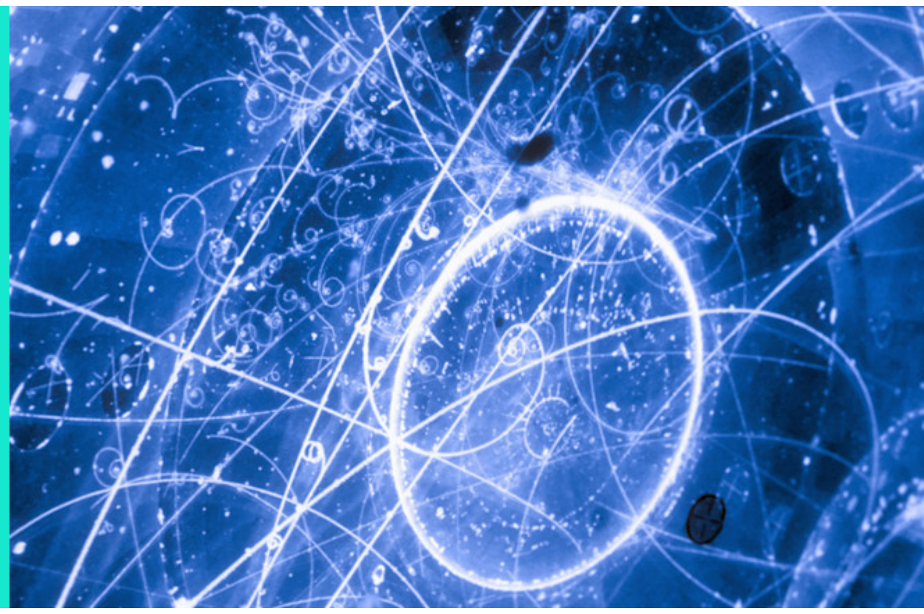
From Precision in Oscillation Searches to Discovery



Iván Martínez Soler

Neutrino-Nucleus Interactions in the Standard Model and Beyond

Durham University

May 15, 2025

IP3

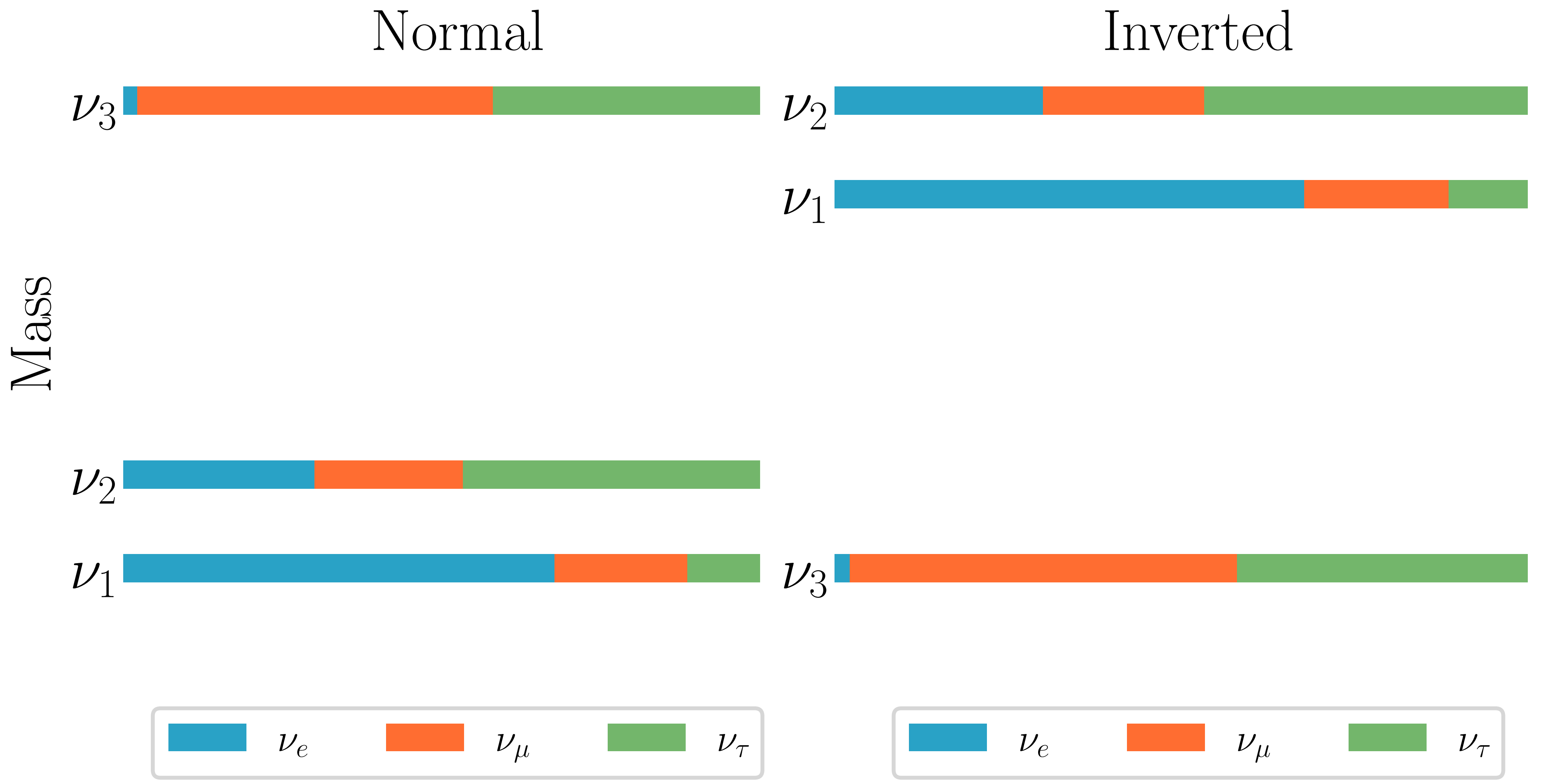
3ν mixing

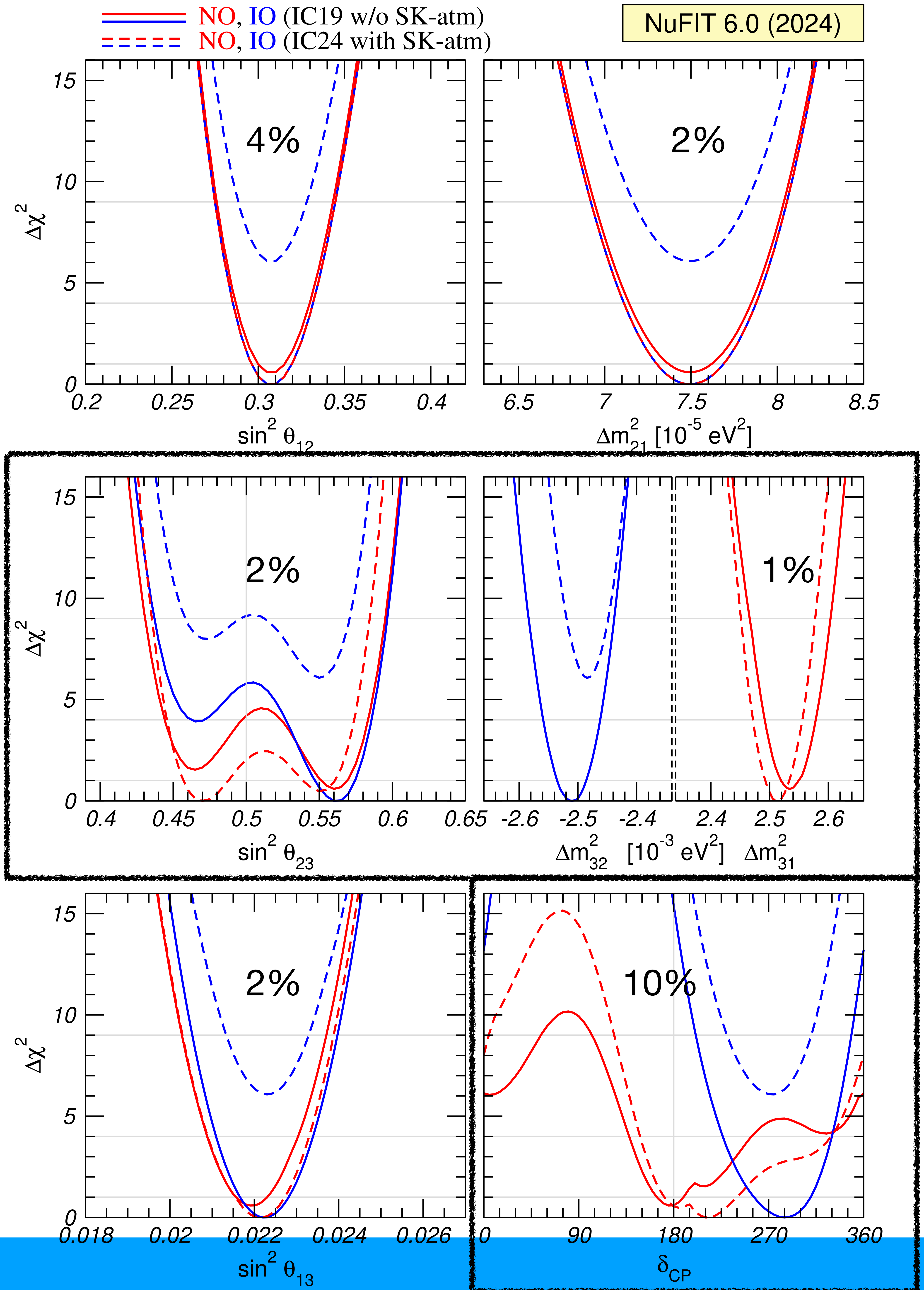
In the 3ν **scenario**, neutrino evolution is described by six parameters

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

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

Mass ordering





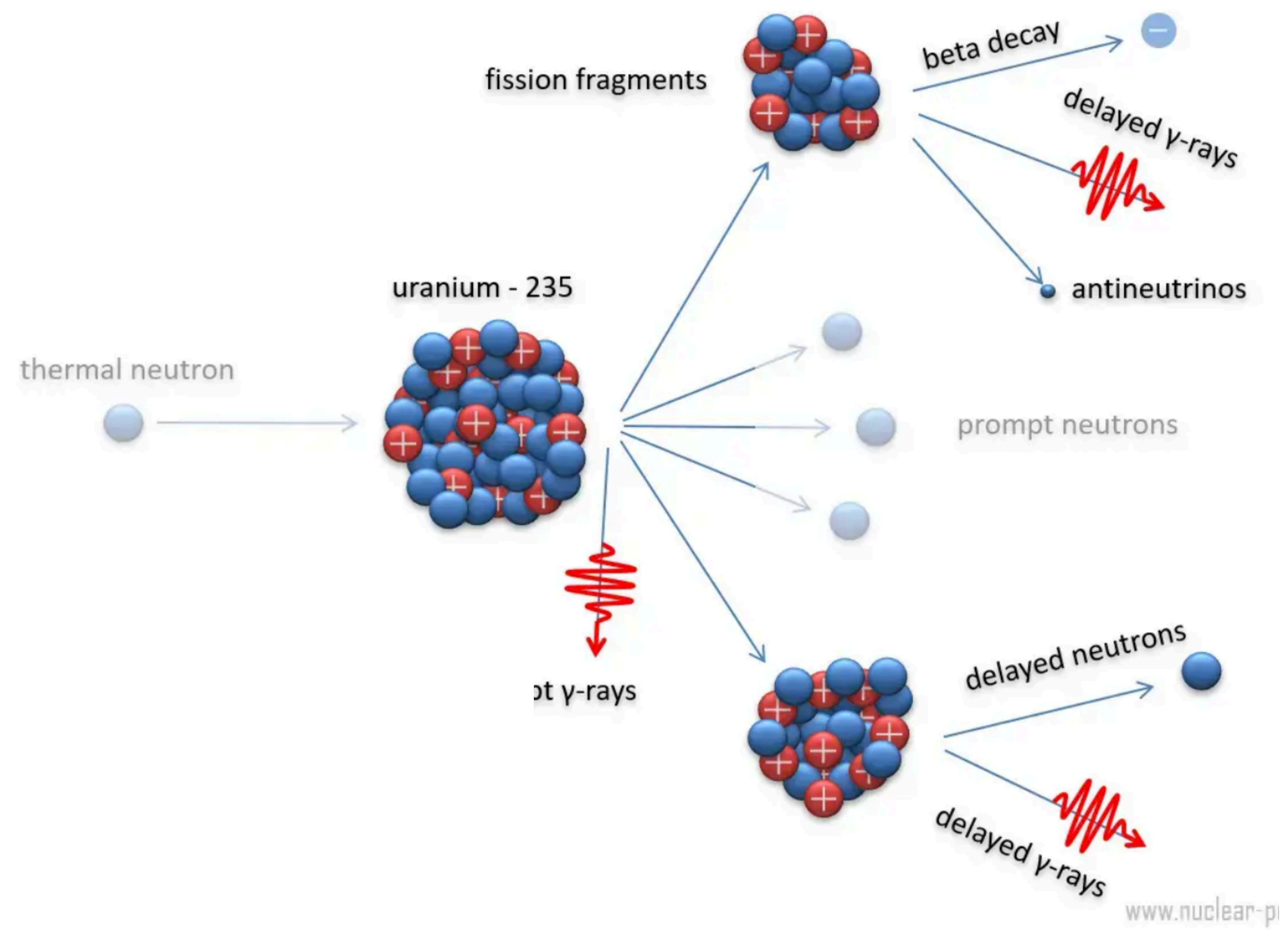
3ν mixing

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

$$i\frac{d\nu}{dE} = \frac{1}{2E}\left(U^{\dagger}\text{diag}(0,\Delta m^2_{21}, \Delta m^2_{31})U\right)\nu \qquad U = U(\theta_{23})U(\theta_{13},\delta_{cp})U(\theta_{12})$$

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

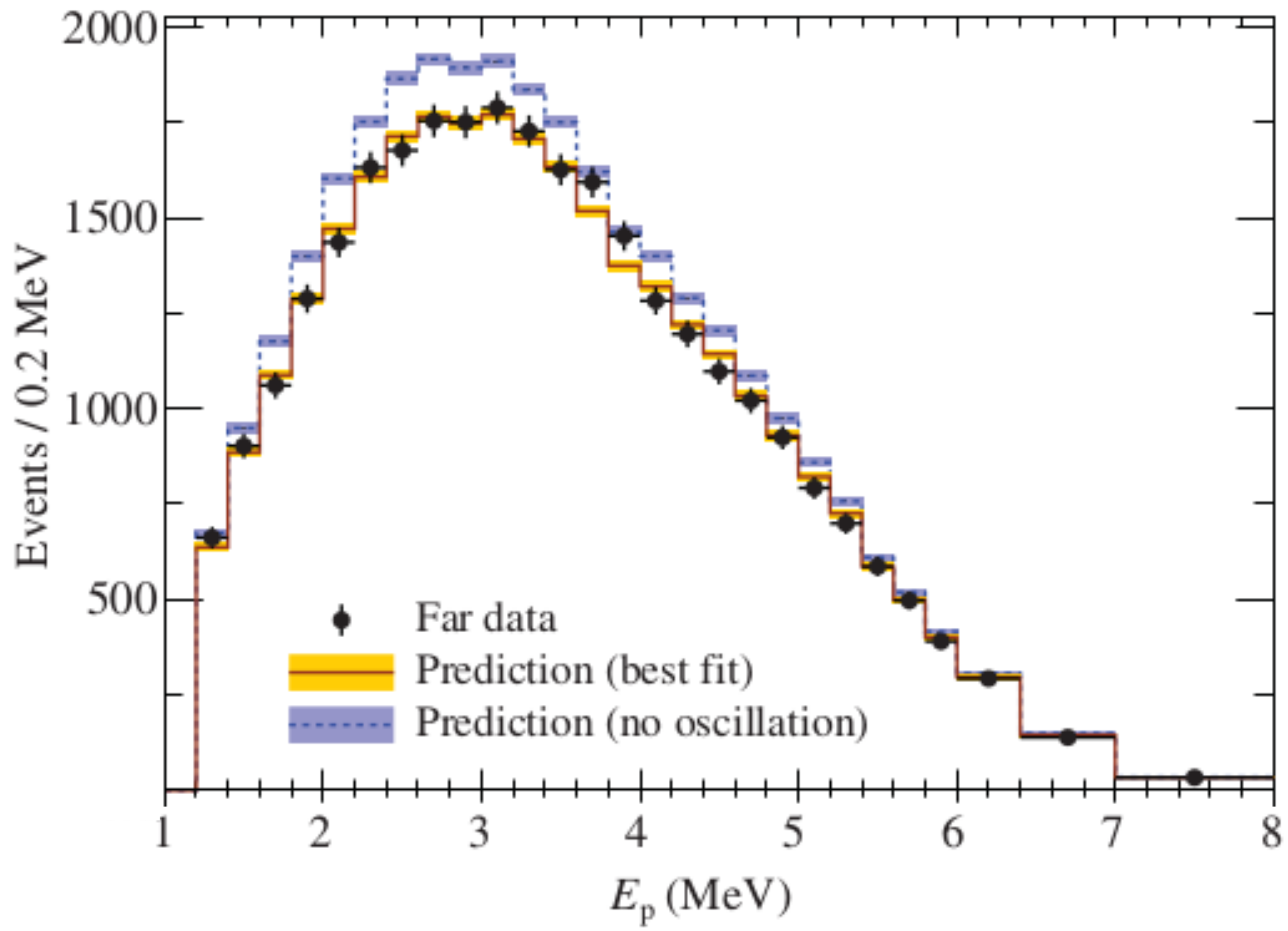
Reactor Neutrinos



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 $\theta_{13} \neq 0$

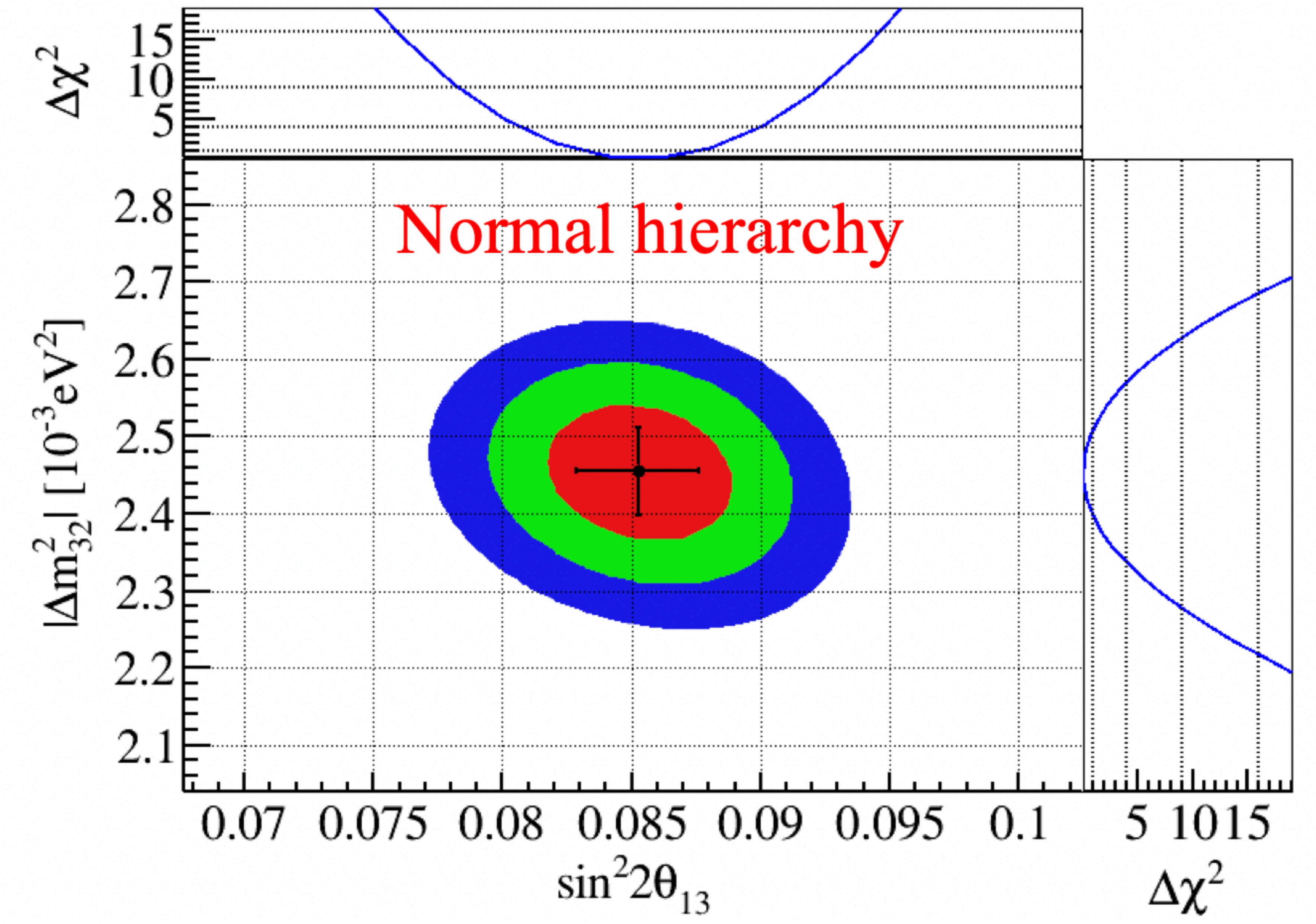
S.H. Seo et al. (RENO) PRD 98 (2018) arXiv:1610.04326

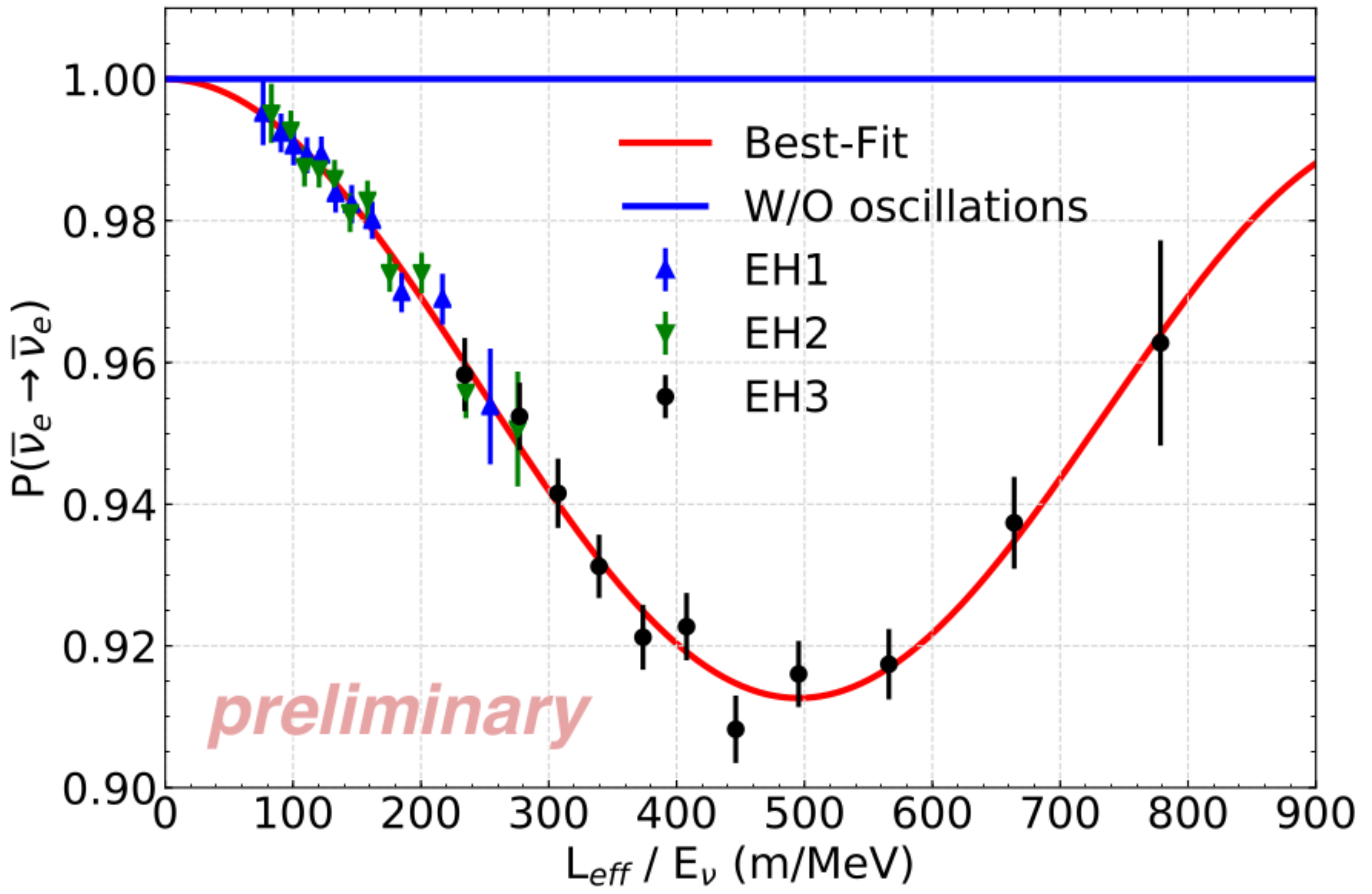
Reactor neutrinos: θ_{13} and Δm^2_{ee}

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

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

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

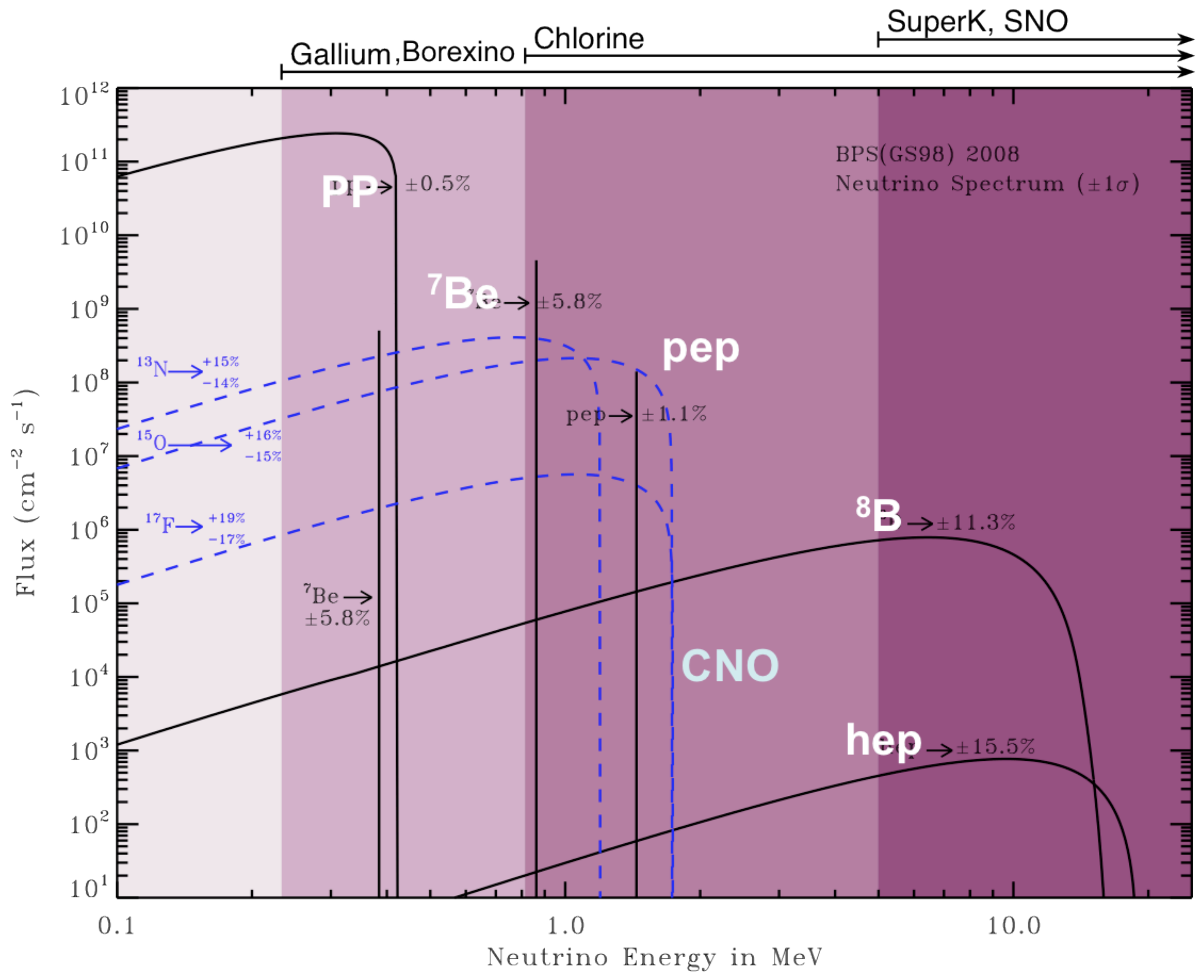




K. Luk (DayaBay) Neutrino 2022

- 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 Neutrinos

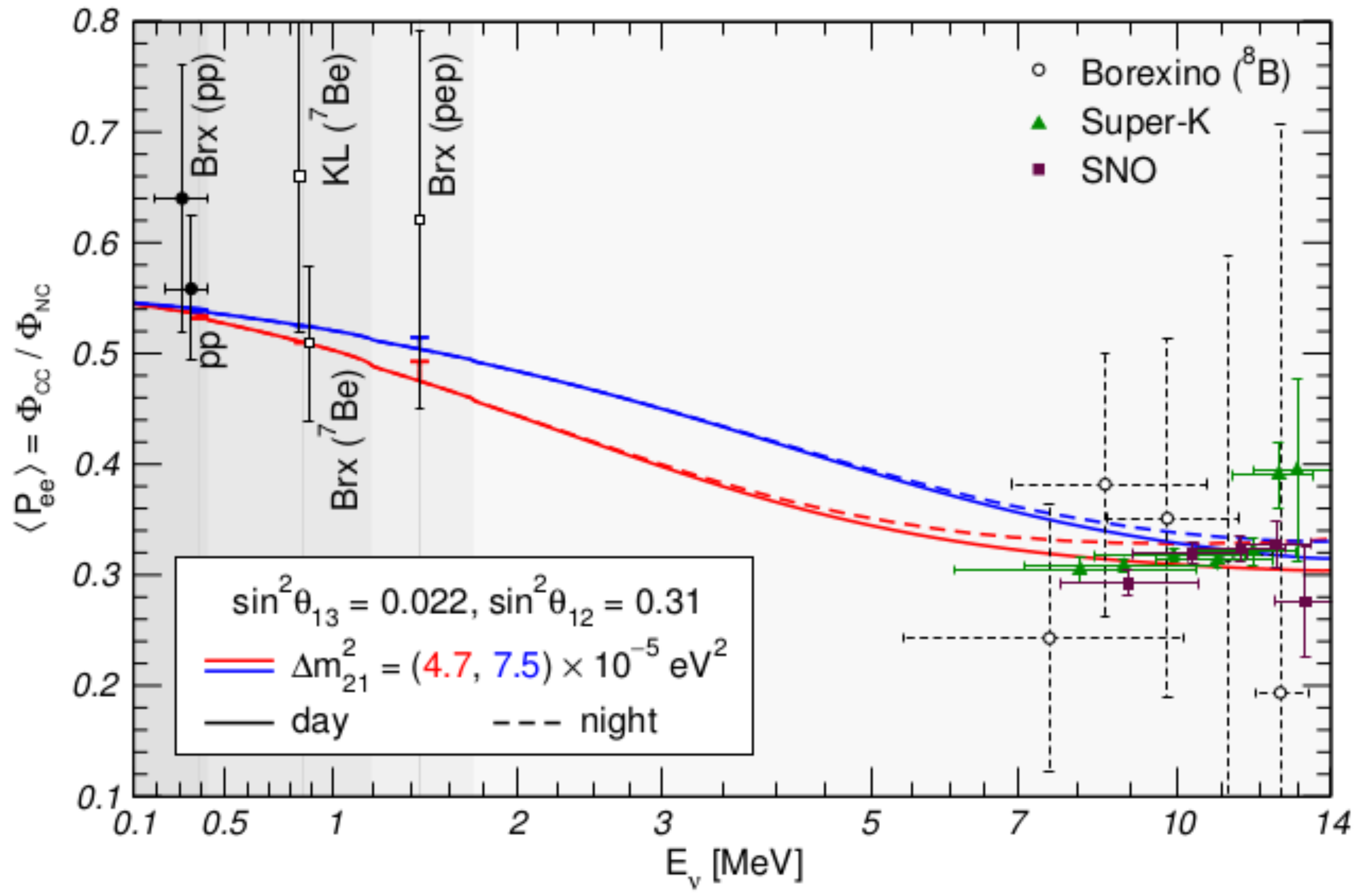


Solar neutrinos are produced by **nuclear fusions** reactions

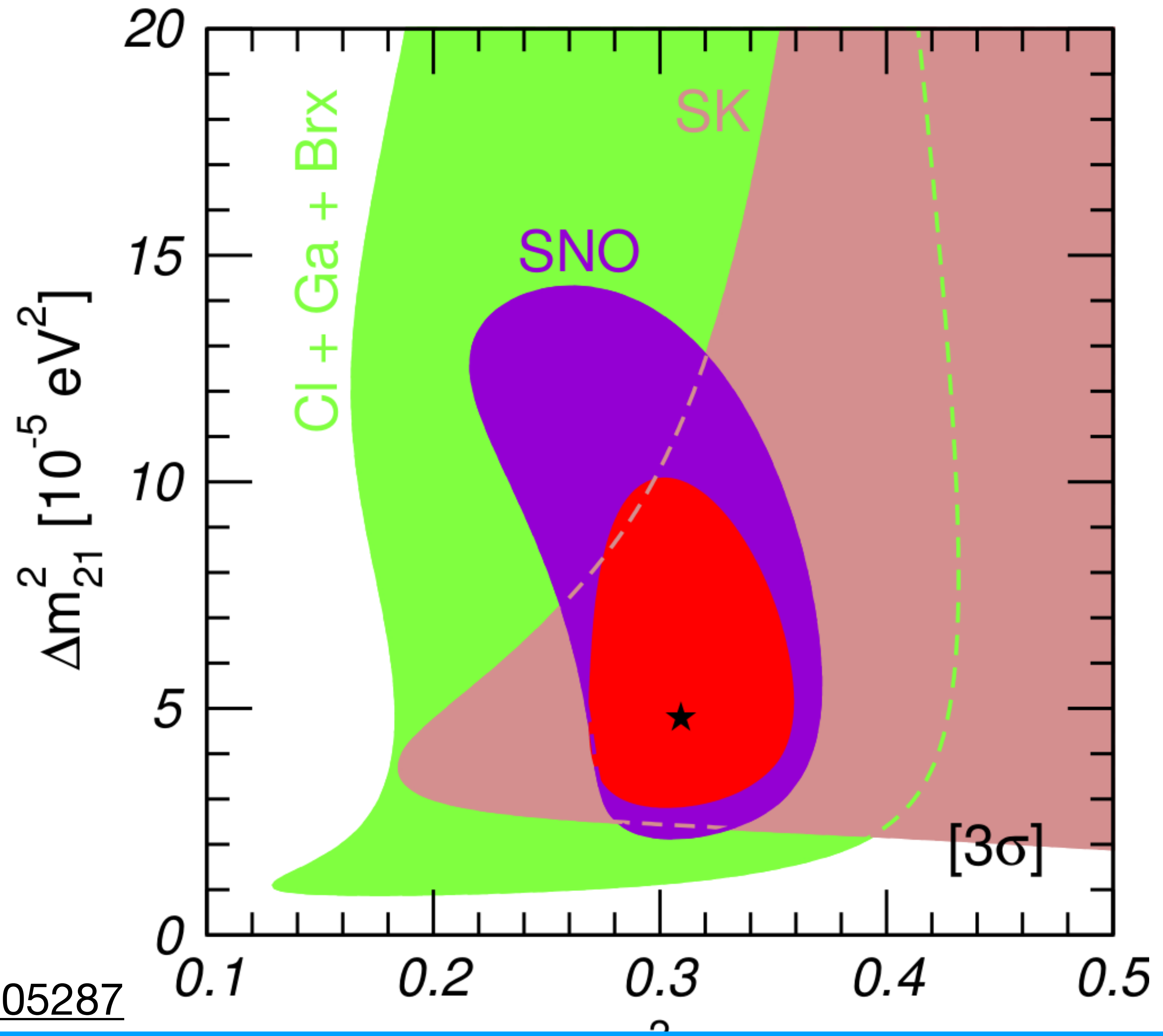
Survival probability for neutrinos from dense solar regions

