Measuring Oscillations with a Million Atmospheric Neutrinos

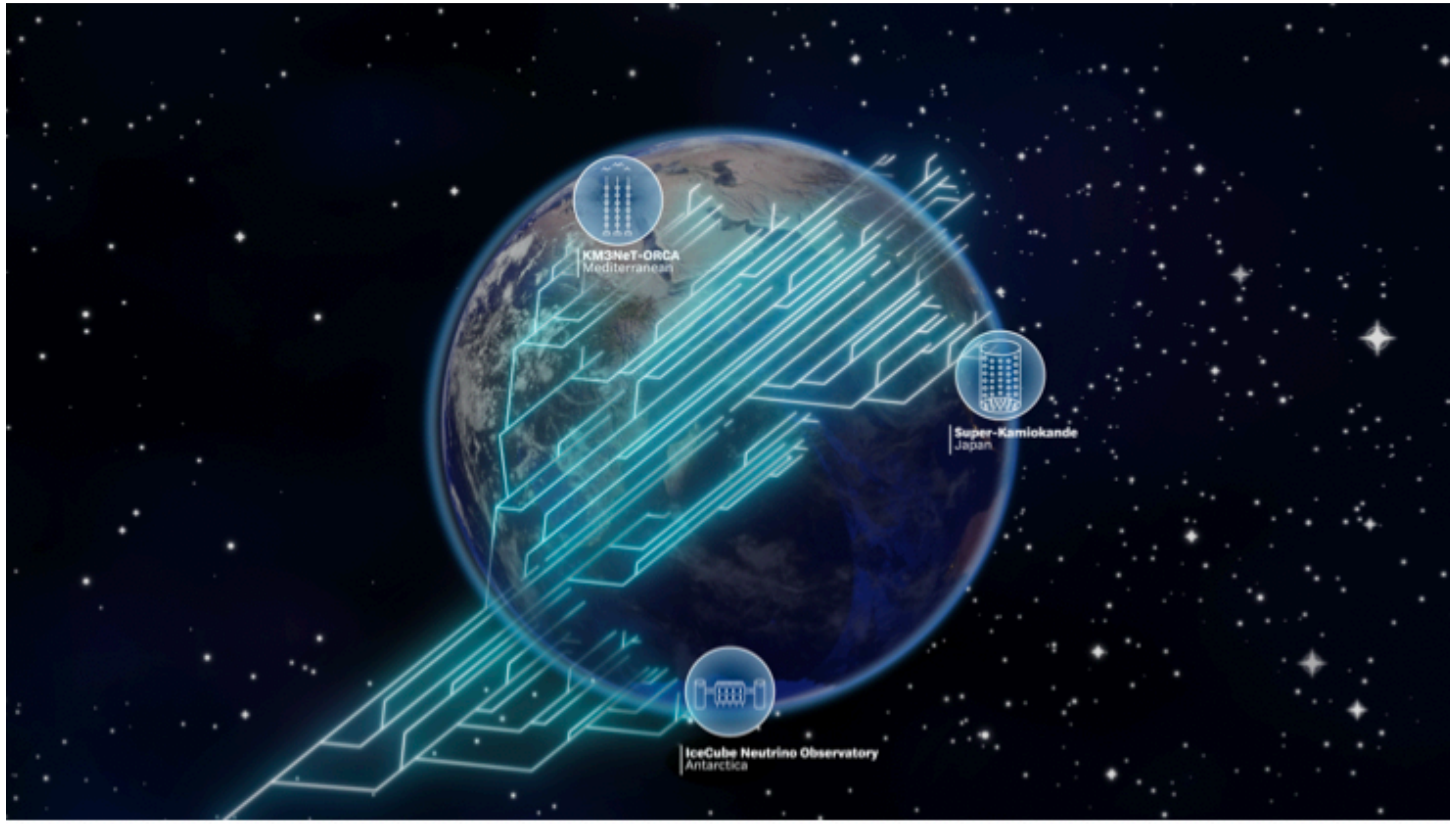
Ivan Martínez Soler

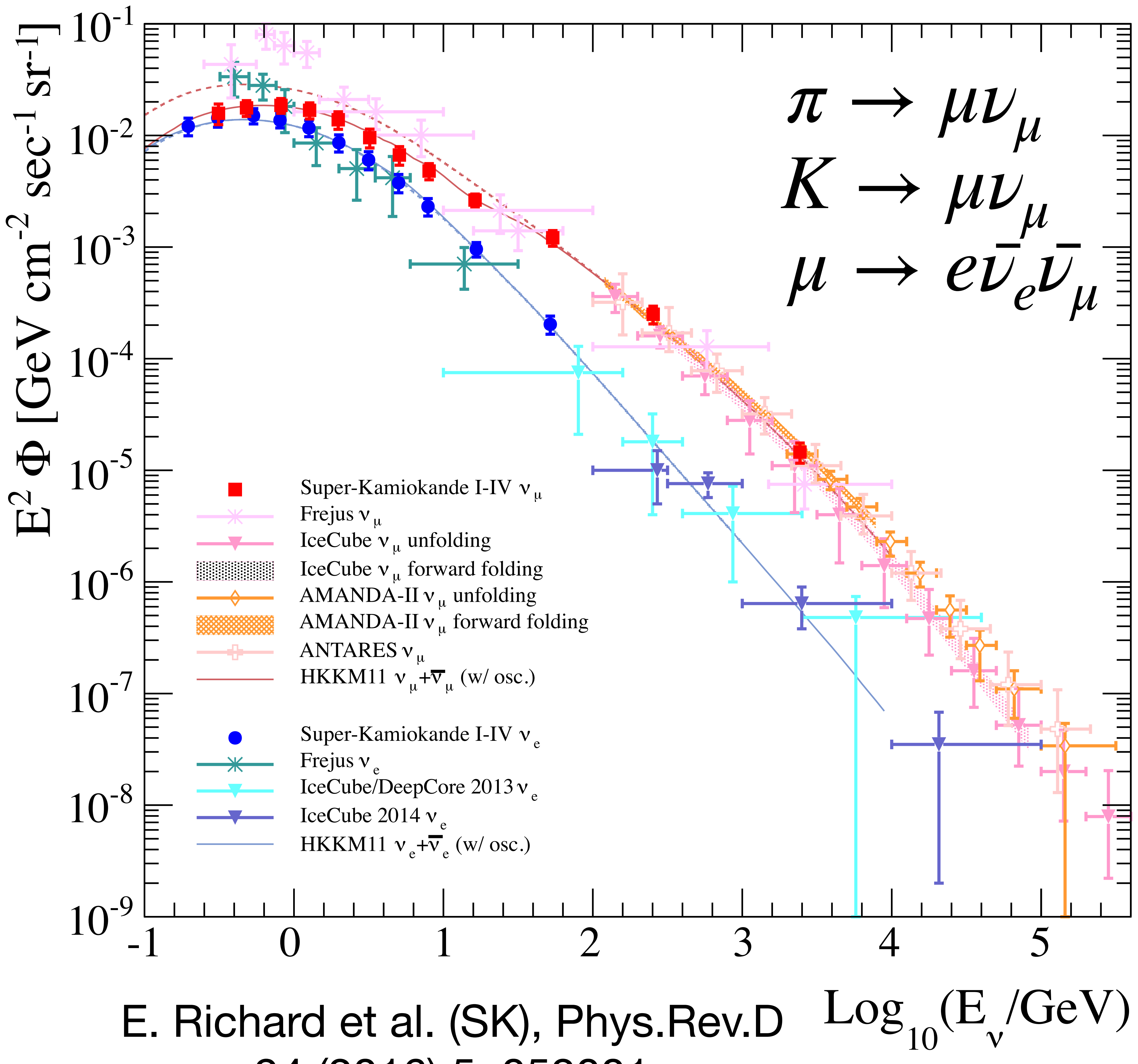
Based on: C. Argüelles, et al., PRX 13 (2023)
S.Giner Olavarrieta, et al., arXiv: 2402.13308
K.J.Kelly, et al., PRL 123 (2019) 8

LA THUILE 2024 - Les Rencontres de Physique de la Vallée d'Aoste.

Atmospheric neutrinos

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



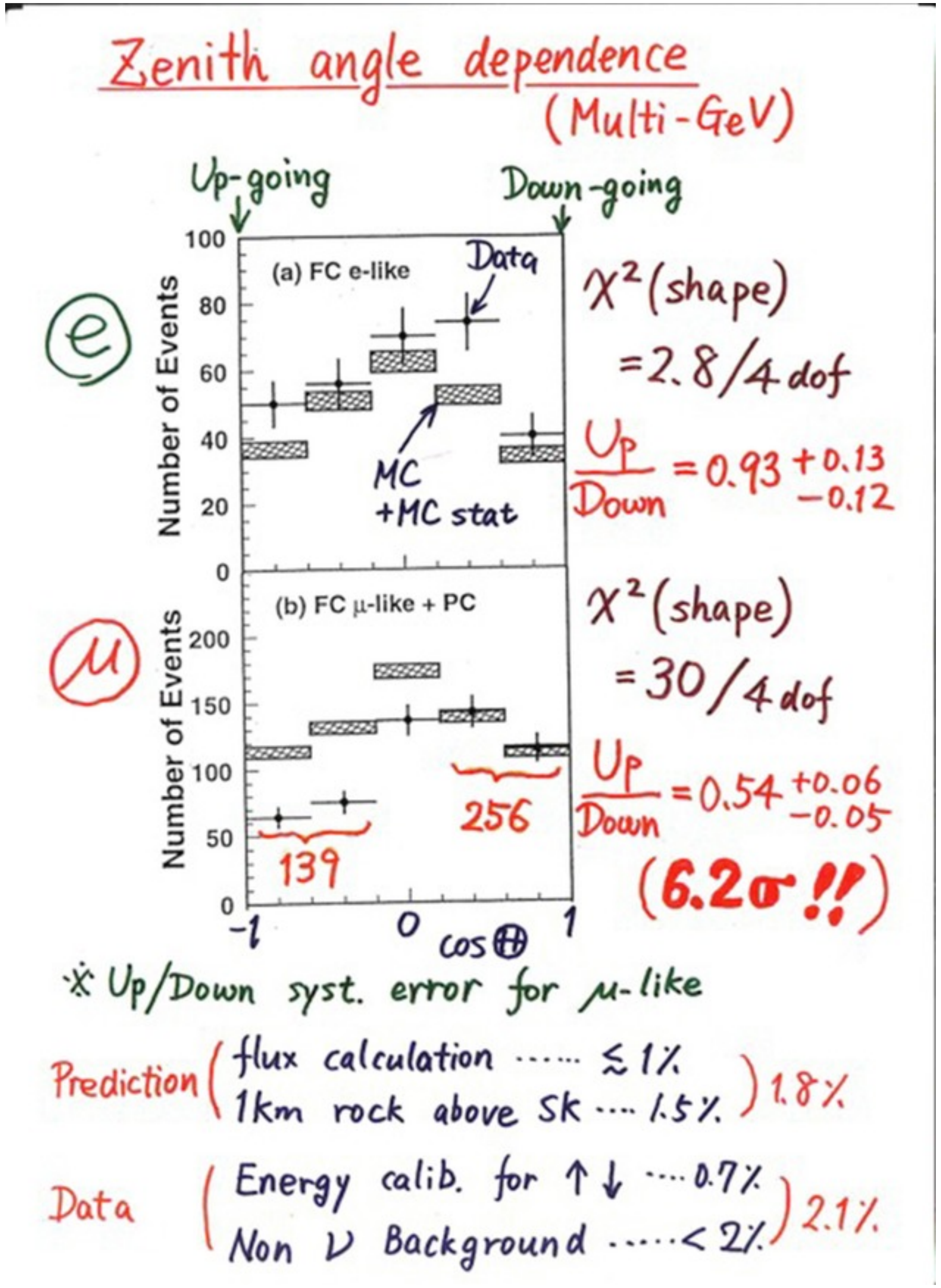


E. Richard et al. (SK), Phys.Rev.D 94 (2016) 5, 052001

Neutrinos have mass!

In the **SM**, neutrinos are **massless particles**

There are experimental **evidence** showing that neutrinos are massive particles



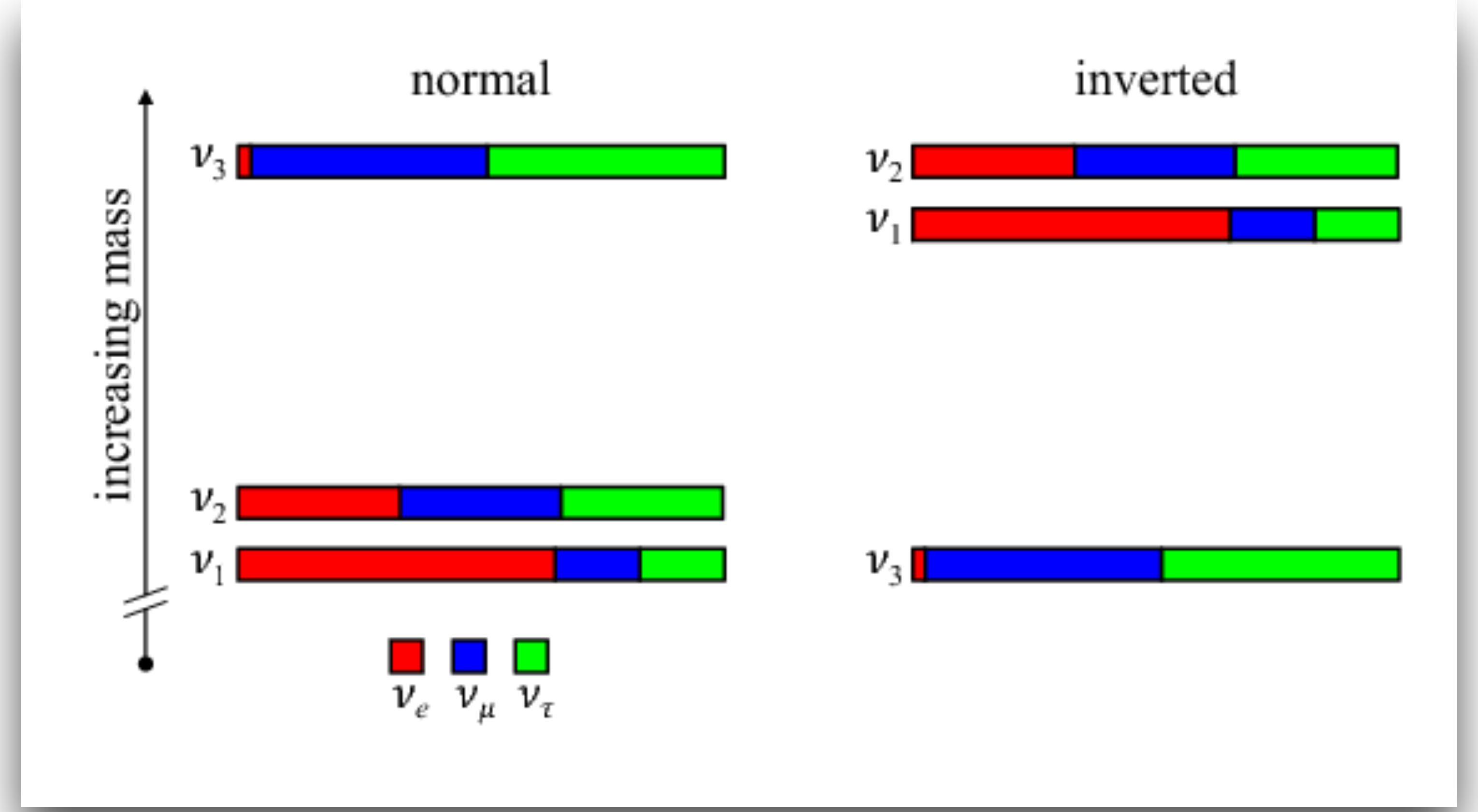
Takaaki Kajita (Super-kamiokande) Neutrino 98

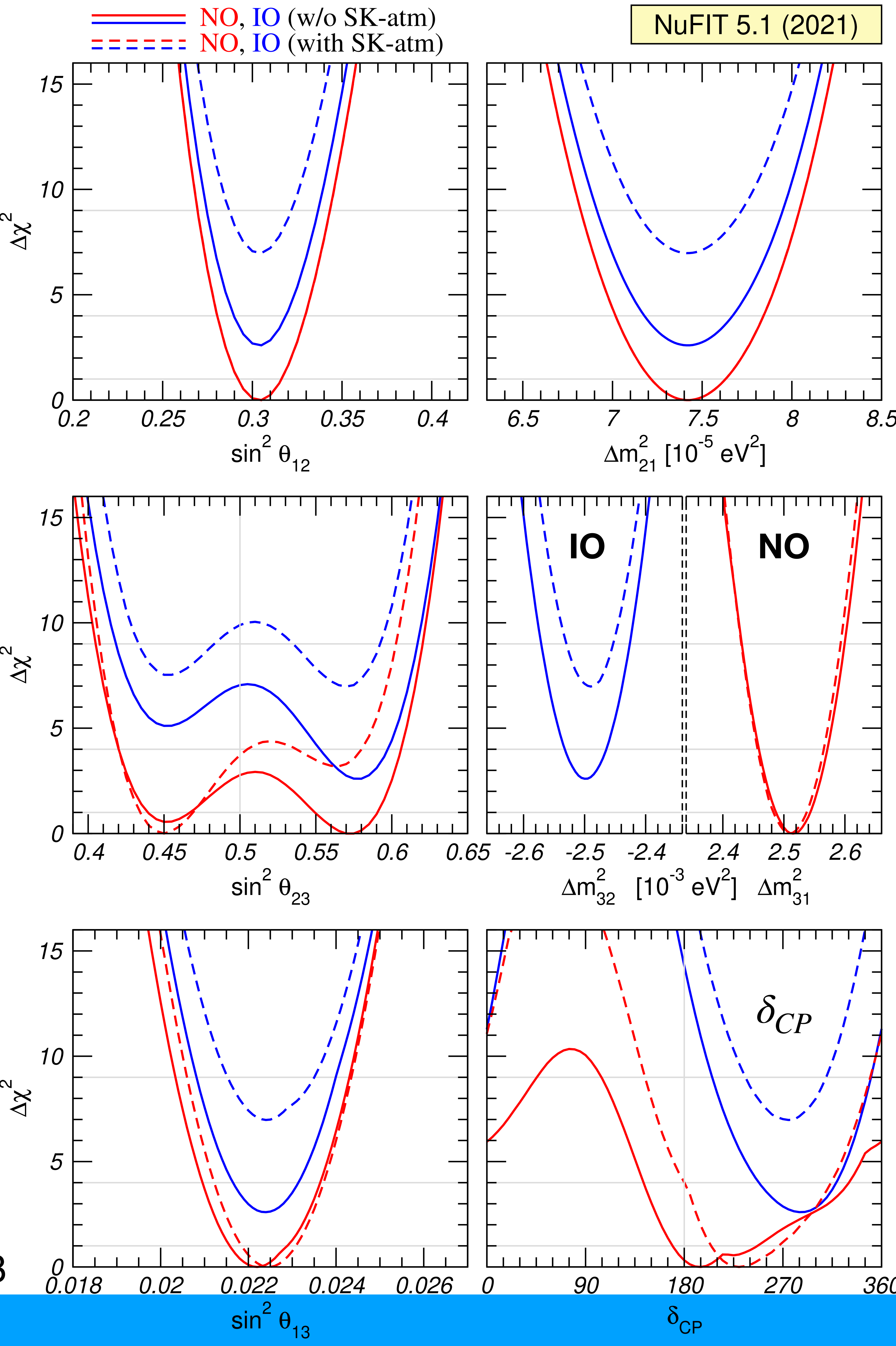
3ν mixing

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

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

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



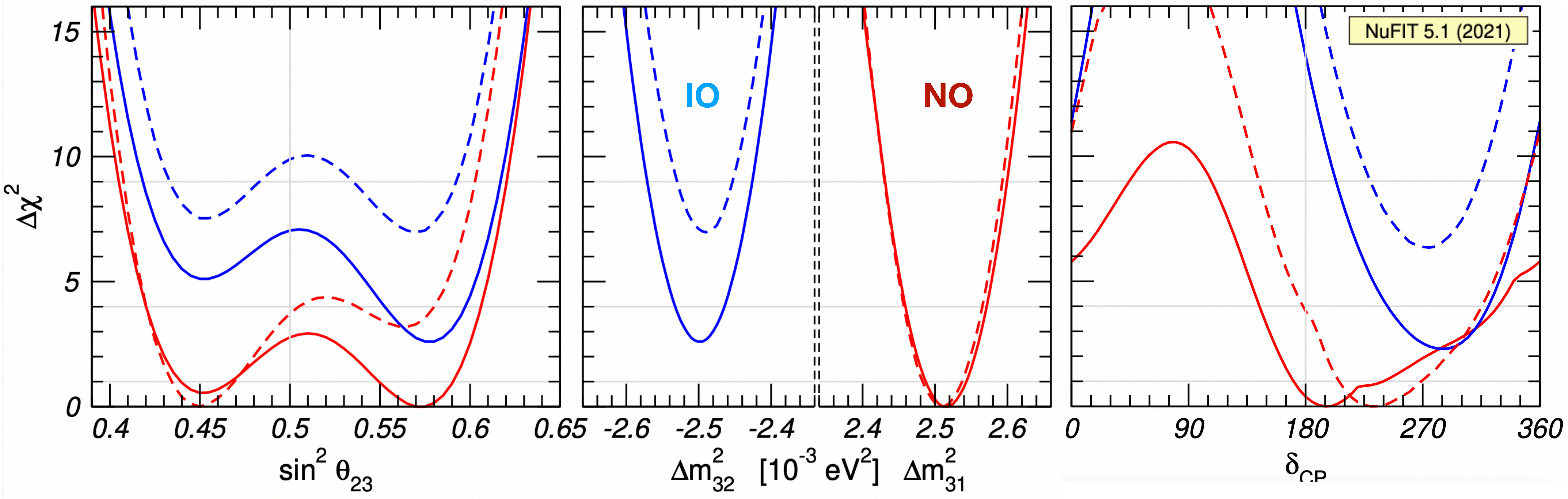


Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP 09 (2020) 178

3ν mixing

The less constrained parameters are:

