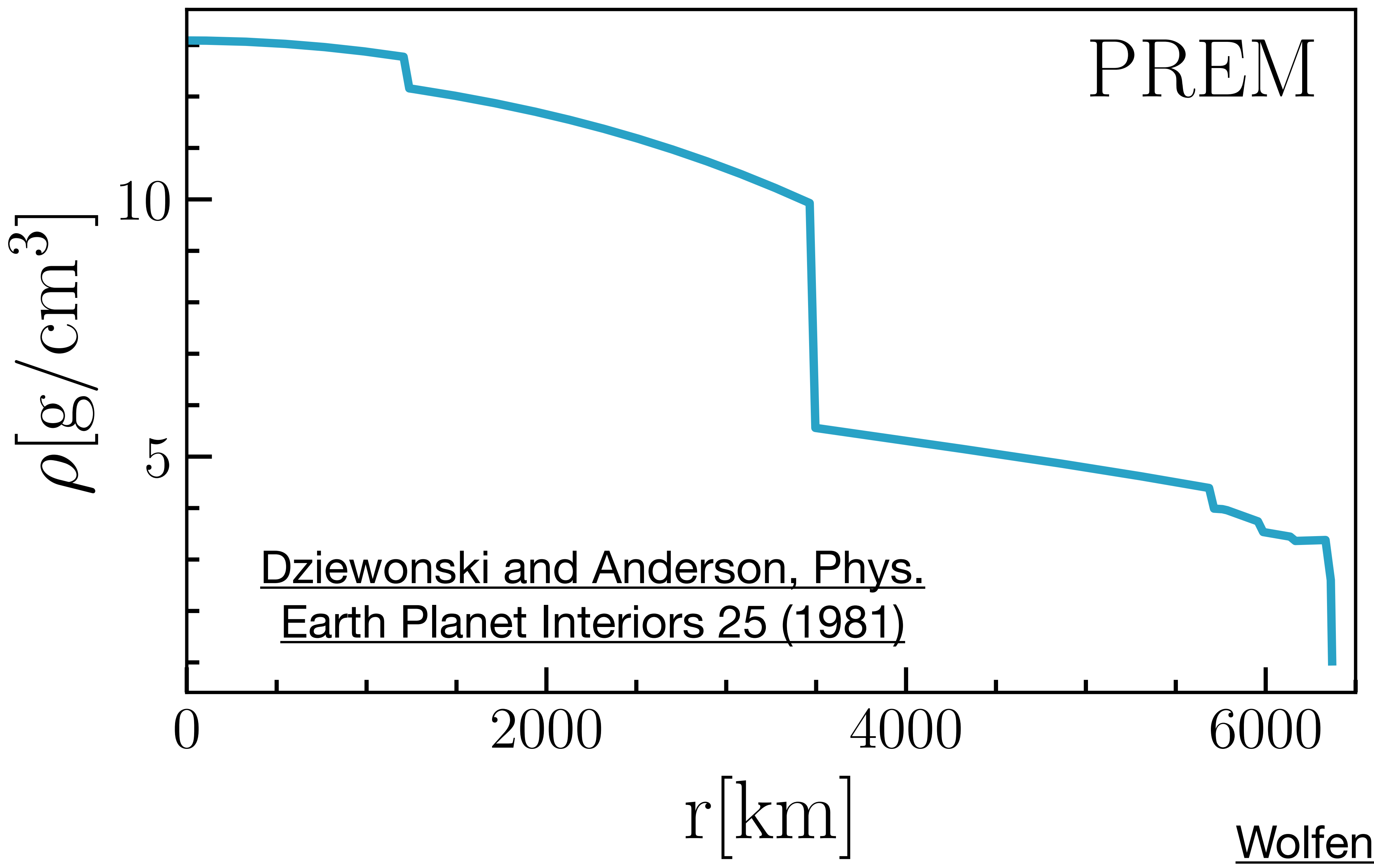
Neutrino Evolution in Matter

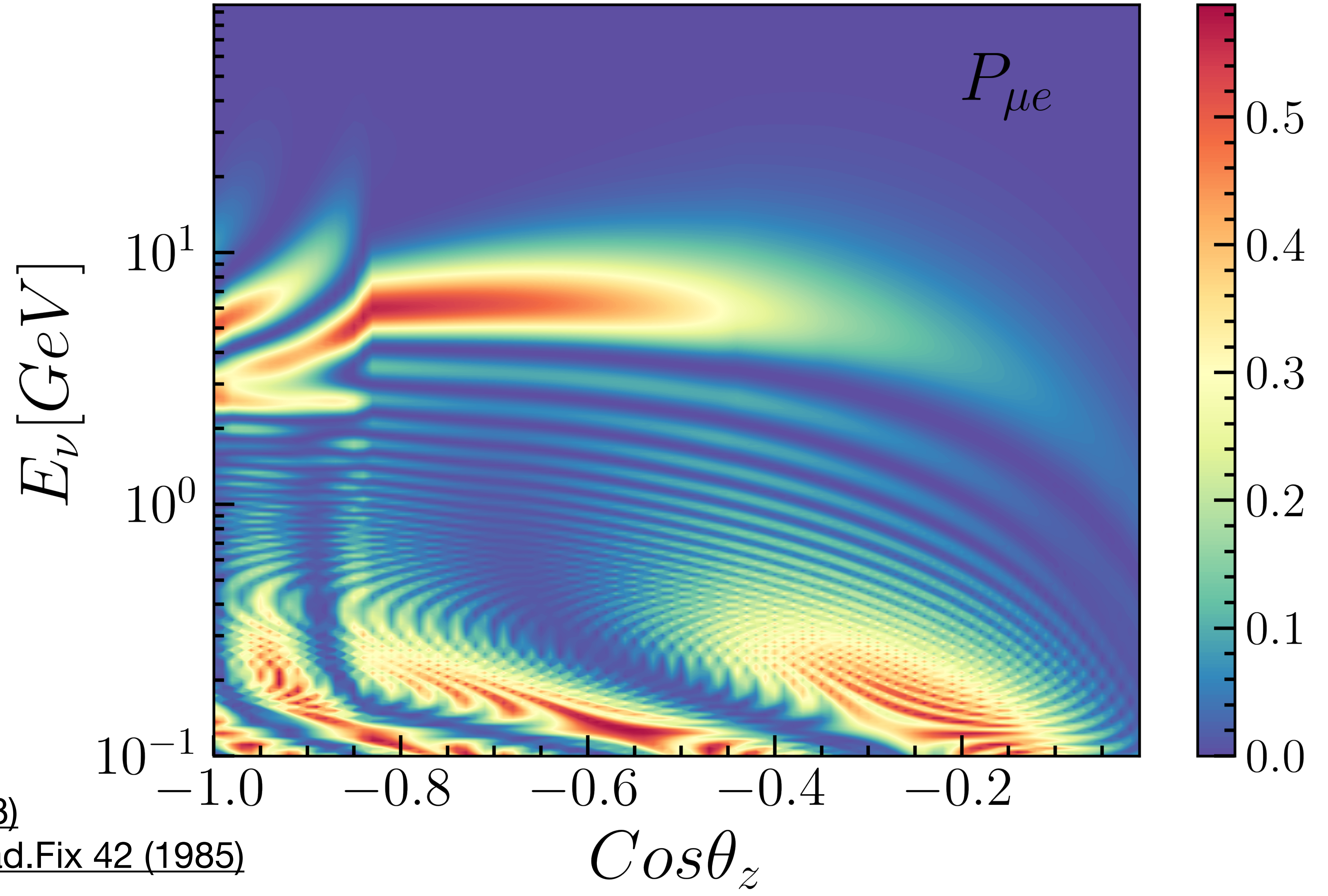


Matter effects play a crucial role in the evolution of atmospheric neutrinos

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

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





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

Sub-GeV

For **E < 1GeV**, atmospheric neutrino oscillations are **dominated by** Δm^2_{21}

- The CP-violation depends on the three oscillation lengths.

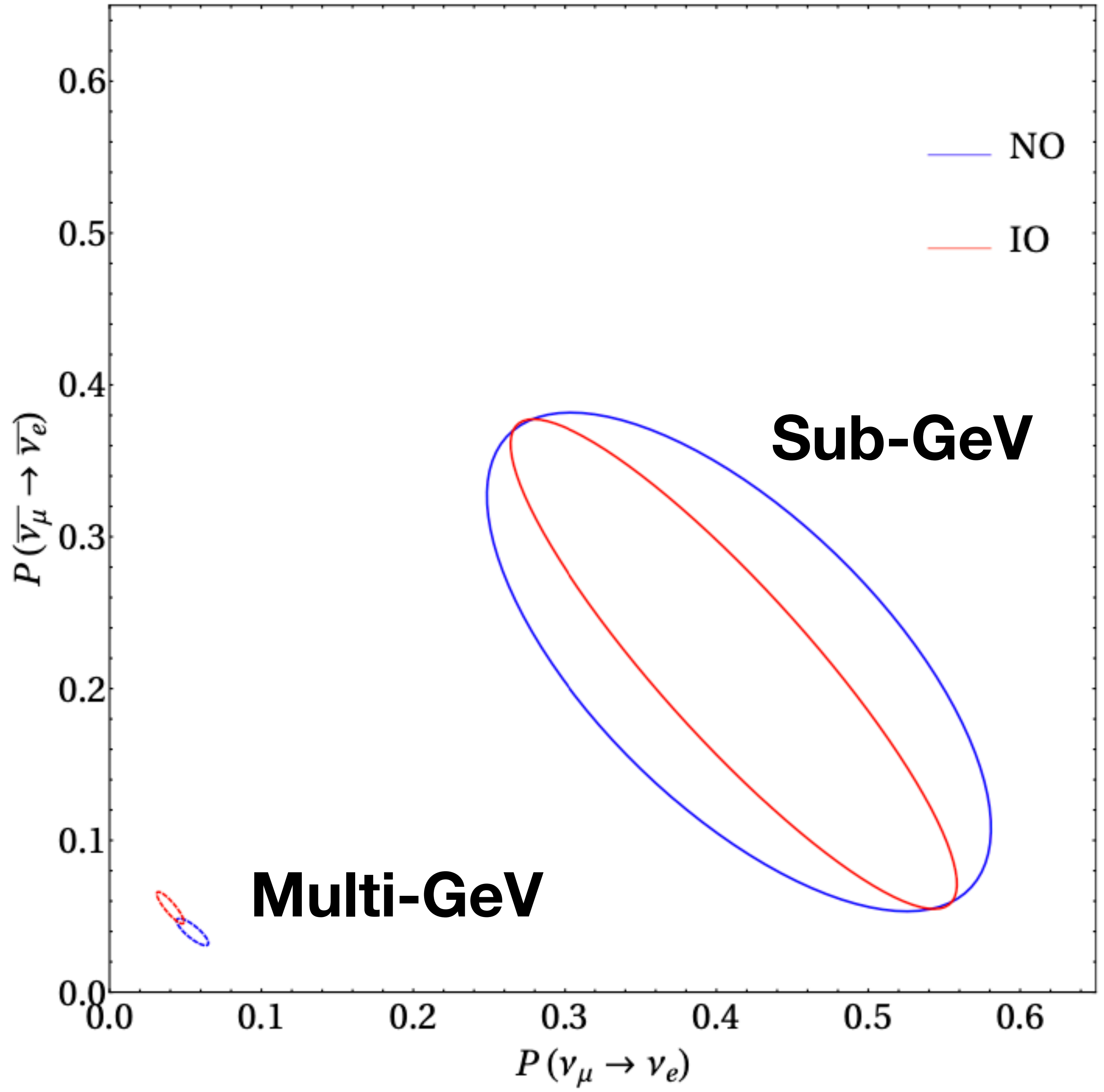
$$P_{CP} = -8J^{max}_{CP}\sin(\delta_{cp})\sin(\Delta_{21})\sin(\Delta_{31})\sin(\Delta_{32})$$

- The oscillations introduced by Δ_{31} and Δ_{32} averaged

Oscillation phase $$\Delta_{ij} = \frac{\Delta m^2_{ij}}{4E_\nu}$$

Peres and Smirnov, NPB 680 (2004) Akhmedov, Maltoni and Smirnov, JHEP 06 (2008)
Peres and Smirnov, PRD 79 (2009) Denton and Parke, PRD 100 (2019) Parke, PRD 103 (2021)

The **CP-violation** term is **enhanced** due to the solar oscillation.



IMS, Minakata, PTEP (2019) 7

Sub-GeV

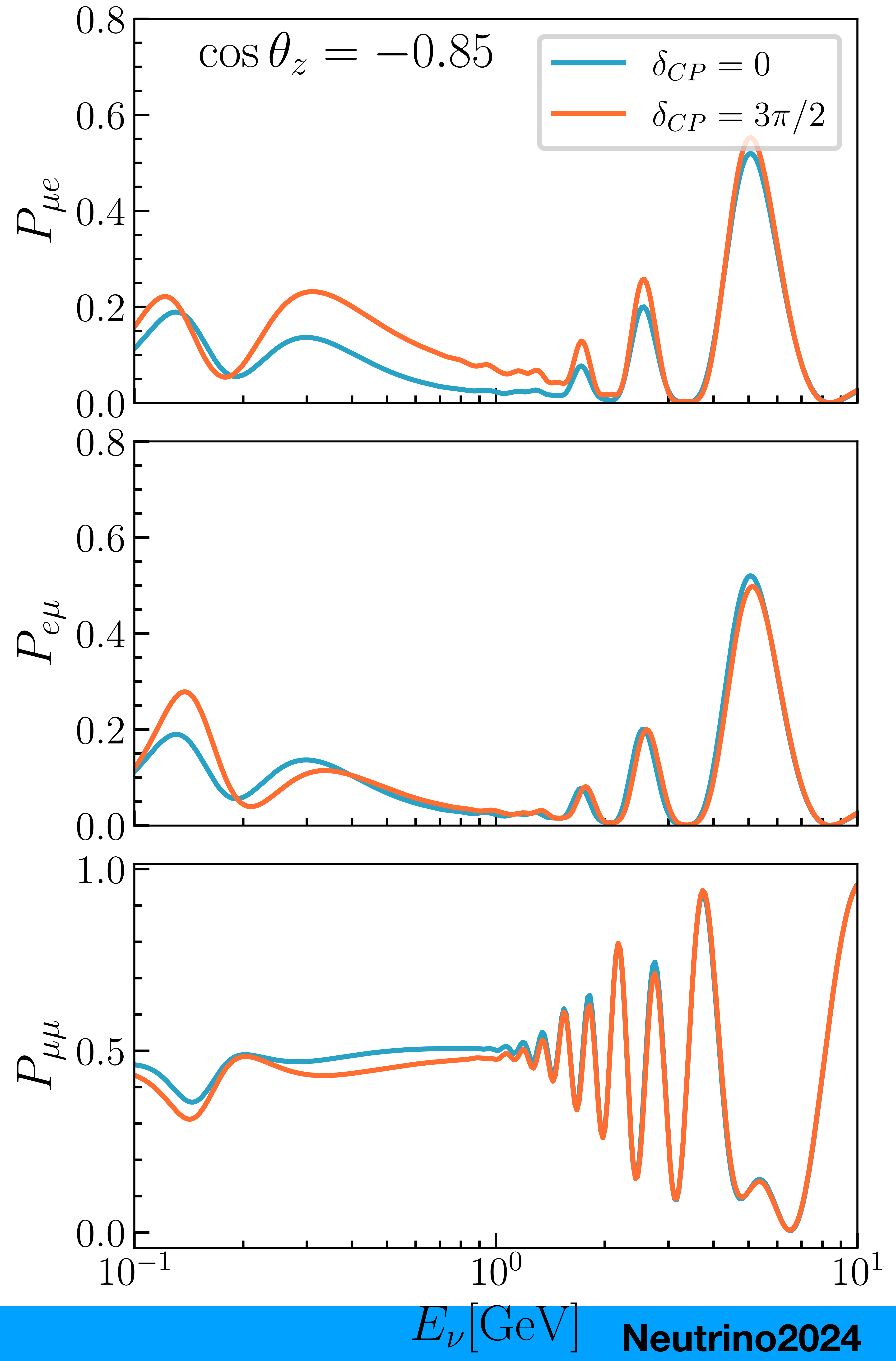
For atmospheric neutrinos, both fluxes are sensitive to δ_{CP}

- 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 $\cos\delta_{CP}$

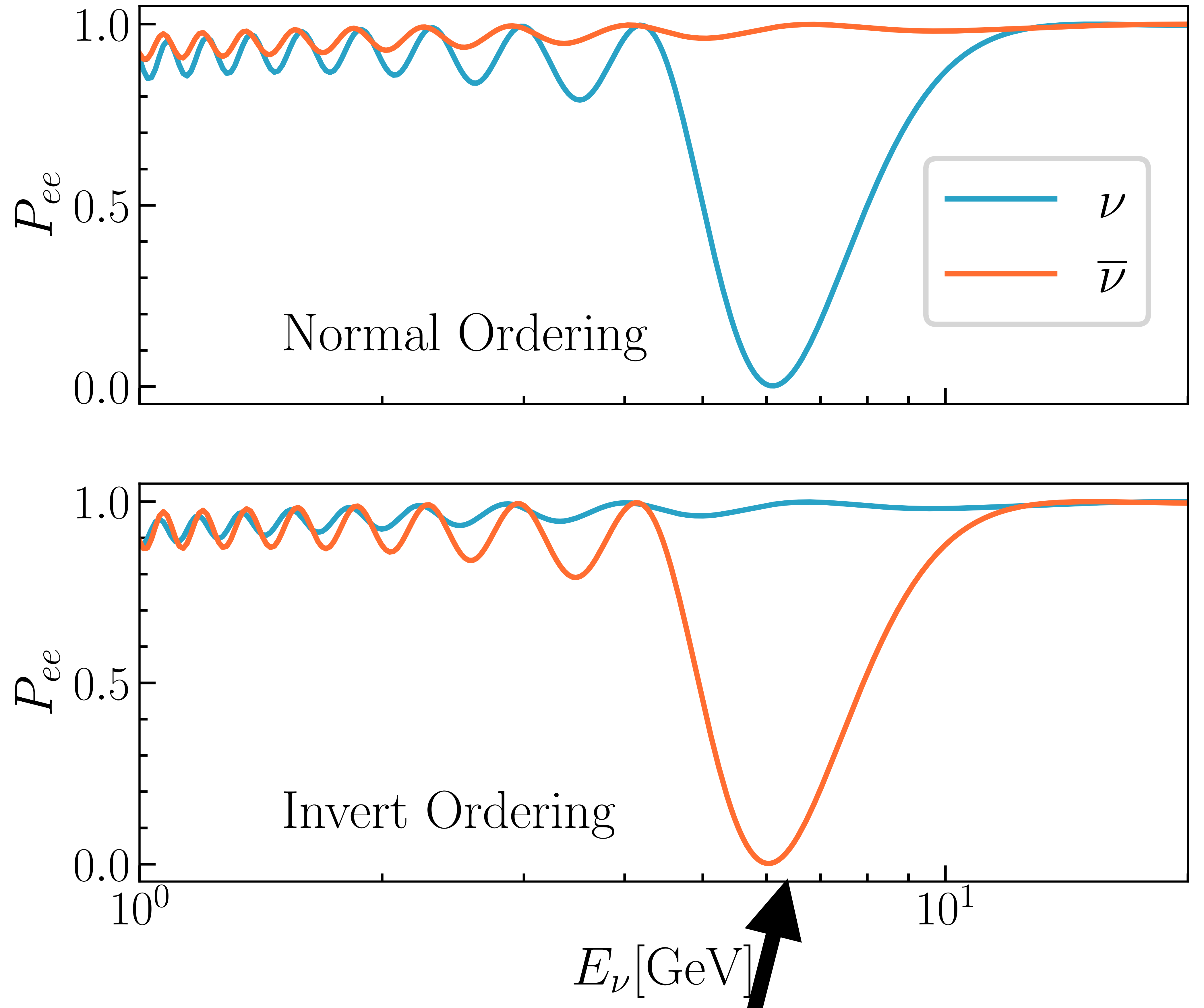


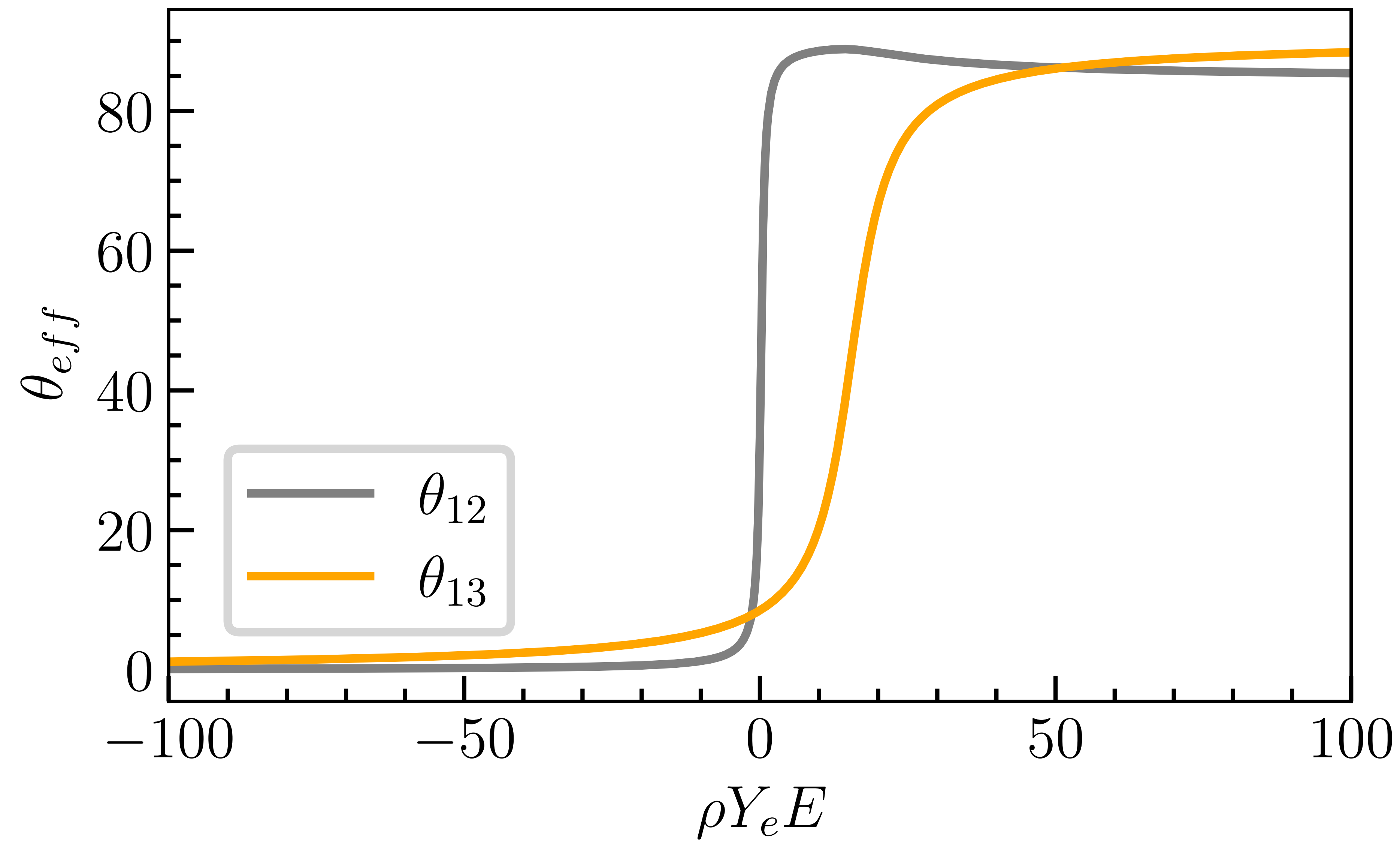
Minakata, Nunokawa, Parke, PLB 537 (2002) Minakata, Nunokawa, Parke, PRD 66 (2002)
Denton and Parke, PRD 109 (2024)

Multi-GeV

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

- The matter effect enhances the oscillation of neutrinos (anti-neutrinos) for NO (IO)





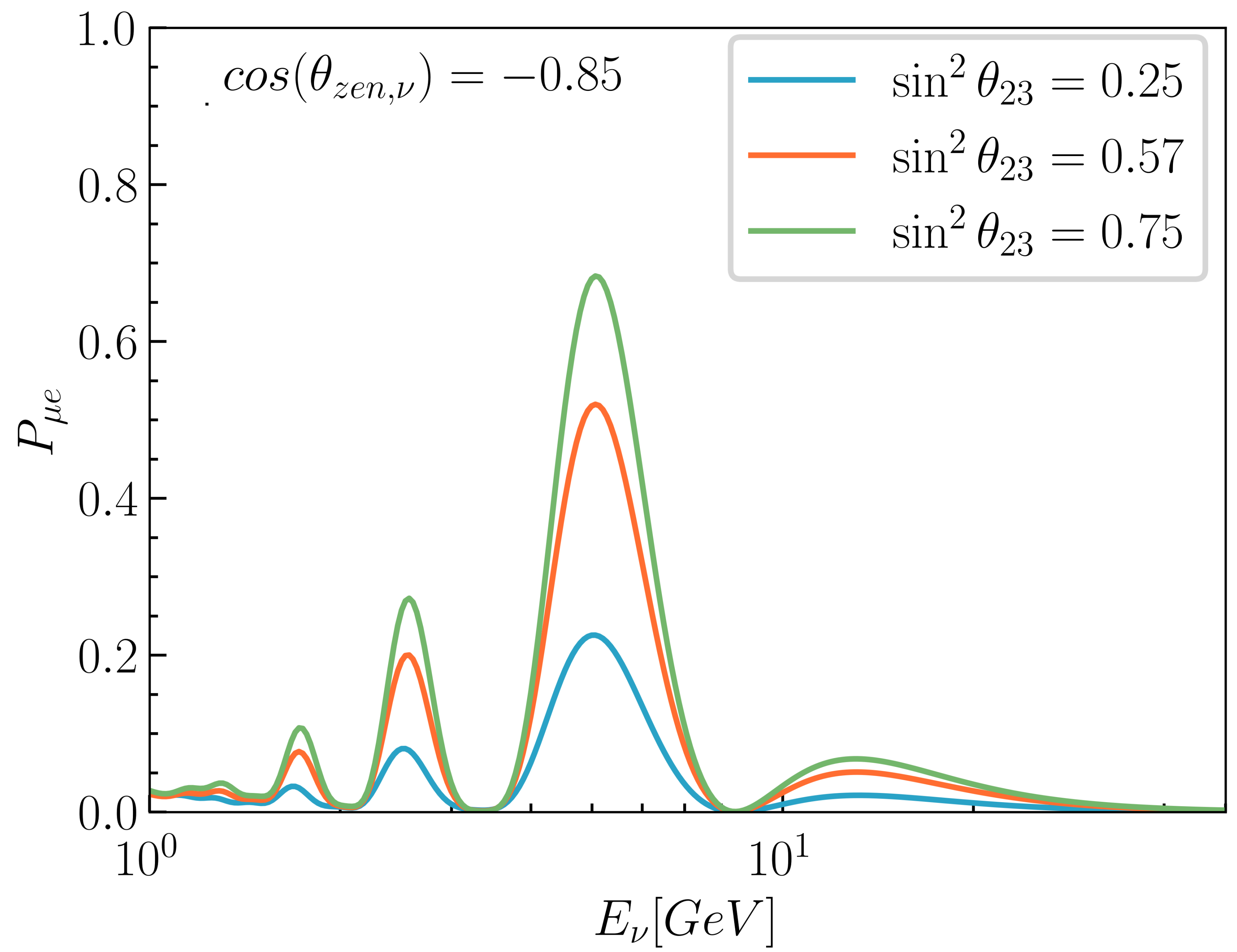
The enhancement of θ_{13}^{eff} lead to a deep in P_{ee} for ν ($\overline{\nu}$) for NO (IO)