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

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



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

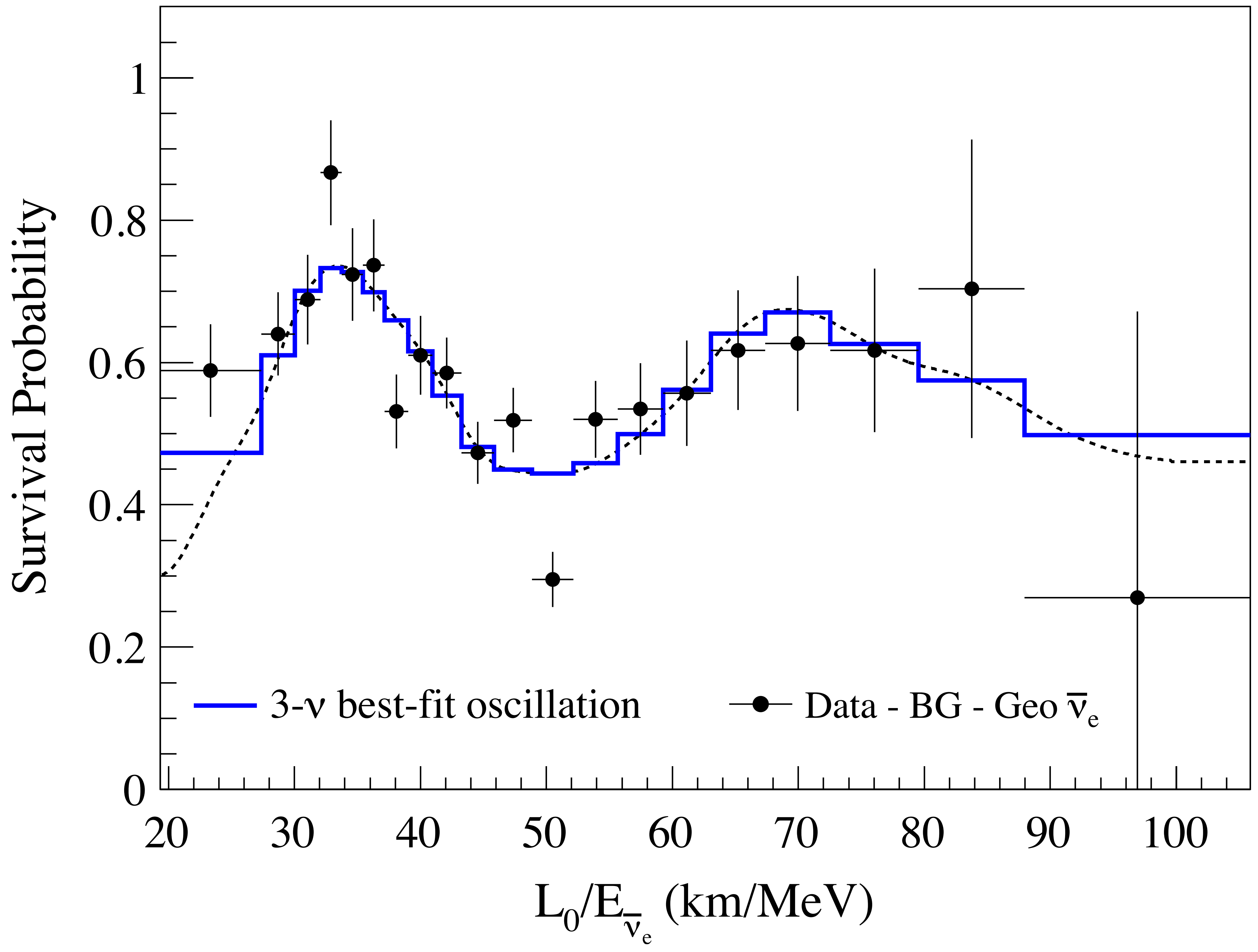


Maltoni and Smirnov, EPJA 52 (2016) arXiv:1507.05287

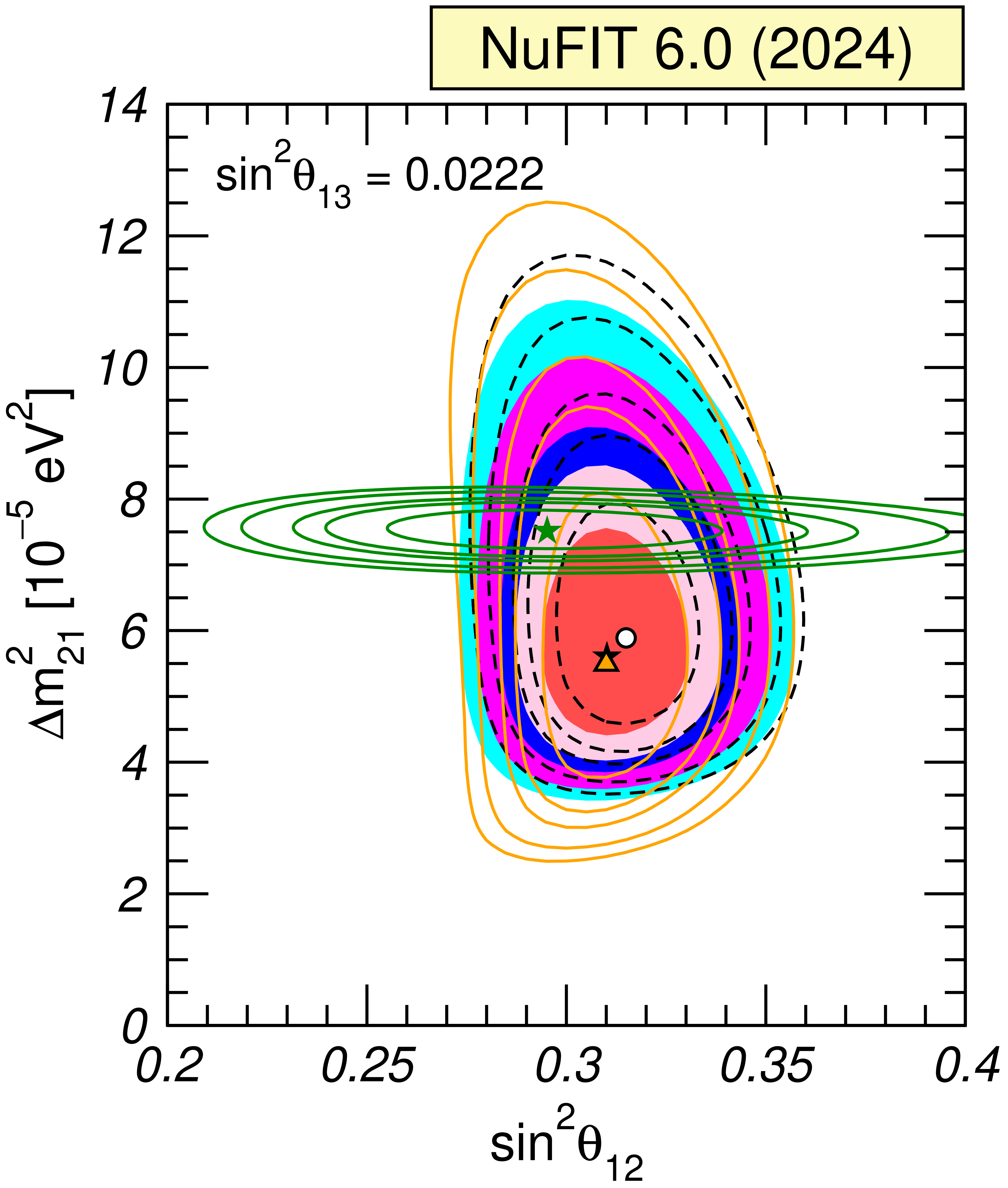
Solar Neutrinos: KamLAND

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

- Baseline ~ 180 km
- $\overline{\nu_e}$ with $E_\nu \sim$ few MeV



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

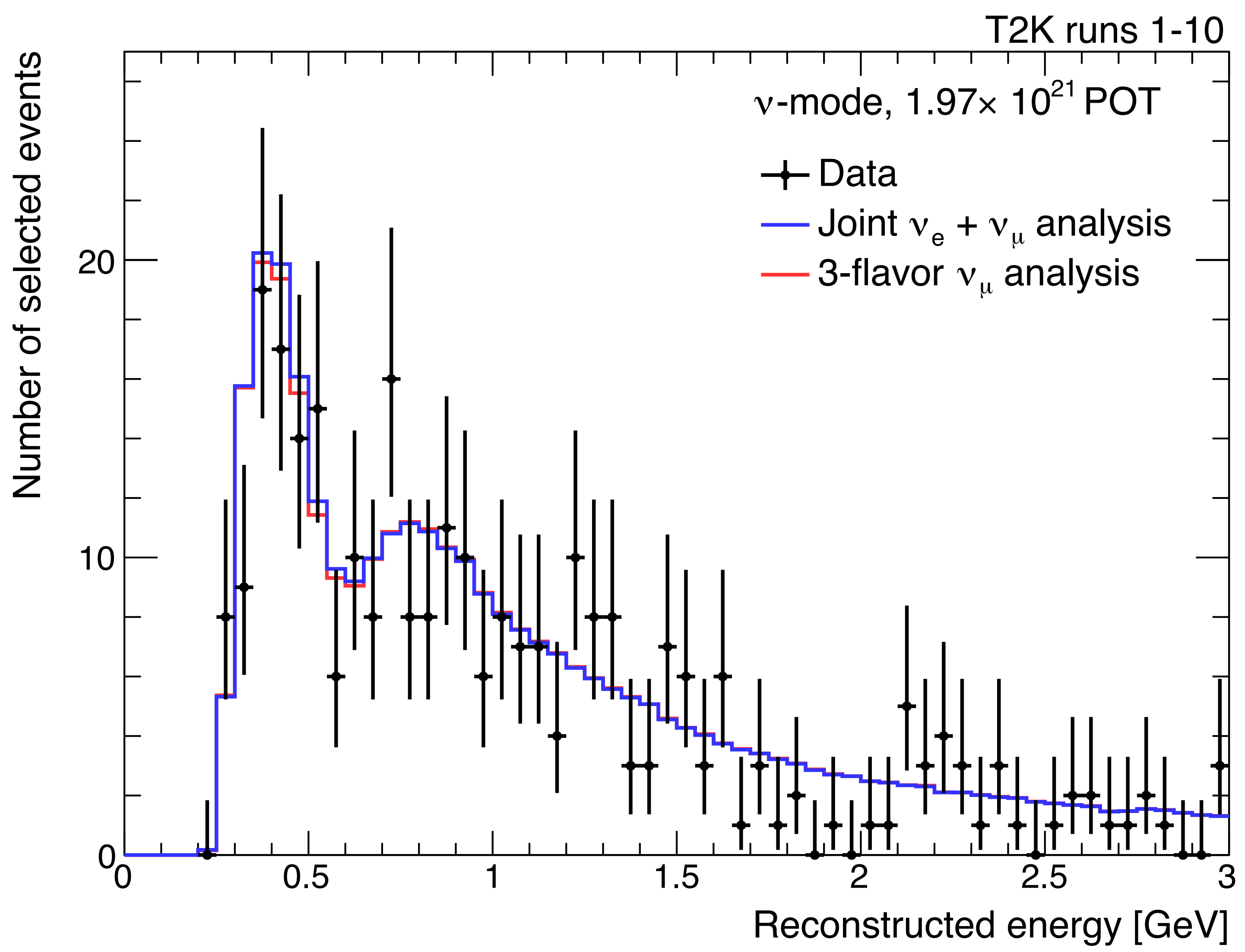


I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

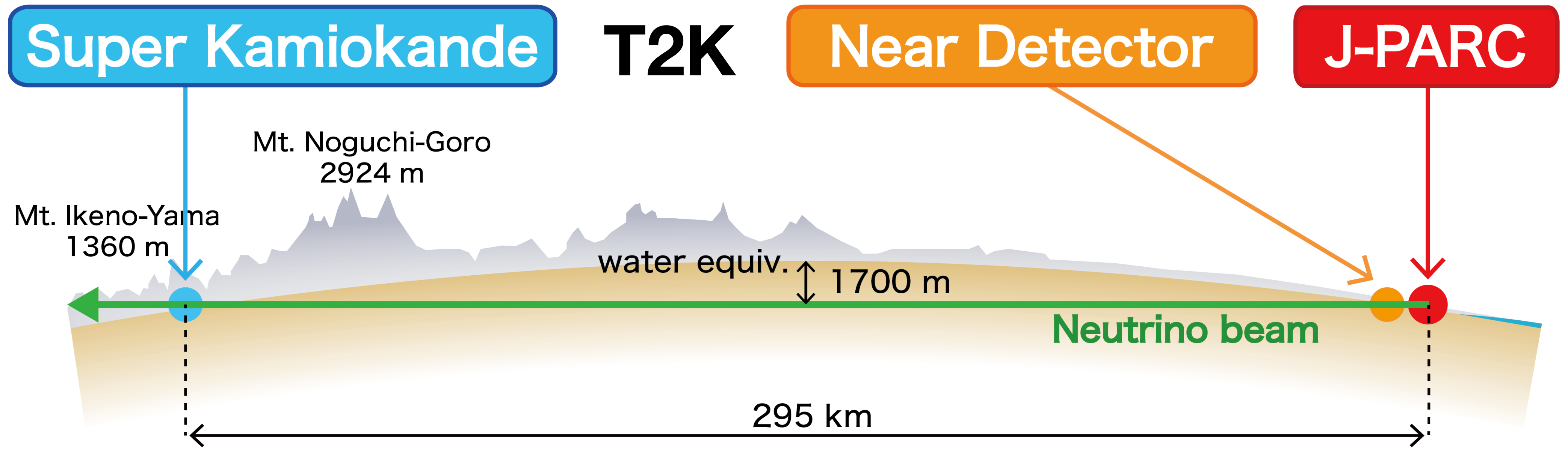
Long-Baseline Accelerators

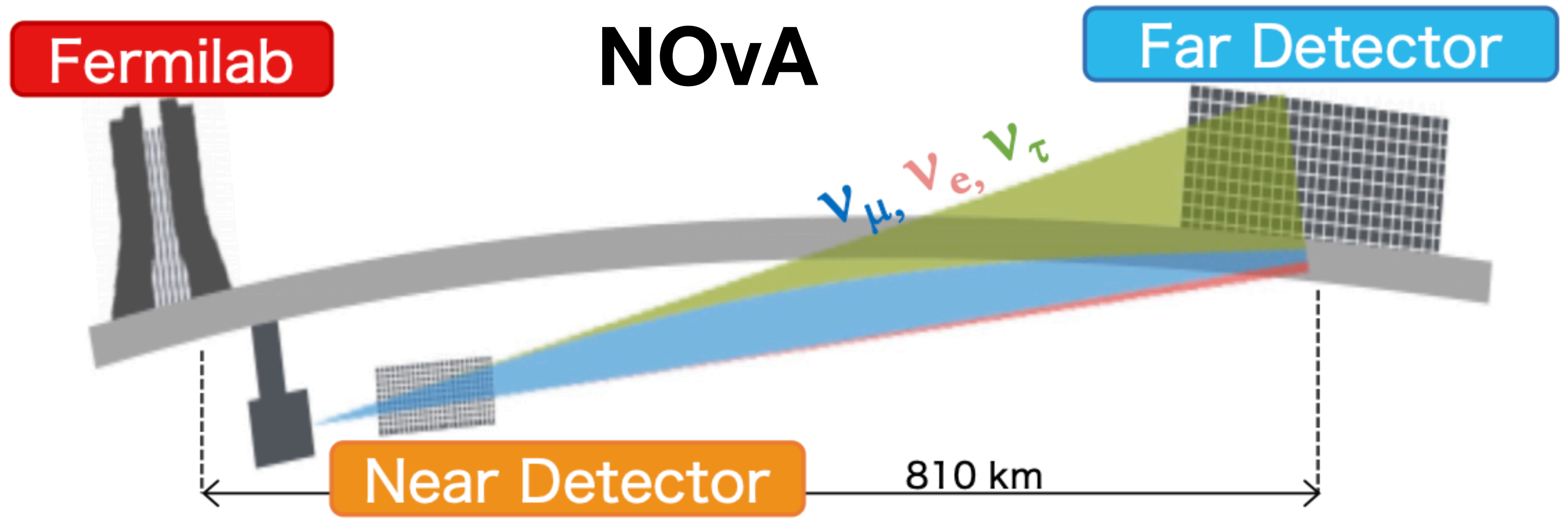
Neutrinos are generated from **pion/kaon decays** caused by an accelerated proton beam hitting a target.

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





Long-Baseline Accelerators

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

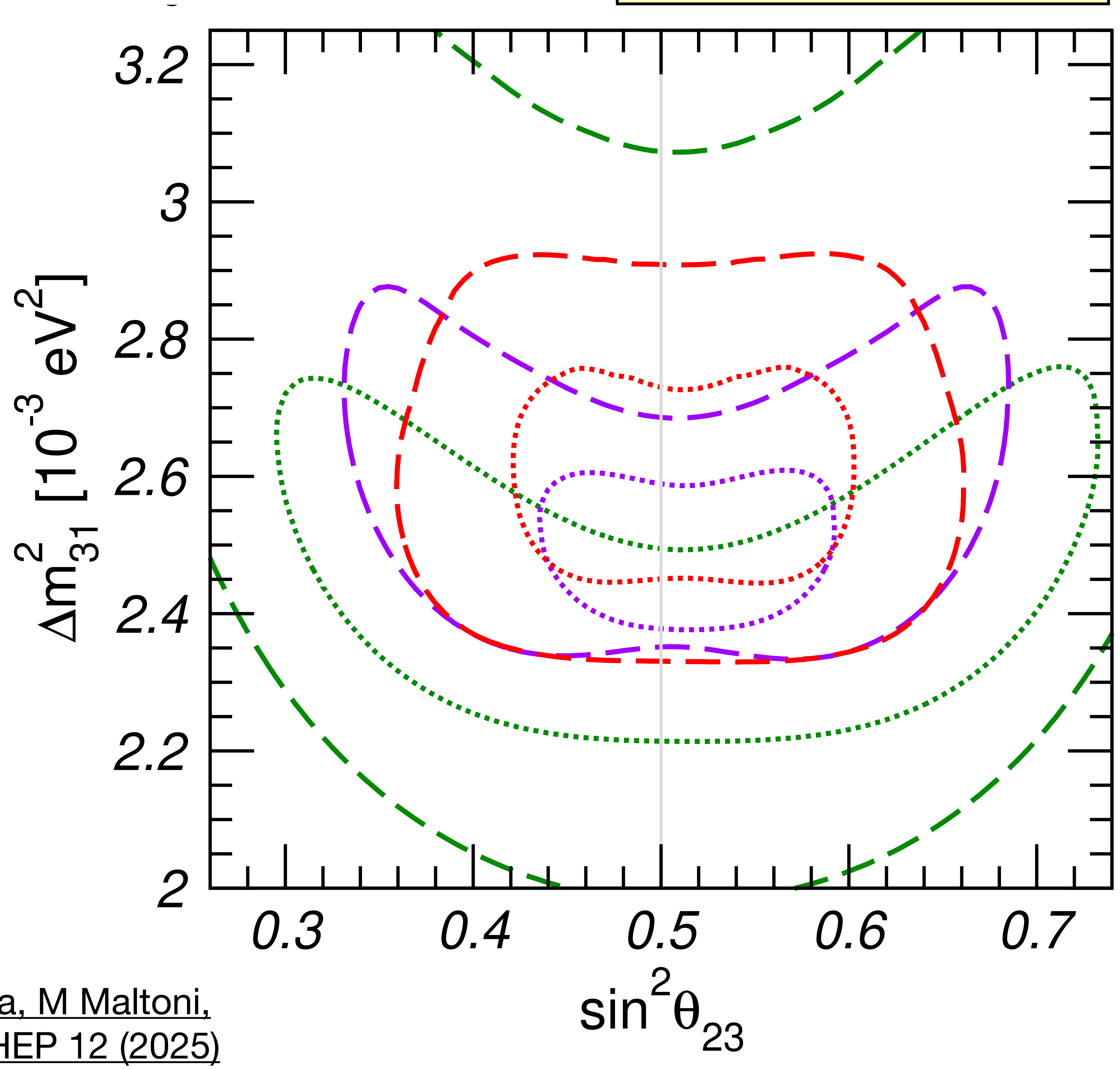
$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E}$$

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

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

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)

Long-Baseline Accelerators

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

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

The appearance channel allows the measurement:

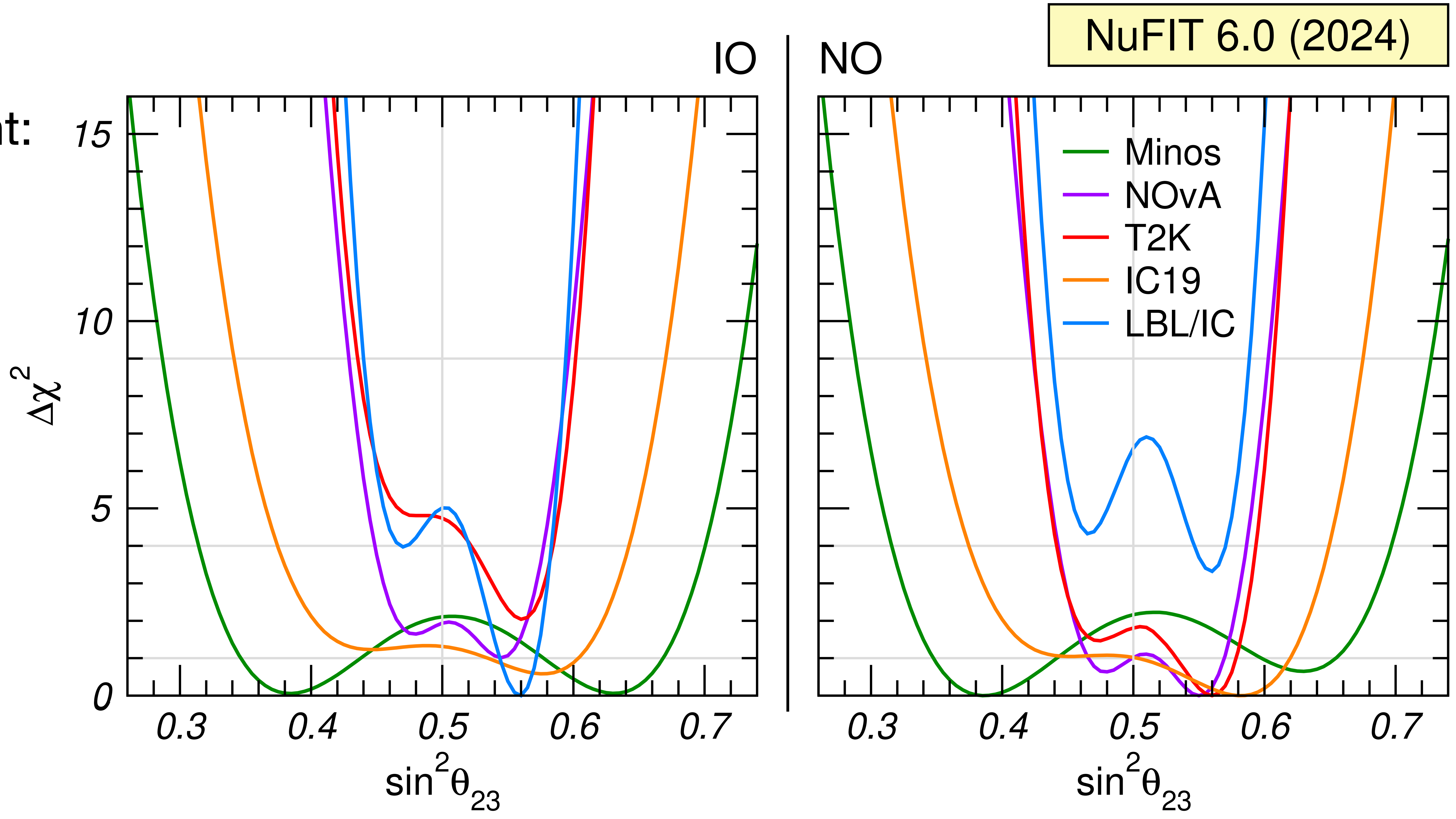
- Mass ordering
- Octant of θ_{23}
- The CP phase
- θ_{13}

$$C = \frac{\Delta m^2_{21} L}{4E} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$o = sign(\Delta m^2_{31})$$

$$A = |2EV/\Delta m^2_{31}|$$

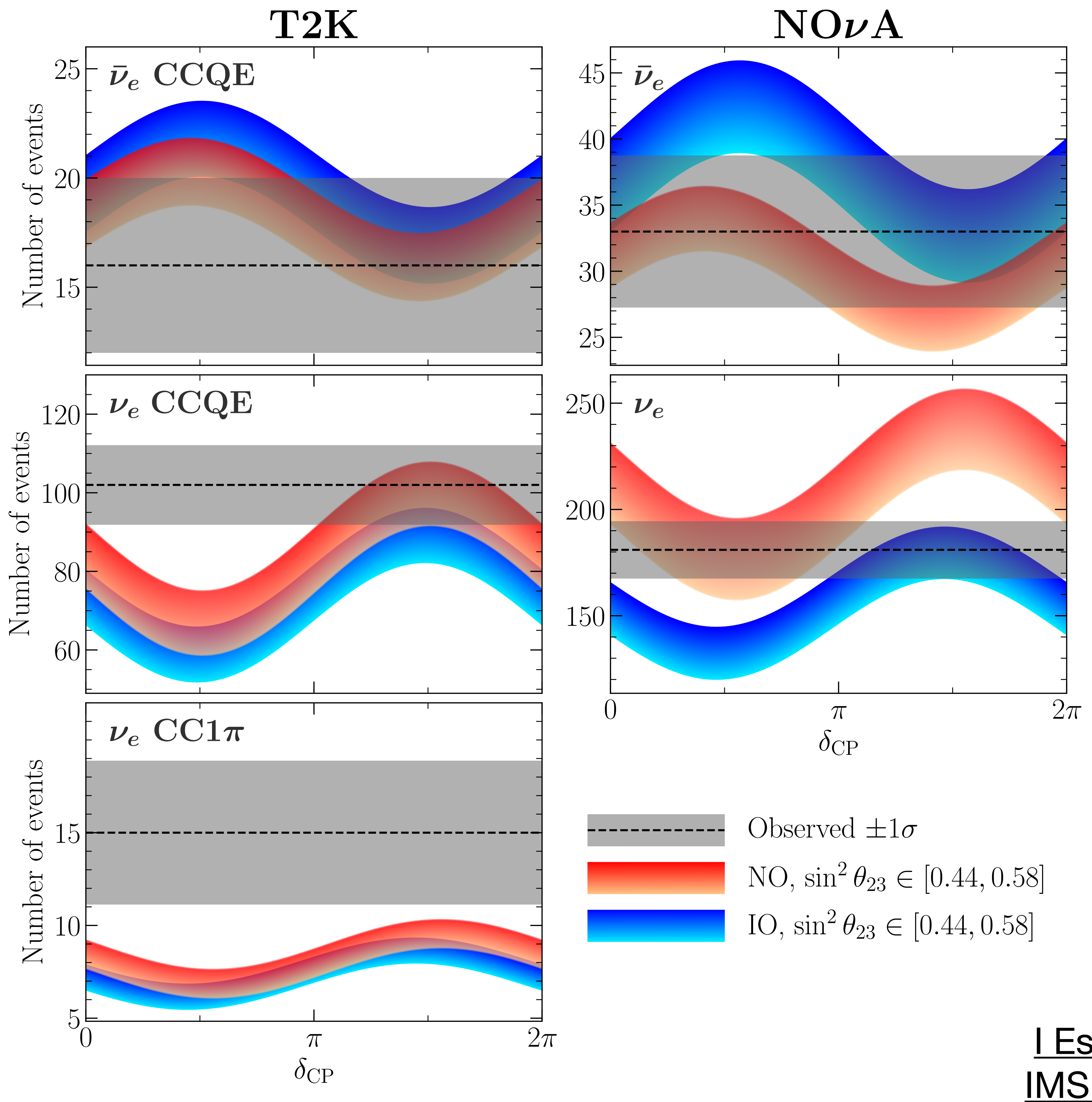
Preference for the **higher-octant and IO**

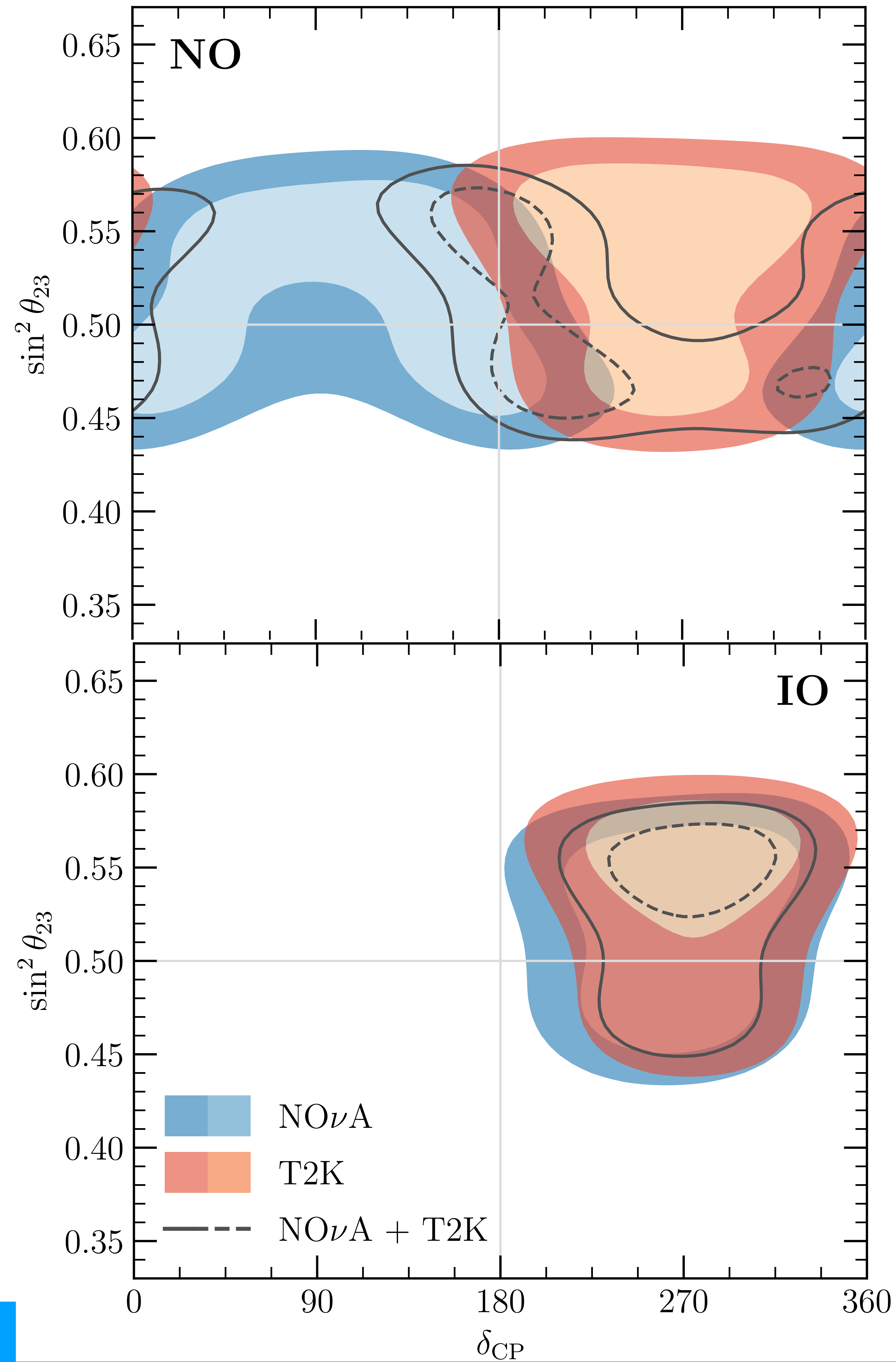


I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

T2K vs NOvA

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

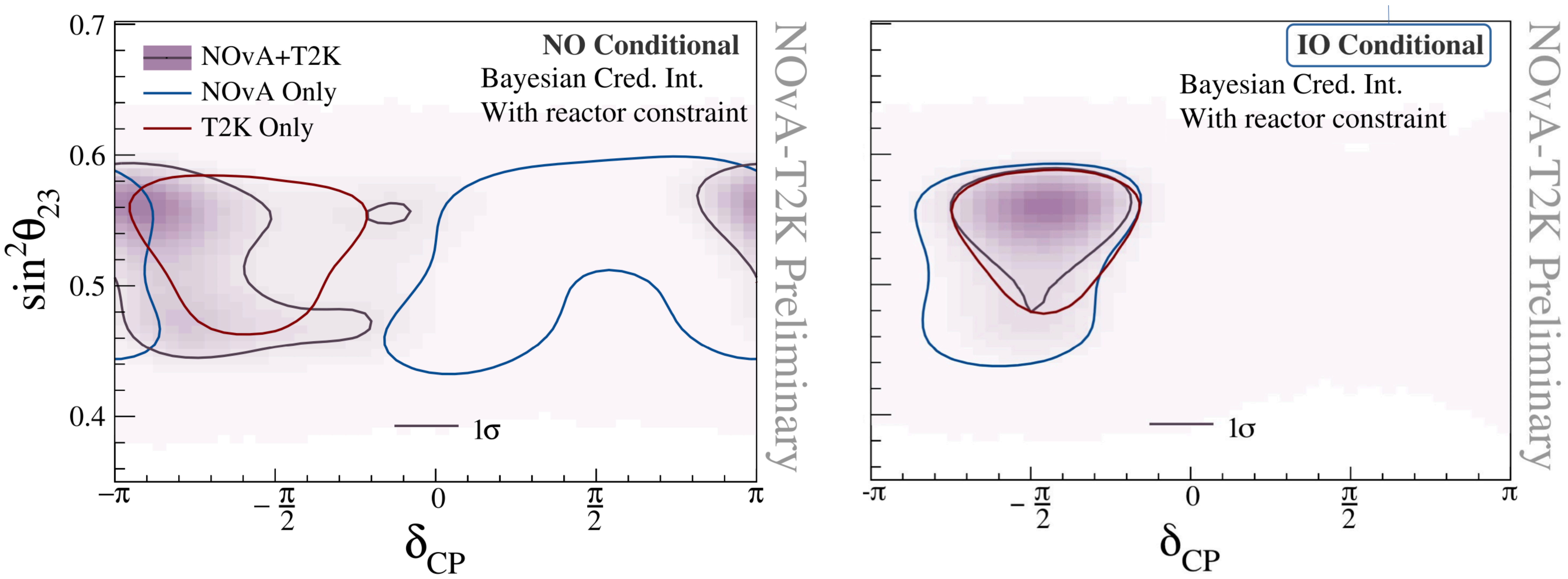




I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

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

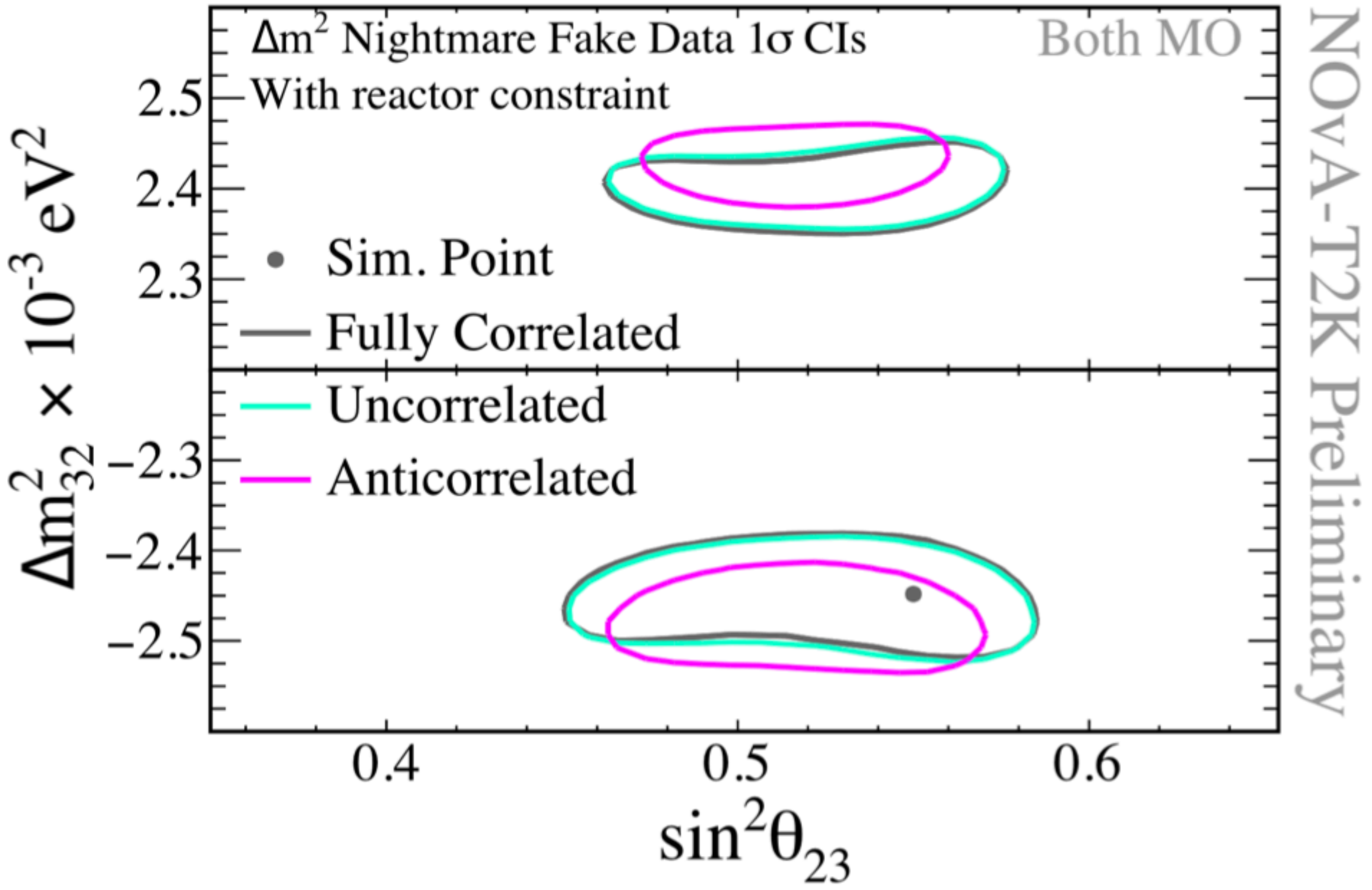
Jeremy Wolcott (Neutrino 2024)

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.

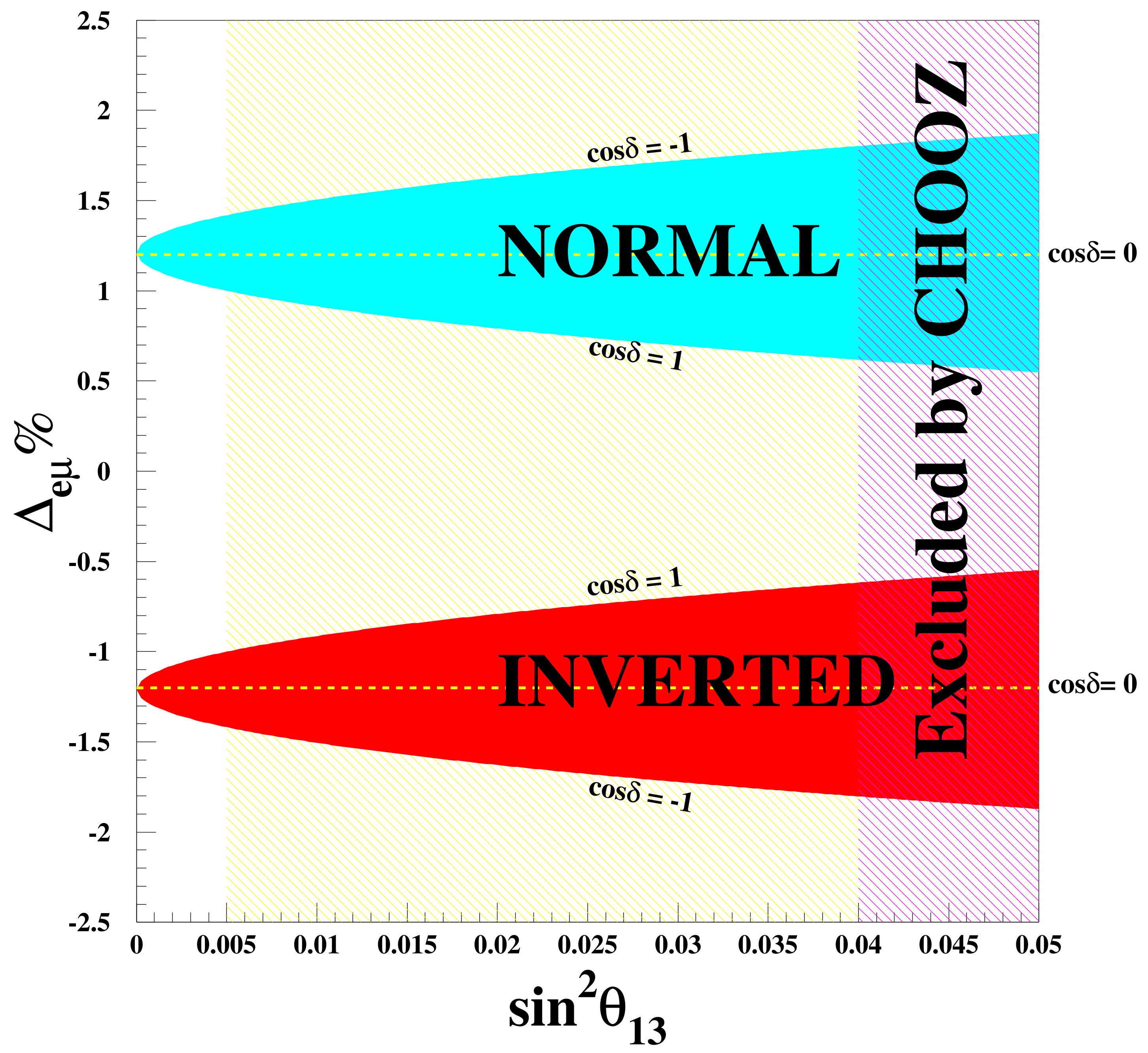


Zoya Vallari (Joint Experimental-Theoretical Physics Seminar, Fermilab, 2024)

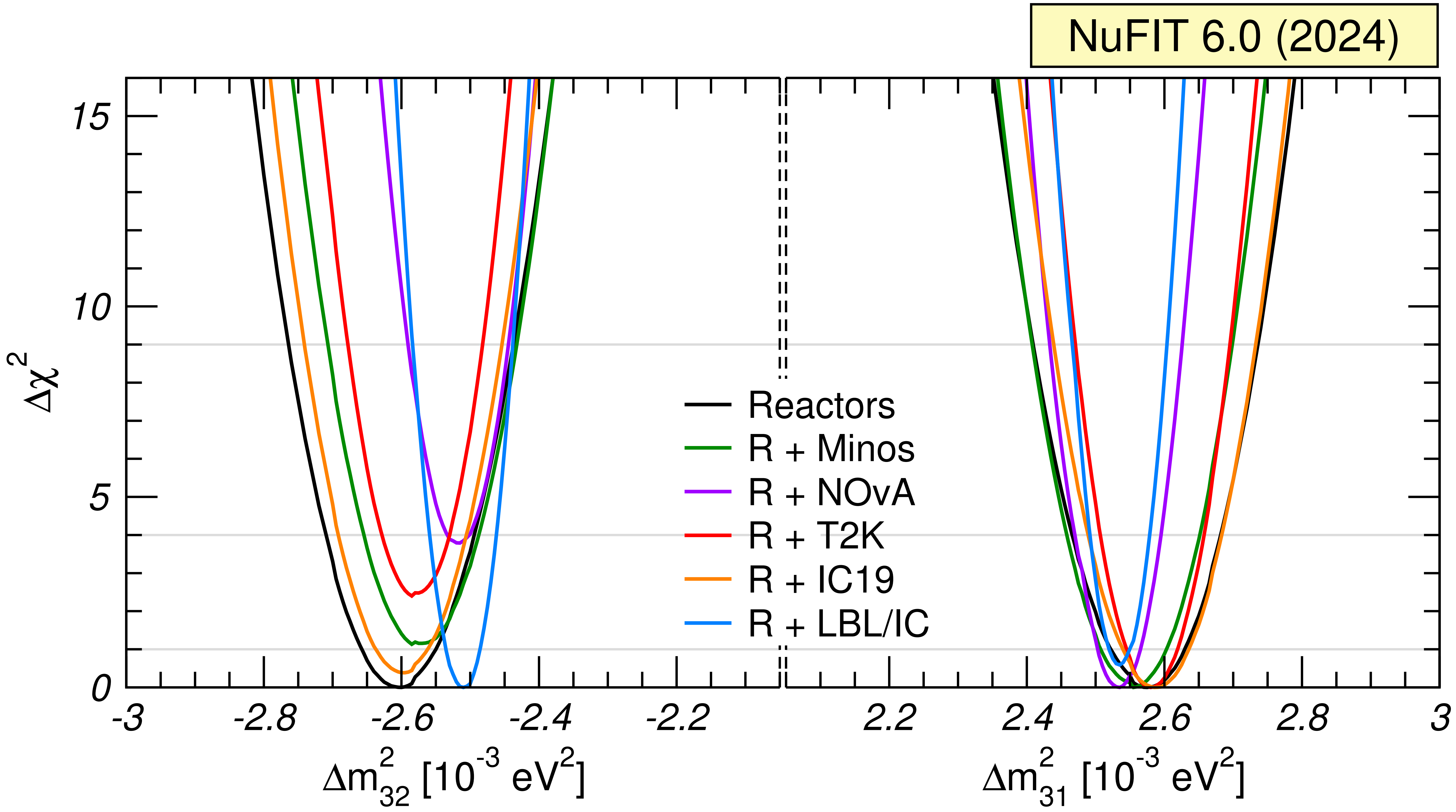
LBL+Reactors

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



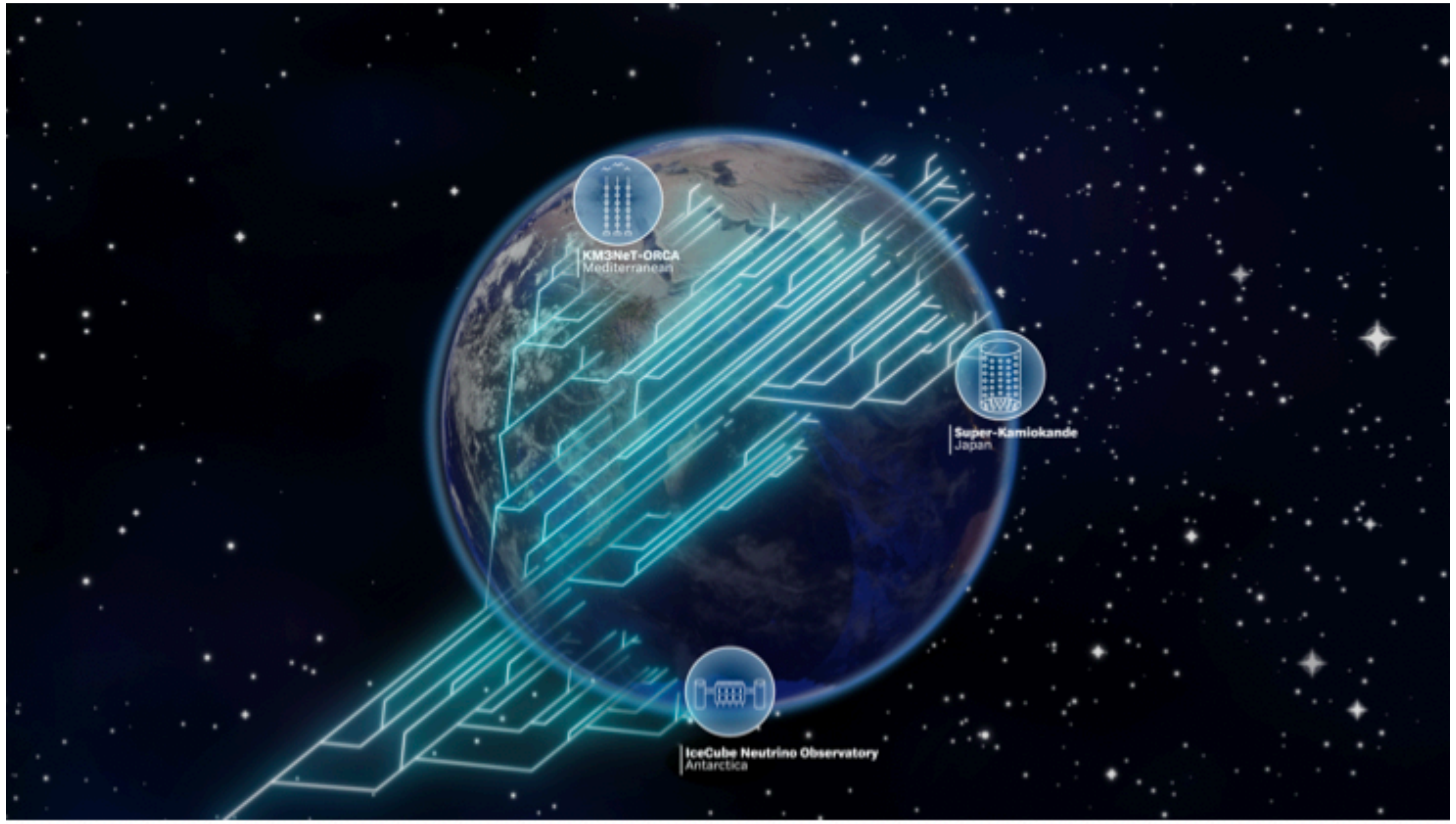
$$\Delta_{e\mu} = (\Delta m^2_{ee} - \Delta m^2_{\mu\mu})/\Delta m^2$$

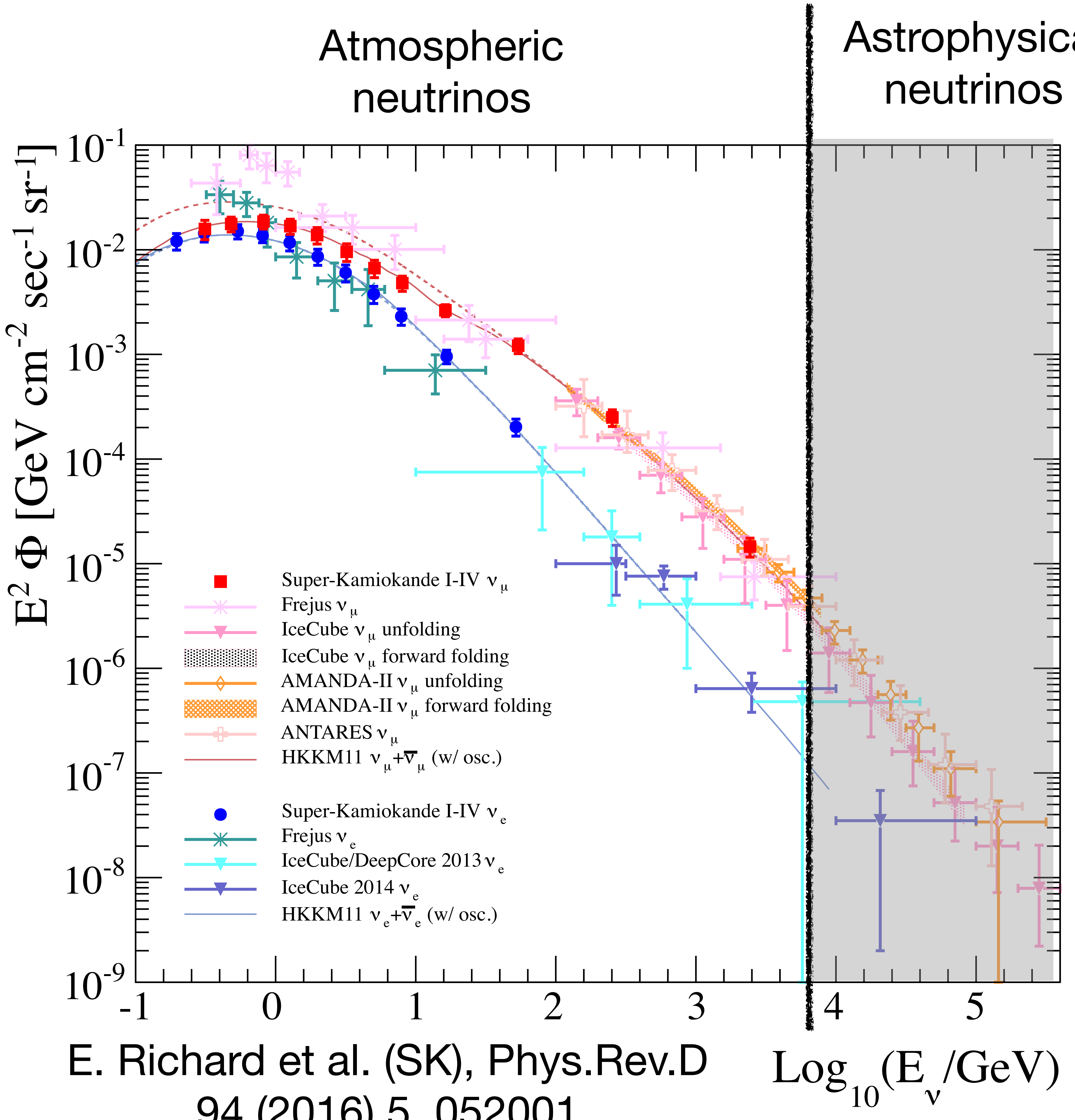
I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

How can atmospheric neutrinos contribute?