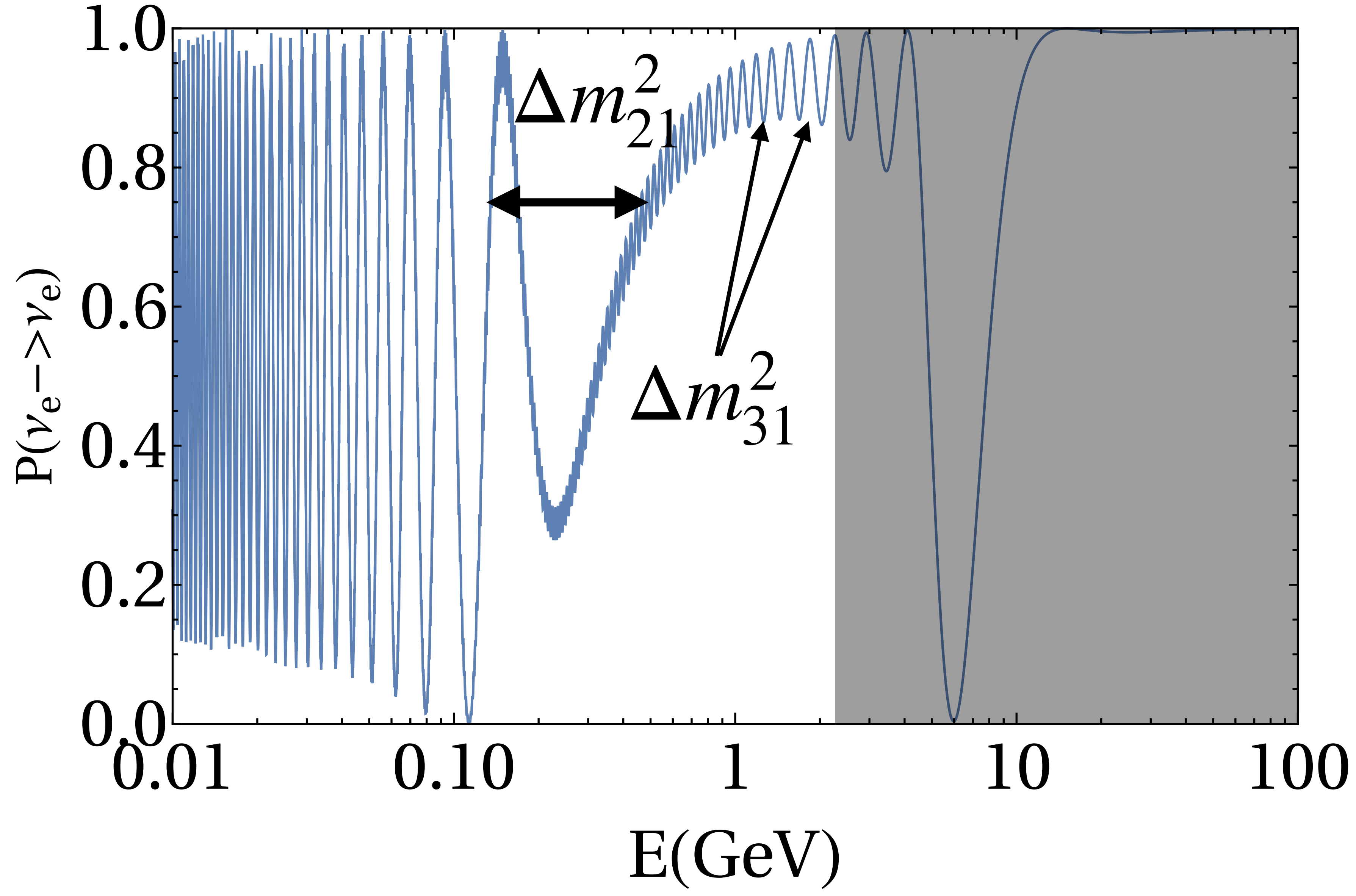
Preference for $\theta_{23} > 45$ Preference for NO at 2σ A small region is excluded at 3σ



This analysis aims to investigate the insight that atmospheric neutrinos can provide on those uncertainties

Sub-GeV

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

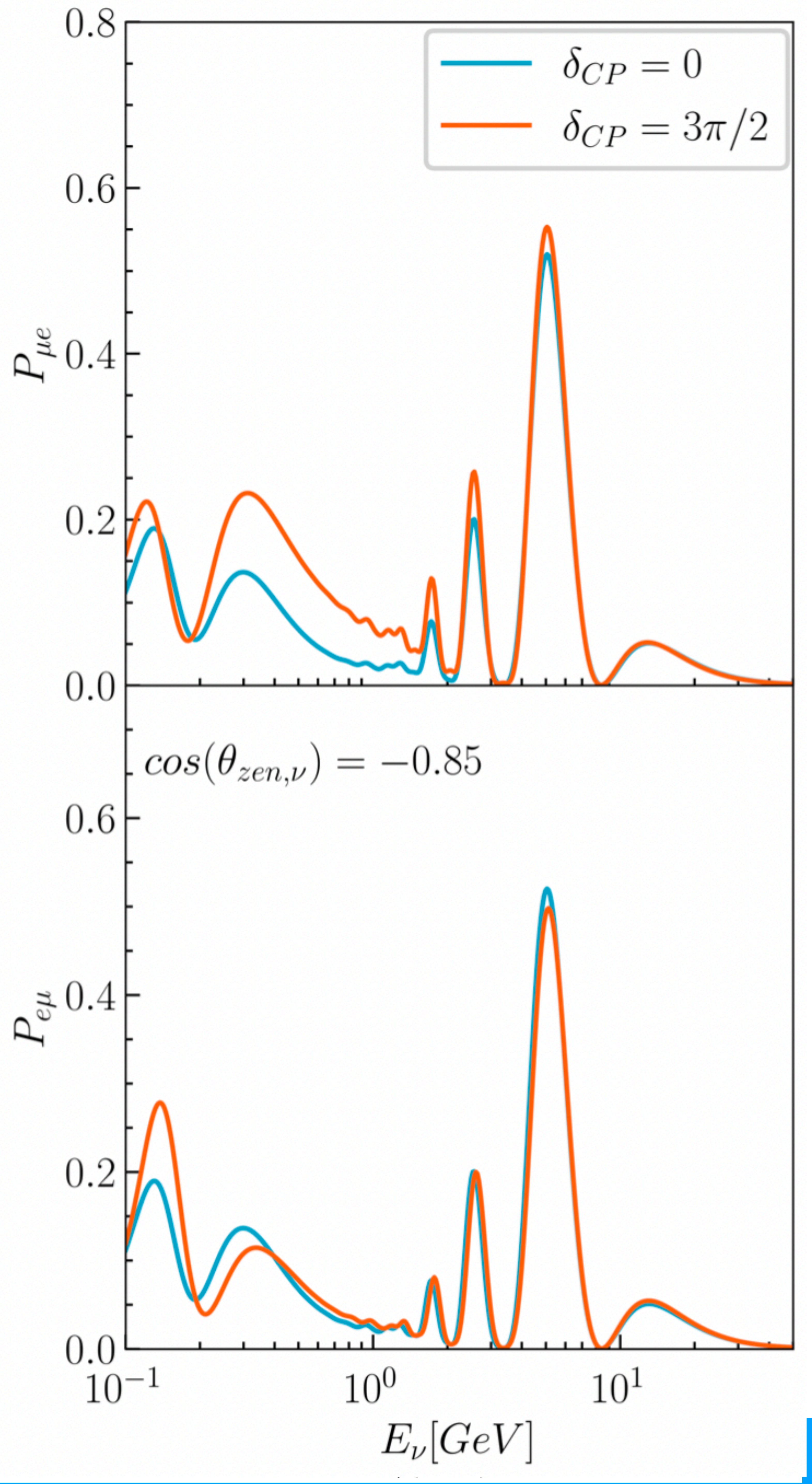


The **CP-violation** term is **enhanced** due to the solar oscillation.

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

For $\delta_{cp} \neq 0$, **the CPT conservation** implies $P(\nu_\mu \to \nu_e) \neq P(\nu_e \to \nu_\mu)$

I. Martinez-Soler, H. Minakata, PTEP (2019) 7, 073B07

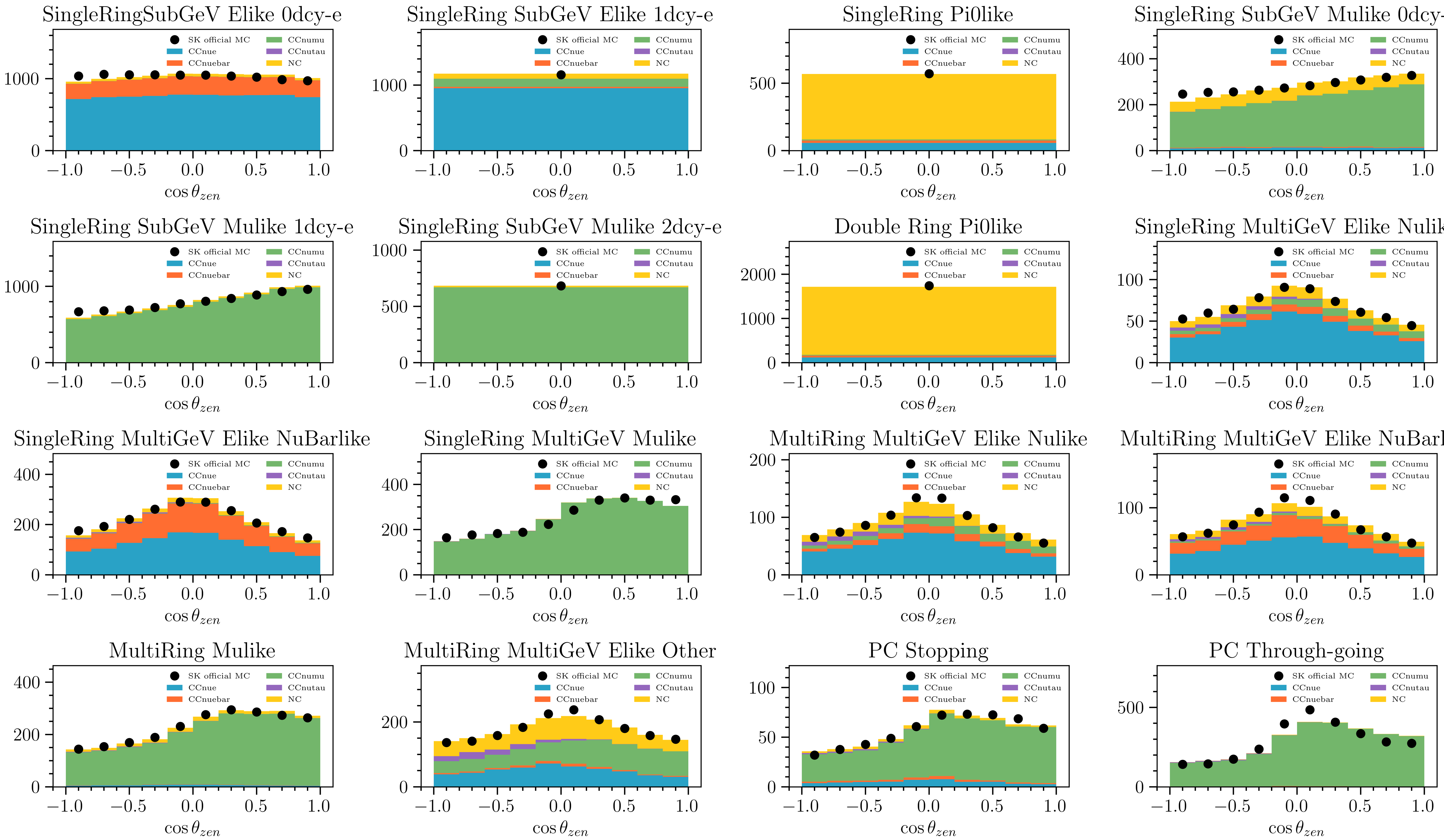


Sub-GeV

Several experiments have measured the neutrino flux at different energy scales. The sub-GeV component has been measured by SK

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



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

- We also included **HK**

Multi-GeV

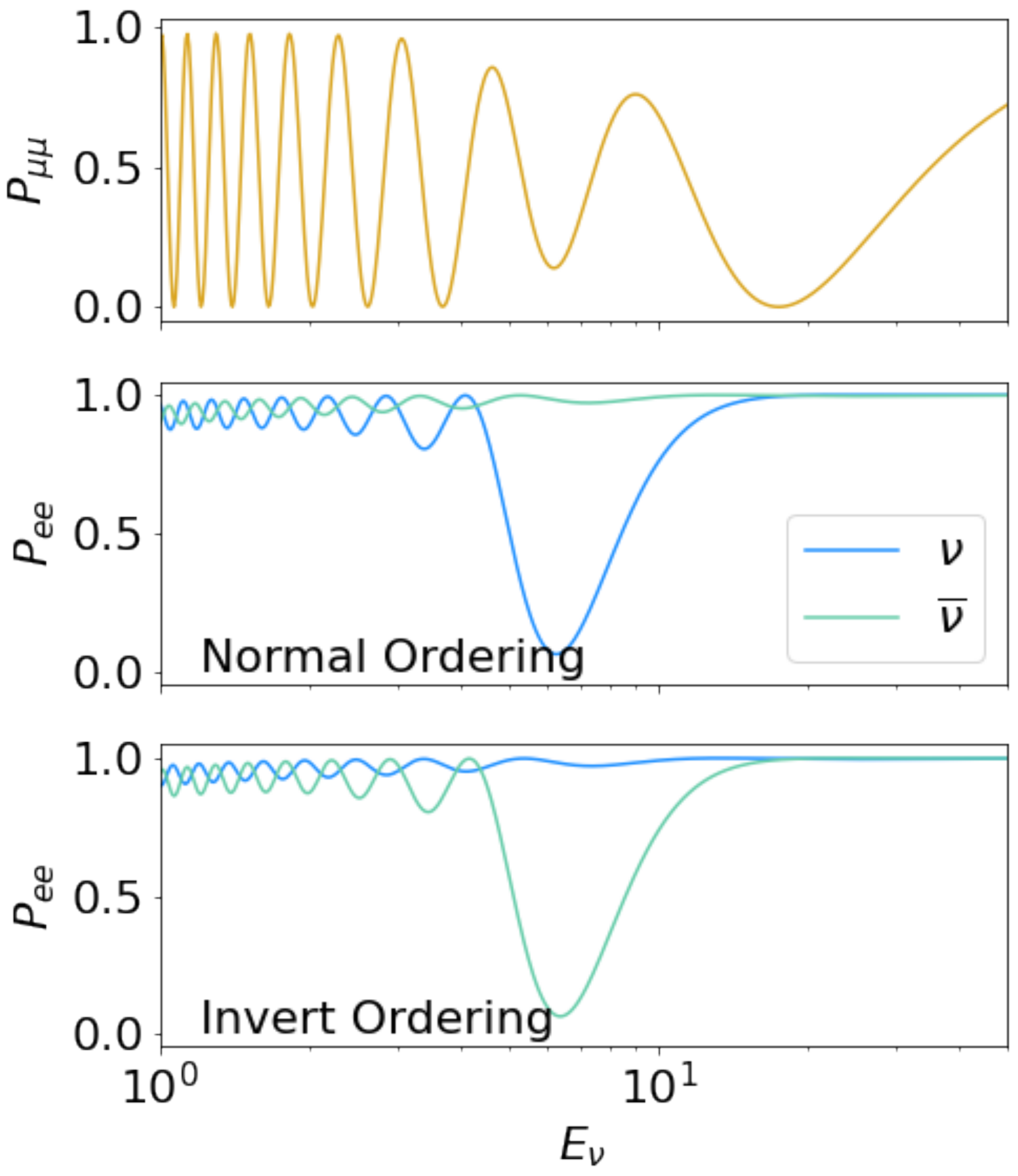
In the multi-GeV region, neutrino evolution is dominated by Δm^2_{31} and $\sin^2\theta_{23}$

At the GeV scale, there is resonant flavor conversion. Neutrinos are sensitive to the **mass ordering**:

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

- The enhancement of the effective θ_{13}. MSW resonance.

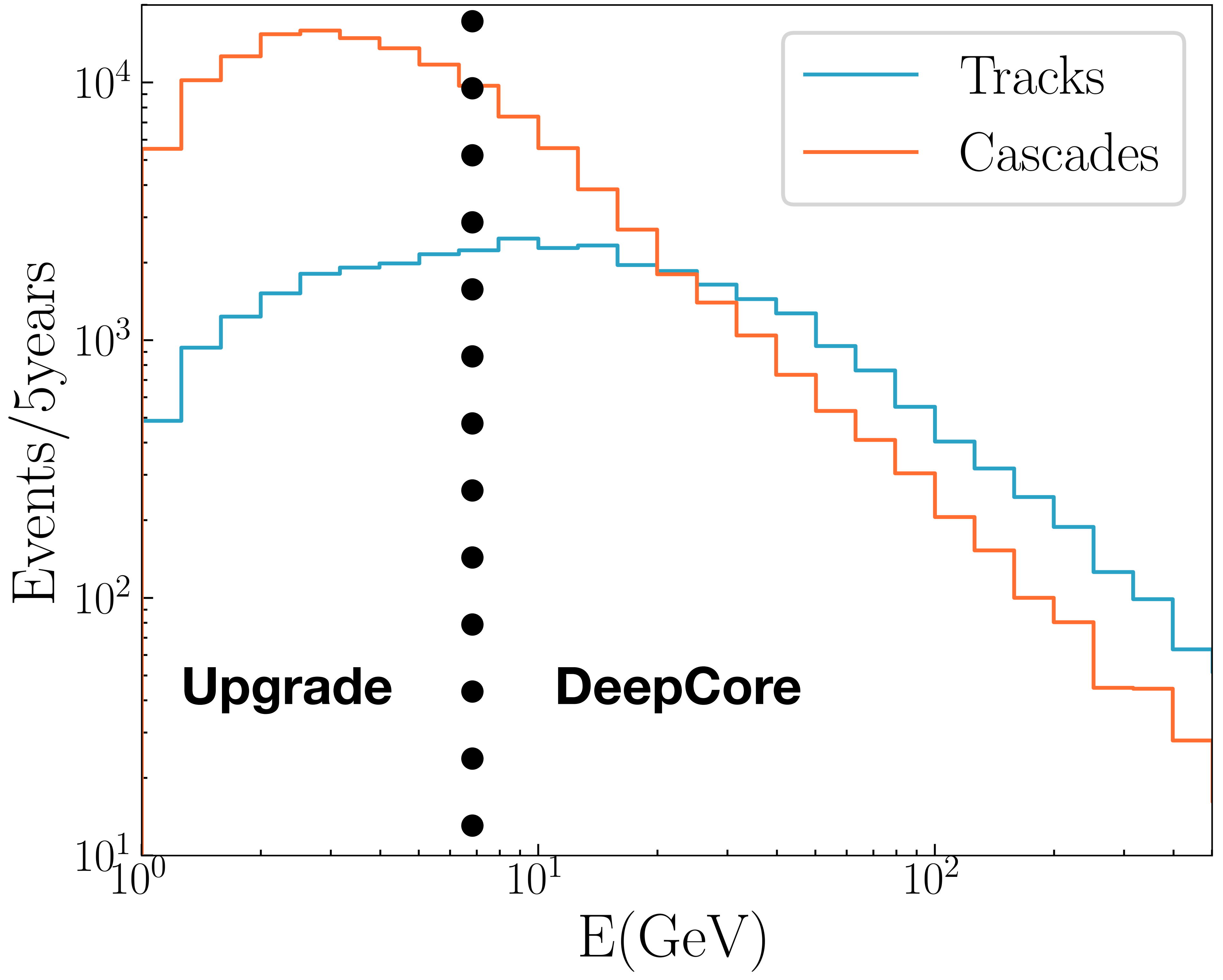
$$E_r \simeq 5.3\text{GeV}\left(\frac{\Delta m^2_{31}}{2.5\times 10^{-3}\text{eV}^2}\right)\left(\frac{cos2\theta}{0.95}\right)\left(\frac{\rho}{6\text{g/cc}}\right)$$



