

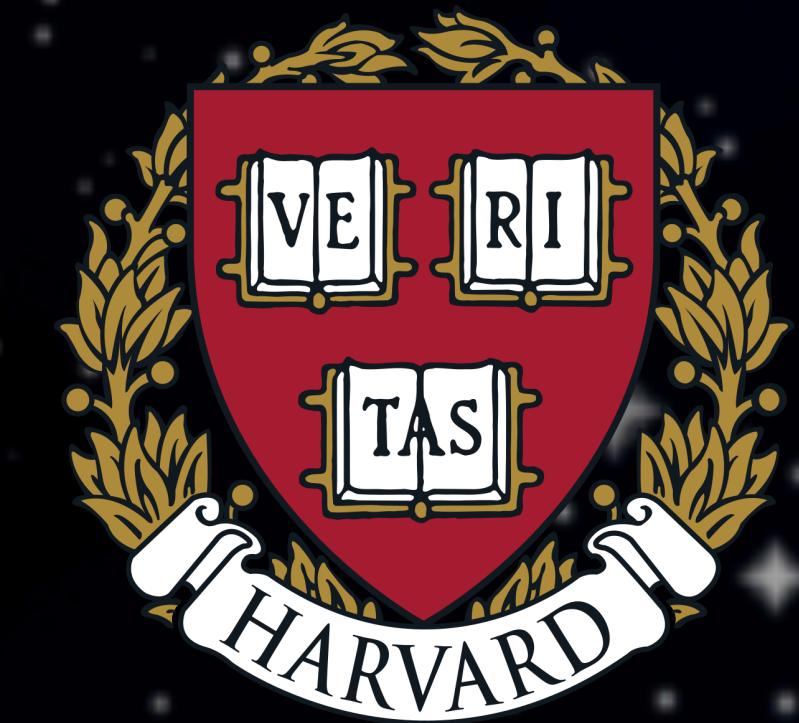
# Measuring oscillations with a million of atmospheric neutrinos

CERN Neutrino Platform Pheno Week 2023

Ivan Martinez-Soler

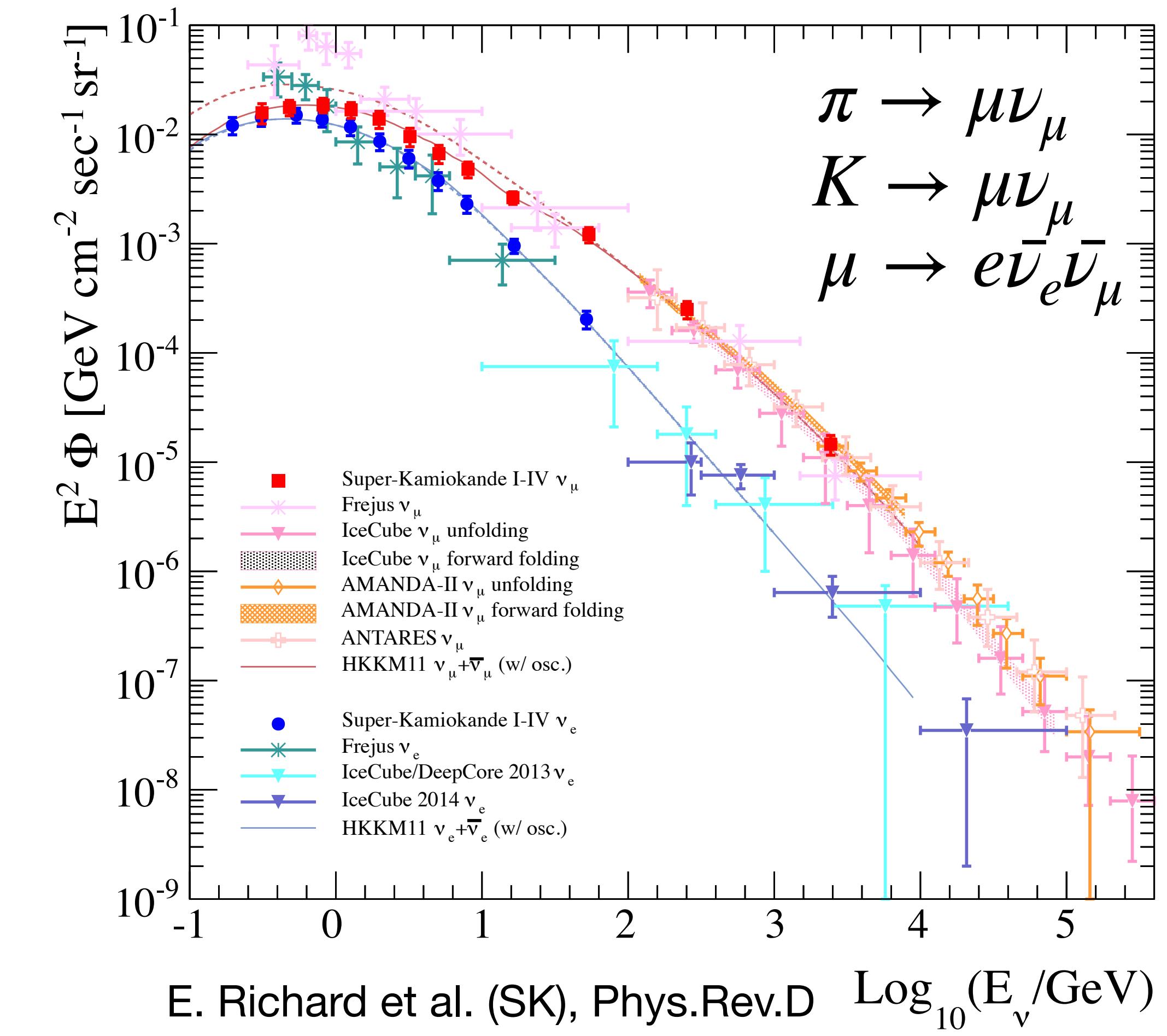
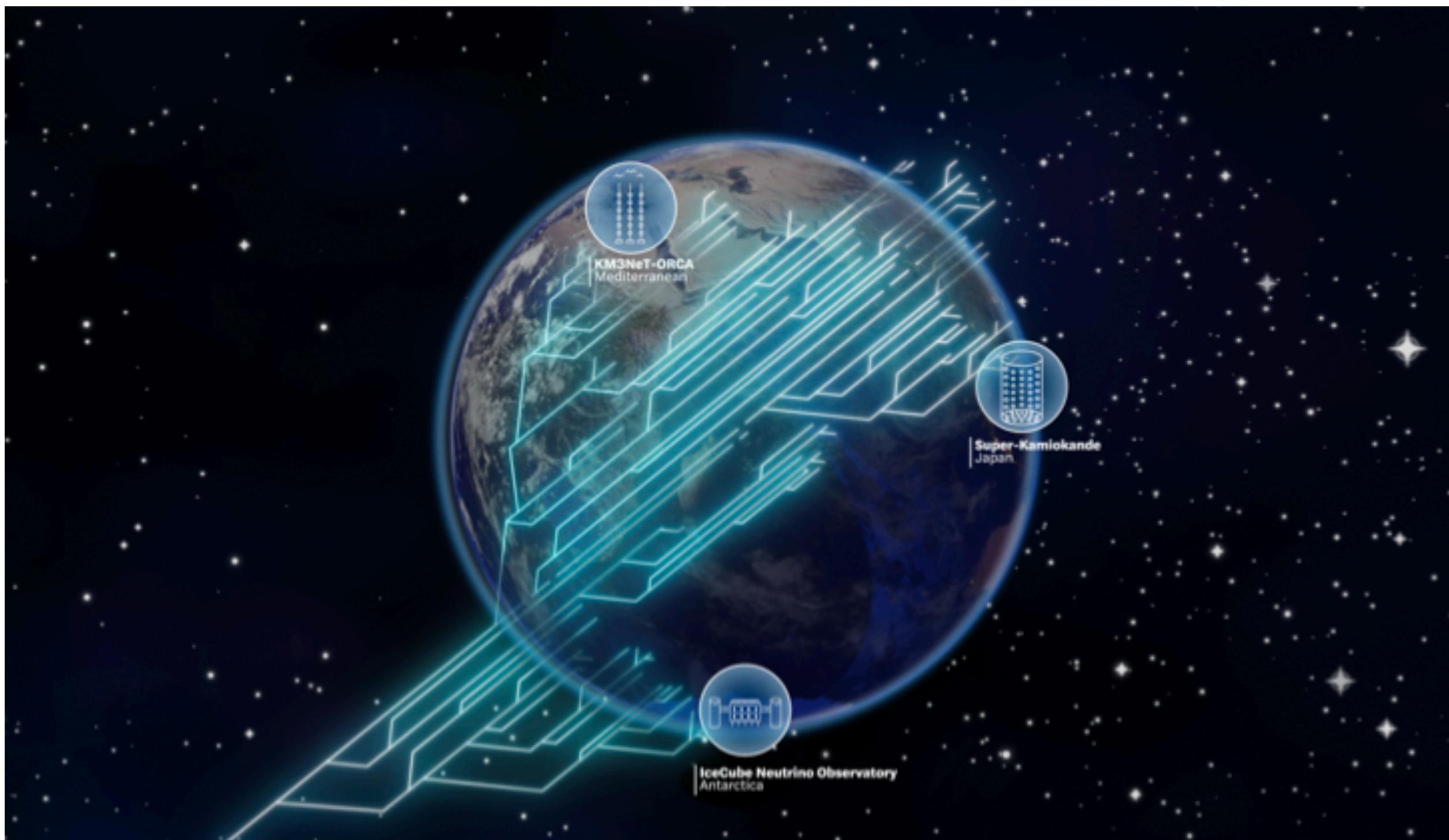
March 14, 2023

IceCube Neutrino Observatory  
Antarctica



# Atmospheric neutrinos

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



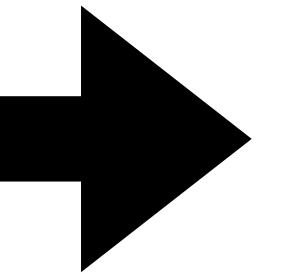
# Atmospheric neutrinos

The atmospheric flux **composition changes** with the energy

$$\phi_{\nu_i} = \phi_p \otimes R_p \otimes Y_{p \rightarrow \nu_i} + \sum_A \phi_A \otimes R_A \otimes Y_{A \rightarrow \nu_i}$$

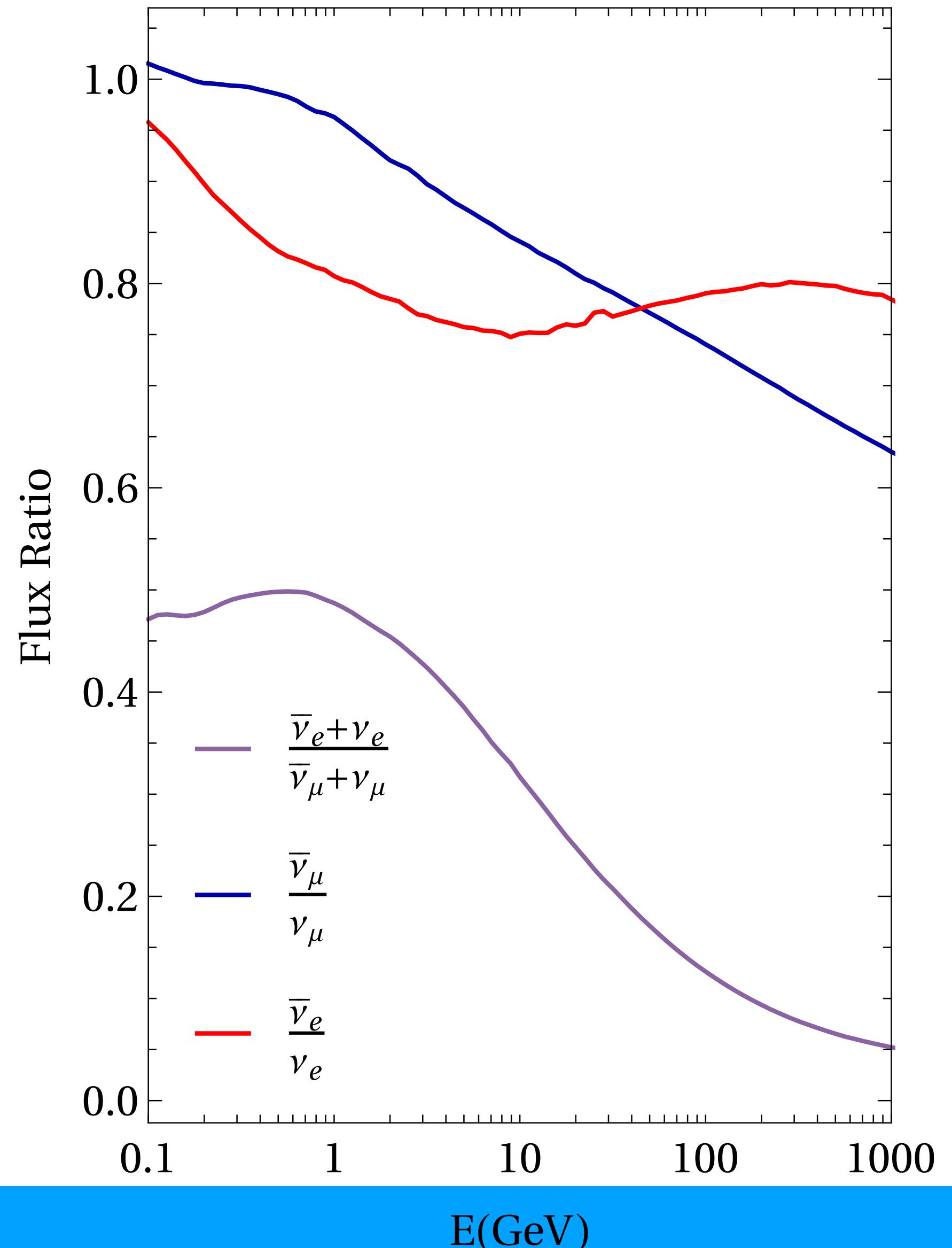
The main components in the flux calculations are:

- **Cosmic ray flux ( $\phi_p$ )**
- **Geomagnetic effects (R)**
- **Hadronic interactions (Y)**



The flux changes with the direction, there is an **enhancement in the horizontal direction**

Honda, Sajjad Athar, Kajita, Kasahara,  
Midorikawa Phys.Rev.D 92 (2015)