Atmospheric Neutrinos

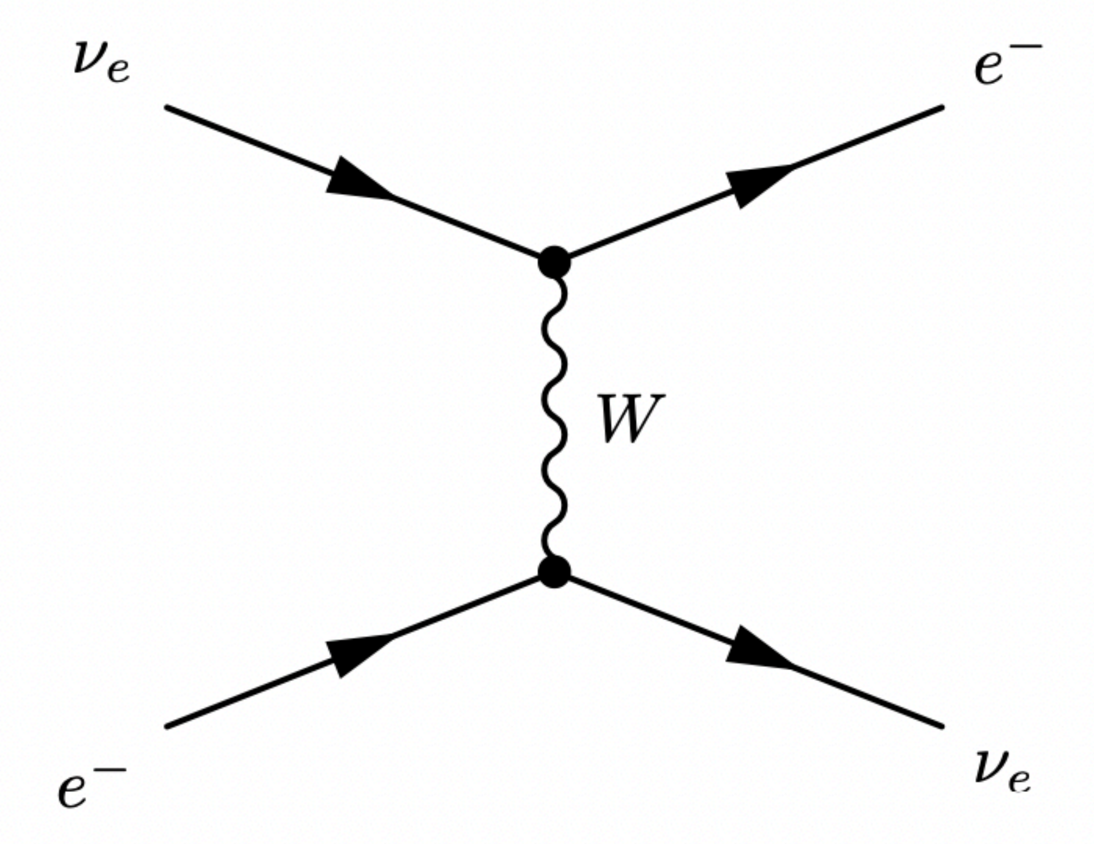
Atmospheric neutrinos are created in the **collision of cosmic rays** with the atmospheric nuclei





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

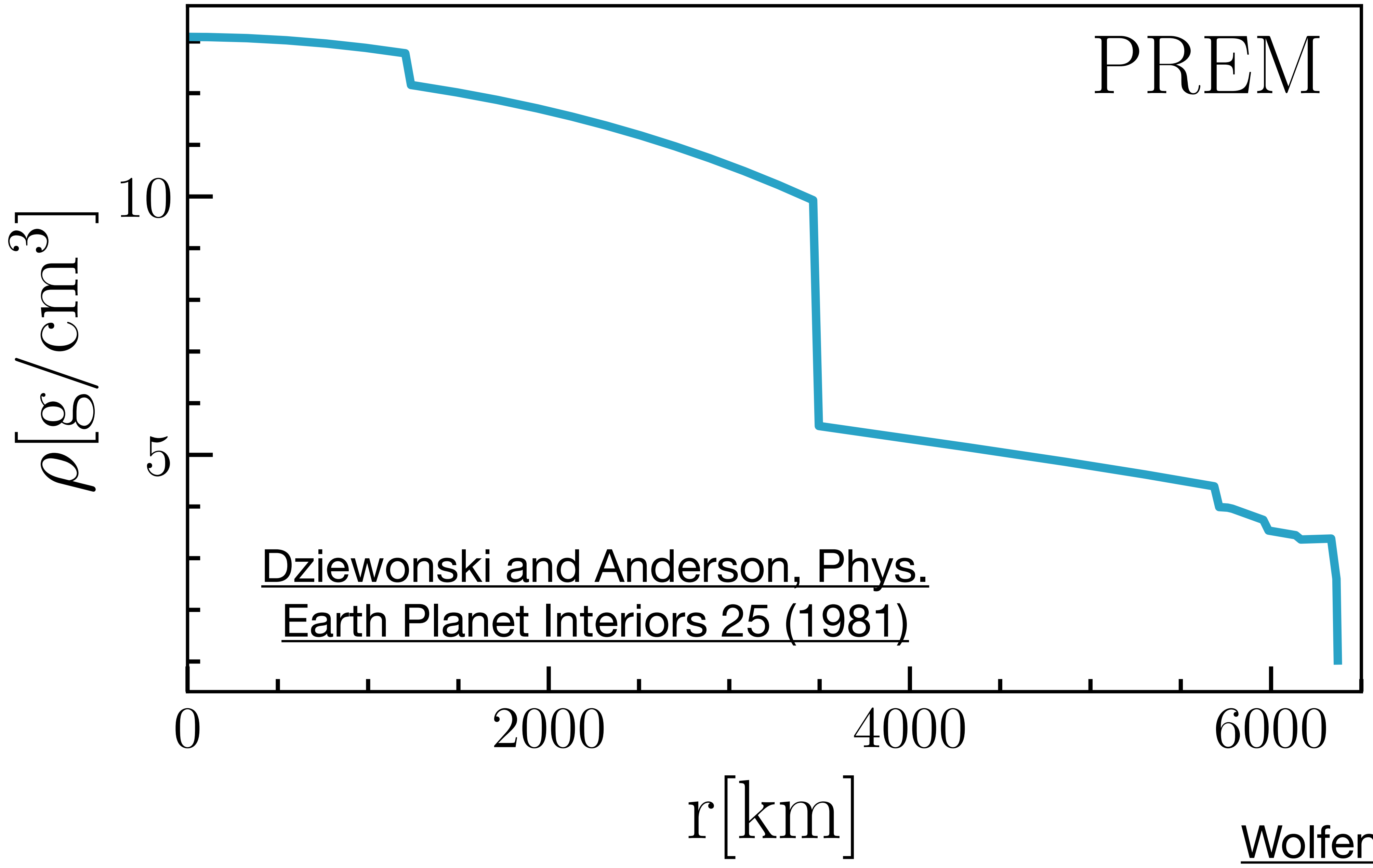
Neutrino Evolution in Matter

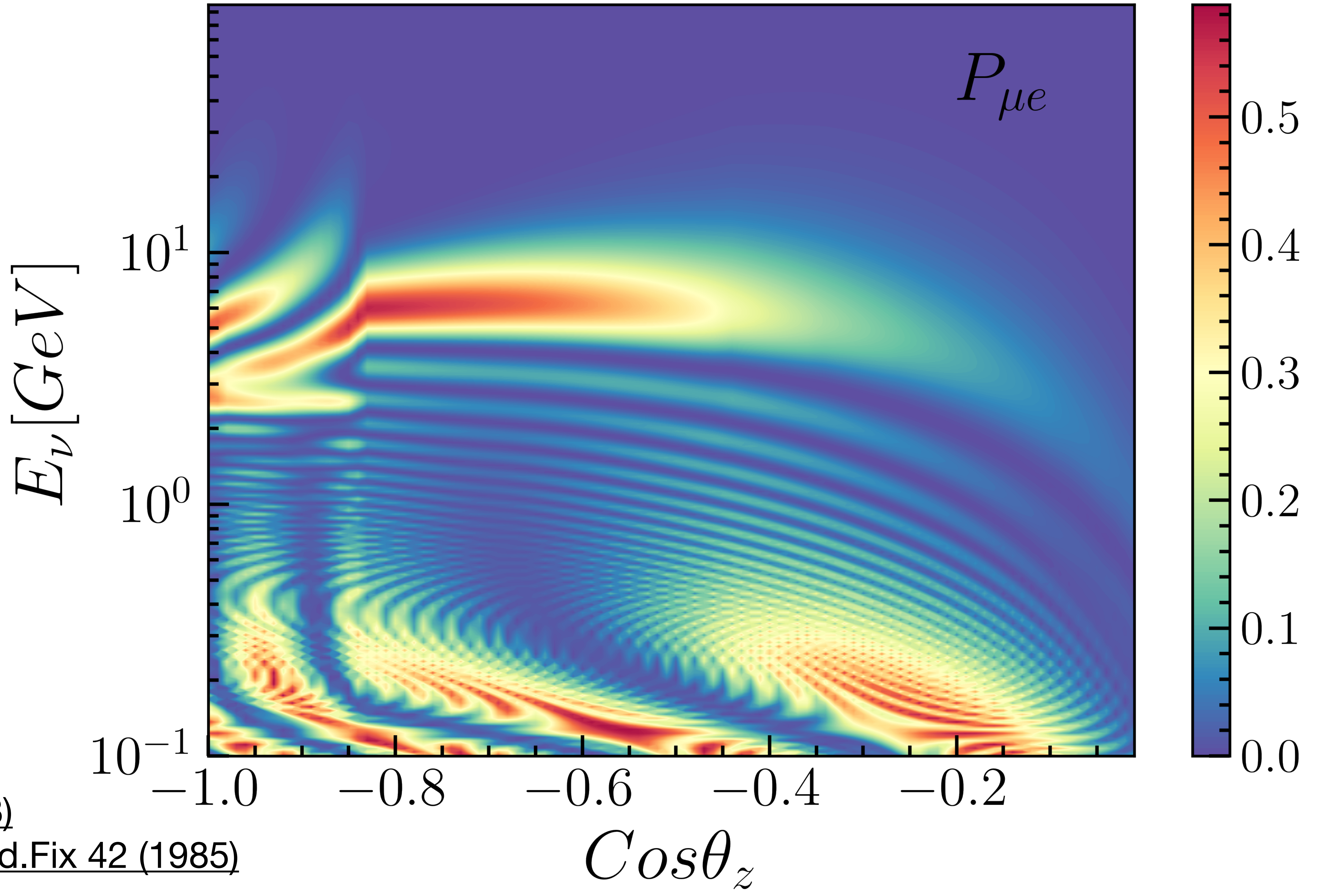


Matter effects play a crucial role in the evolution of atmospheric neutrinos

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

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





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

Sub-GeV

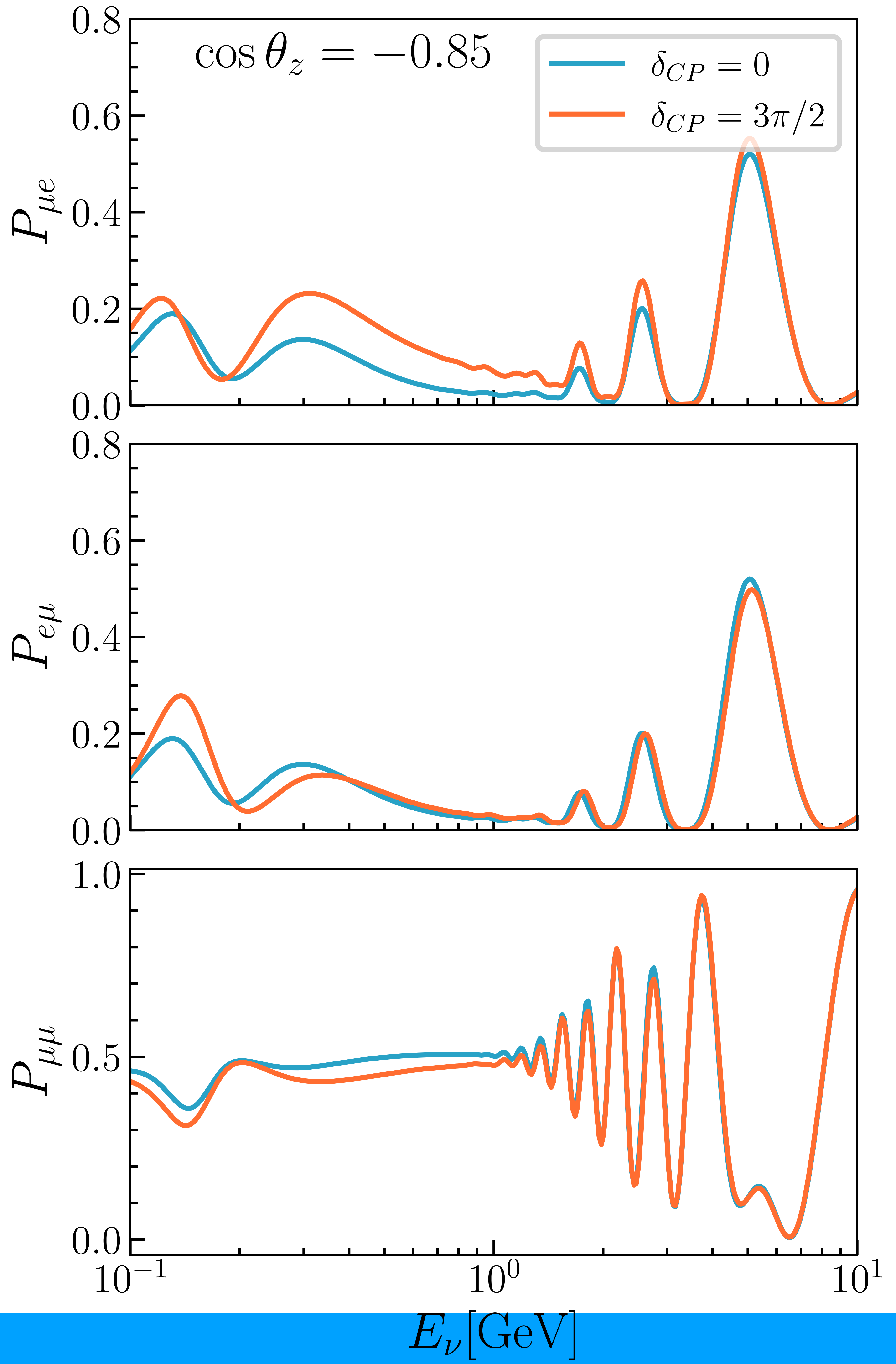
For atmospheric neutrinos, both fluxes are sensitive to δ_{CP}

- 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

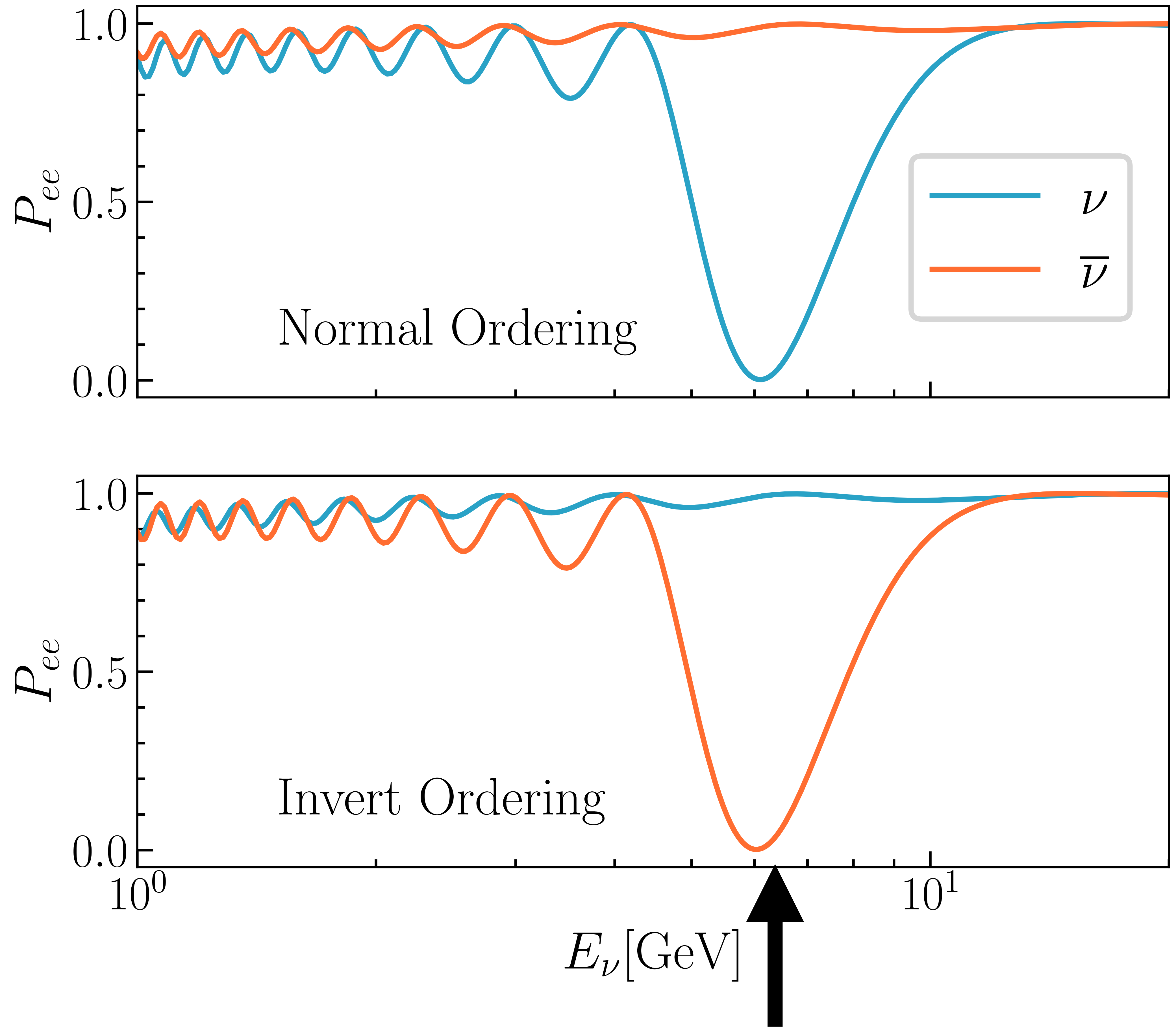
- $P_{\mu\mu}$ contribute to measuring the phase via $\cos\delta_{CP}$



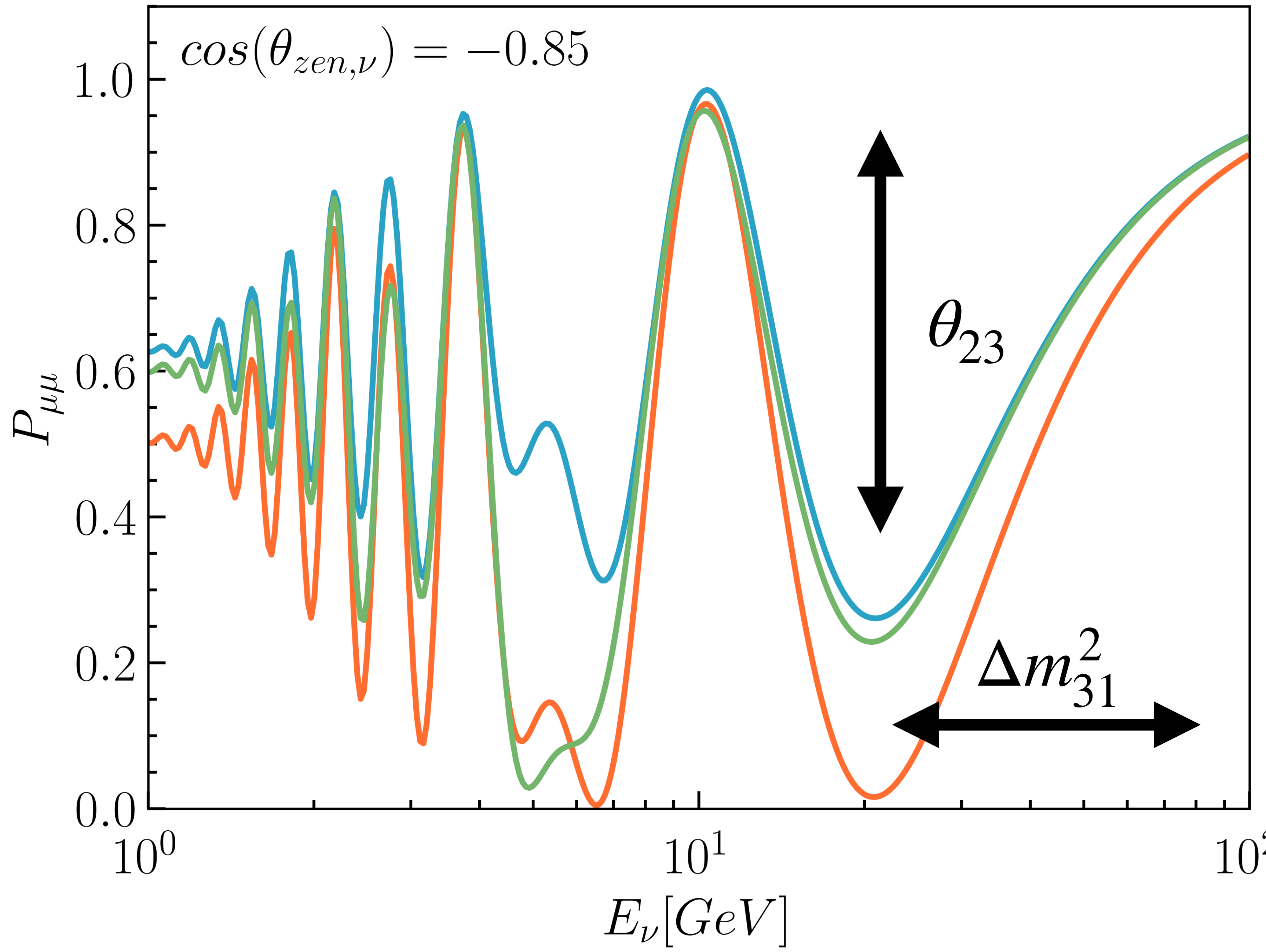
Minakata, Nunokawa, Parke, PLB 537 (2002) Minakata, Nunokawa, Parke, PRD 66 (2002)
Denton and Parke, PRD 109 (2024)

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)

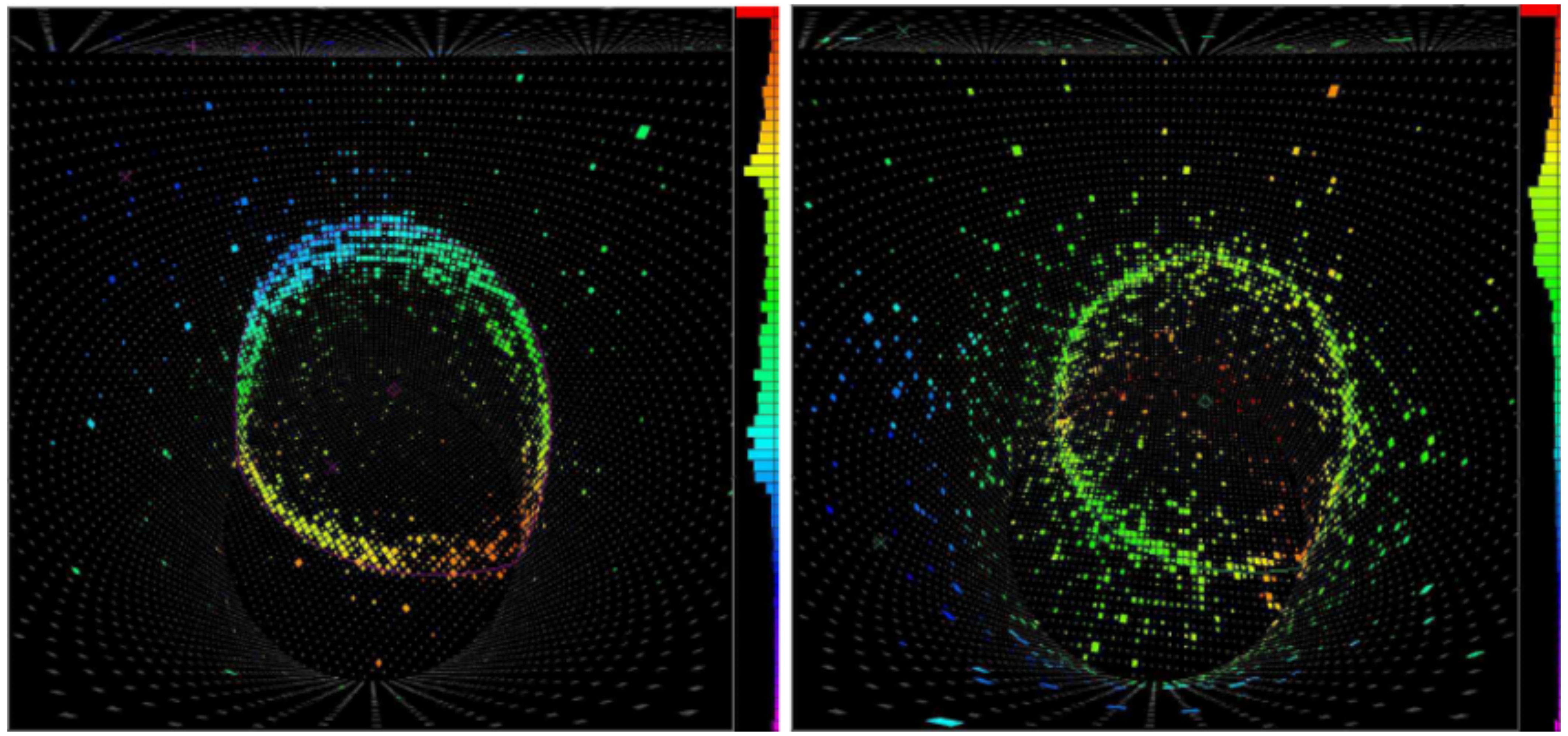
Akhmedov, Maltoni and Smirnov, JHEP 05 (2007)

Super-Kamiokande

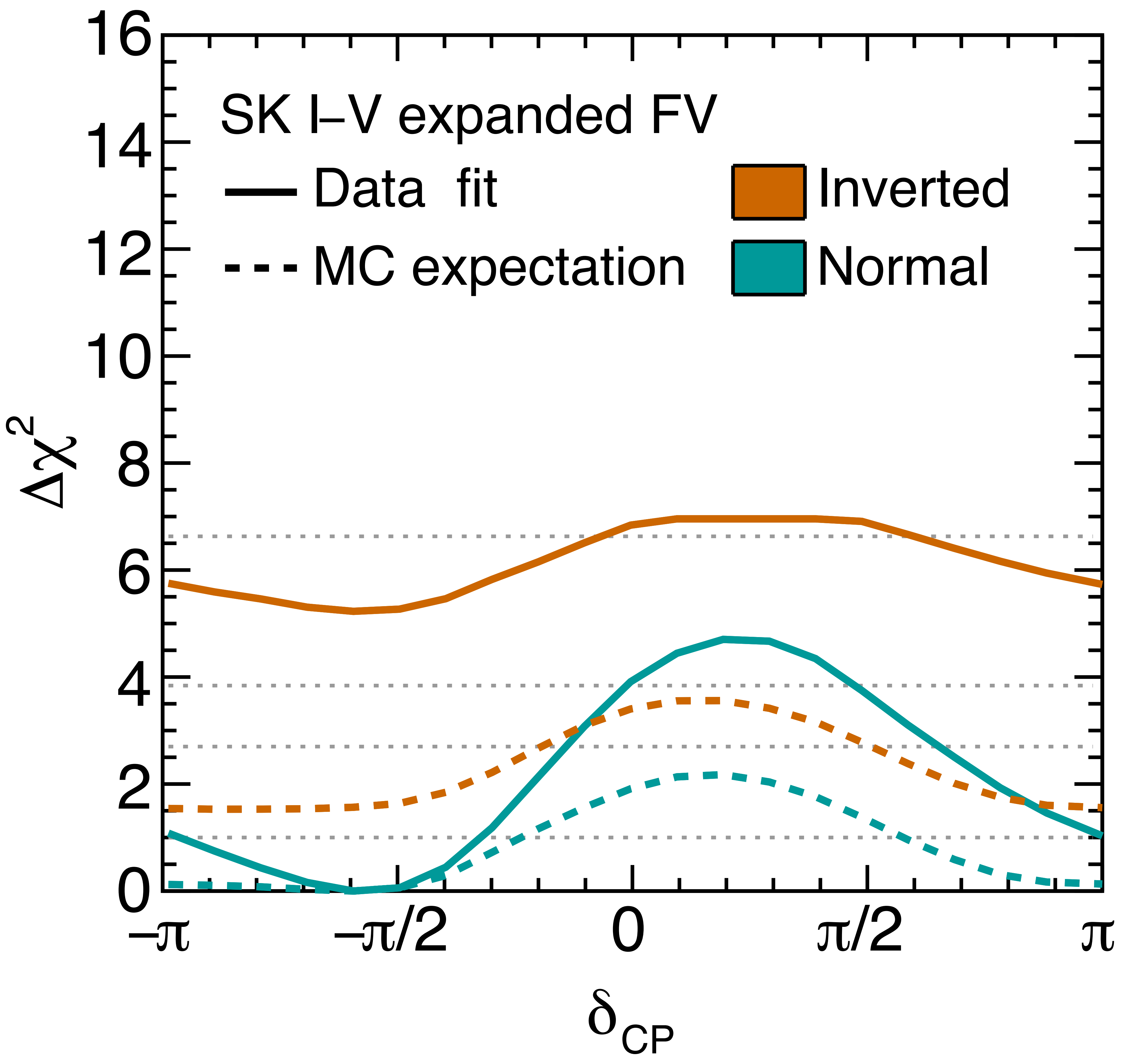
Several experiments have measured the atmospheric neutrino flux, with **SK** starting from the **sub-GeV scale**.

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)

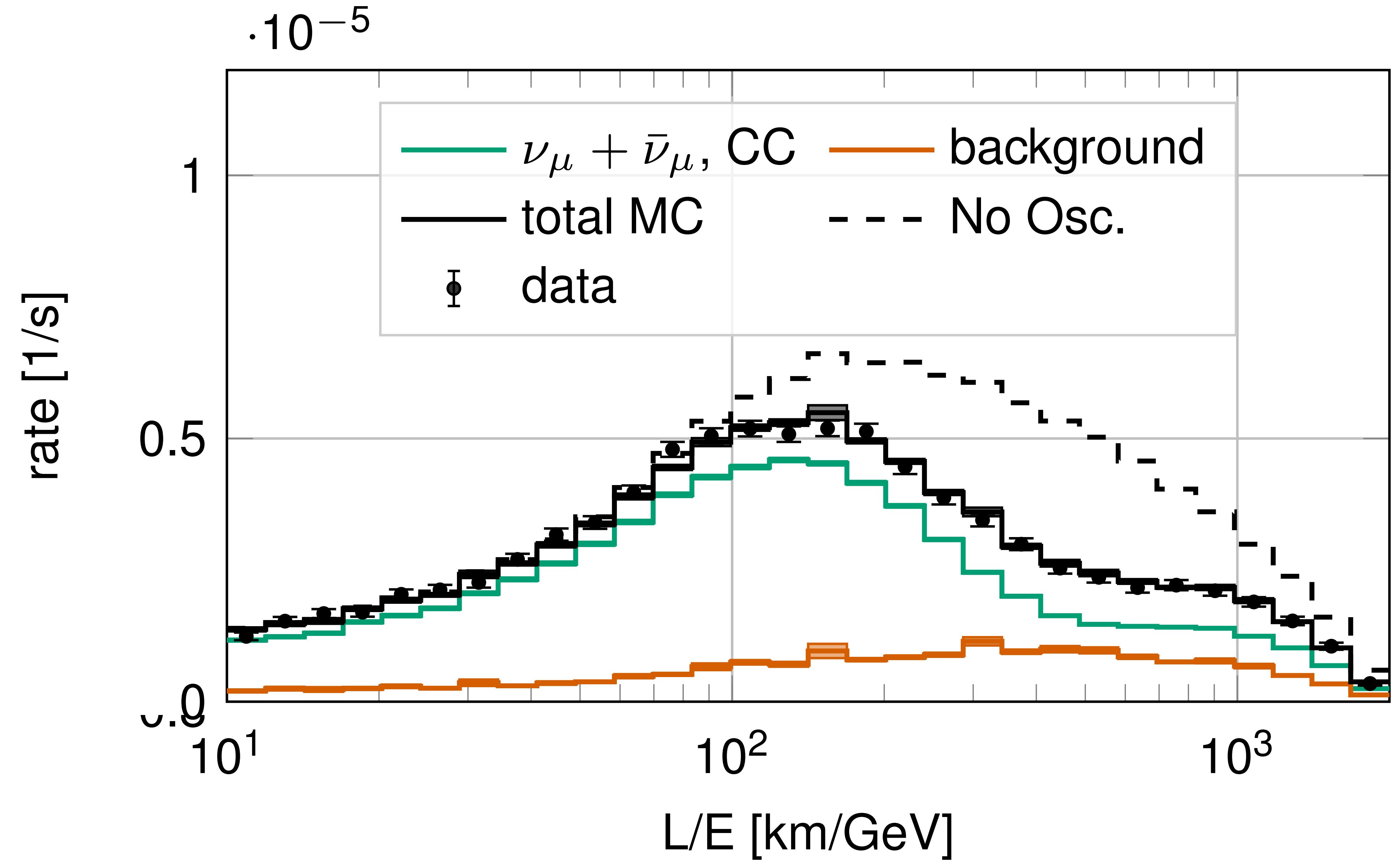


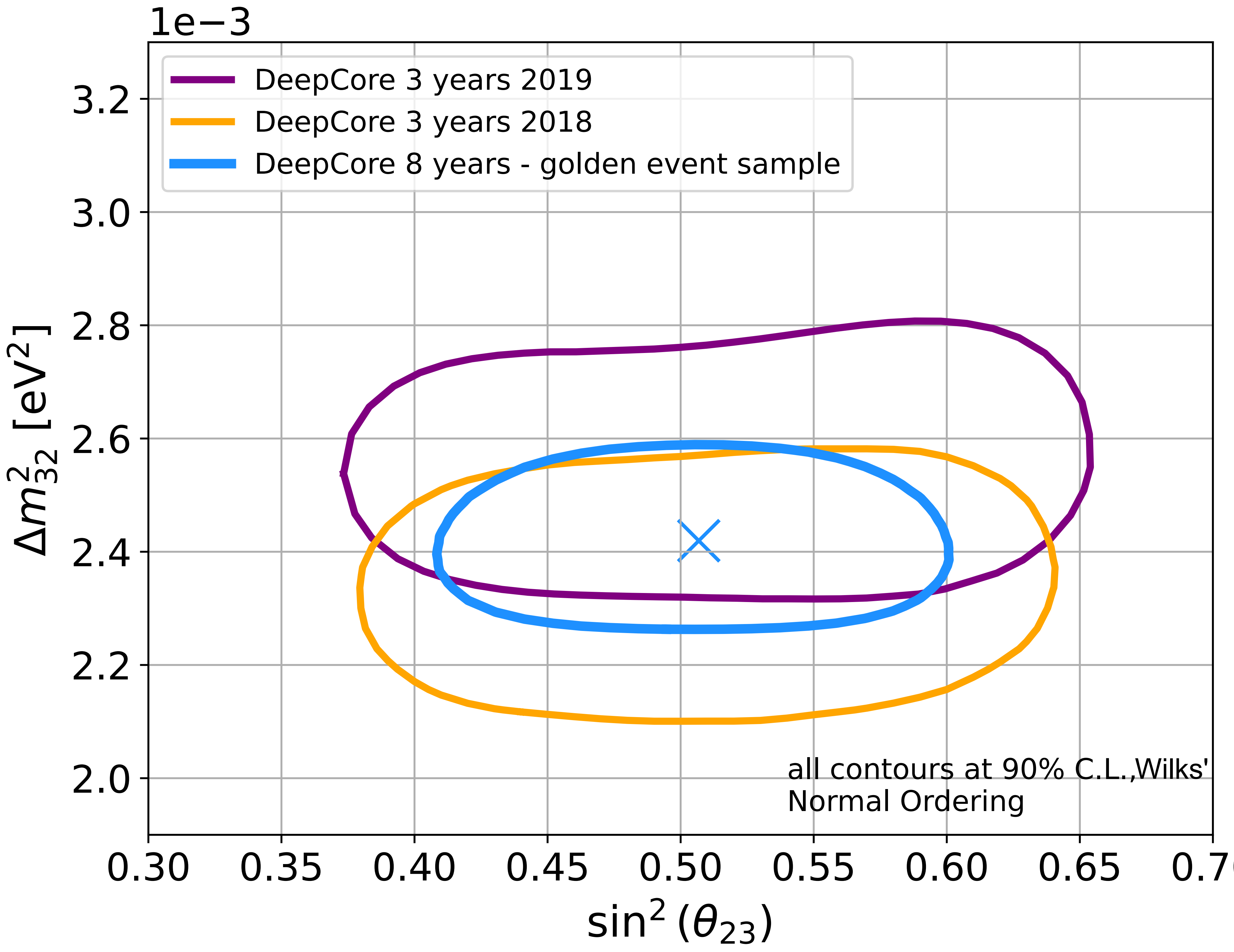
Wester et al. (Super-Kamiokande), arXiv: 2311.05105

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



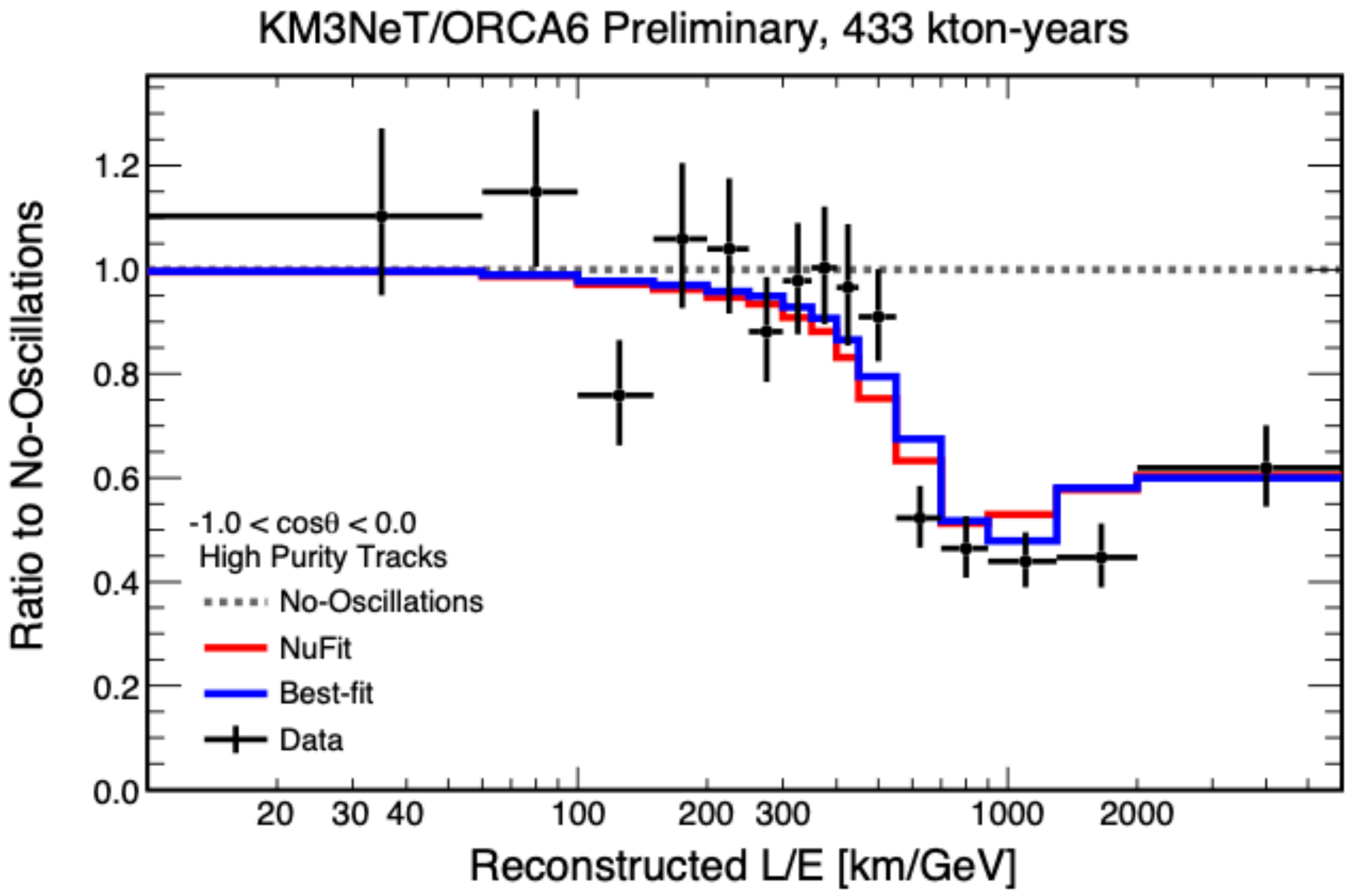


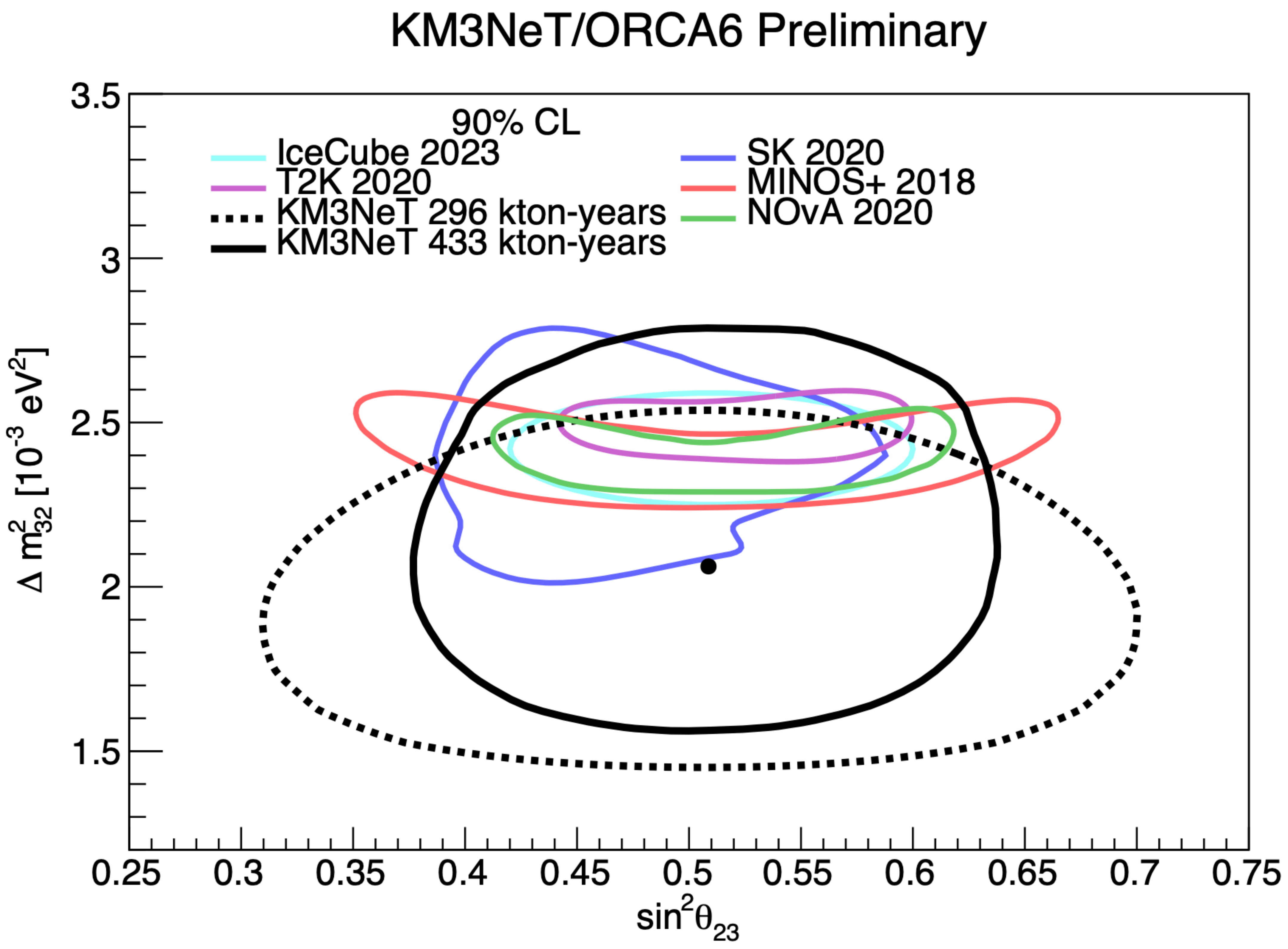
Abbasi et al. (IceCube), PRD 108 (2023)
Abbasi et al. (IceCube), arXiv: 2405.02163