Multi-GeV

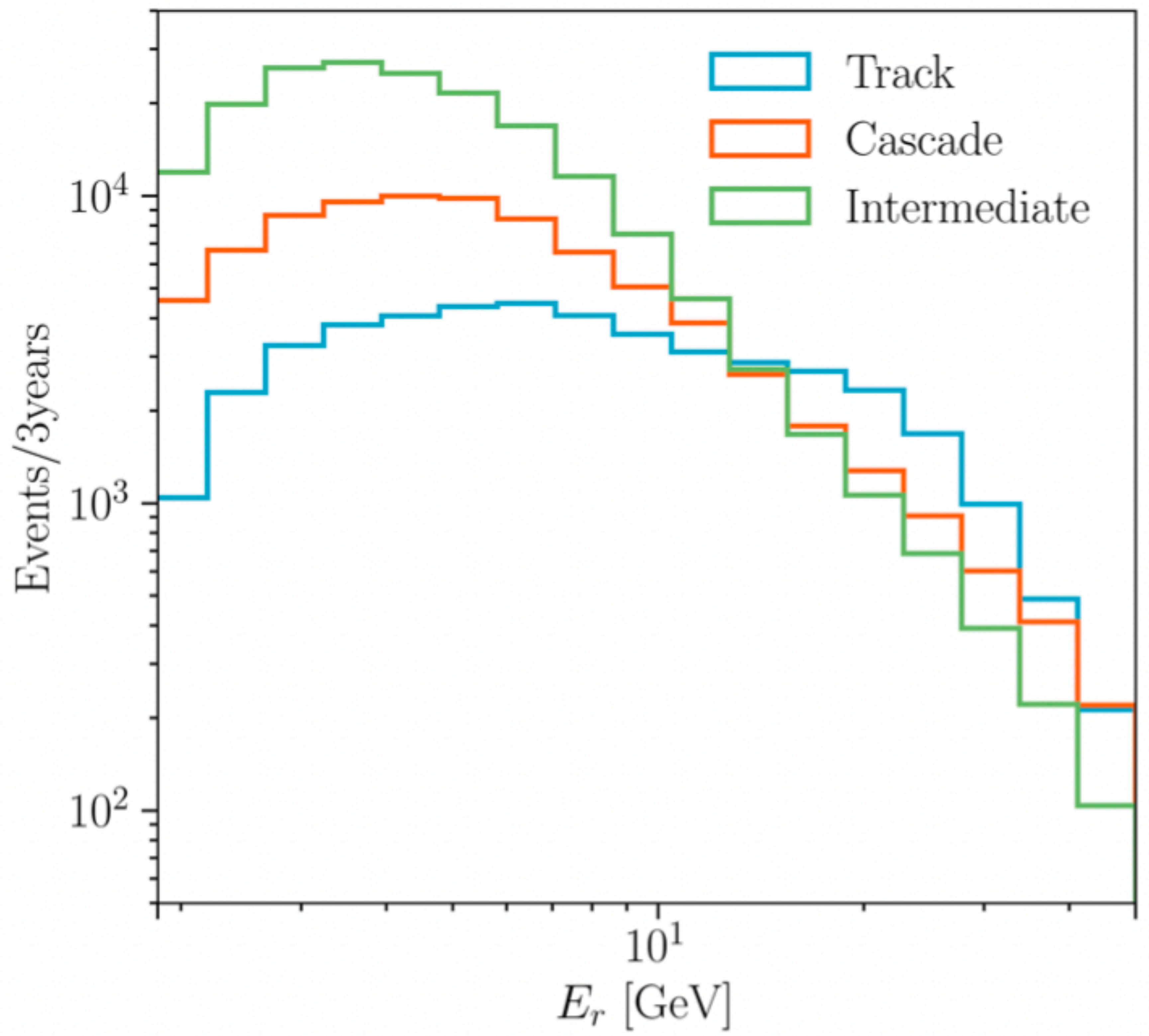
The **neutrino telescopes** measure the high-energy part of the atmospheric neutrino flux

IceCube



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

ORCA



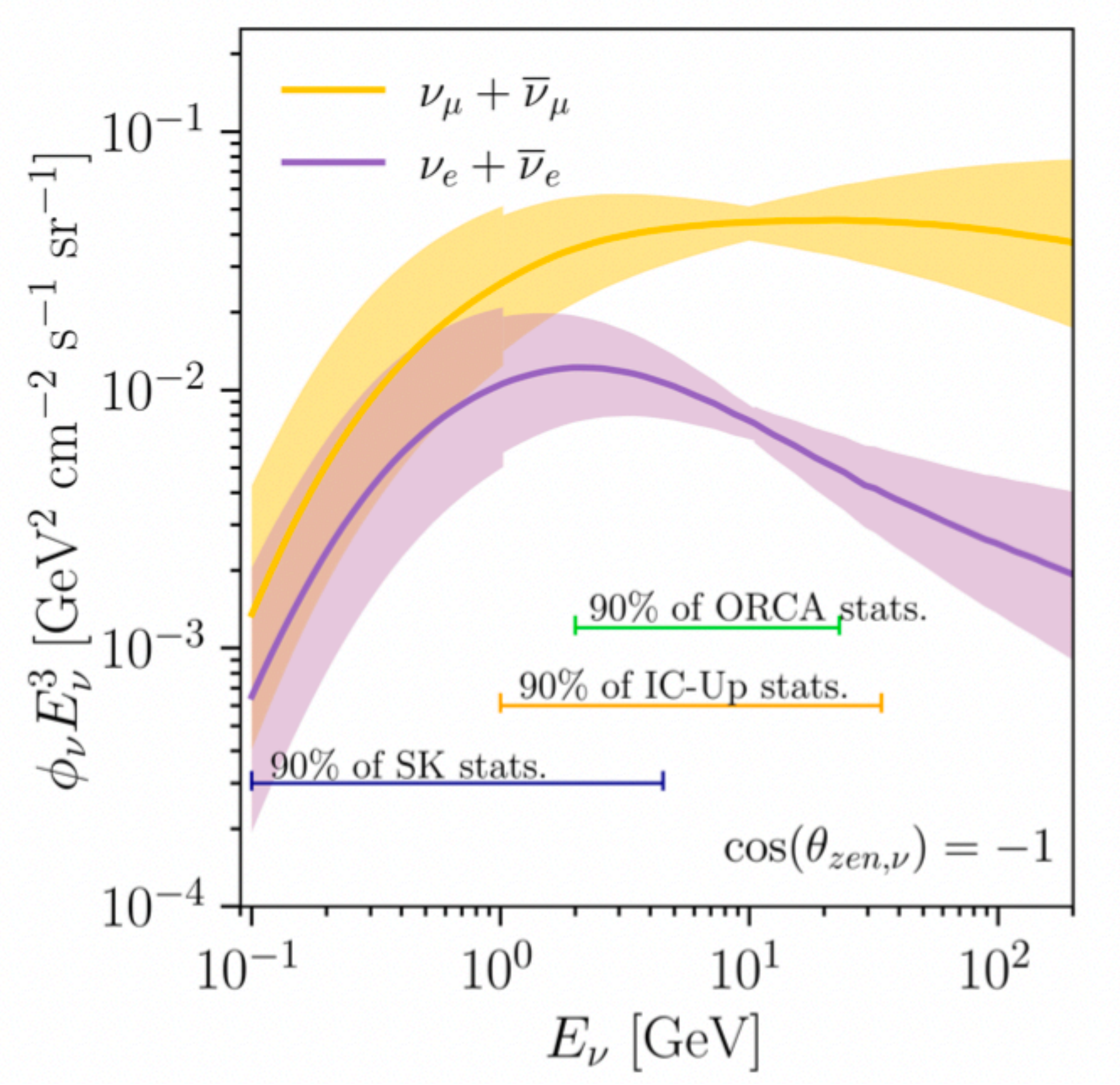
We developed an MC for ORCA based on energy and Zenit reconstruction provided by the collaboration

Systematic uncertainties

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

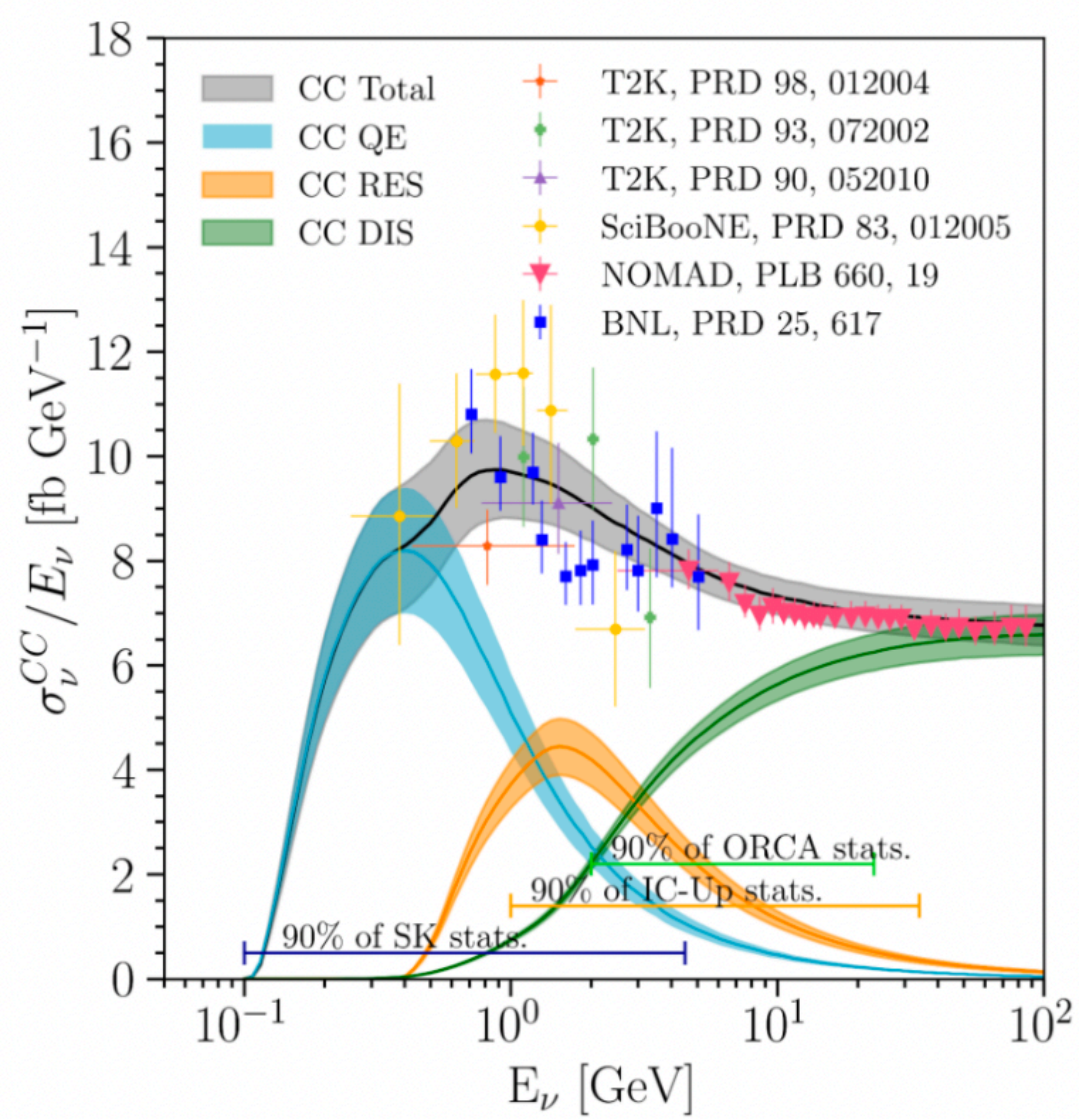
Flux systematics

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



Cross-section systematics

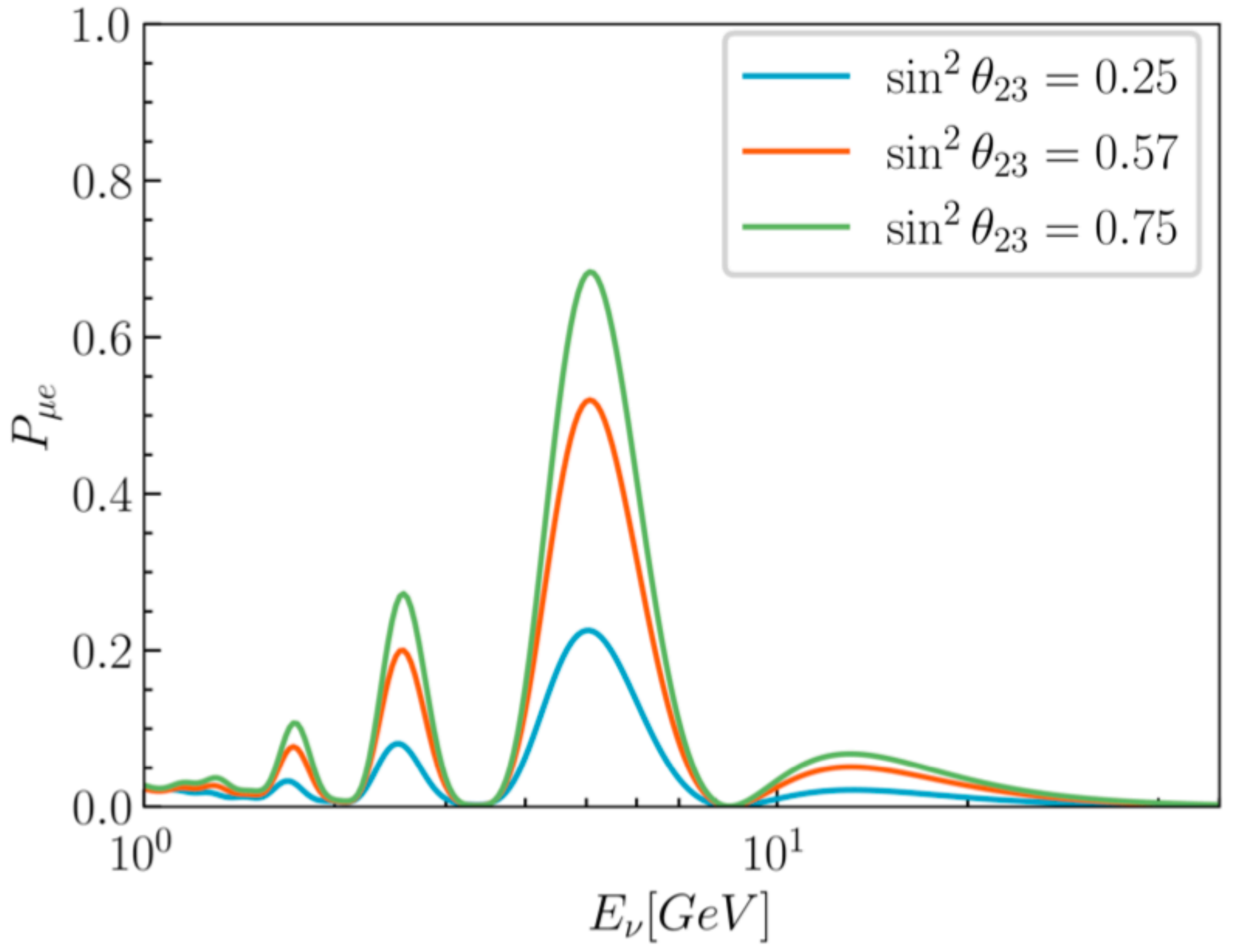
Different types of interactions affect the atmospheric neutrino interaction due to the large energy range covered

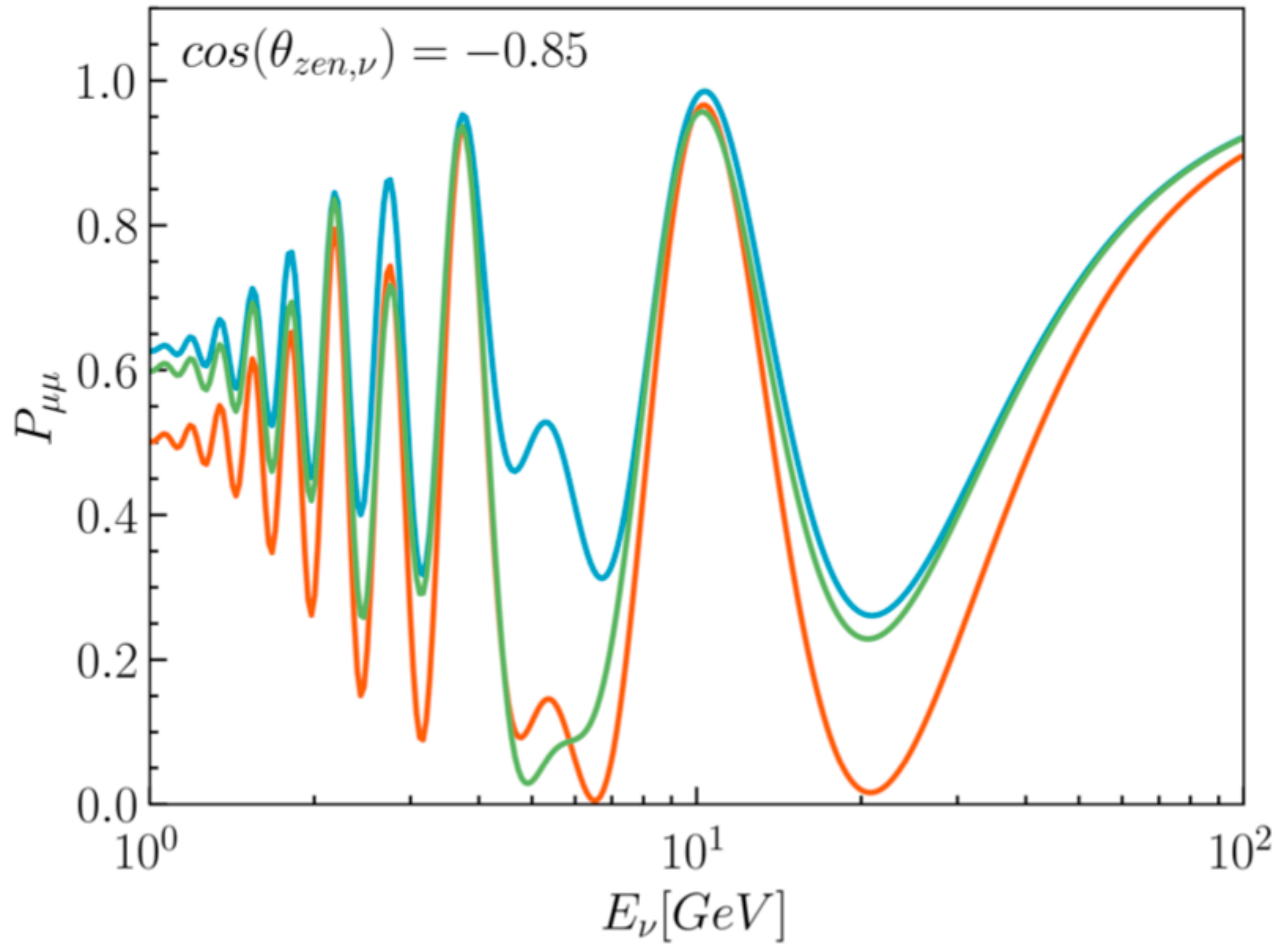


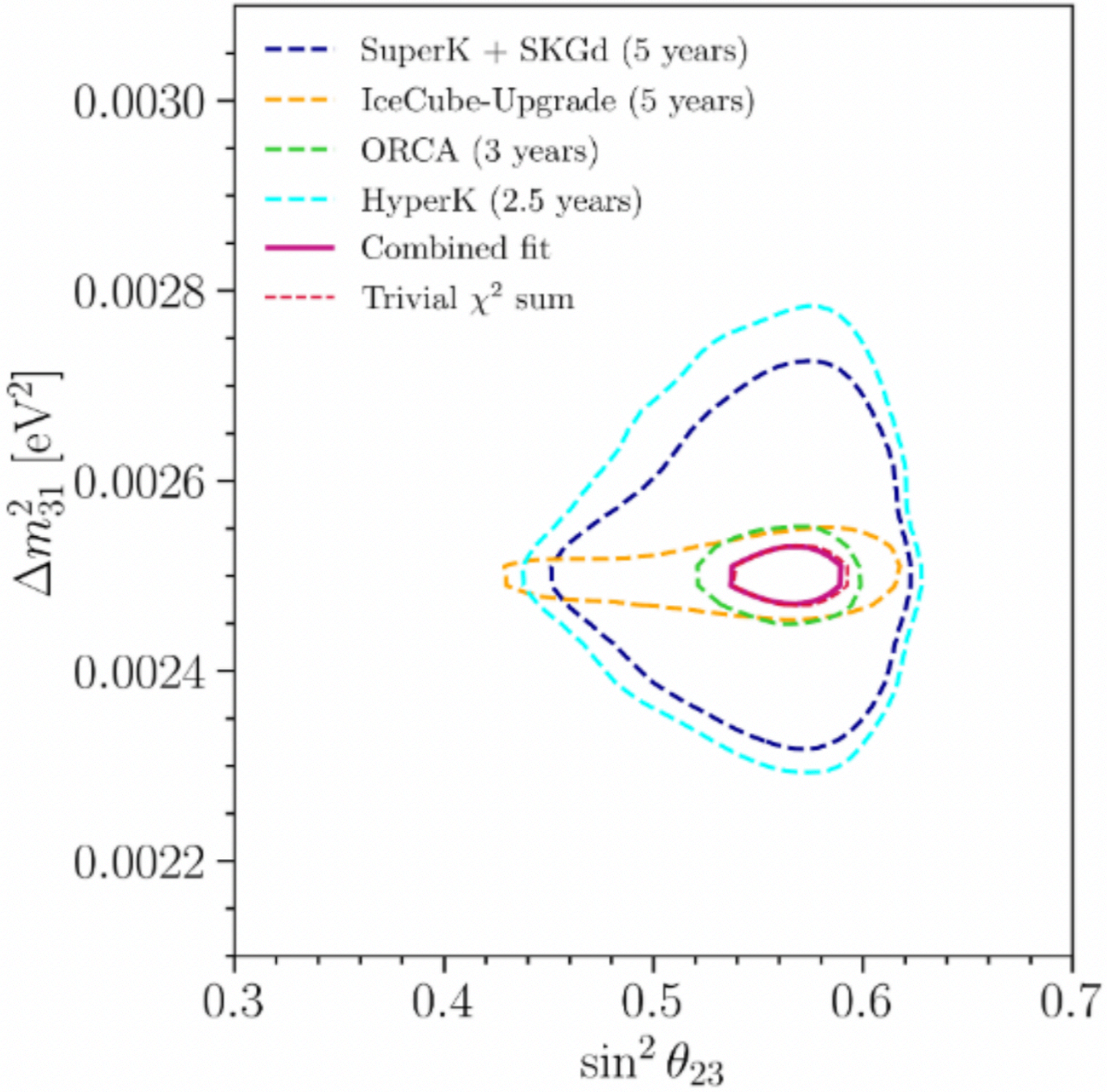
Systematic	Uncer./Prior
CCQE	10%
CCQE $\nu/\overline{\nu}$	10%
CCQE e/μ	10%
CC1 π	10%
CC1 π $\pi^0/\pi^\pm$	40%
CC1 π $\nu_e/\overline{\nu_e}$	10%
CC1 π $\nu_\mu/\overline{\nu_\mu}$	10%
Coh. π	100%
Axial Mass	10%
NC hadron	5%
NC over CC	10%
ν_τ	25%
Neutron prod.	15%
DIS	10%