Palomares-Ruiz and Petcov, NPB 712 (2005)

Akhmedov, Maltoni and Smirnov, JHEP 05 (2007)

Multi-GeV

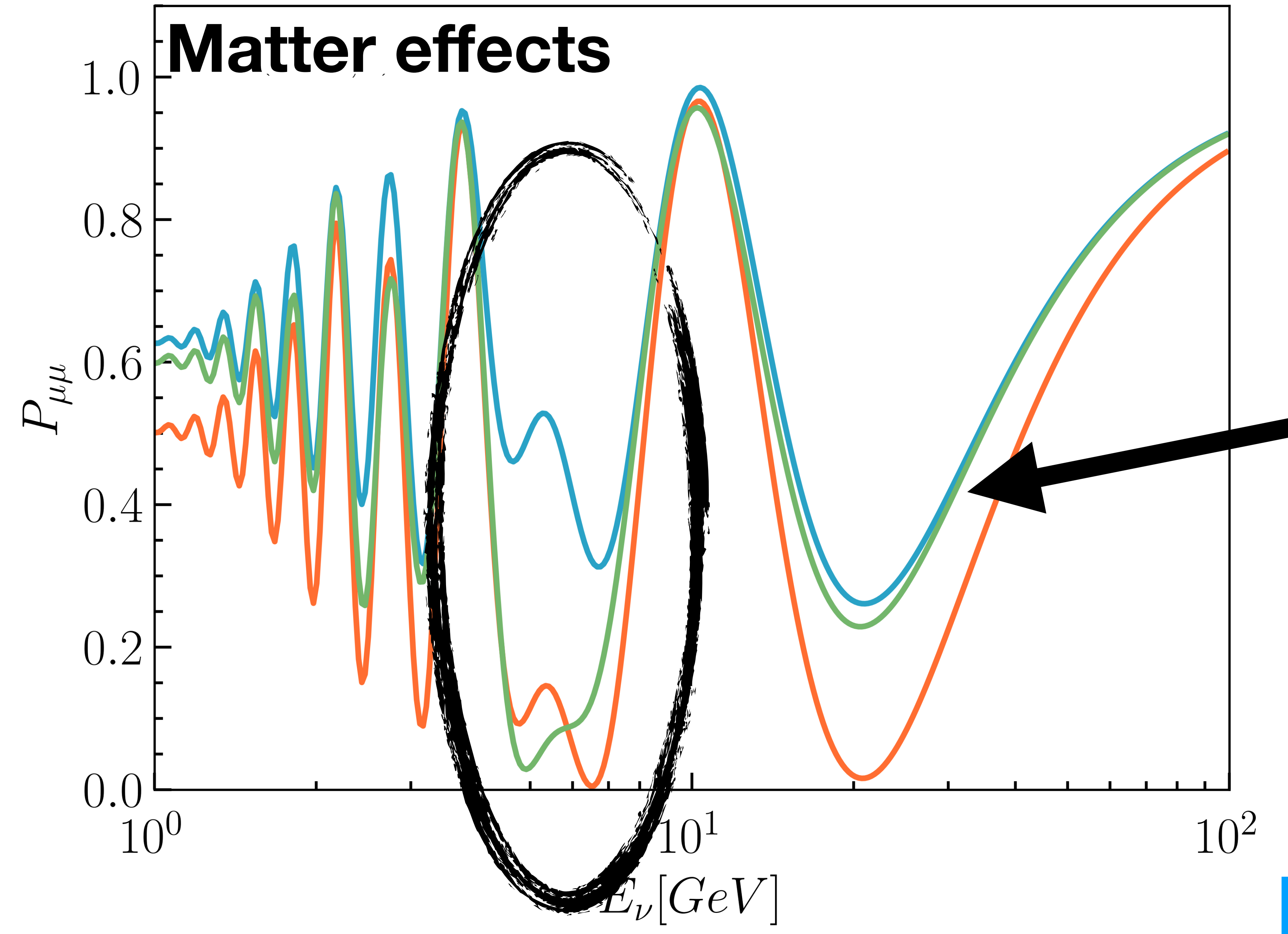
In the multi-GeV region, neutrino evolution is dominated by Δm^2_{31} and $\sin^2\theta_{23}$



- $P_{\mu e}$ shows a linear dependence on the octant of θ_{23}

- $P_{\mu\mu}$ can determine whether θ_{23} is **maximal mixing**.

- The **matter effects** can **resolve** the degeneracy between the two **octants**.



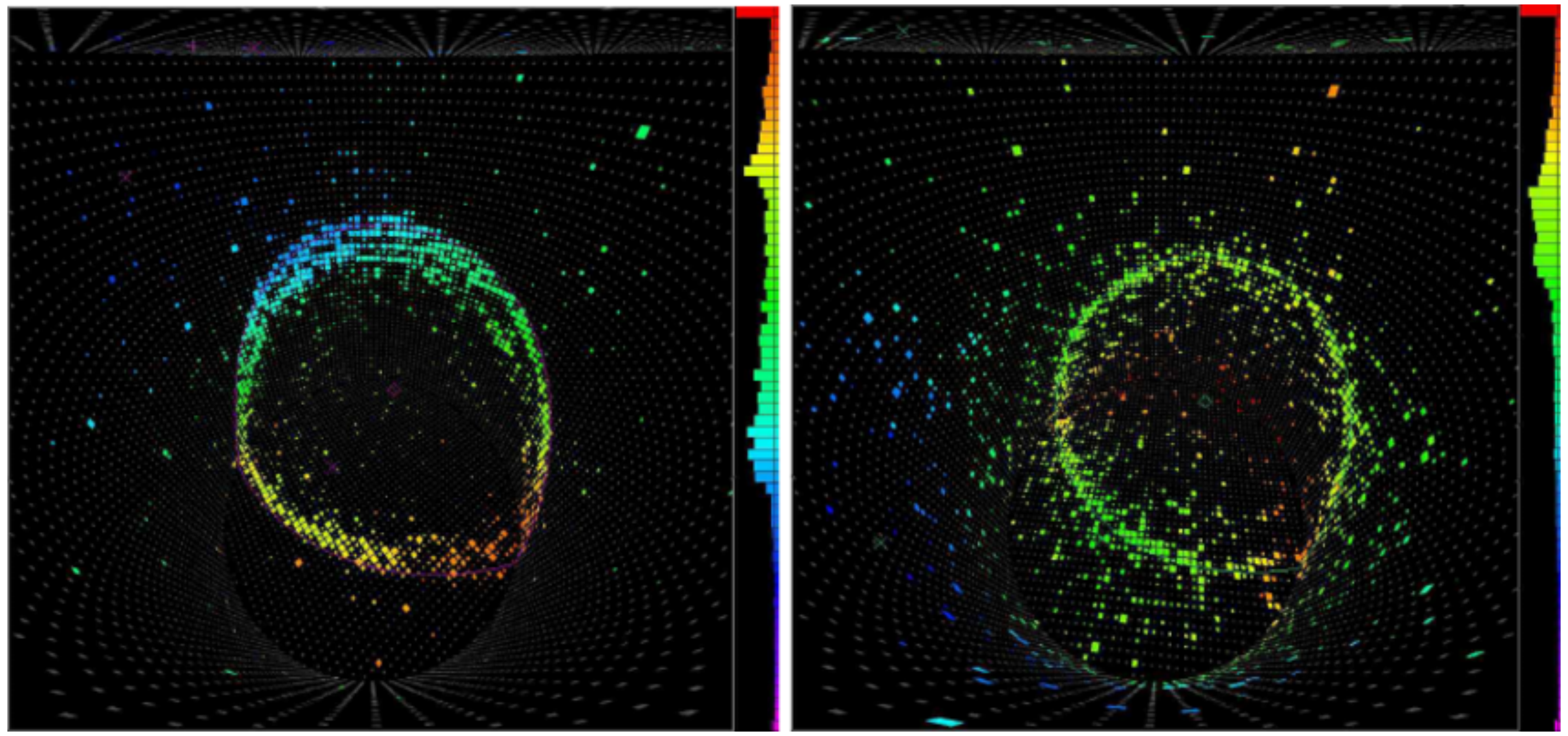
Symmetric with respect to θ_{23} octant

Super-Kamiokande

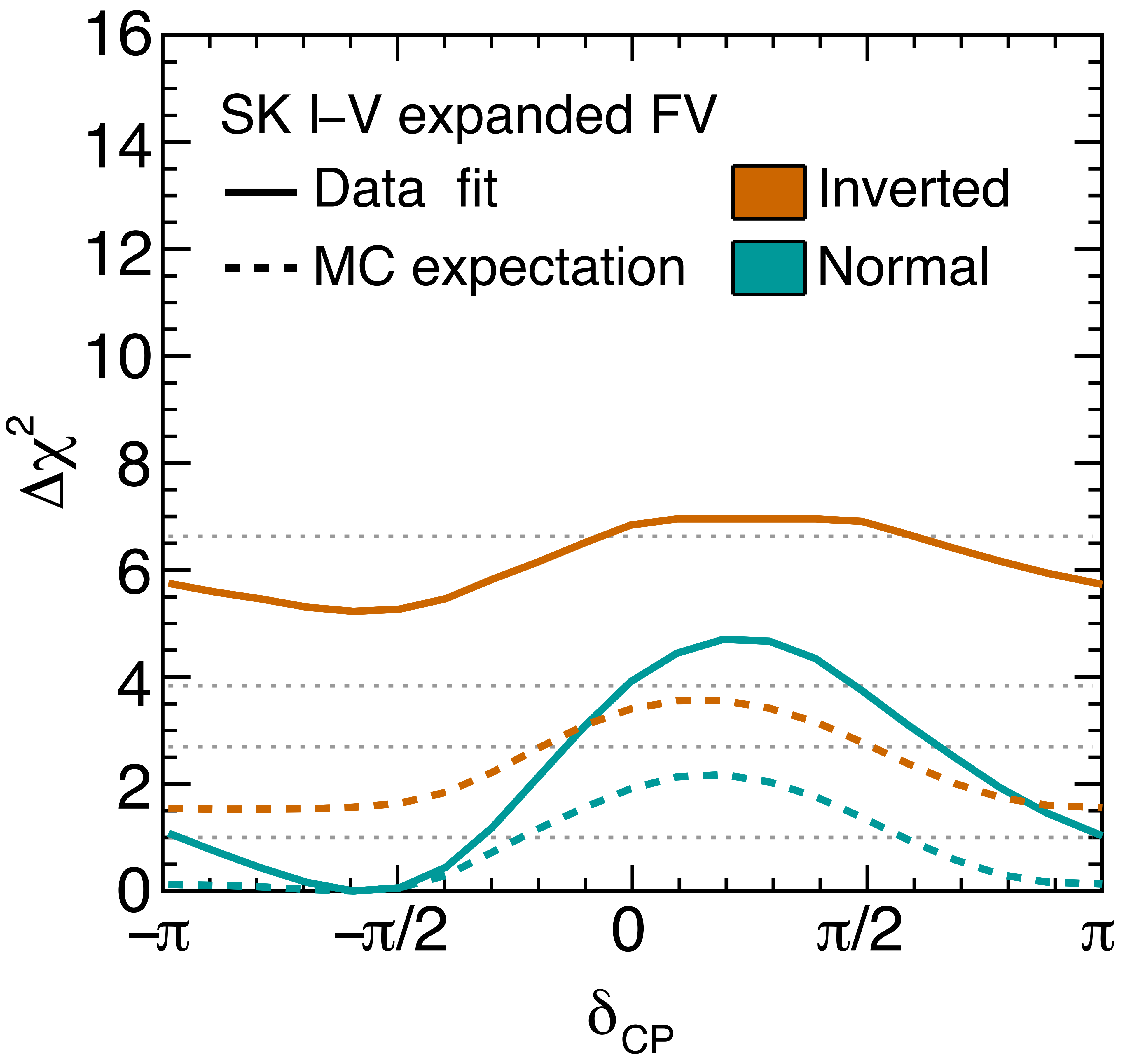
Several experiments have measured the atmospheric neutrino flux, with **SK** starting from the **sub-GeV scale**.

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)



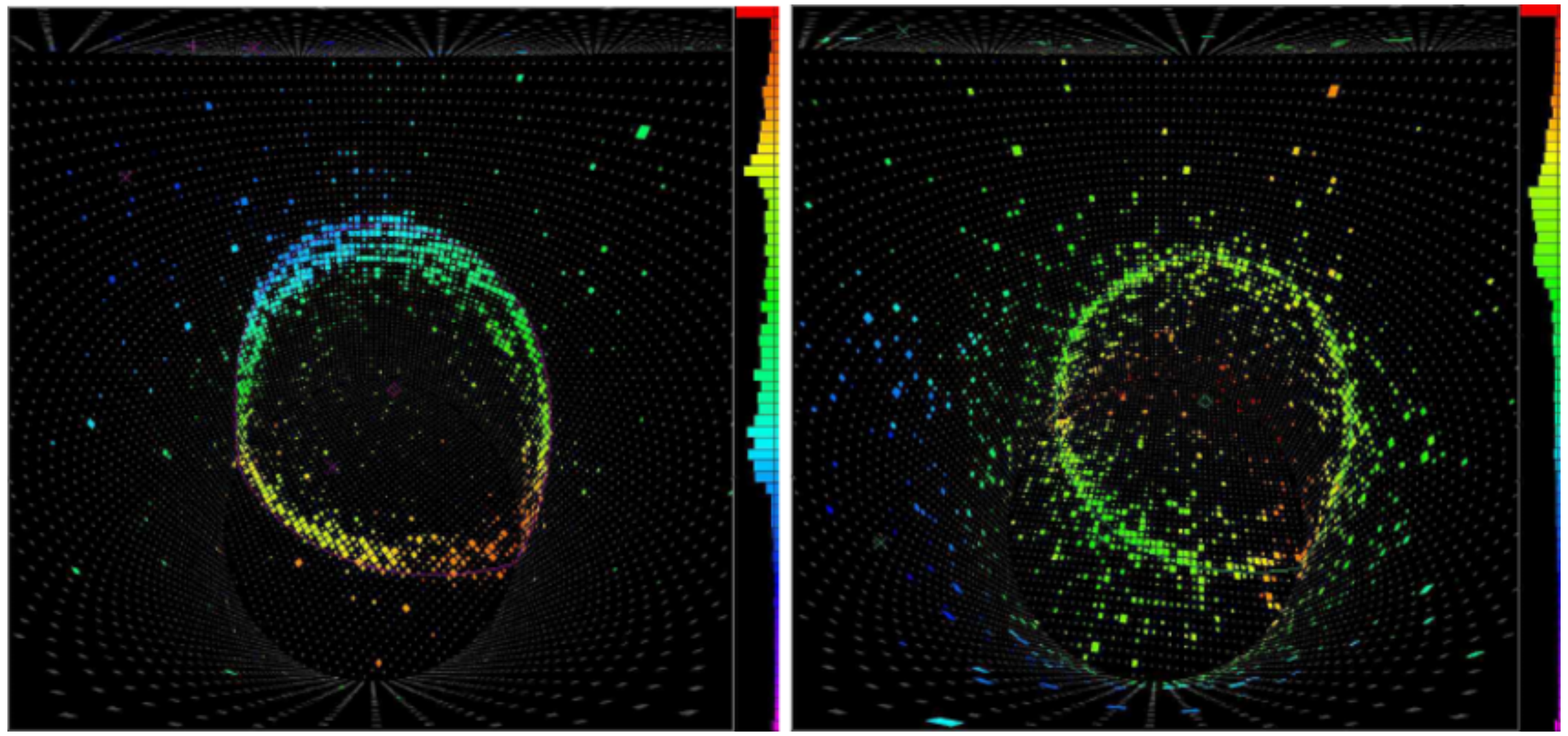
Wester et al. (Super-Kamiokande), arXiv: 2311.05105

Hyper-Kamiokande

Hyper-Kamiokande is the **next generation** of water-Cherenkov experiment in Japan

Super-Kamiokande (SK)

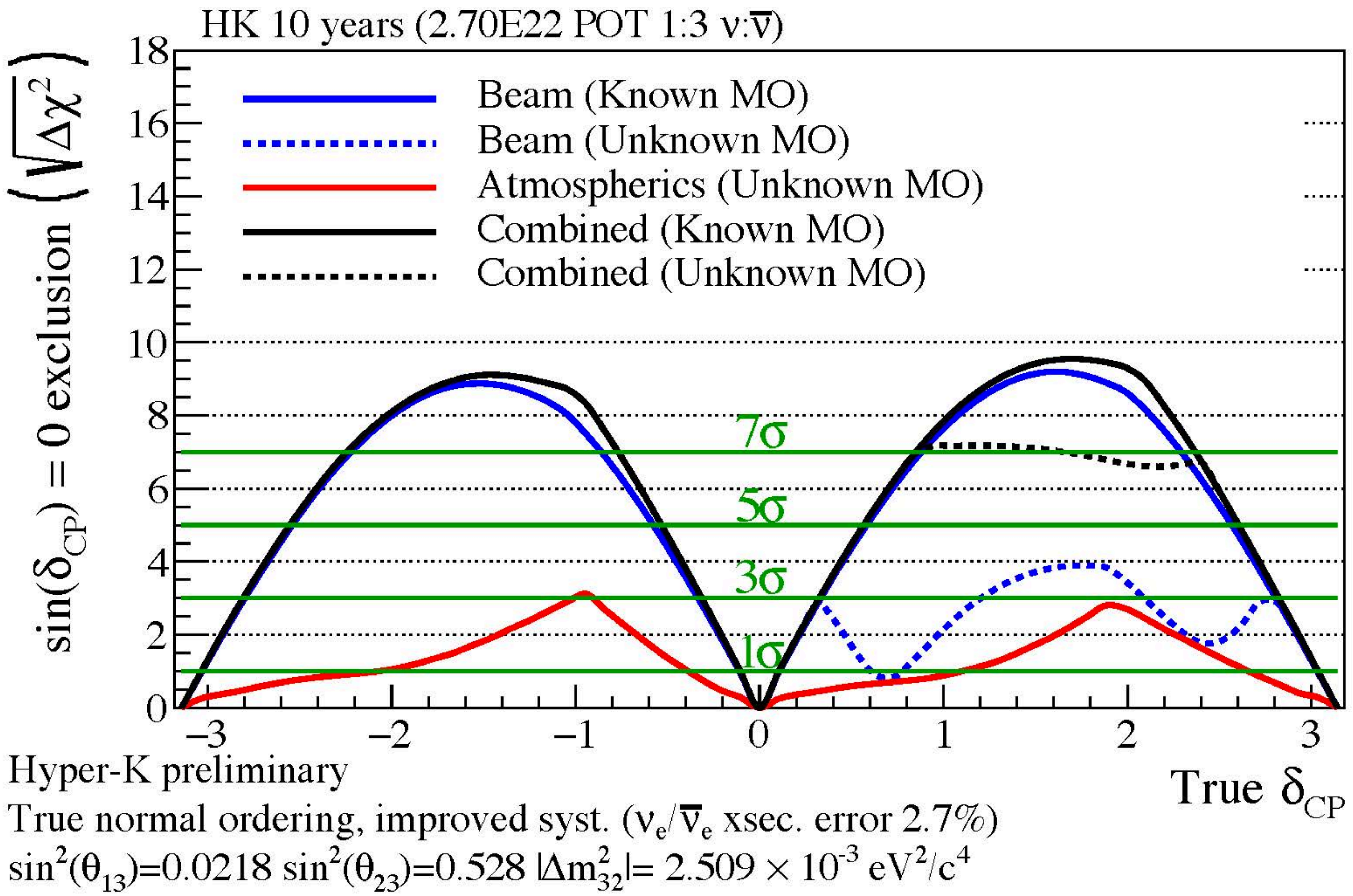
- 22.5 kton water Cherenkov
- Small sample at multi-GeV due to the volume
- The event sample is divided in FC, PC and Up-μ



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

Hyper-Kamiokande (HK)

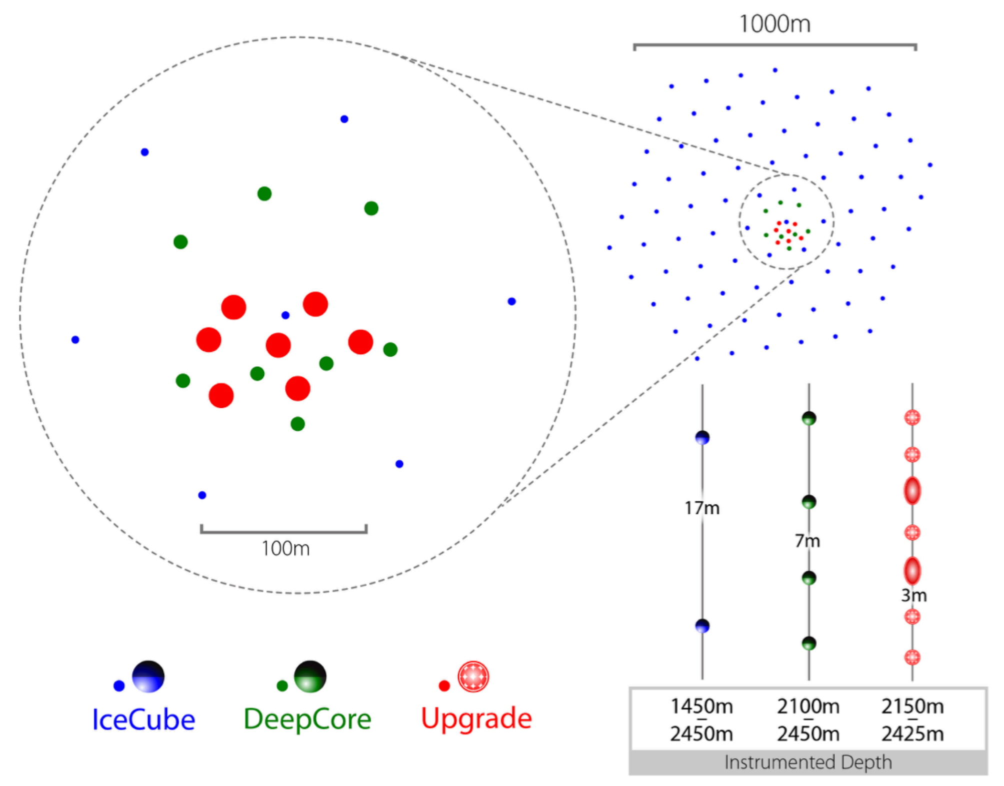
- 187 kton water Cherenkov (8.4 larger than SK)
- 20% photo coverage with improved photosensors