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



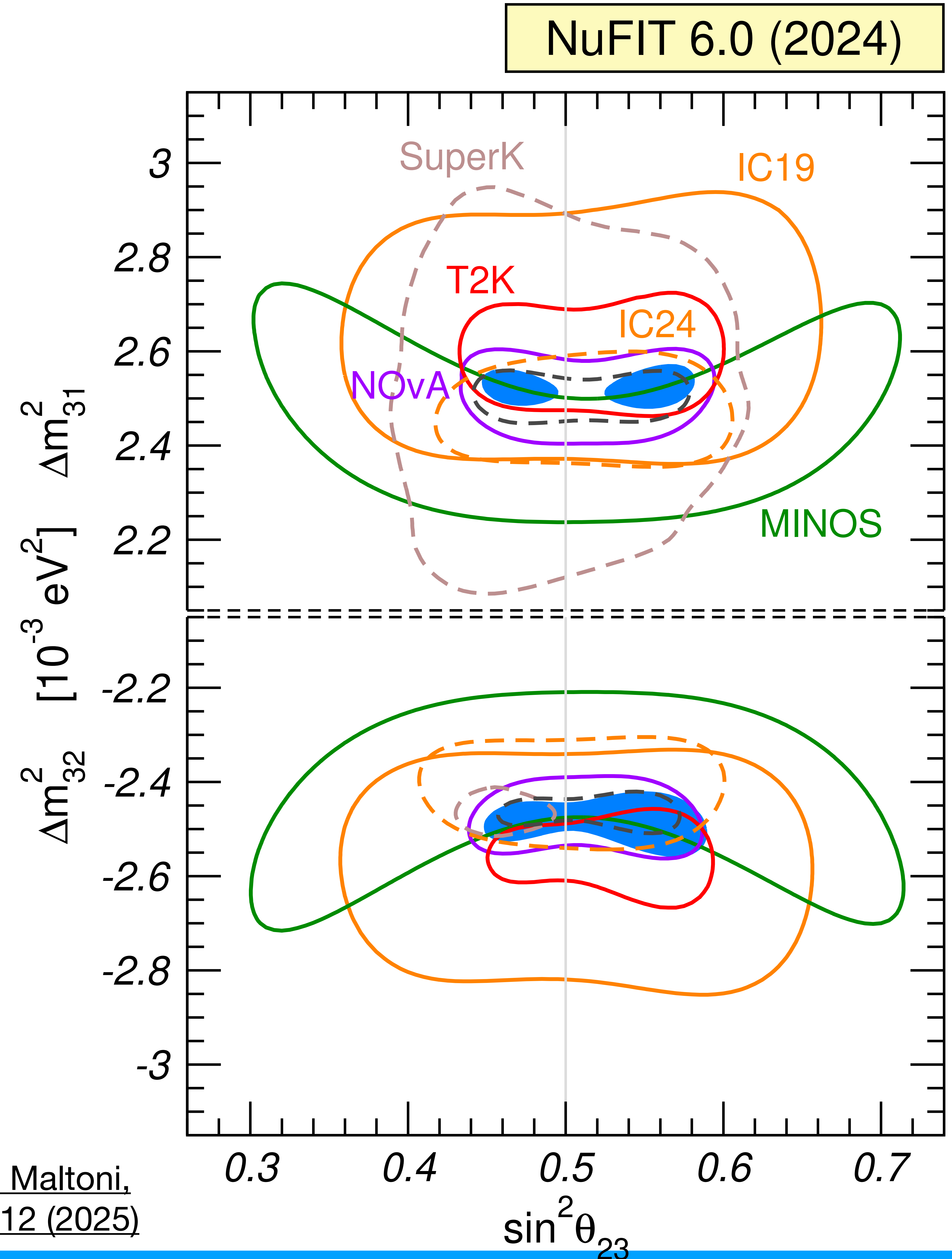


Carretero et al. (KM3NeT), PoS ICRC2023
Aiello (KM3NeT), EPJC 82, 26 (2022)

Atmospheric Mass-Squared Splitting

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

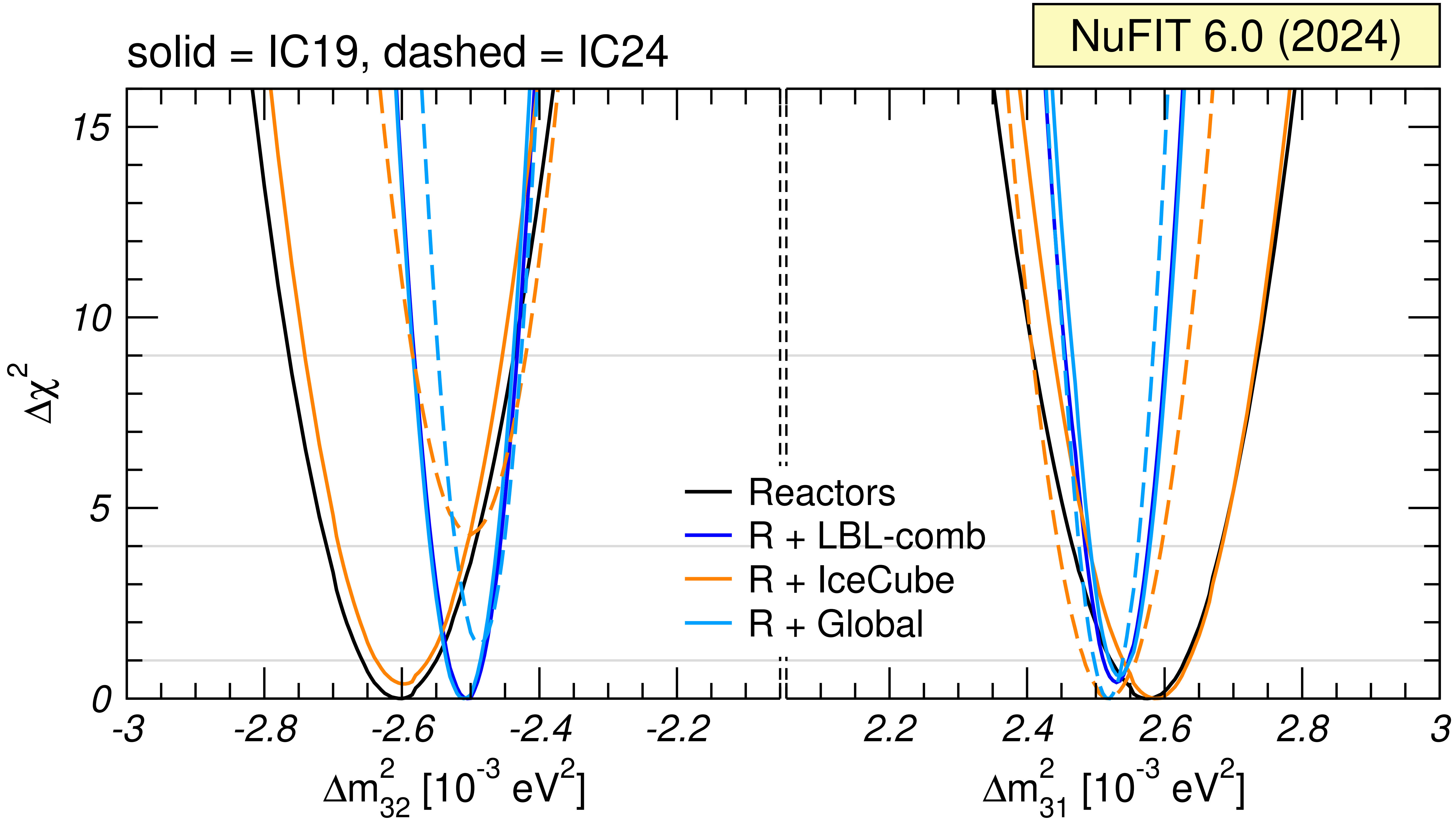
- Colored regions: LBL+IC19
- Black-dashed: LBL+IC24+SK
- Good agreement with **reactor** experiments
- Preference for the higher octant ($\sin^2\theta_{23} = 0.561$)



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 $\Delta\chi^2 \sim 6.1$



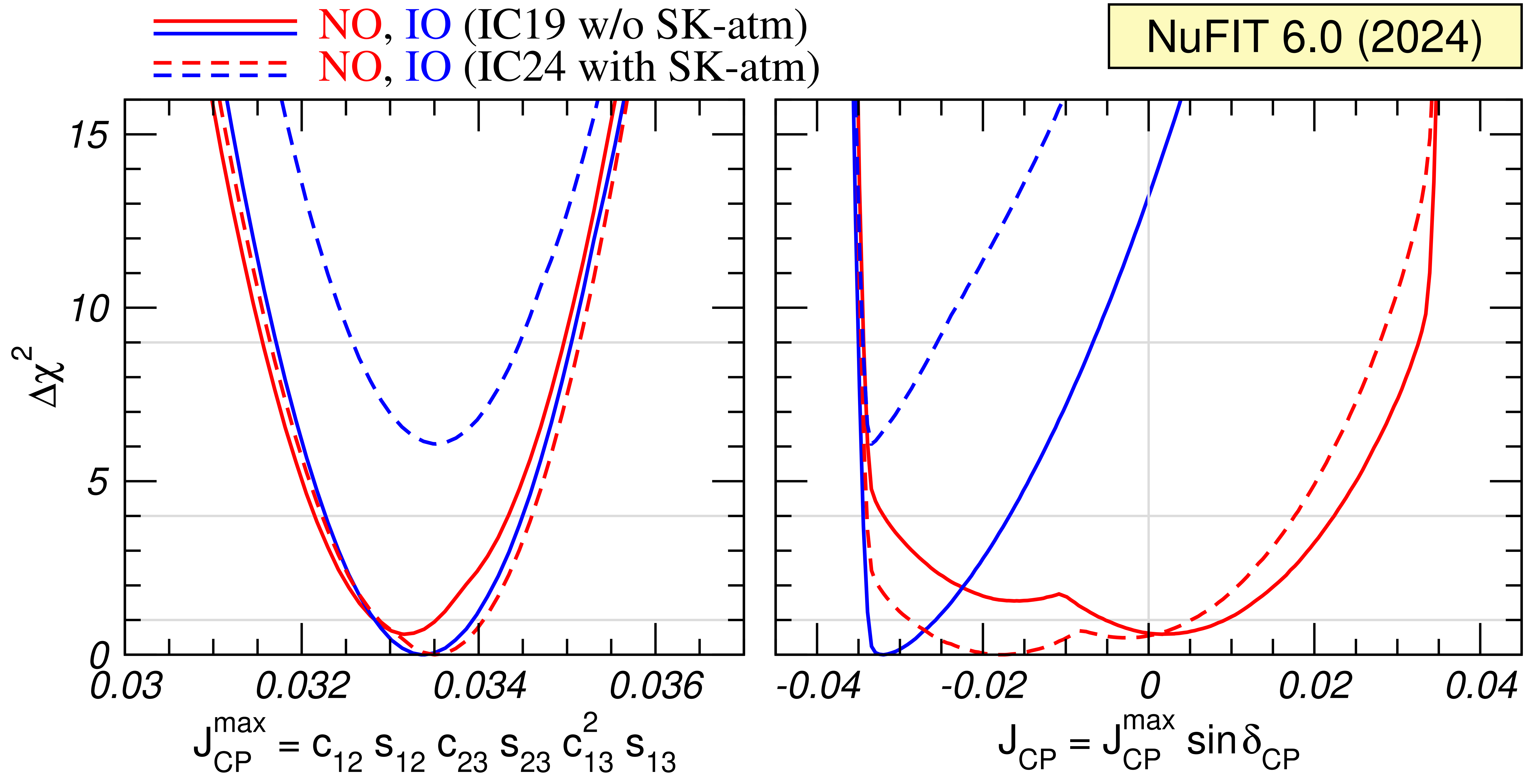
I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

CP-violation

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

CP-conservation is margnizaly disfavored

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

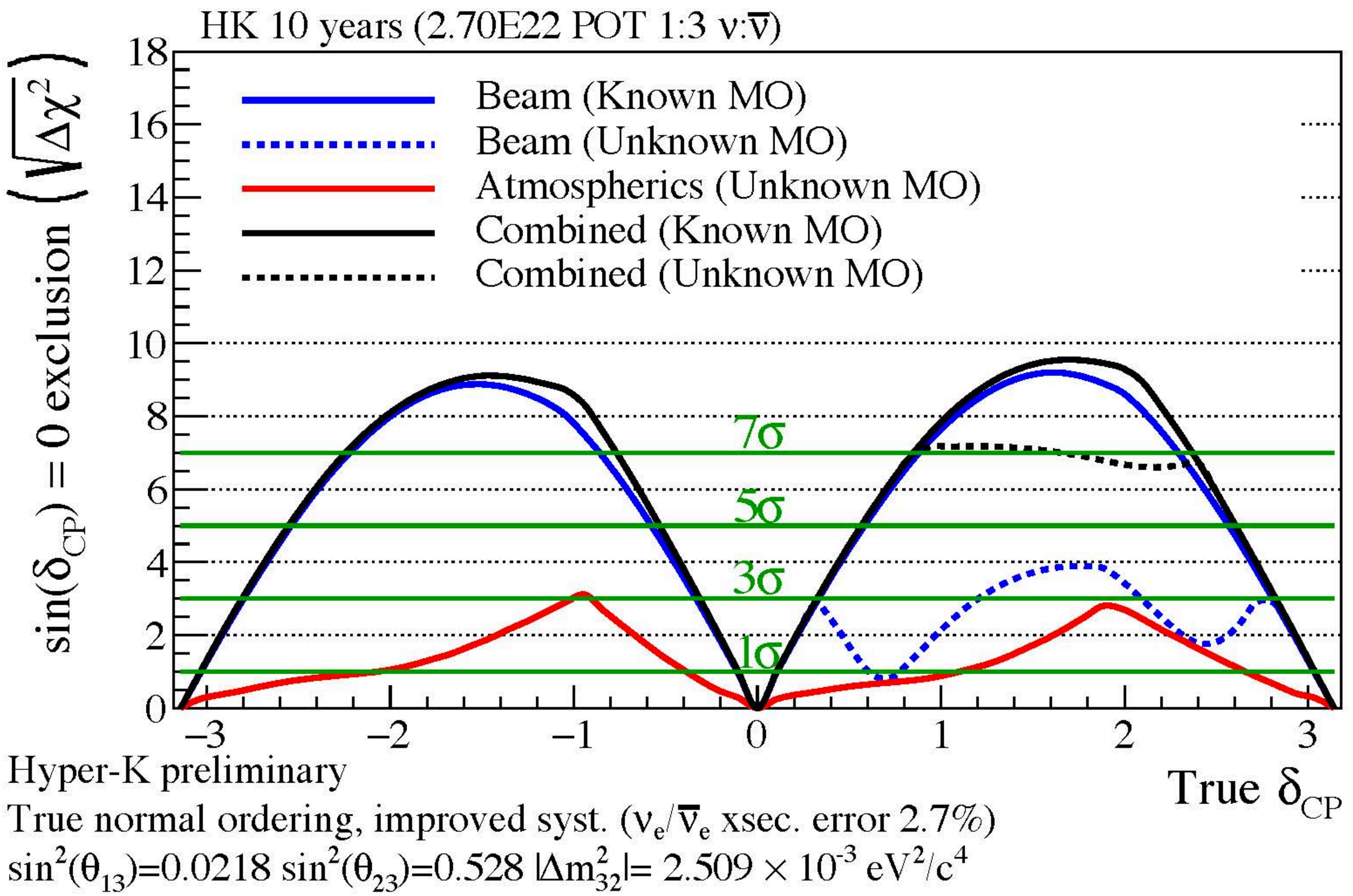


I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

Future Measurements

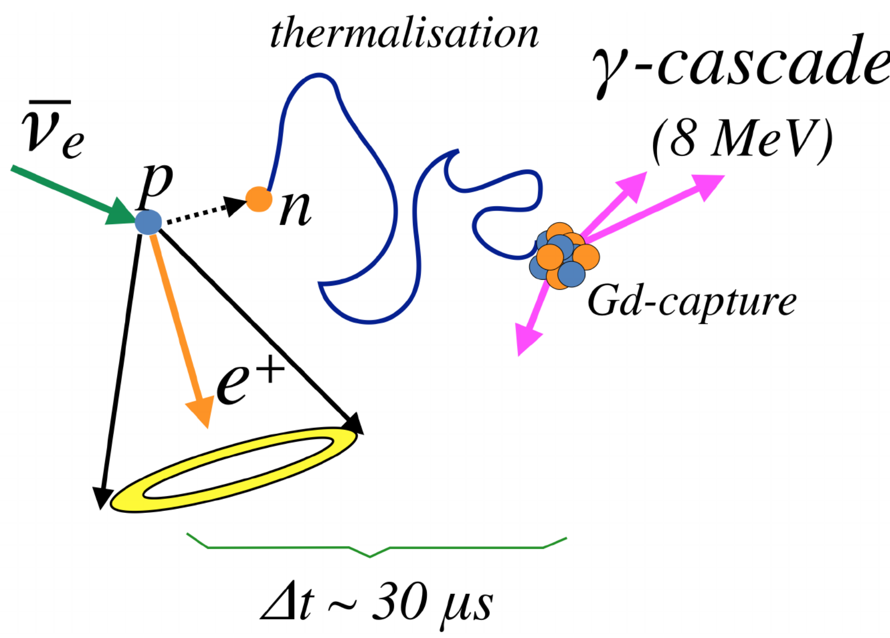
Super-/Hyper-Kamiokande

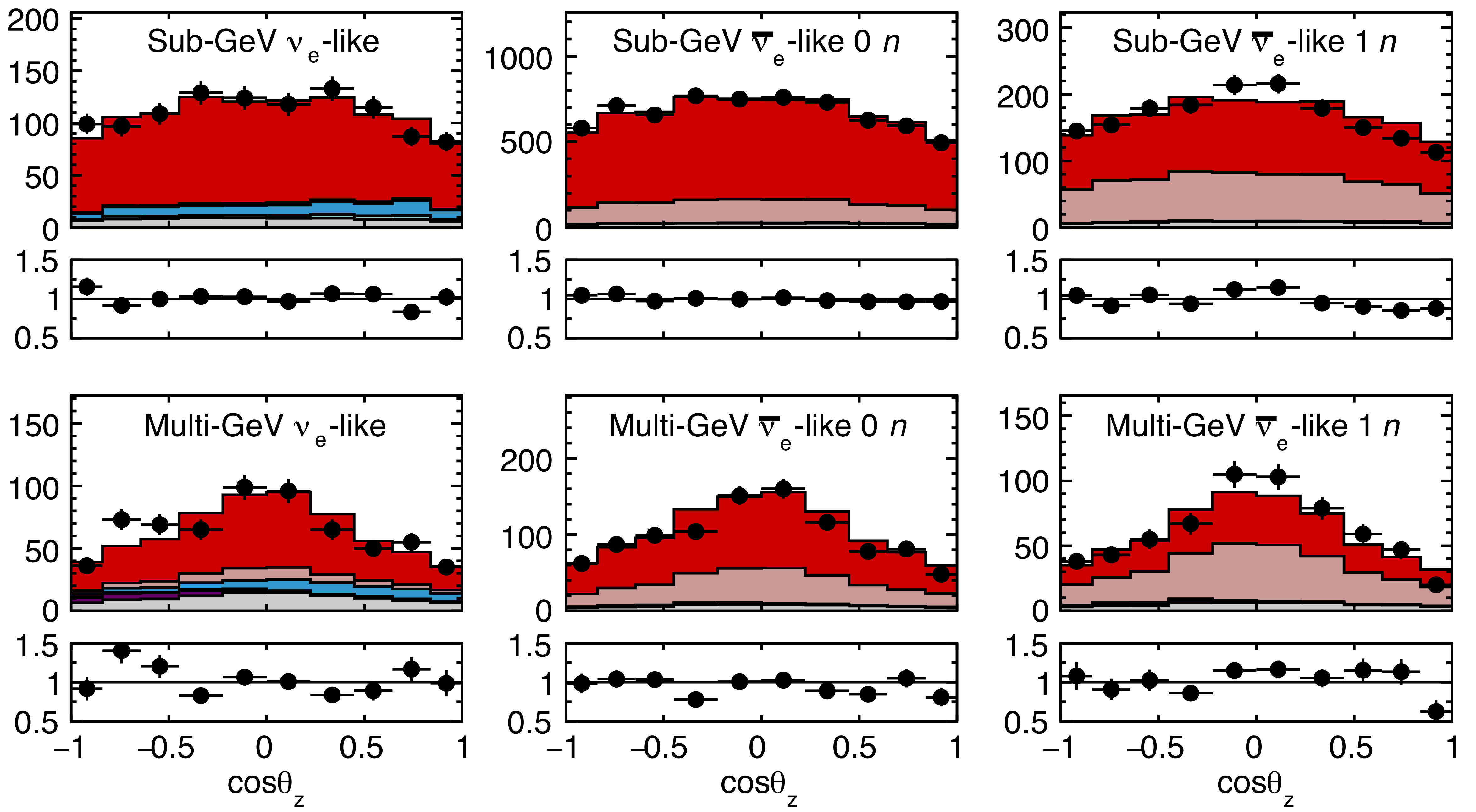
In the future, several experiments are going to measure the **atmospheric** neutrino flux with **high precision**



Bian,et al. (Hyper-Kamiokande), arXiv:2203.02029

Gadolinium (Gd) in water helps SK **tag neutrons** and distinguish neutrinos from antineutrinos





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

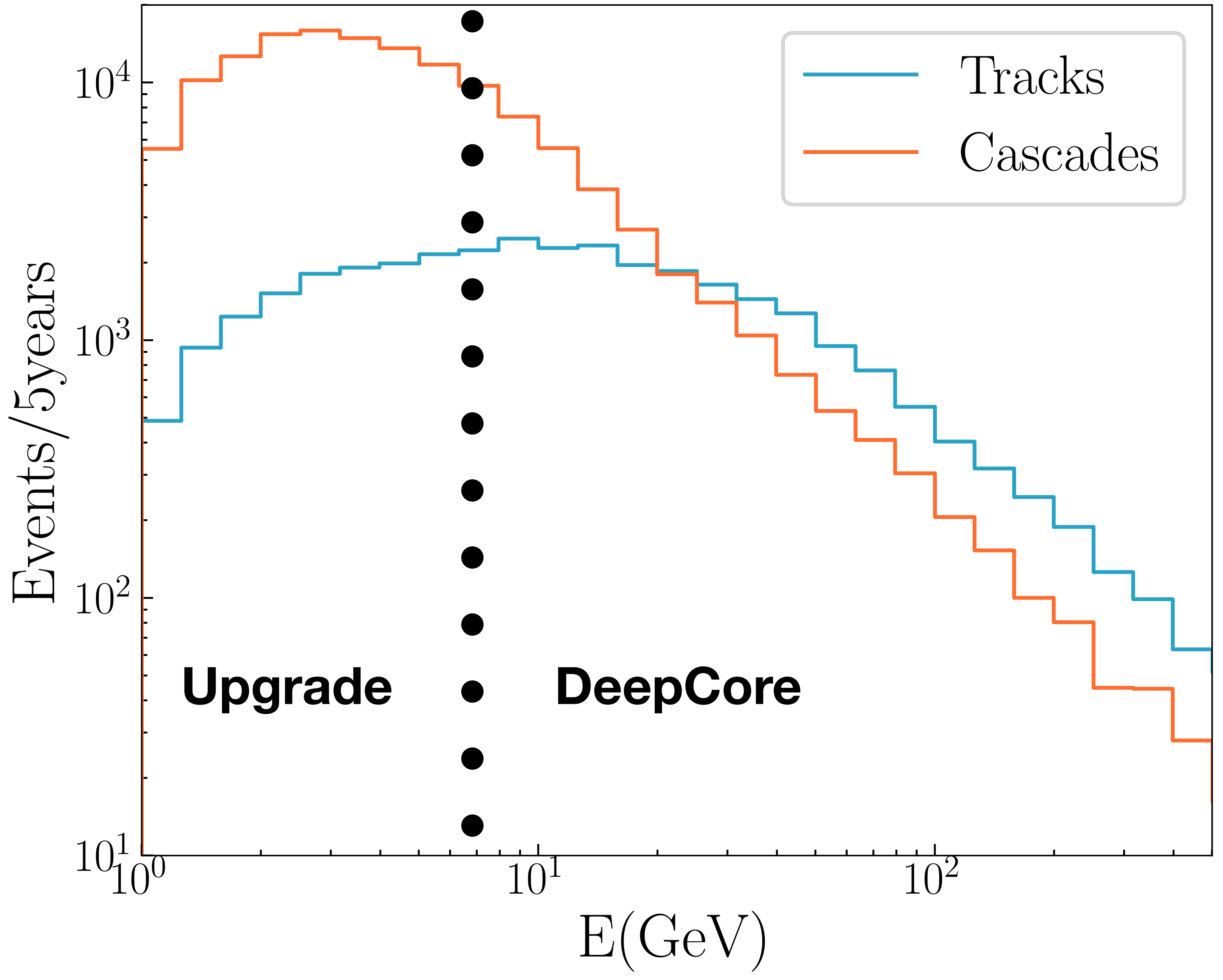
Beacom and Vagins, PRL 93 (2004)

P.F. Menéndez, Ph.D. thesis

Neutrino Telescopes

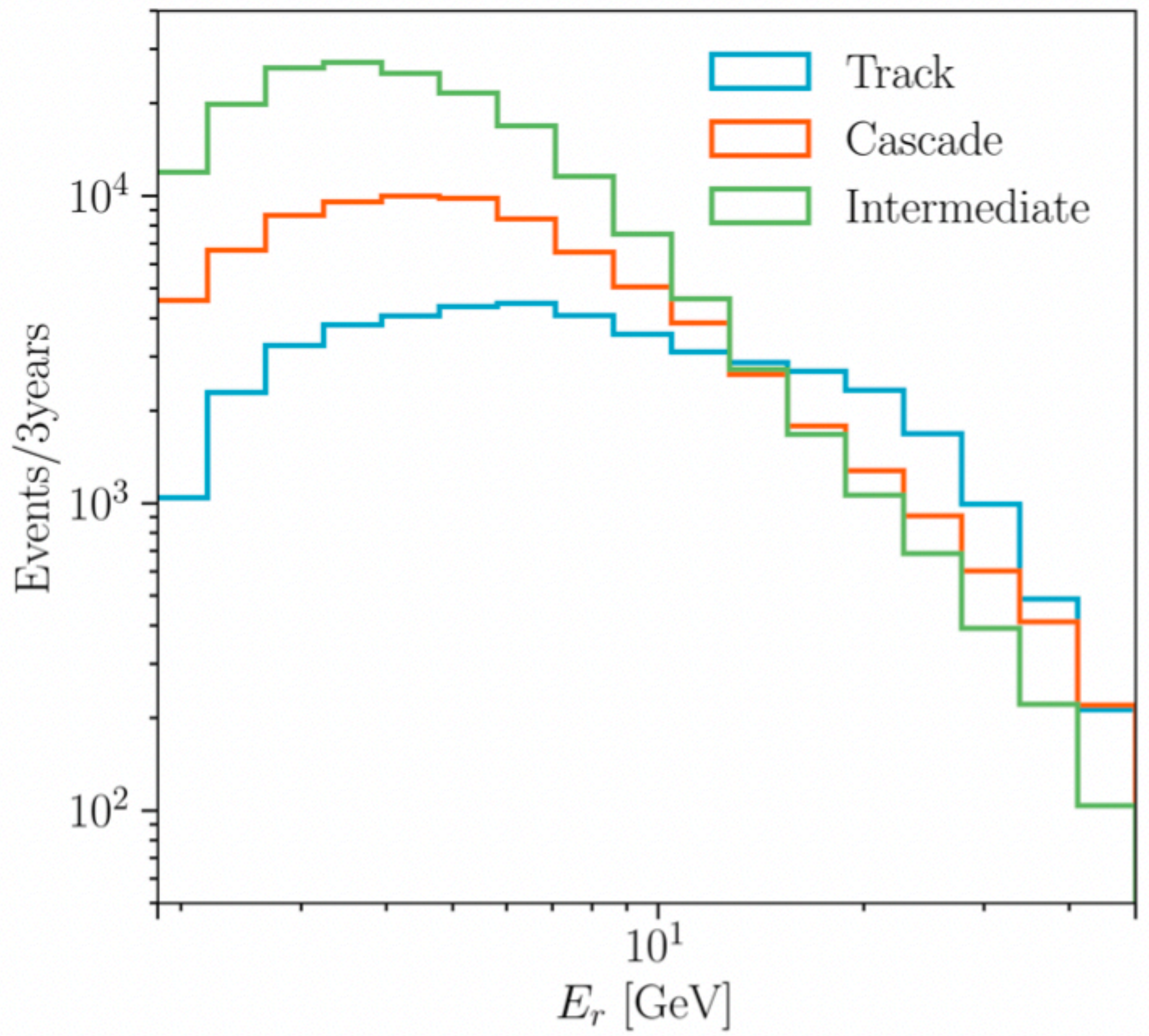
The **neutrino telescopes** measure the high-energy part of the atmospheric neutrino flux

IceCube



- $\sim 1\text{km}^3$ ice Cherenkov
- The upgrade will add seven additional strings lowering the energy threshold to ~1GeV

ORCA



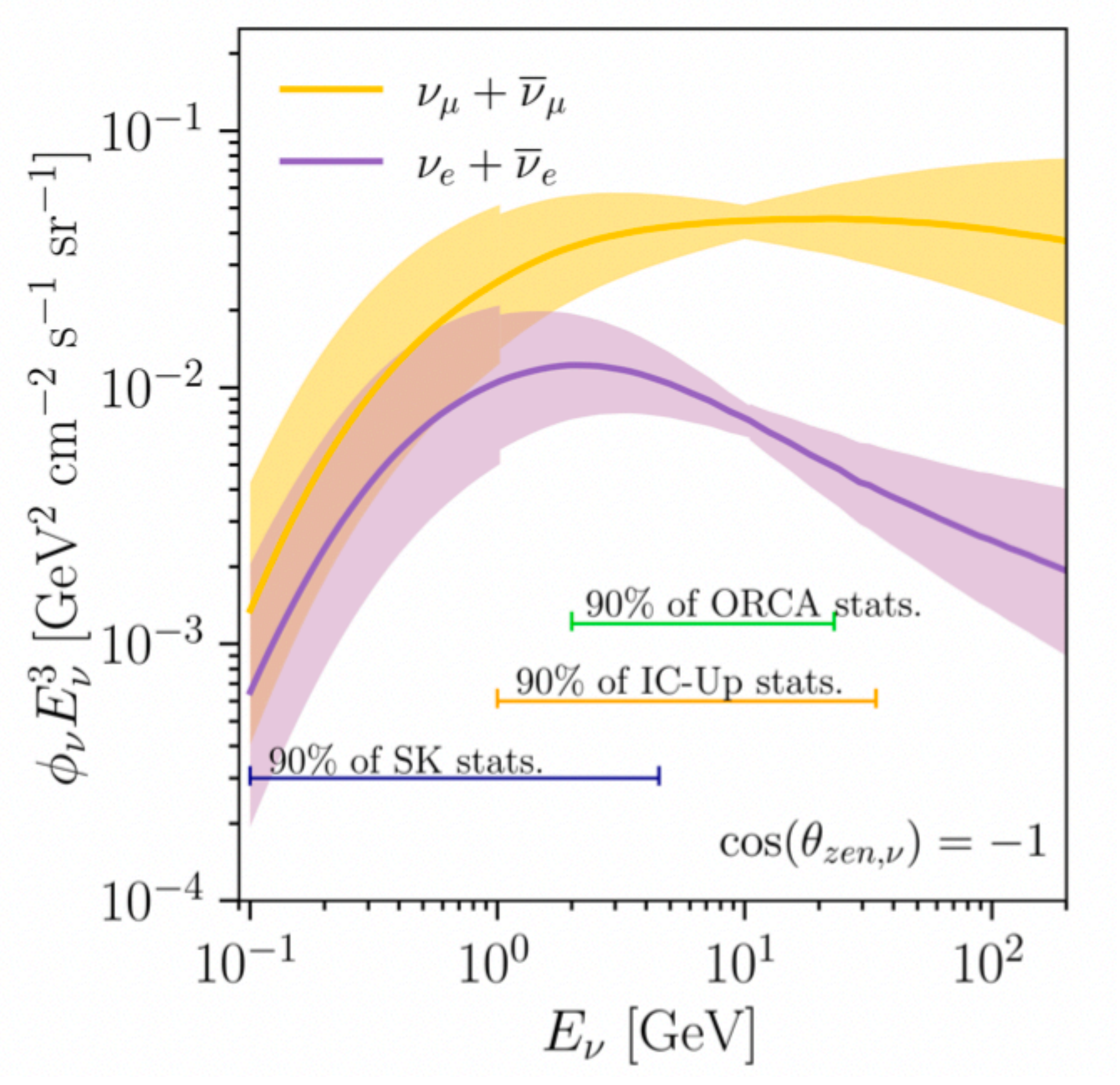
We developed an MC for ORCA based on energy and Zenit reconstruction provided by the collaboration

Systematic uncertainties

The uncertainties on the atmospheric neutrino **flux** and the **cross-section** are common to all detectors.

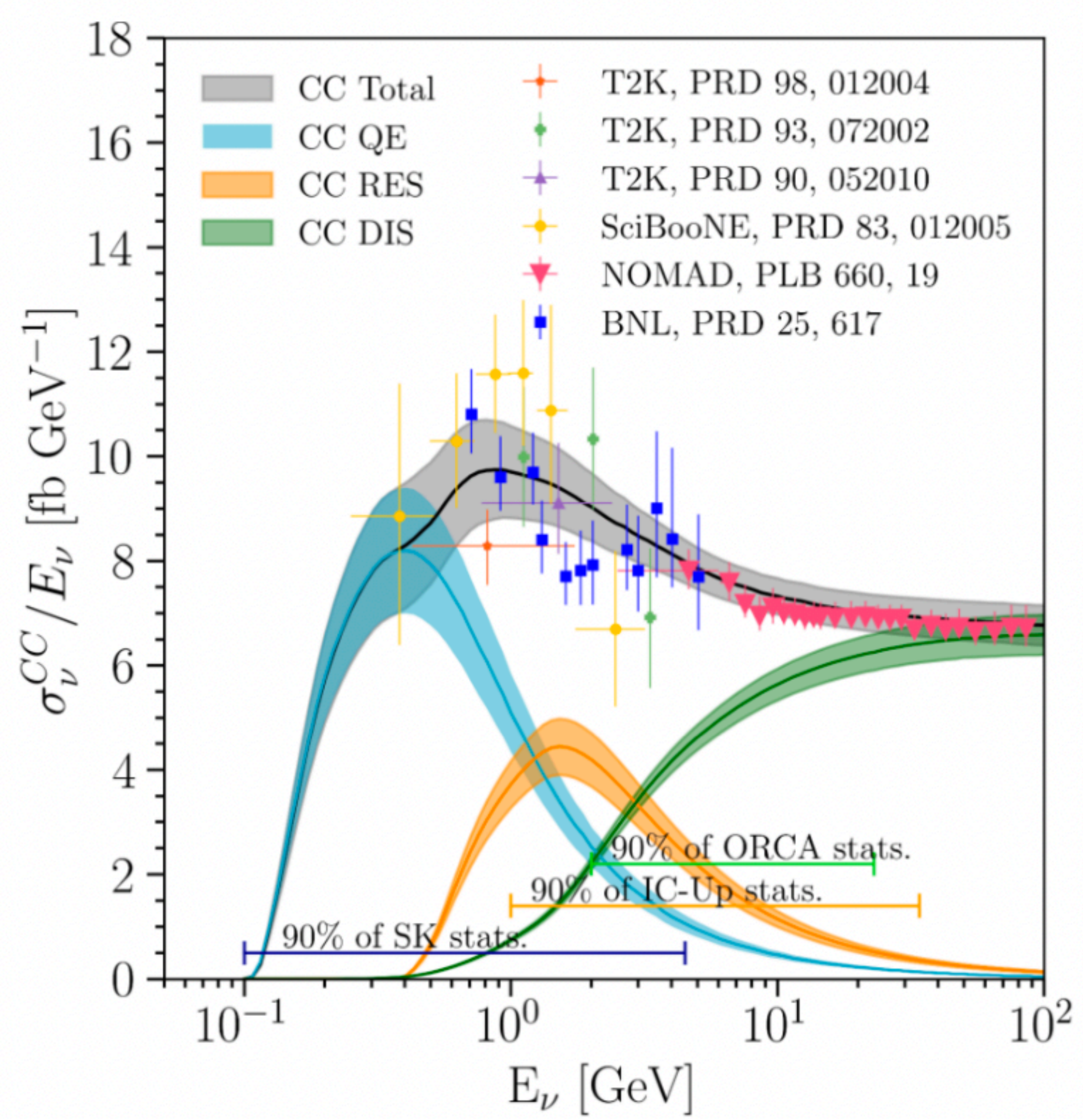
Flux systematics

We account for the uncertainties over the normalization, energy dependence, up/down, ν_e/ν_μ, $\overline{\nu}/\nu$



Cross-section systematics

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

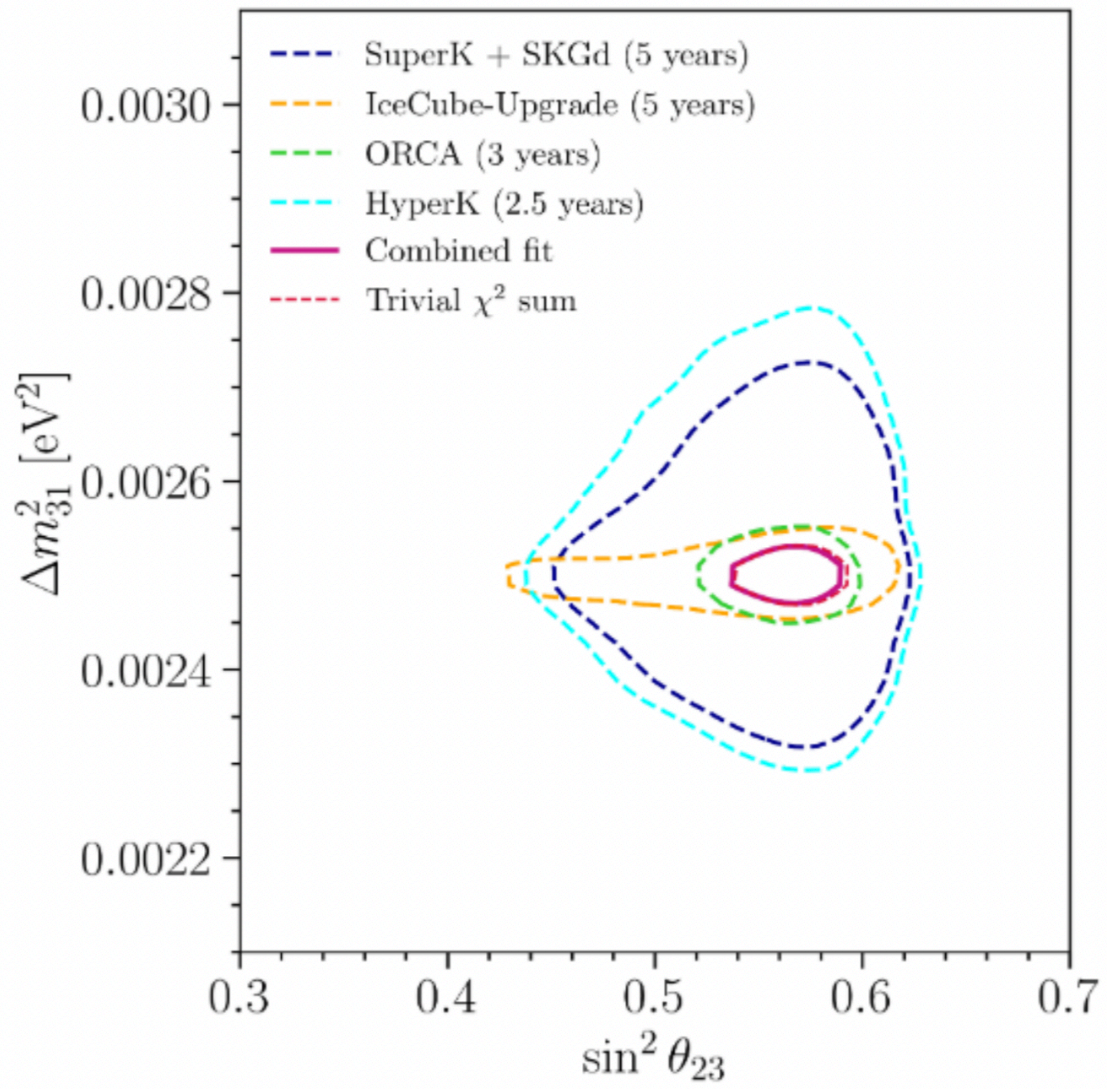


Systematic	Uncer./Prior
CCQE	10%
CCQE $\nu/\overline{\nu}$	10%
CCQE e/μ	10%
CC1 π	10%
CC1 π $\pi^0/\pi^\pm$	40%
CC1 π $\nu_e/\overline{\nu_e}$	10%
CC1 π $\nu_\mu/\overline{\nu_\mu}$	10%
Coh. π	100%
Axial Mass	10%
NC hadron	5%
NC over CC	10%
ν_τ	25%
Neutron prod.	15%
DIS	10%

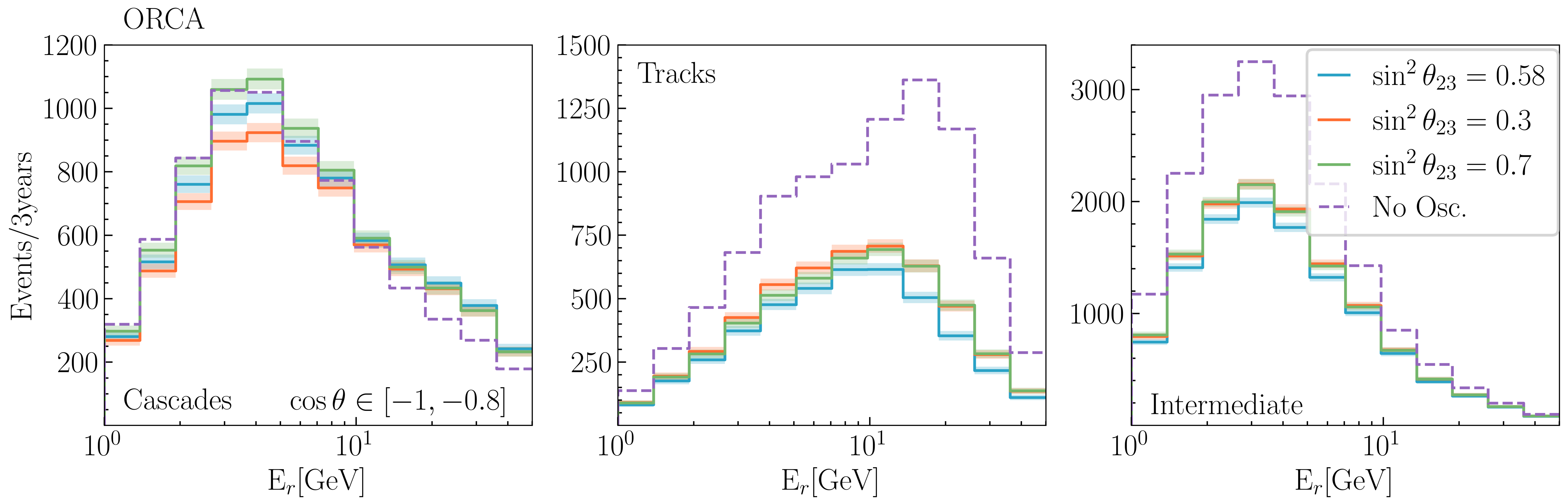
Ivan Martinez-Soler (IPPP)