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**





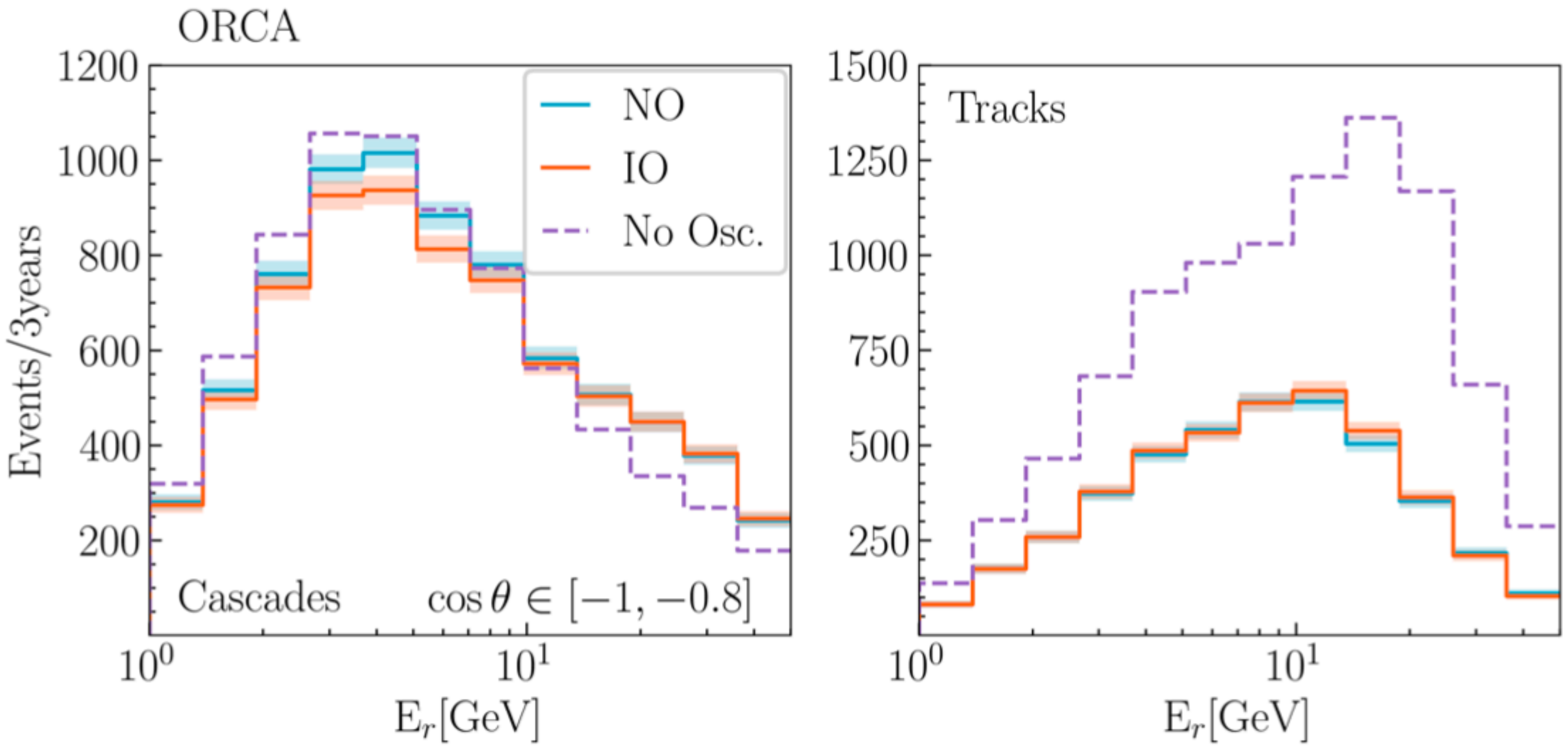


C.A. Argüelles, P. Fernandez, I. Martinez-Soler and M. Jin, PRX 13 (2023) 4, 041055

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}

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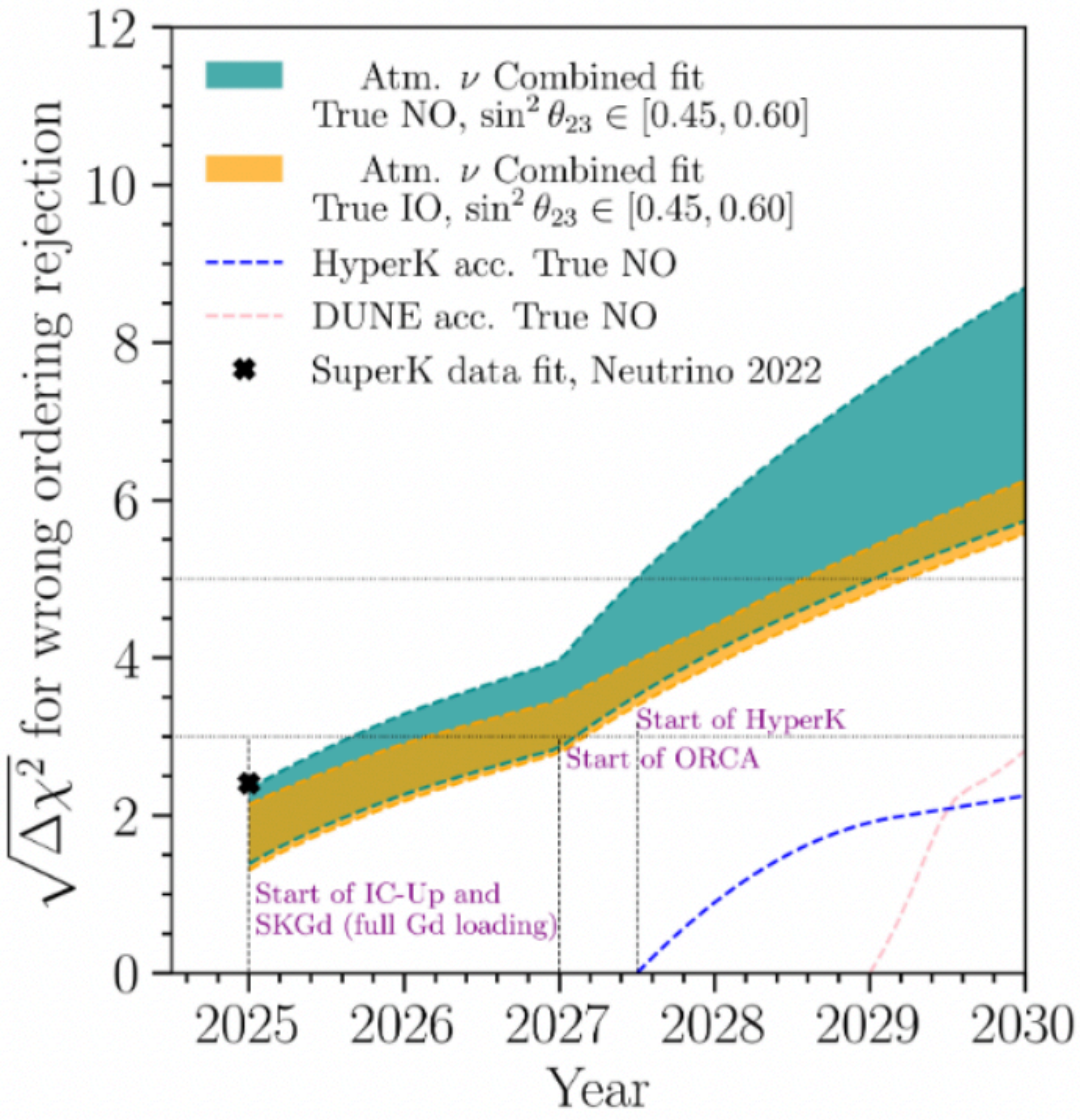
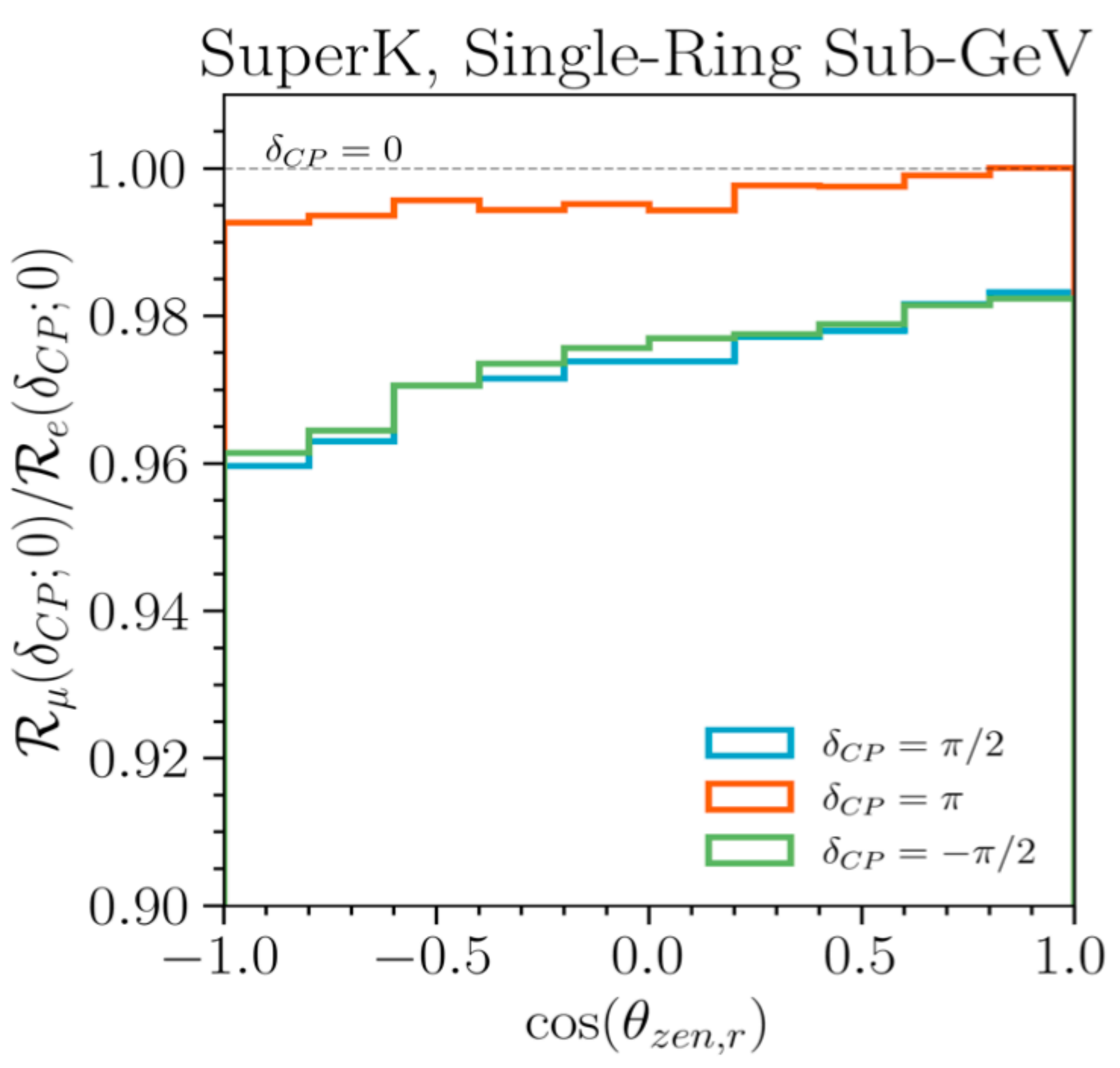
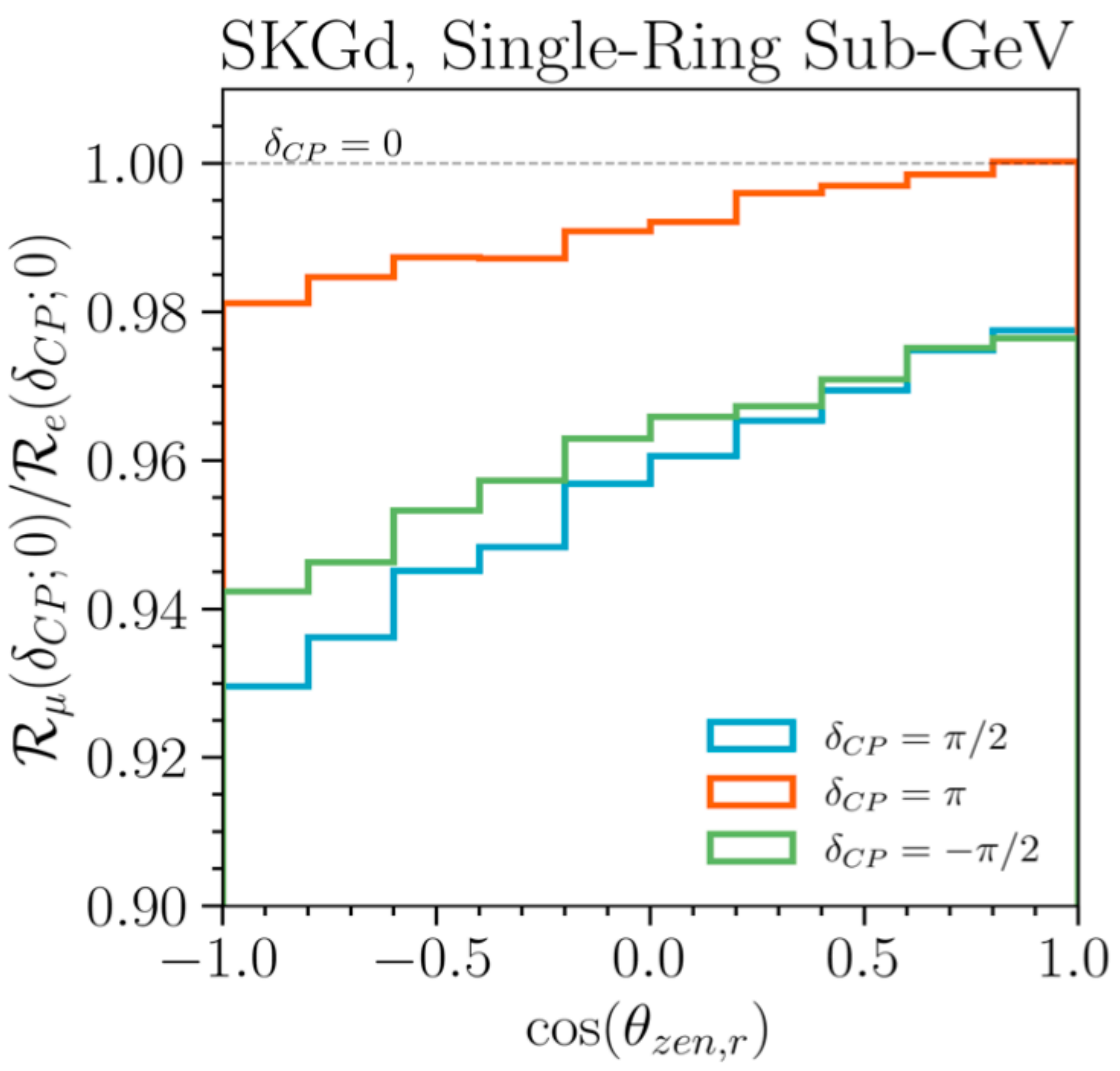


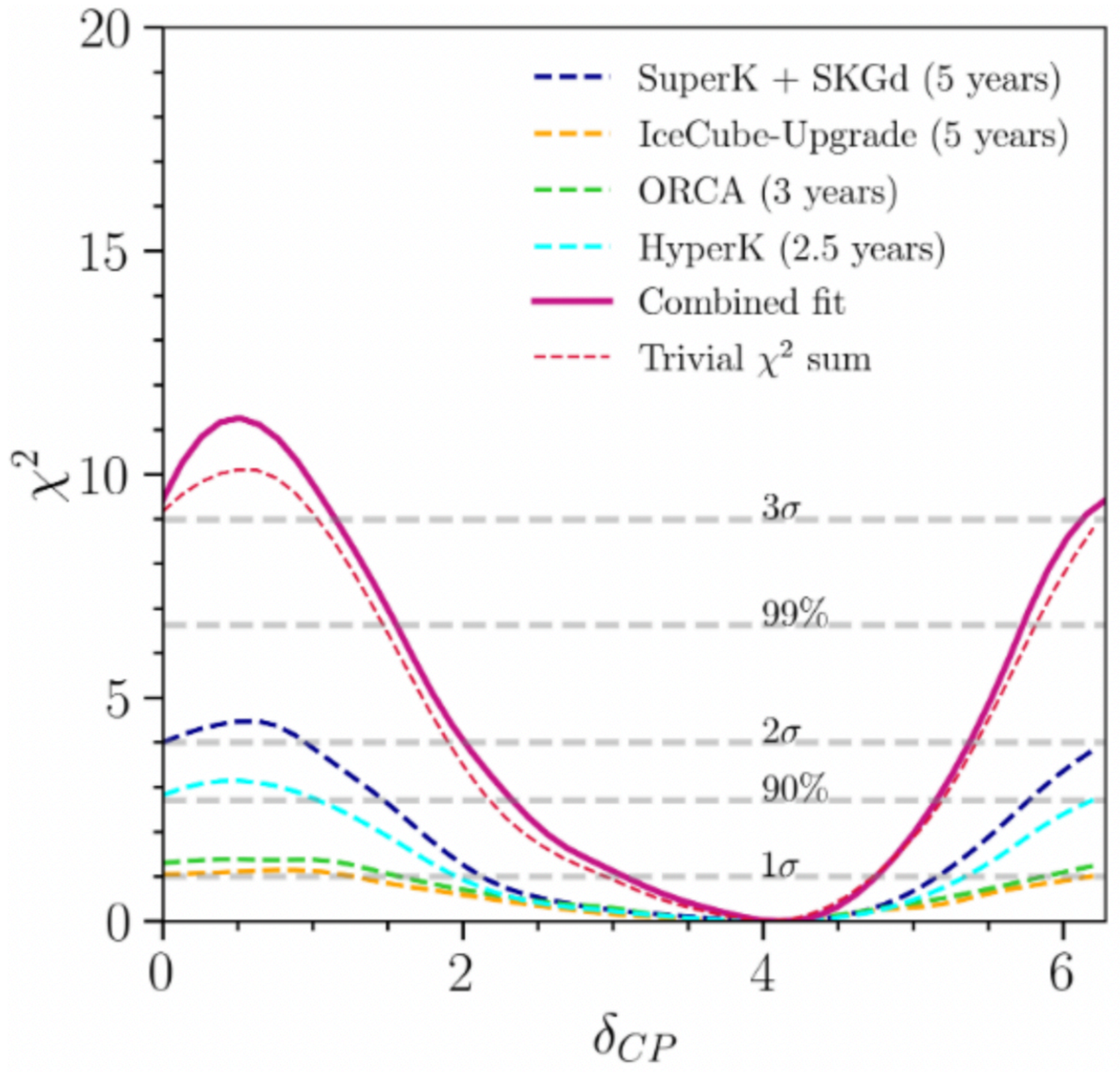
Combined analysis: δ_{cp}

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





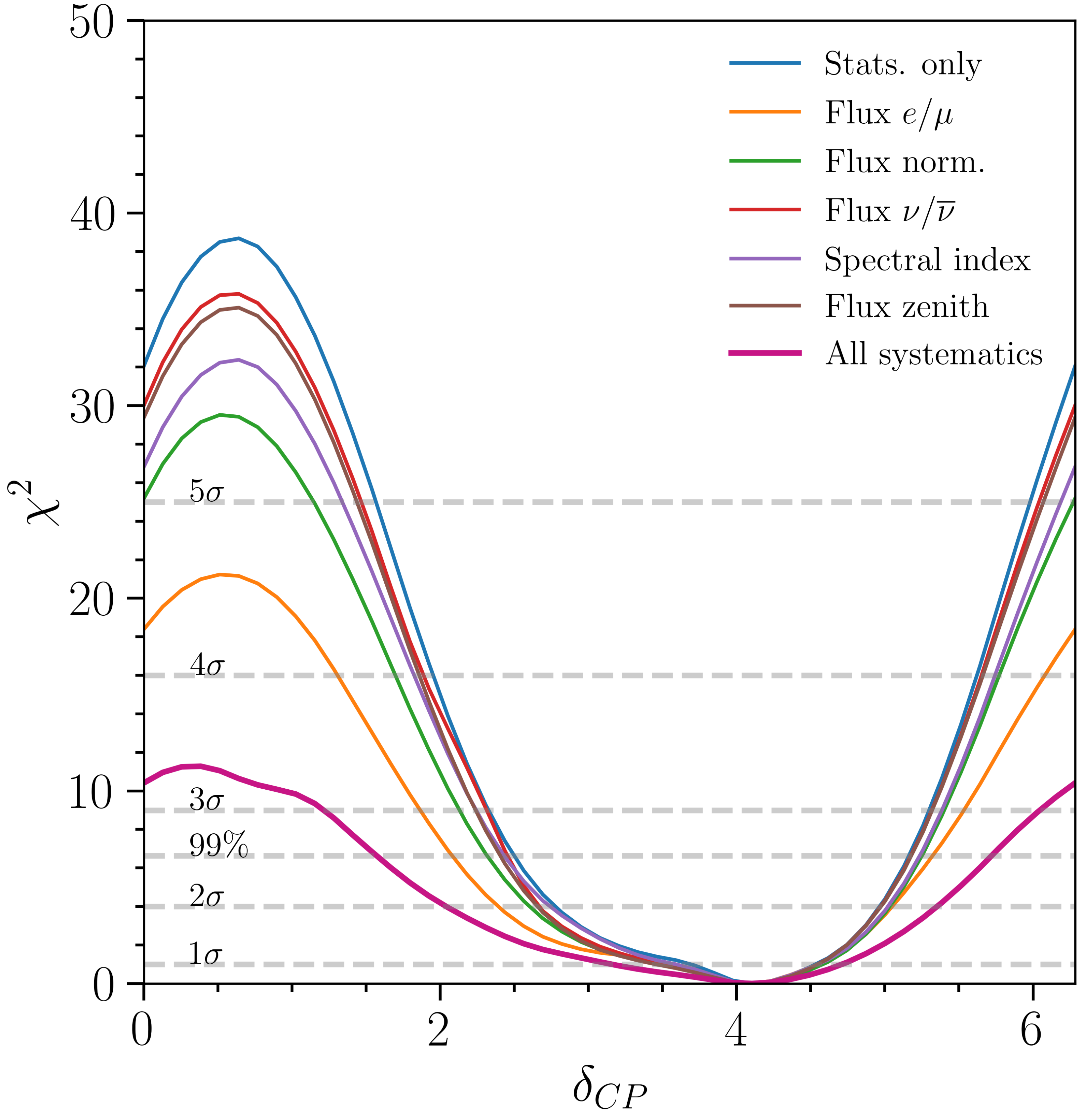


C.A. Argüelles, P. Fernandez, I. Martinez-Soler and M. Jin, PRX 13 (2023) 4, 041055