Bian et al. (Hyper-Kamiokande), Snowmass 2021

Abe et al. (Hyper-Kamiokande), arXiv:1803.04163

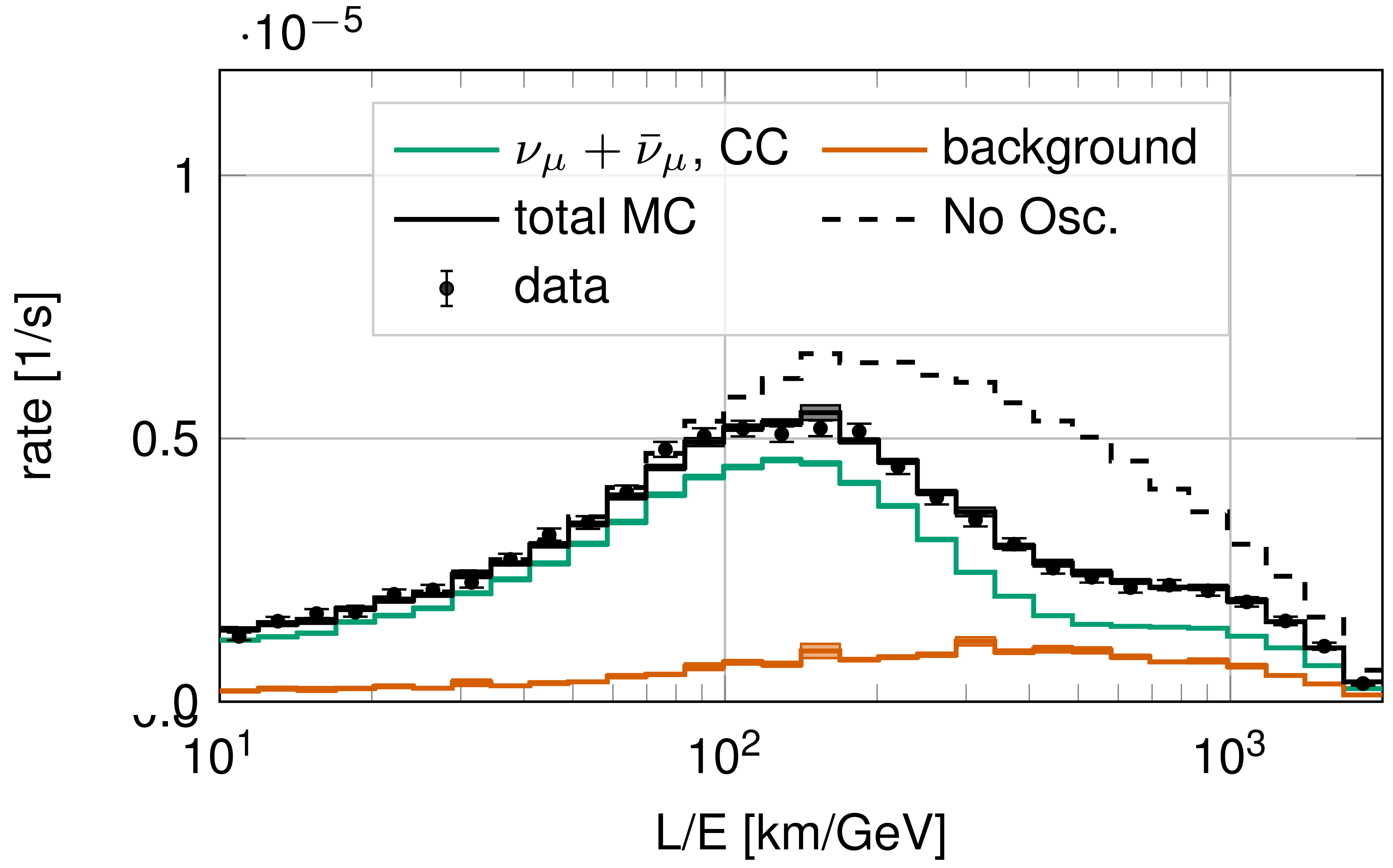
IceCube

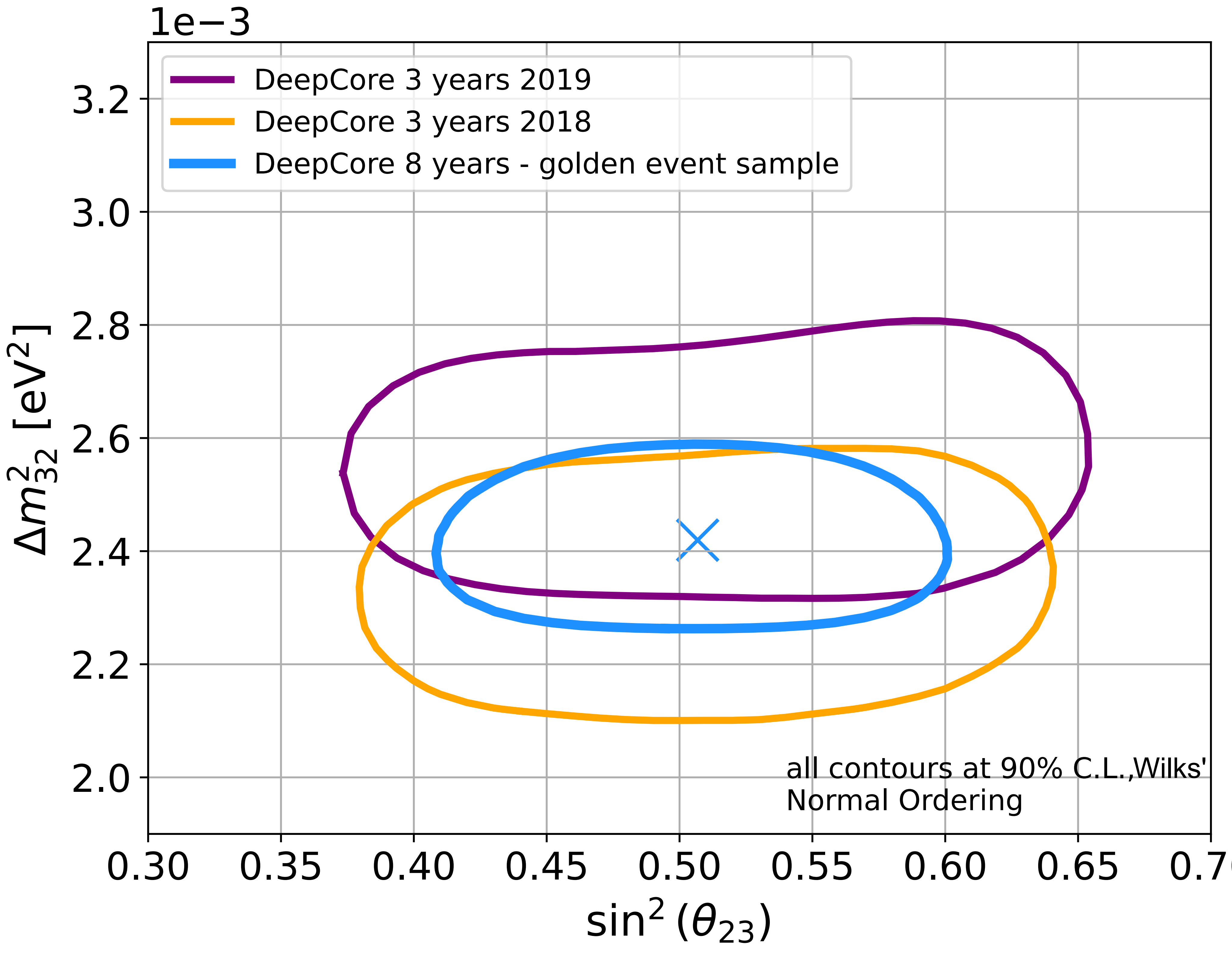


Ishihara (IceCube), PoS ICRC2019

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
- The upgrade will add seven additional strings lowering the energy threshold to ~1GeV



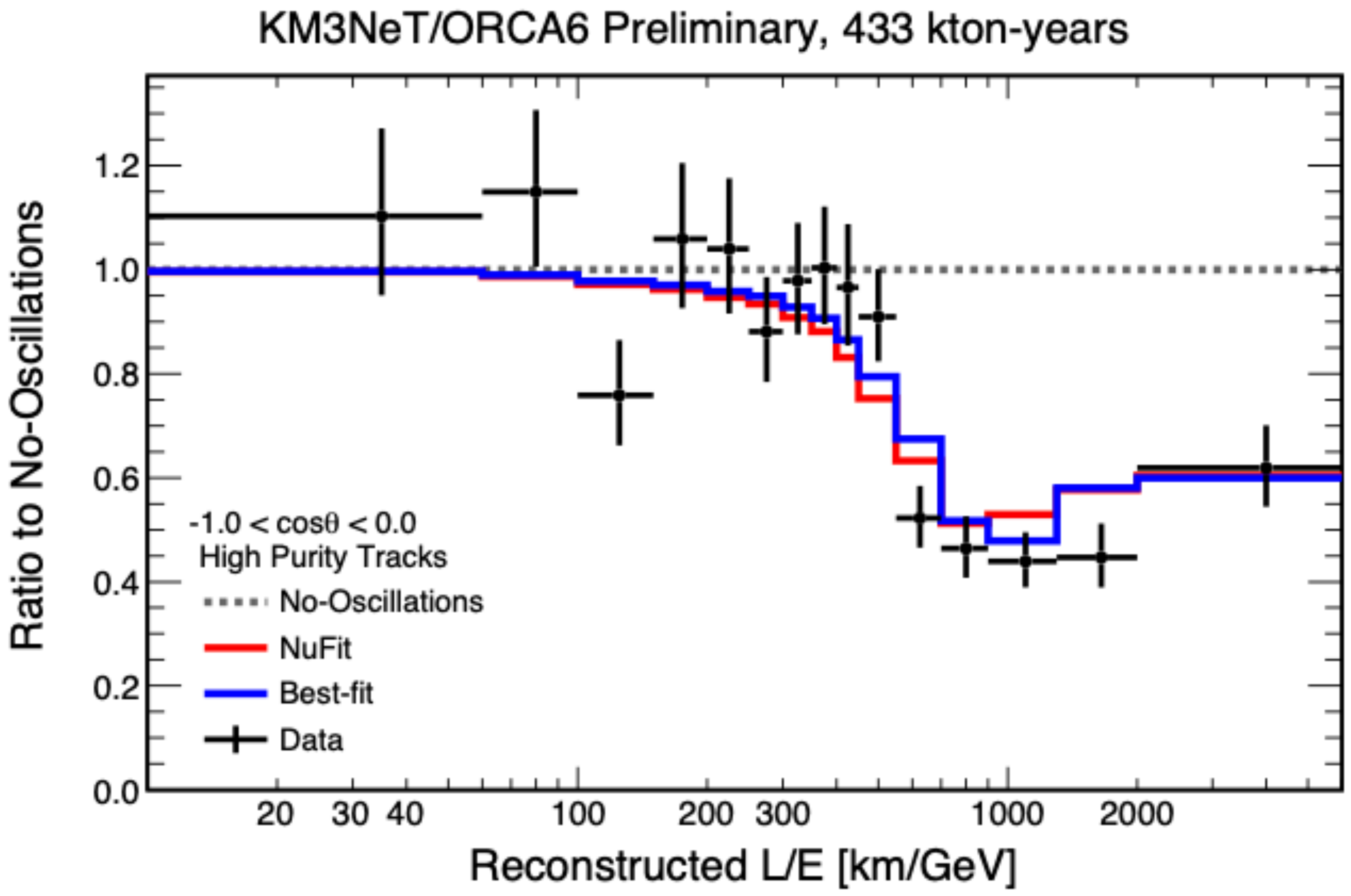


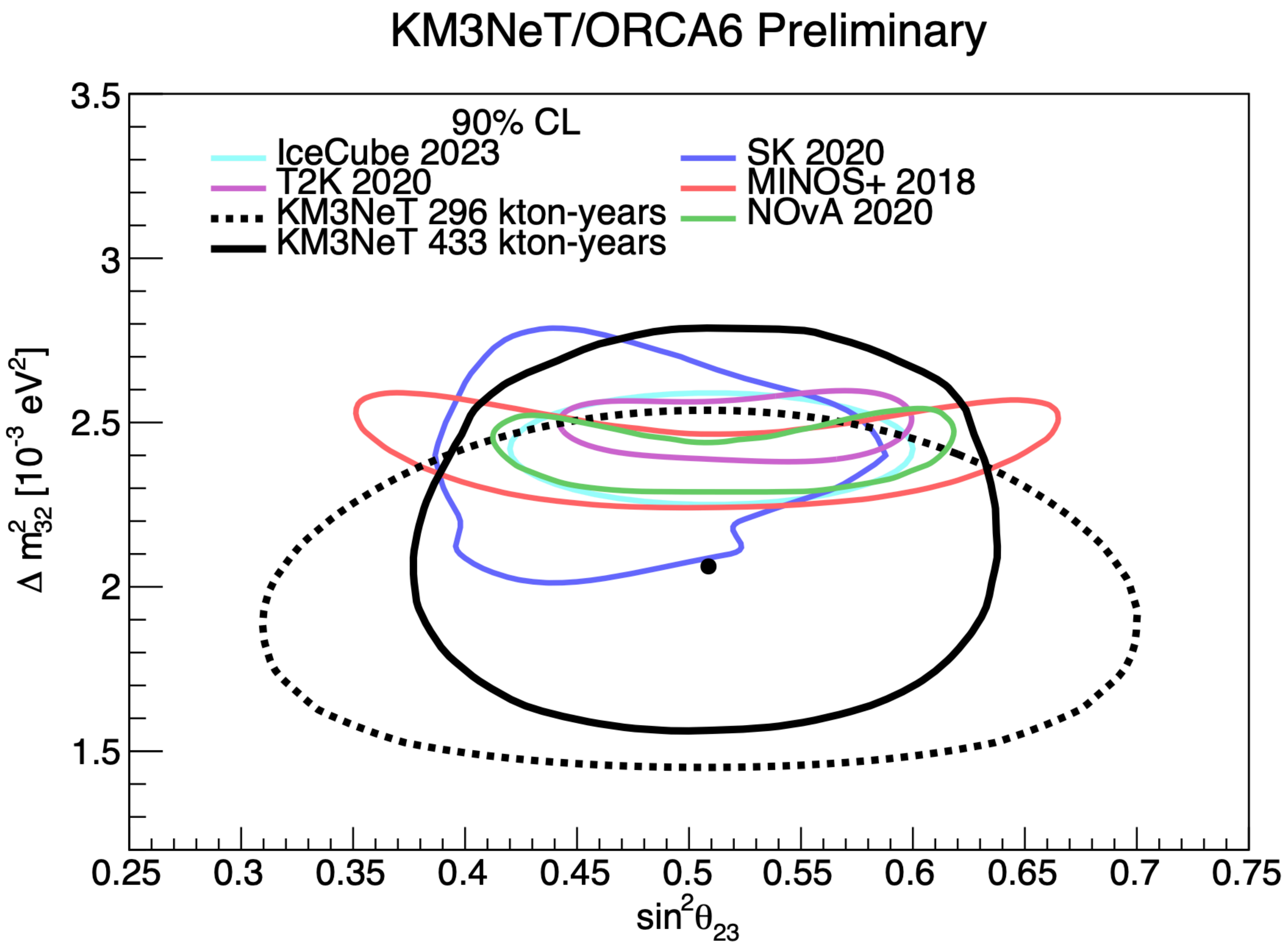
Abbasi et al. (IceCube), PRD 108 (2023)
Abbasi et al. (IceCube), arXiv: 2405.02163

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





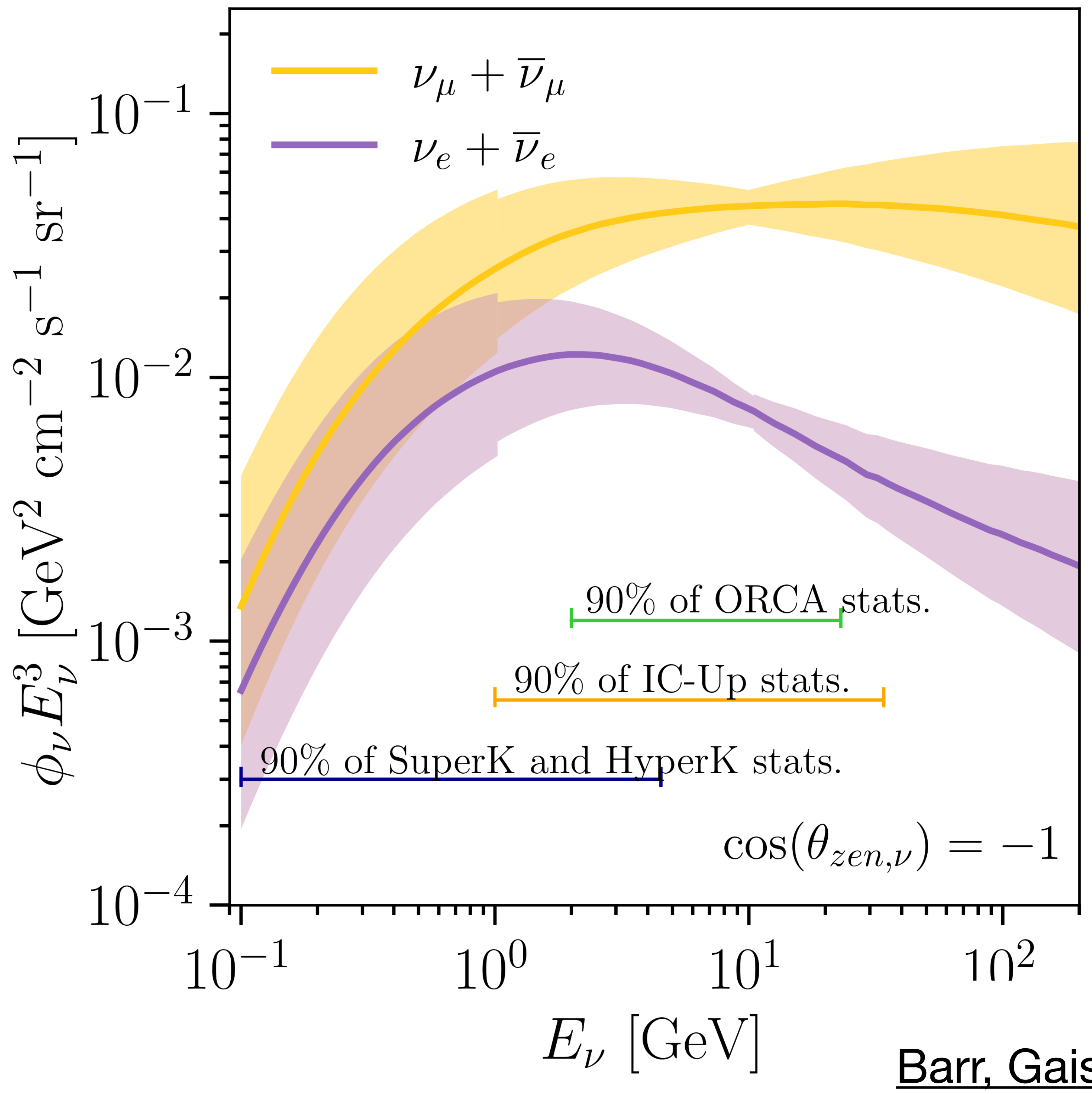
Carretero et al. (KM3NeT), PoS ICRC2023
Aiello (KM3NeT), EPJC 82, 26 (2022)

Systematic Uncertainties

Combining all experiments reduces the systematic impacts, thereby **enhancing the sensitivity**

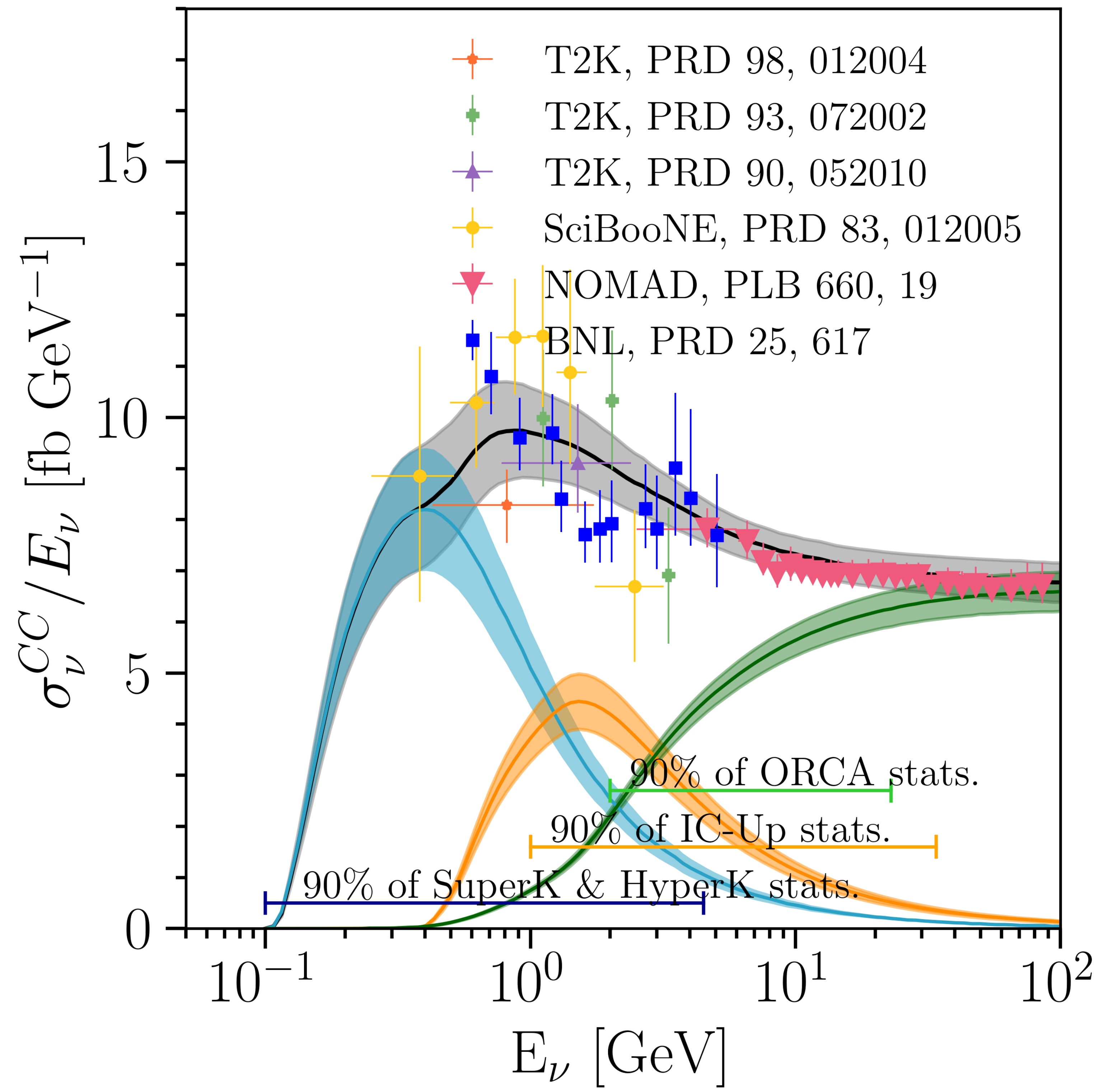
Flux systematics

The flux has uncertainties in normalization, energy dependence, up/down, ν_e/ν_μ, $\overline{\nu}/\nu$



Cross-section systematics

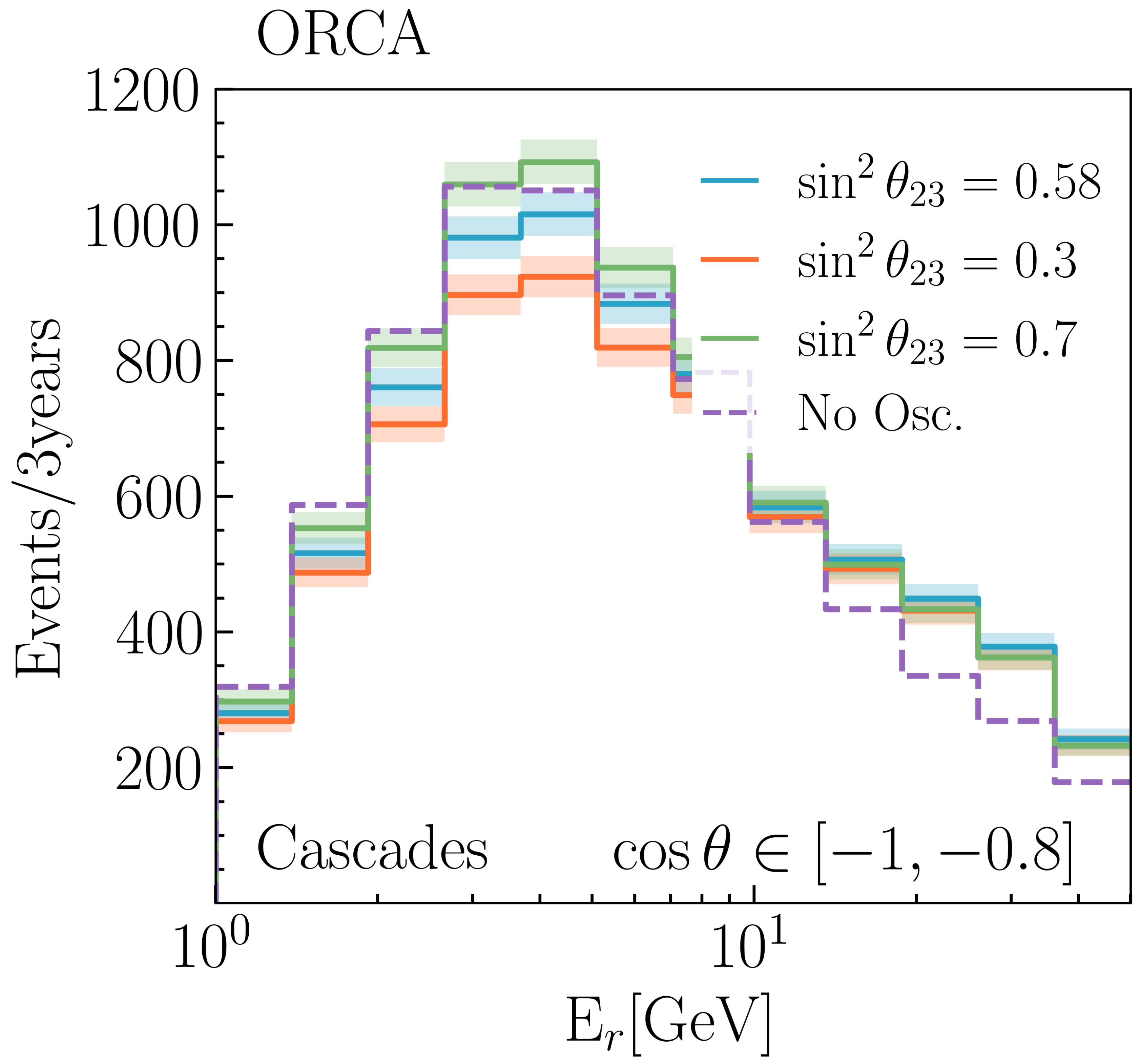
The wide range of energy of the flux leads atmospheric neutrinos to engage in diverse interactions.