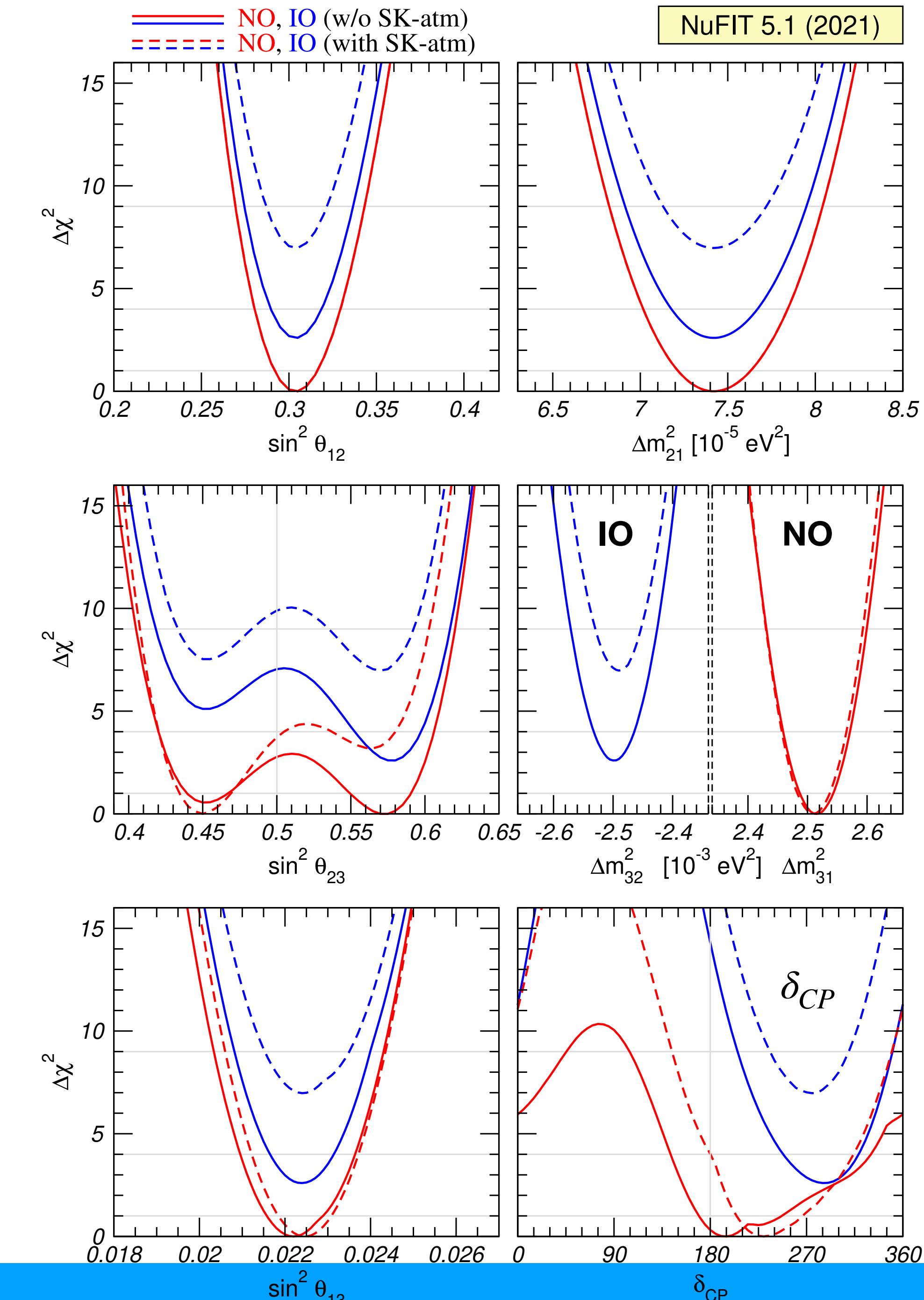
# $3\nu$ mixing

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

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

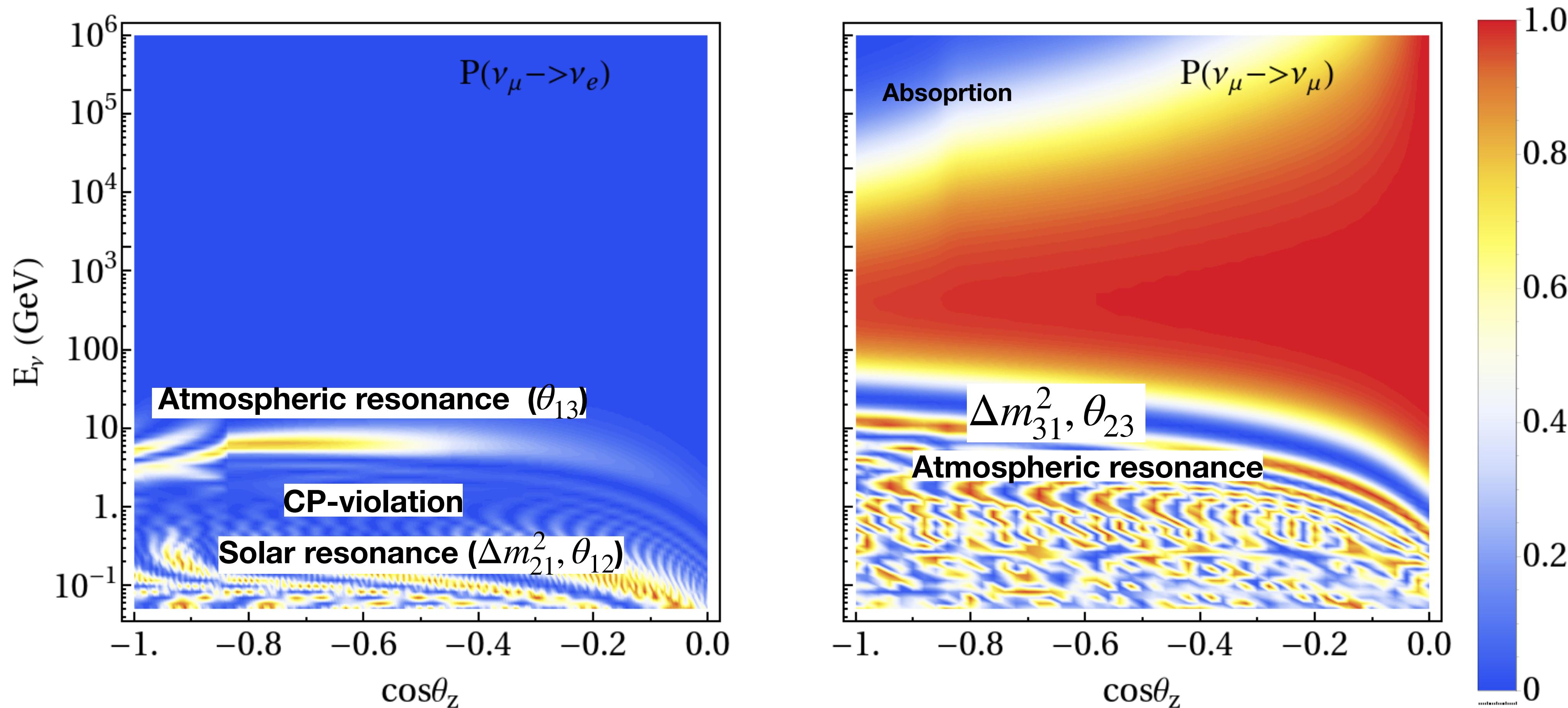
$$U = U(\theta_{23}) U(\theta_{13}, \delta_{cp}) U(\theta_{12})$$

- The less constrained parameters are:
- Mass ordering
  - Octant of  $\theta_{23}$
  - CP-phase



# $3\nu$ mixing through the Earth

A rich phenomenology is accessible using atmospheric neutrinos



# Sub-GeV atmospheric neutrinos

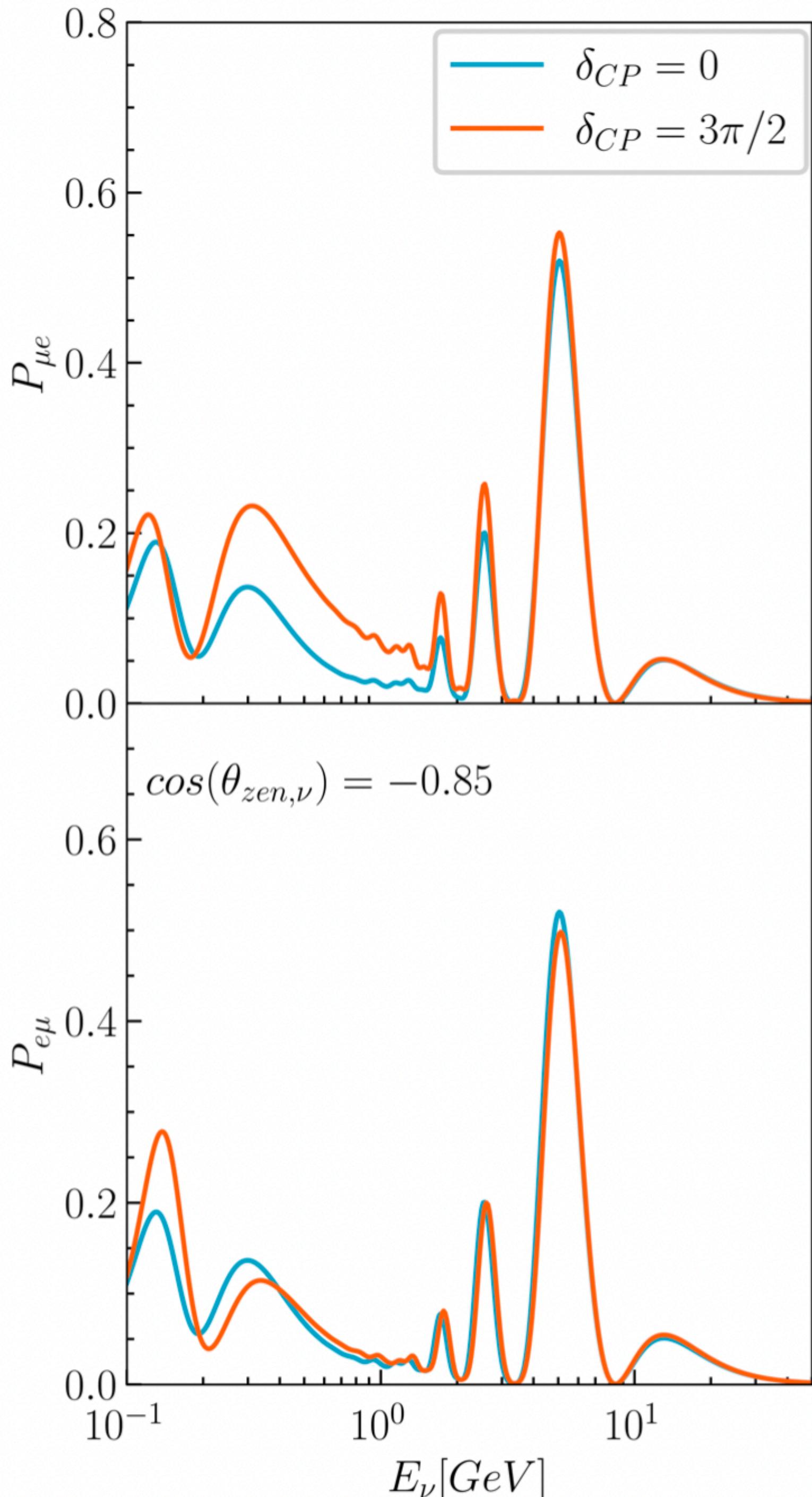
For  $E < 1\text{GeV}$ , atmospheric neutrino oscillations are **dominated by  $\Delta m_{21}^2$**  what enhances the **CP-violation** term

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

For  $\delta_{cp} \neq 0$ , the **CPT conservation** implies

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

- The impact  $\delta_{cp}$  depends on the neutrino direction and it is independent of the neutrino energy.



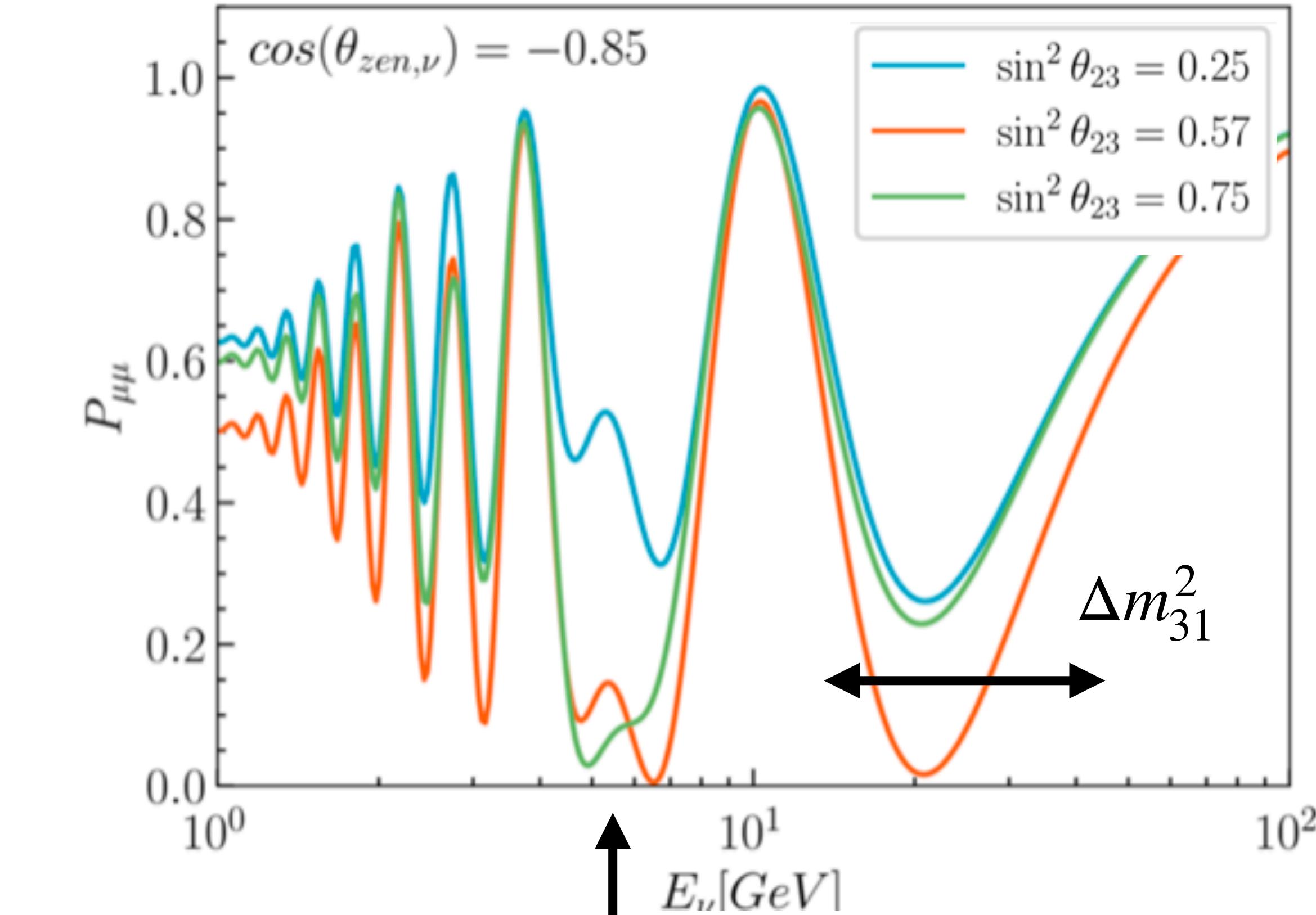
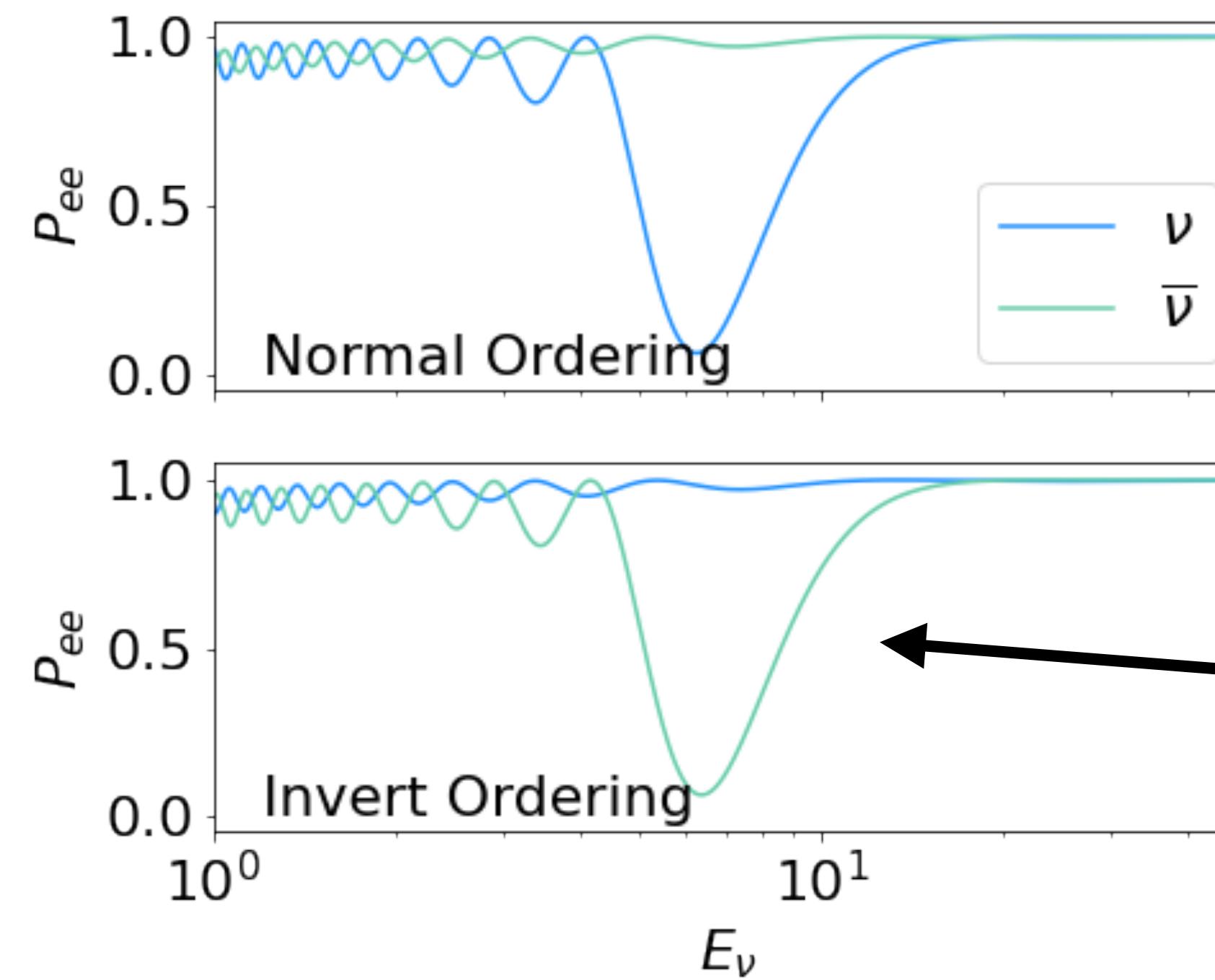
K.J. Kelly, P.A.N. Machado, I. Martinez-Soler, S.J. Parke Y.F.Perez-Gonzalez, PRL 123 (2019)  
I. Martinez-Soler, H. Minakata, PTEP (2019) 7, 073B07

# Multi-GeV atmospheric neutrinos

In the **multi-GeV region**, atmospheric neutrinos evolution is dominated by  $\Delta m_{31}^2$  and  $\theta_{23}$ .

At the GeV scale, there is **resonant flavor conversion** due to enhancement  $\theta_{13}$ .