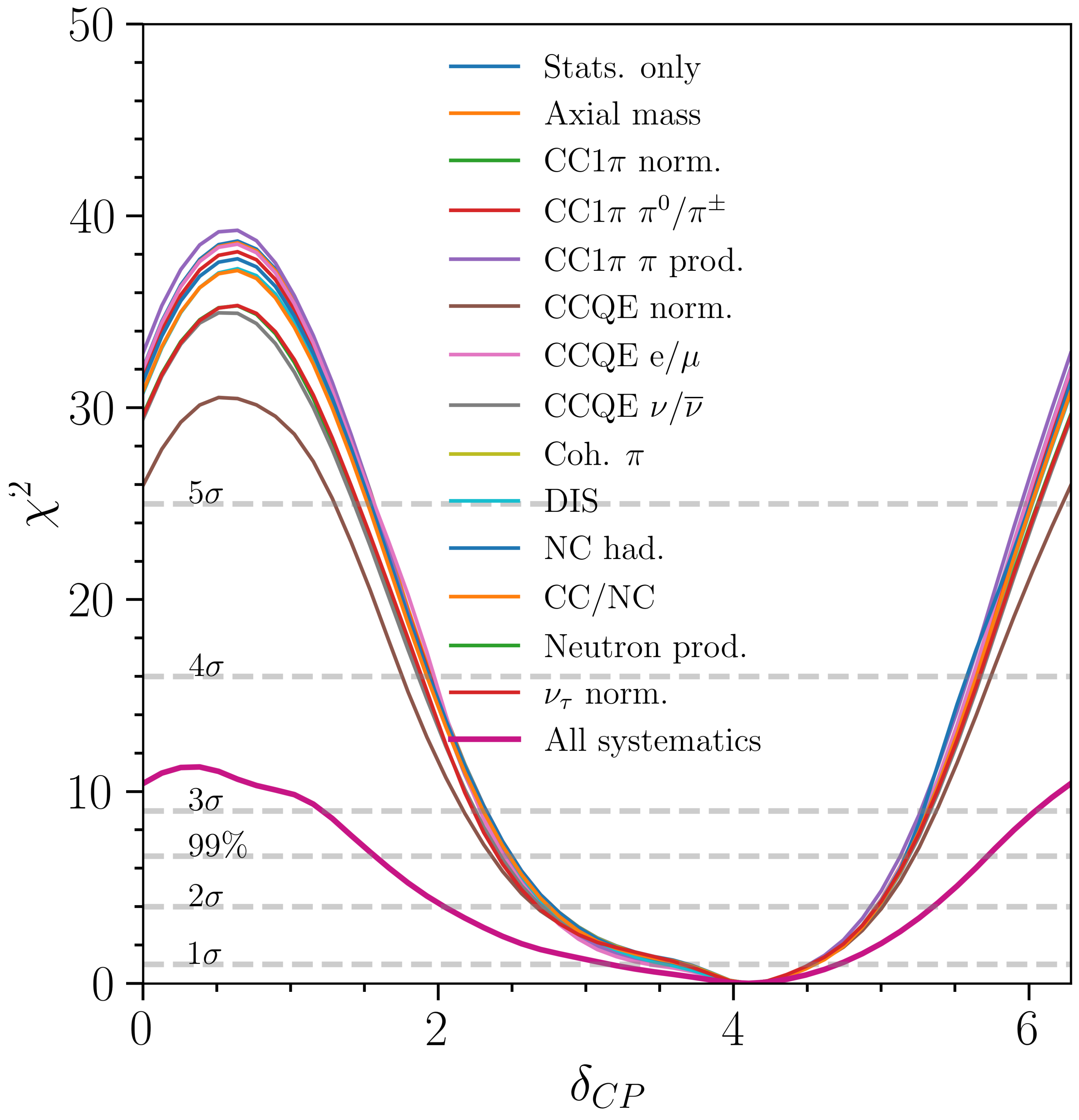
Systematic impact

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

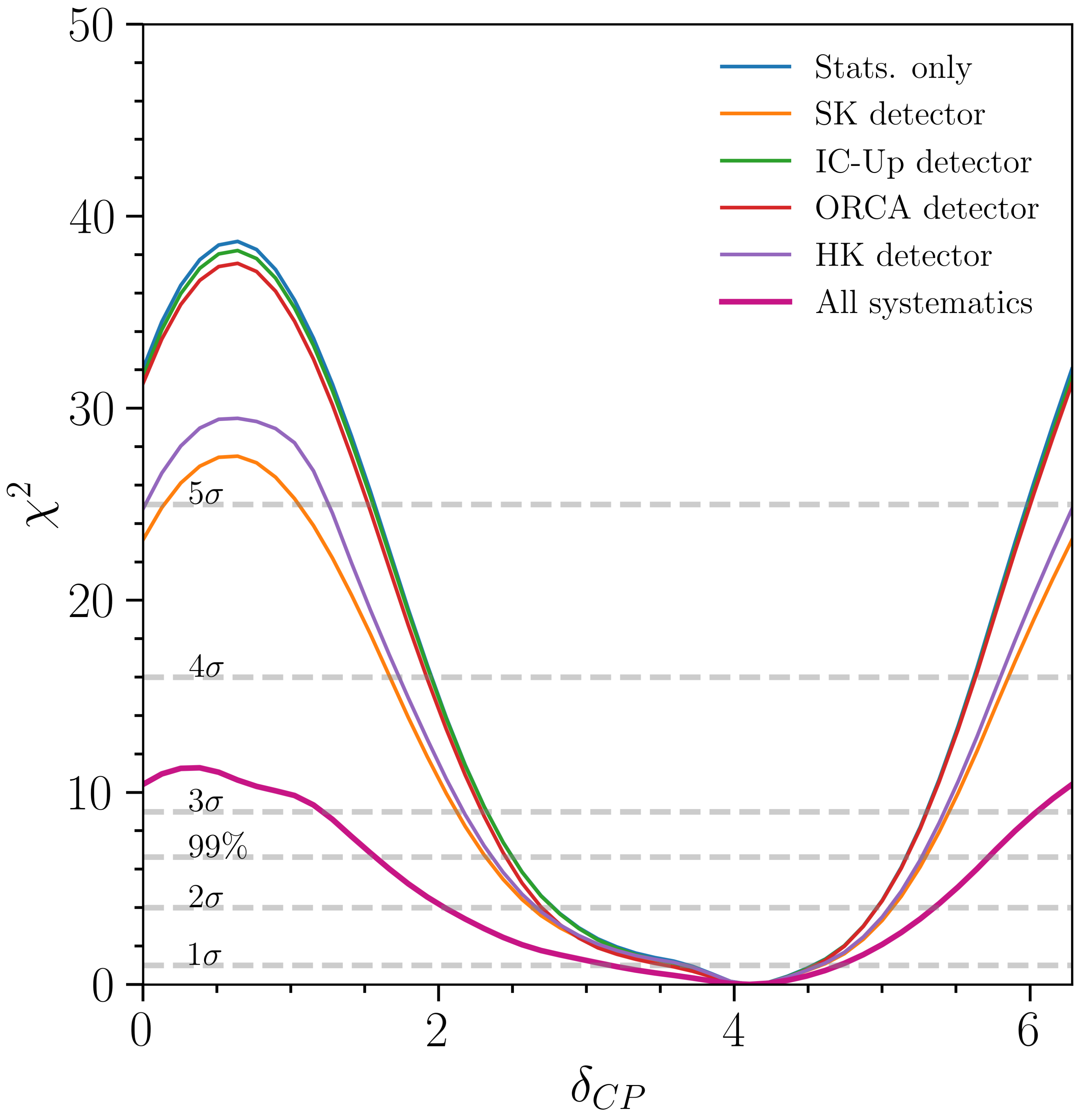
Flux



Cross-section



Detector



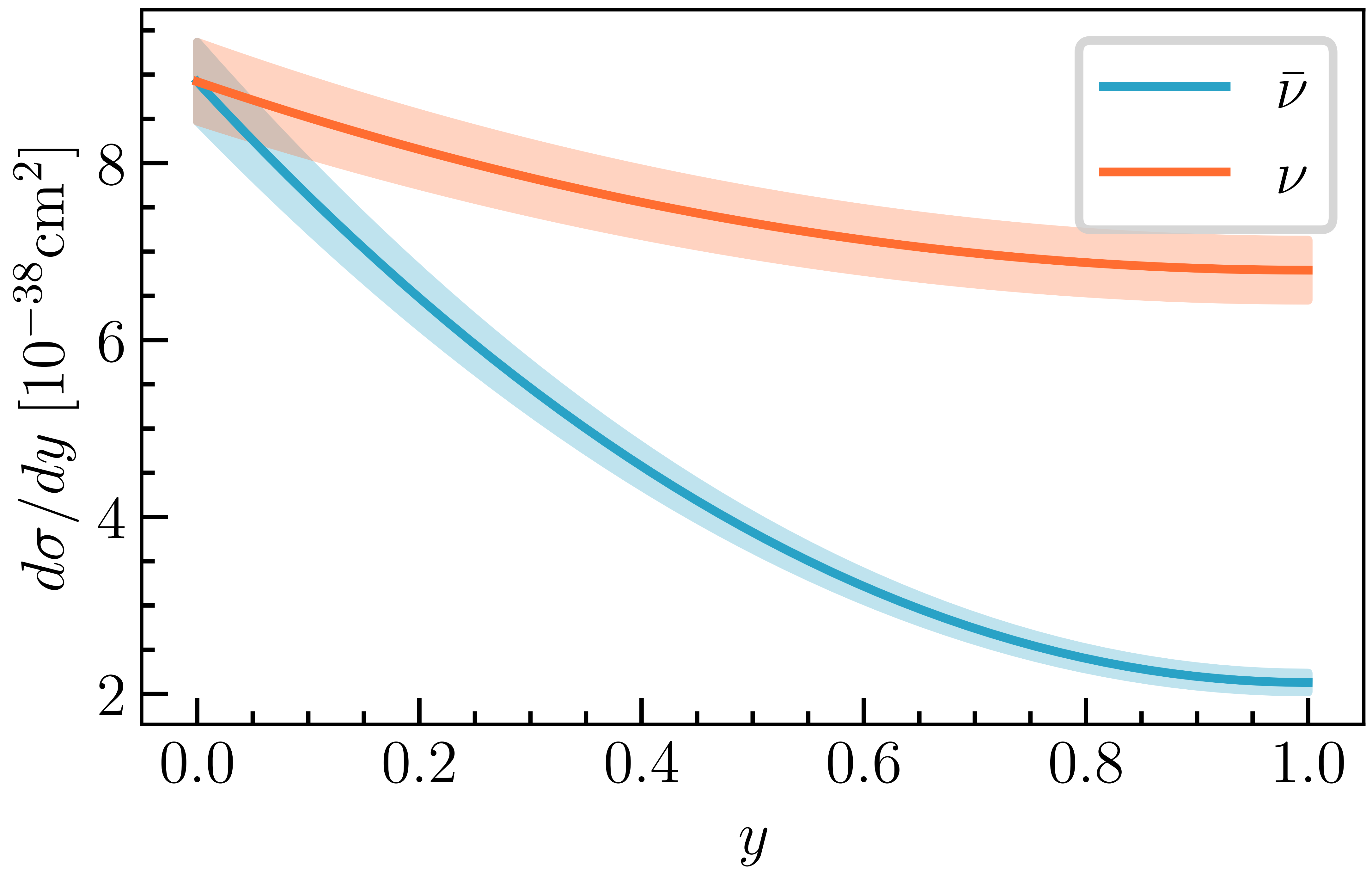
C.A. Argüelles, P. Fernandez, I. Martinez-Soler and M. Jin, PRX 13 (2023) 4, 041055

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

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



S.Giner Olavarrieta, M. Jin, C. Argüelles, P. Fernández, IMS, arXiv: 2402.13308

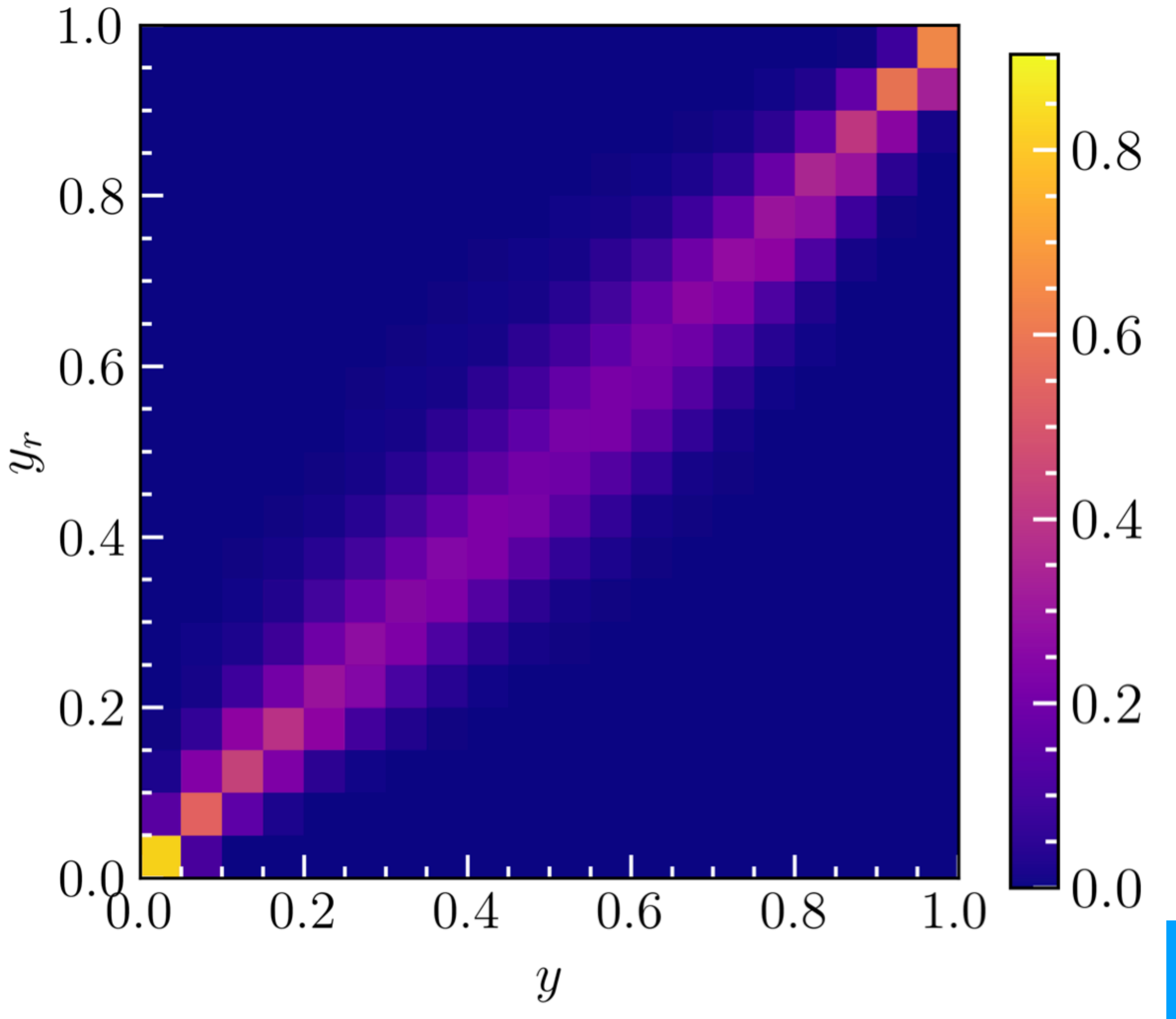
See also: Ribordy and Smirnov, Phys.Rev.D, 87, 113007 (2013)

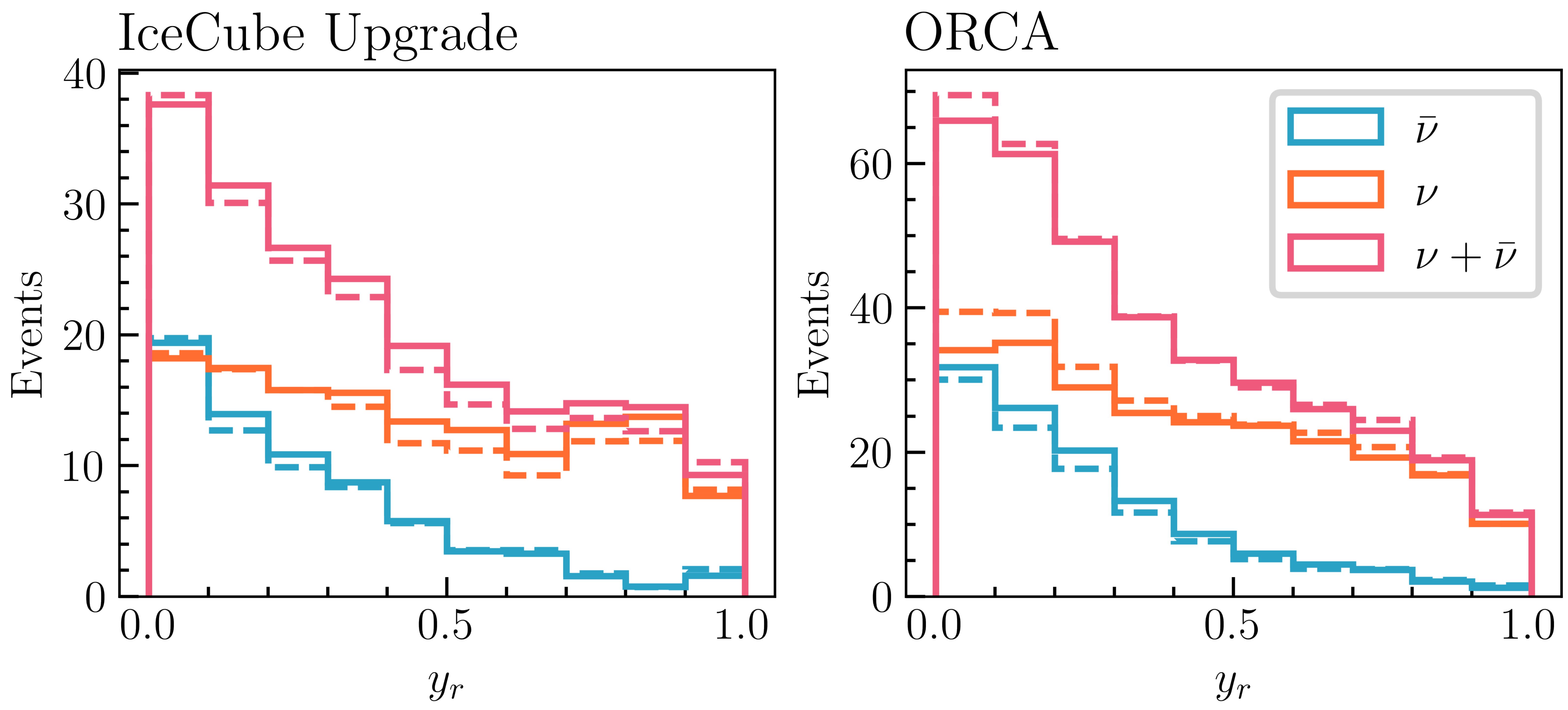
Boosting the Sentivity with Inelasticity