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**



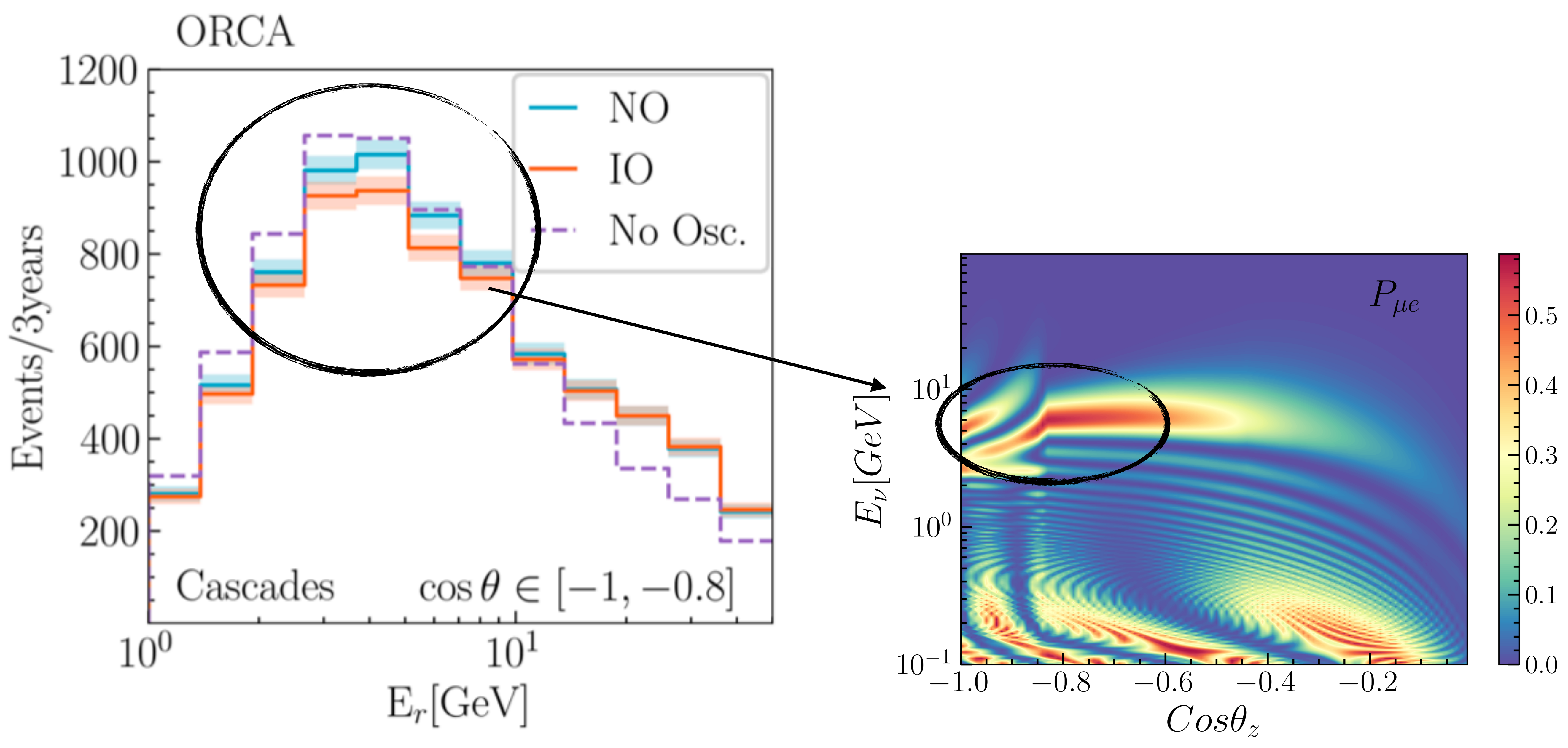
~10GeV neutrino reconstruction improves $\sin^2\theta_{23}$ and Δm^2_{31}precision

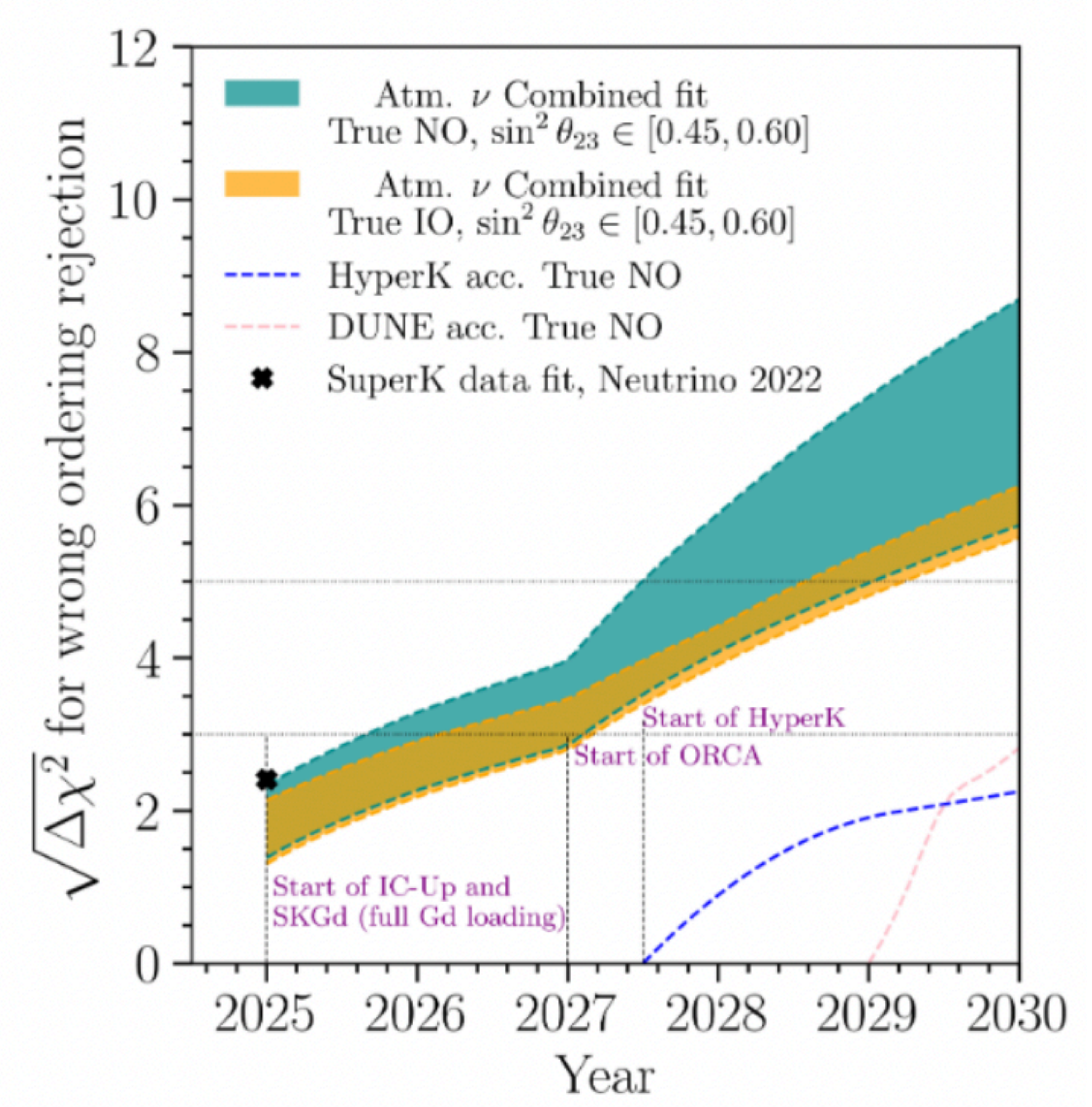


Argüelles, Fernandez, IMS and Jin, PRX 13 (2023)

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.





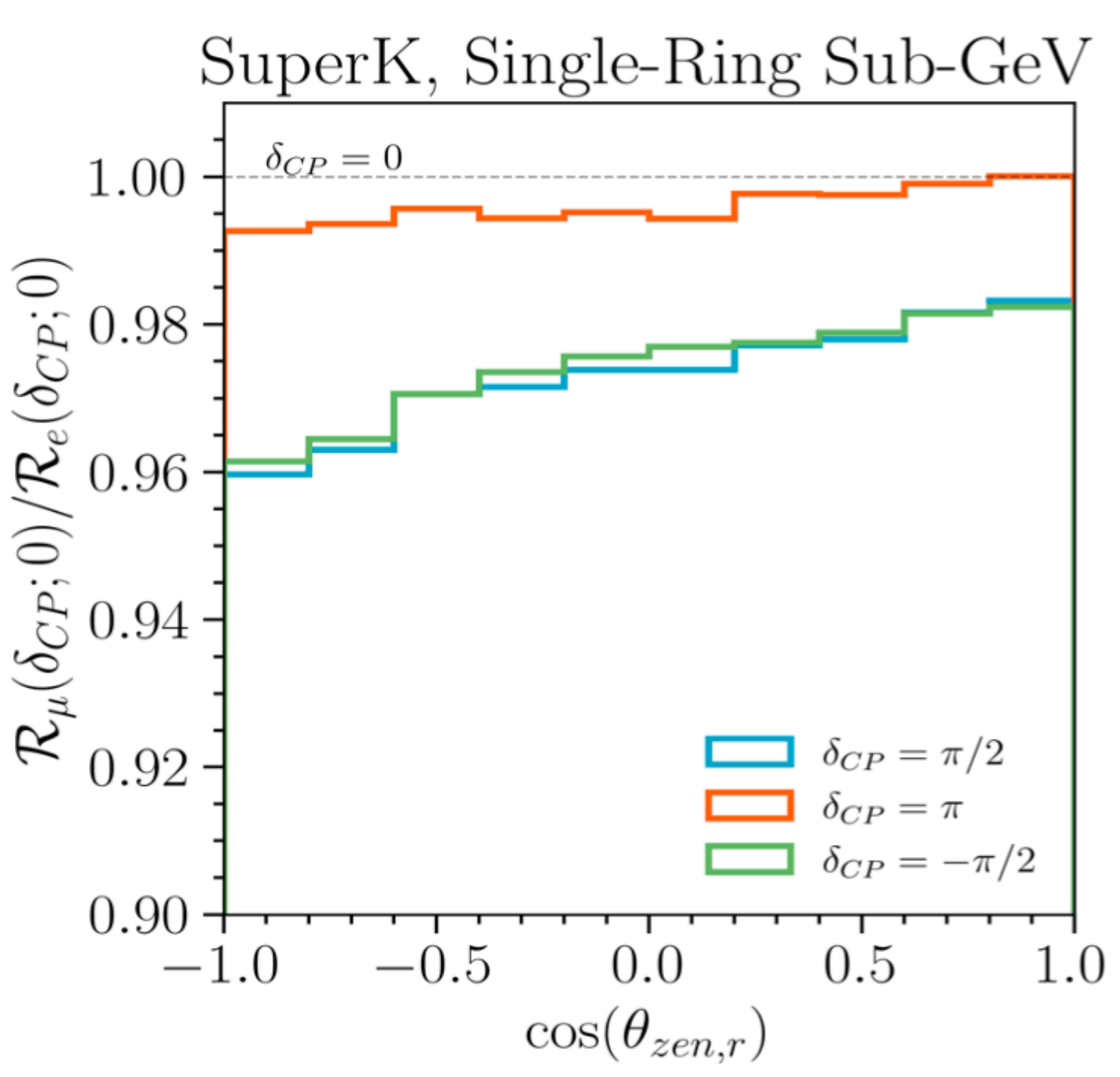
Very localized effect, requires good energy and angular resolution.

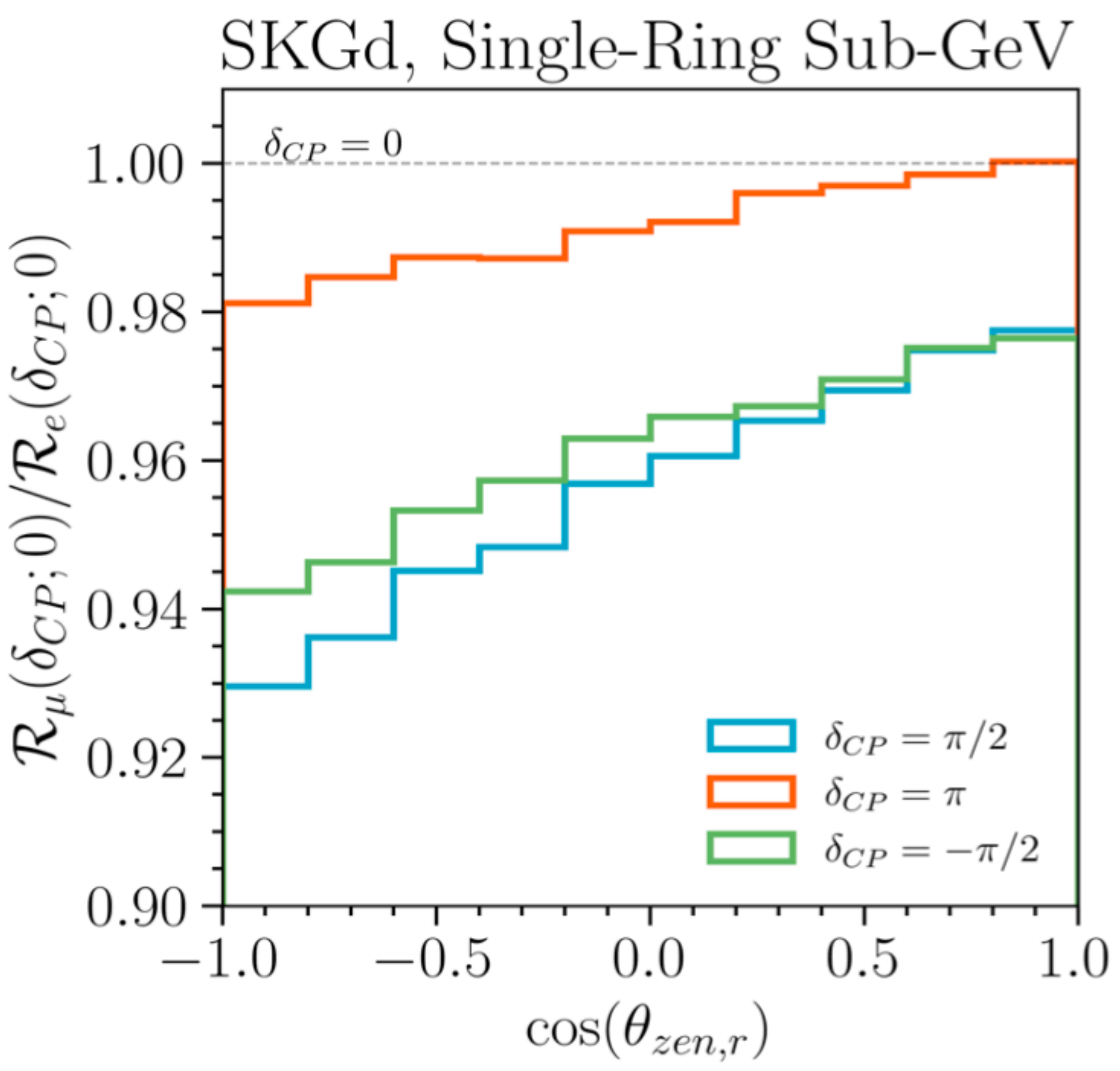
Argüelles, Fernandez, IMS and Jin, PRX 13 (2023)

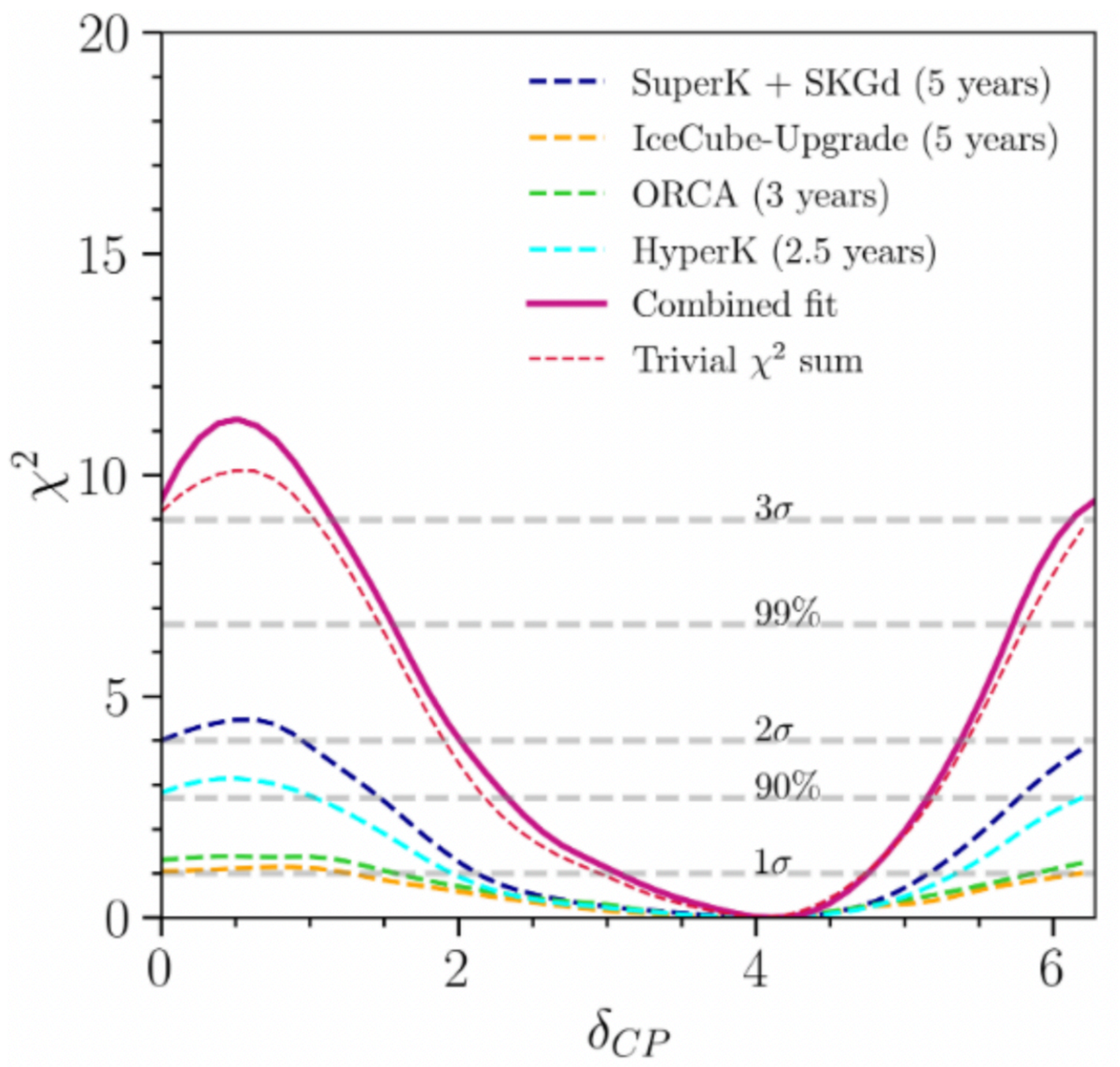
Combined analysis: δ_{cp}

The sensitivity to δ_{cp} is dominated by **Super-Kamiokande**

- The samples that dominate the sensitivity are the e-like and μ-like with no neutron tagged





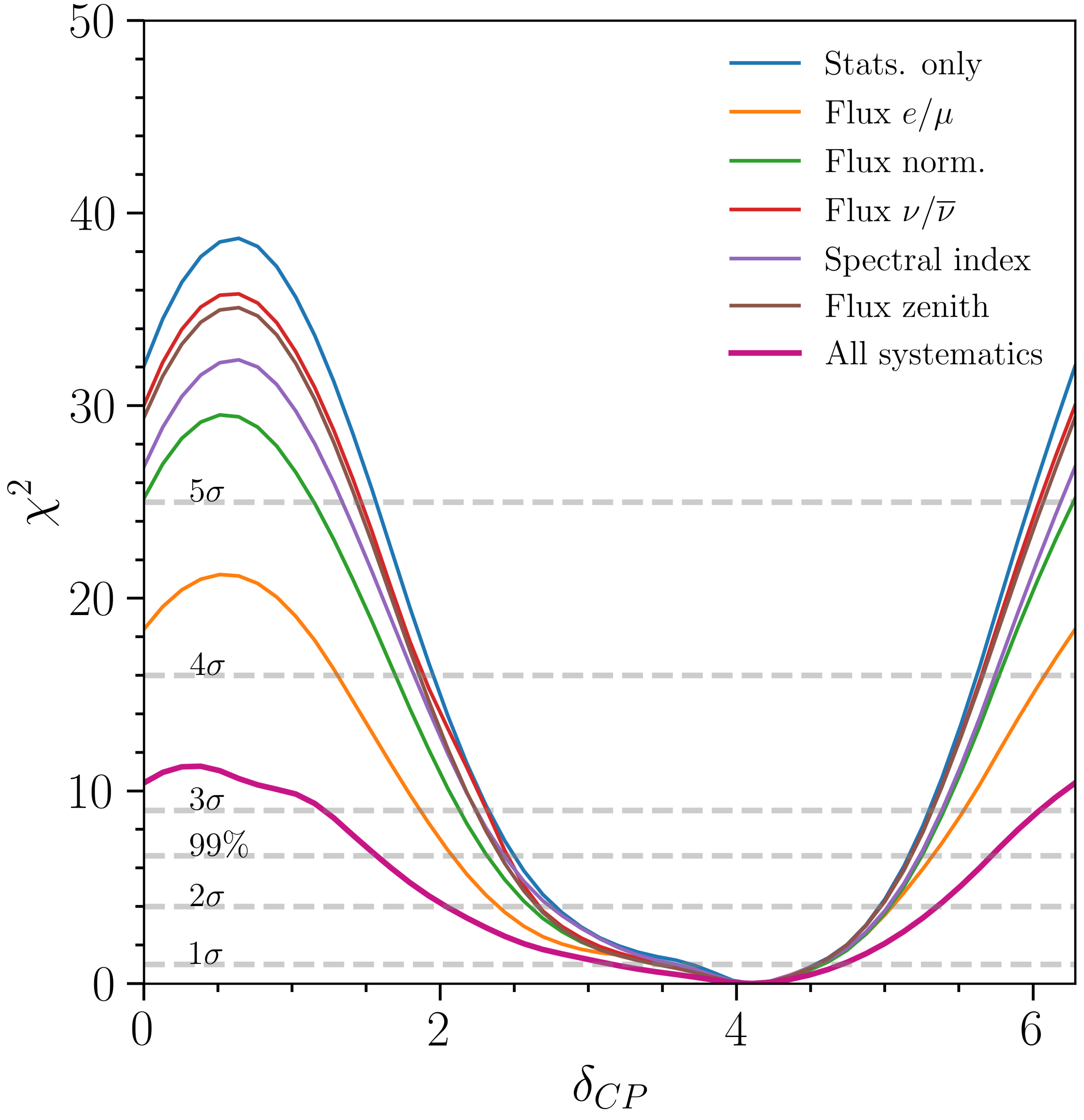


Argüelles, Fernandez, IMS and Jin, PRX 13 (2023)

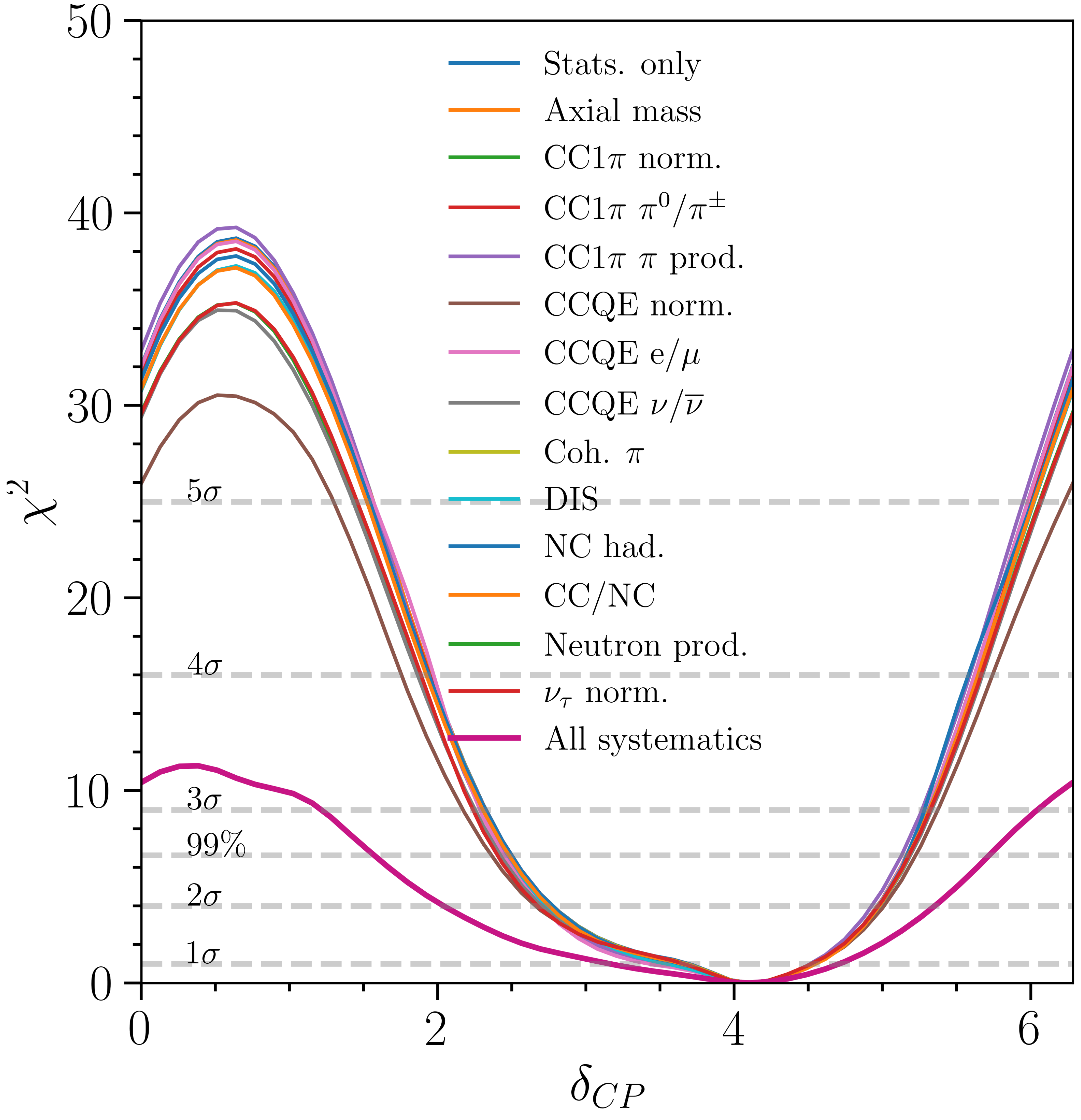
Systematic impact

A **detailed analysis** of all the systematics is performed. The uncertainties related to the **flux** have a larger impact on δ_{CP}

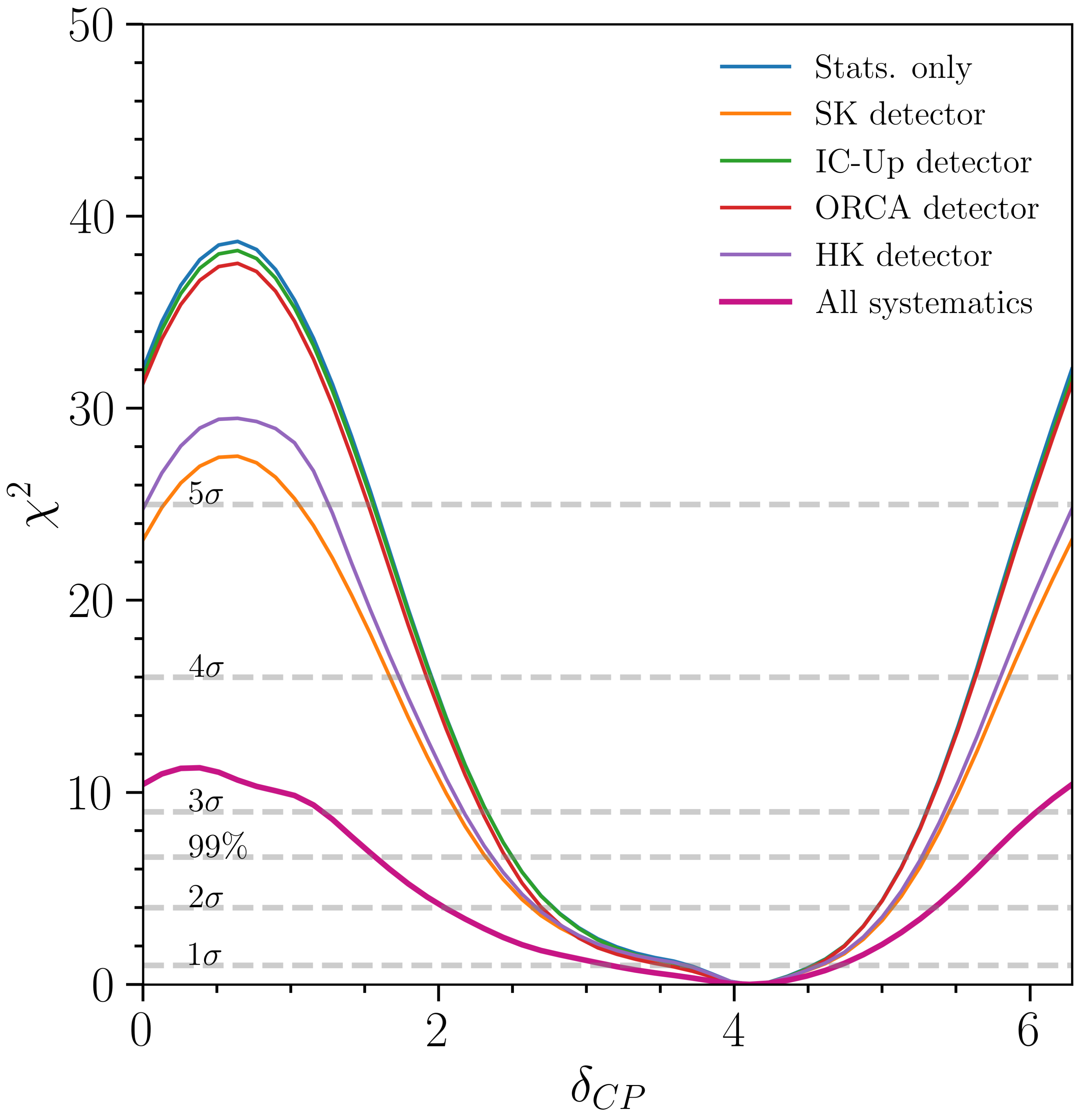
Flux



Cross-section



Detector

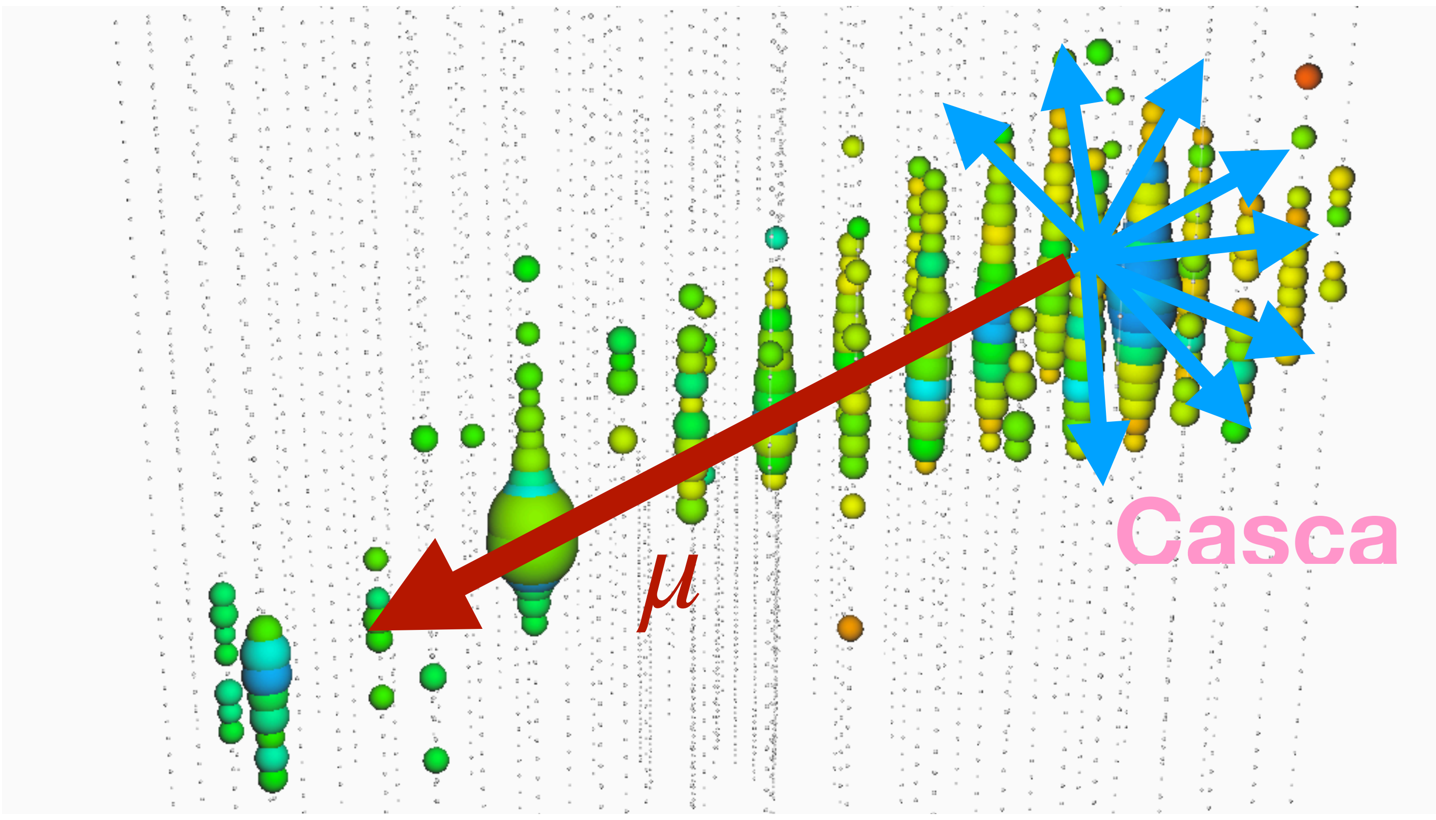


Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

Boosting the Sentivity with Inelasticity

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

- ν_μ- CC interaction the energy is devided between tracks and cascades.

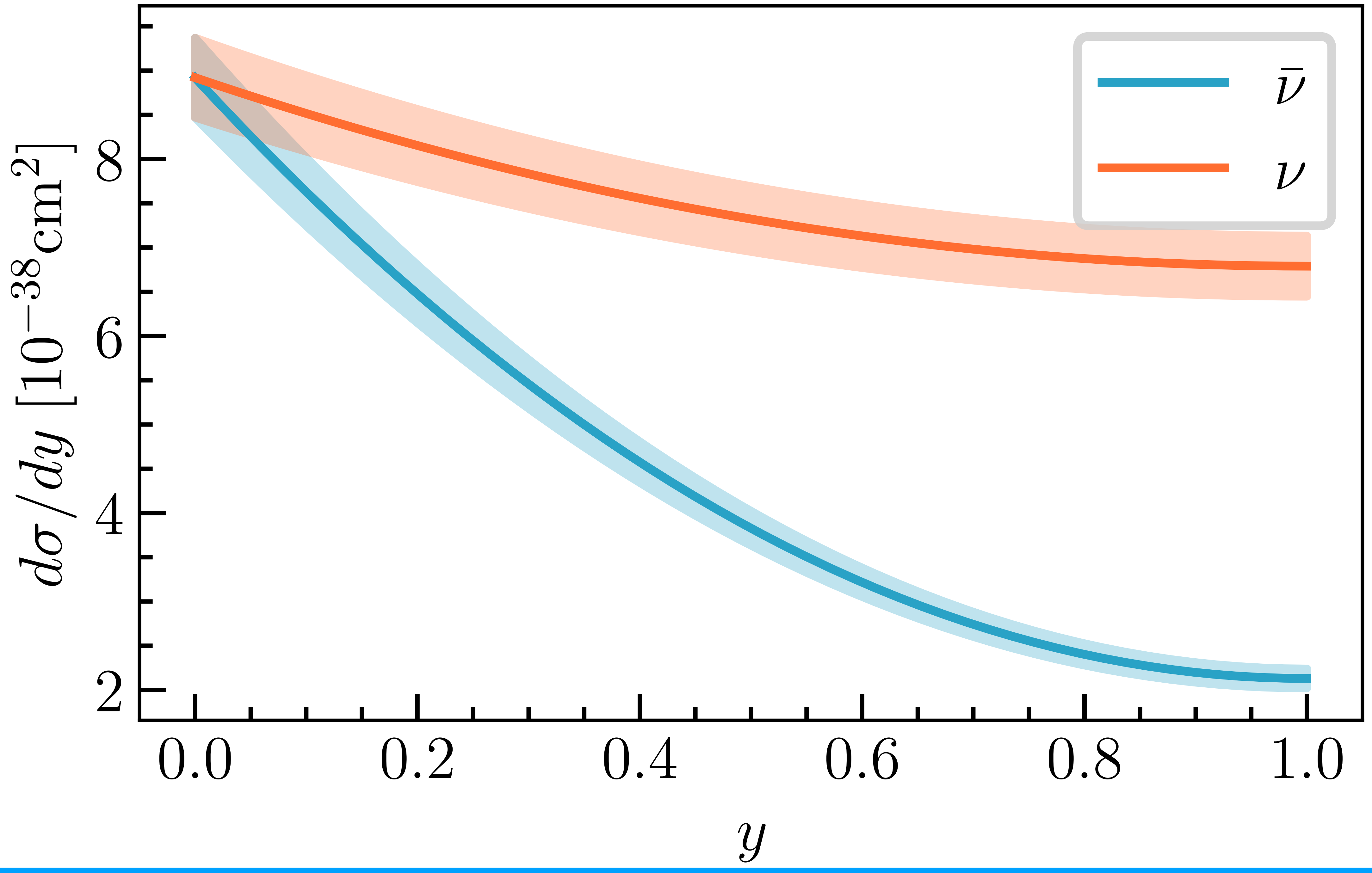


- Neutrinos and antineutrinos divide their energy differently between the leptonic and the hadronic part differently

$$\frac{d\sigma^{CC}_{\overset{(-)}{\nu}}}{dydx} = \frac{G_F^2 xs}{2\pi}\left(\overset{(-)}{Q}(x) + \bar{Q}(x)\times(1-y)^2\right)$$

Q(x): Parton Distribution functions

$$y = \frac{E^{casc}}{E_\nu}$$



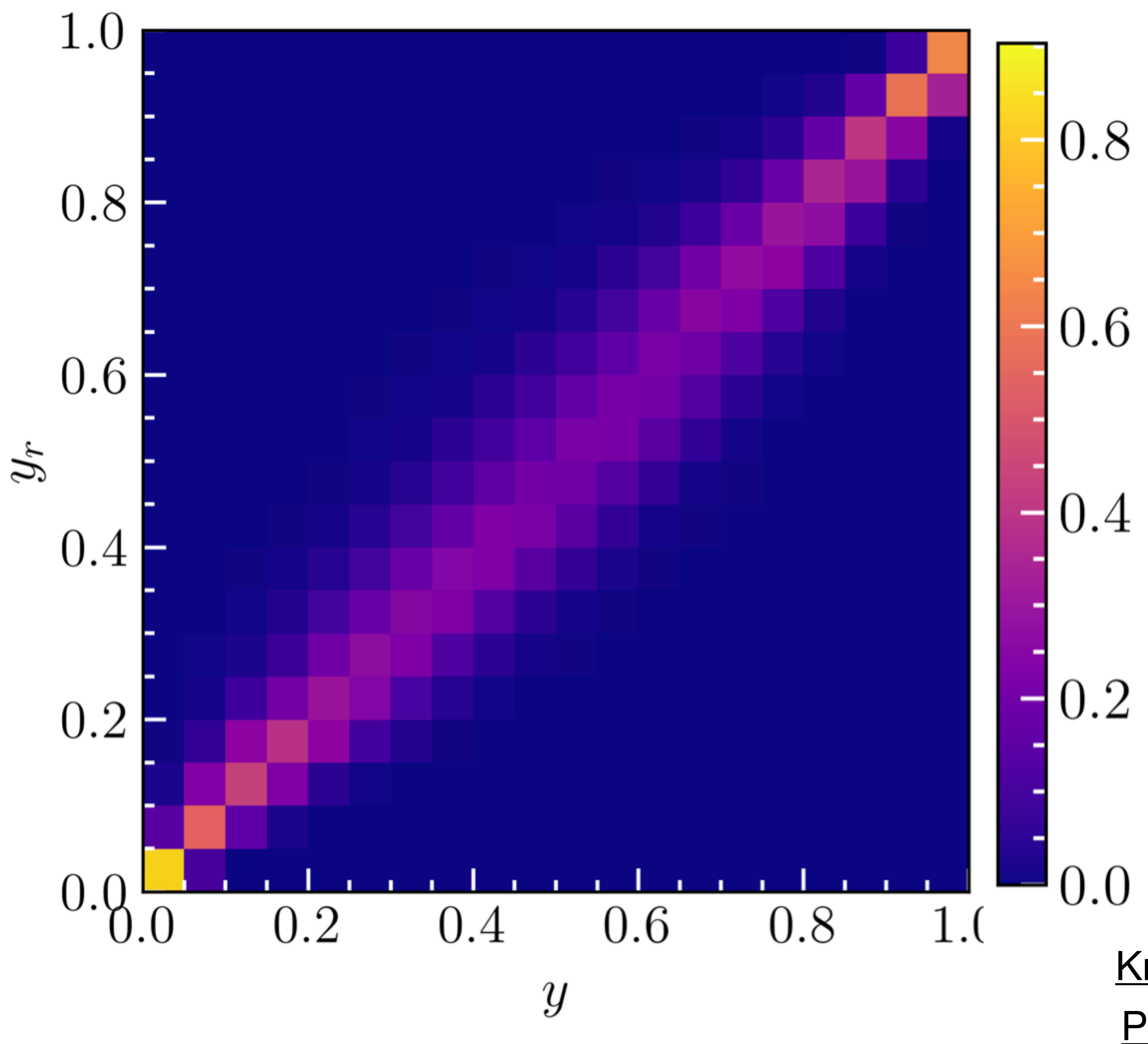
Ribordy and Smirnov, PRD, 87 (2013)

Giner Olavarrieta, Jin, Argüelles, Fernández, **IMS**, PRD 110 (2024)

Boosting the Sentivity with Inelasticity

The reconstructed inelasticity is based on the reconstructed energies of the track and the cascade.