**Mass ordering sensitivity**

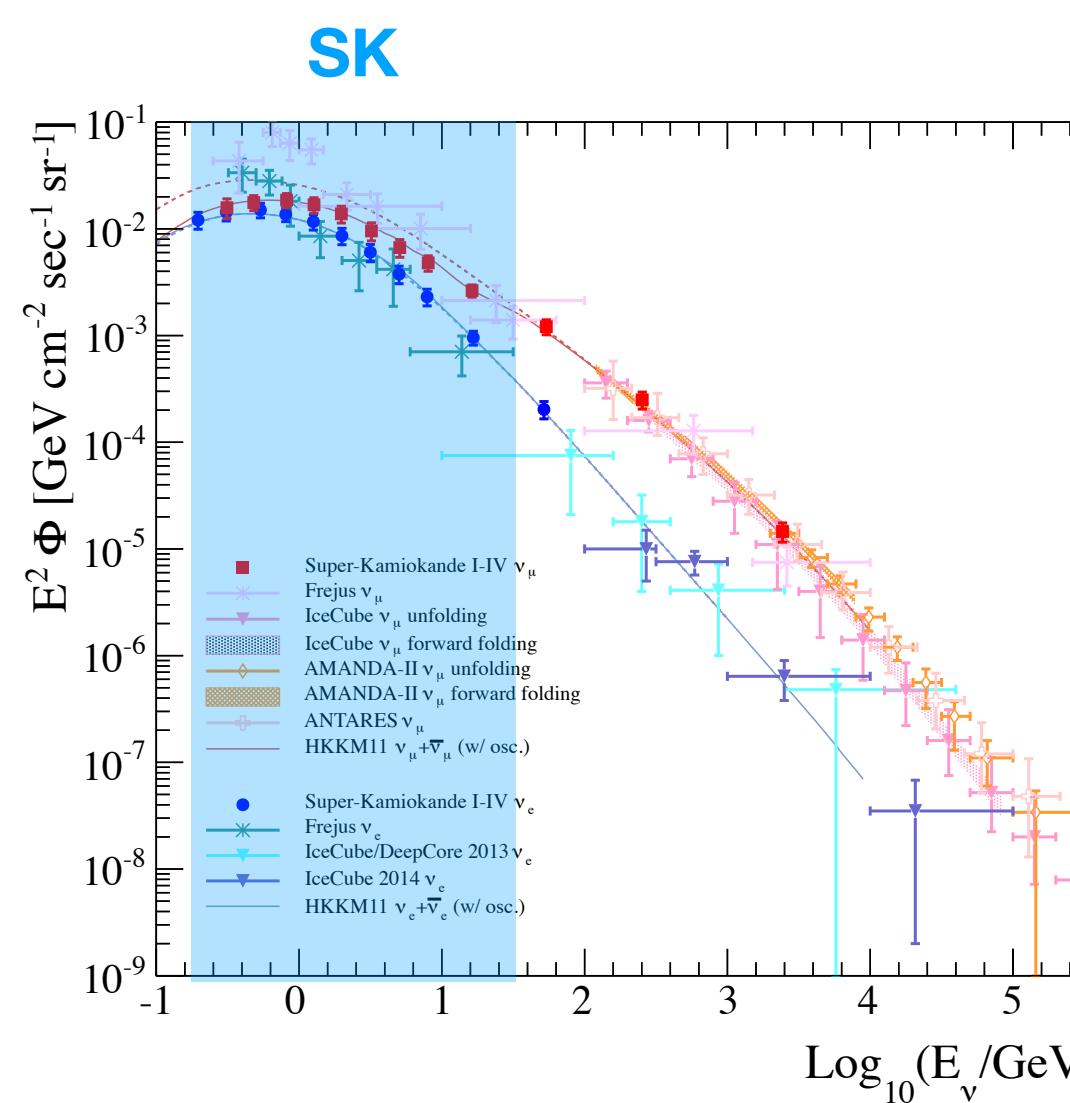


# Detection of atmospheric neutrinos

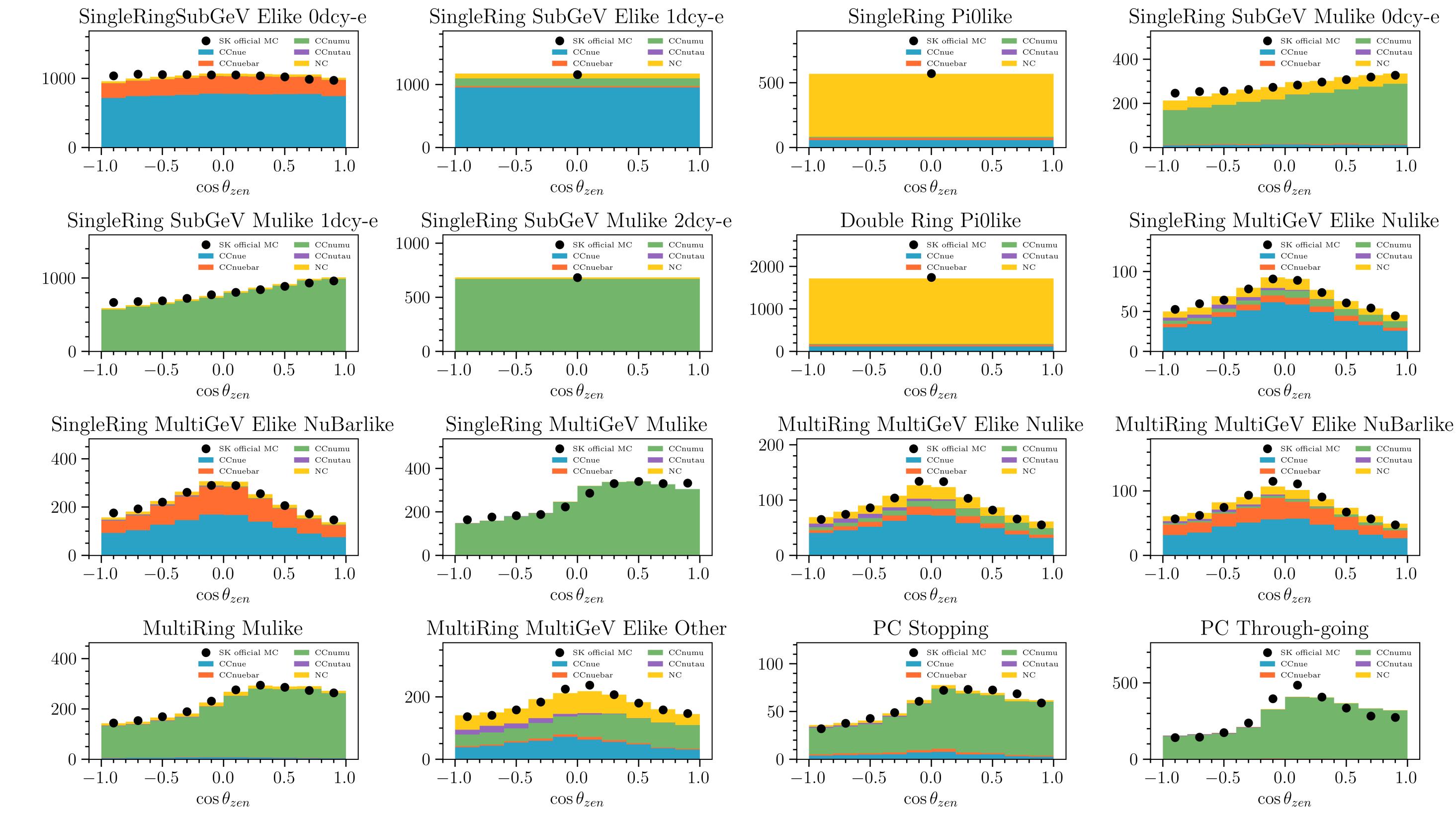
At present, several experiments have measured the neutrino flux at different energy scales

## Super-Kamiokande (SK)

- 22.5 kton water Cherenkov
- Measures the flux from the sub-GeV region
- Small sample at multi-GeV due to the
- Event sample is divided in FC, PC and Up- $\mu$



We developed a simulation of **SK** that includes **all the phases**:

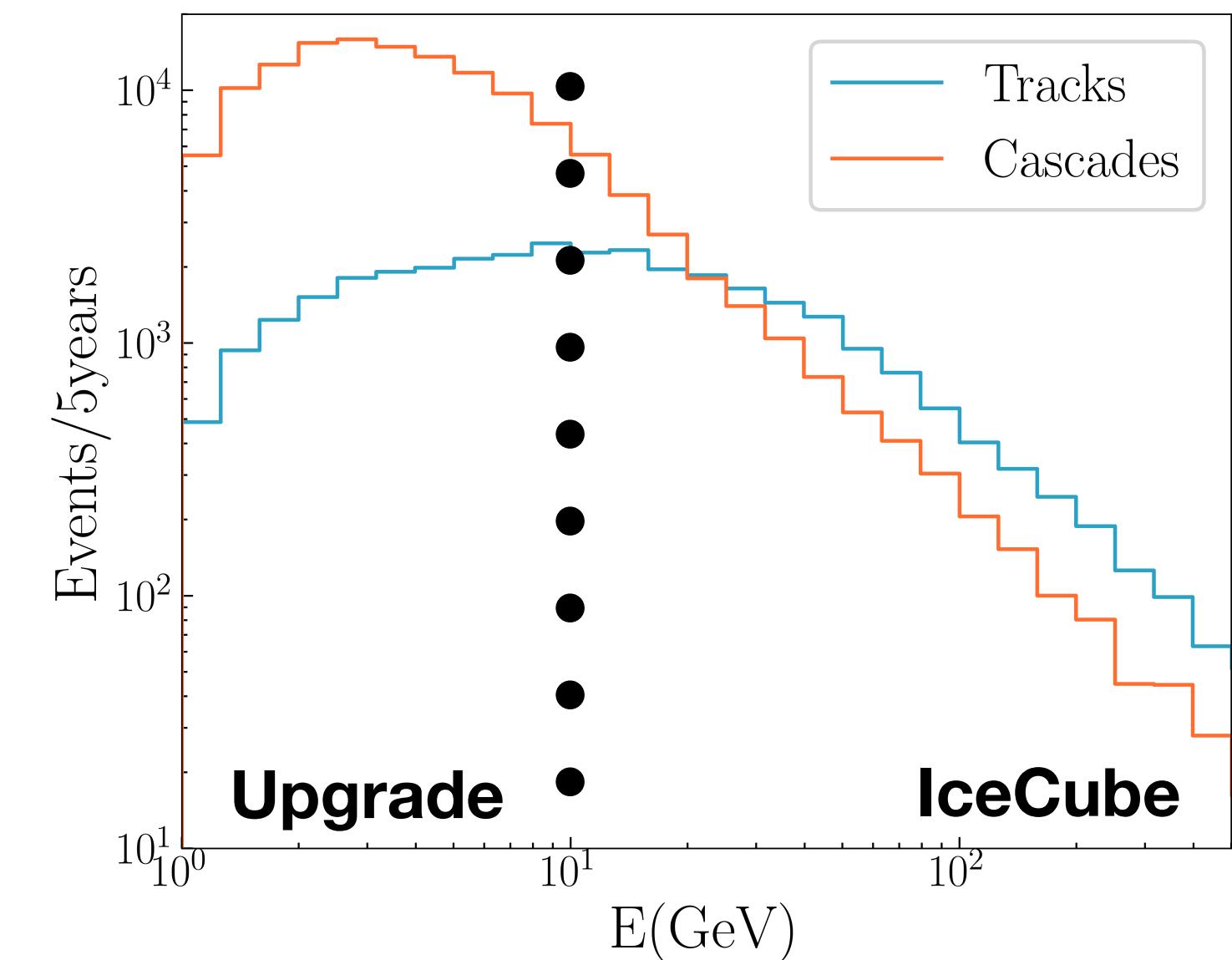
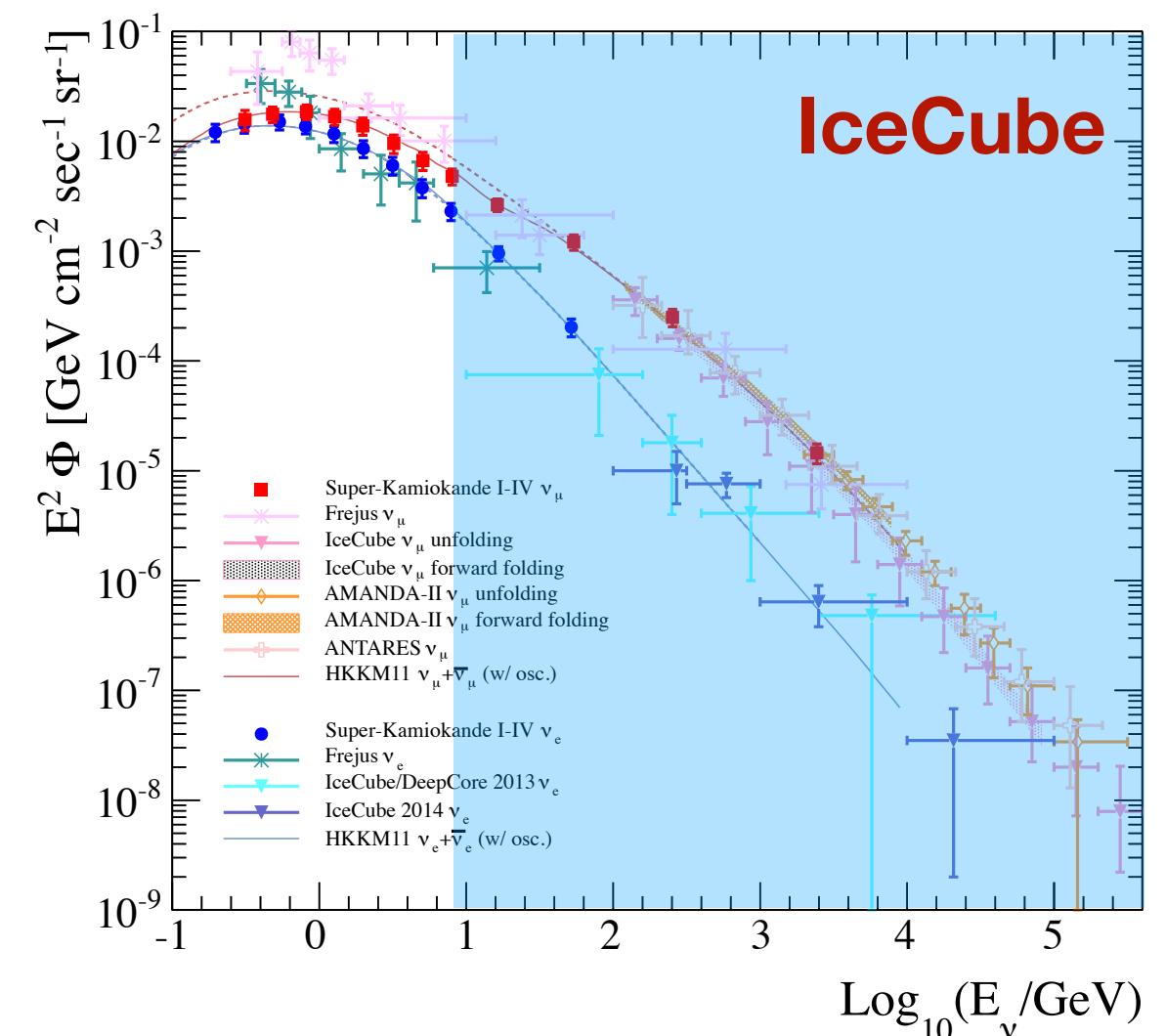
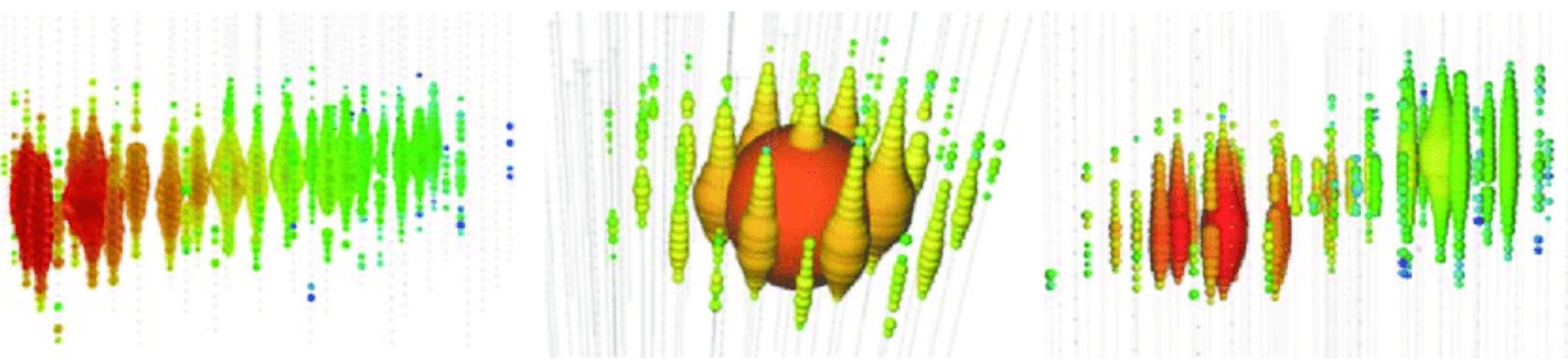


# Detection of atmospheric neutrinos

The high-energy part of the flux is measured by IceCube

IceCube

- $\sim 1\text{ km}^3$  ice Cherenkov
- Measures the high-energy part of the flux
- The sample is divided into tracks and cascades