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

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

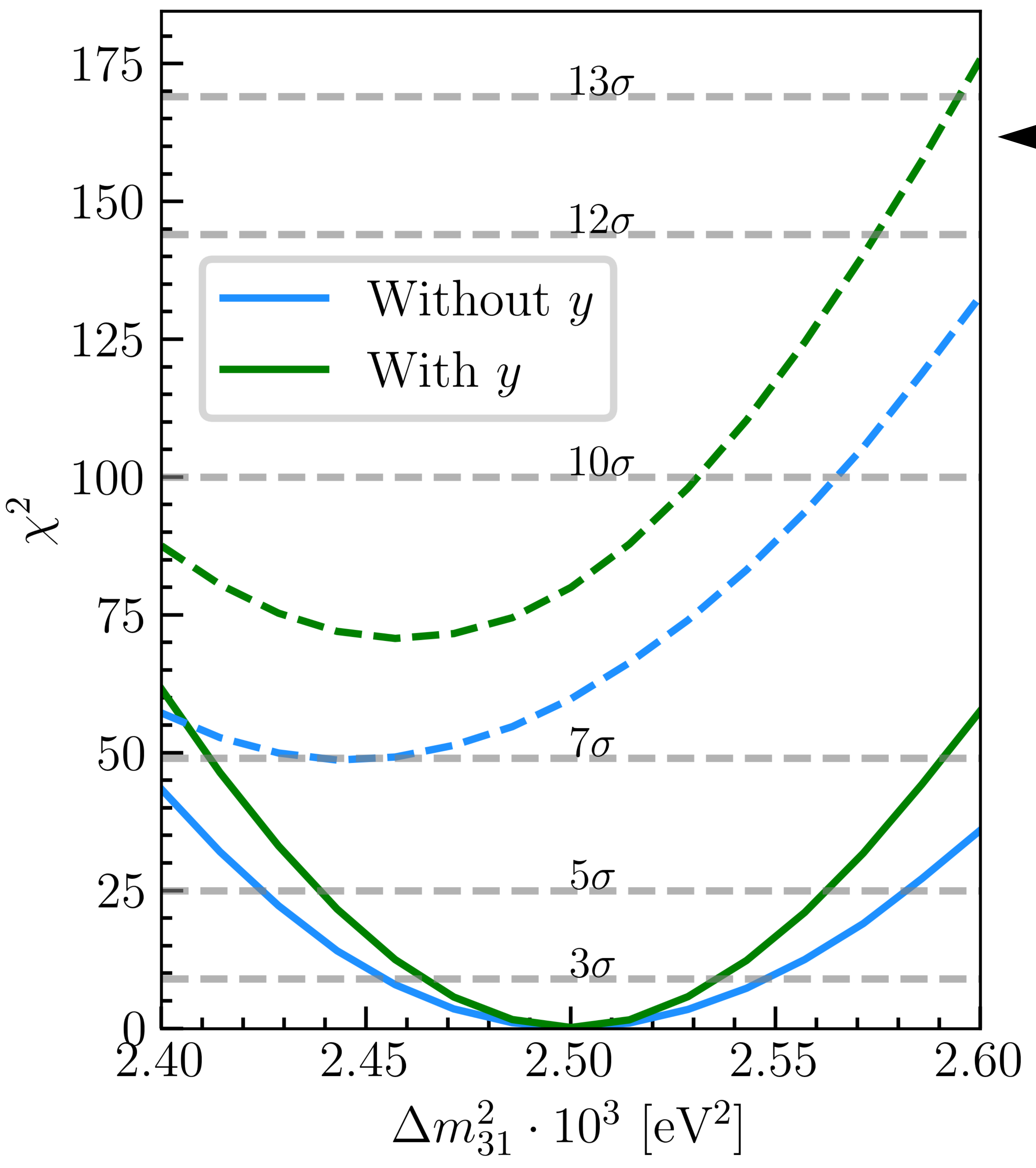
Reconstructed inelasticity





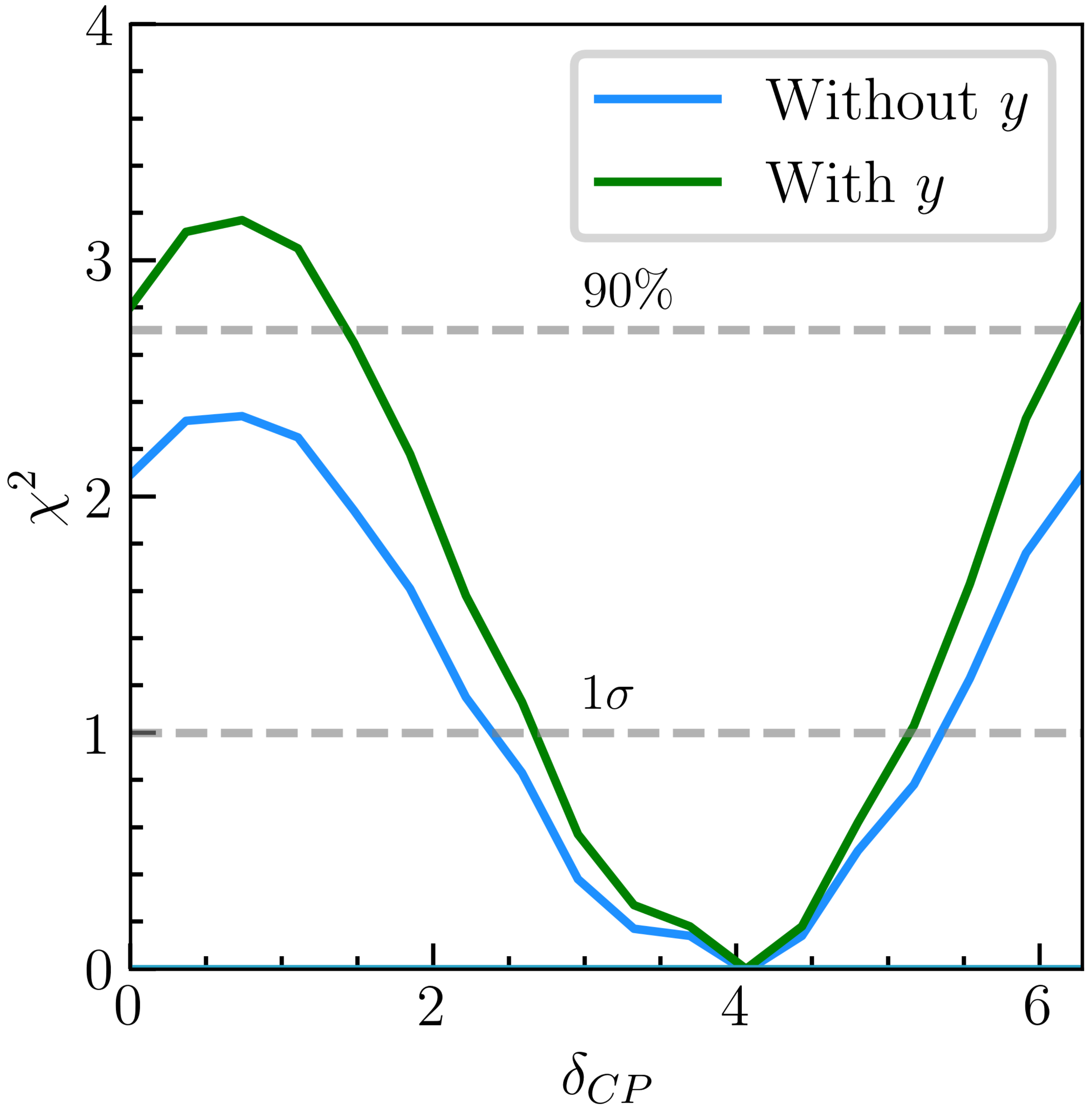
S.Giner Olavarrieta, M. Jin, C. Argüelles, P. Fernández, IMS, arXiv: 2402.13308

Boosting the Sentivity with Inelasticity



- 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%



S.Giner Olavarrieta, M. Jin, C. Argüelles, P. Fernández, IMS, arXiv: 2402.13308

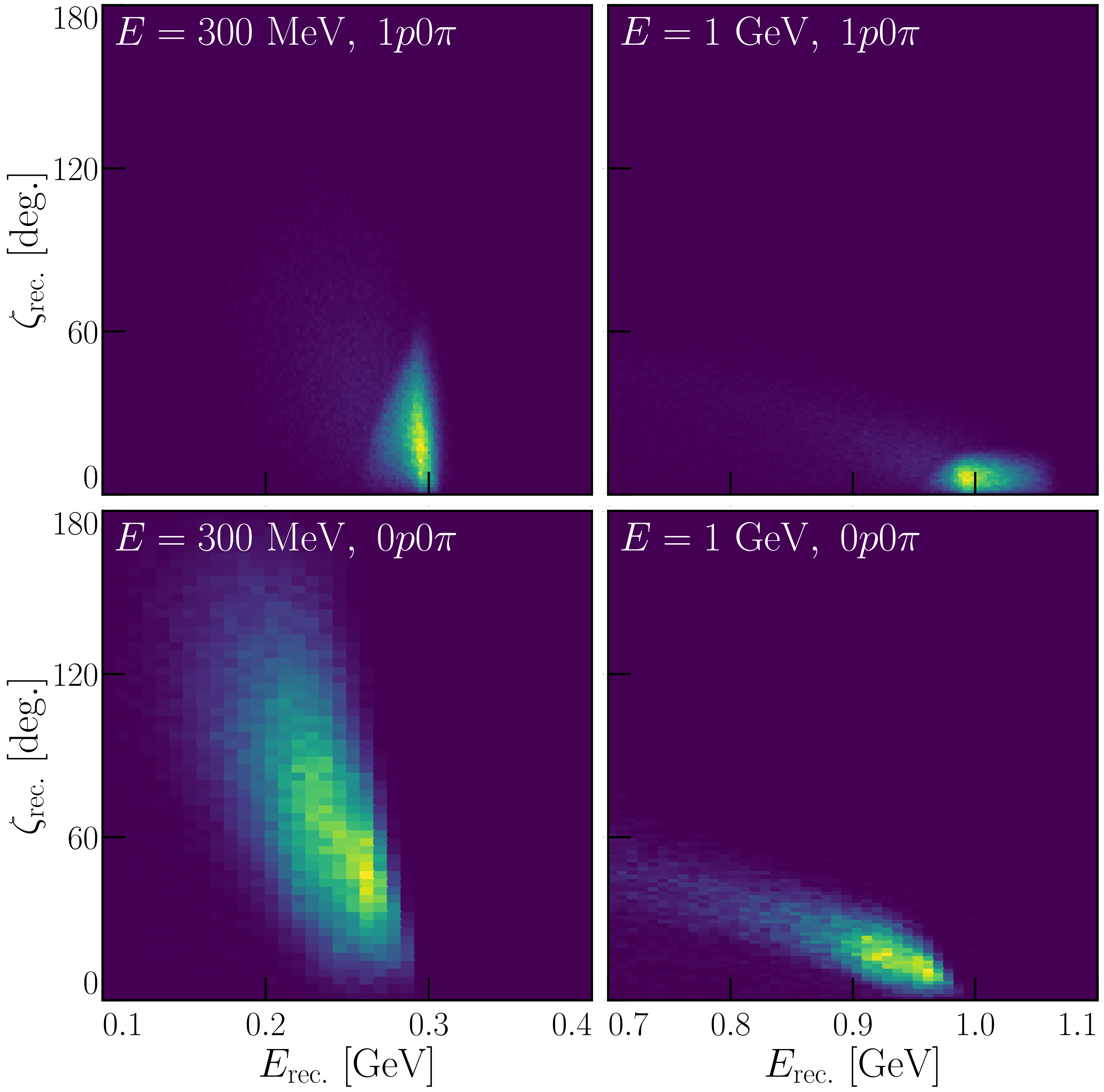
Future Experiments: DUNE

LArTPCs:

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

We consider **events topologies** based on the **number of visible protons and pions** in the final state (CC – NpMπ).

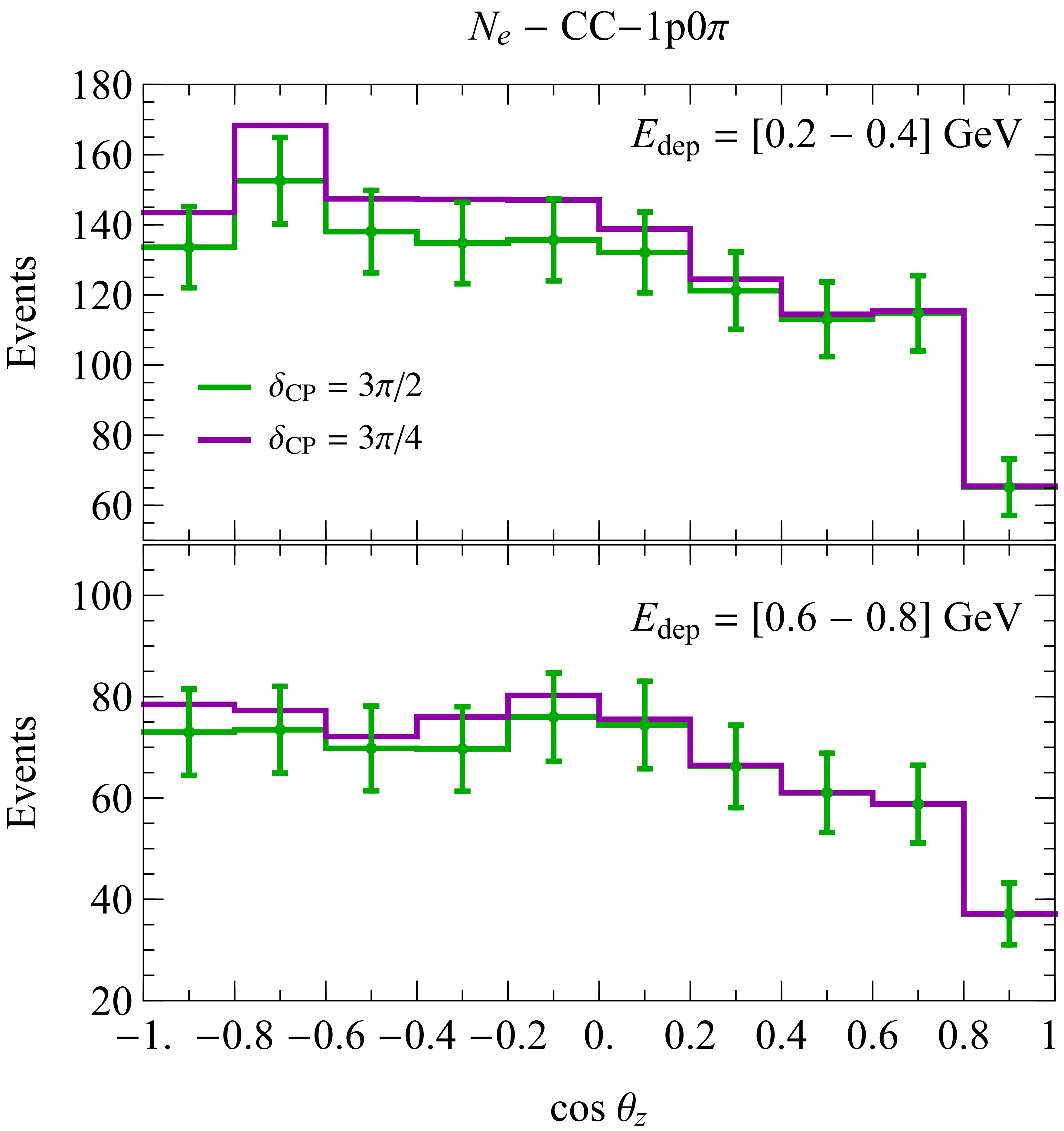
Np	Events/400 kton year
CC-0p0π	~7000
CC-1p0π	~12000
CC-2p0π	~500
CC-0p1π	~200



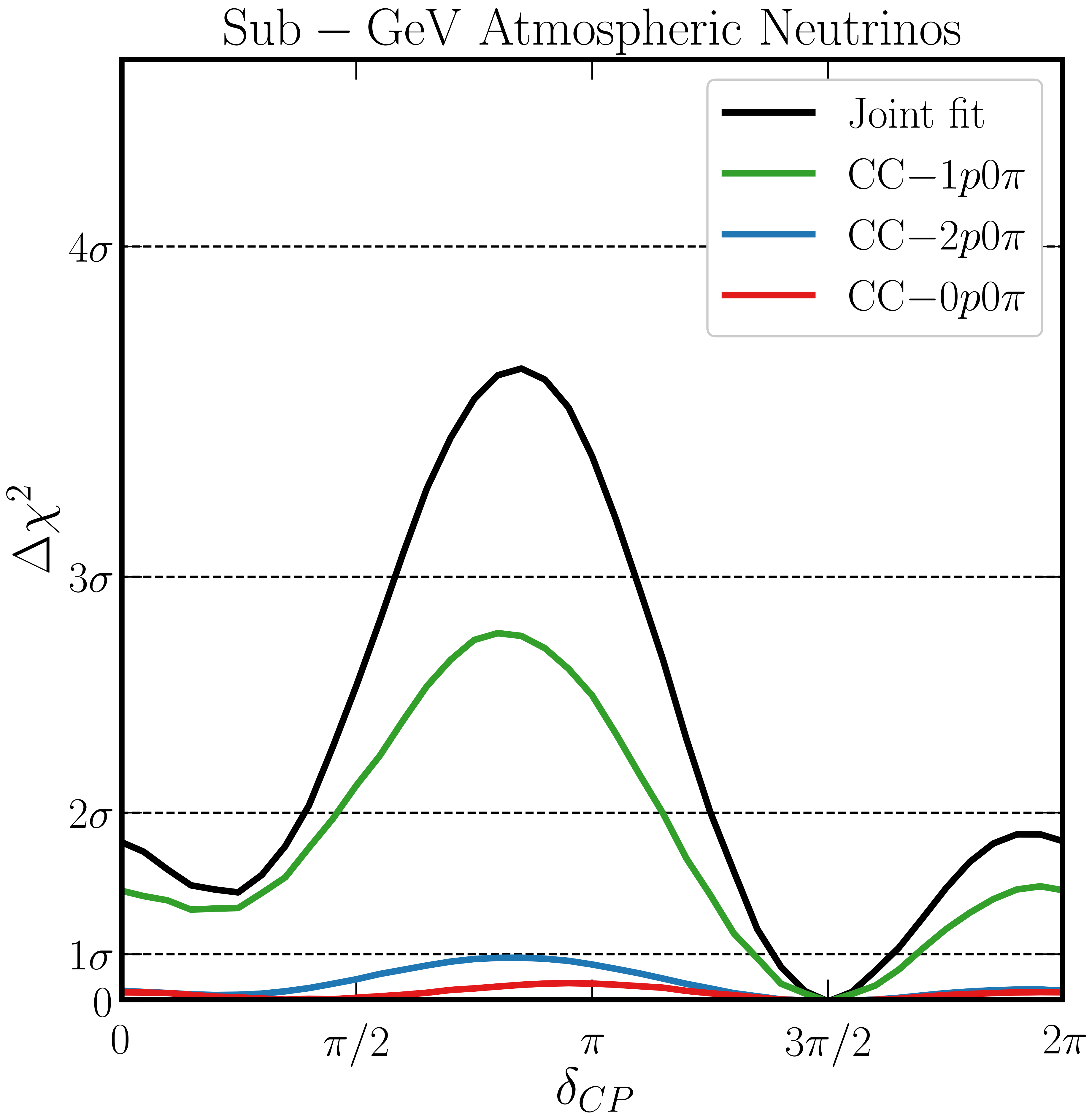
KJ.Kelly, P.A.N.Machado, IMS, S.J.Parke
Y.F.Perez-Gonzalez, Phys.Rev.Lett 123 (2019) 8