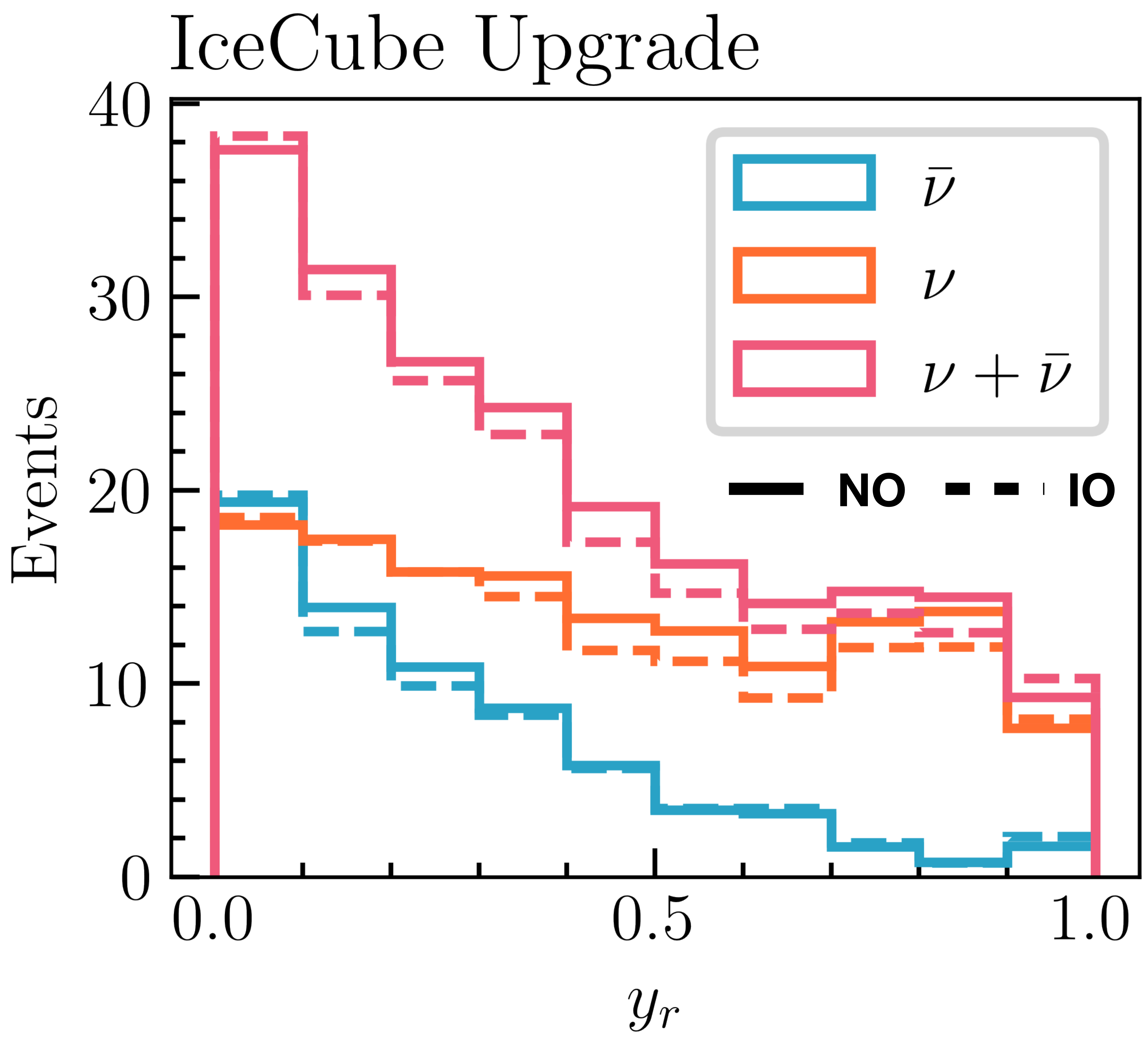
Reconstructed inelasticity



$$y_r = \frac{E_r^{casc}}{E_r^{casc} + E_r^{track}}$$

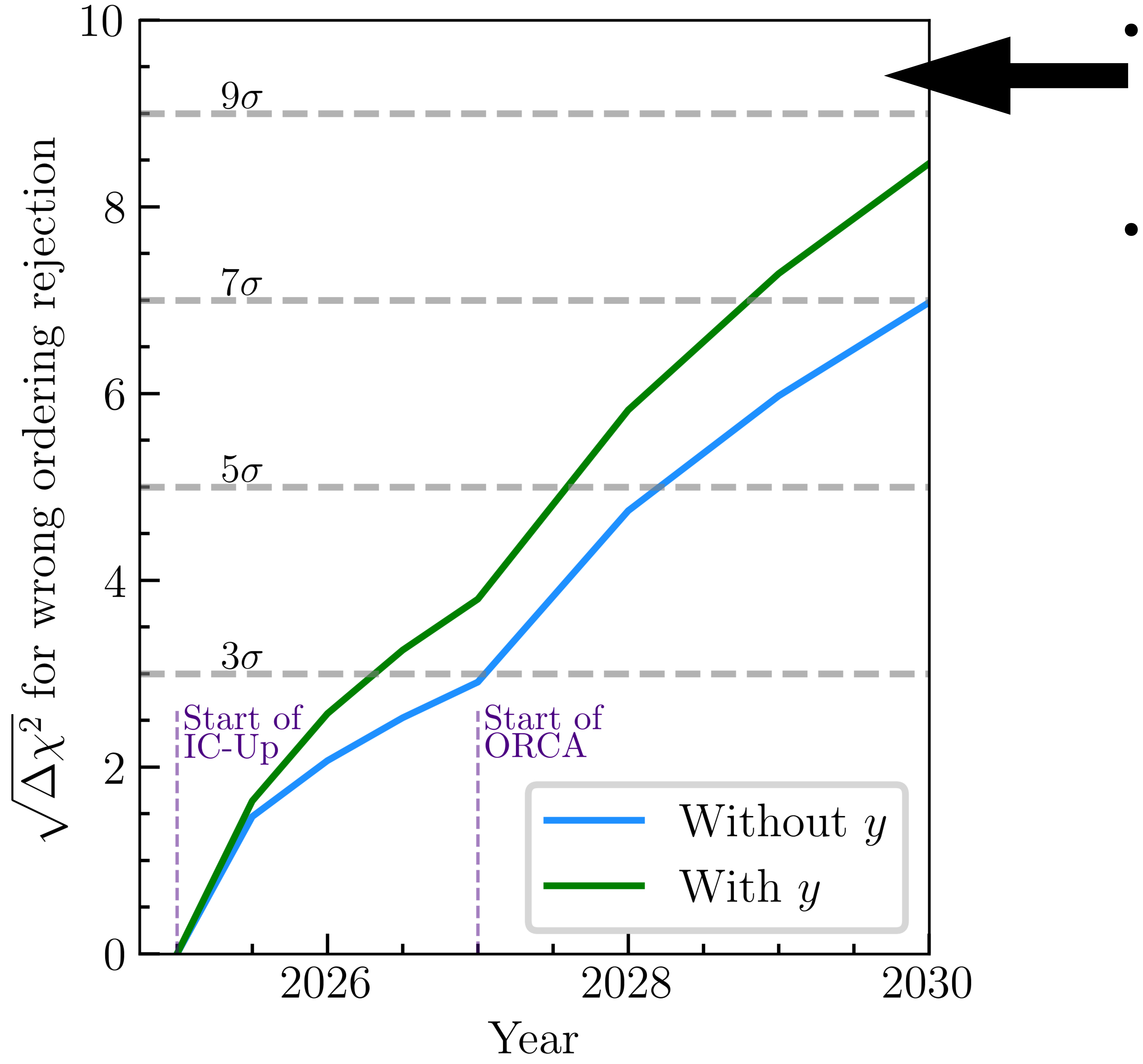
Kronmueller et al. (IceCube), ICRC2019

Peterson et al. (IceCube), PoS ICRC2023



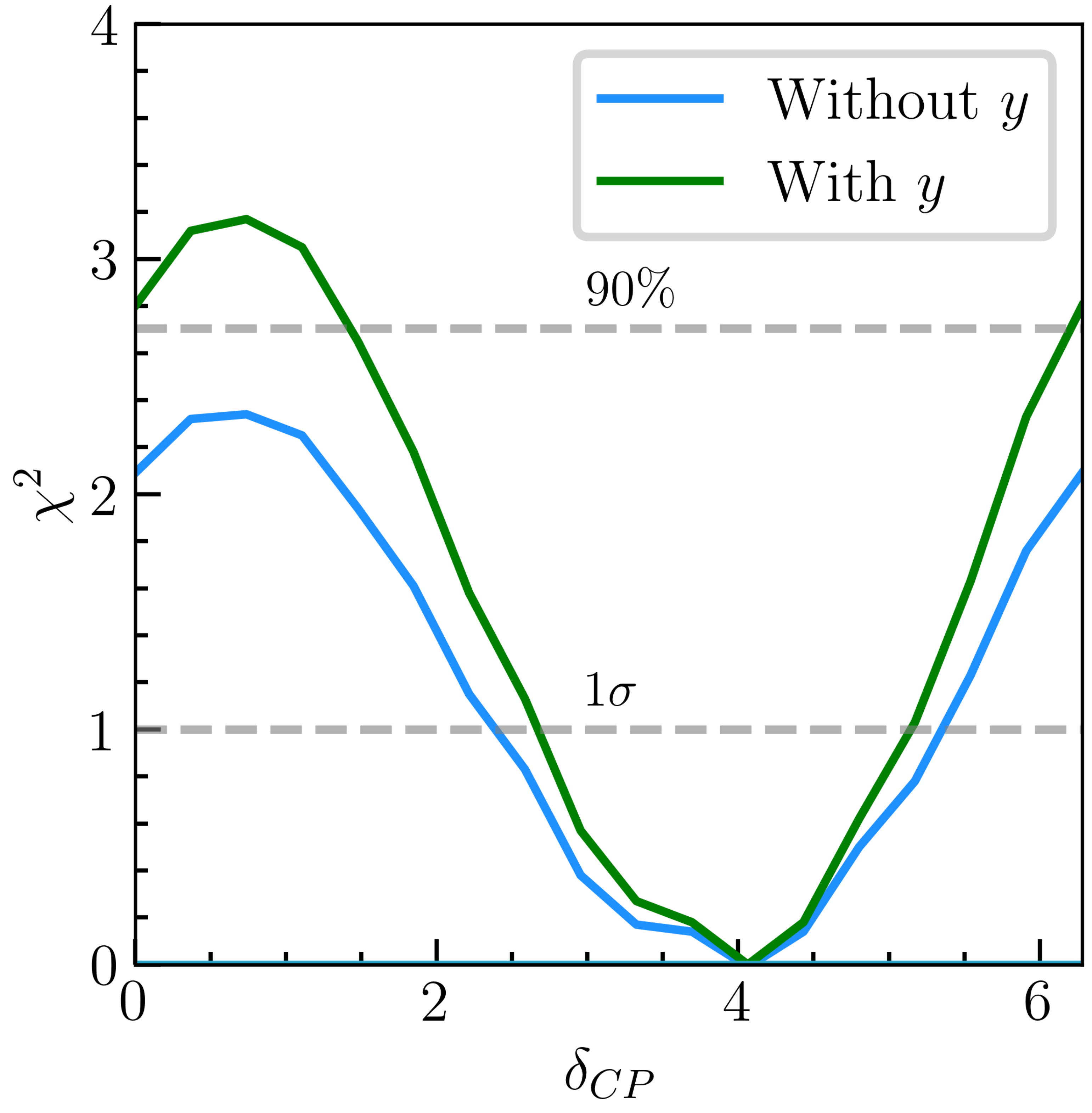
Giner Olavarrieta, Jin, Argüelles, Fernández, **IMS**, PRD 110 (2024)

Boosting the Sentivity with Inelasticity



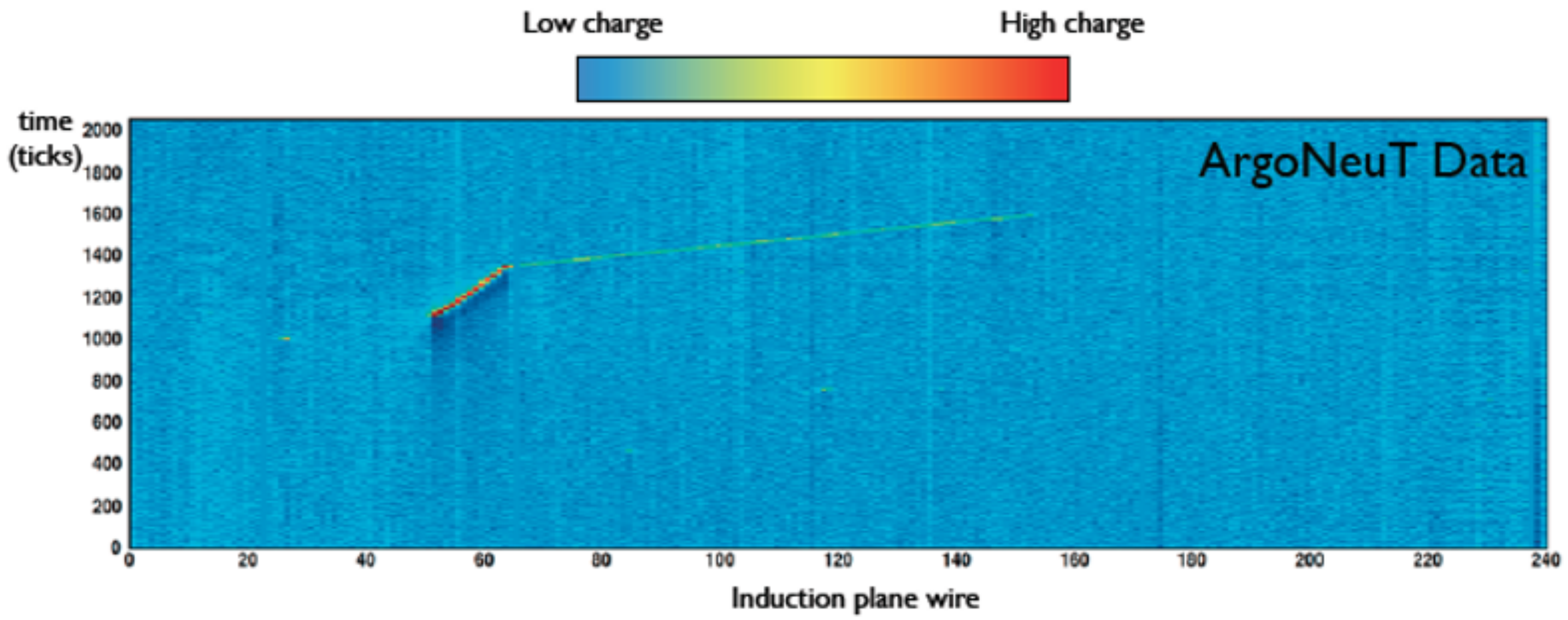
Giner Olavarrieta, Jin, Argüelles, Fernández, **IMS**, PRD 110 (2024)

- The **inelasticity** allows for a **50% increase** in sensitivity to the **mass ordering**, reaching 8.4σ in 5 years.
- In the case of δ_{CP}, the sensitivity increases by 15%



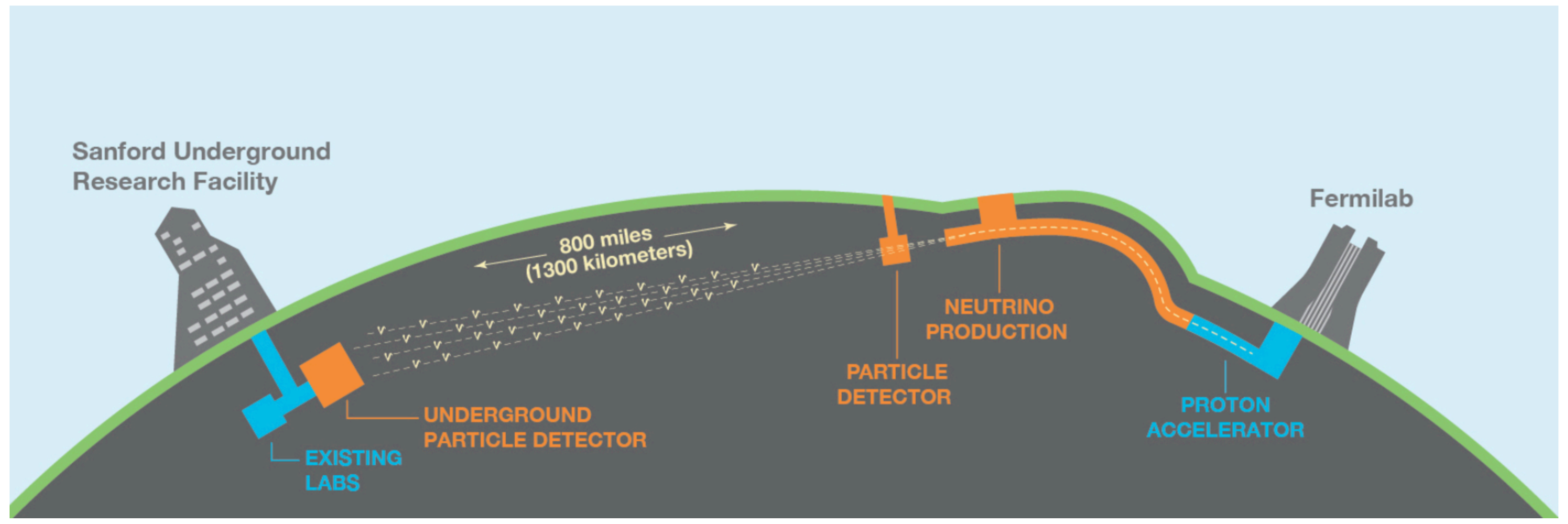
LArTPCs

- Excellent capabilities to **identify charged particles**.
- Precise measurement of the **energy and the direction** of low-energy charged particles

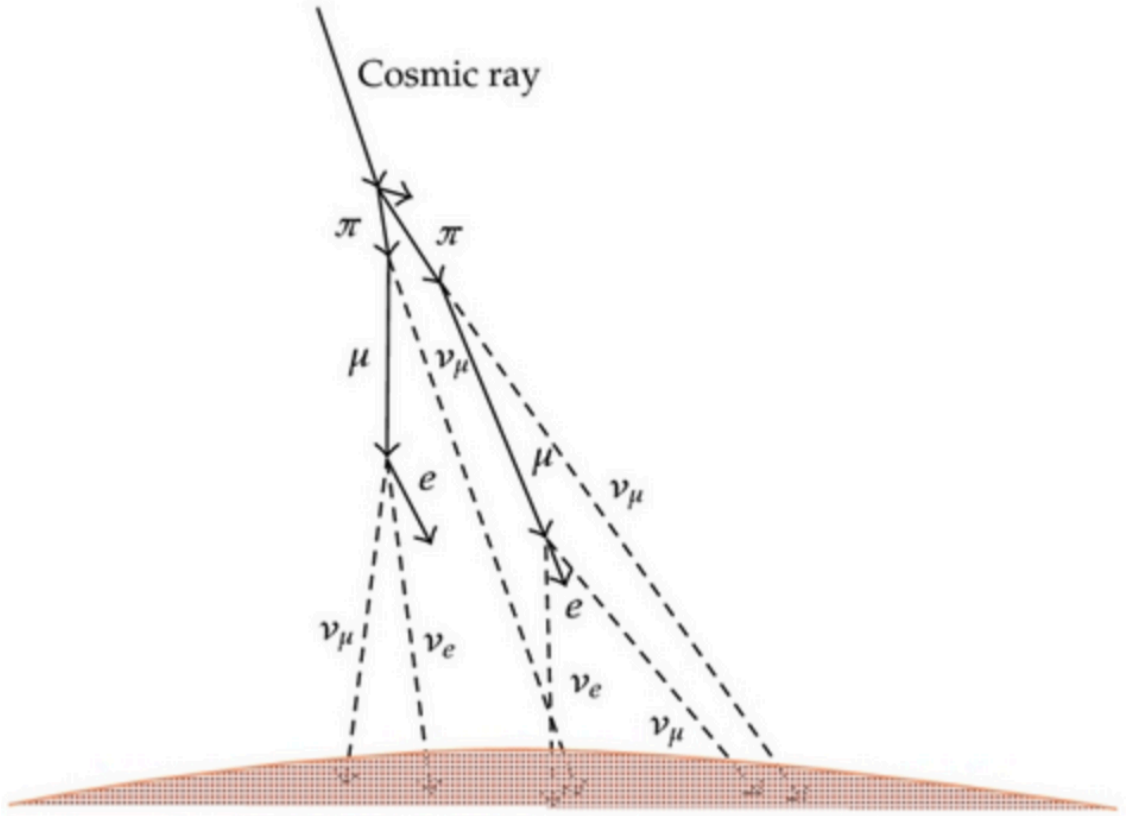


Anderson et al. (ArgoNeuT), JINST 7 (2012)

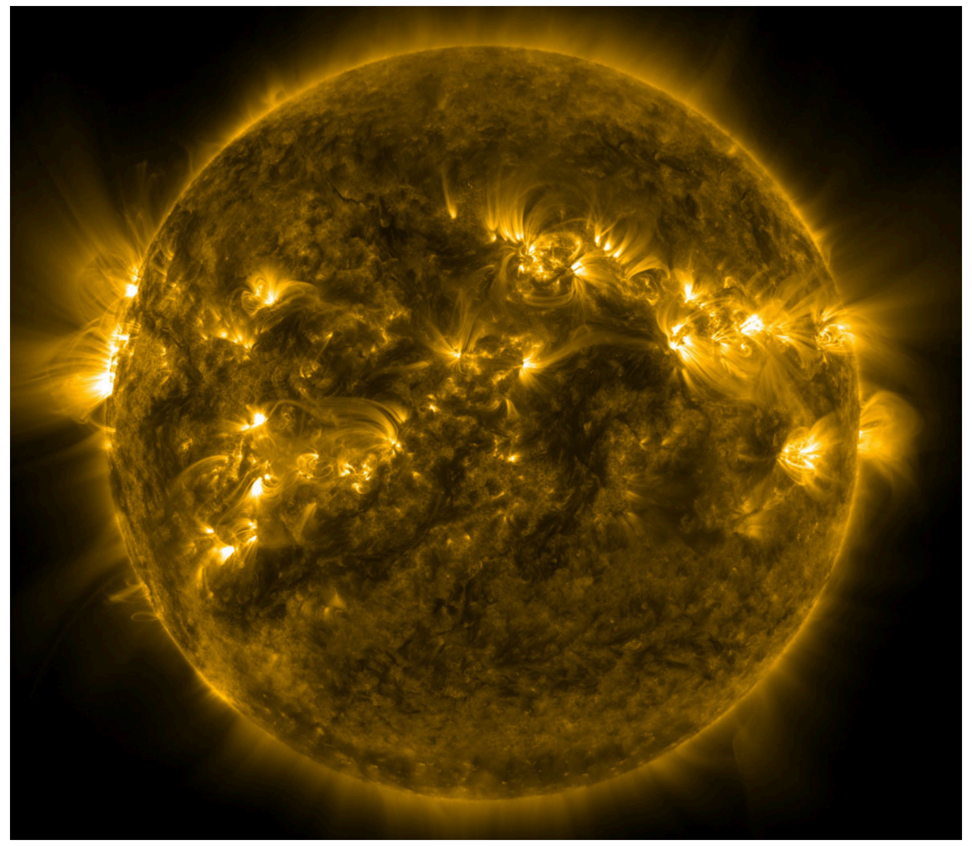
Accelerator



Atmospheric



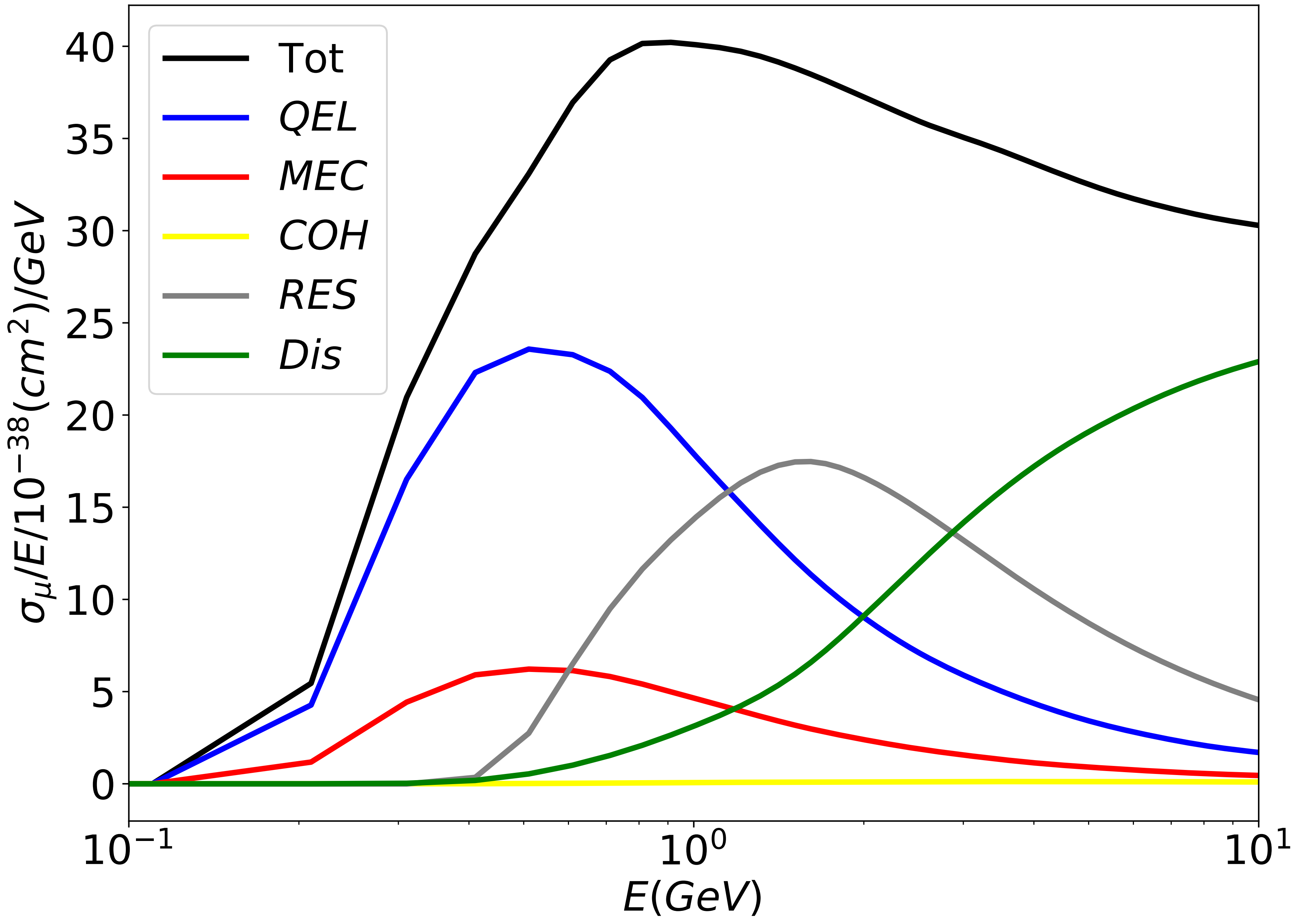
Solar



Capozzi, Li, Beacom, PRL 123 (2019)

LArTPCs

We simulate neutrino scattering on Argon using **NuWro** event generator.



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

$\bar{\nu}$ dominated → CC-0p0π

ν dominated → CC-1p0π

Np	Events/400 kton year
CC-0p0π	~7000
CC-1p0π	~12000
CC-2p0π	~500
CC-0p1π	~200

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

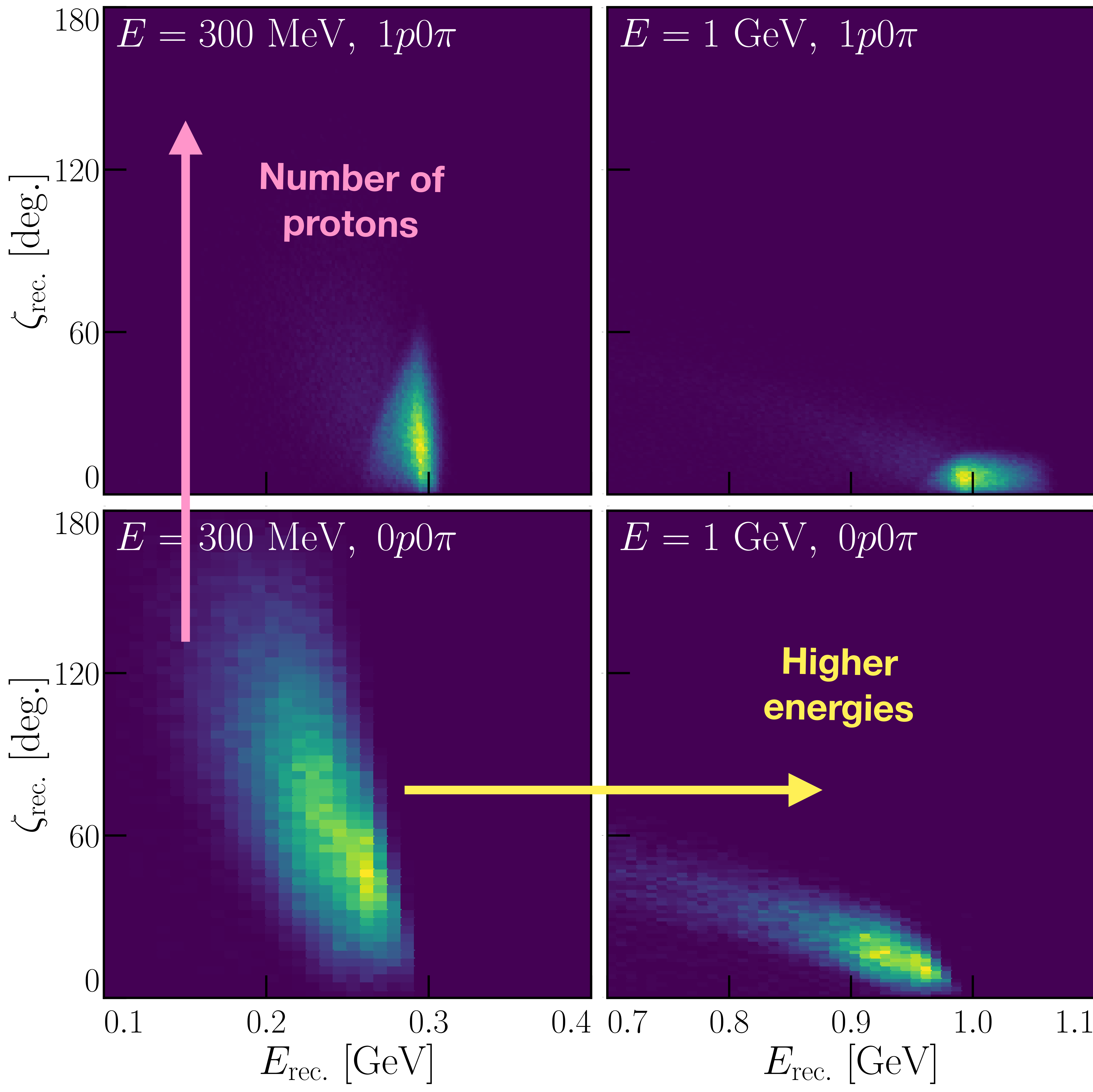
LArTPCs

Calorimetric reconstruction provides good results for GeV neutrinos with visible protons

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

	K.E.	Ang.	E
P	30MeV	10	10%
π	30MeV	10	10%
Λ	30MeV	10	10%
$\mu^\pm$	5MeV	2	5%
e	10MeV	2	5%

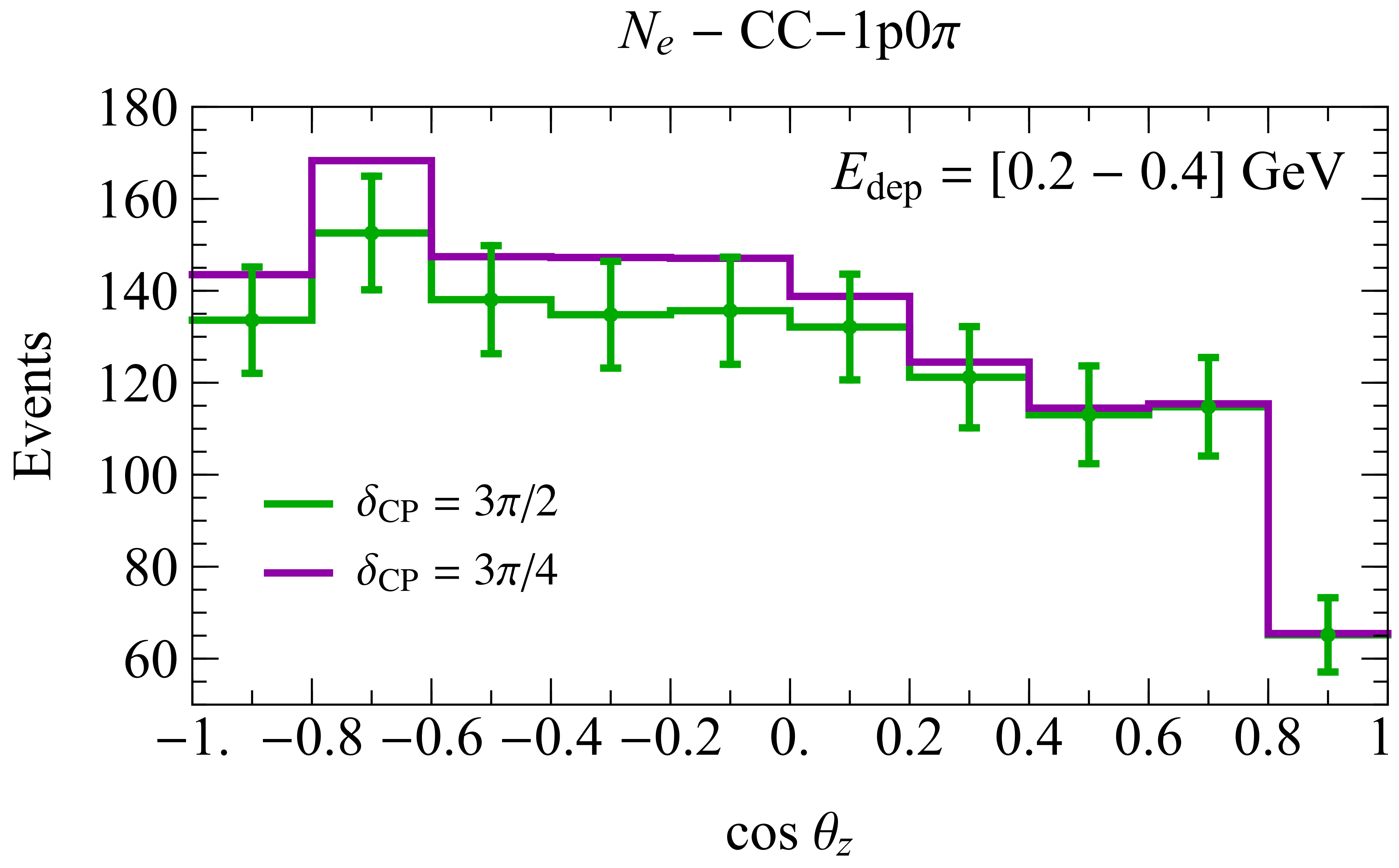
Kelly, Machado, IMS, Parke, Perez-Gonzalez, PRL 123 (2019)

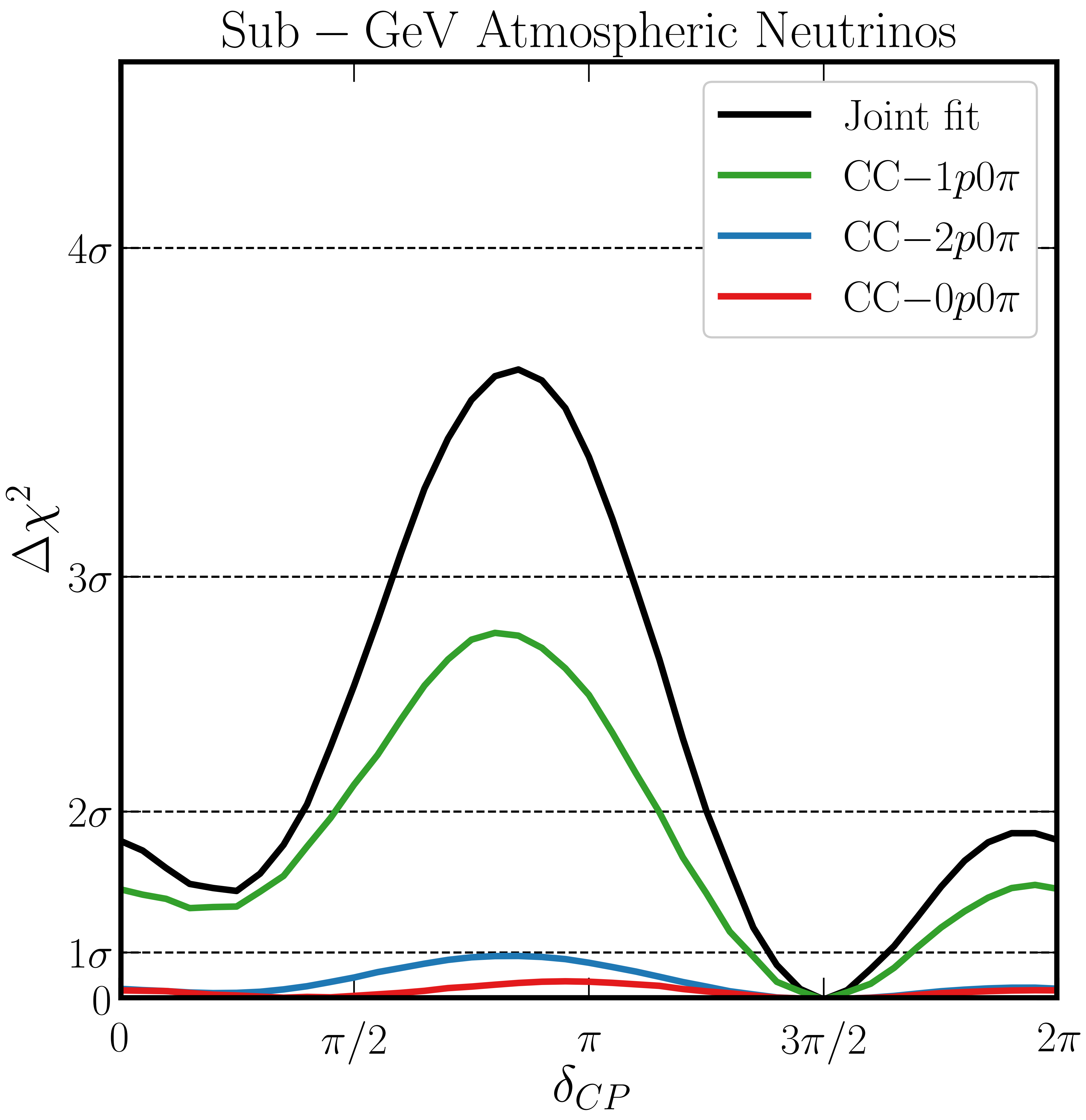


LArTPCs

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

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

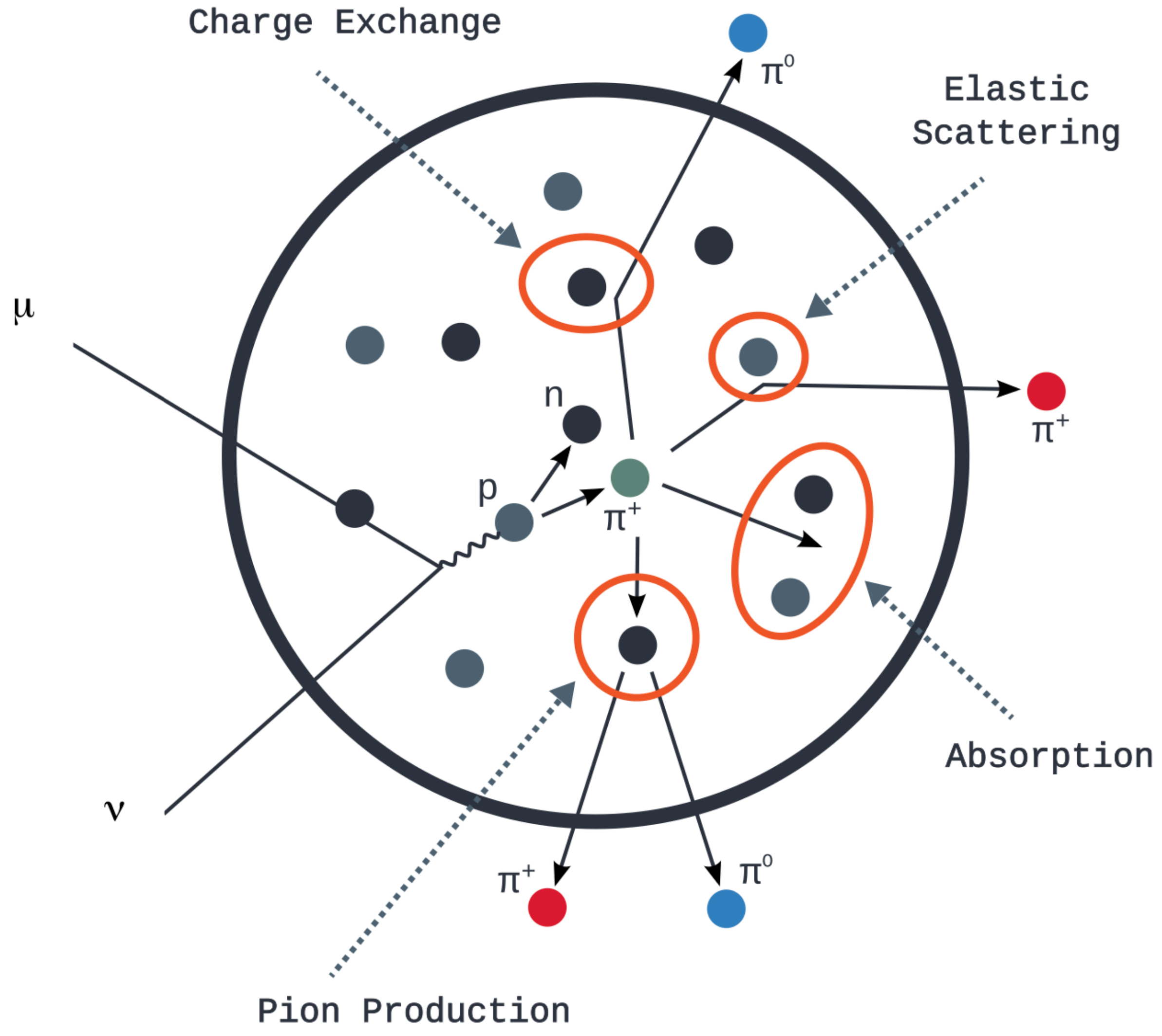




Kelly, Machado, IMS, Parke, Perez-Gonzalez, PRL 123 (2019)

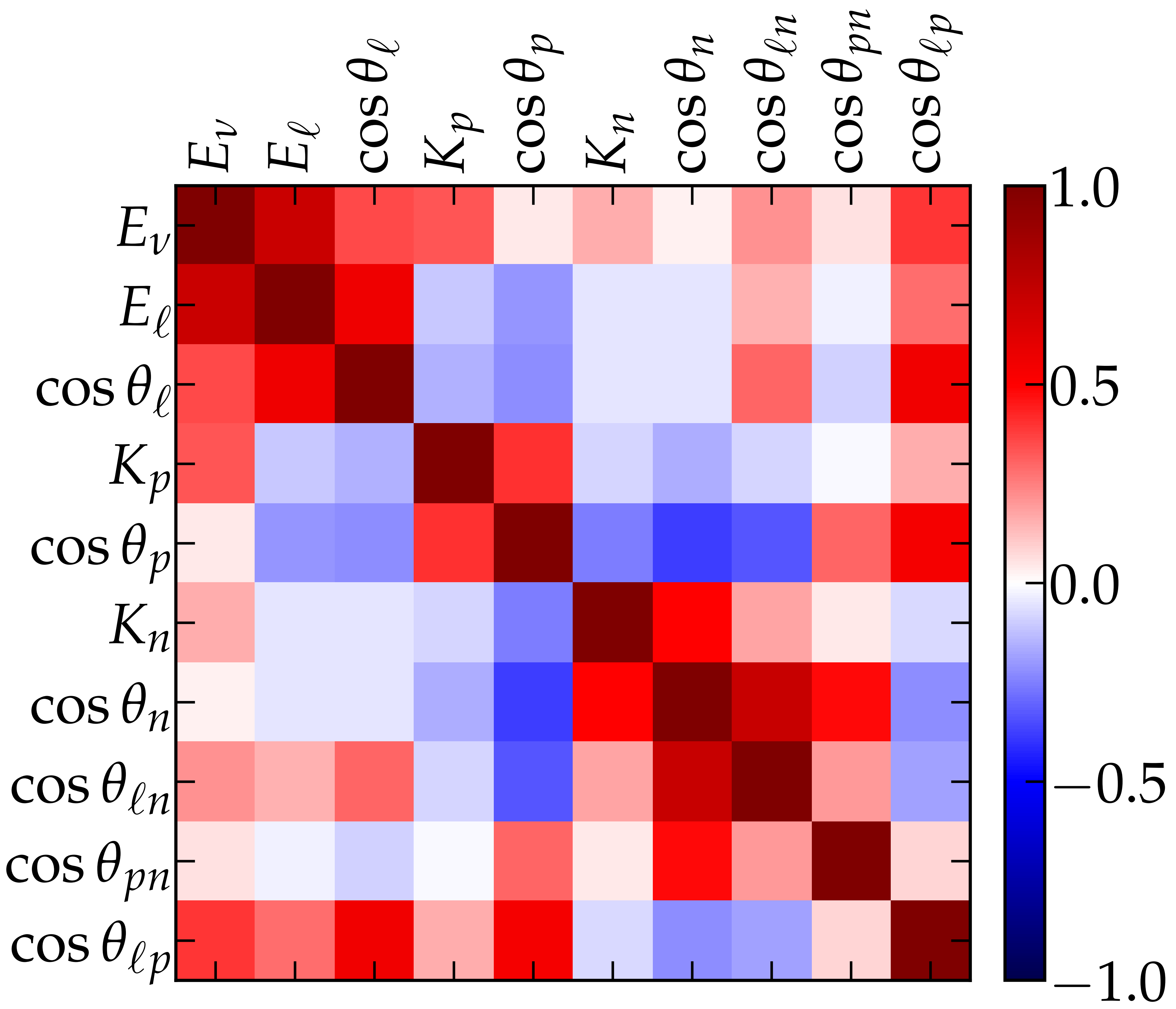
LArTPCs-DNN

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



Alvarez-Ruso et al. (NuSTEC), Prog.Part.Nucl.Phys. 100 (2018)