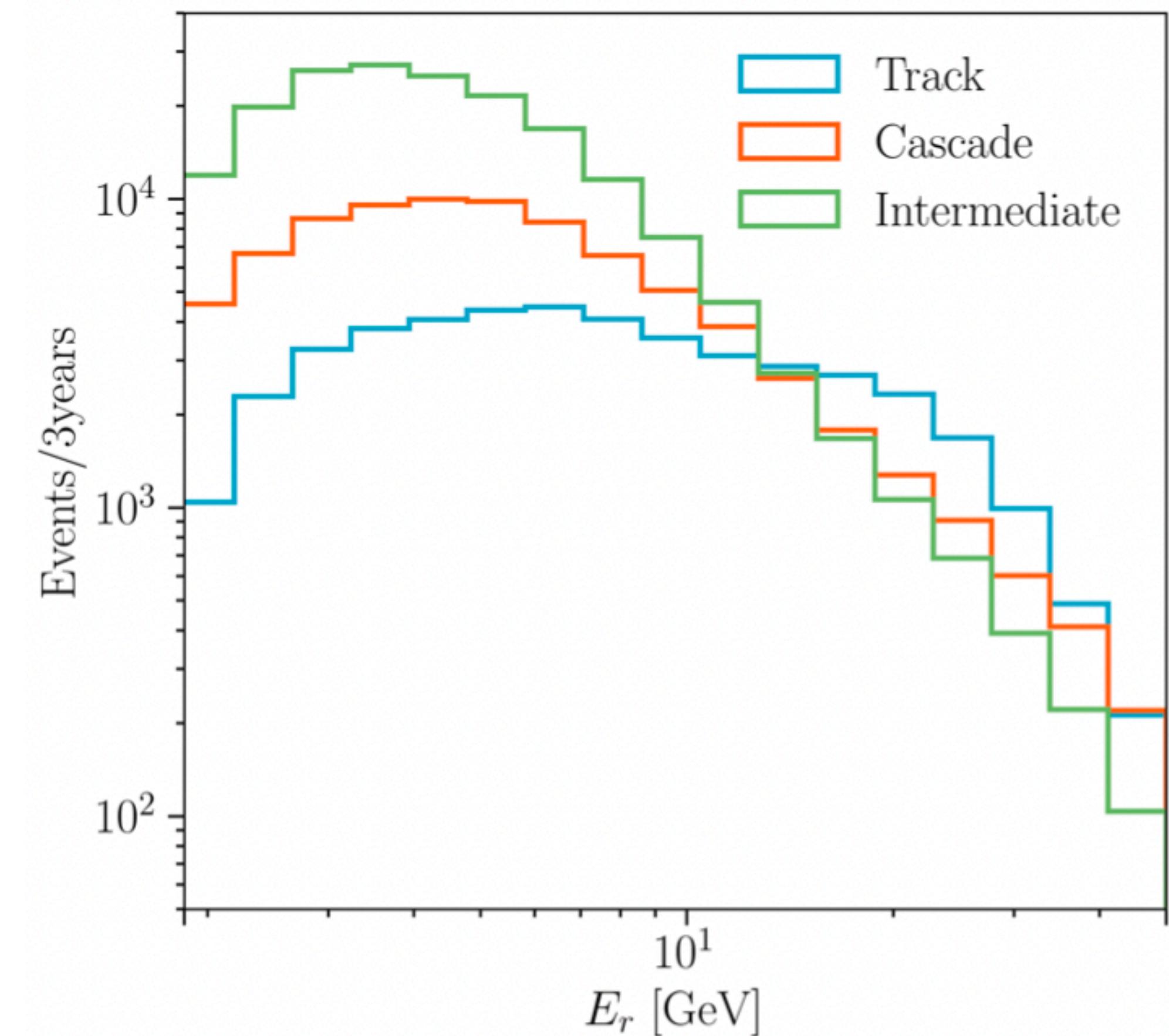
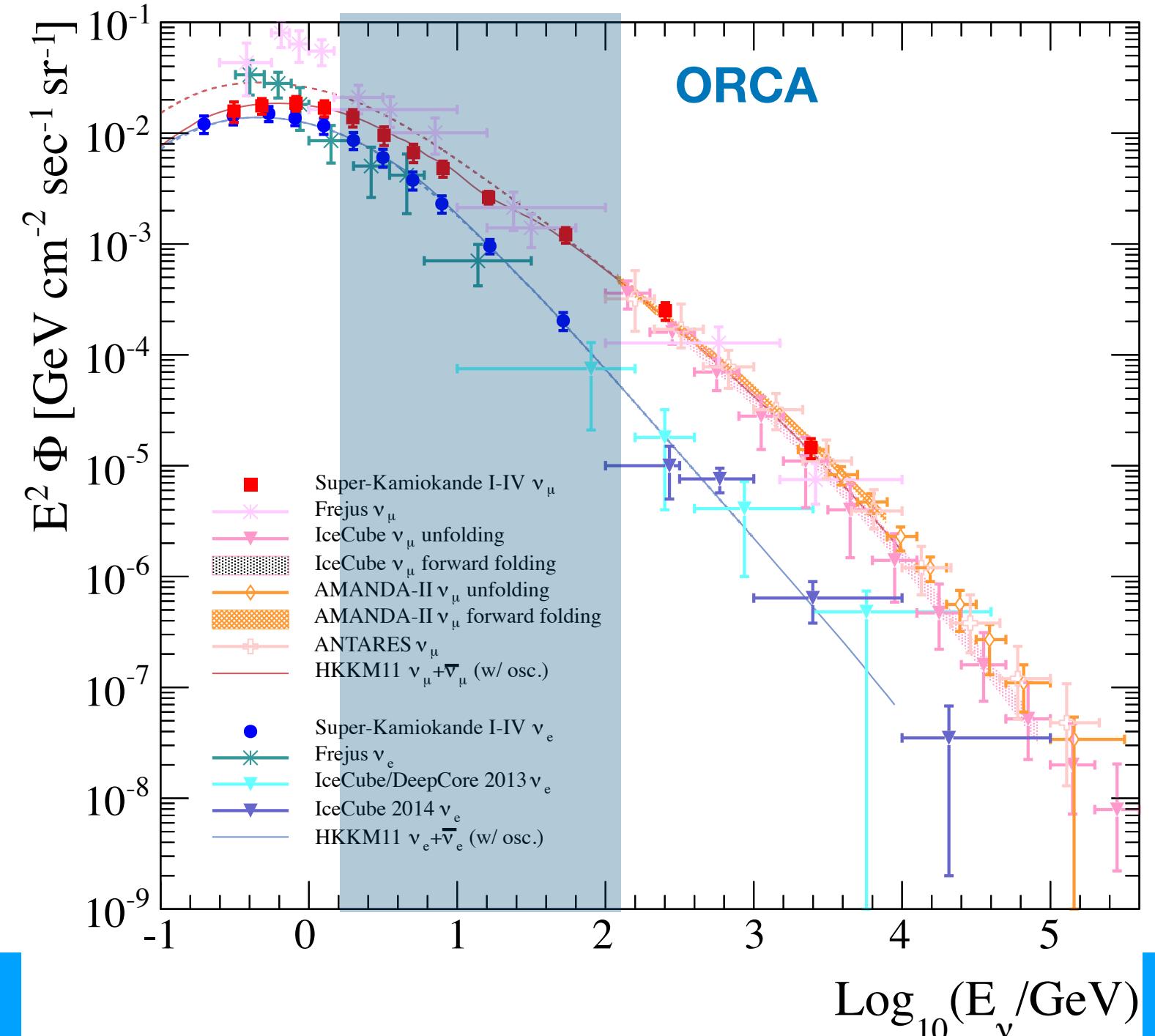
In this analysis, we have focused on the **IceCube upgrade**:

- 7 additional strings with a denser distribution of high-efficiency photosensors
- Lower energy threshold ( $E > 1\text{ GeV}$ )

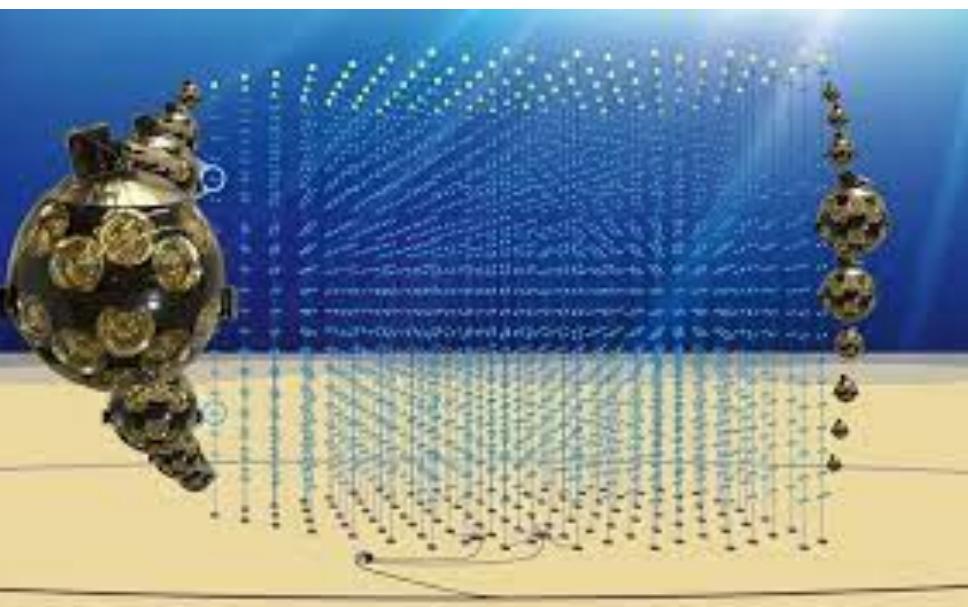
# ORCA

**ORCA** measures the multi-GeV component of the atmospheric neutrino flux :

- We have developed our MC for ORCA based on the energy and Zenit reconstruction provided by the collaboration.
- **Three morphologies** are considered: tracks, cascades, and intermediates events.
- The energies range extends from 1.85GeV to 53GeV.



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

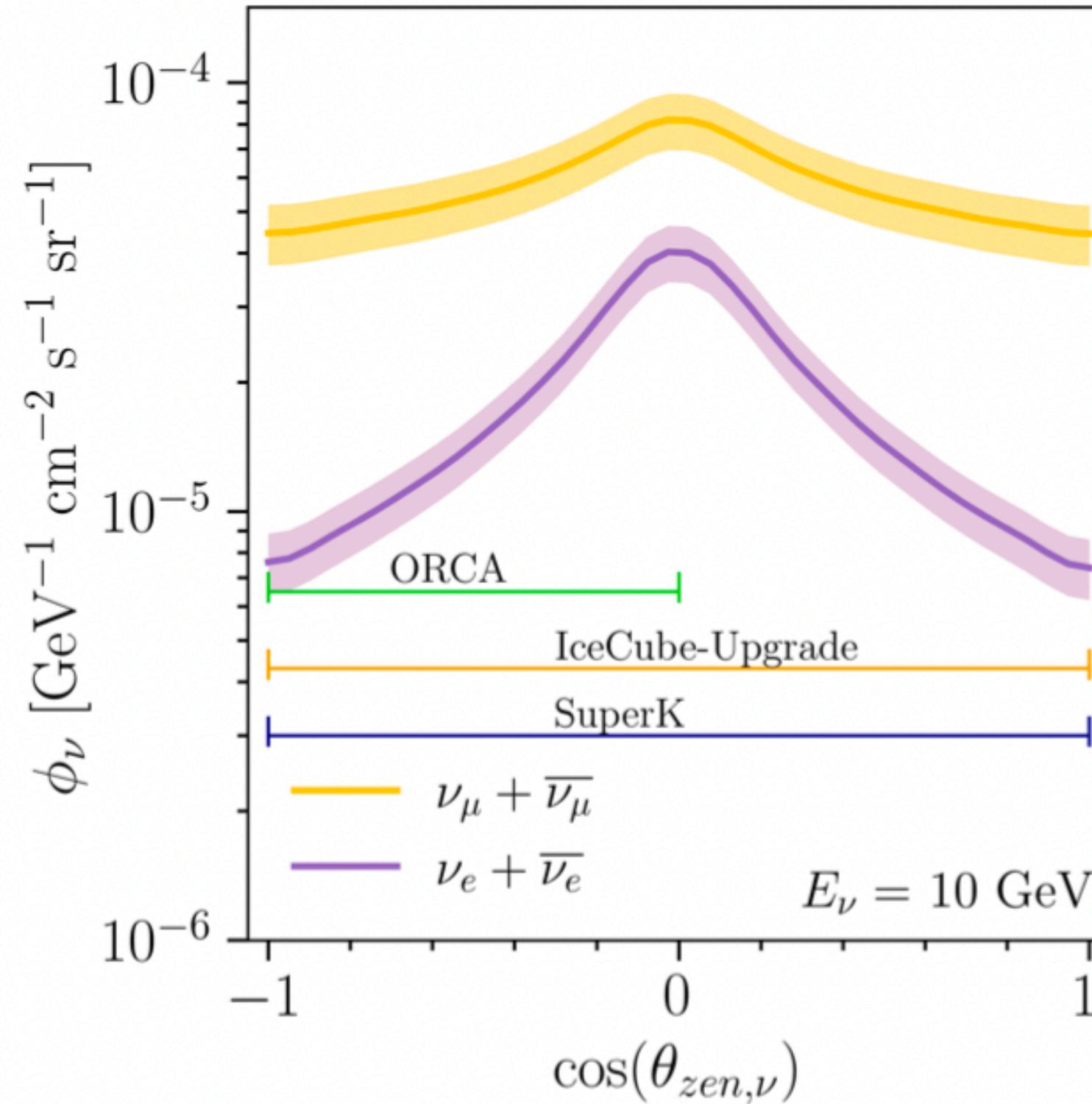
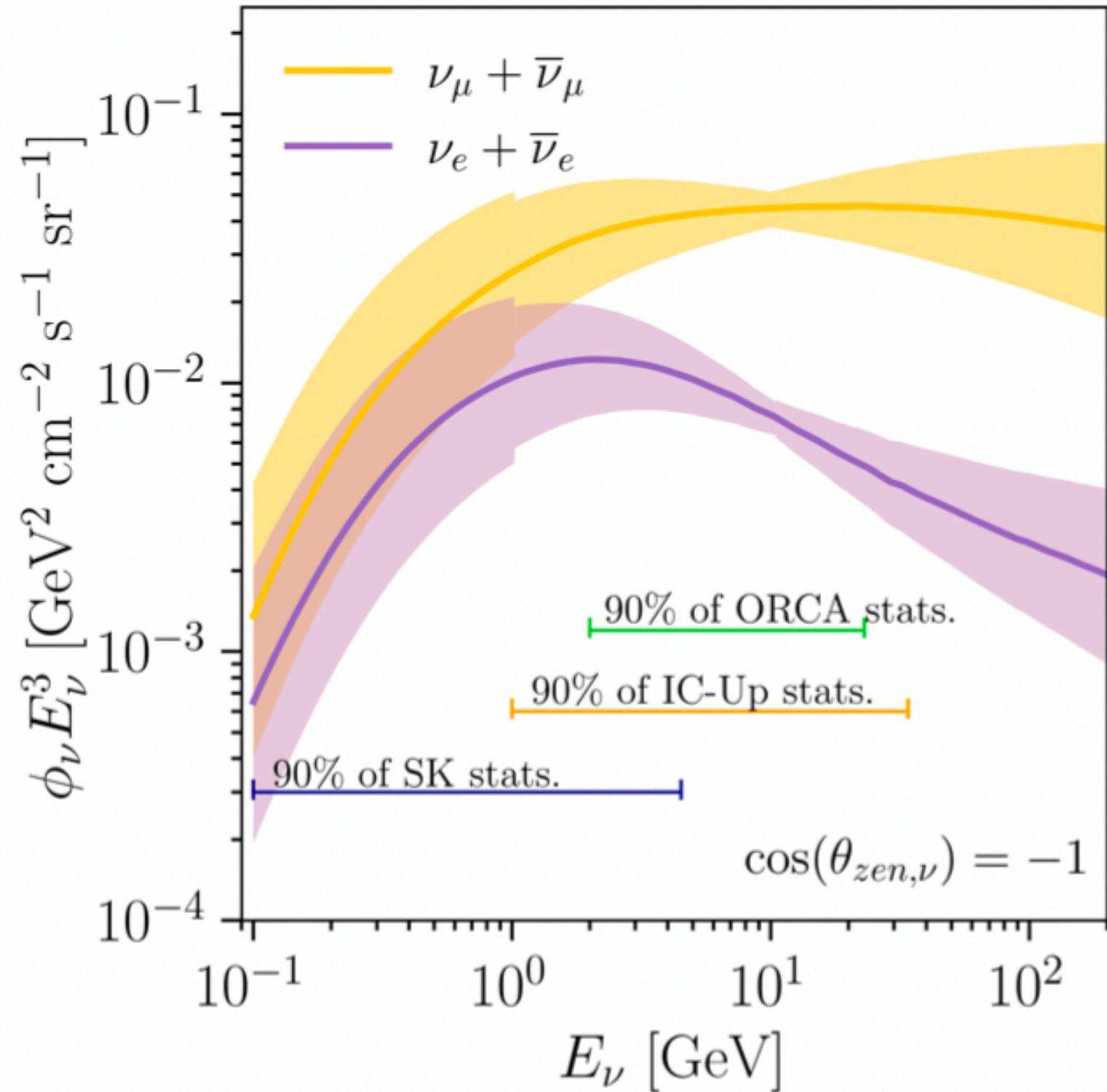


# Flux uncertainties

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**

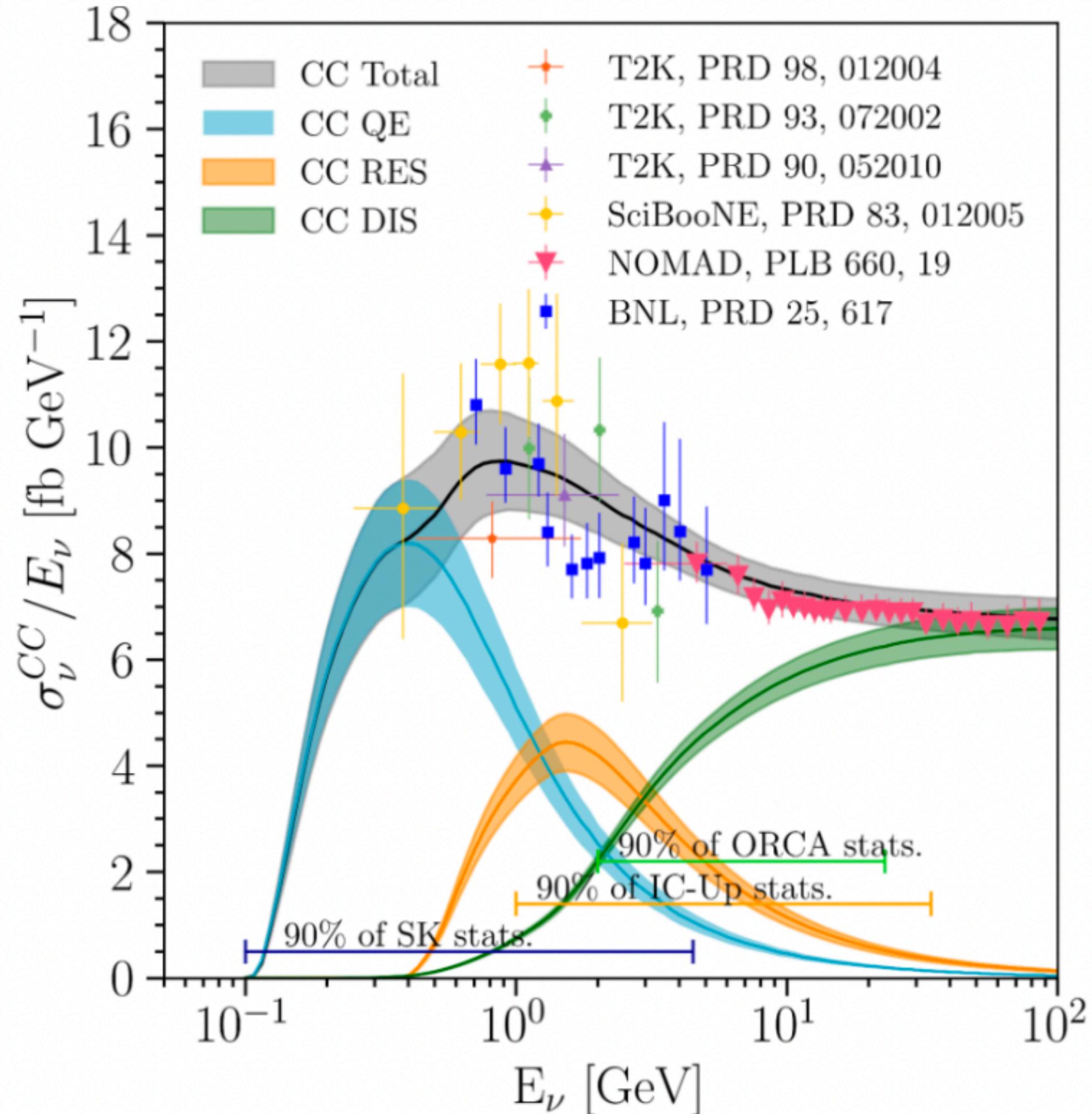


Systematic	Uncert./Priors
$\Phi_0(E < 1 \text{ GeV})$	25%
$\Phi_0(E > 1 \text{ GeV})$	15%
$\nu_e/\nu_\mu$	2%
$\bar{\nu}/\nu$	2%
$\delta$	20%
$C_{u,d}$	2%