Future Experiments: DUNE

δ_{cp} induces a large deviation in the number of expected events for DUNE



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



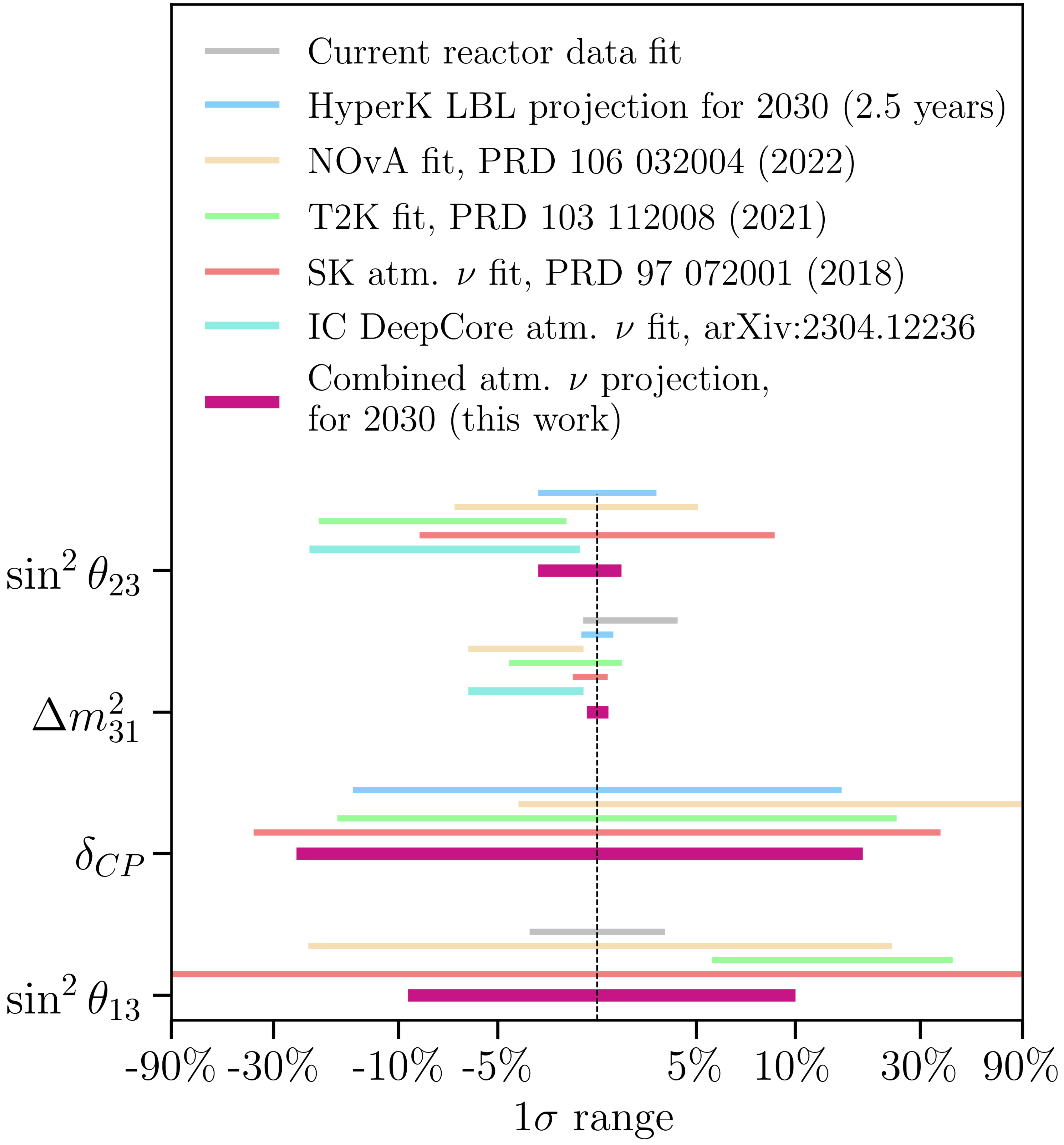
KJ.Kelly, P.A.N.Machado, I. Martinez-Soler, S.J.P Y.F.Perez-Gonzalez, Phys.Rev.Lett 123 (2019) 8

Conclusions

- The 3ν mixing scenario explains with good accuracy most of the data measured in reactors, accelerators, solar, and atmospheric neutrinos

- 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 can improve the precision over the CP phase



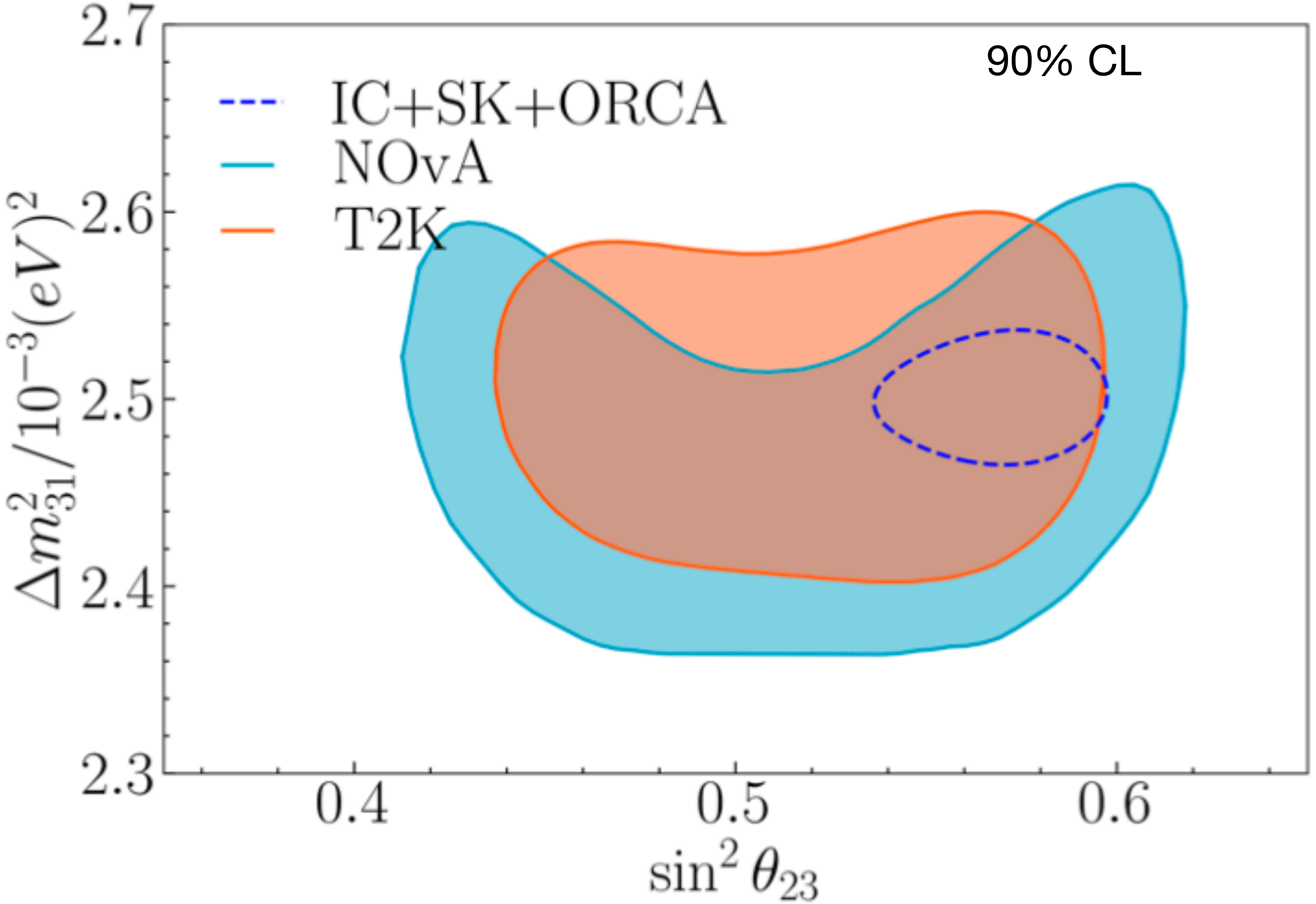
C.A. Argüelles, P. Fernandez, I. Martinez-Soler and M. Jin, PRX 13 (2023) 4, 041055

Thanks!

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

The **SK+IC-upgrade+ORCA** will have better sensitivity than **LBL** and **reactor** experiments.

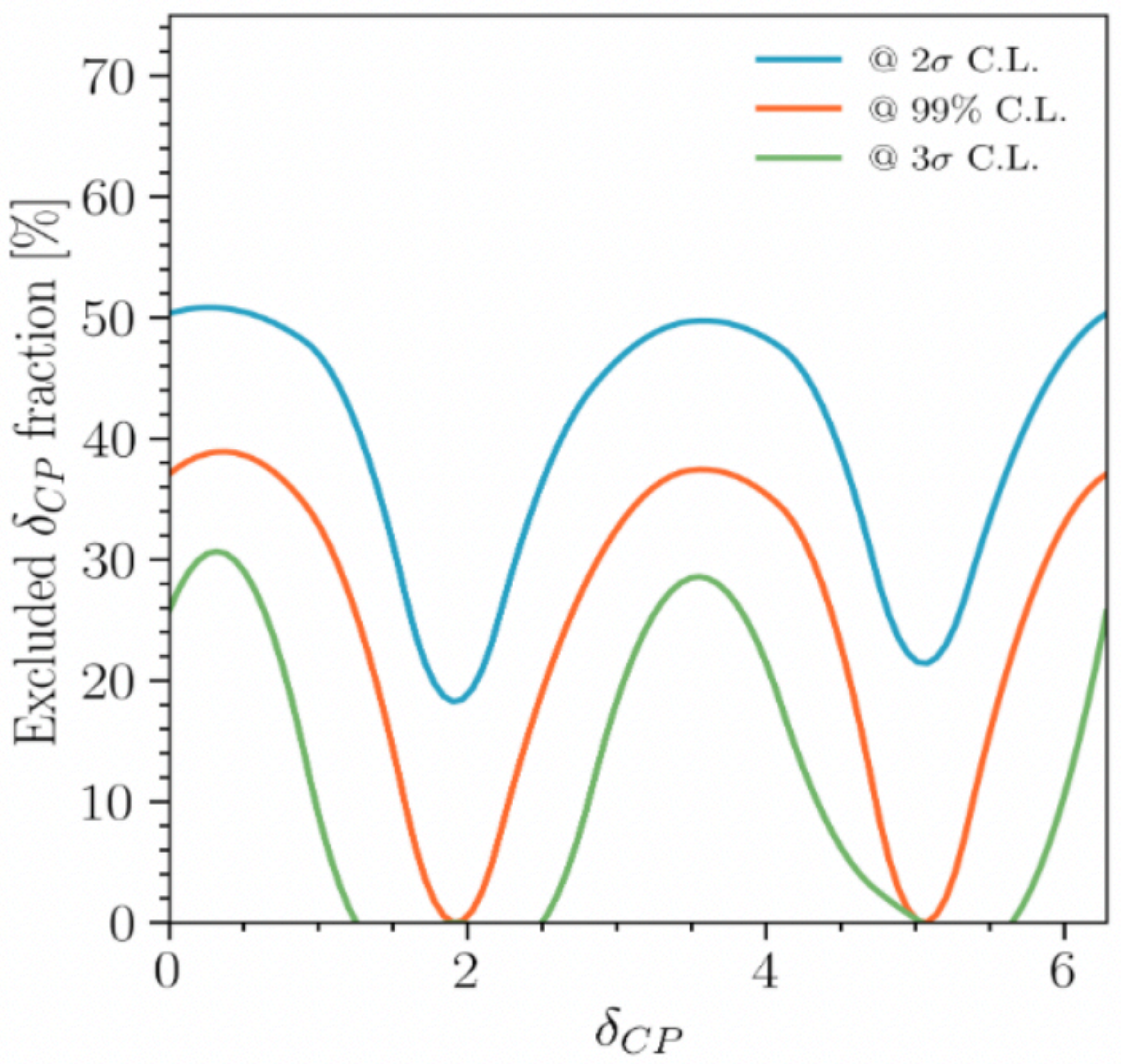
- $\sin^2\theta_{13}$ = 0.022 (fixed)
- Profiled over δ_{cp}



Combined analysis: δ_{cp}

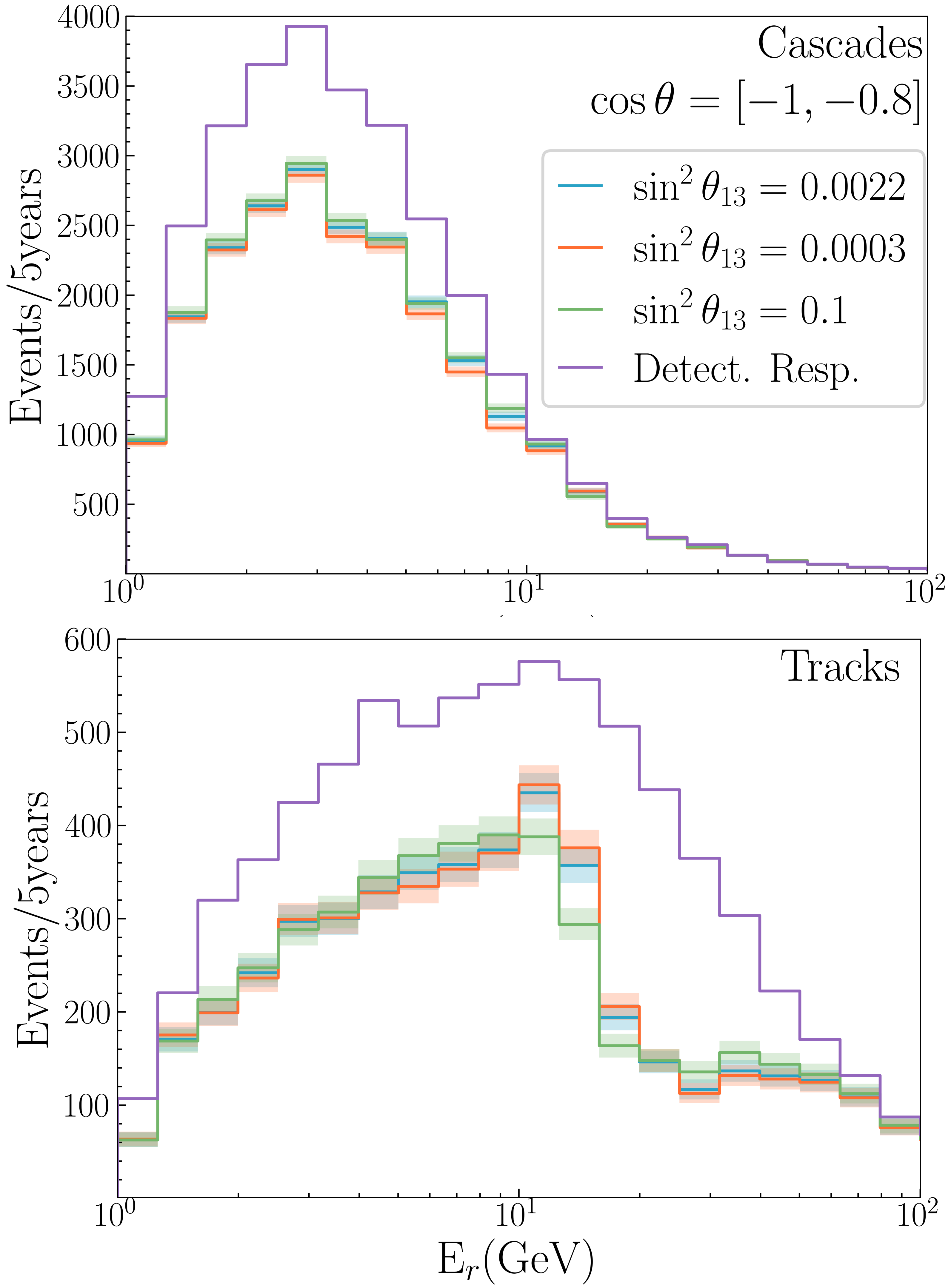
The sensitivity to the CP phase depends on the true value

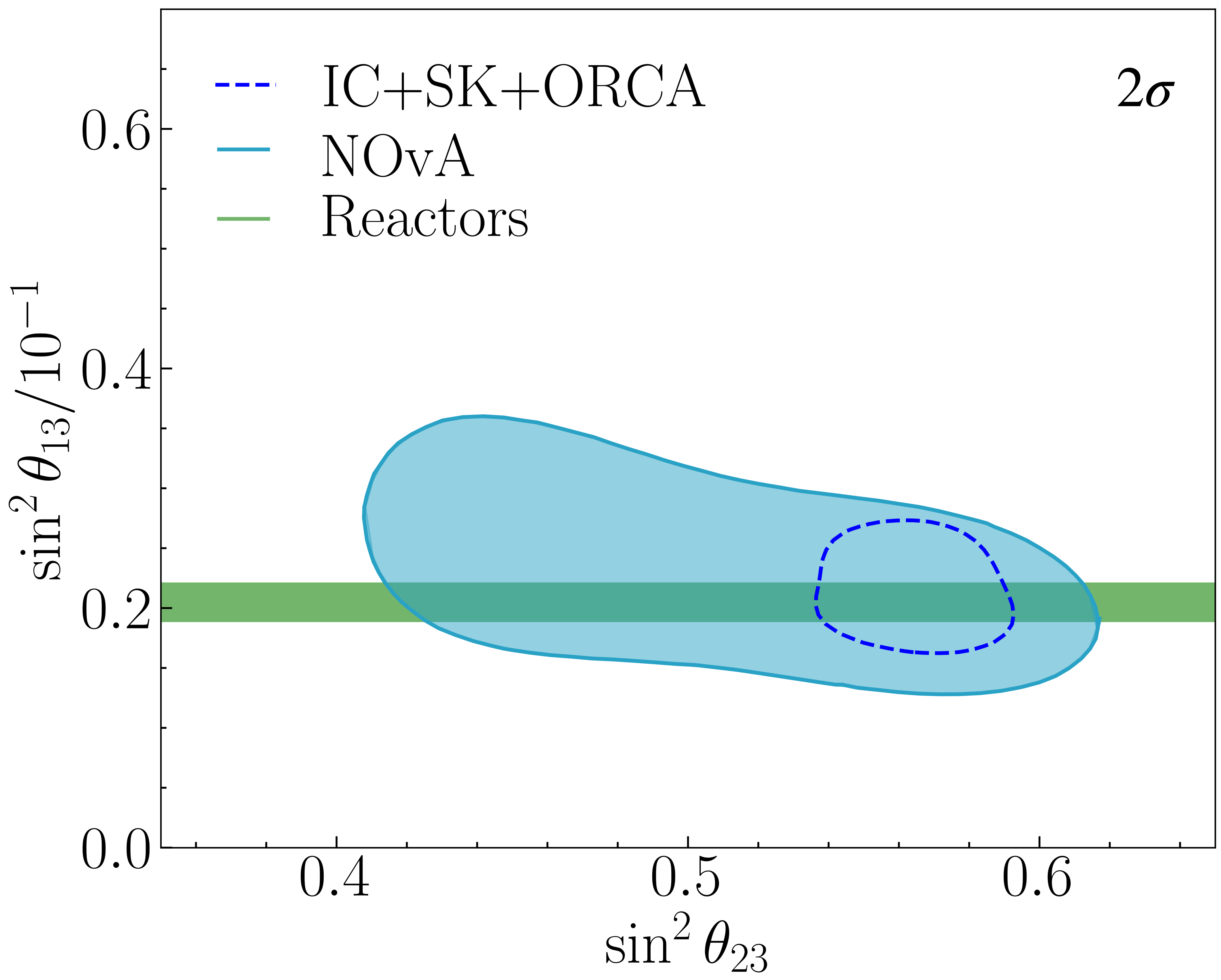
A large fraction of δ_{CP} can be excluded at 99% CL for any value of δ_{CP} using only atmospheric neutrinos



Bonus: sensitivity over θ_{13}

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





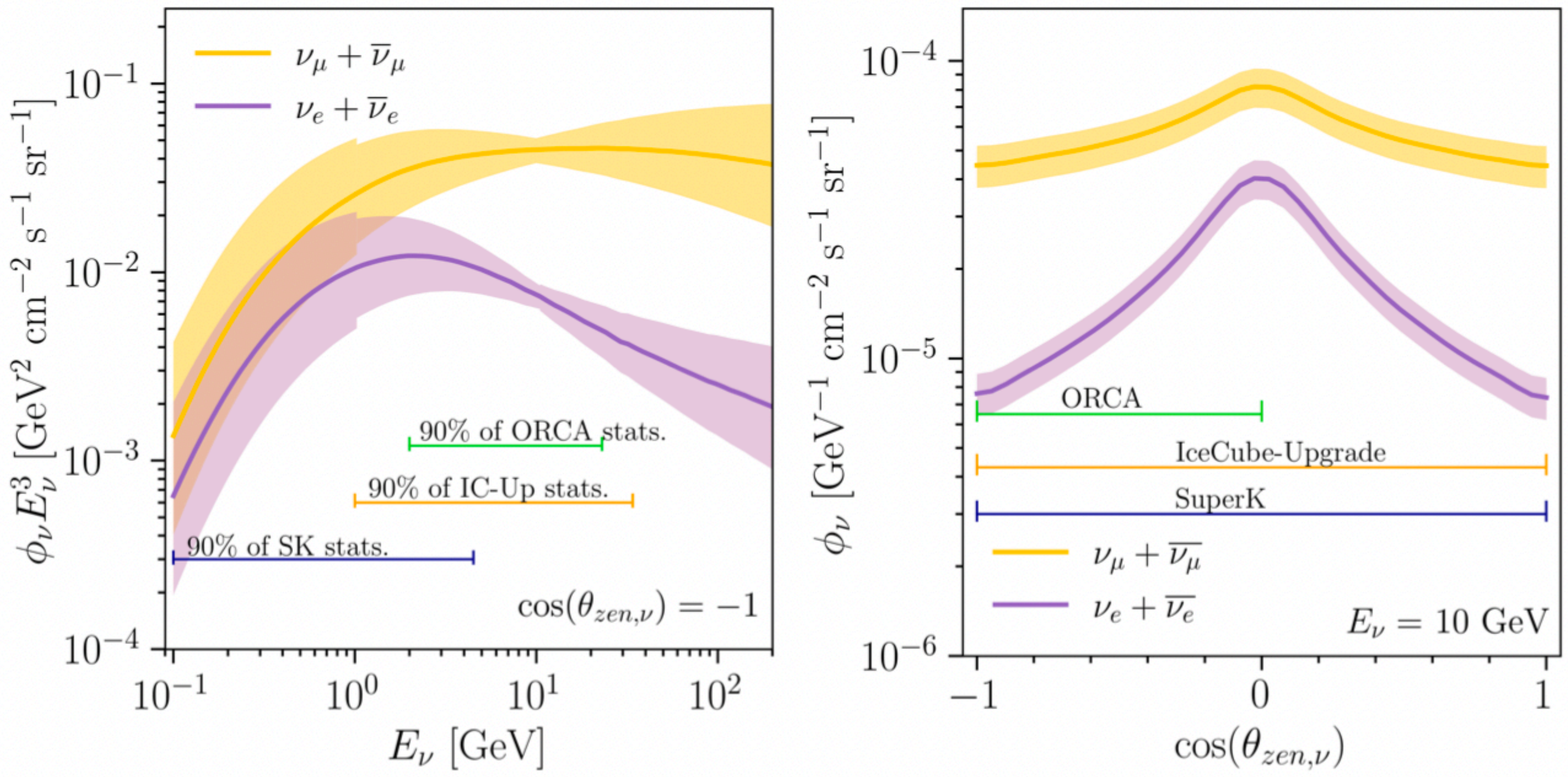
C.A. Argüelles, P. Fernandez, I. Martinez-Soler and M. Jin, arXiv:2211.02666