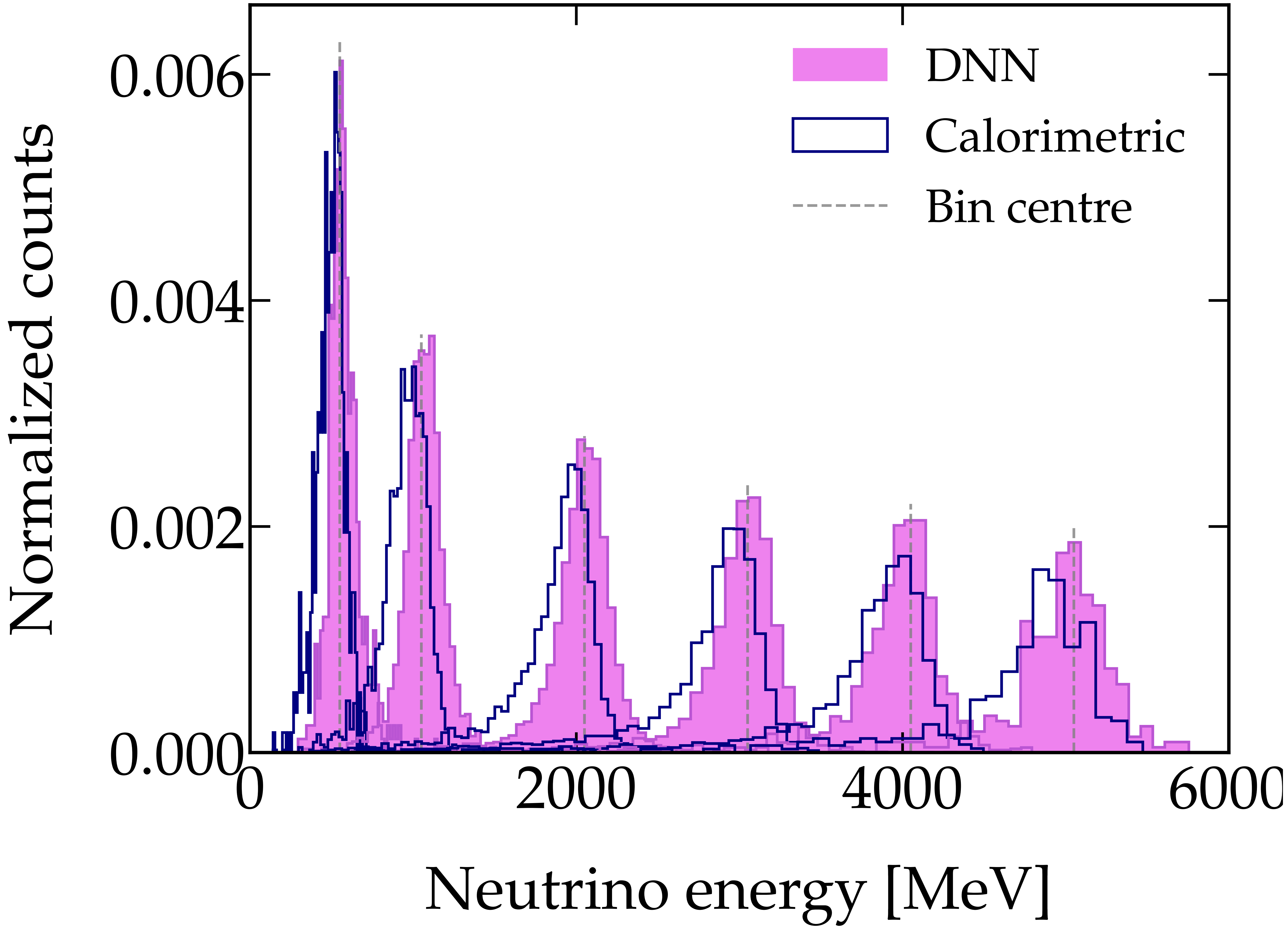
Complex correlation between the neutrino and the final state kinematics

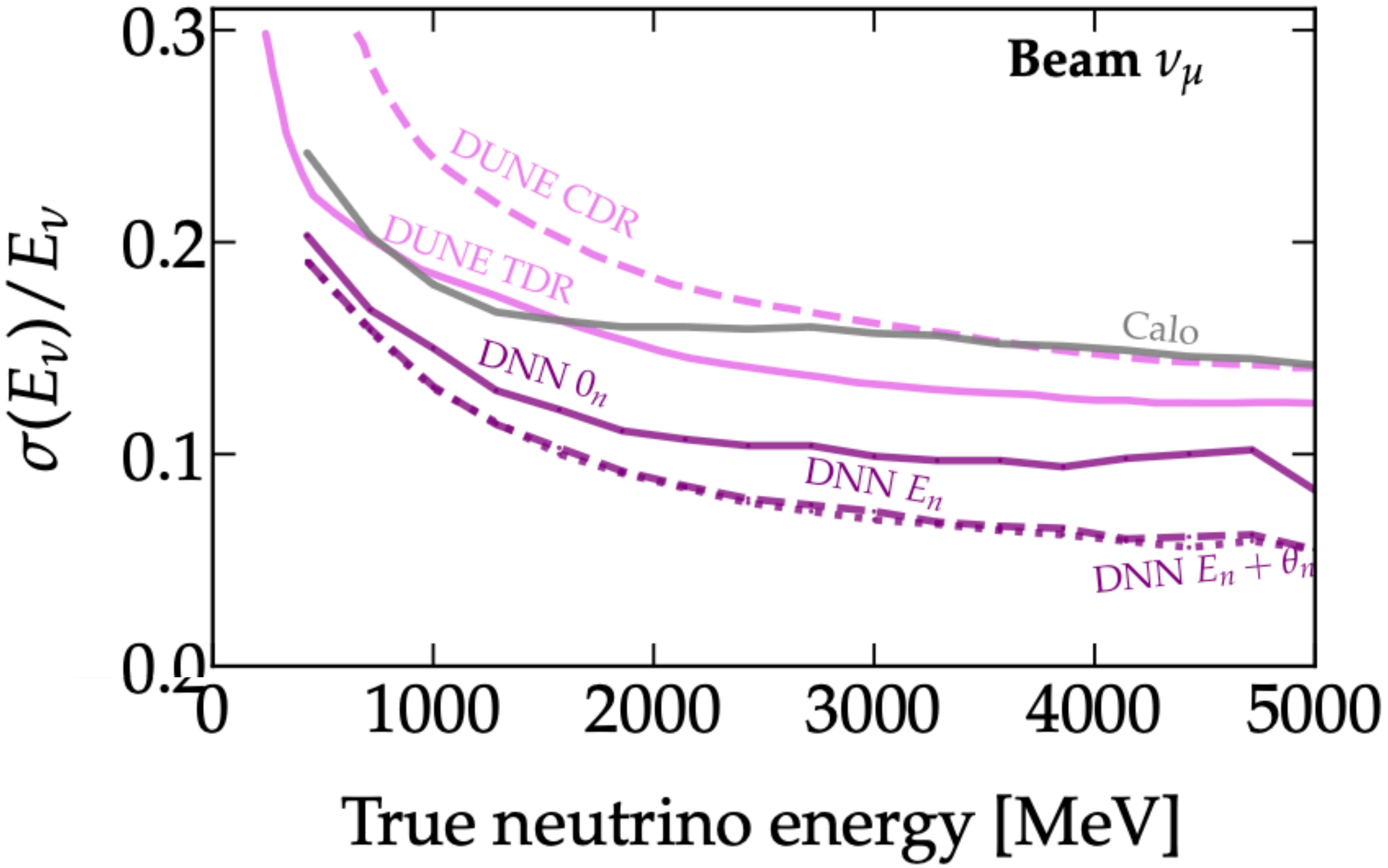


Kopp, Machado, MacMahon, IMS, arXiv: 2405.15867

LArTPCs-DNN

DNN improves the neutrino energy resolution at all the energies

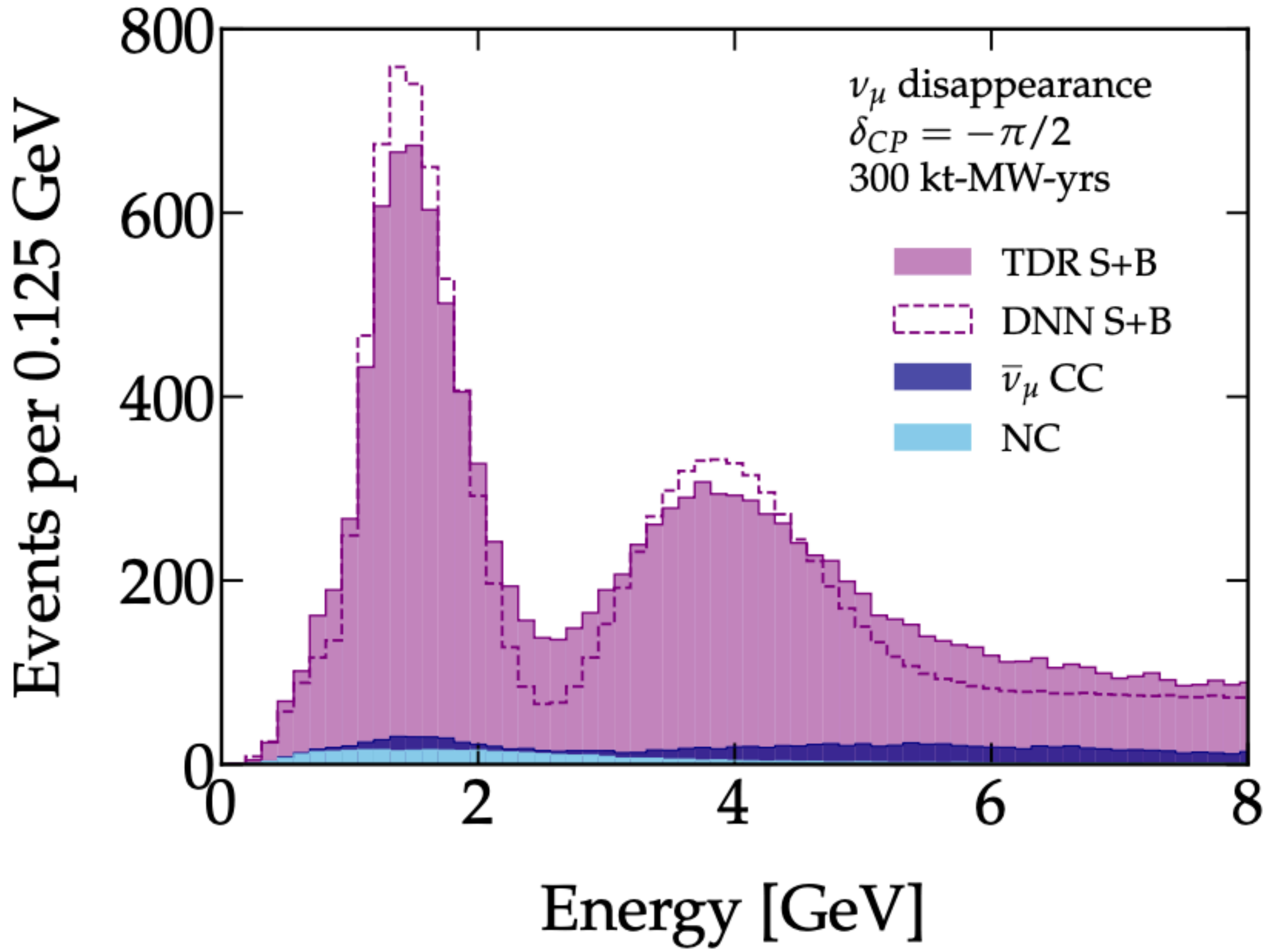


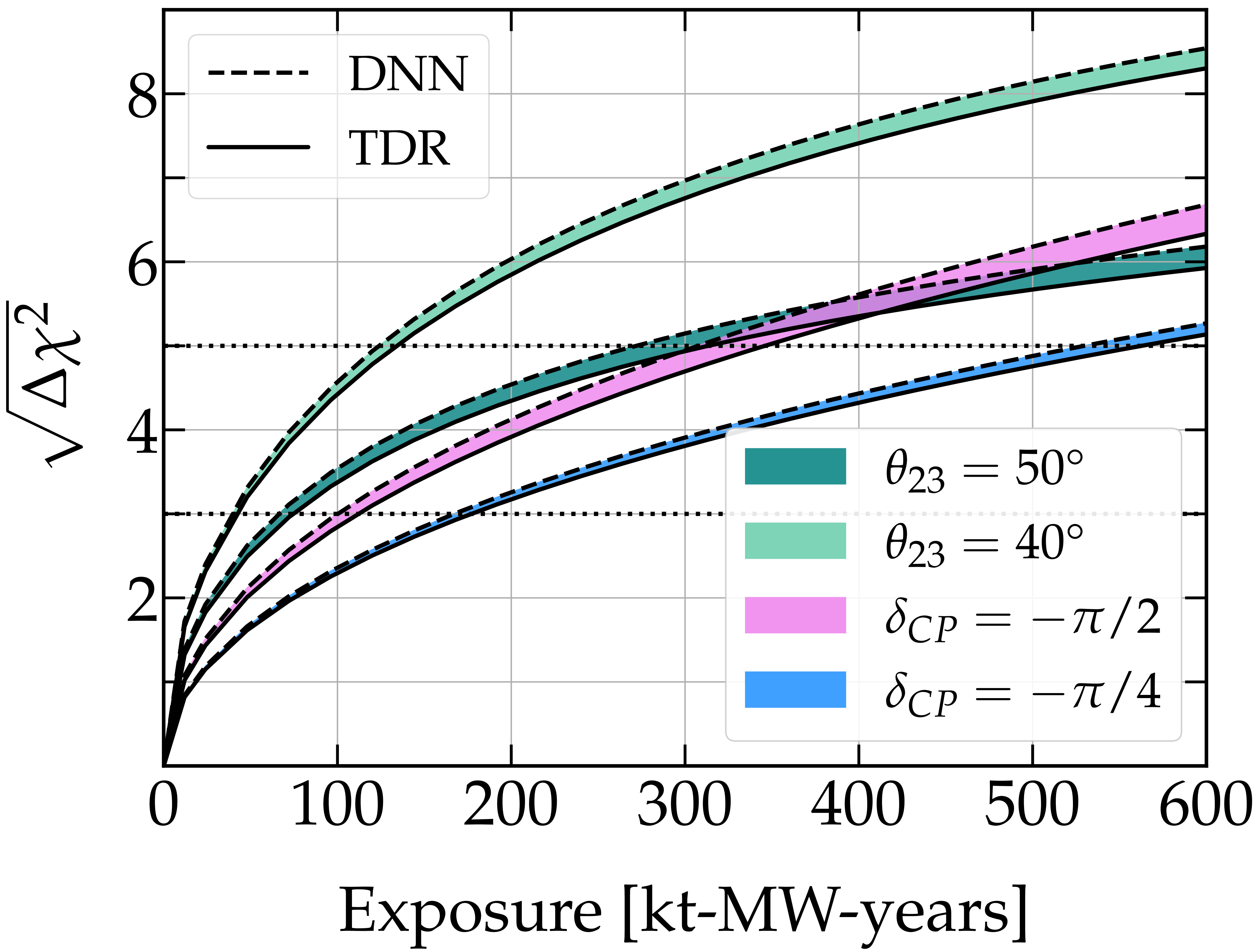


Kopp, Machado, MacMahon, IMS, arXiv: 2405.15867

LArTPCs-DNN

The improvement obtained by DNN leads to an increase in sensitivity to the oscillation parameters.



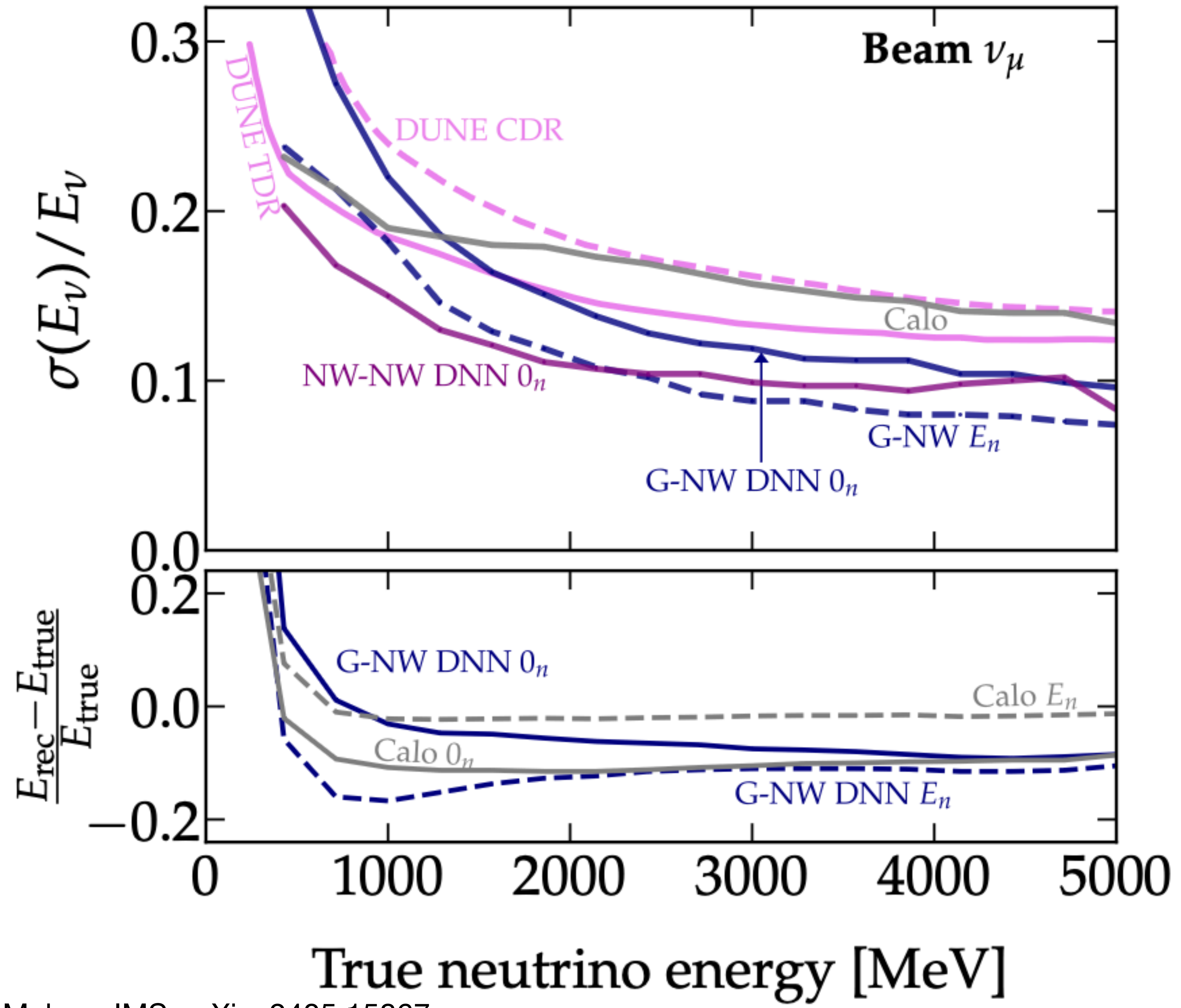


Kopp, Machado, MacMahon, IMS, arXiv: 2405.15867

LArTPCs-DNN

Mismodeling neutrino-nucleus cross-sections reduces energy resolution and biases reconstruction

The **DNN trained on NuWro** has been applied to events generated with **GENIE**.



Kopp, Machado, MacMahon, IMS, arXiv: 2405.15867

BSM

Heavy Sterile Neutrino

To explain the origin of the neutrino masses, the SM can be considered as a low energy effective model

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \frac{\mathscr{L}_{d=5}}{\Lambda} + \cdots$$

- At d=5, we have the Weinberg operator

Type-I seesaw:
- Introduce right-handed neutrinos
- Allow L number violation

$$\mathscr{L}^{\nu}_{mass} \supset Y_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} M_R \bar{N}^c_R N_R + h.c.$$

- For $M_R >> v$

$$m_\nu \sim \frac{Y^\dagger_\nu Y_\nu v^2}{M_R} \qquad m_N \approx M_R + \mathcal{O}(m_\nu)$$

- Neutrino masses can be smaller than other fermion masses
- Heavy neutrinos can hardly be tested
- There are other scenarios where the Majorana mass can take smaller values

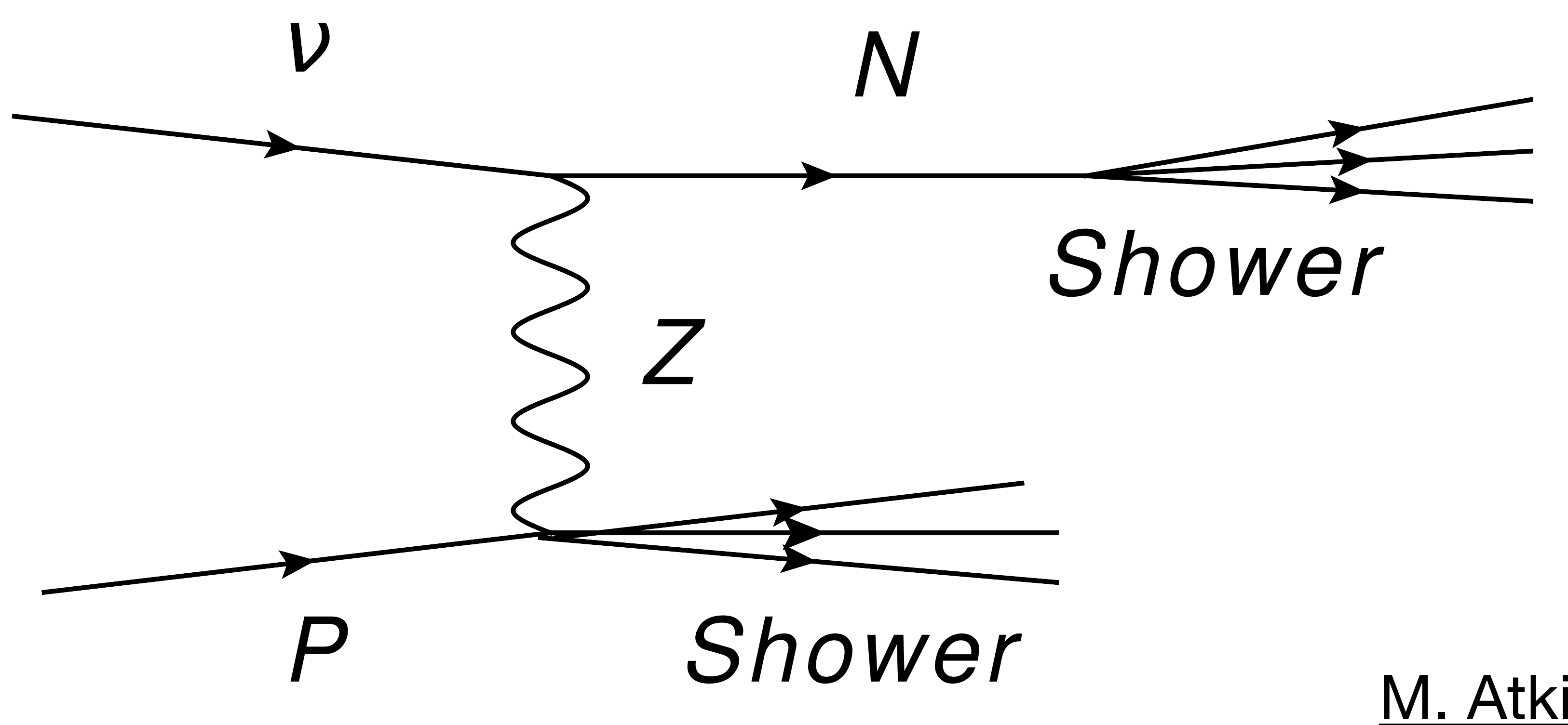
Heavy Sterile Neutrino

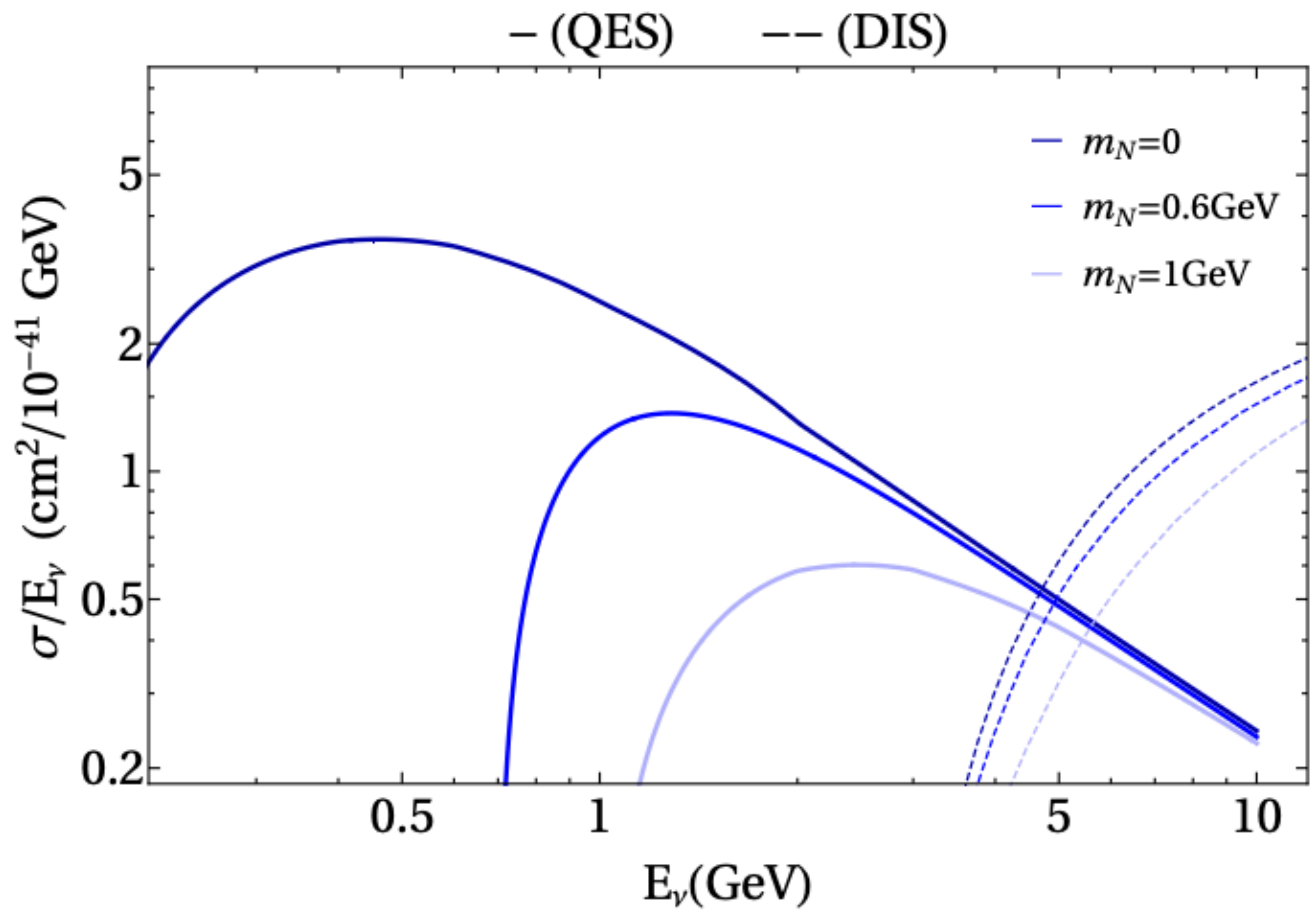
In the presence of N_R, the flavor states can be written as a superposition of massive states as

$$\nu_{\alpha L} = \sum U_{\alpha m}\nu_{mL} + U_{\alpha 4}N_{4L}$$

We can look for HNLs using **double bang signals**

$$\nu + N \to N_4 + \text{shower}$$
$$N_4 \to \nu + \text{signal}$$





M. Atkinson, P. Coloma, IMS, N. Rocco, IM Shoemaker, JHEP 04 (2022)

Heavy Sterile Neutrino

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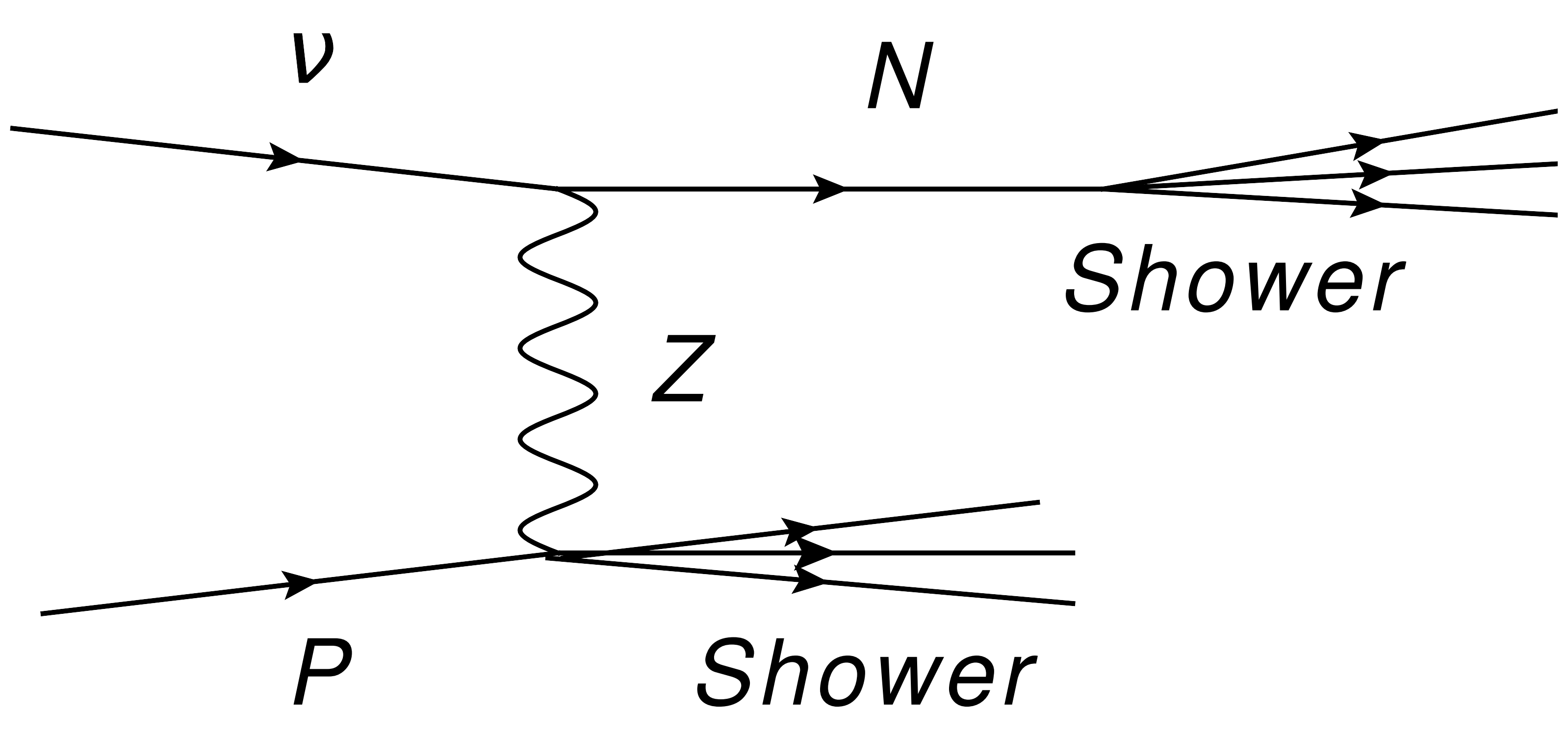
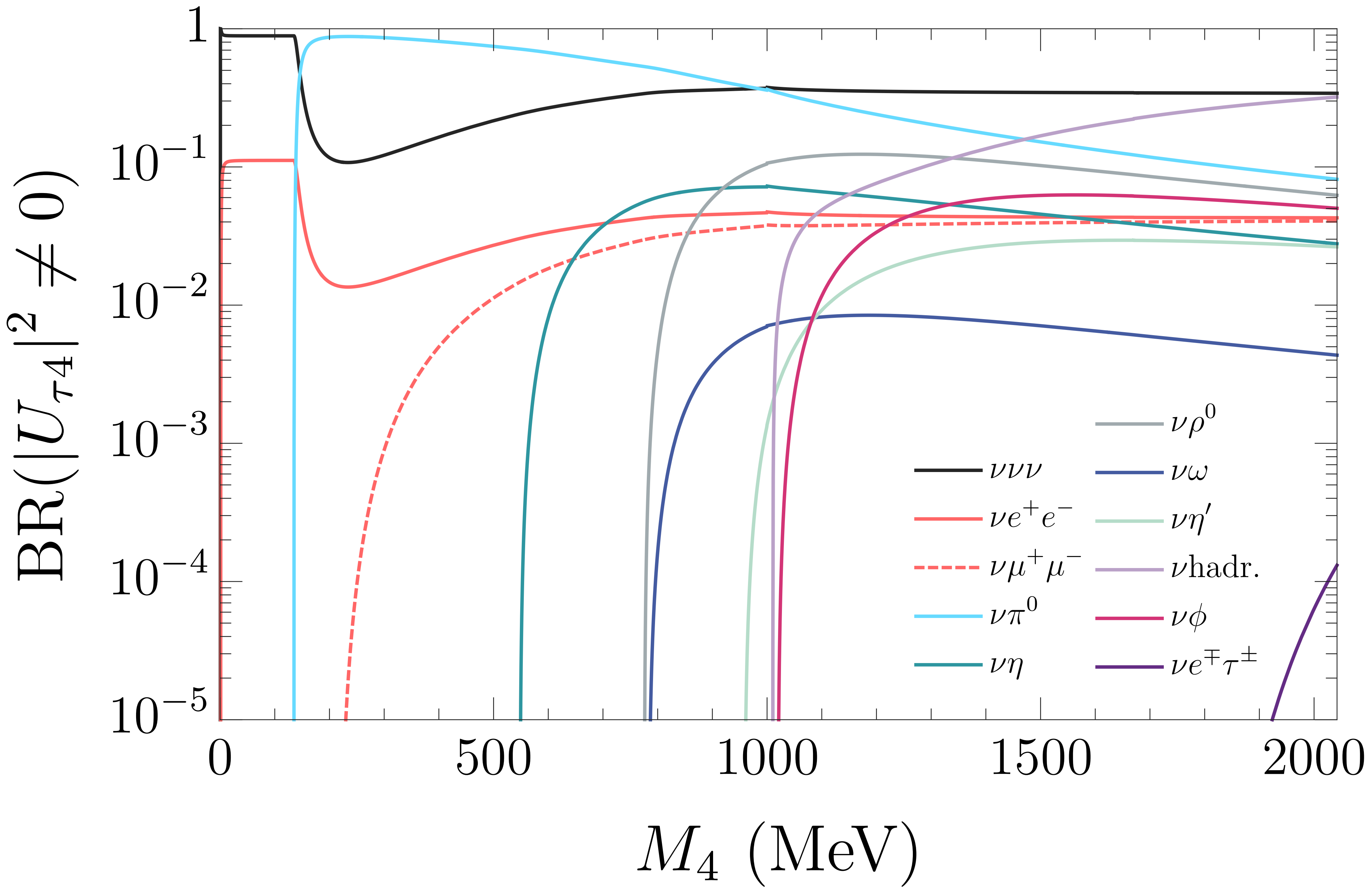




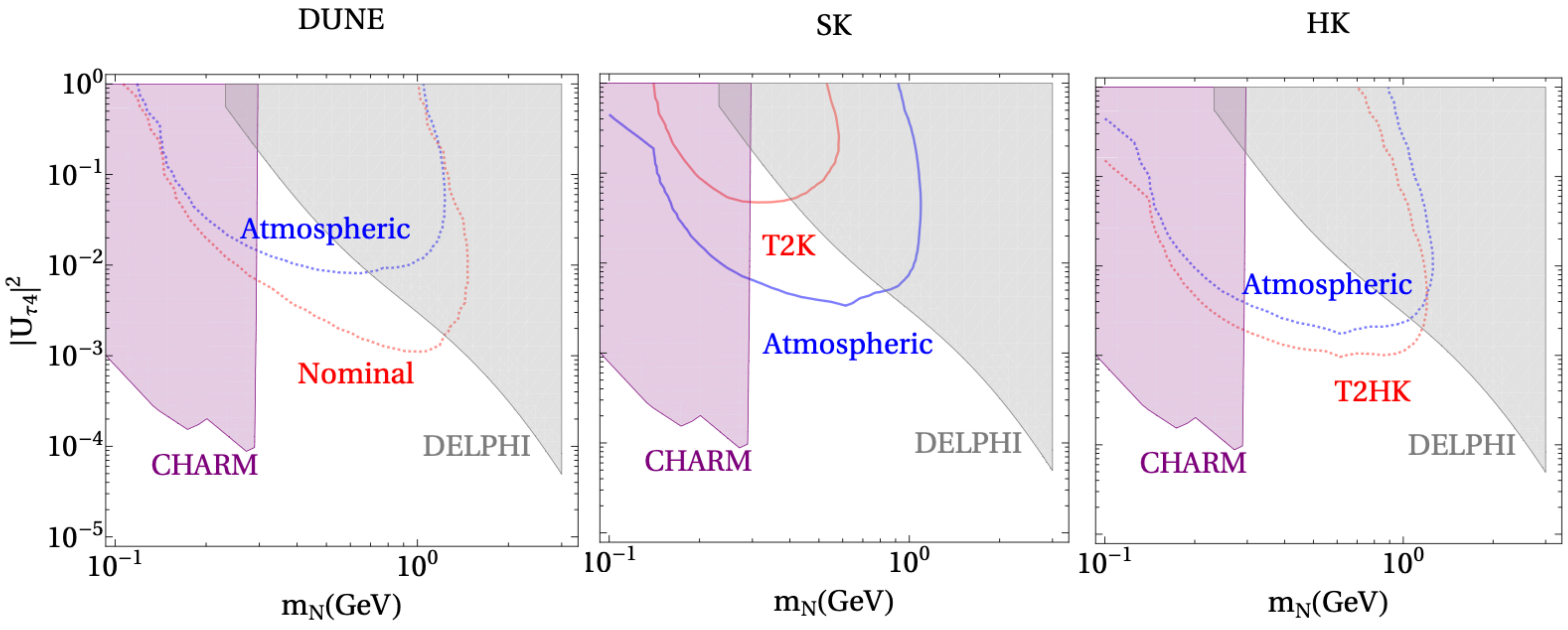
P Coloma, E. Fernandez-Martinez, M. Gonzalez-Lopez, J. Hernandez-Garcia, Z. Pavlovic, EPJC 81 (2021)

Heavy Sterile Neutrino

Several experiments can search for HNLs by looking for a double-bang event topology

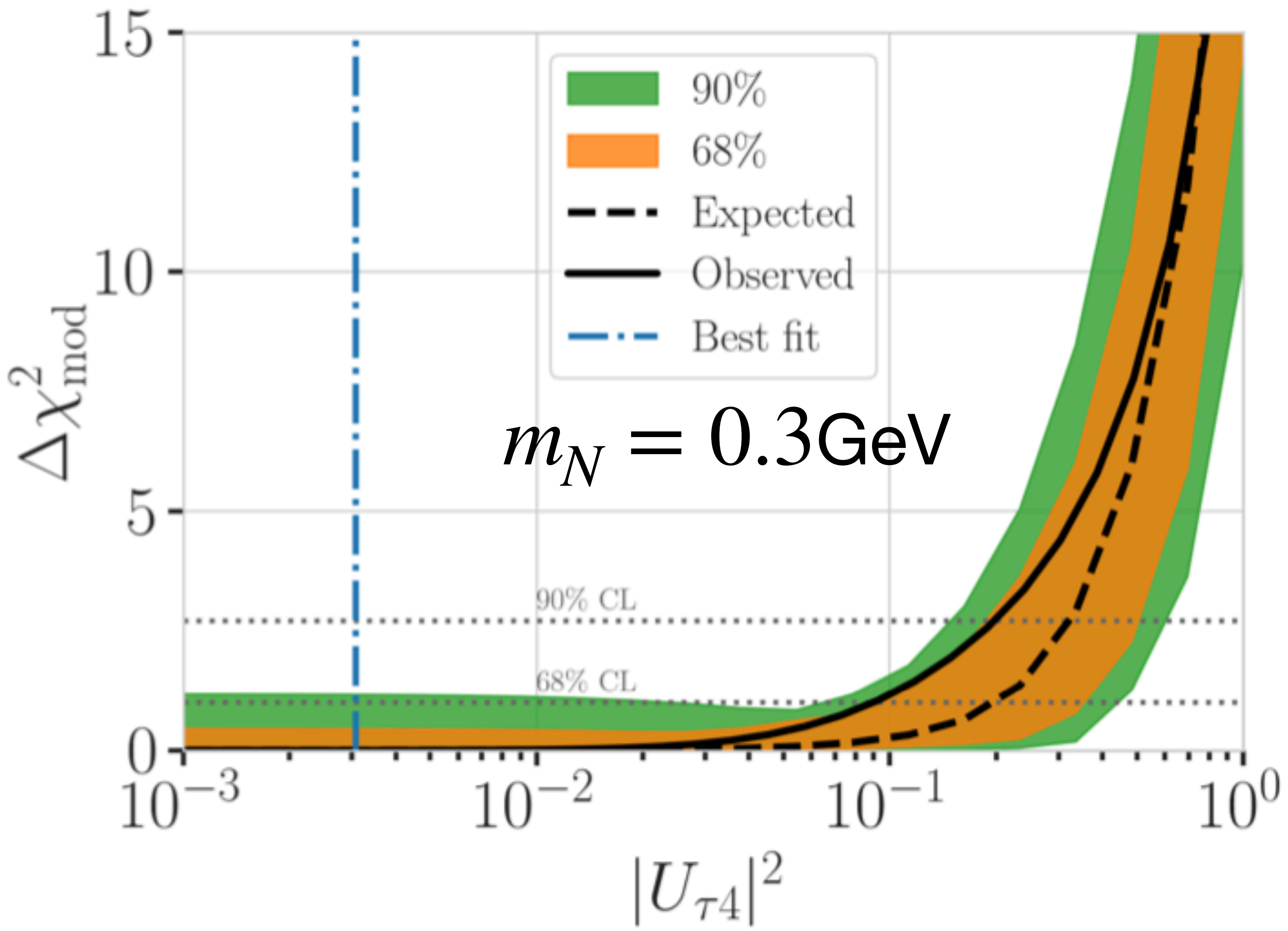
For masses around the GeV scale, $U_{\tau 4}^2 < 10^{-6}$

Fernandez-Martinez, Gonzalez-Lopez, Hernandez-Garcia, Hostert, Lopez-Pavon, JHEP 09 (2023)



M. Atkinson, P. Coloma, IMS, N. Rocco, IM Shoemaker, JHEP 04 (2022)

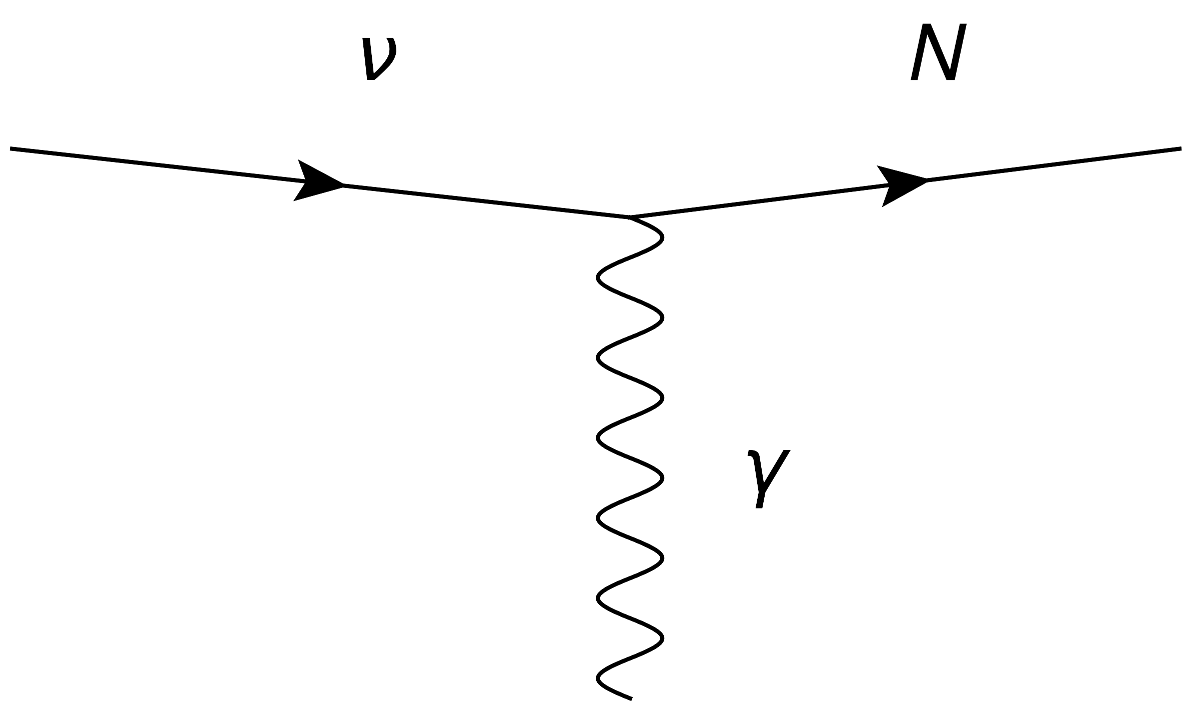
IceCube has used this topology to search for HNLs