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

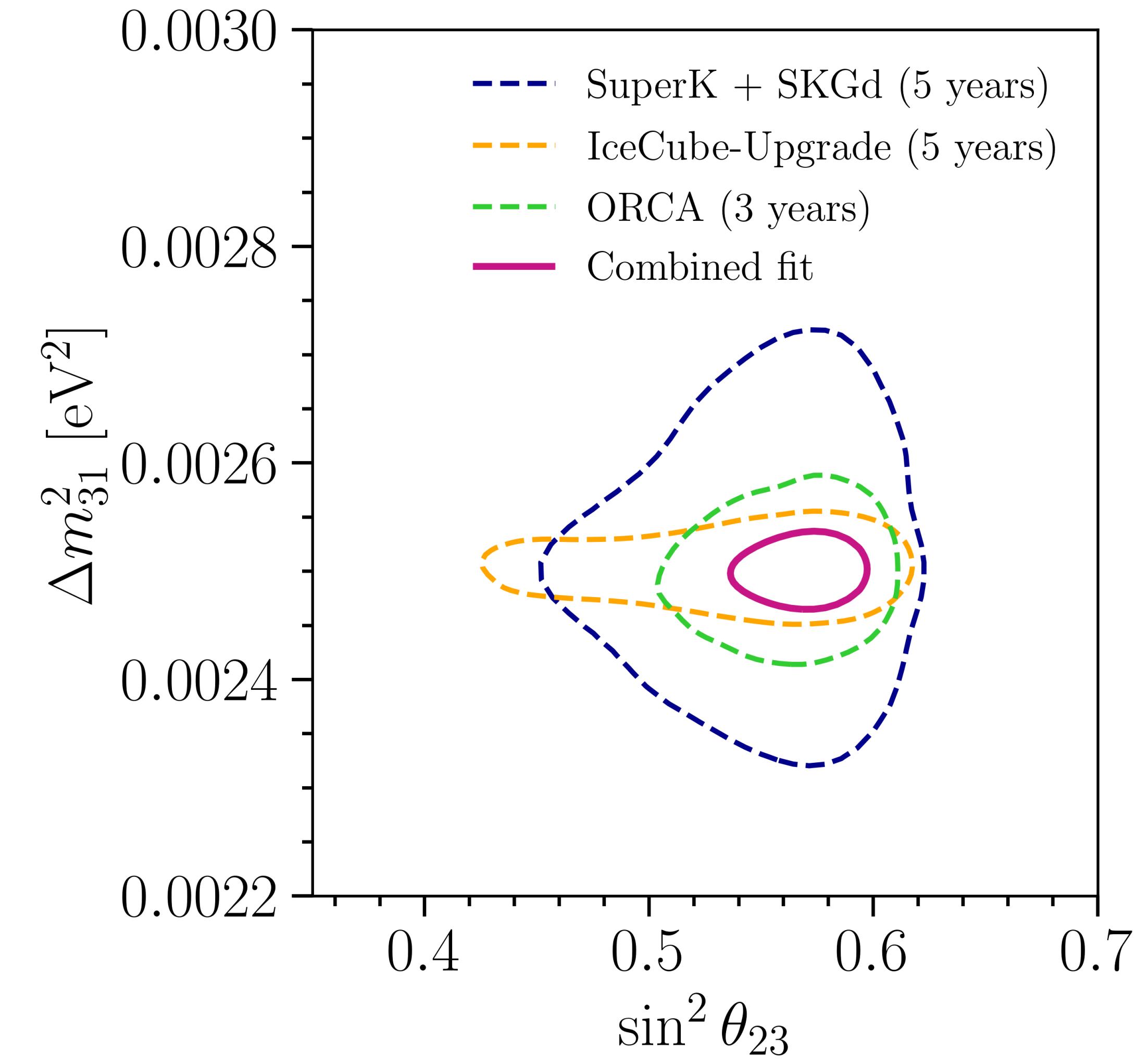
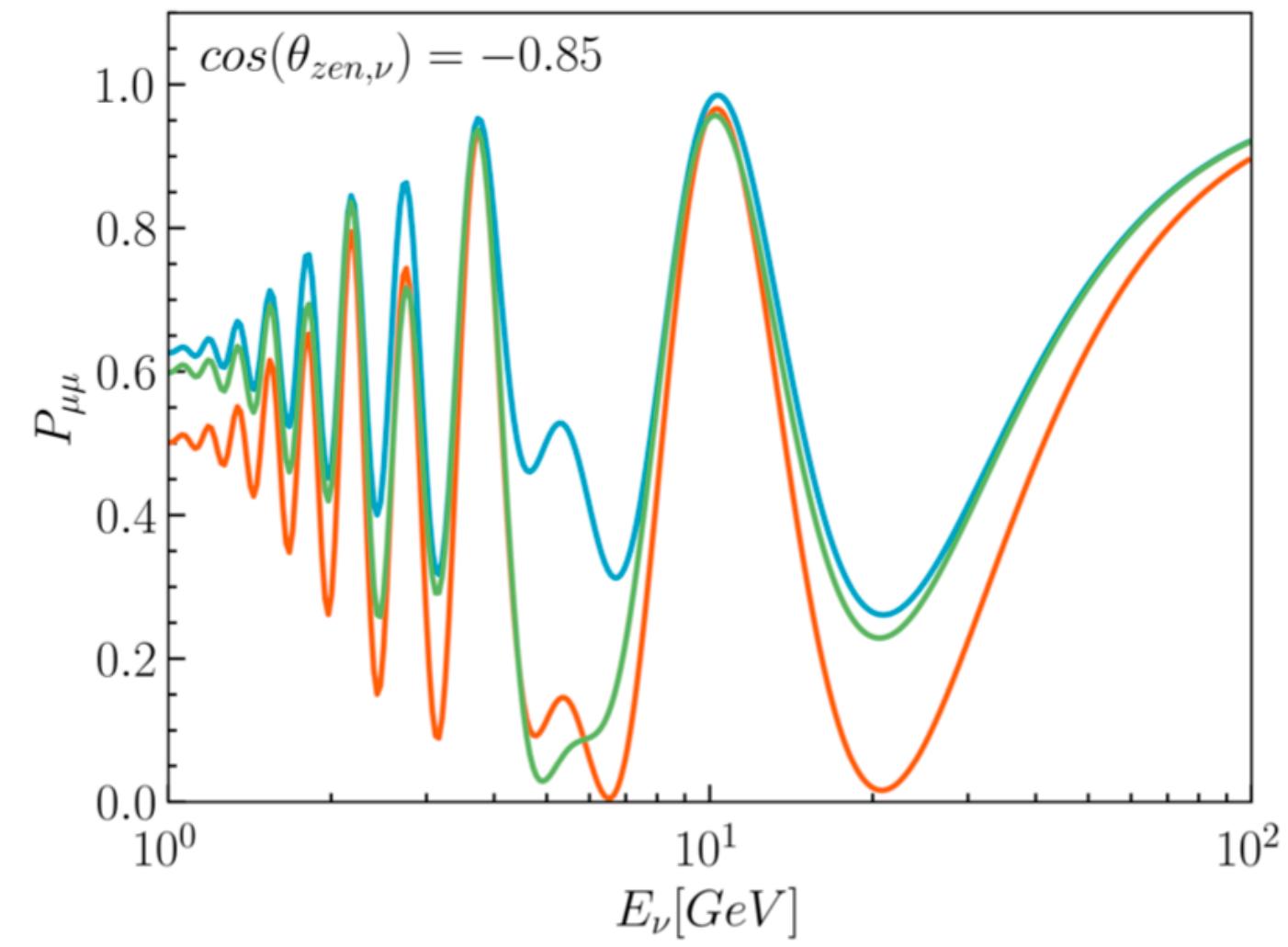
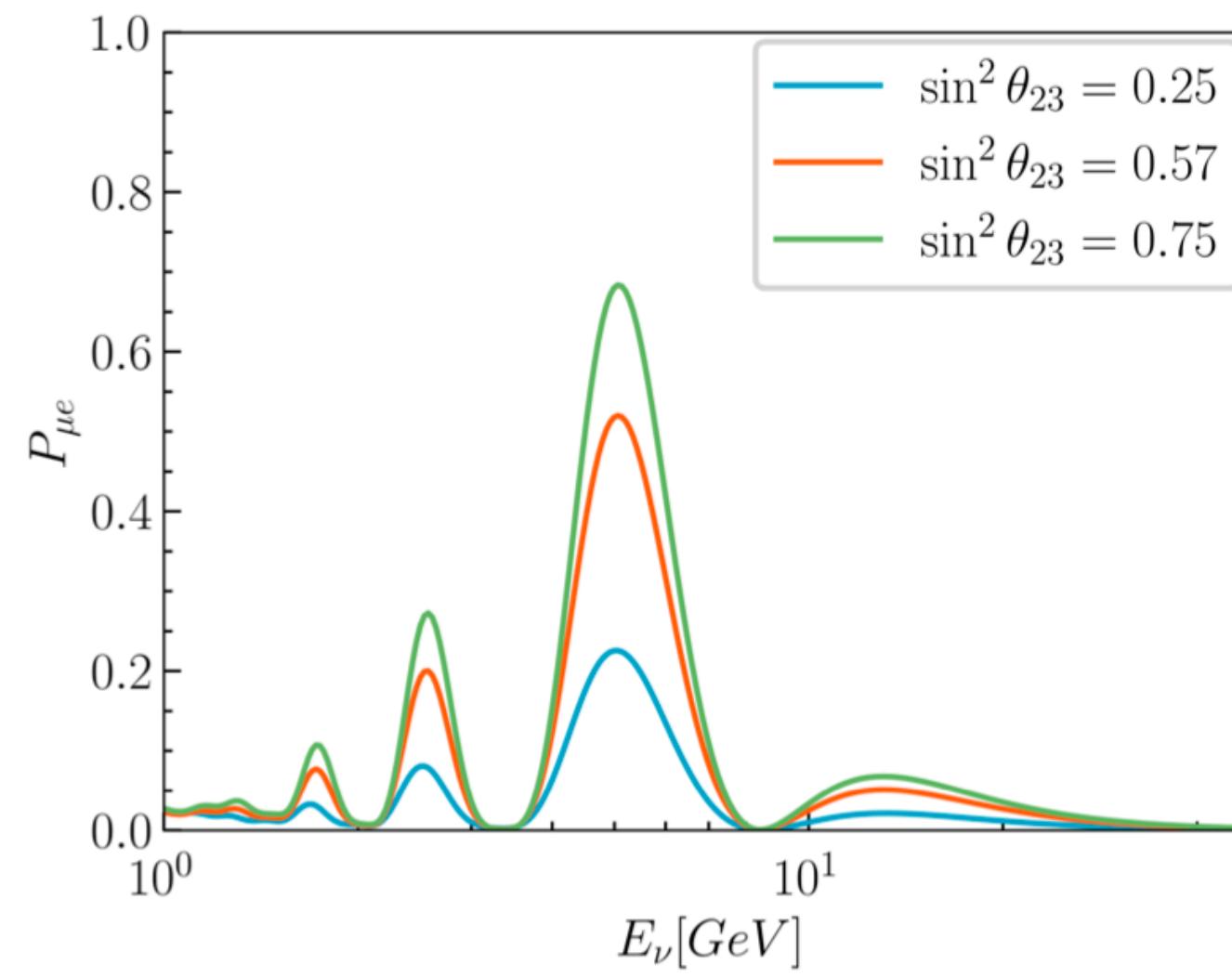


Systematic	Uncer./Prior
CCQE	10%
CCQE $\nu/\bar{\nu}$	10%
CCQE $e/\mu$	10%
CC1 $\pi$	10%
CC1 $\pi$ $\pi^0/\pi^+$	40%
CC1 $\pi$ $\nu_e/\bar{\nu}_e$	10%
CC1 $\pi$ $\nu_\mu/\bar{\nu}_\mu$	10%
Coh. $\pi$	100%
Axial Mass	10%
NC hadron prod.	5%
NC over CC	10%
$\nu_\tau$	25%
Neutron prod. (SK)	15%
DIS	10%

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

# Combined analysis: $\theta_{23}$ and $\Delta m_{31}^2$

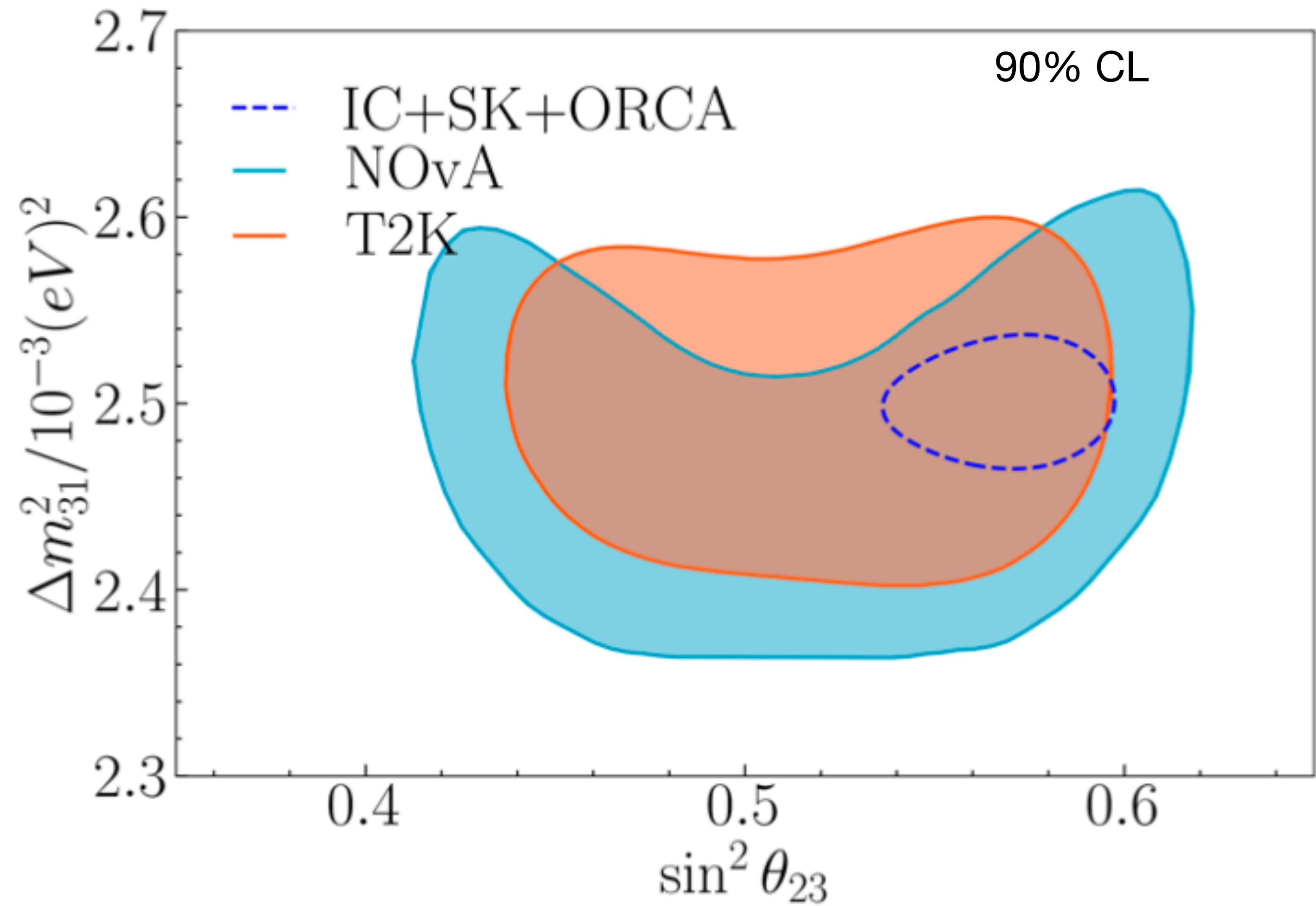
Making a **combined analysis** of **SK**, **IceCube-upgrade** and **ORCA** we have estimated the sensitivity to  $\delta_{cp}$ ,  $\theta_{23}$  and the **mass ordering**



# Combined analysis: $\theta_{23}$ and $\Delta m_{31}^2$

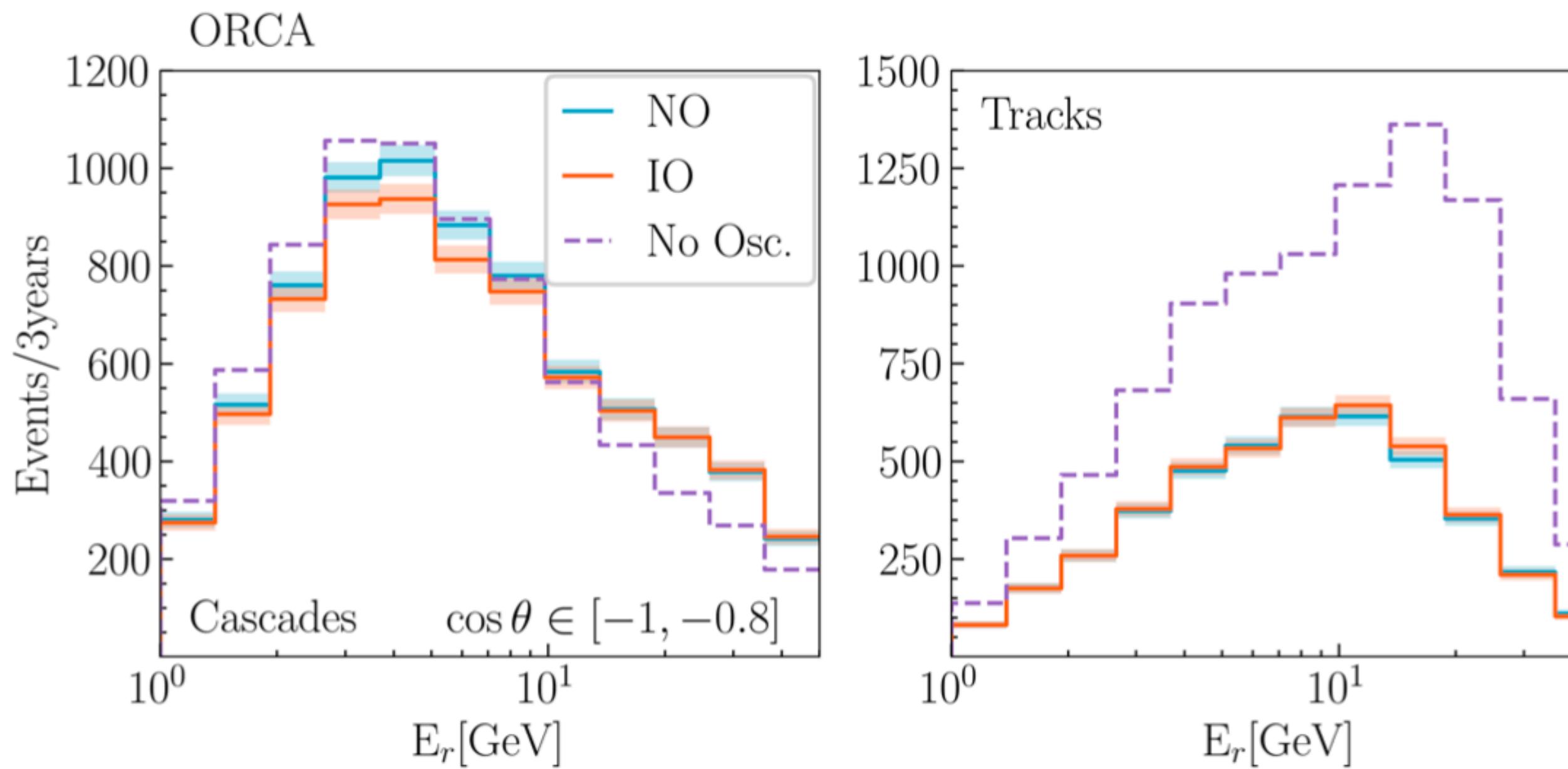
The **SK+IC-upgrade+ORCA** will have better sensitivity than **LBL** and **reactor** experiments.