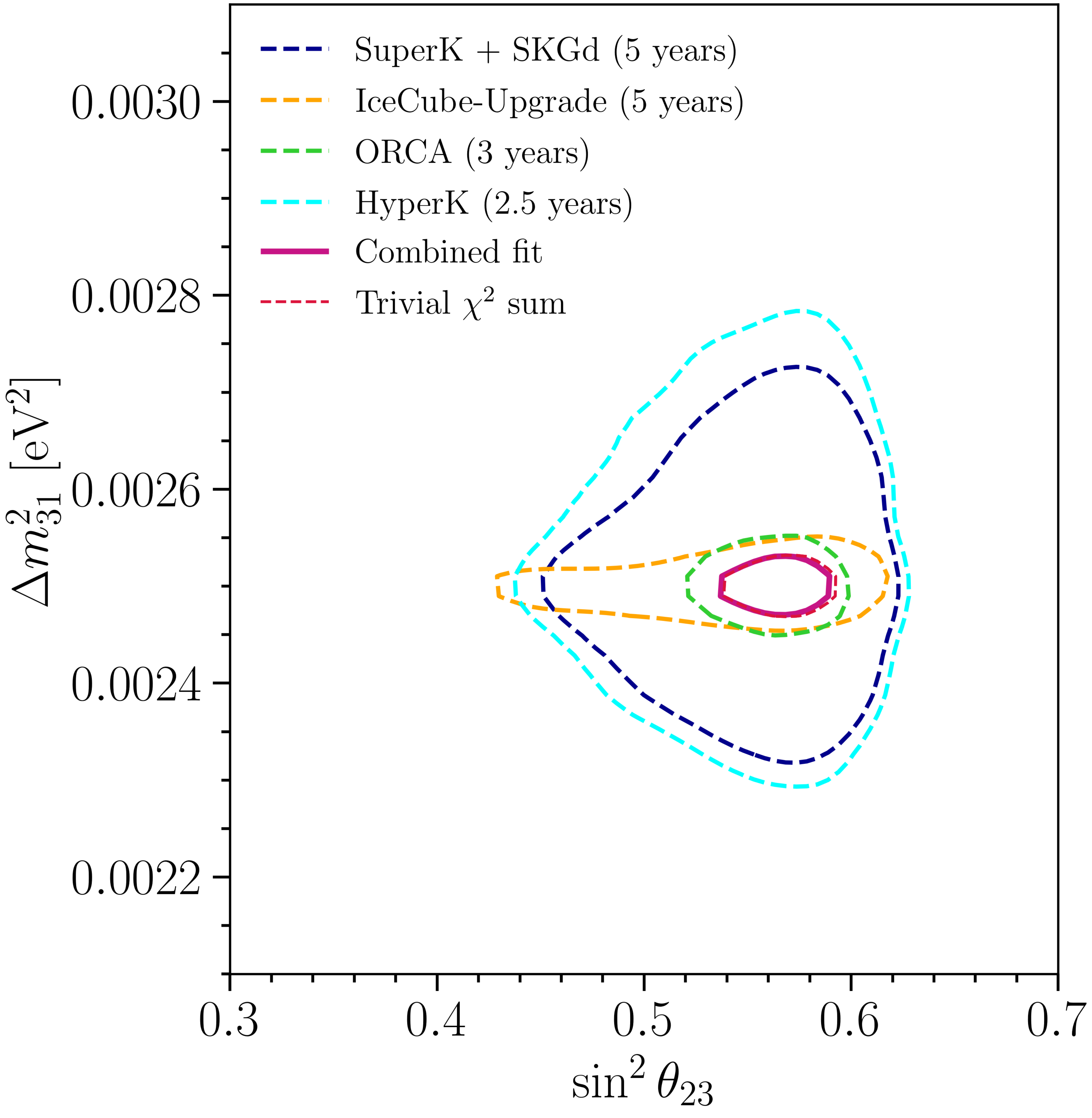


Barr, Gaisser, Robbins, Stavev, PRD 74 (2006)
Yañez-Garza and Fedynitch, PRD 107 (2023)

Combined Analysis: θ_{23} and Δm^2_{31}

Making a **combined analysis** of **SK, HK, IceCube-upgrade** and **ORCA** we have estimated the sensitivity to δ_{cp}, θ_{23} and the **mass ordering**



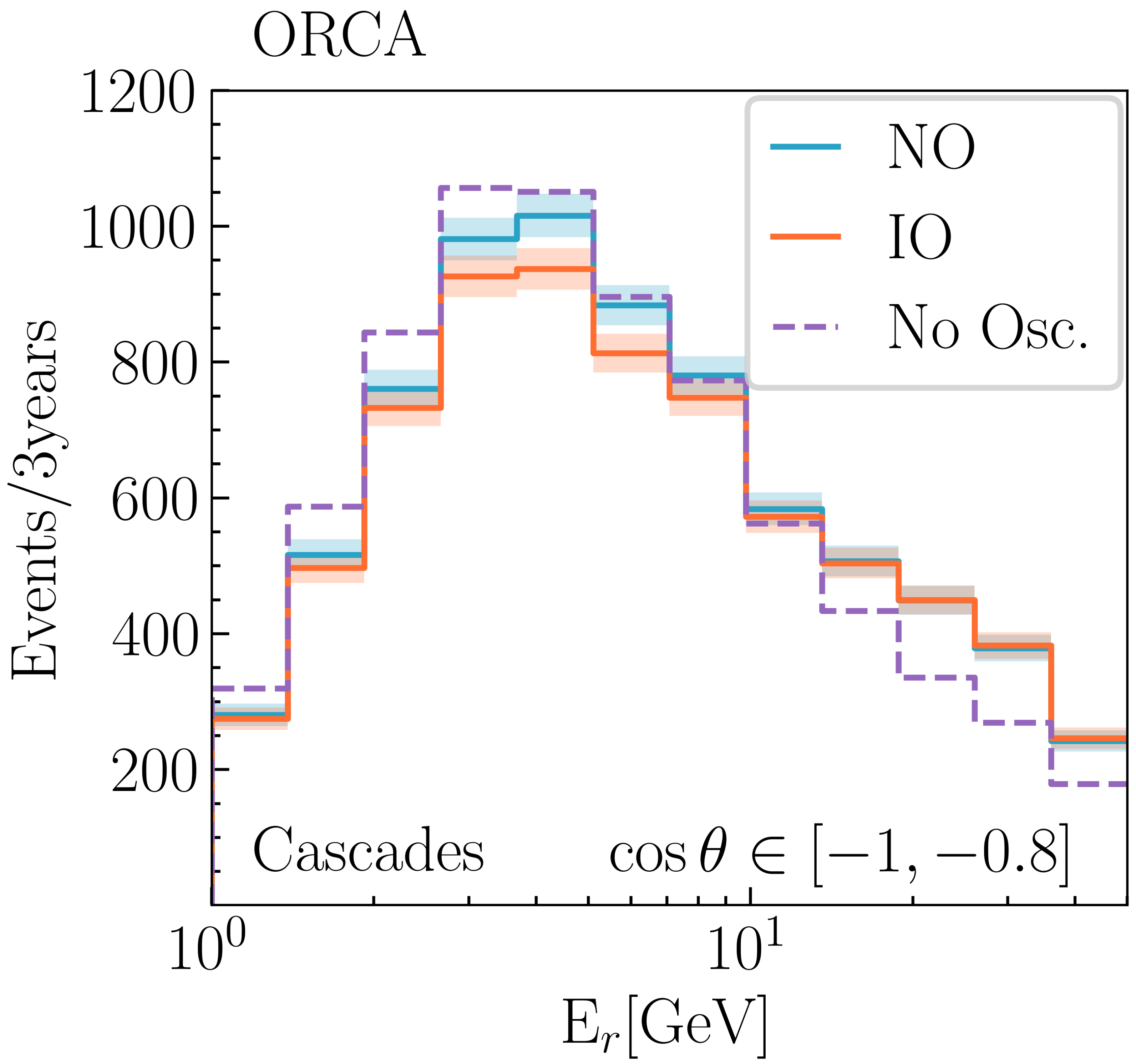


Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

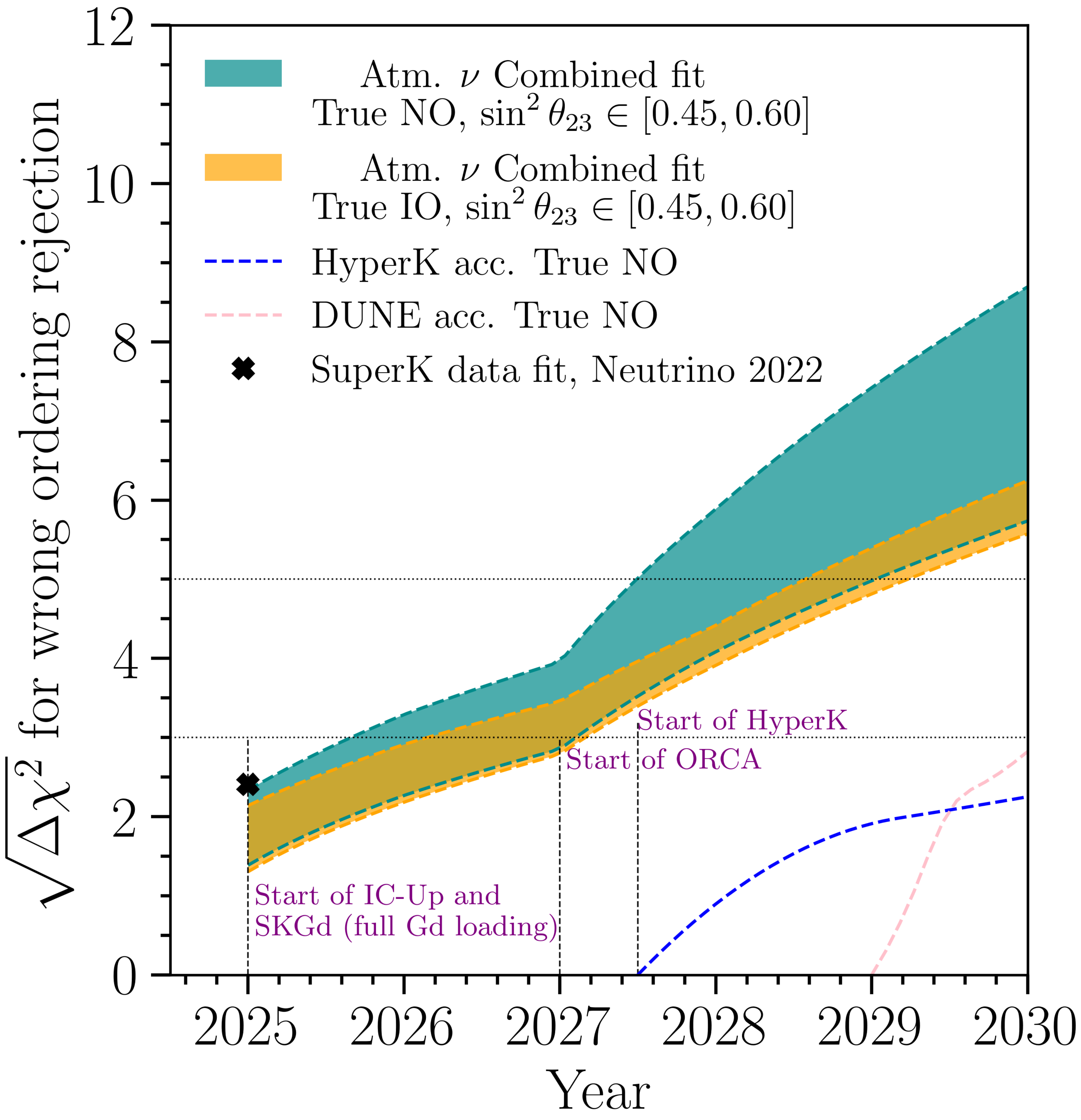
Combined Analysis: Mass Ordering

- The **sensitivity** to the ordering is dominated by the cascades crossing the core in IC-upgrade and ORCA around the GeV.

- We expect to reach 6σ by the end of the decade.



- $\sin^2\theta_{13}$ = 0.022 (fixed)
- Profiled over δ_{cp}

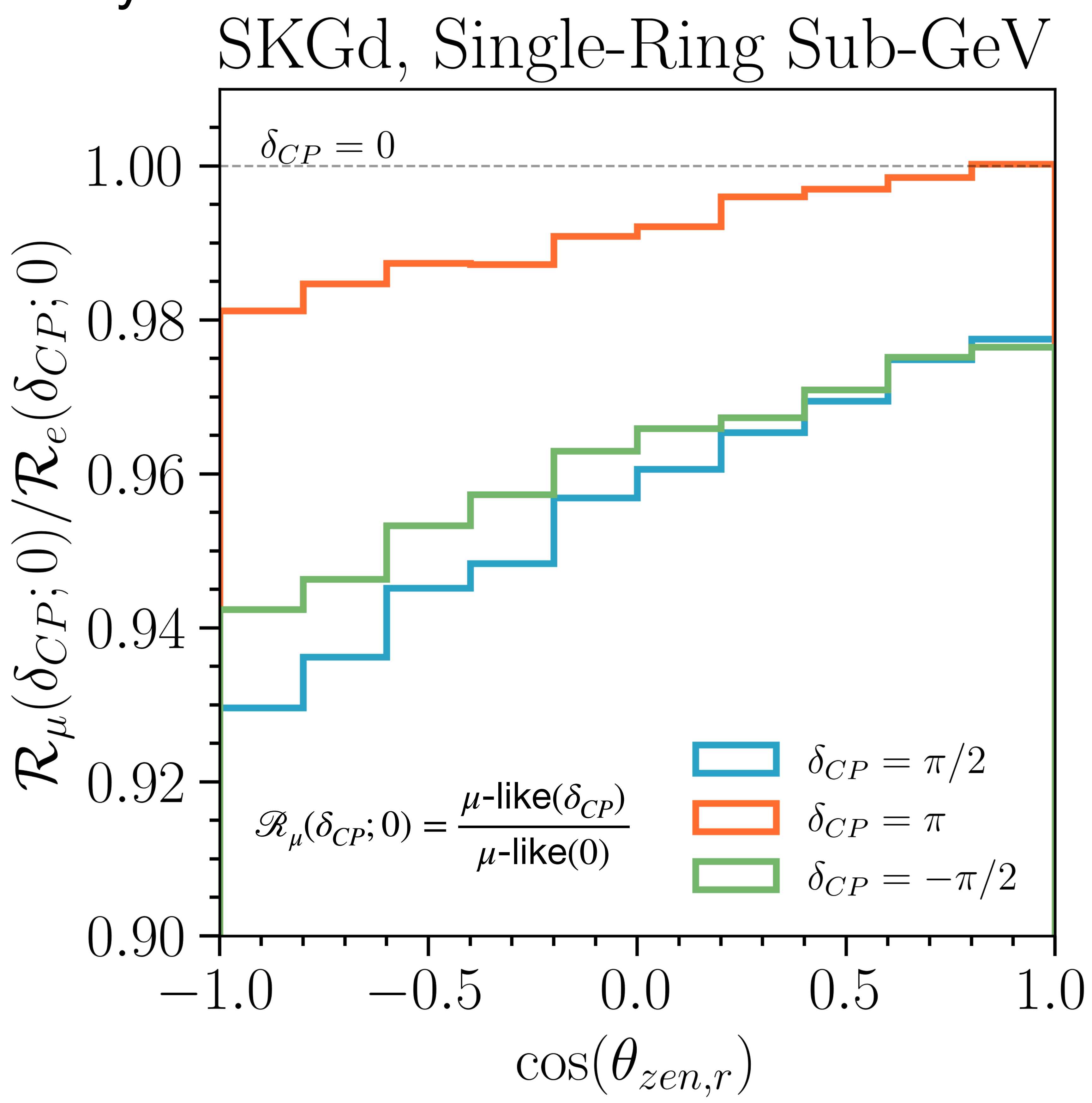


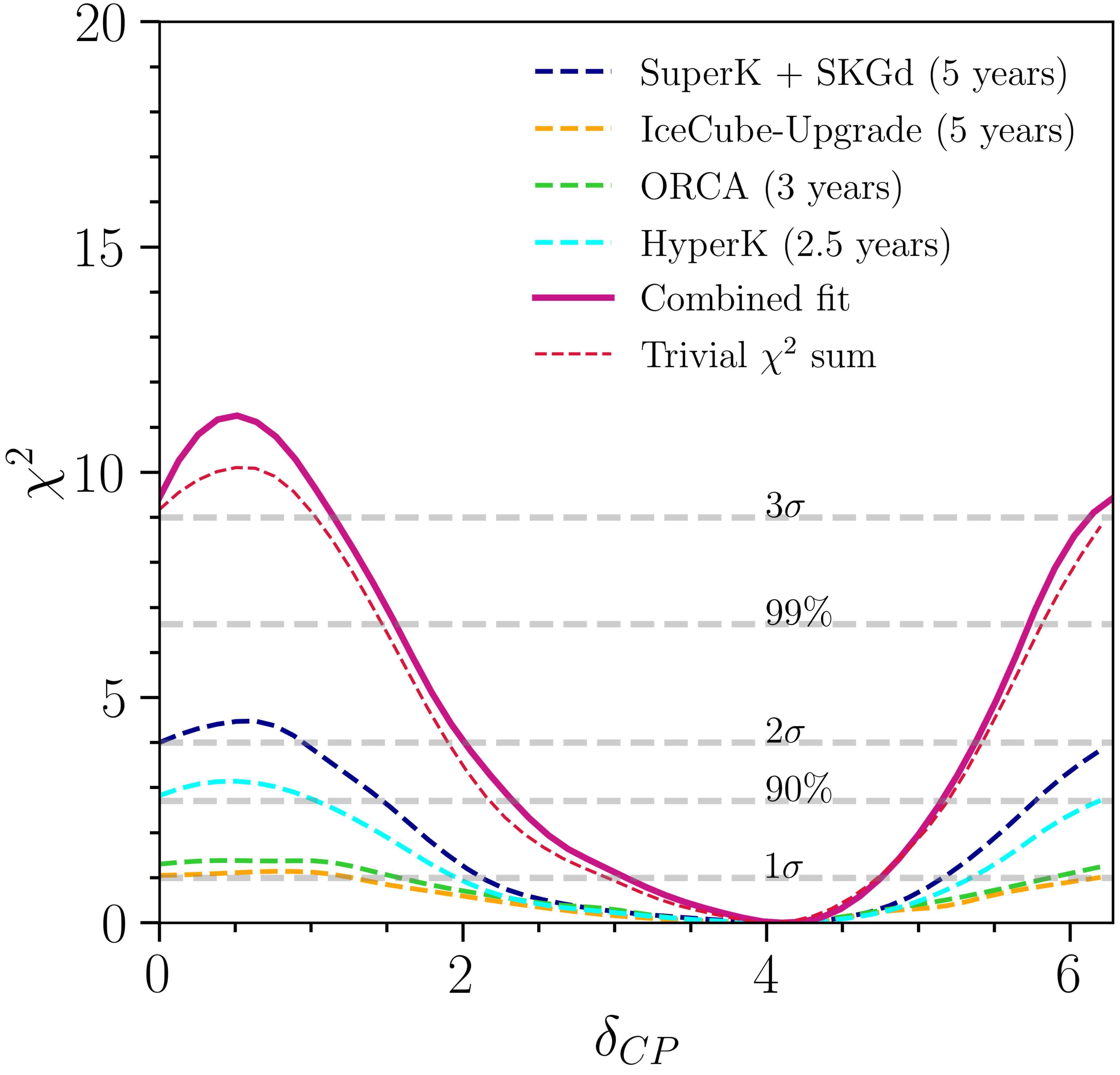
Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

Combined analysis: δ_{cp}

The sensitivity to δ_{cp} is dominated by **SK** and **HK**

- The e-like and μ-like without neutron tagged dominates the sensitivity

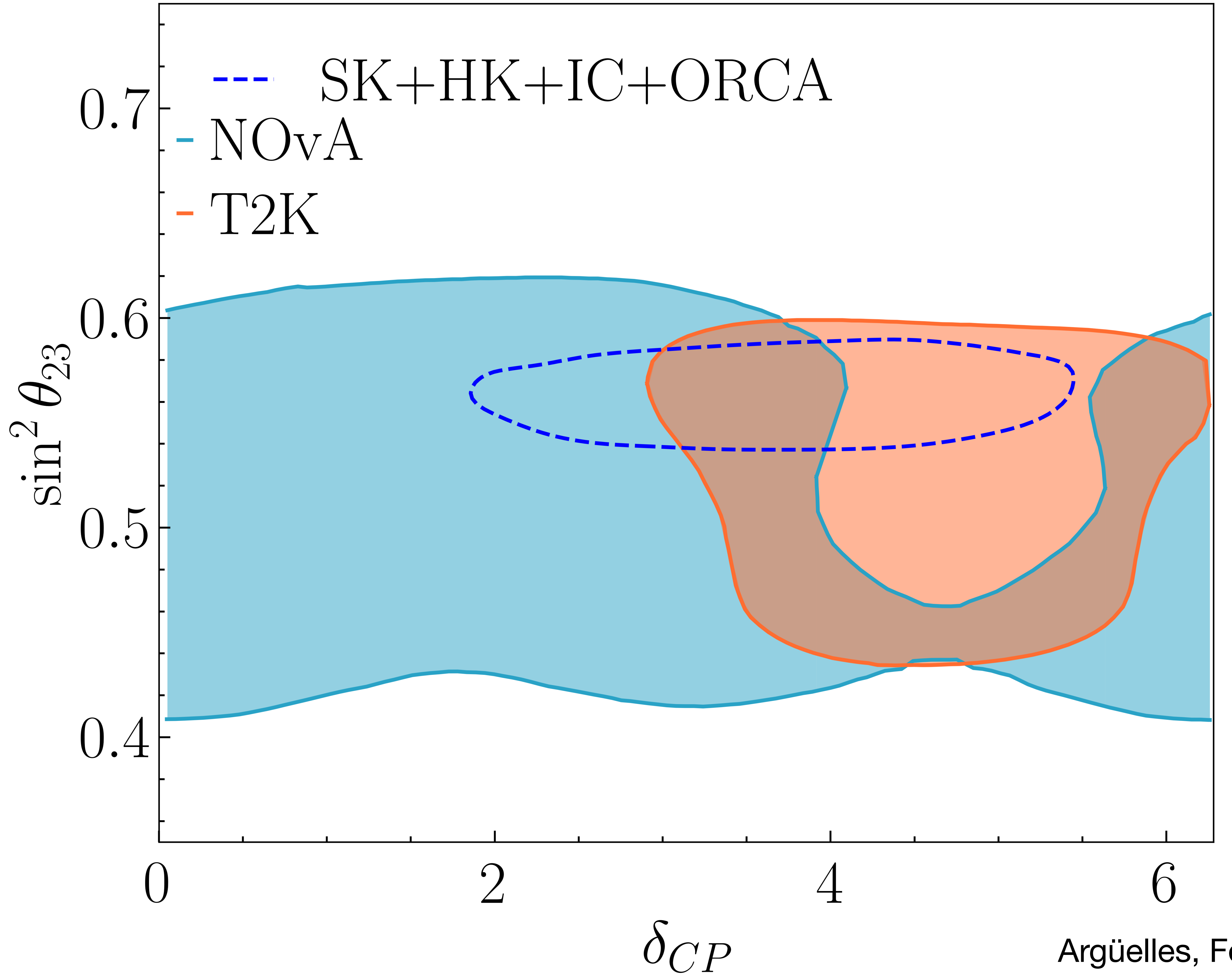




Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

Complementarity between Atm. and LBL

Atmospheric neutrinos can provide complementary constraints on oscillation parameters



Abe et al. (T2K), EPJC 83 (2023)

Acero et al. (NOvA), PRD 106 (2022)

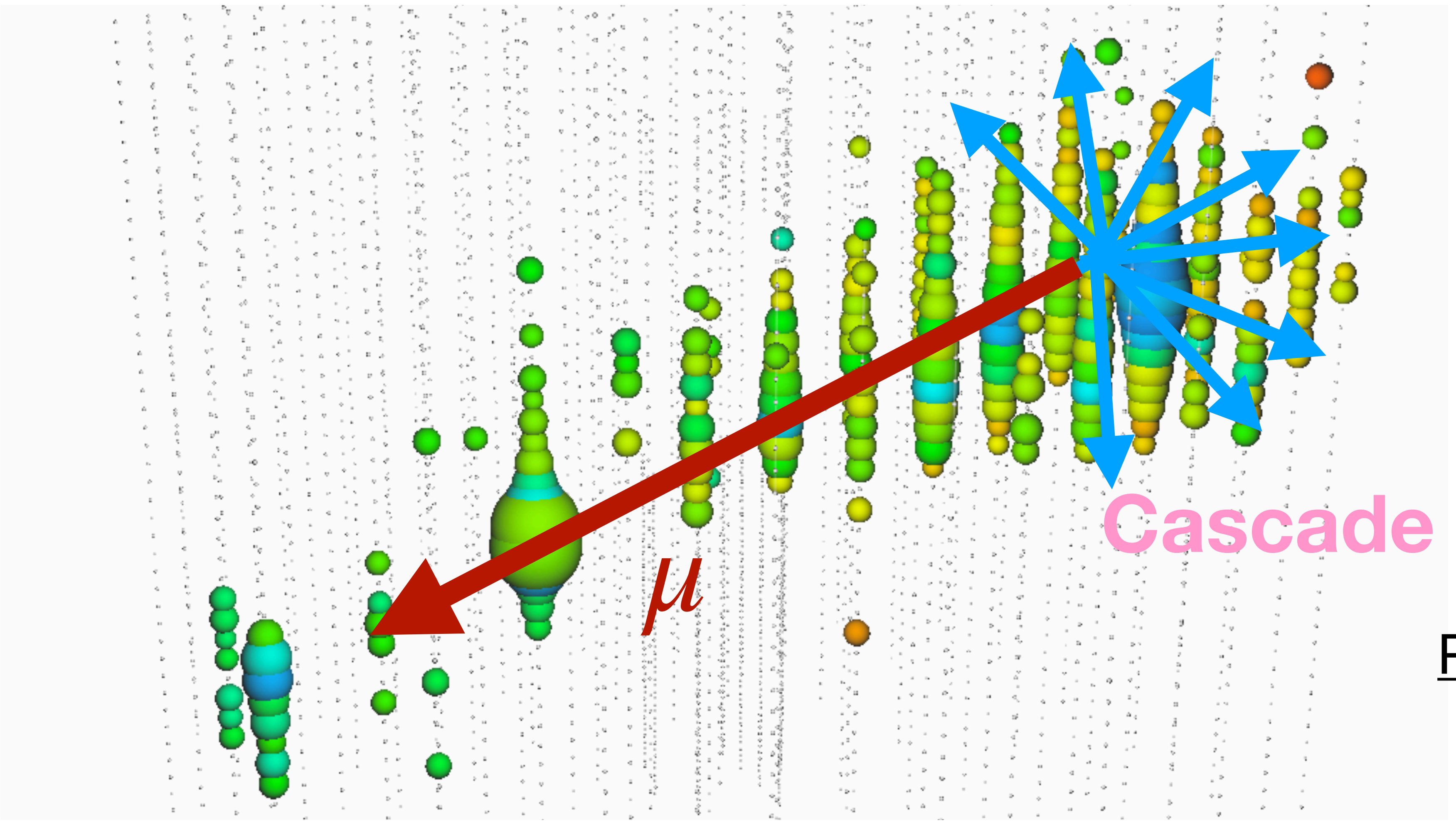
Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

Boosting the Sensitivity: Inelasticity

The **mass ordering** and the **CP-phase** predict **different oscillations** for neutrinos and antineutrinos.