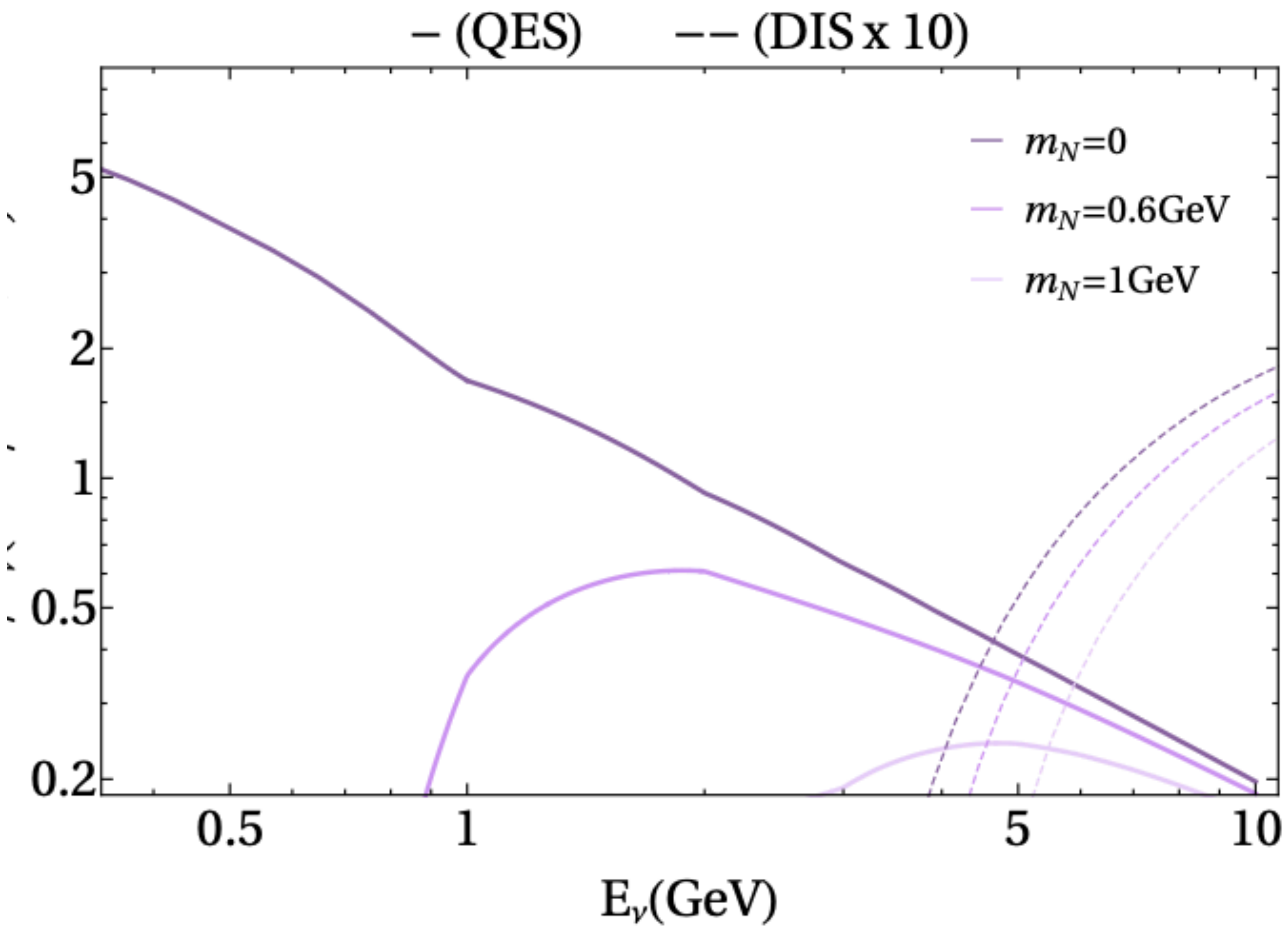
Abbasi et al. (IceCube), arXiv:2502.09454

Transition Magnetic Moment

Active and HNL states may be coupled via a **transition dipole moment**



$$\mathscr{L} \supset -\mu_\nu \bar{N}_4 \sigma_{\mu\nu} P_L \nu_\alpha F^{\mu\nu}$$

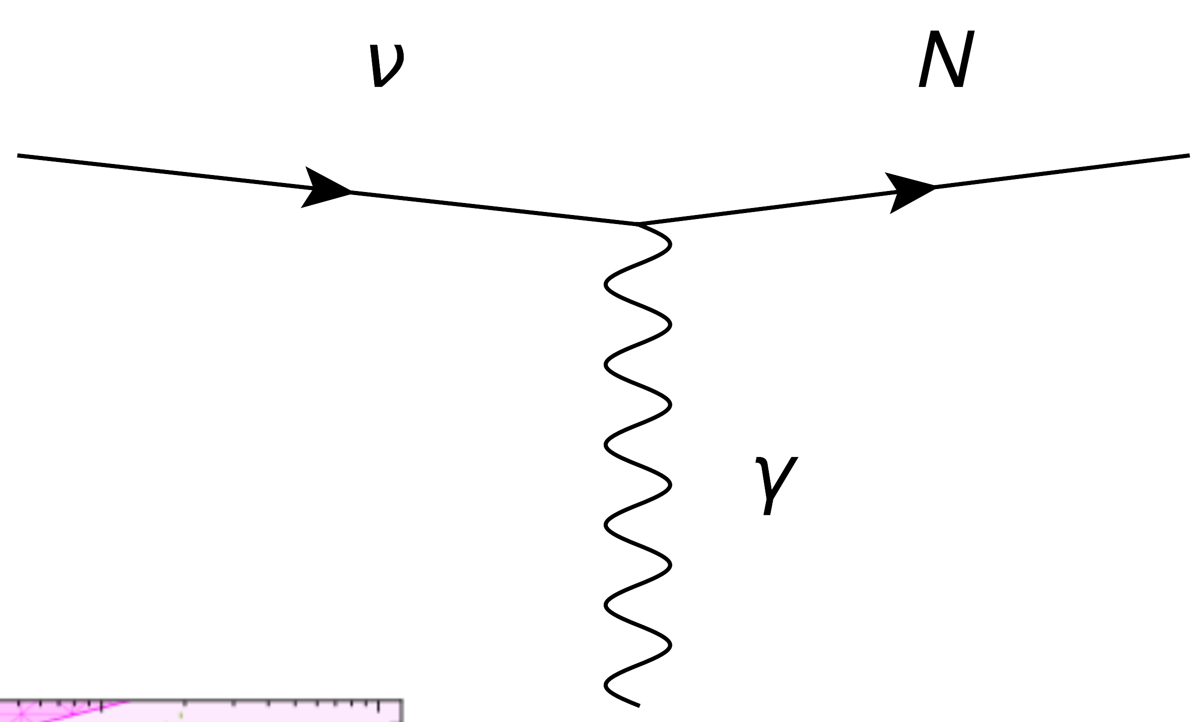


We are going to consider that both the HNL production and decay are given by the dipole moments ($N \to \nu_i \gamma$)

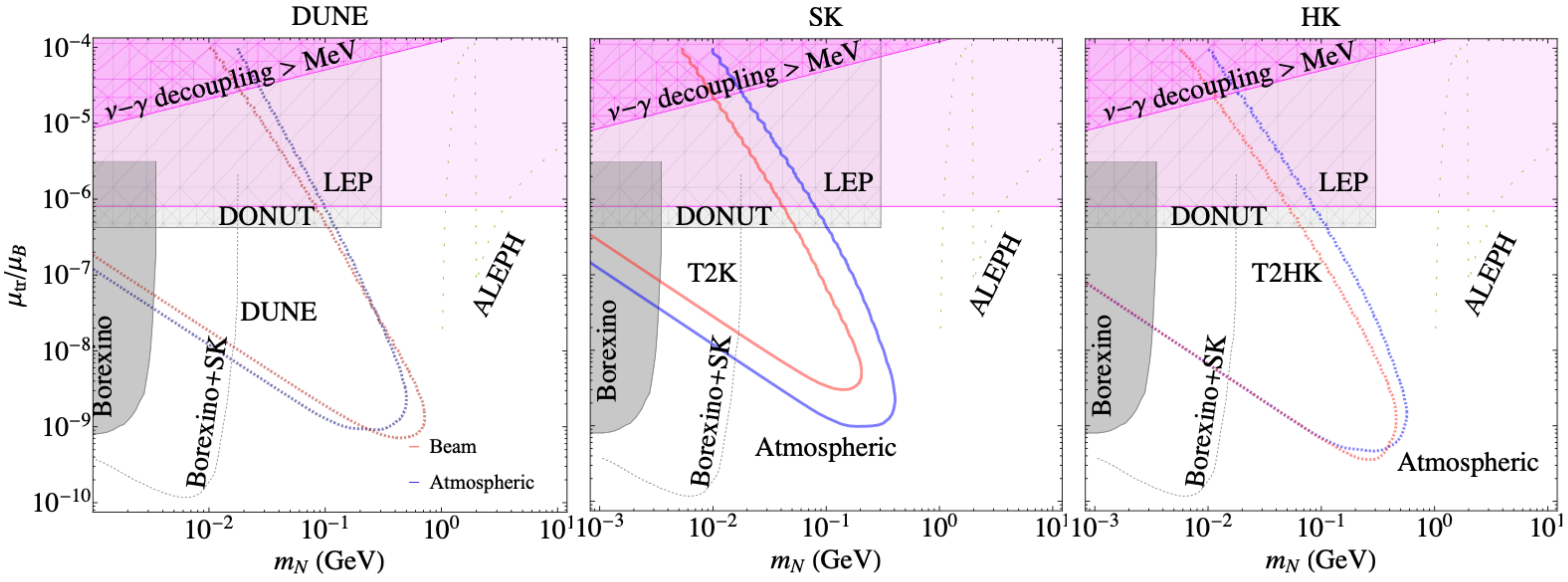
$$\Gamma = \frac{\mu_\nu^2 M_4^3}{4\pi}$$

M. Atkinson, P. Coloma, IMS, N. Rocco, IM Shoemaker, JHEP 04 (2022)

Transition Magnetic Moment



Active and HNL states may be coupled via a **transition dipole moment**



M. Atkinson, P. Coloma, IMS, N. Rocco, IM Shoemaker, JHEP 04 (2022)

Conclusions

Neutrino physics is entering the **precision** era. Most parameters are known at the percent level, but several open questions remain:

- For θ_{23}, small preference for the **lower octant** (higher octant), combining IC24+SK+global fit (global)
- For δ_{cp}, almost **the entire region is allowed**, with CP-conservation preferred for NO and maximal CP-violation for IO.
- **Mass ordering** shows small preference until IC24+SK is included, which favors NO.

With the next generation of experiments, **precise knowledge of the neutrino-nucleon cross-section** in a wide energy range (from ~100 MeV to ~100 GeV) will be essential to probe neutrino oscillation and search for BSM.

Deep neural networks (DNN) can improve the neutrino reconstruction, leveraging the rich data expected from the next-generation experiments

Thanks!

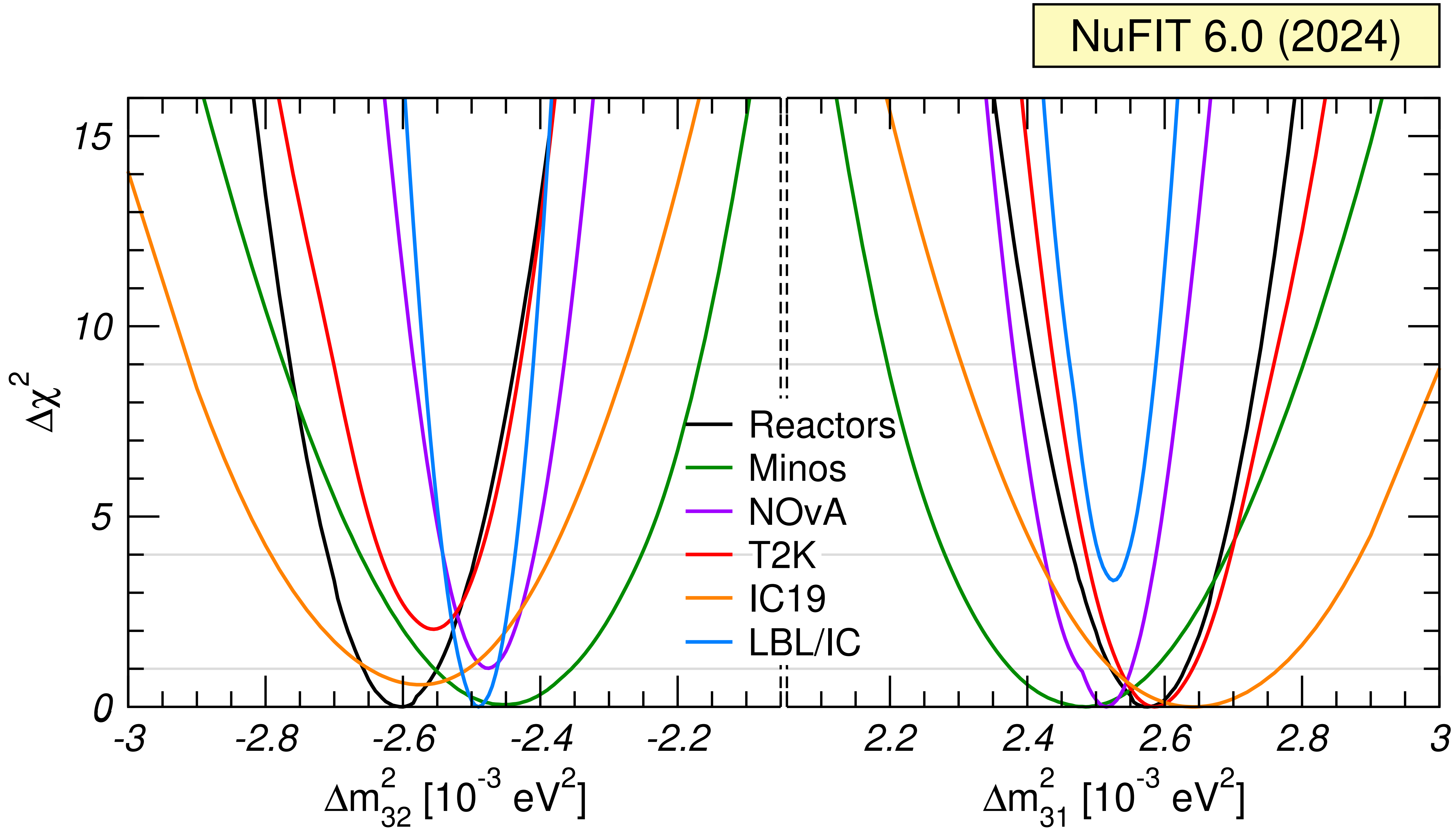
Conclusions

	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

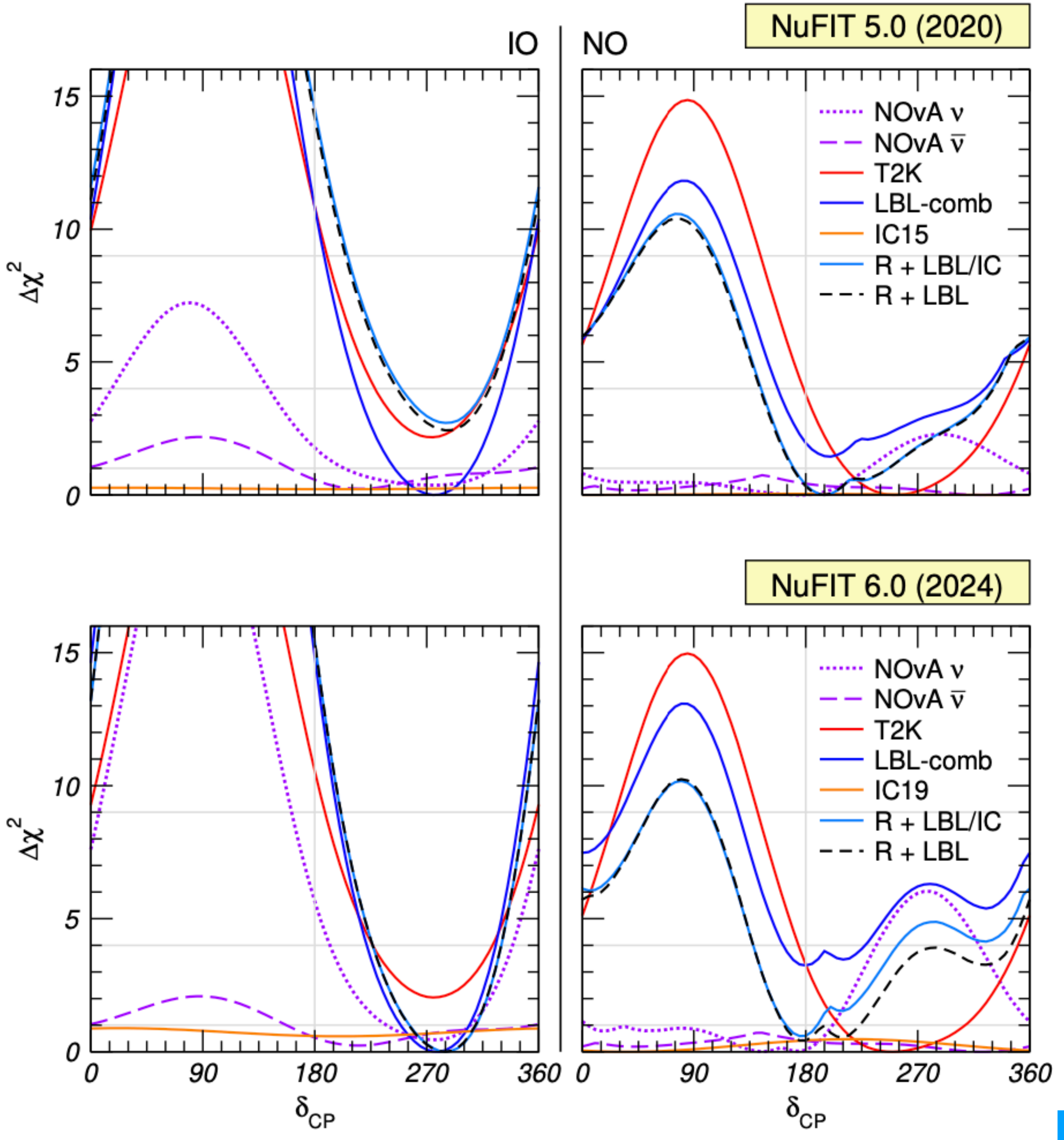
Long-Baseline Accelerators

- Each experiment shows a preference for NO
- The LBL combination leads to a preference for IO due to NOvA T2K tensions



Long-Baseline Accelerators

The LBL combined analysis favors CP phase near $\delta_{CP} \sim 212^o$

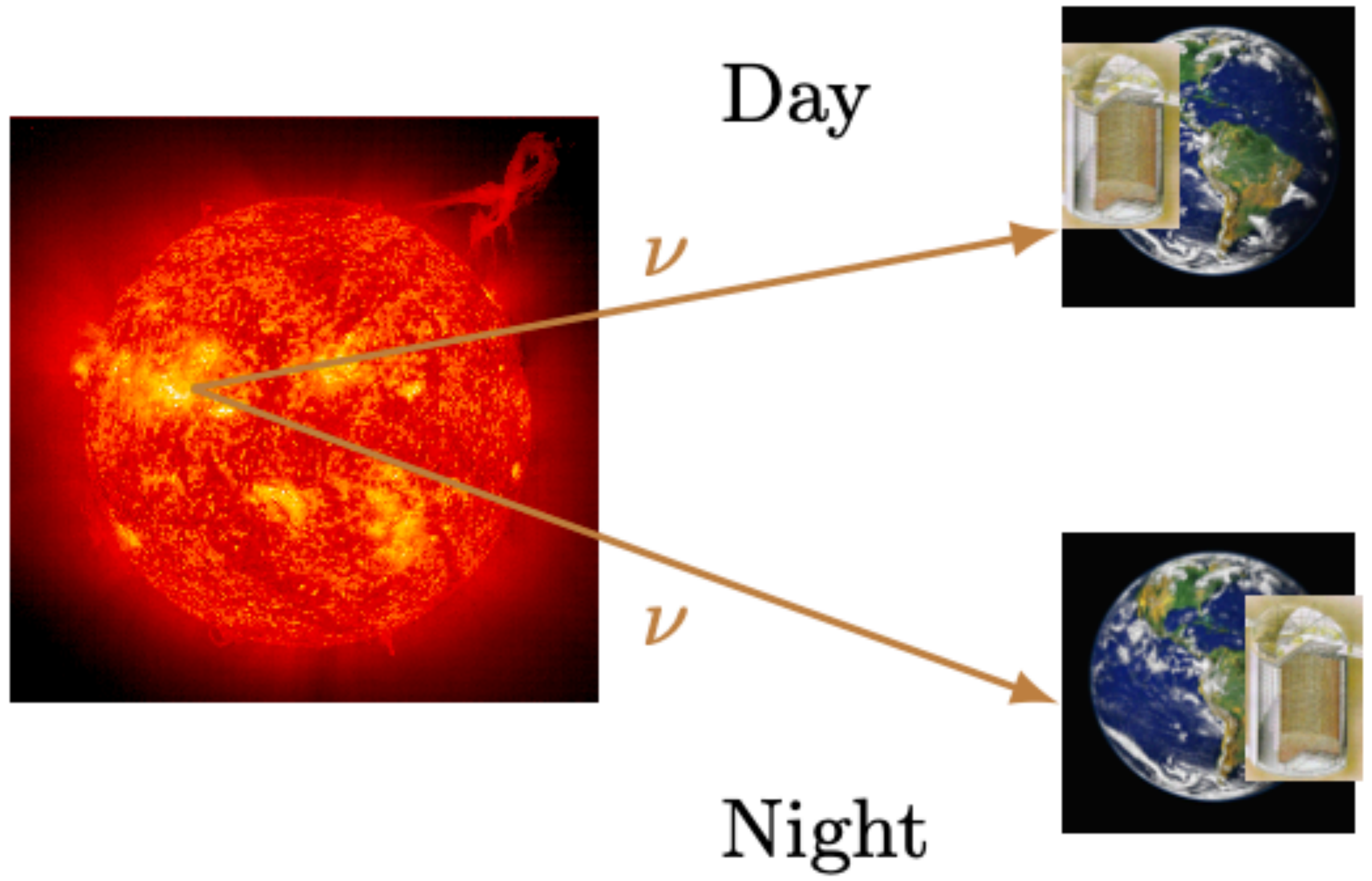


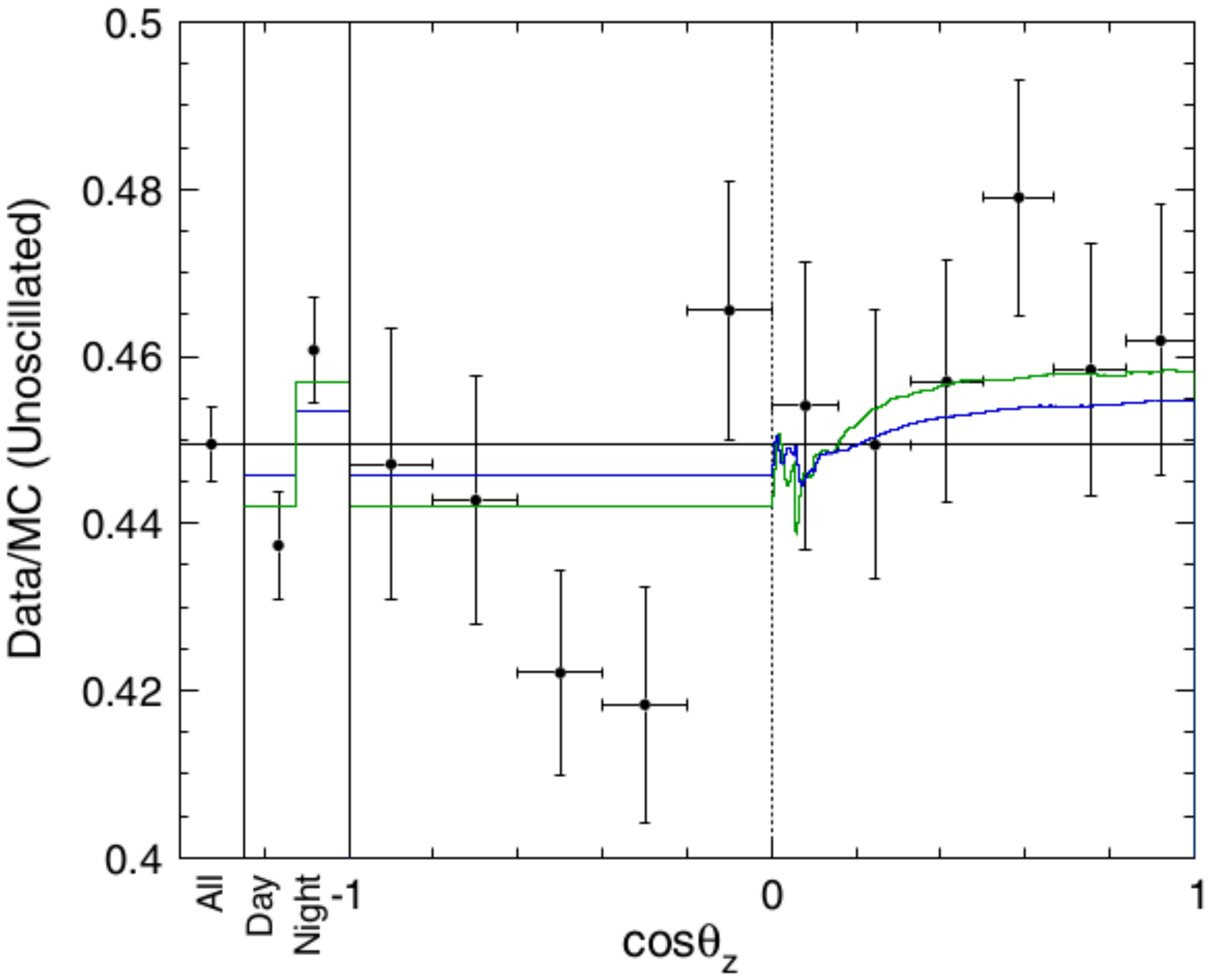
Solar Neutrinos: Day-Night Asymmetry

Day-night asymmetry shows a preference for lower Δm^2_{21}

$$A_{D/N} = \frac{\Phi_{\text{day}} - \Phi_{\text{night}}}{0.5 * (\Phi_{\text{day}} + \Phi_{\text{night}})}$$

SK4-2055	SK4-2970
$-3.1\,\%$	$-2.1\,\%$

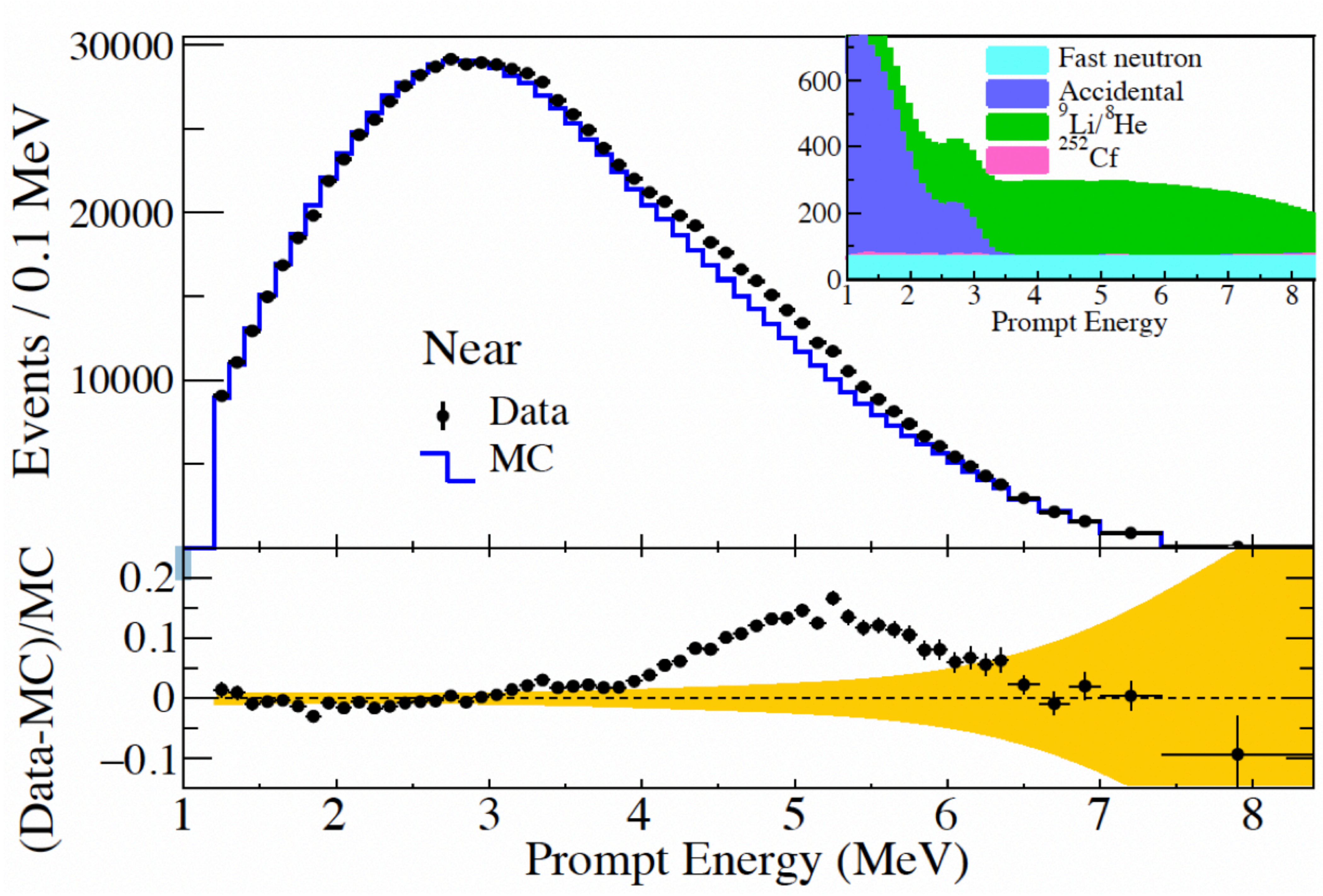




K. Abe et al., PRD 94 (2016) arXiv:1606.07538

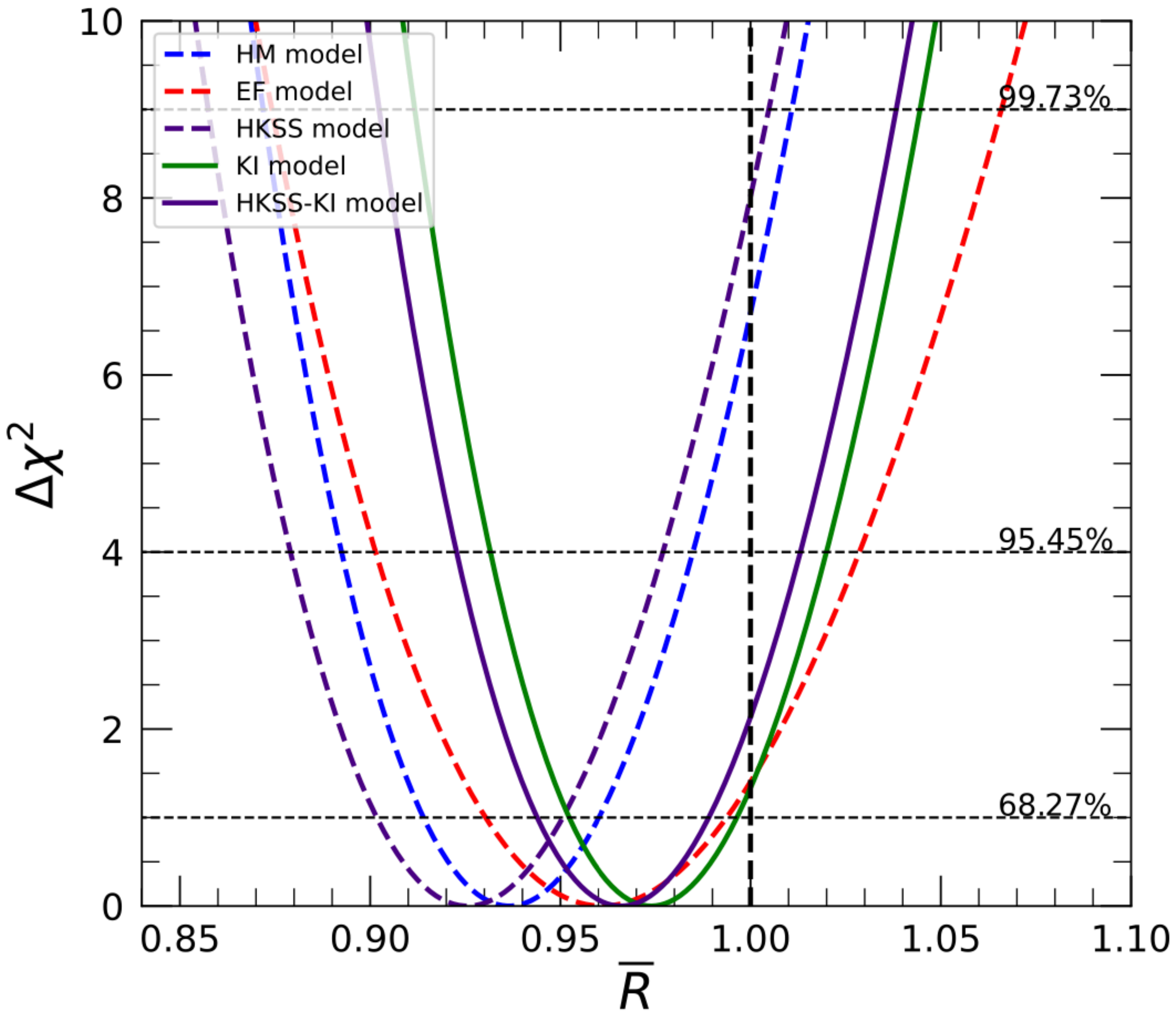
Reactor Flux Uncertainties

The flux shows an excess at 5 MeV



Kwang Joo (RENO), Neutrino 2022

Reevaluations of the $\overline{\nu}_e$ flux determined a deficit in the experimental data

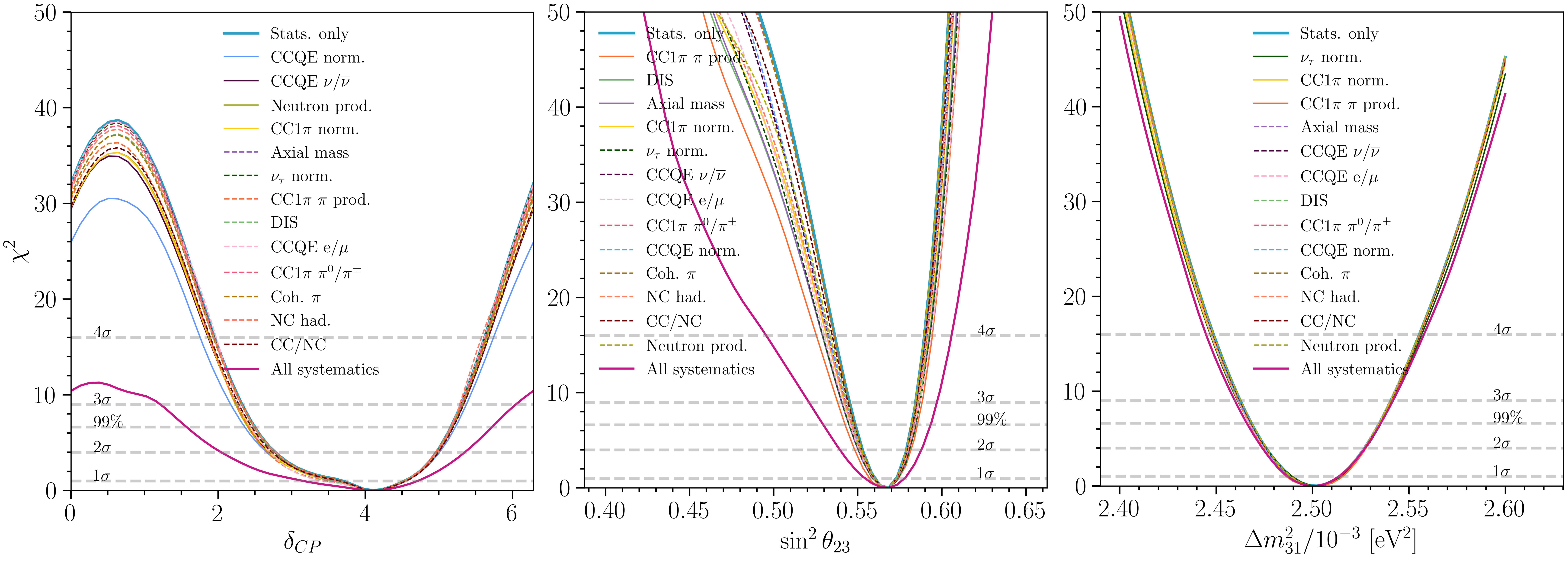


Giunti, Li, Ternes, Xin PLB 829 (2110.06820)

- New evaluations of the flux aliviate those tensions
- The uncertainties do not affect the determination of the oscillation parameters because they are based on a near/far comparison

Systematic impact

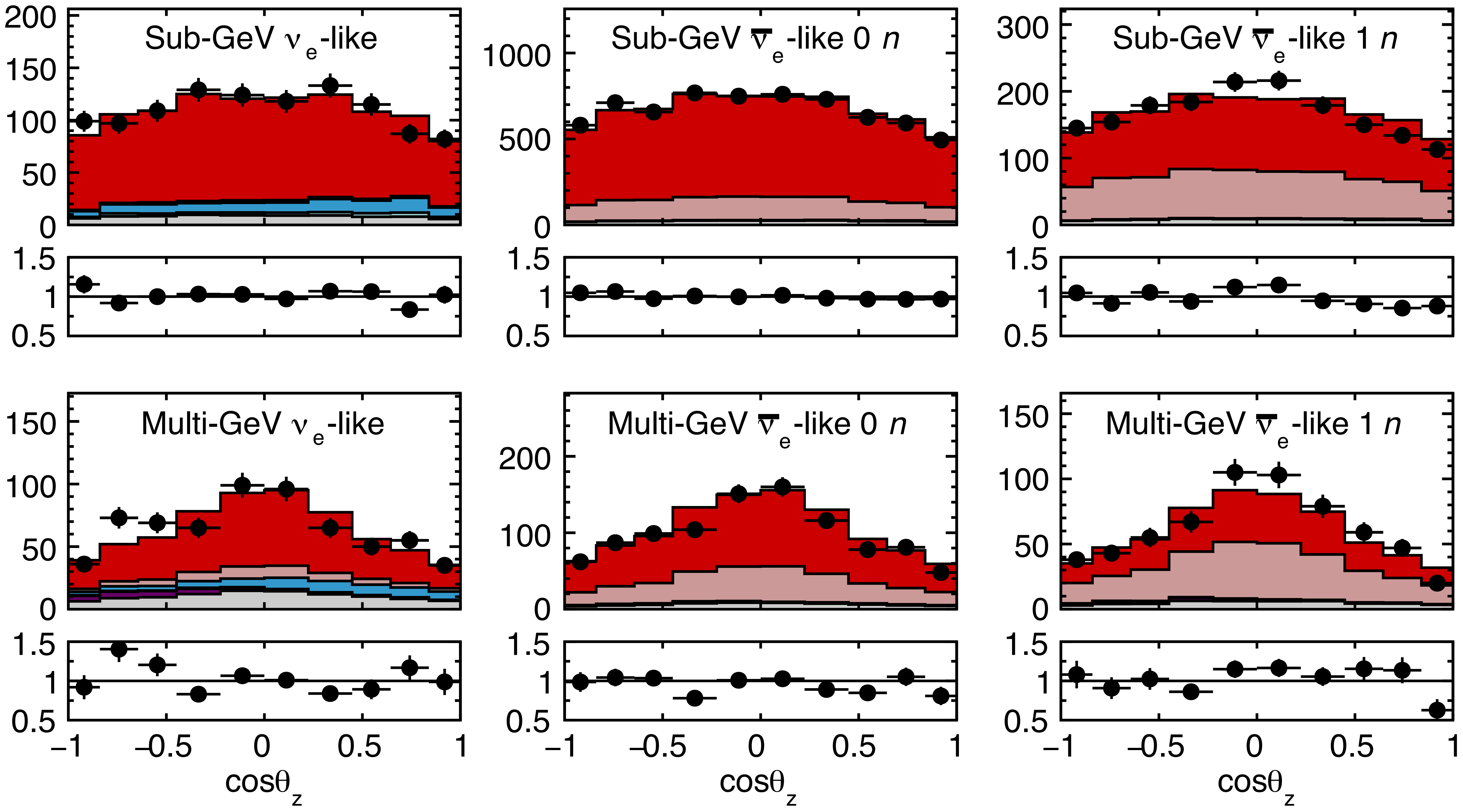
Among the other parameters, the cross-section uncertainties have the largest impact on the CP-phase

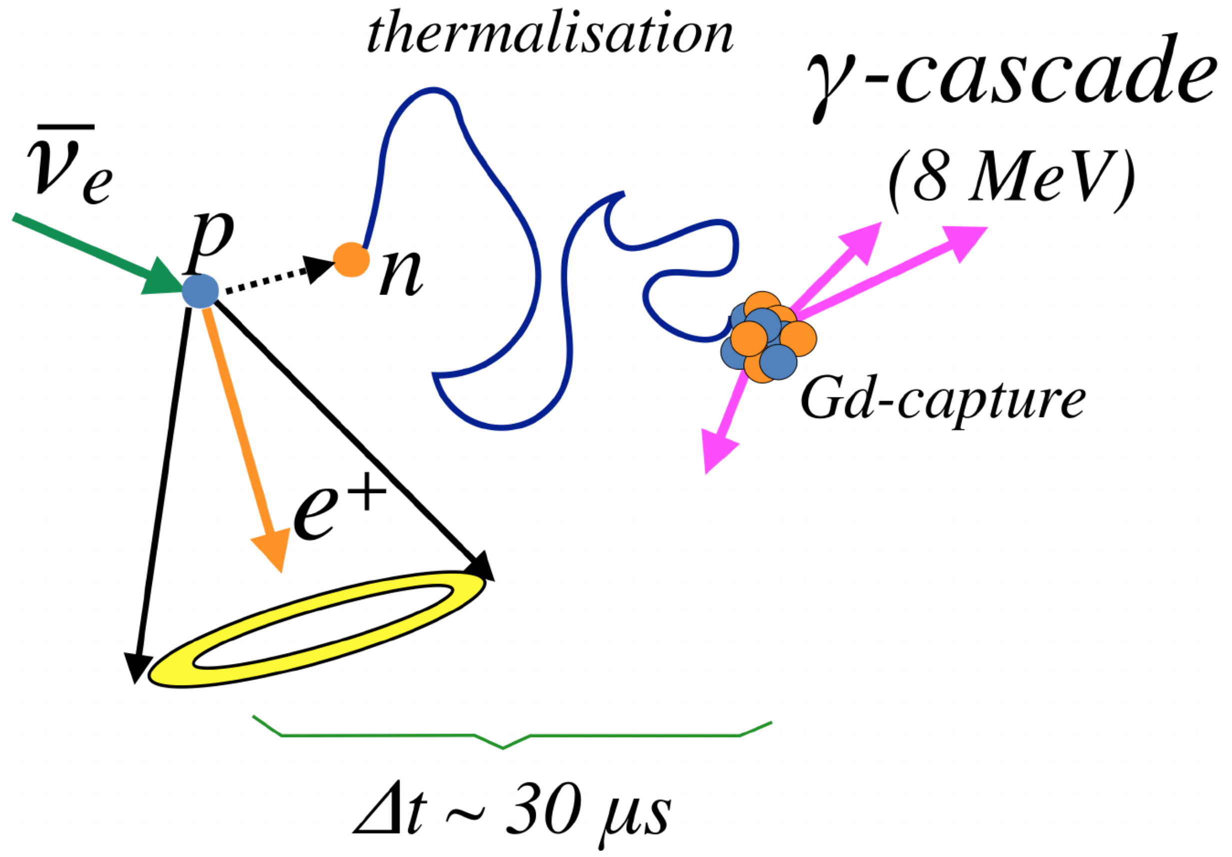


Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

Super-/Hyper-Kamiokande

Gadolinium (Gd) in water helps Super-Kamiokande tag neutrons and distibguish neutrinos from antineutrinos





Beacom and Vagins, PRL 93 (2004)

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

P.F. Menéndez, Ph.D. thesis