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



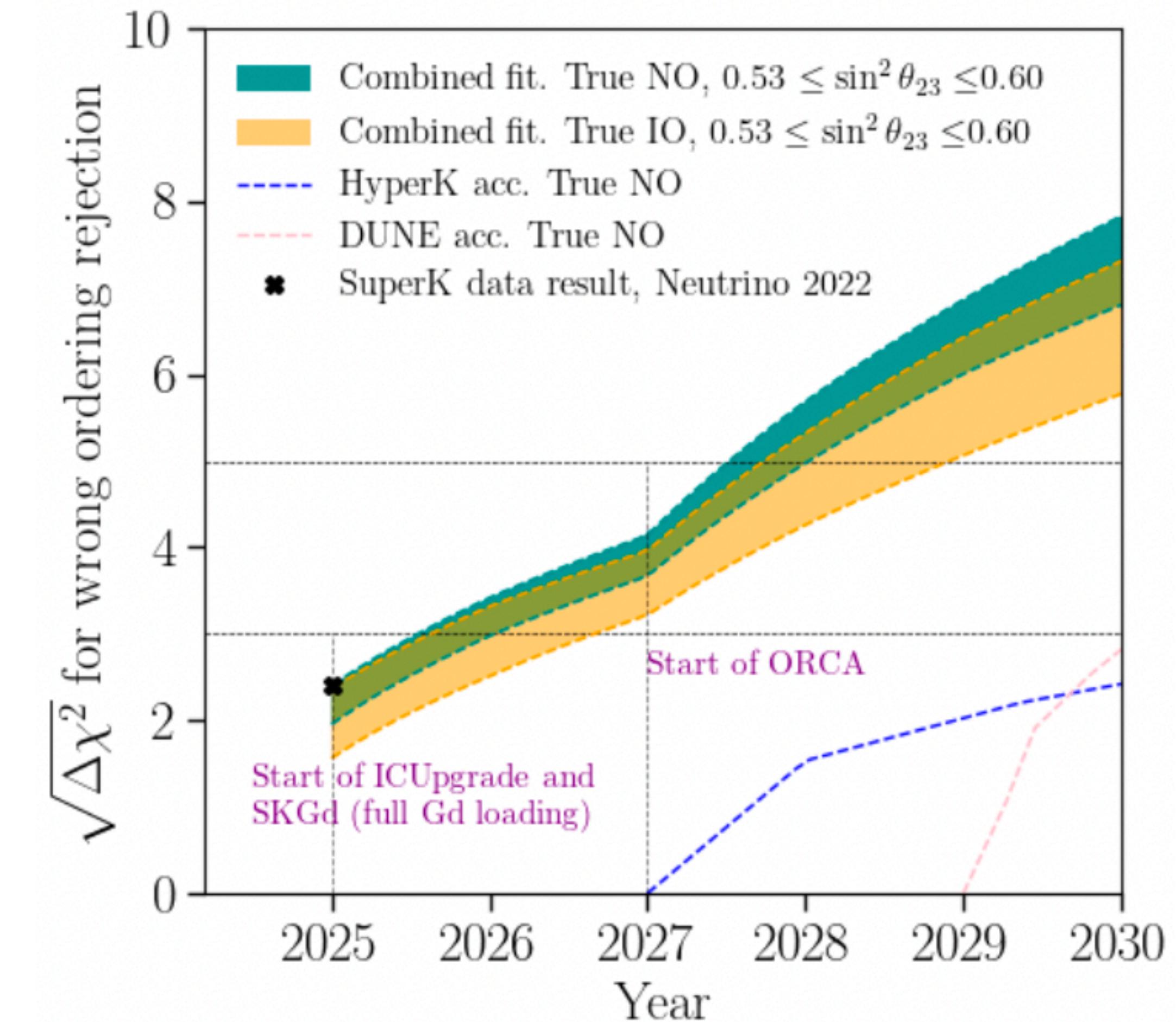
# Combined analysis: mass ordering

- 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  $6\sigma$  by the end of the decade.



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

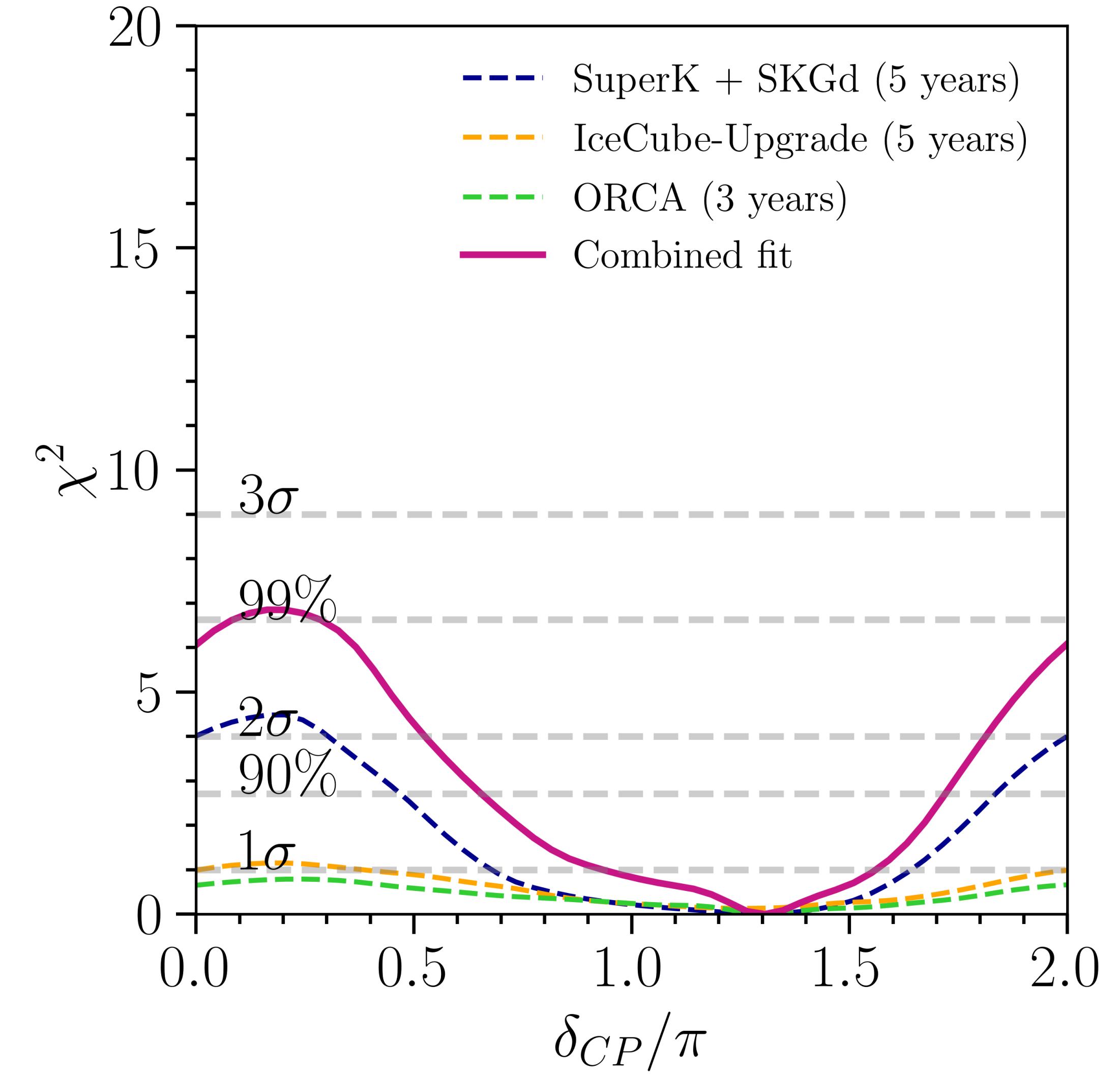
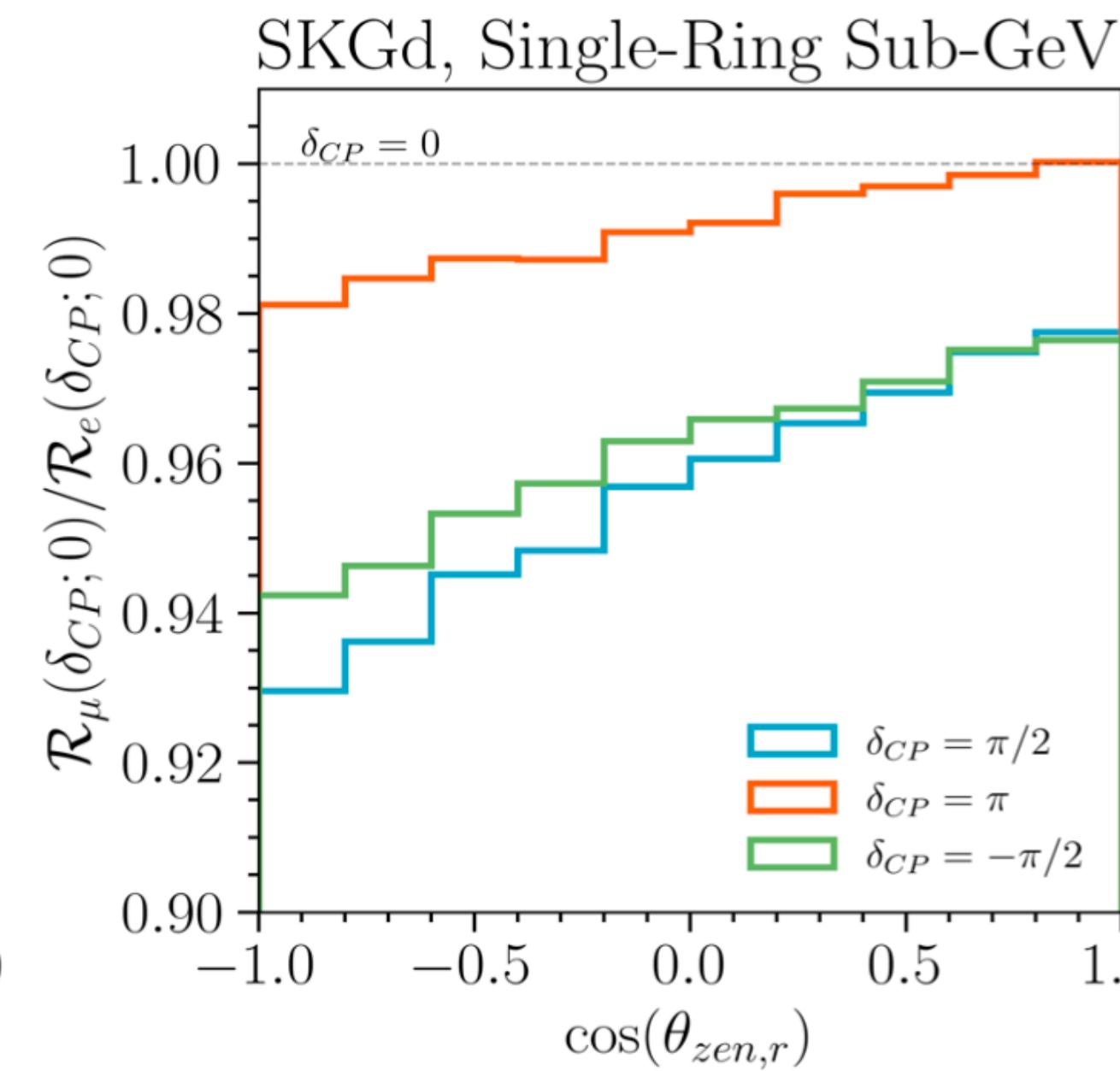
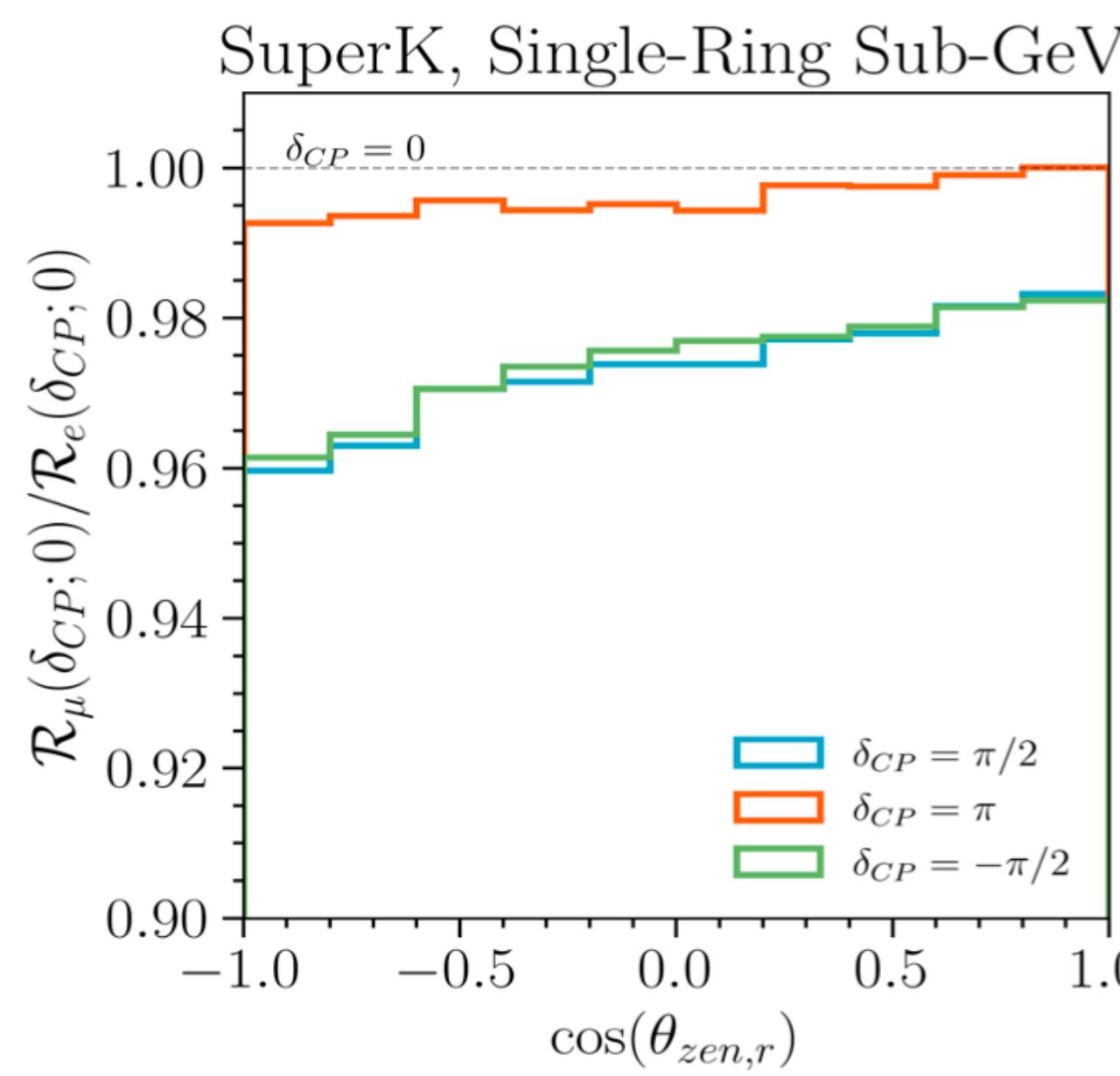
C.A. Argüelles, P. Fernandez, I. Martinez-Soler  
and M. Jin, arXiv:2211.02666