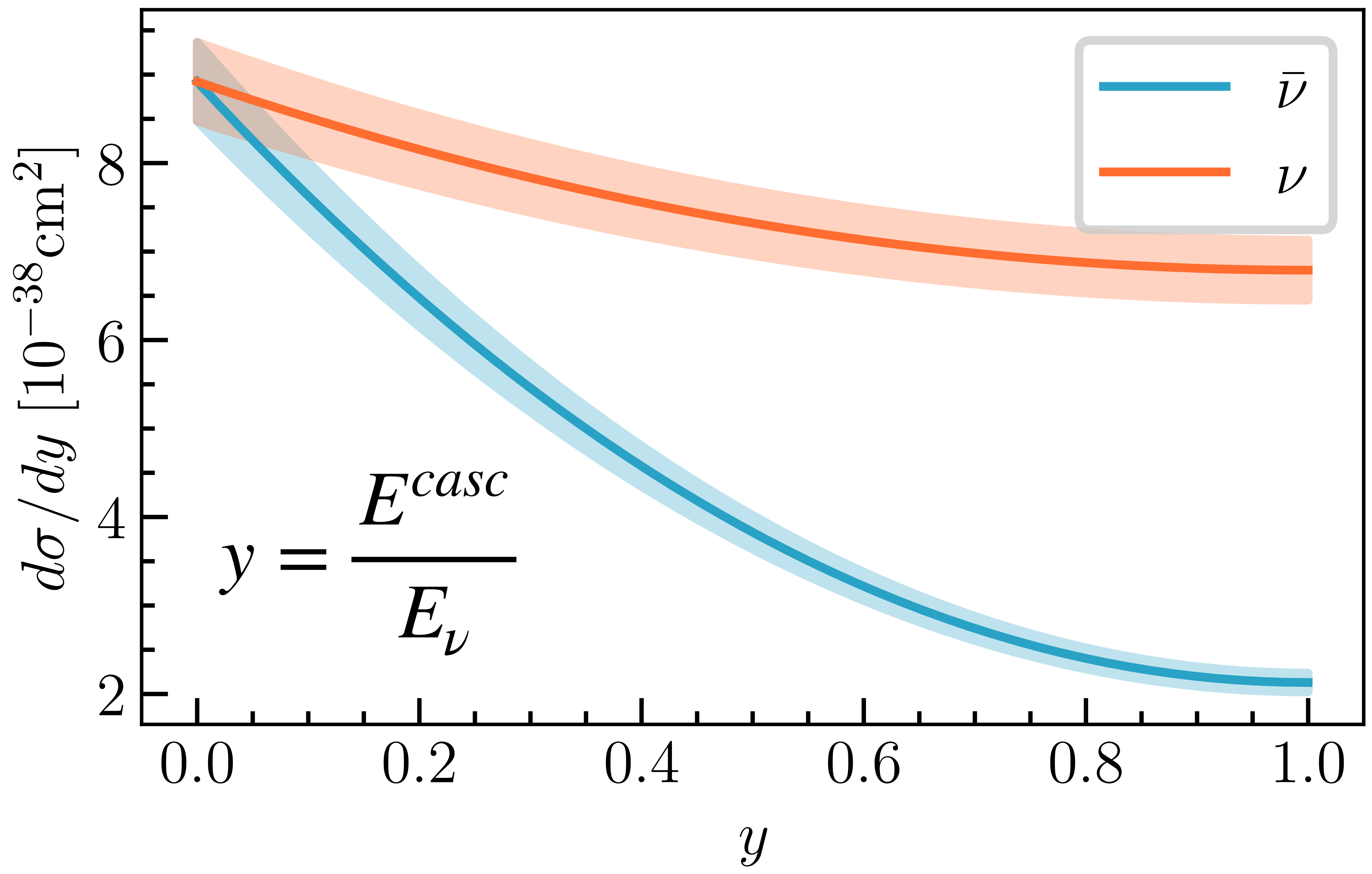
- In ν_μ- CC interactions, the energy is divided between **tracks** and **cascades**.
- Neutrinos and antineutrinos distribute their energy differently between the leptonic and the hadronic vertex.

Ribordy and Smirnov, PRD, 87 (2013)



Kronmueller et al. (IceCube), ICRC2019

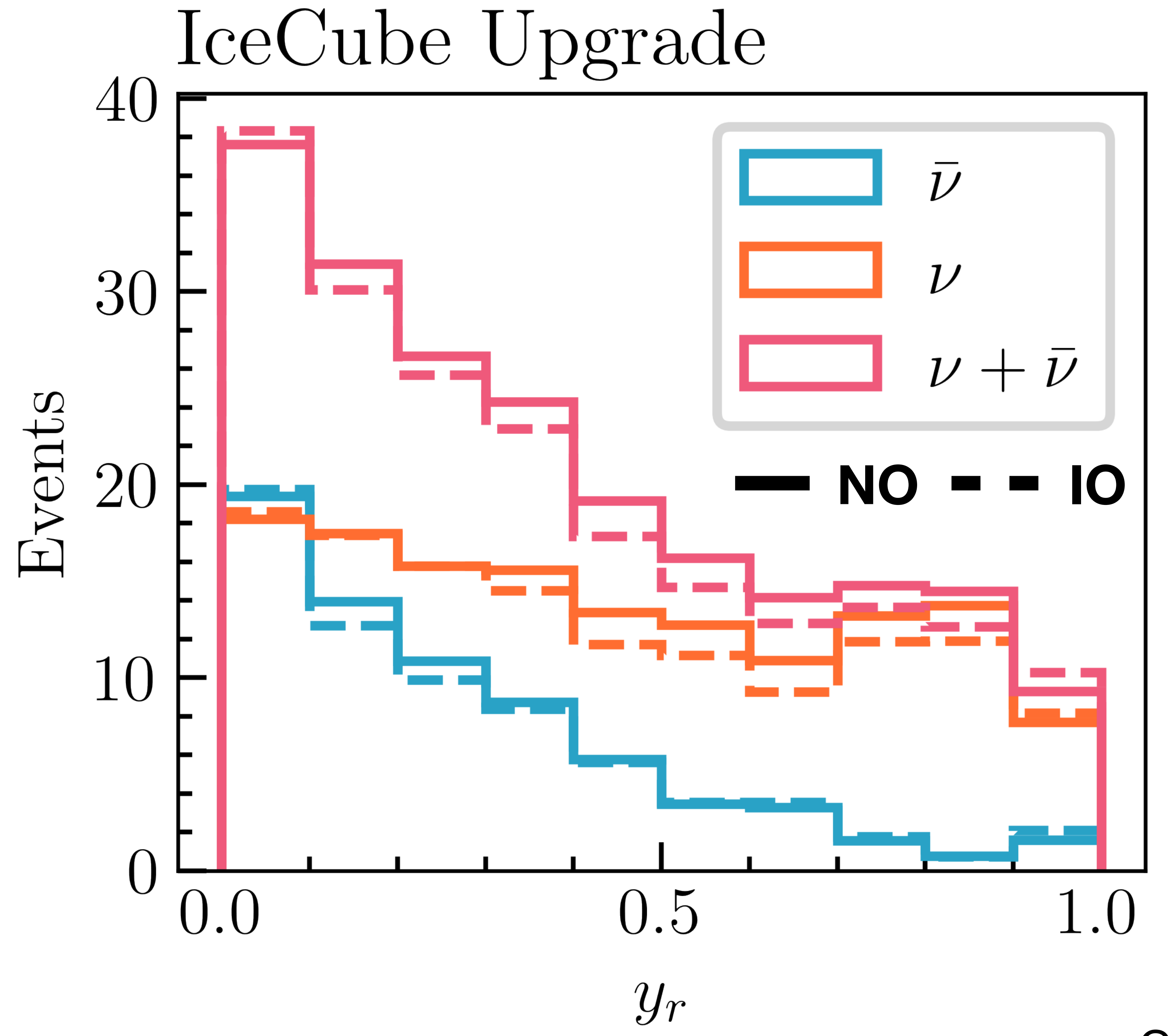
Peterson et al. (IceCube), PoS ICRC2023

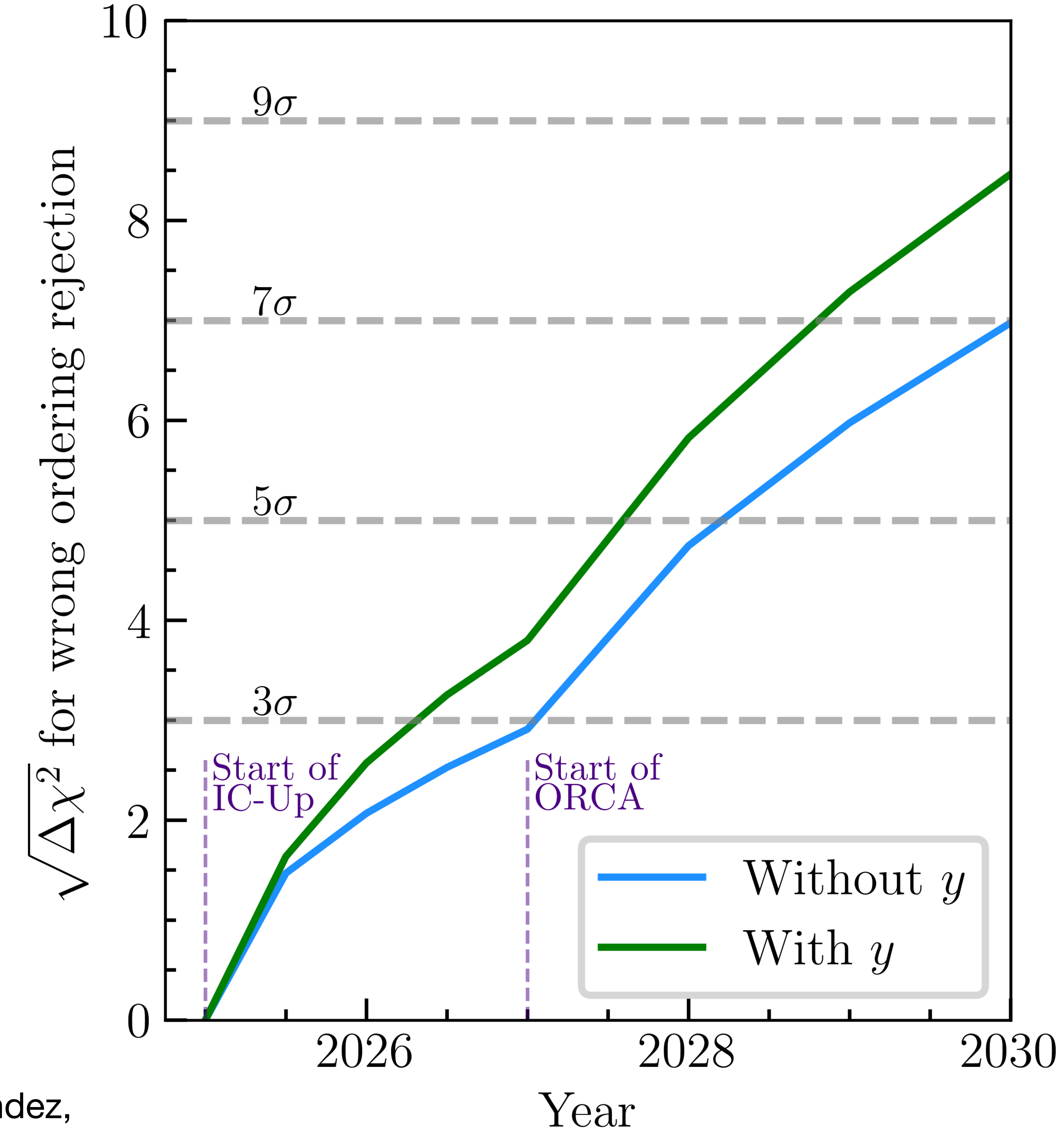


Giner Olavarrieta, Jin, Argüelles, Fernández, **IMS**, arXiv: 2402.13308

Boosting the Sensitivity: Inelasticity

The **inelasticity** allows for a **50% increase** in sensitivity to the **mass ordering**.

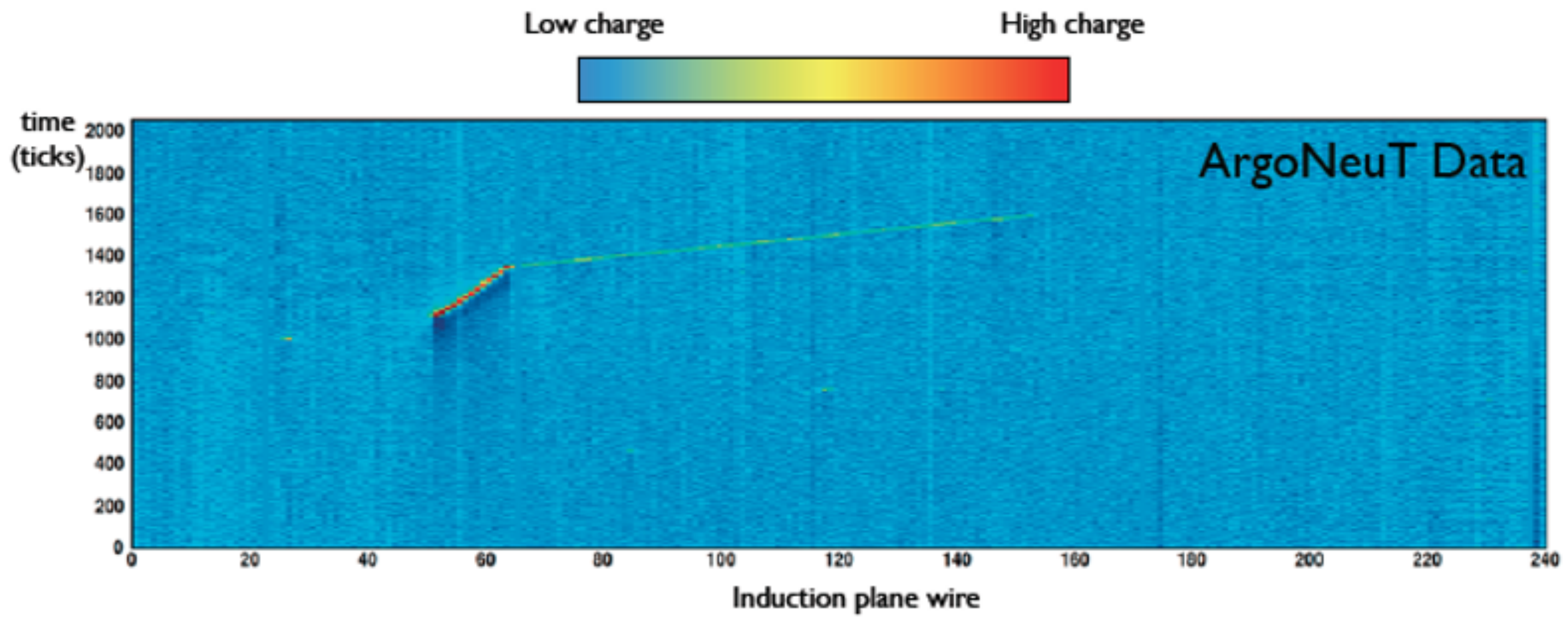




Giner Olavarrieta, Jin, Argüelles, Fernández, **IMS**, arXiv: 2402.13308

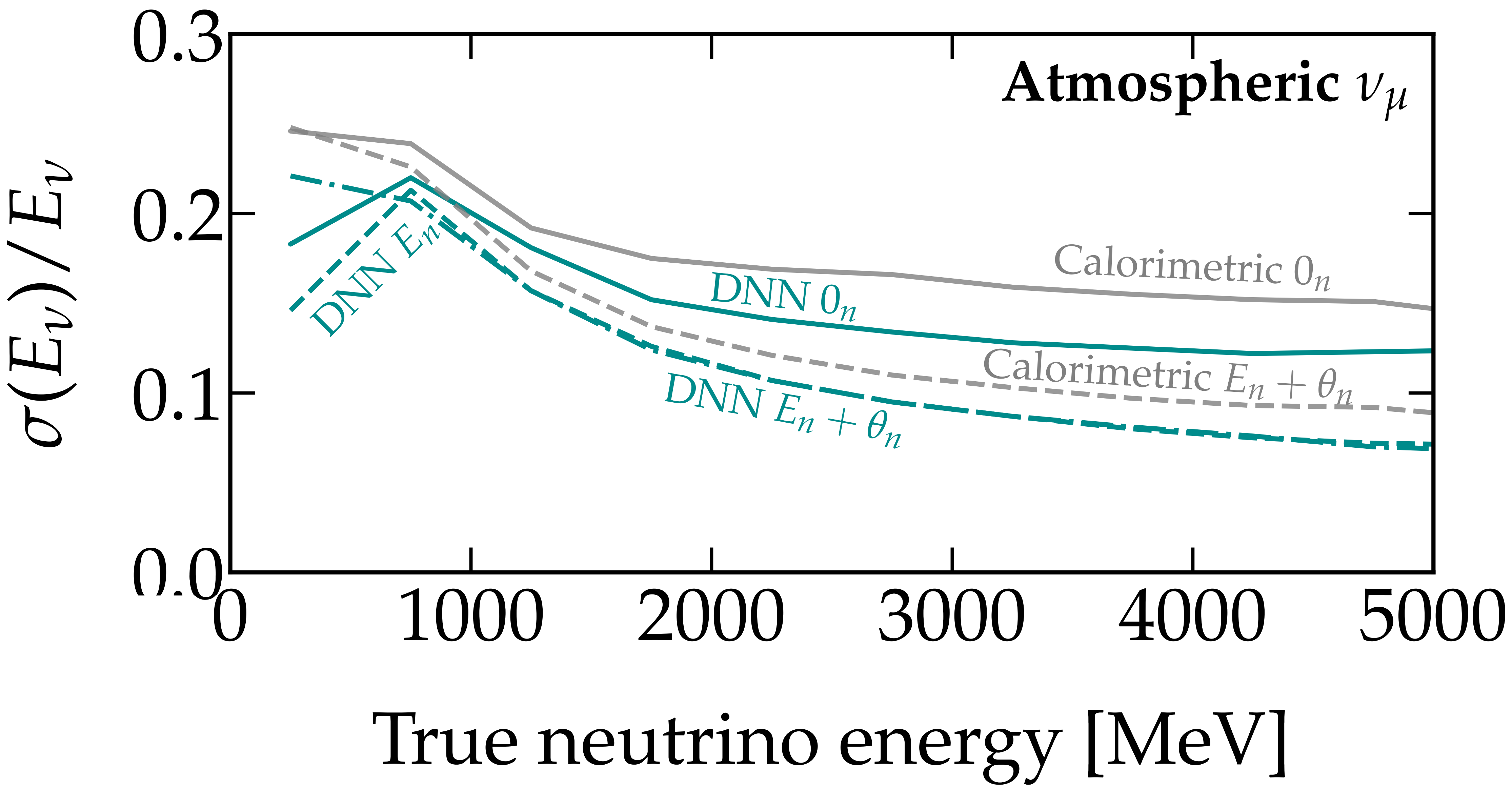
LArTPCs

- Excellent particle **identification** capabilities.
- Precise measurement of **low-energy** particle kinematics.



Anderson et al. (ArgoNeuT), JINST 7 (2012)
Abi et al. (DUNE), arXiv: 2002.03005

Understanding how **incoming neutrinos correlate** with **final states** enhances neutrino reconstruction.



Kopp, Machado, MacMahon, **IMS**, arXiv: 2405.15867

LArTPCs

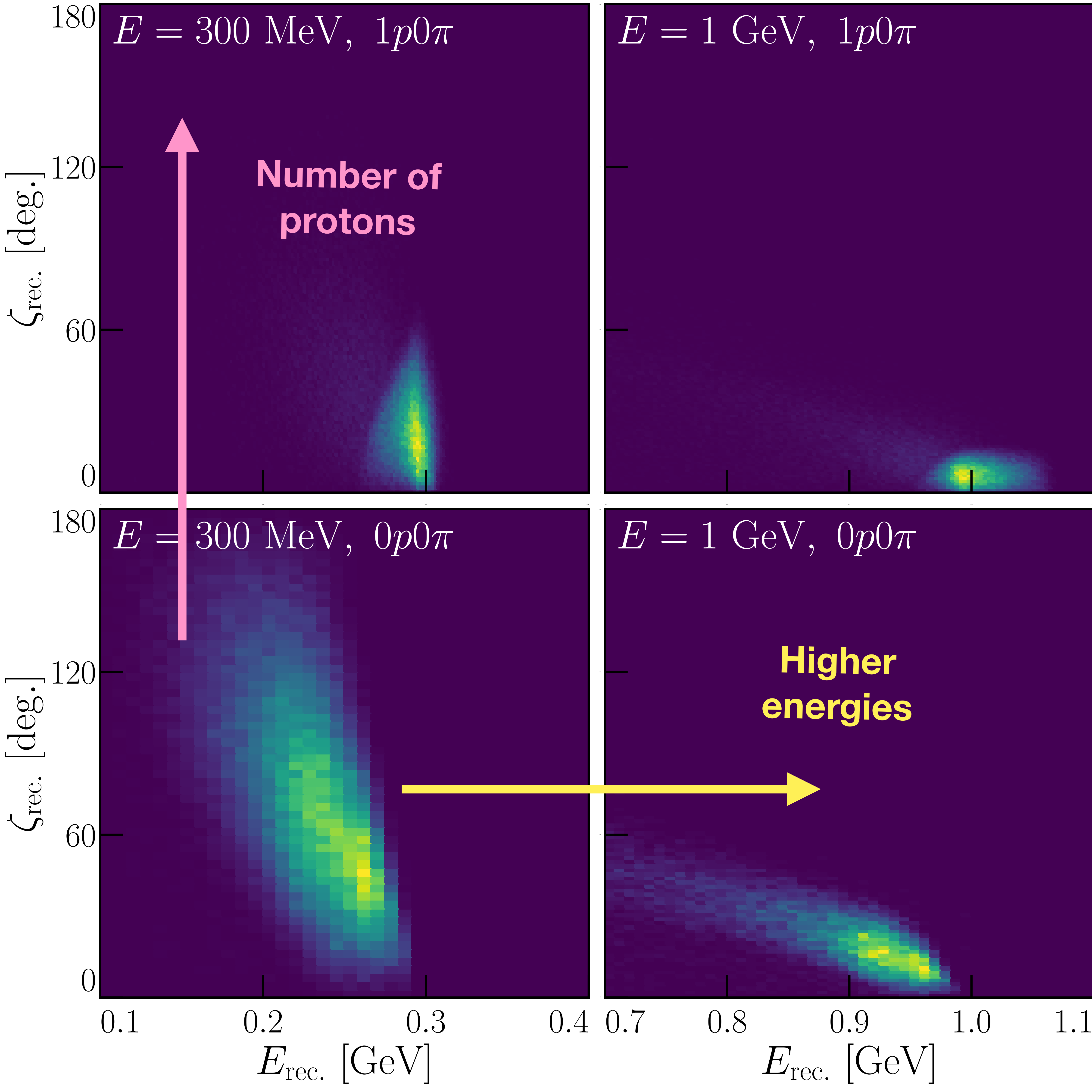
Calorimetric reconstruction provides good results for GeV neutrinos with visible protons

$$E_\nu^{\rm cal} = E_\ell + \sum_i^{\rm mesons} E_i + \sum_i^{\rm baryons} K_i$$

Events topologies based on **visible protons** allows **statistical separation** of neutrinos and antineutrinos

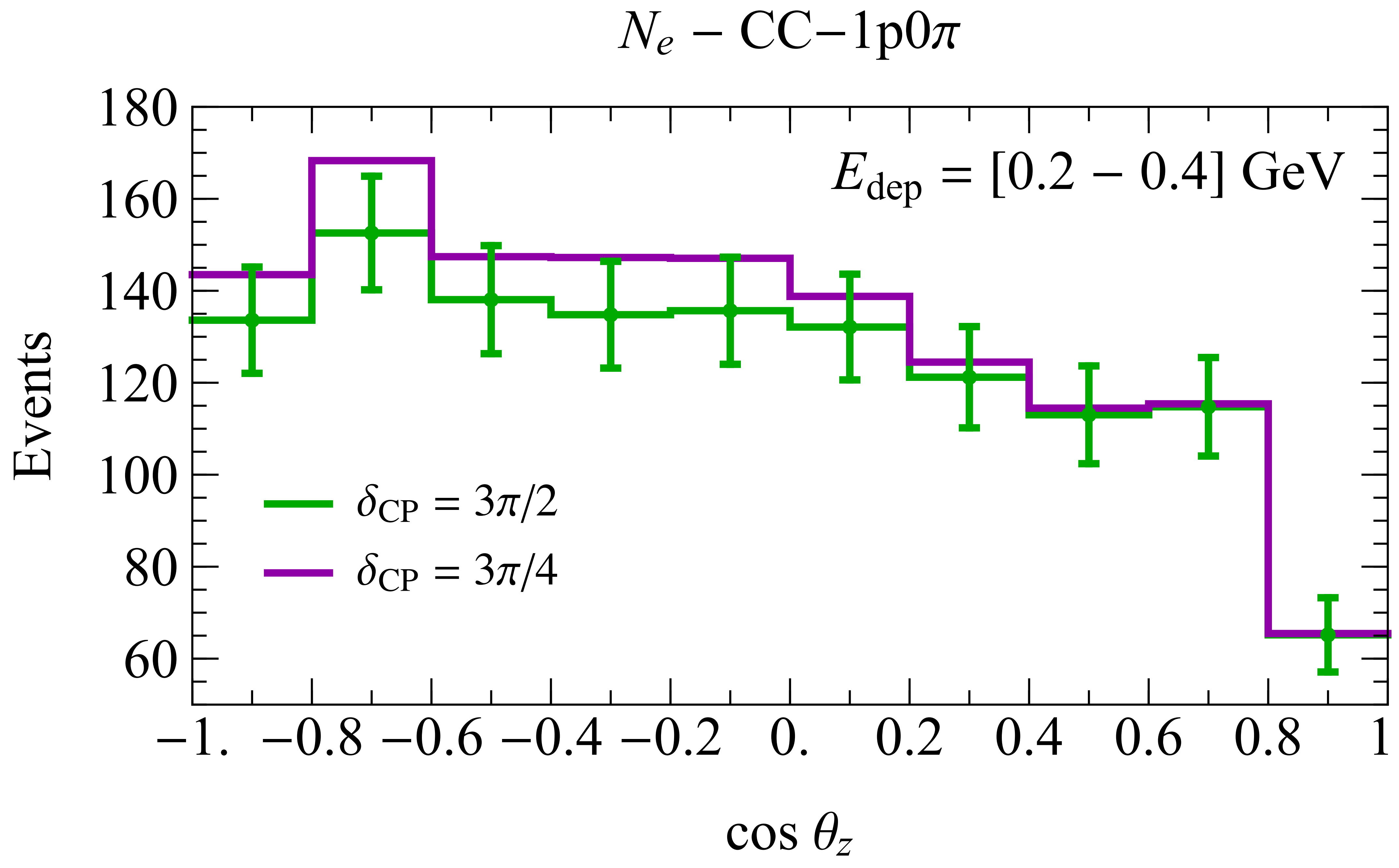
Number of protons	Events/400 kton year	
CC-0p0π	~7000	$\overline{\nu}$ dominated
CC-1p0π	~12000	ν dominated