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

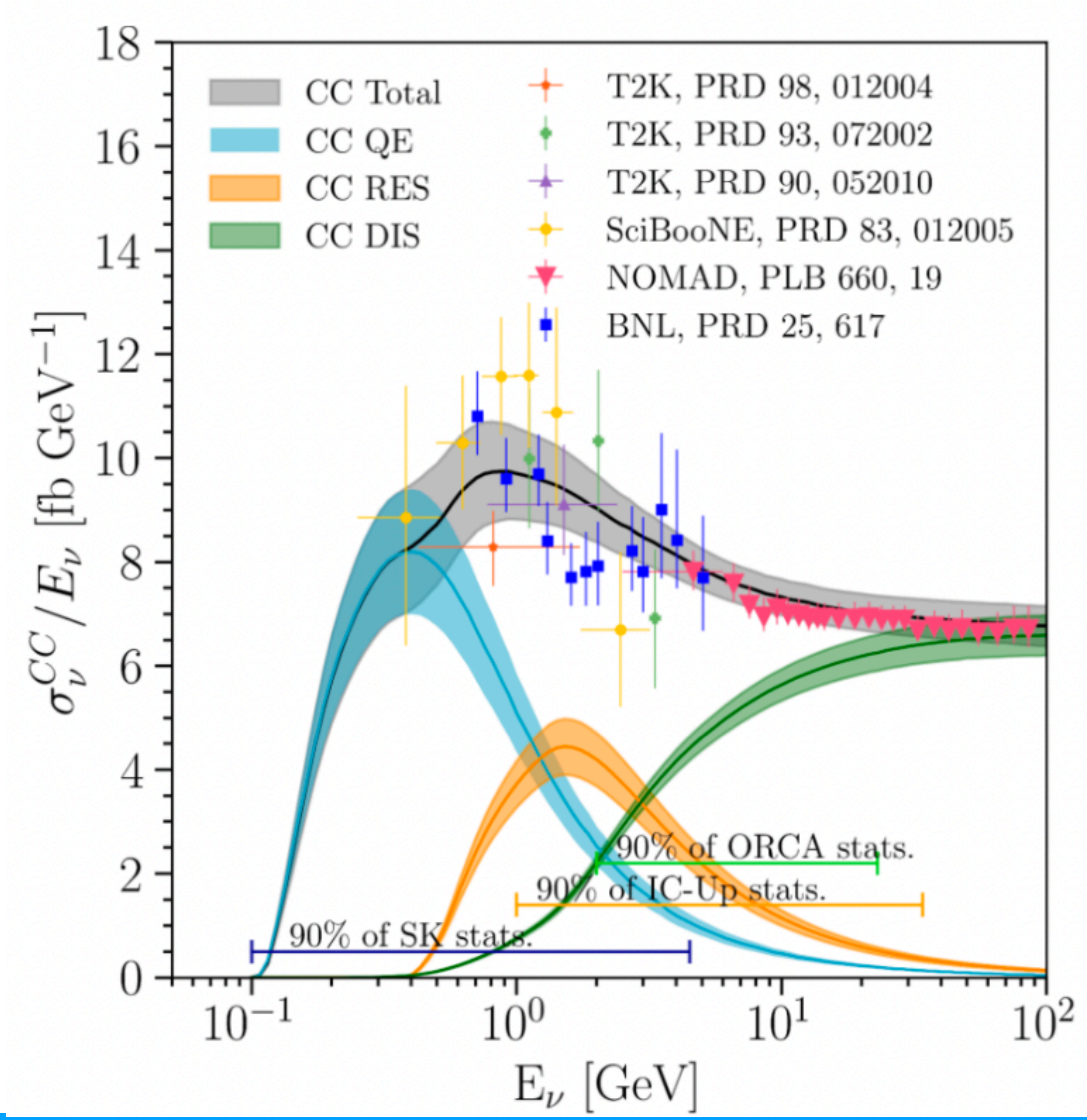


Systematic	Uncert./Priors
$\Phi_0(E < 1$ GeV$)$	25%
$\Phi_0(E > 1$ GeV$)$	15%
ν_e/ν_μ	2%
$\overline{\nu}/\nu$	2%
δ	20%
$C_{u,d}$	2%

K. Abe et al. (Super-Kamiokande), Phys.Rev.D97 (2018) 7, 072001

Cross-section uncertainties

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



K. Abe et al. (Super-Kamiokande), Phys.Rev.D97 (2018) 7, 072001

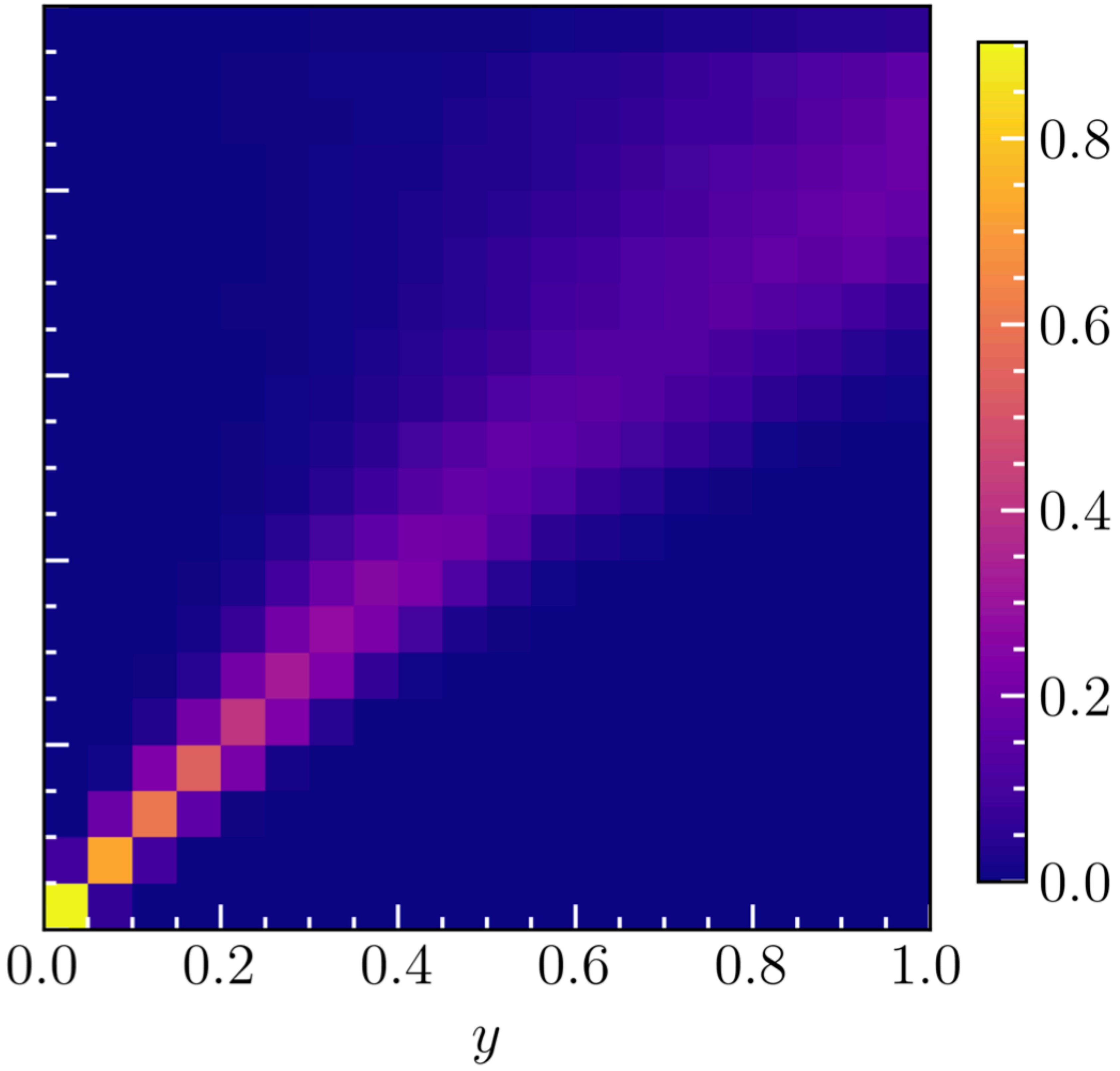
These systematics are common to both experiments

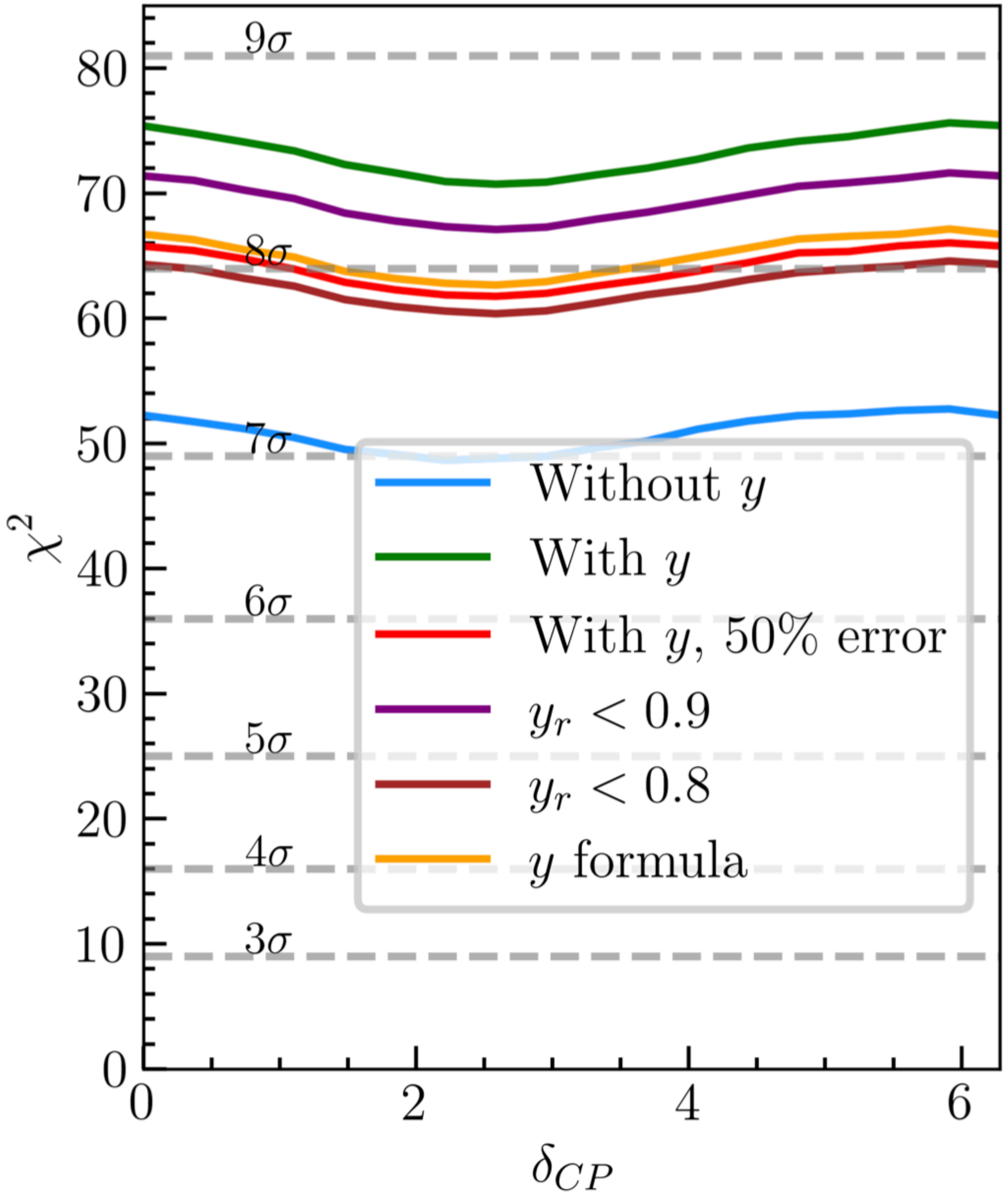
Systematic	Uncer./Prior
CCQE	10%
CCQE $\nu/\overline{\nu}$	10%
CCQE e/μ	10%
CC1 π	10%
CC1π $\pi^0/\pi^\pm$	40%
CC1π $\nu_e/\overline{\nu_e}$	10%
CC1π $\nu_\mu/\overline{\nu_\mu}$	10%
Coh.π	100%
Axial Mass	10%
NC hadron prod.	5%
NC over CC	10%
ν_τ	25%
Neutron prod. (SK)	15%
DIS	10%

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.

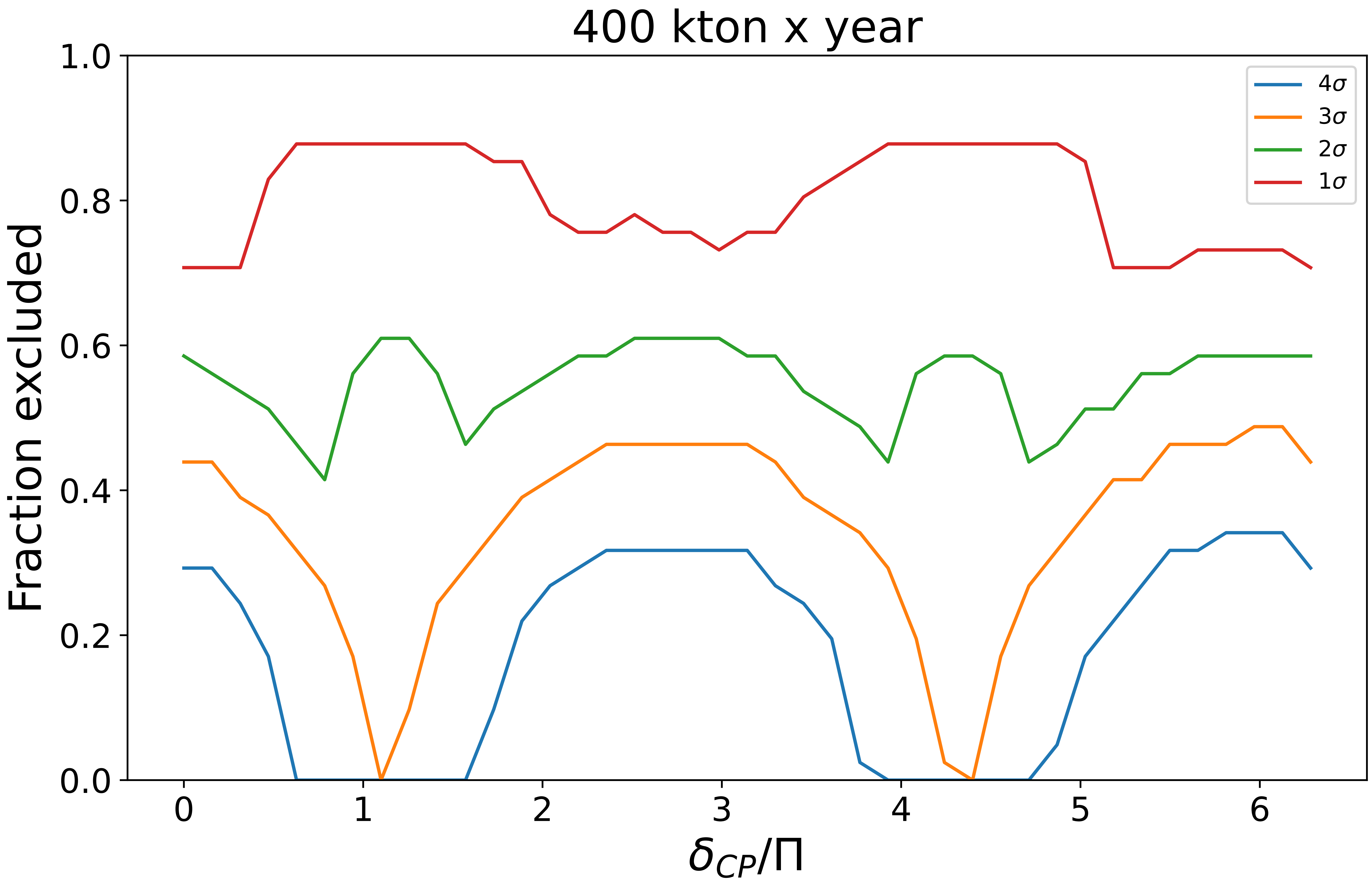




Ivan Martinez-Soler (IPPP)

Future Experiments: DUNE

Fraction of δ_{CP} excluded by DUNE



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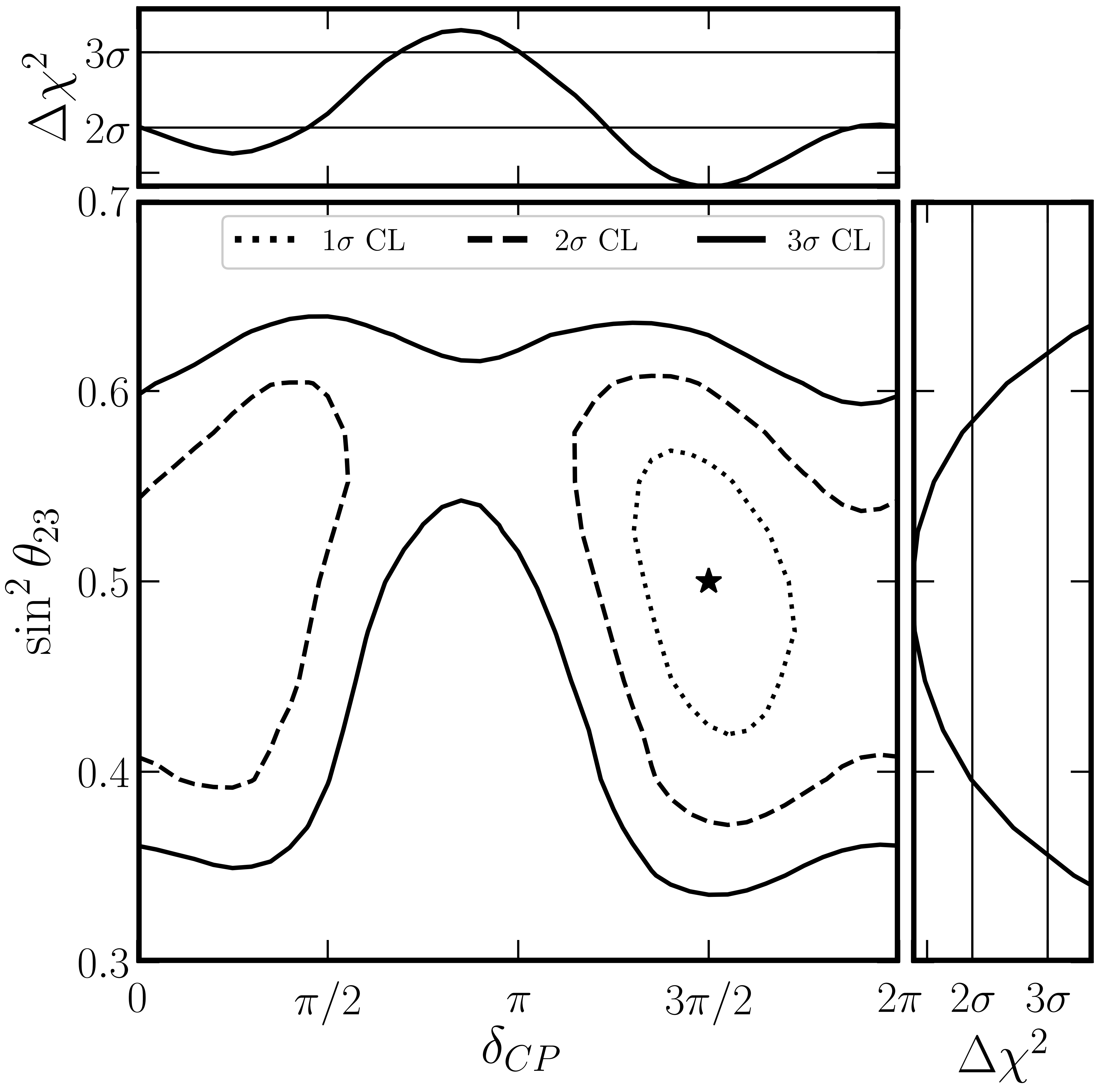
Future Experiments: DUNE



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