# Combined analysis: $\delta_{cp}$

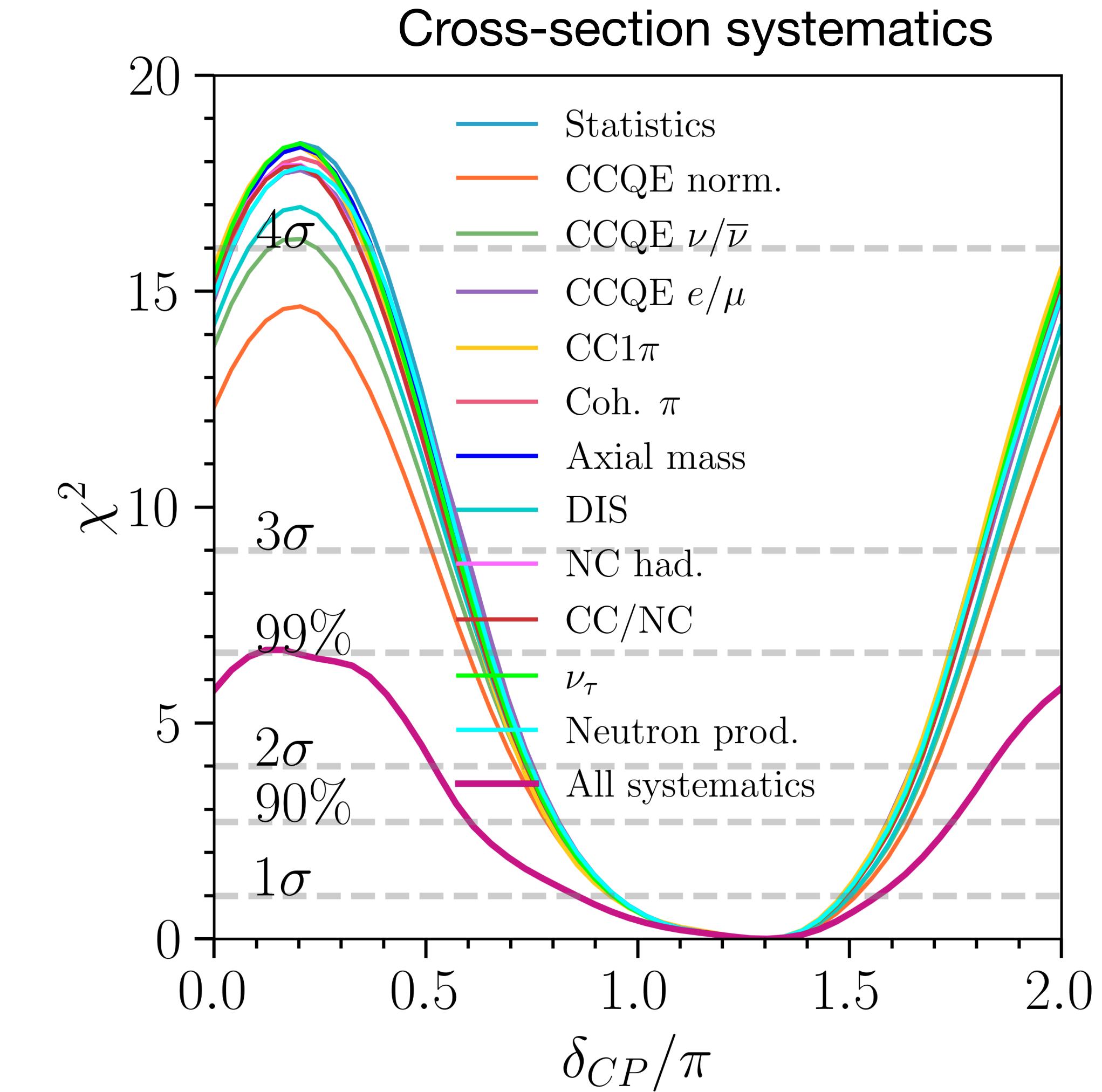
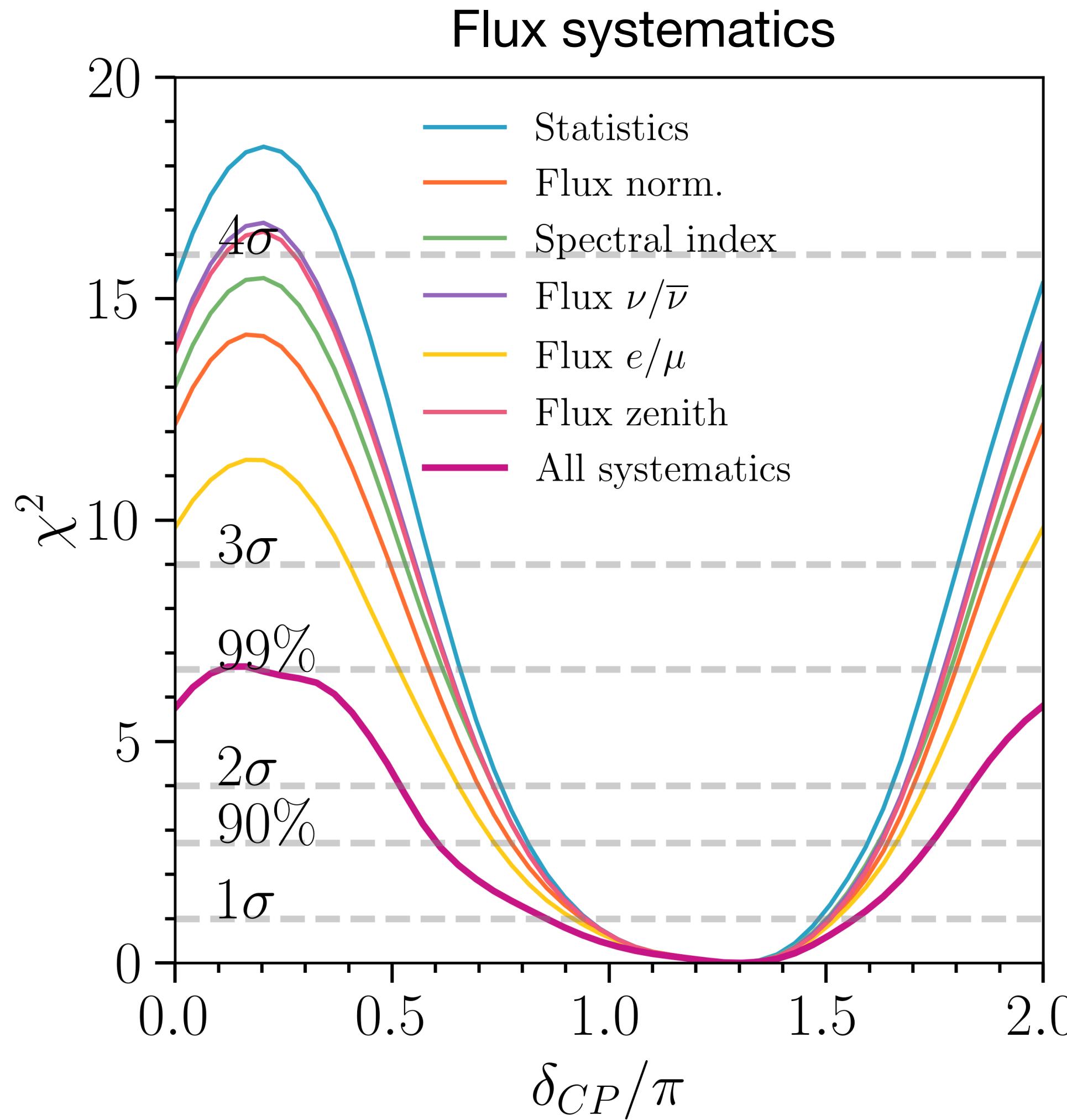
The sensitivity to  $\delta_{cp}$  is dominated by Super-Kamiokande

- The samples that dominate the sensitivity are the e-like and  $\mu$ -like with no neutron tagged



# Systematic impact

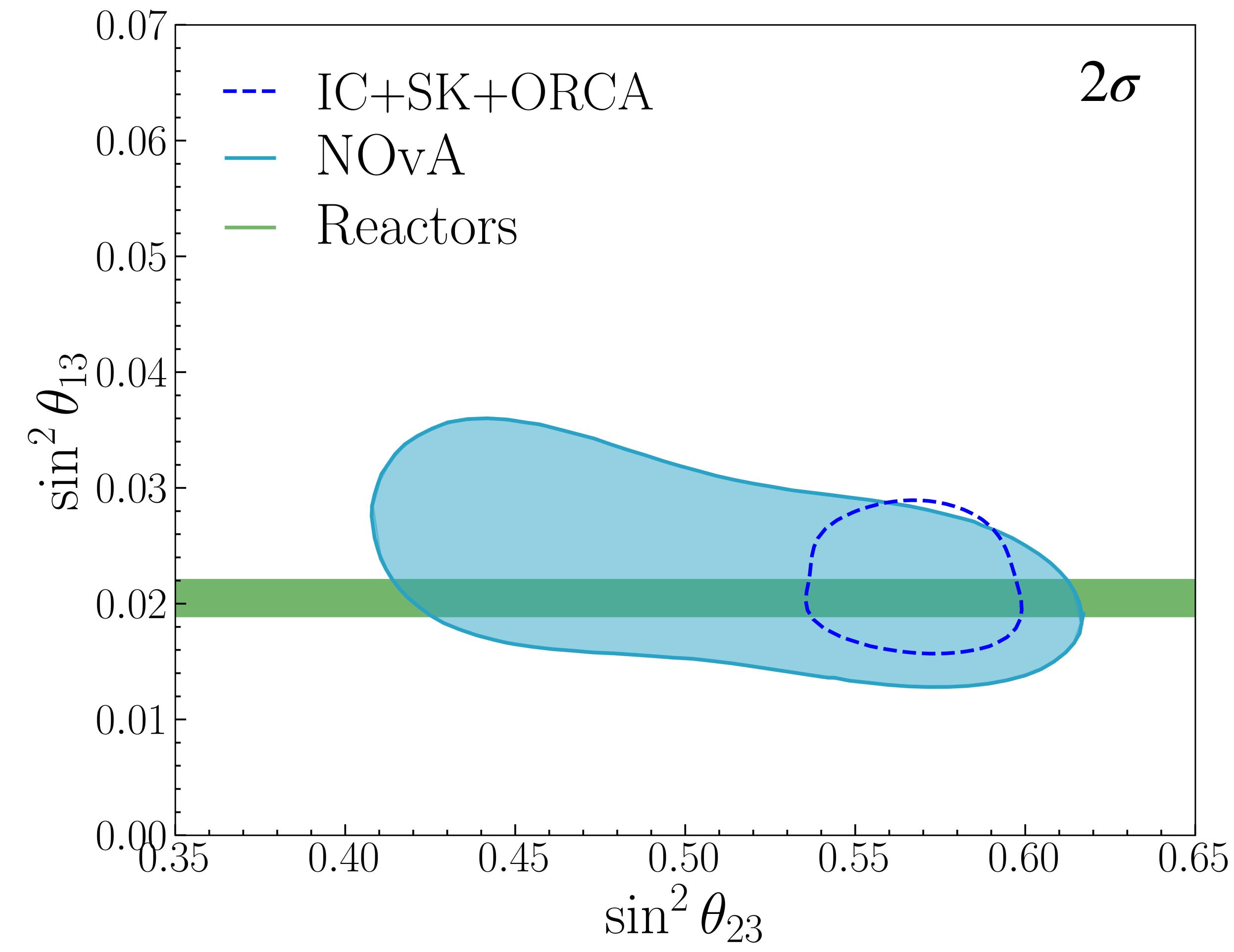
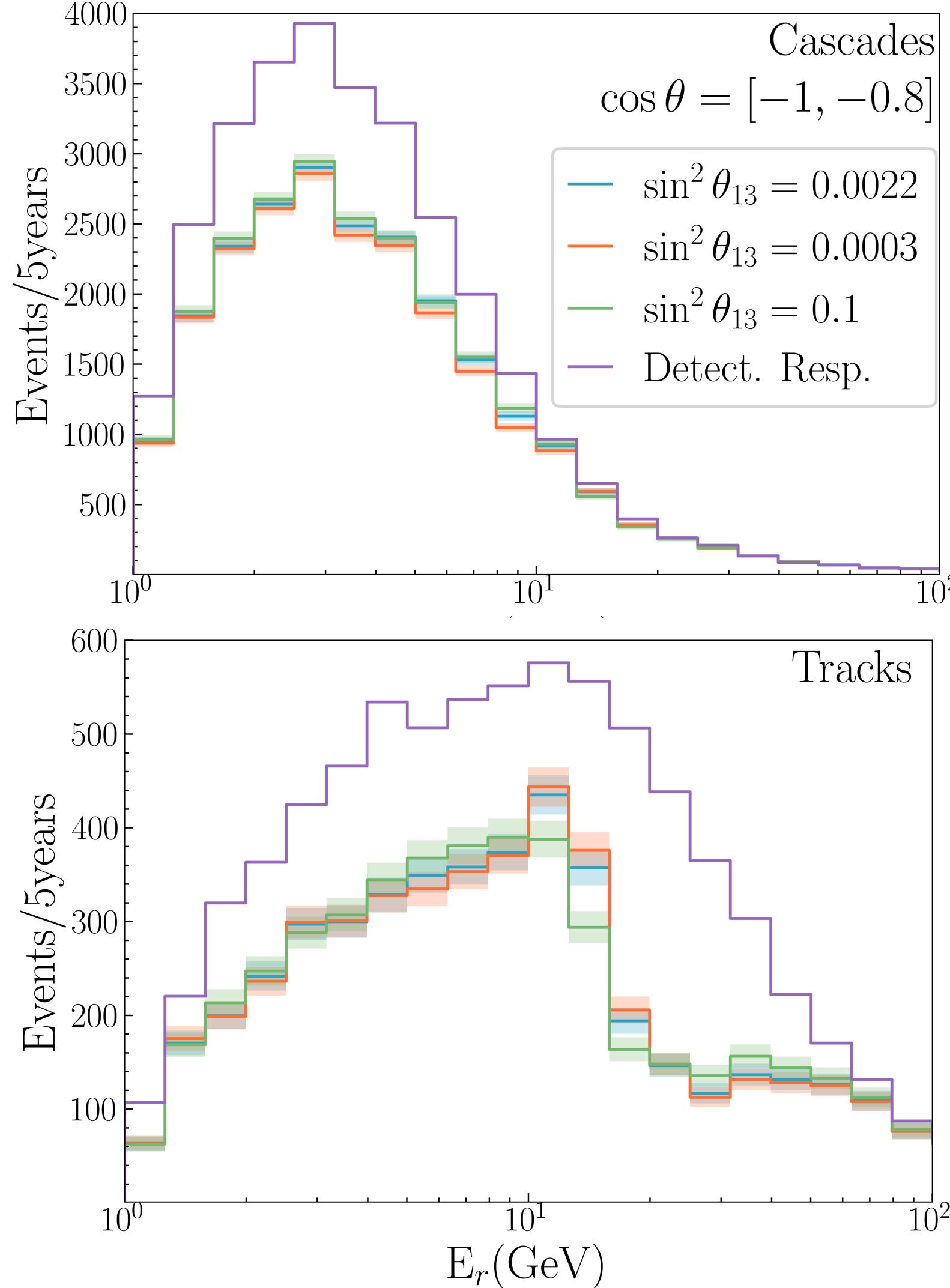
What systematic has a larger impact?



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

# Bonus: sensitivity over $\theta_{13}$

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

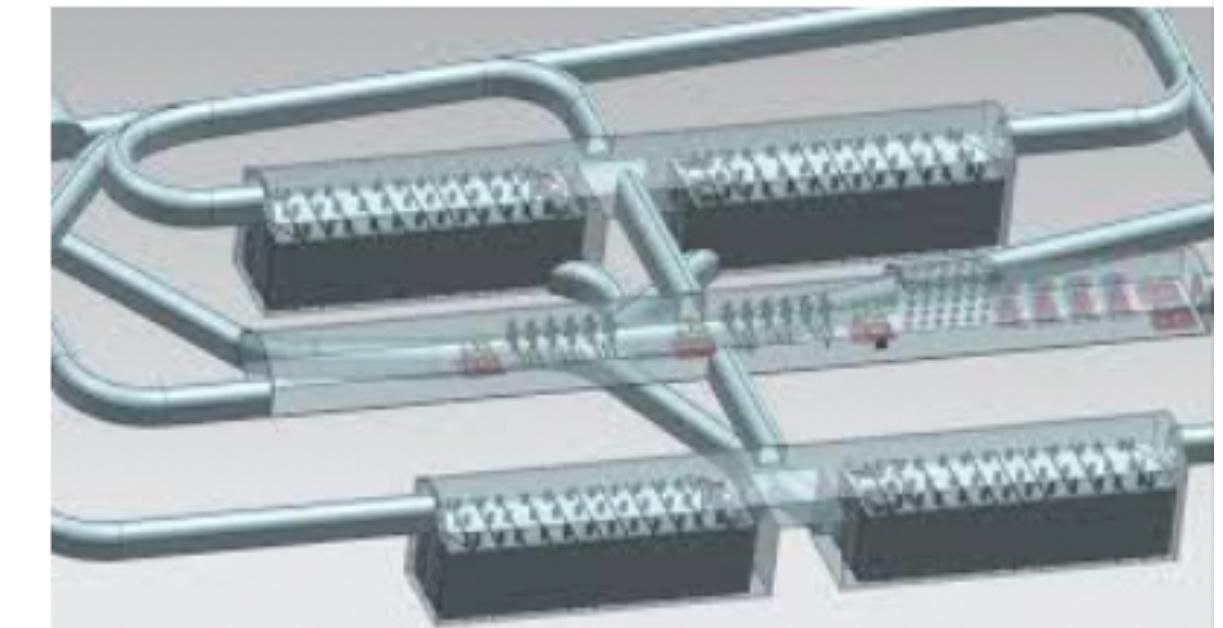


# **Next-generation of experiments: DUNE**

# Next generation experiments: DUNE

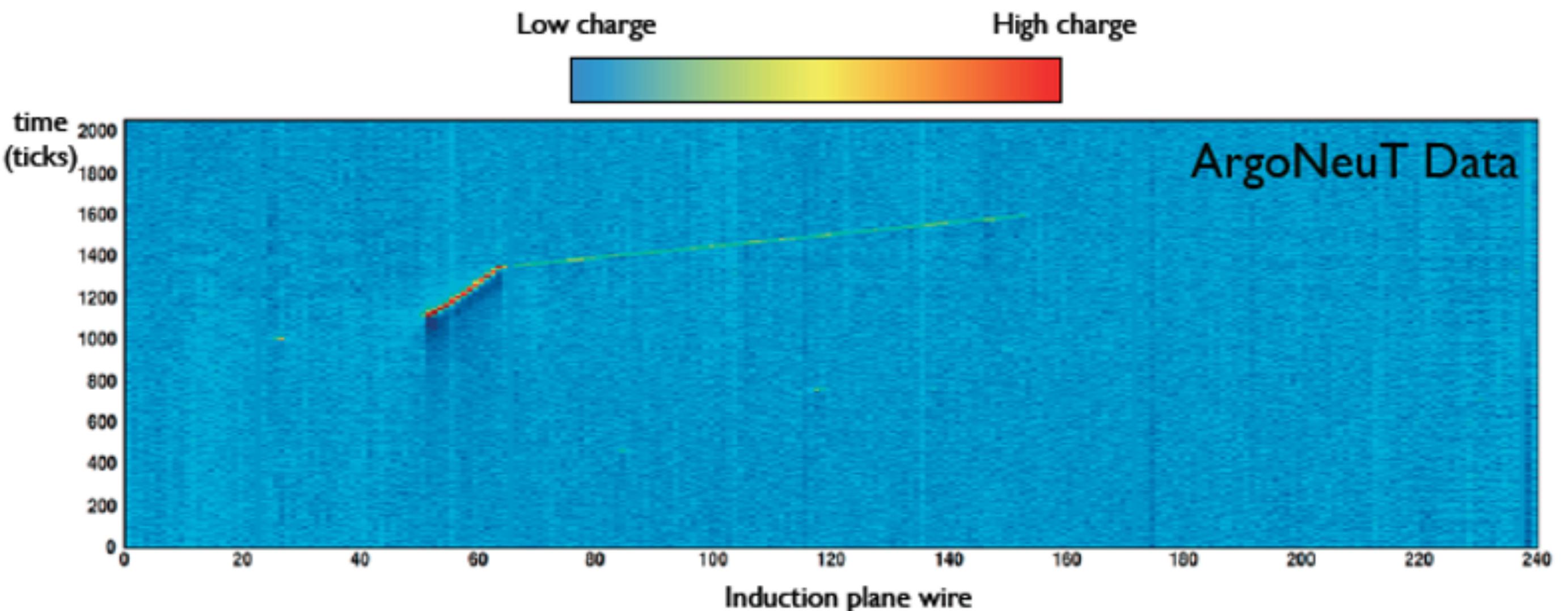
## LArTPCs:

- Excellent capabilities to **identify charged particles**.
- Precise measurement of the **energy and the direction** of low-energy charged particles
- Neutrino energy and direction are reconstructed from the event topology.