Kelly, Machado, **IMS**, Parke, Perez-Gonzalez, PRL 123 (2019)



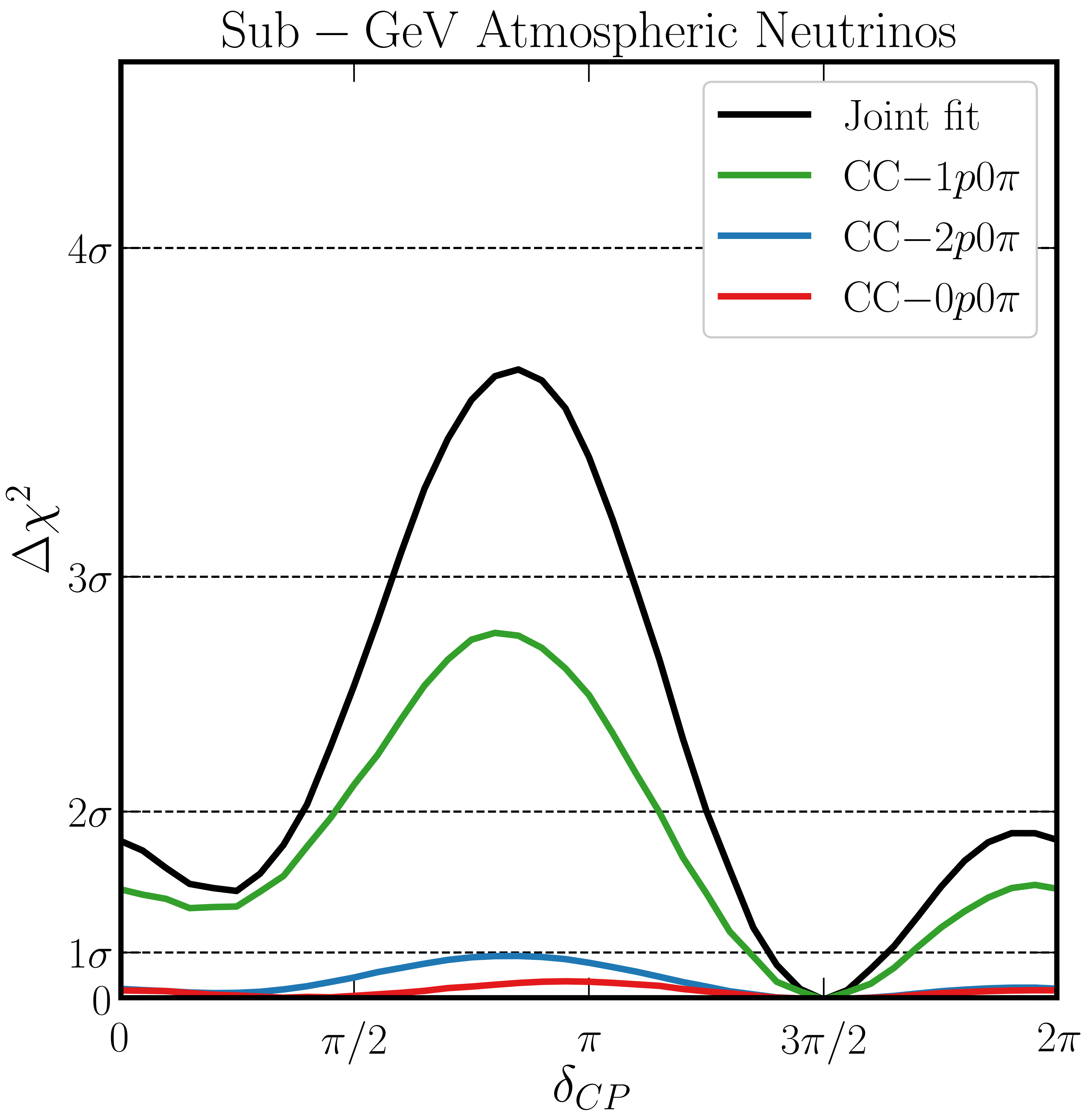
LArTPCs

δ_{cp} causes a **significant deviation** in DUNE's expected **sub-GeV events**.



Kelly, Machado, **IMS**, Parke, Perez-Gonzalez, PRL 123 (2019)

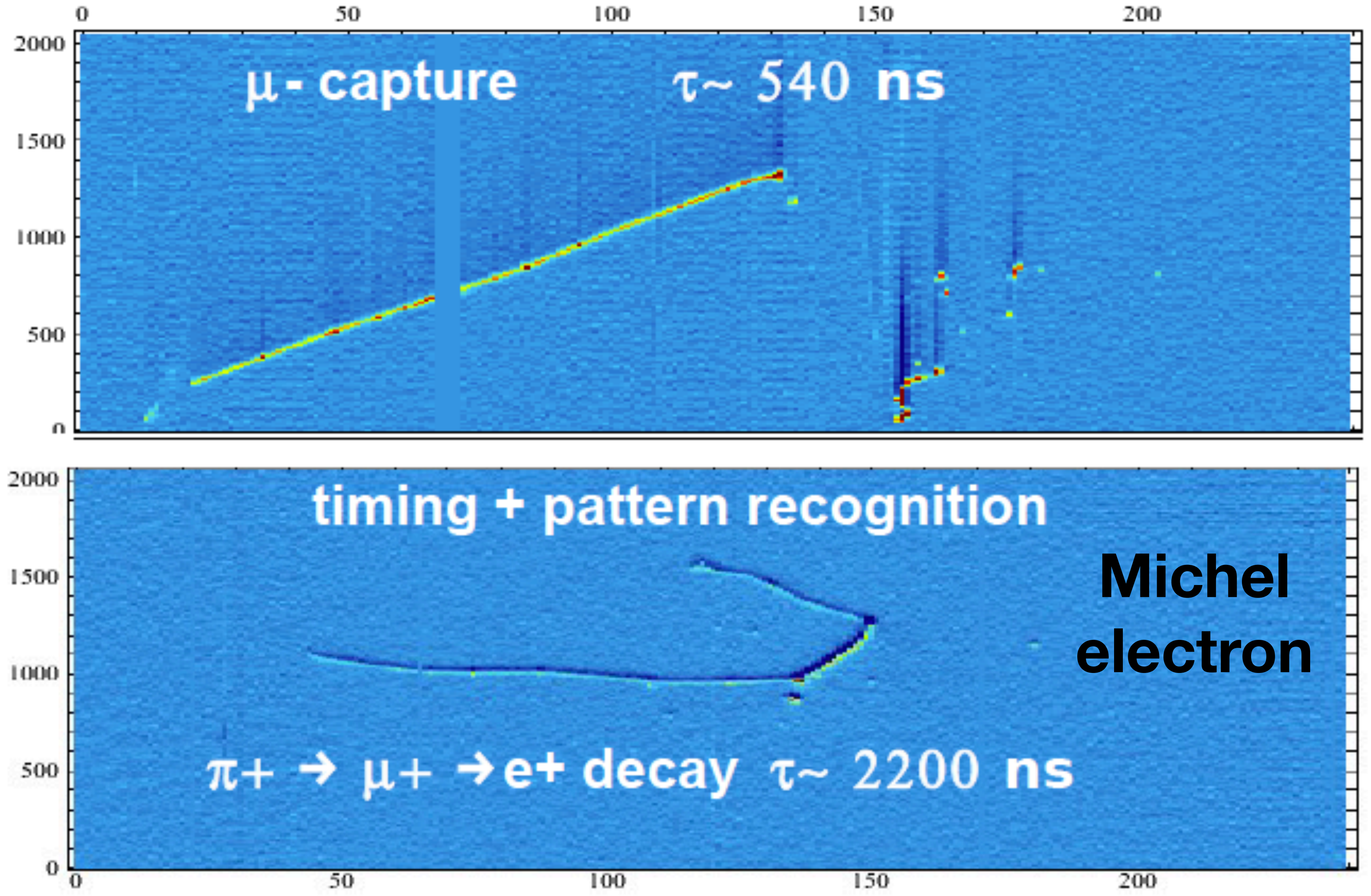
DUNE can exclude ranges of δ_{cp} with more than **3σ confidence**



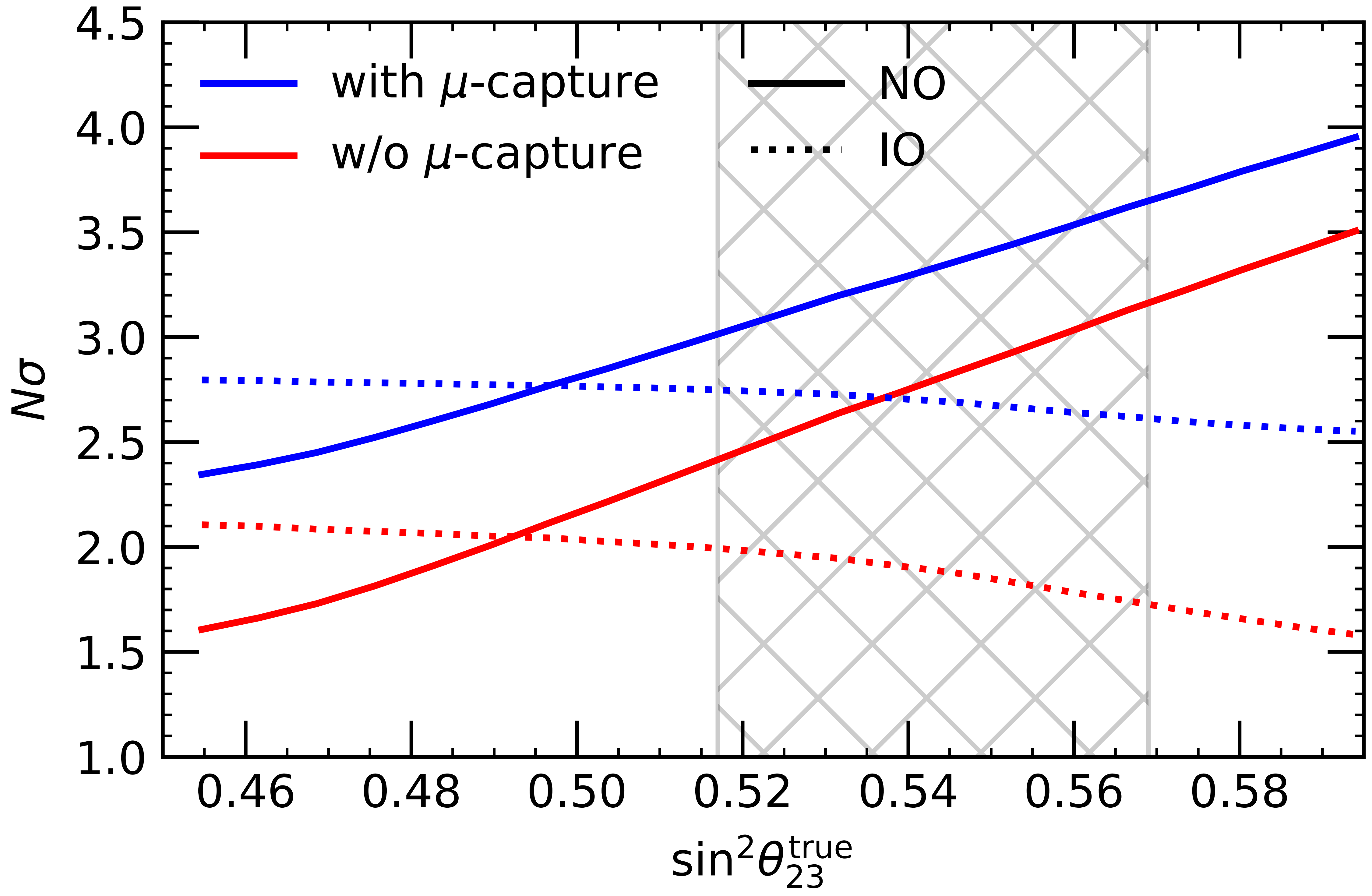
LArTPCs

Expanding the analysis to **higher energies** will allow the measurement of **mass ordering**

- The **energy and angular resolution** of LArTPCs allow for resolving **matter effects**.
- Identifying **Michel electrons** and μ^- **capture** enhances neutrino and antineutrino **separation.**



F. Cavanna et al. (LArIAT), arXiv: 1406.5560
M. Sorel, JINST 9 (2014) P10002
Abi et al. (DUNE), arXiv: 2002.03005



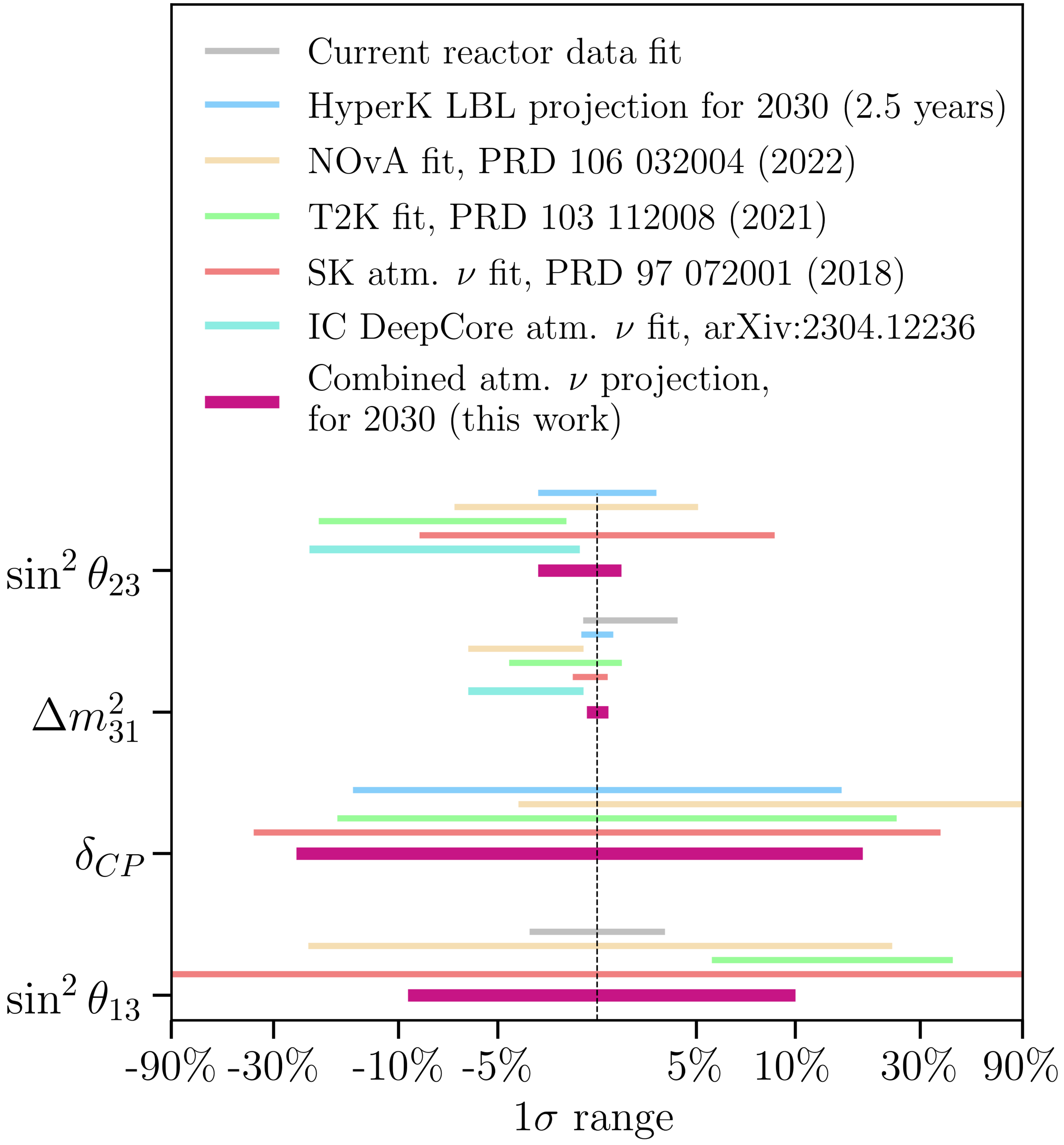
Ternes, Gariazzo, Hajjar, Mena, Sorel and Tórtola, PRD 100 (2019)

Conclusions

- Neutrino oscillation is entering the precision era, but unknown parameters remain.

- In the near future, atmospheric neutrinos can provide valuable information about the less constraints parameters:
  - The ordering can be resolved to $\sim 6\sigma$
  - The wrong θ_{23} octant can be excluded at 3σ
  - Part of the parameter space of the CP phase can be explored at 3σ

- In the future, new detectors like DUNE will be able to improve the precision over the CP phase and the mass ordering.



Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

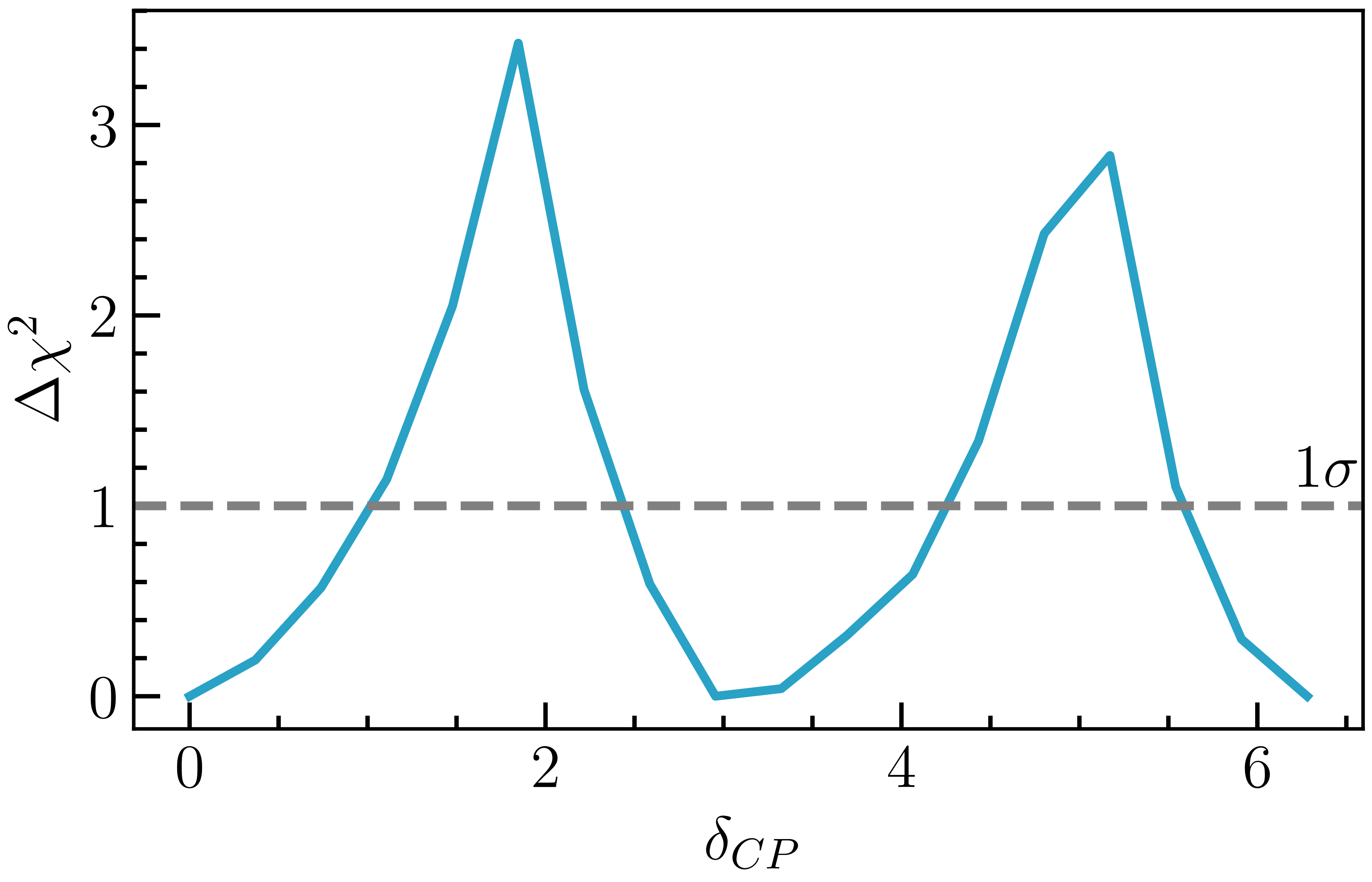
Grazie!

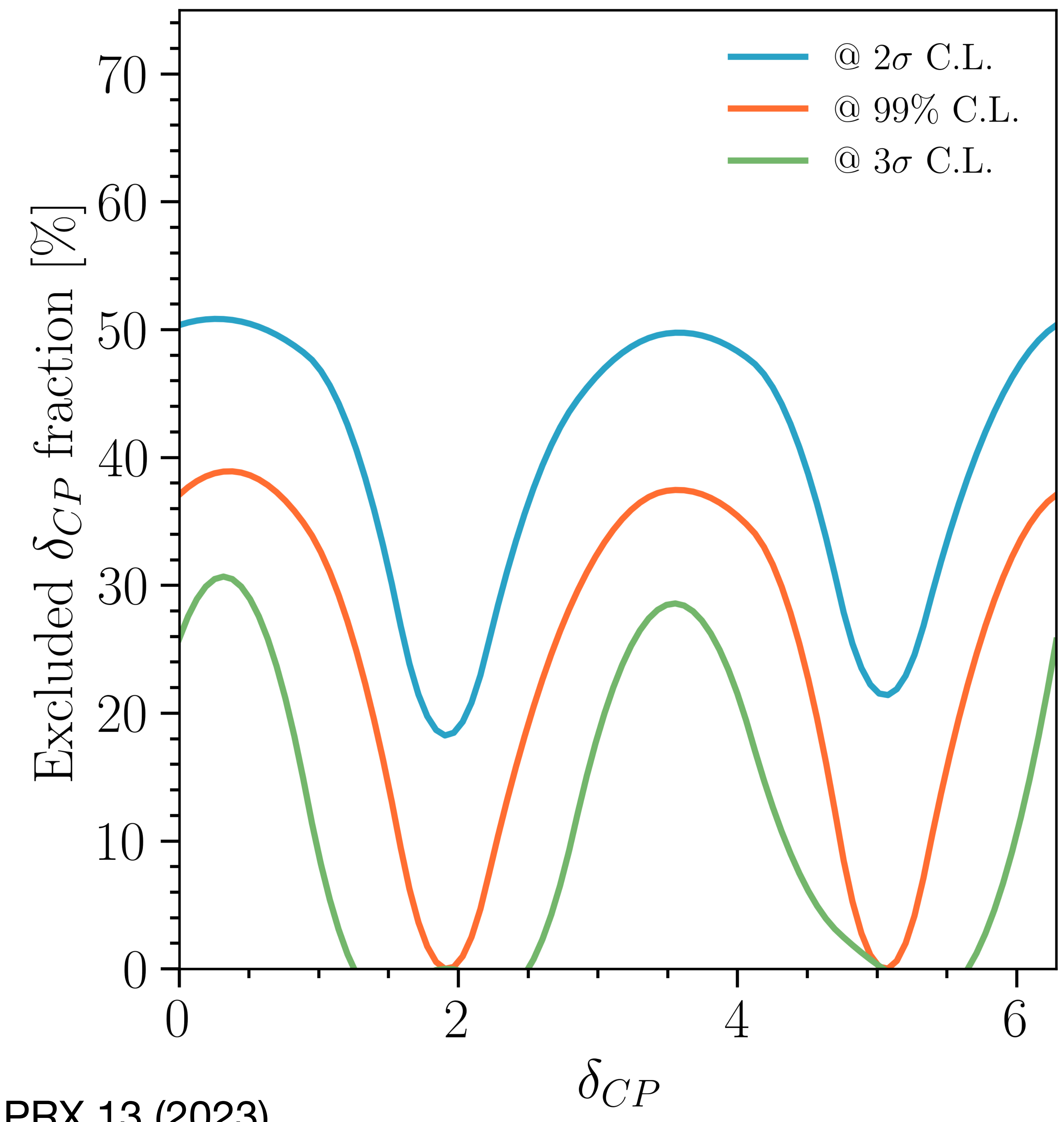
Combined analysis: δ_{cp}

The **sensitivity to the CP phase** depends on the true value

A large fraction of δ_{CP} can be excluded at 99% CL using only atmospheric neutrinos

CP-violation sensitivity

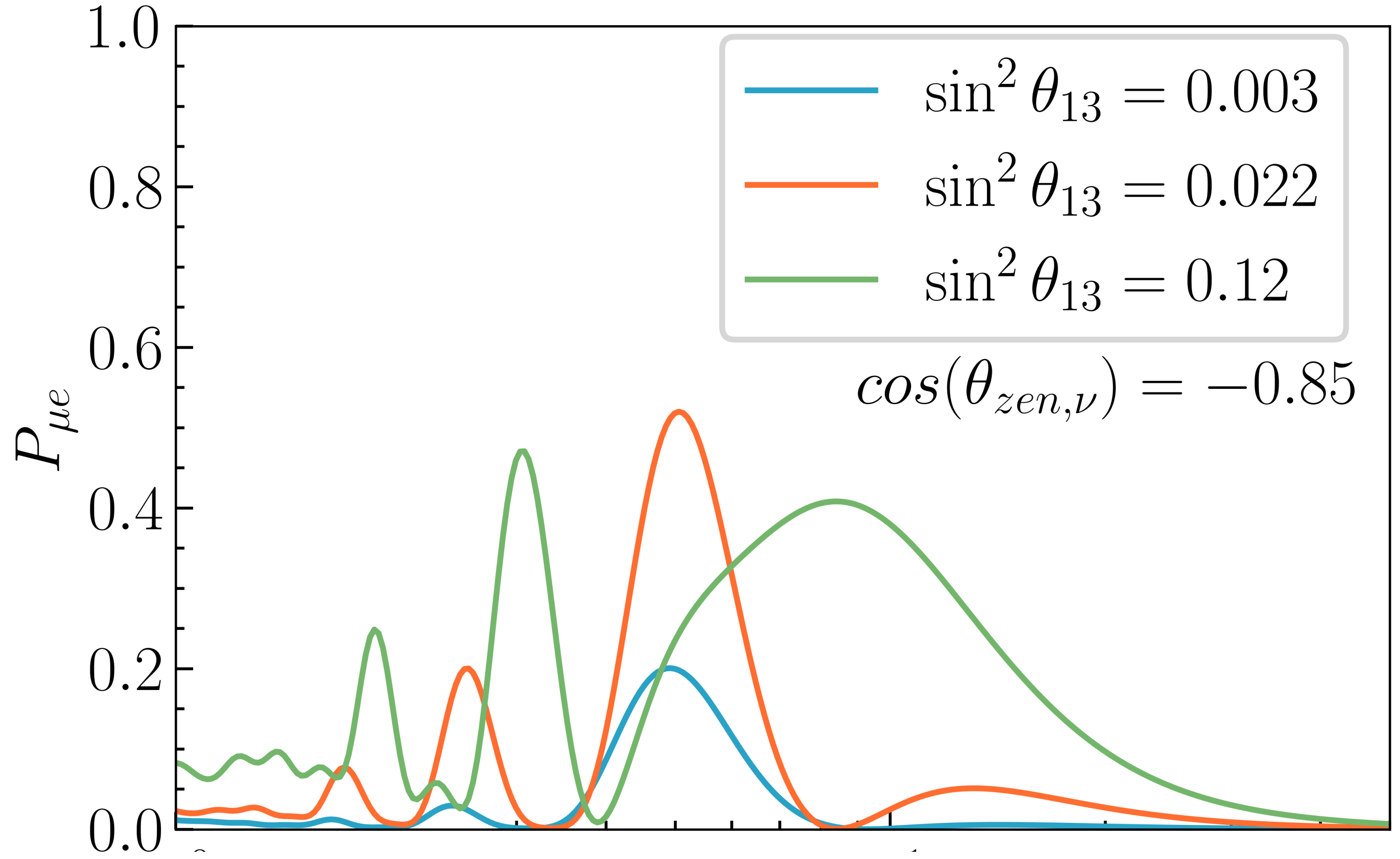


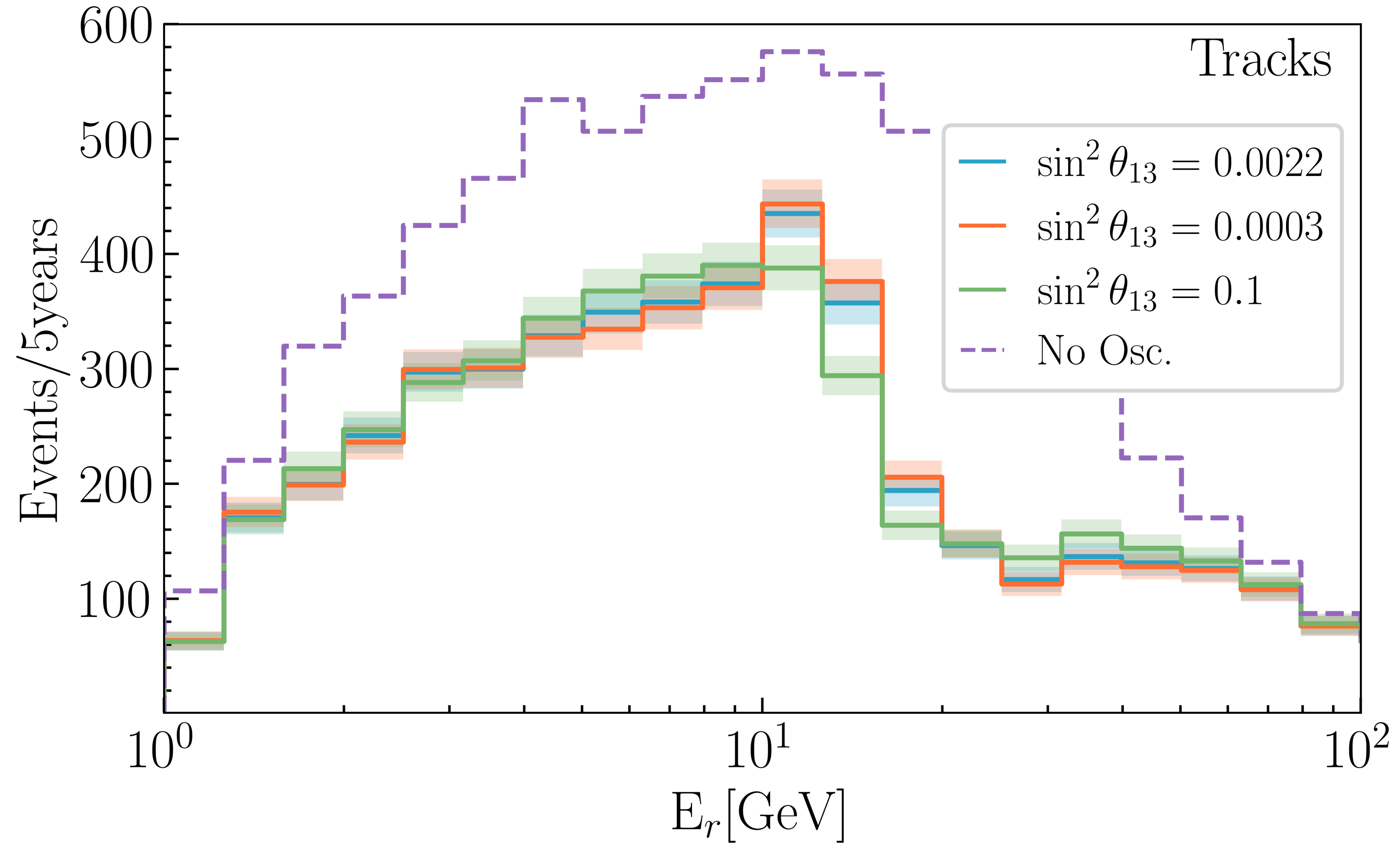


Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

Bonus: sensitivity over θ_{13}

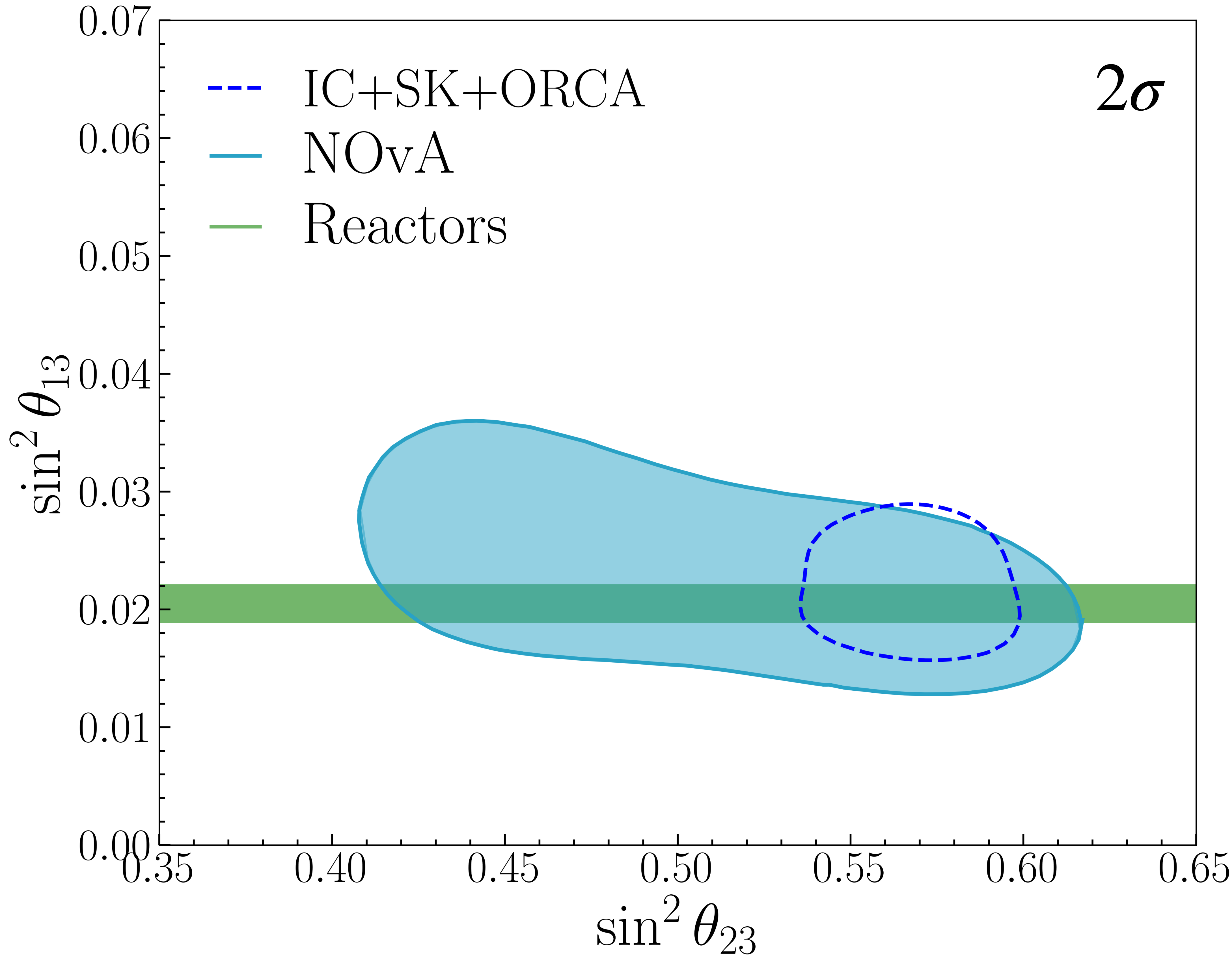
The measurement of the atmospheric resonance also gives us a sensitivity to $\sin^2\theta_{13}$





The value of θ_{13} determine the energy where the MSW resonance happen

Tracks are very sensitive to large values of θ_{13}



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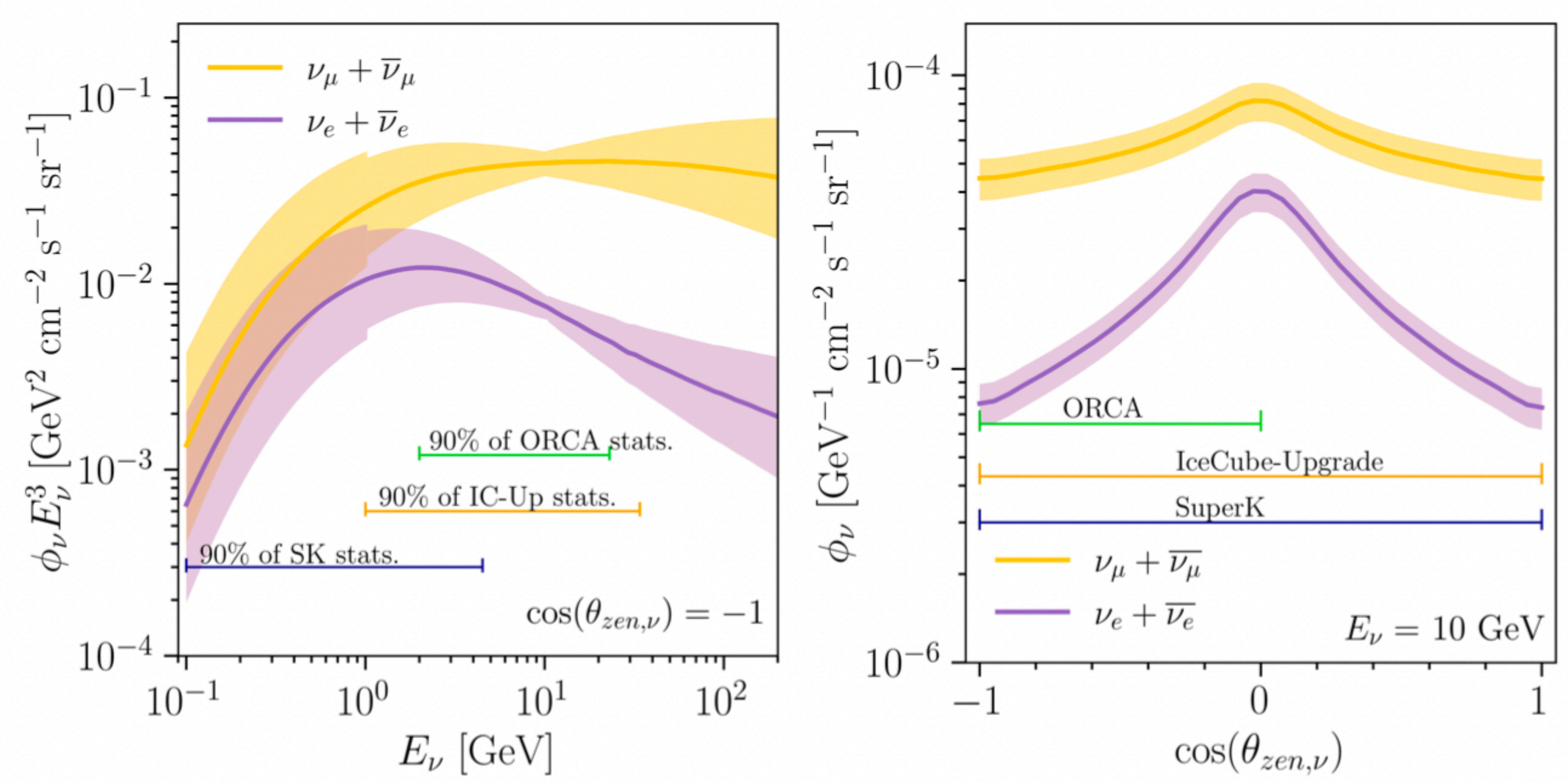
Flux uncertainties

The uncertainties on the atmospheric neutrino flux reduce the sensitivity to the mixing parameters.

$$\Phi_\alpha(E, \cos\zeta) = f_\alpha(E, \cos\zeta)\Phi_0\left(\frac{E}{E_0}\right)^\delta \eta(\cos\zeta)$$

These systematics are common to both experiments

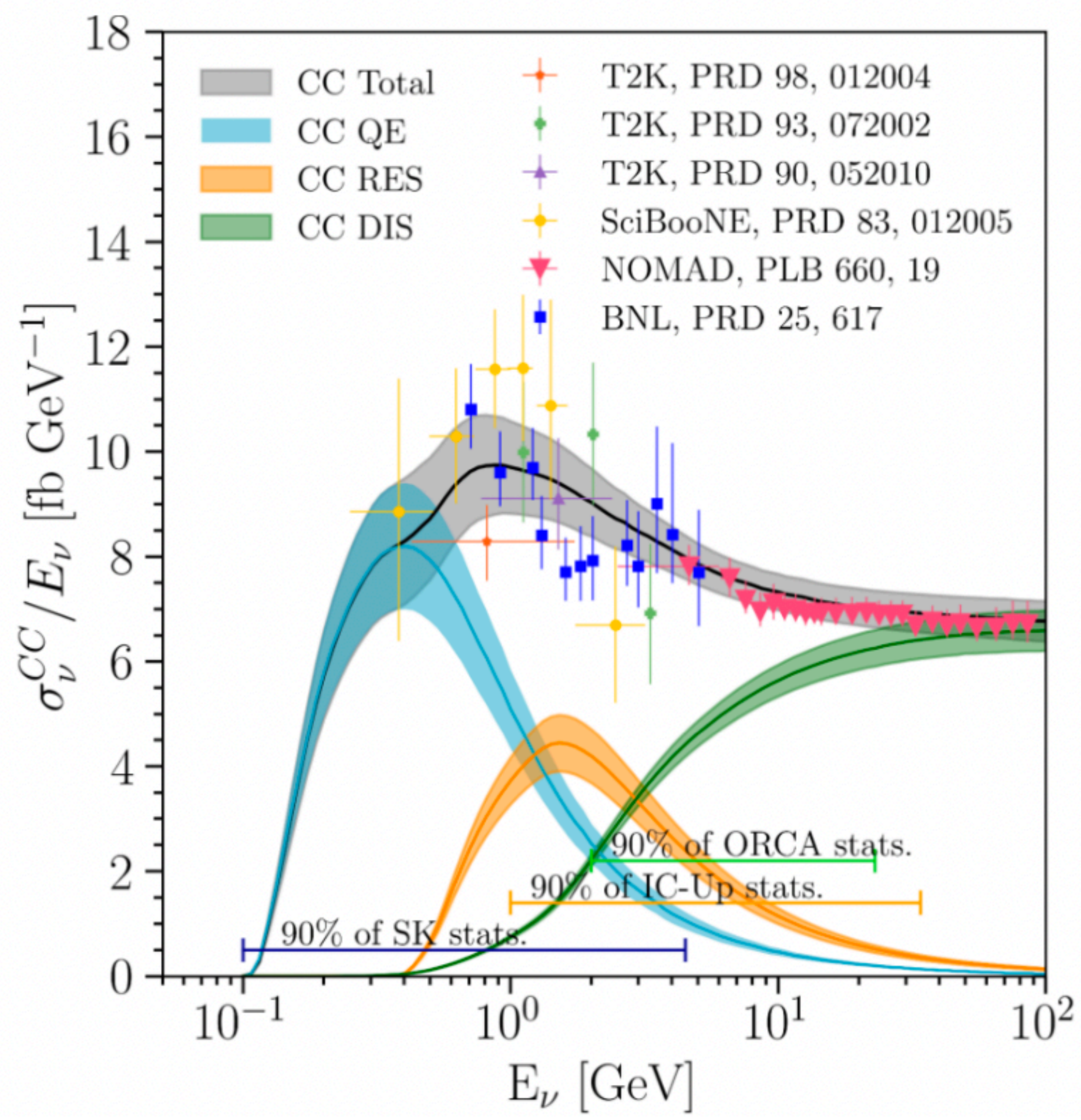


Systematic	Uncert./Priors
$\Phi_0(E < 1$ GeV$)$	25%
$\Phi_0(E > 1$ GeV$)$	15%
ν_e/ν_μ	2%
$\overline{\nu}/\nu$	2%
δ	20%
$C_{u,d}$	2%

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

Cross-section uncertainties

Different types of interactions affect the atmospheric neutrino interaction due to the large energy range covered by the flux



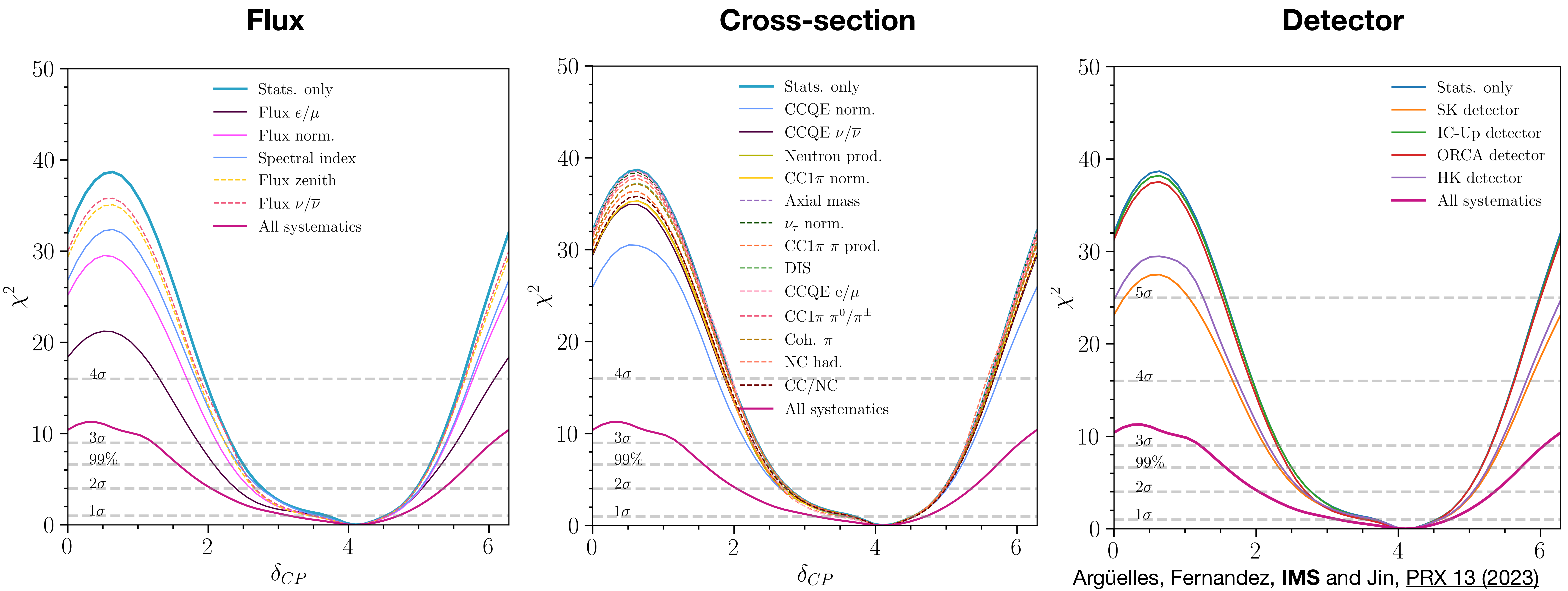
These systematics are common to water Cherenkov experiments

Systematic	Uncer./Prior
CCQE	10%
CCQE $\nu/\bar{\nu}$	10%
CCQE e/μ	10%
CC1 π	10%
CC1π $\pi^0/\pi^\pm$	40%
CC1π $\nu_e/\overline{\nu_e}$	10%
CC1π $\nu_\mu/\overline{\nu_\mu}$	10%
Coh.π	100%
Axial Mass	10%
NC hadron prod.	5%
NC over CC	10%
ν_τ	25%
Neutron prod. (SK)	15%
DIS	10%

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

Systematic Impact

A **detailed analysis** of all the systematics was performed, revealing that **flux uncertainties** had a larger impact on δ_{CP}

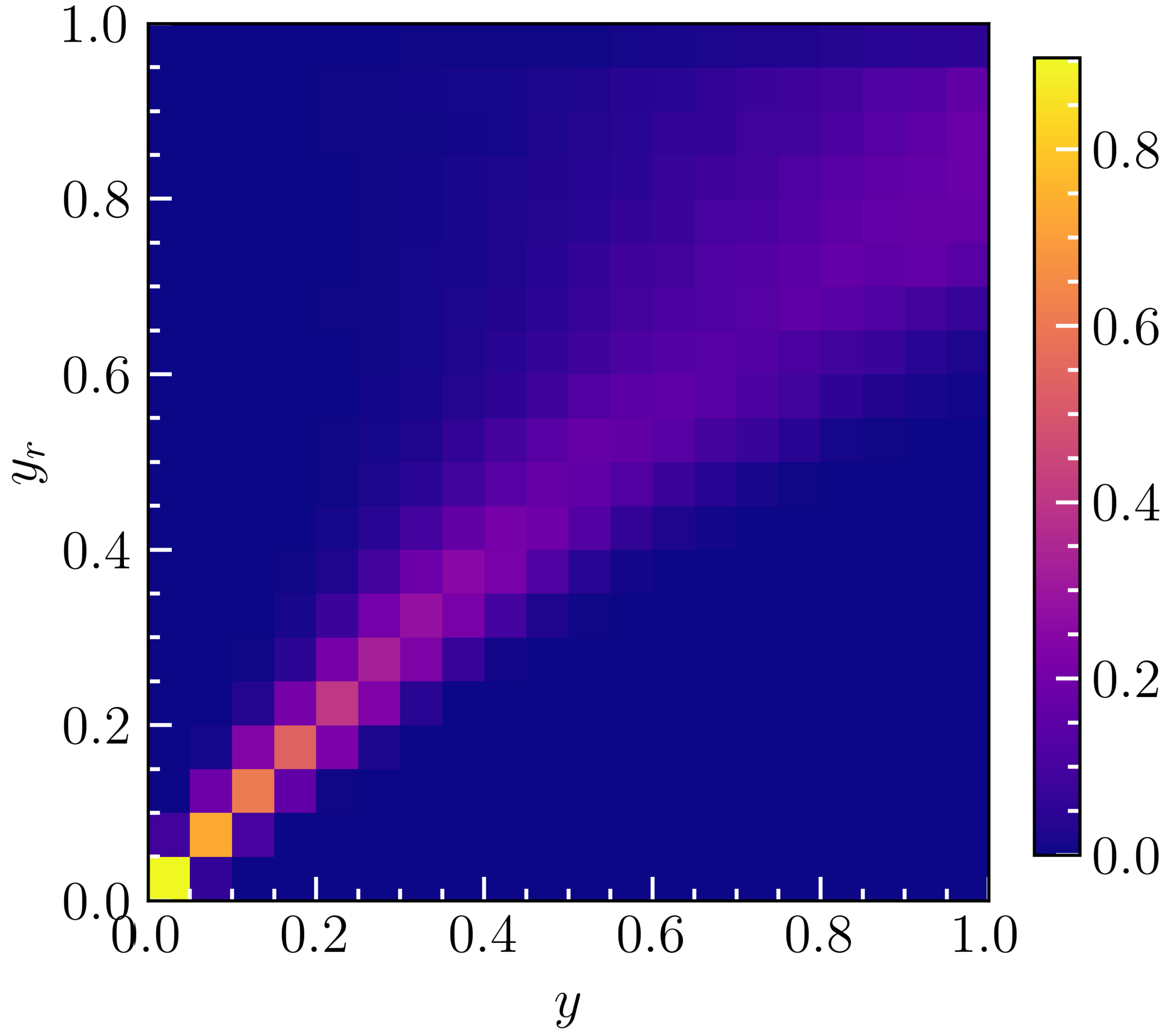


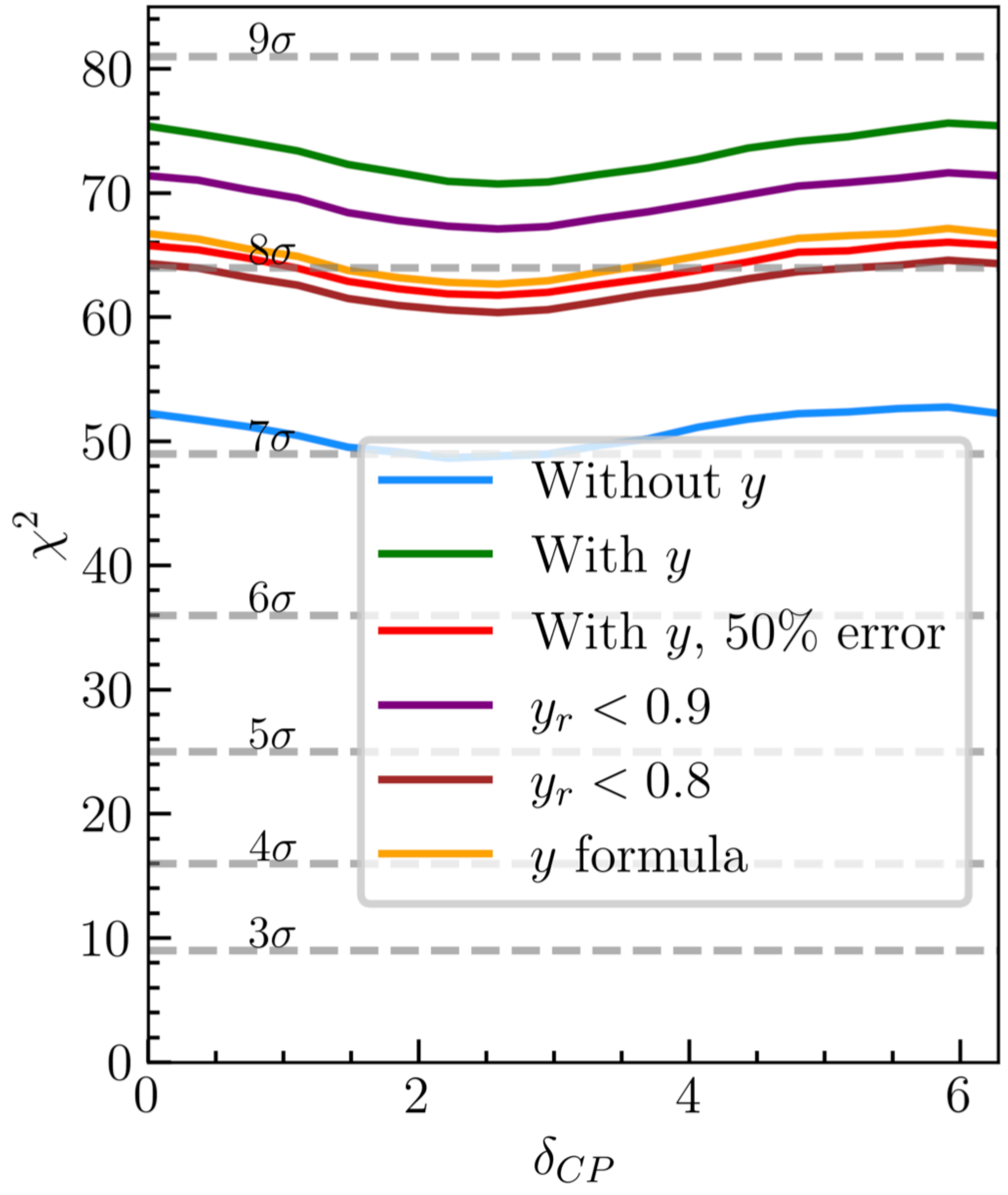
Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

Booting the Sentivity with Inelasticity

To test the results, we explored different uncertainties in the inelasticity

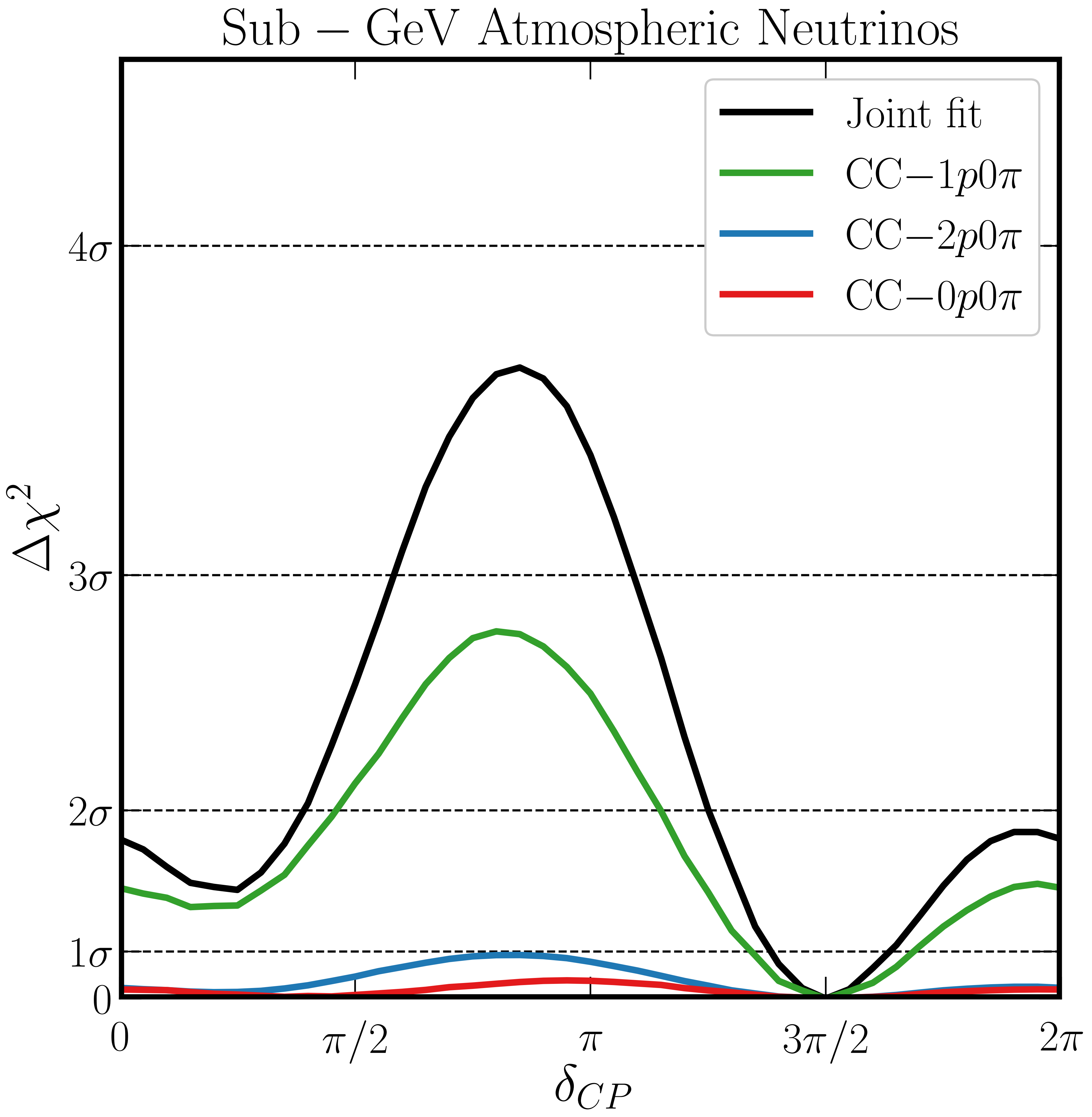
There is a large uncertainty in the inelasticity when most of the energy goes to the cascade.



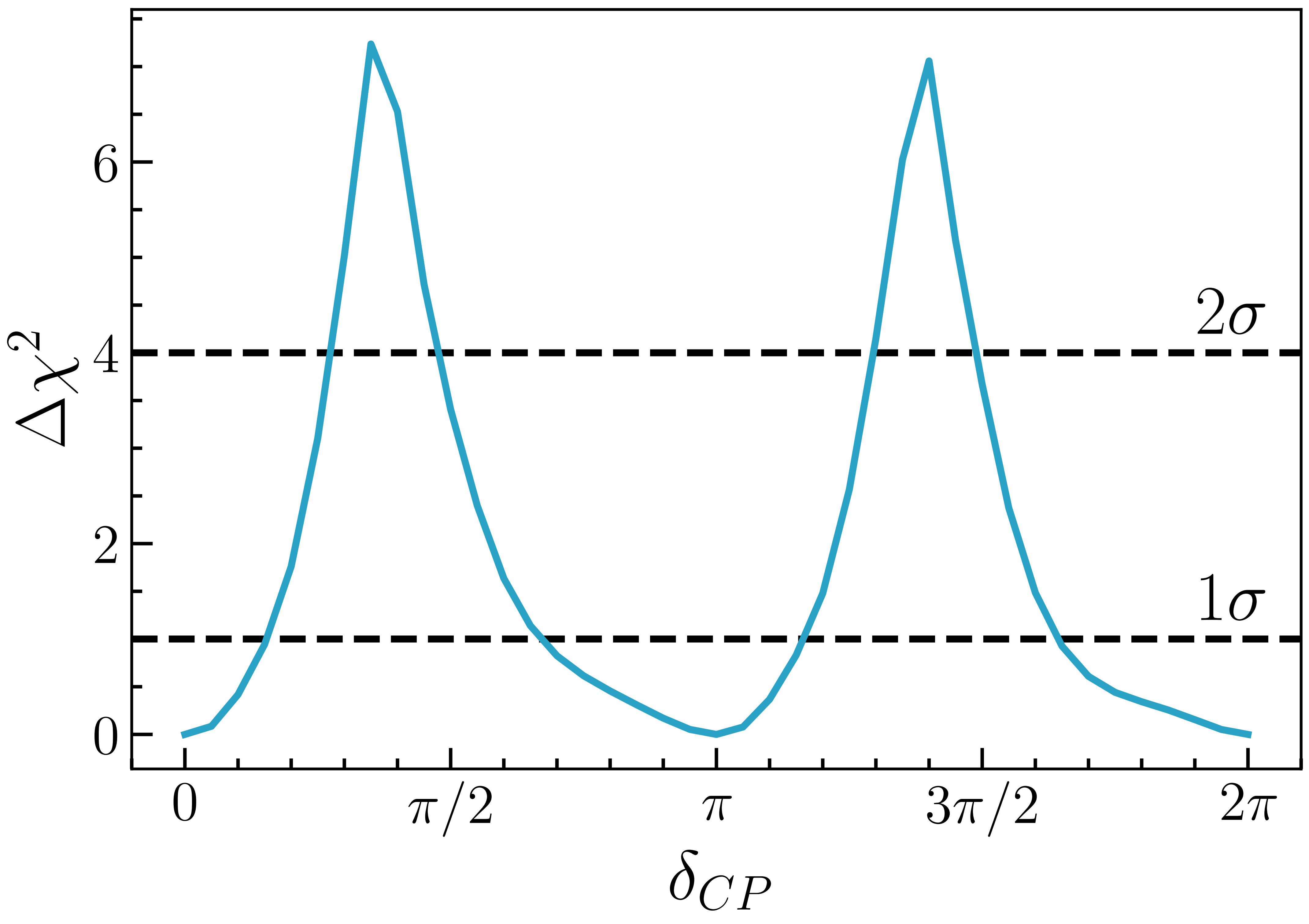


LArTPCs

DUNE can exclude some values of δ_{cp} to more than 3σ



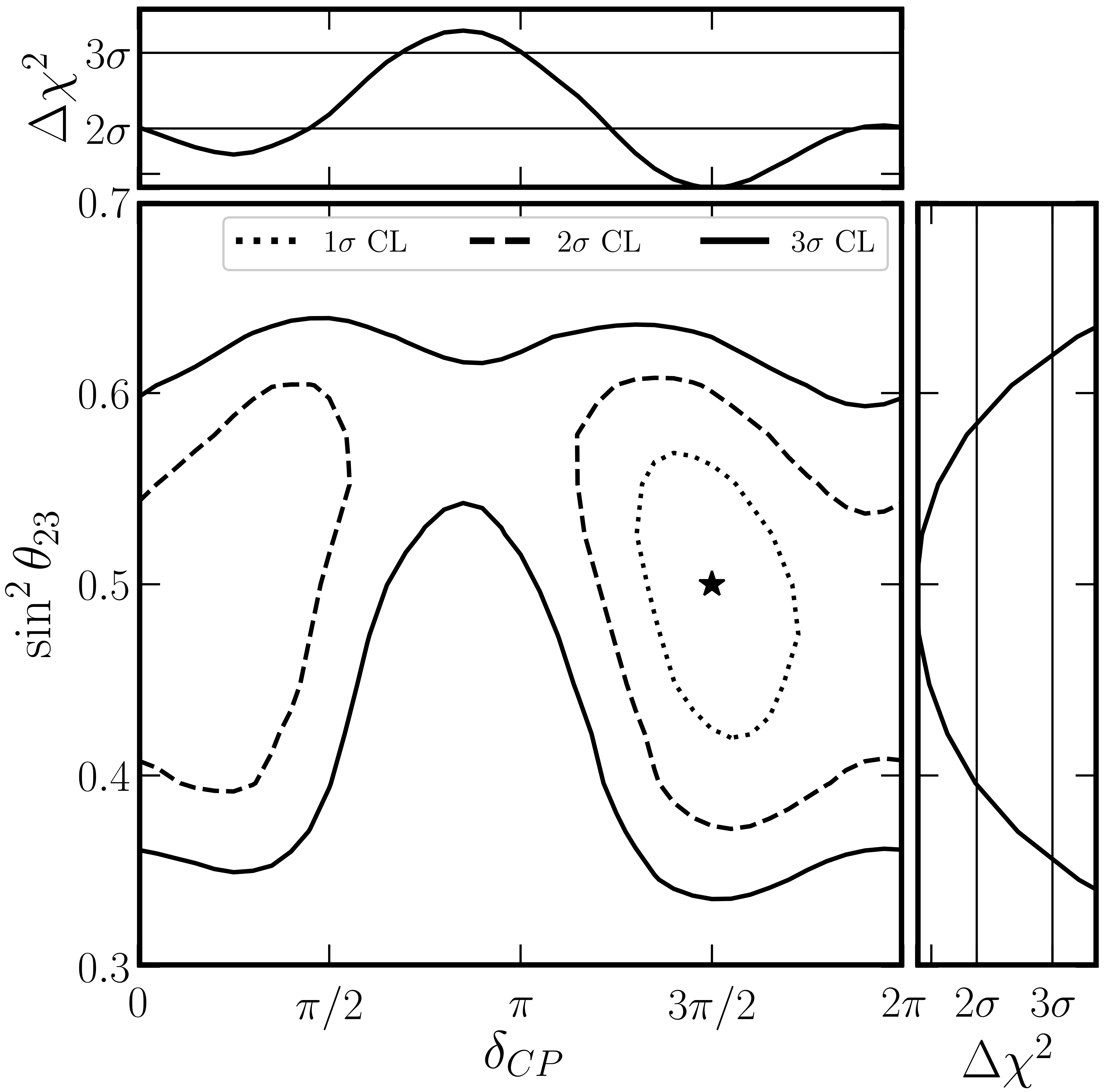
Sensitivity to CP violation



Kelly, Machado, **IMS**, Parke, Perez-Gonzalez, PRL 123 (2019)

LArTPCs

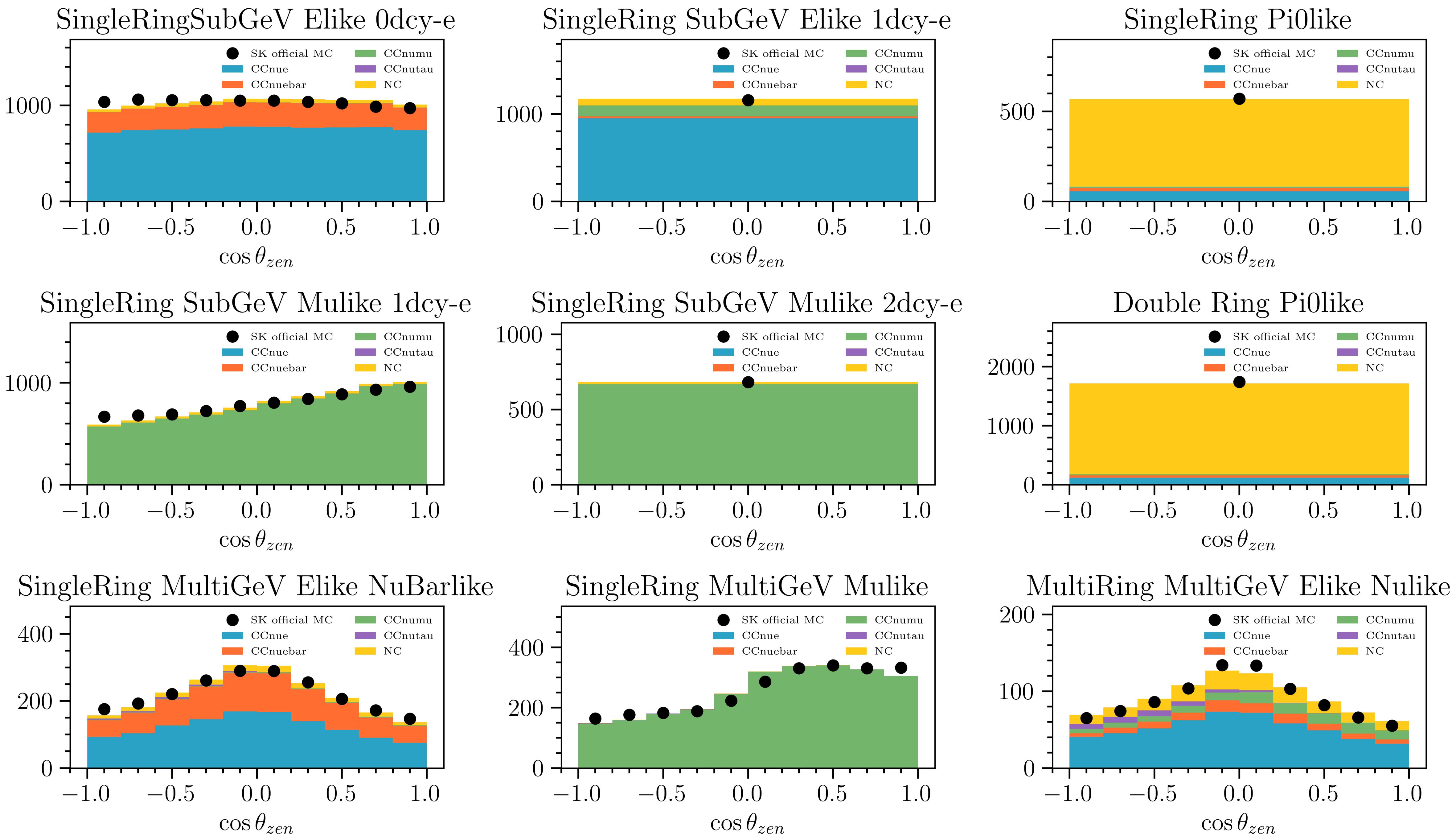
In case of a tension in the determination of δ_{CP}, atmospheric neutrinos can contribute to solve it

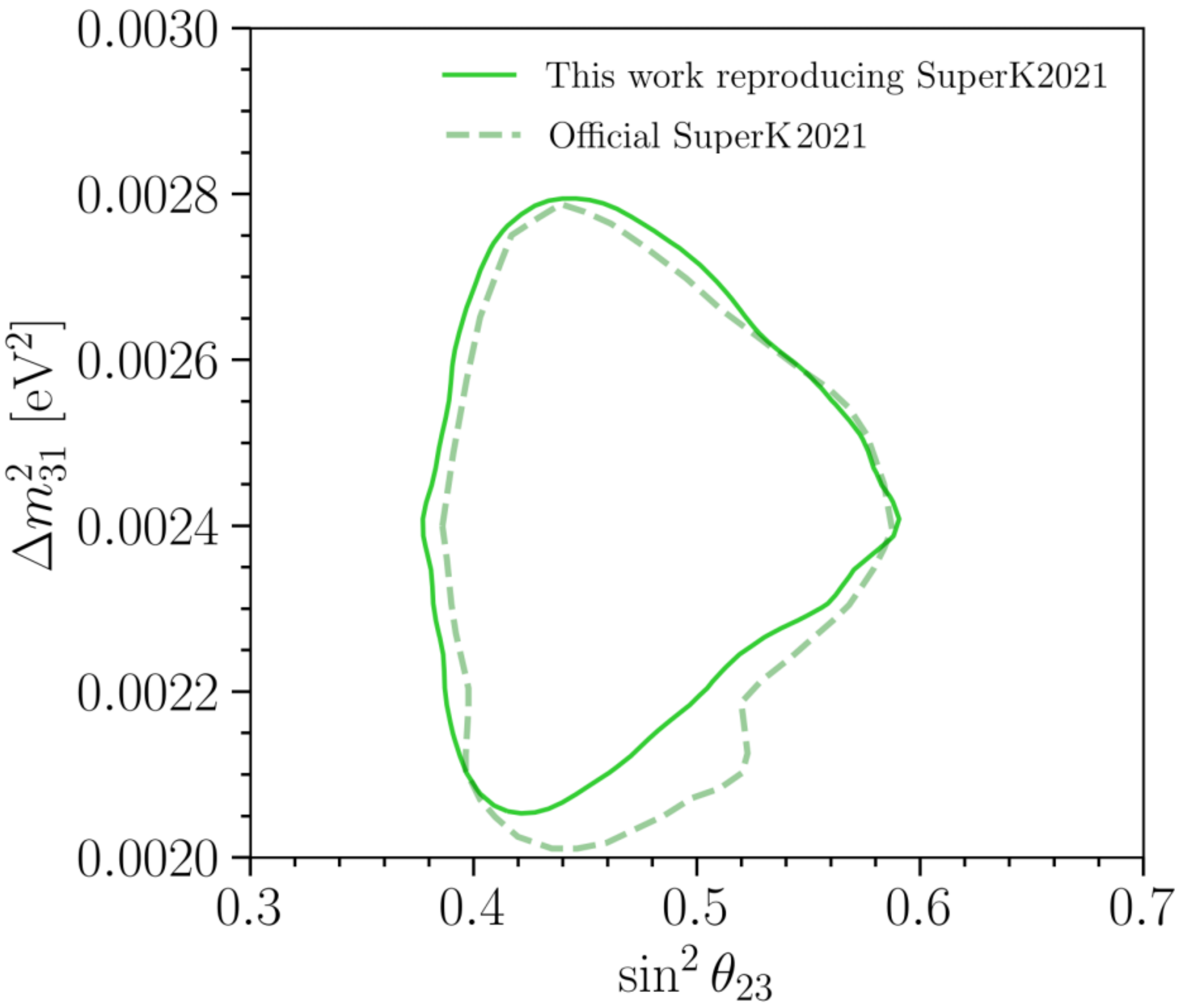


Kelly, Machado, **IMS**, Parke, Perez-Gonzalez, PRL 123 (2019)

Super-Kamiokande

We have developed a simulation of **SK** considering **all the phases** and **Hyper-Kamiokande**

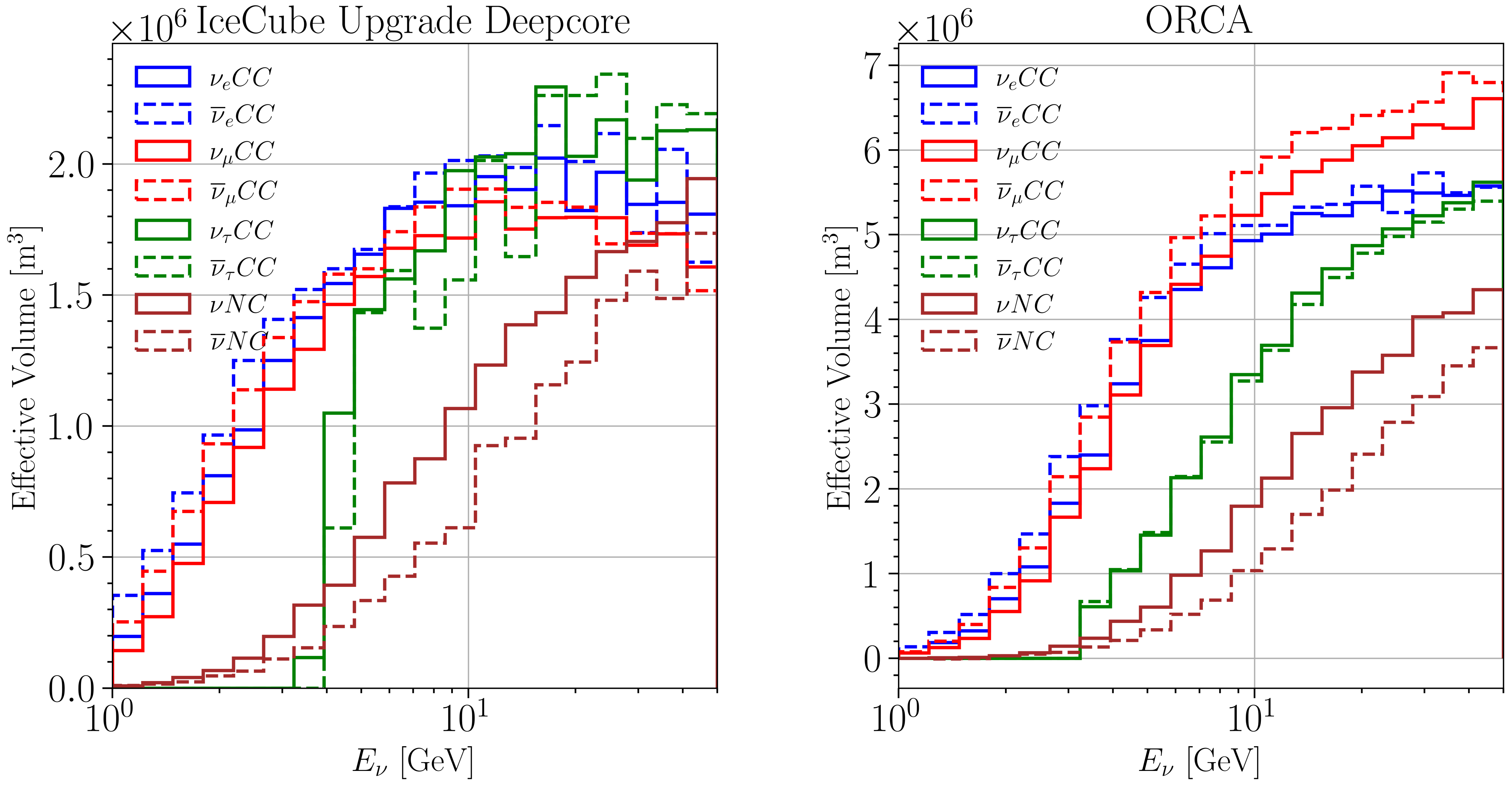




Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

Comparison between Neutrino Telescopes

Effective volume



Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)