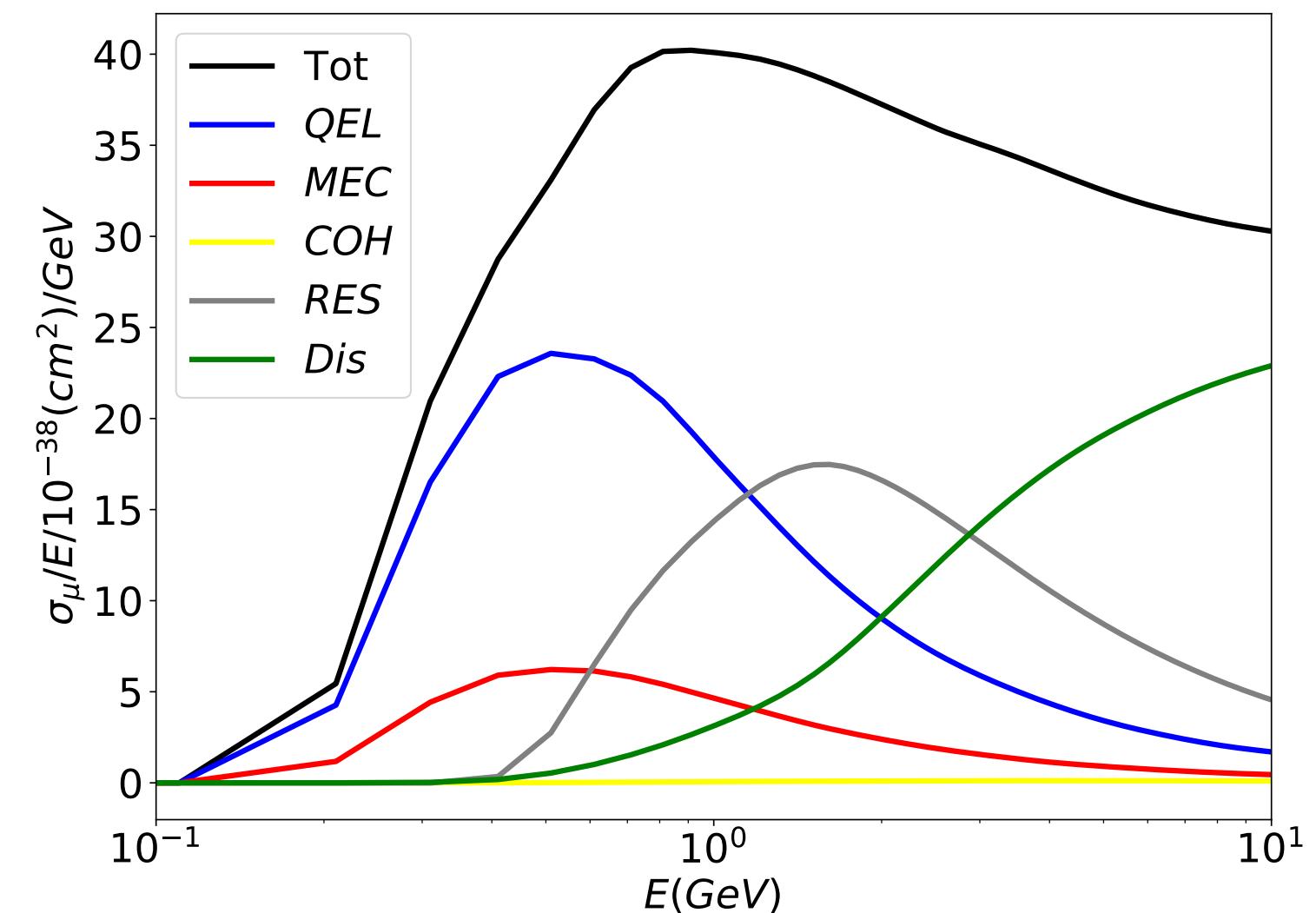
$$E_{\nu}^{dep} = E_l + K_p + \dots$$

See Wenjie Wu's talk



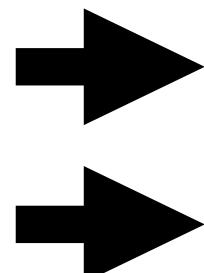
# Next generation experiments: DUNE

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



$\bar{\nu}$  dominated

$\nu$  dominated



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

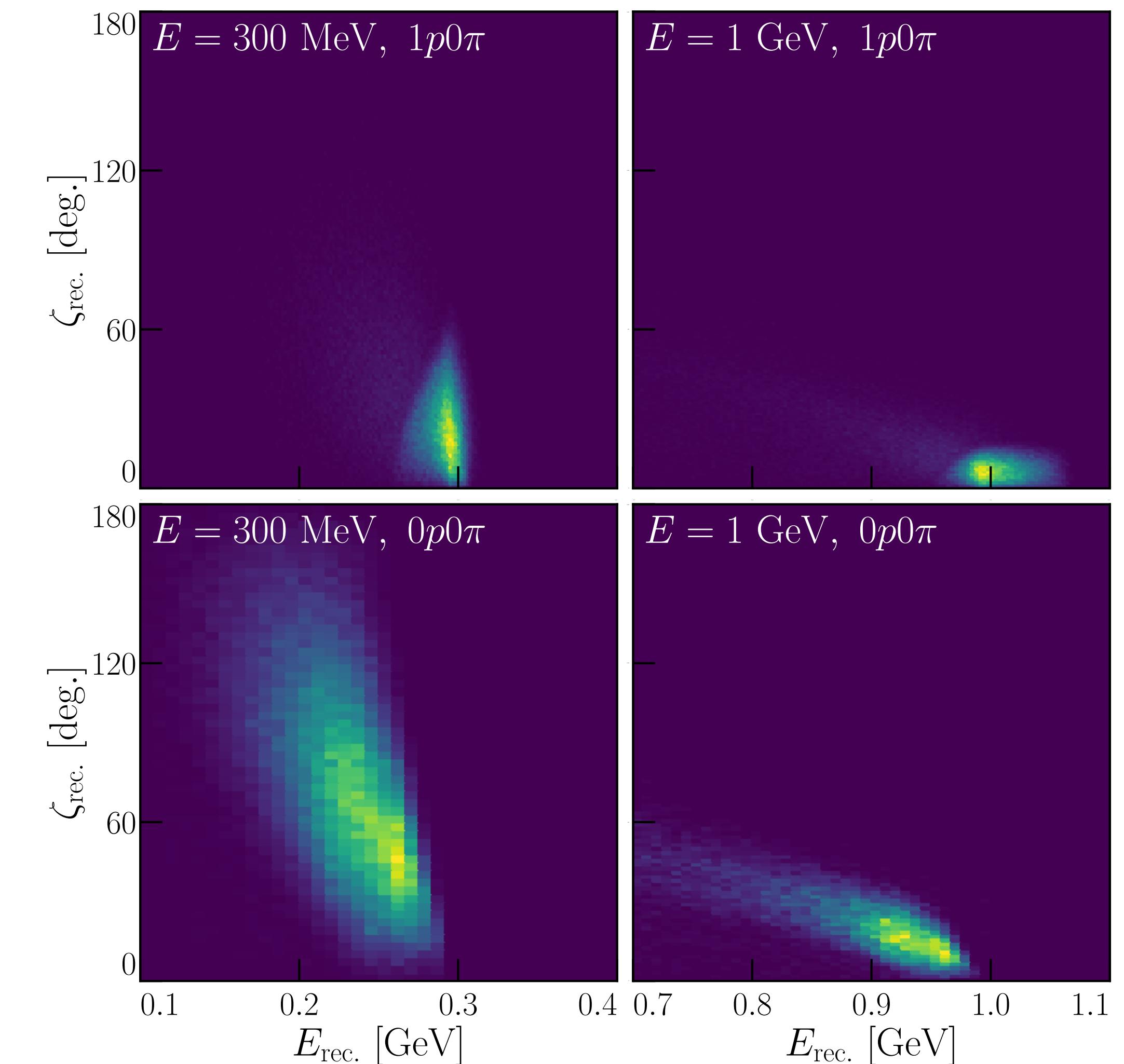
Np	Events/400 kton year
CC-0p0π	~7000
CC-1p0π	~12000
CC-2p0π	~500
CC-0p1π	~200

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

# DUNE: Event reconstruction

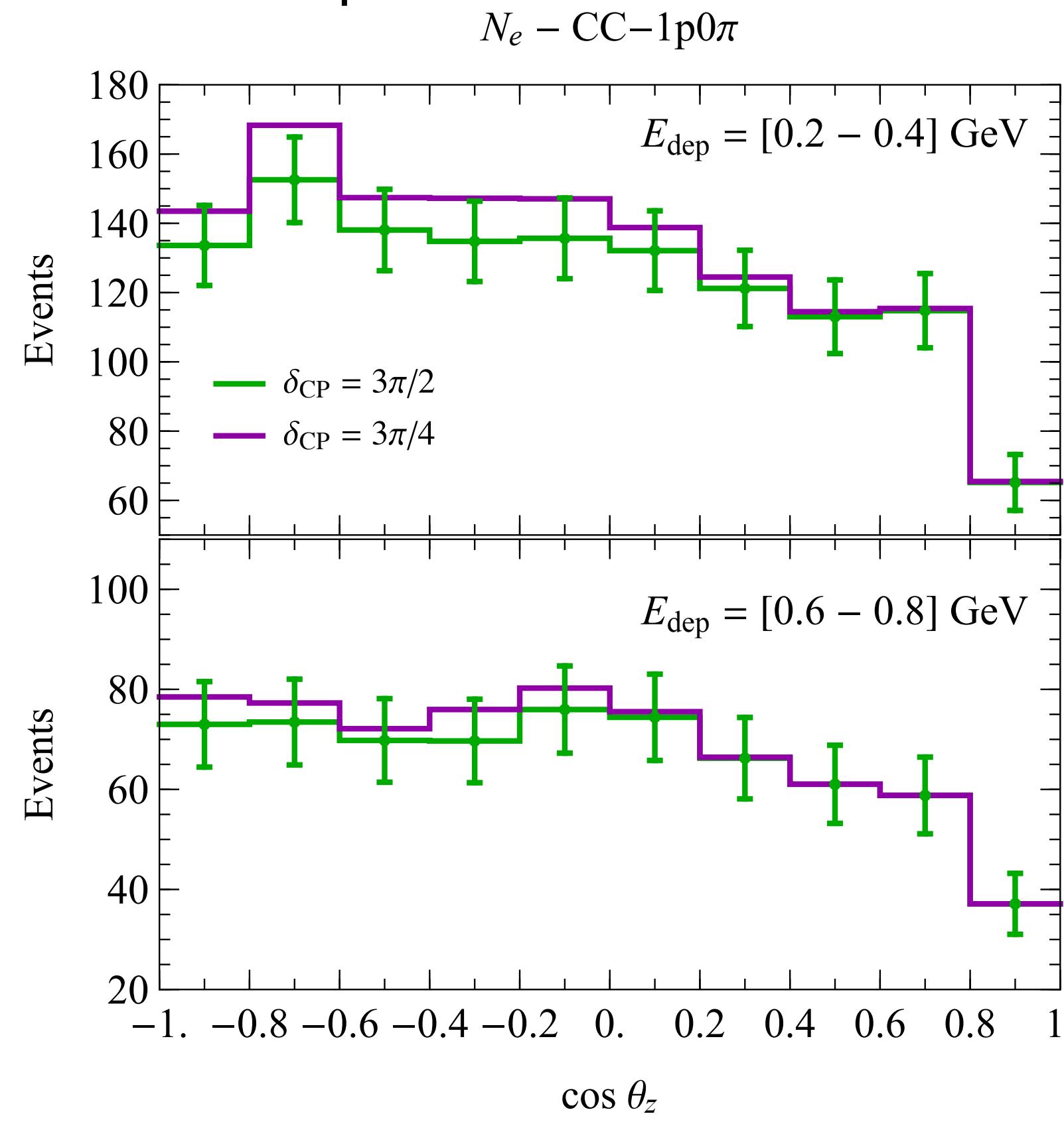
To simulate the event reconstruction, we consider a minimum kinetic energy and a finite energy and direction resolutions

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

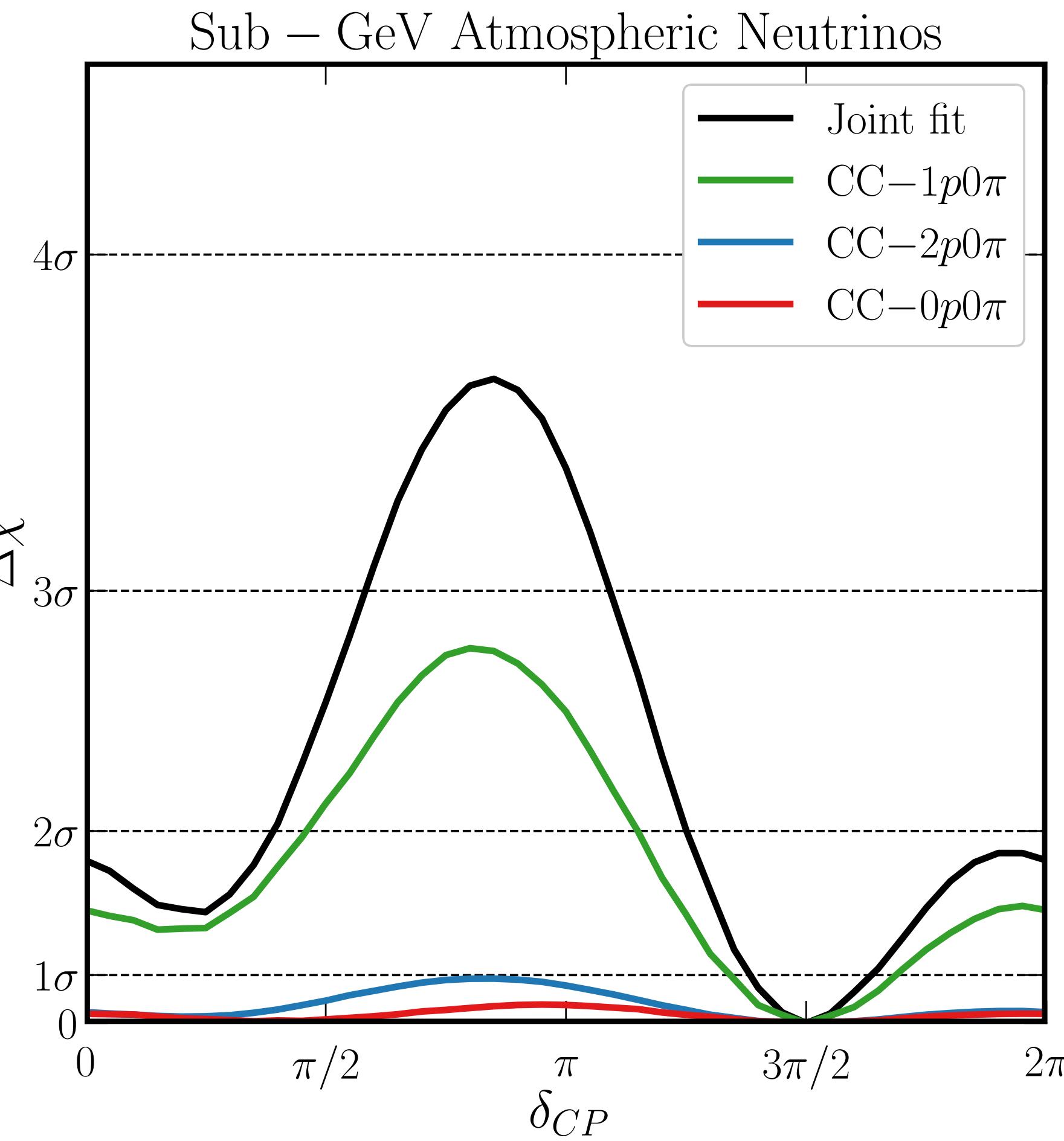


# DUNE sensitivity

$\delta_{cp}$  induces a large deviation in the number of expected events for DUNE



DUNE can exclude some values of  $\delta_{cp}$  to more than  $3\sigma$



For other searches with atm see C.A. Ternes, S. Gariazzo, R. Hajjar, O. Mena, M. Sorel, PRD 100 (2019) 9

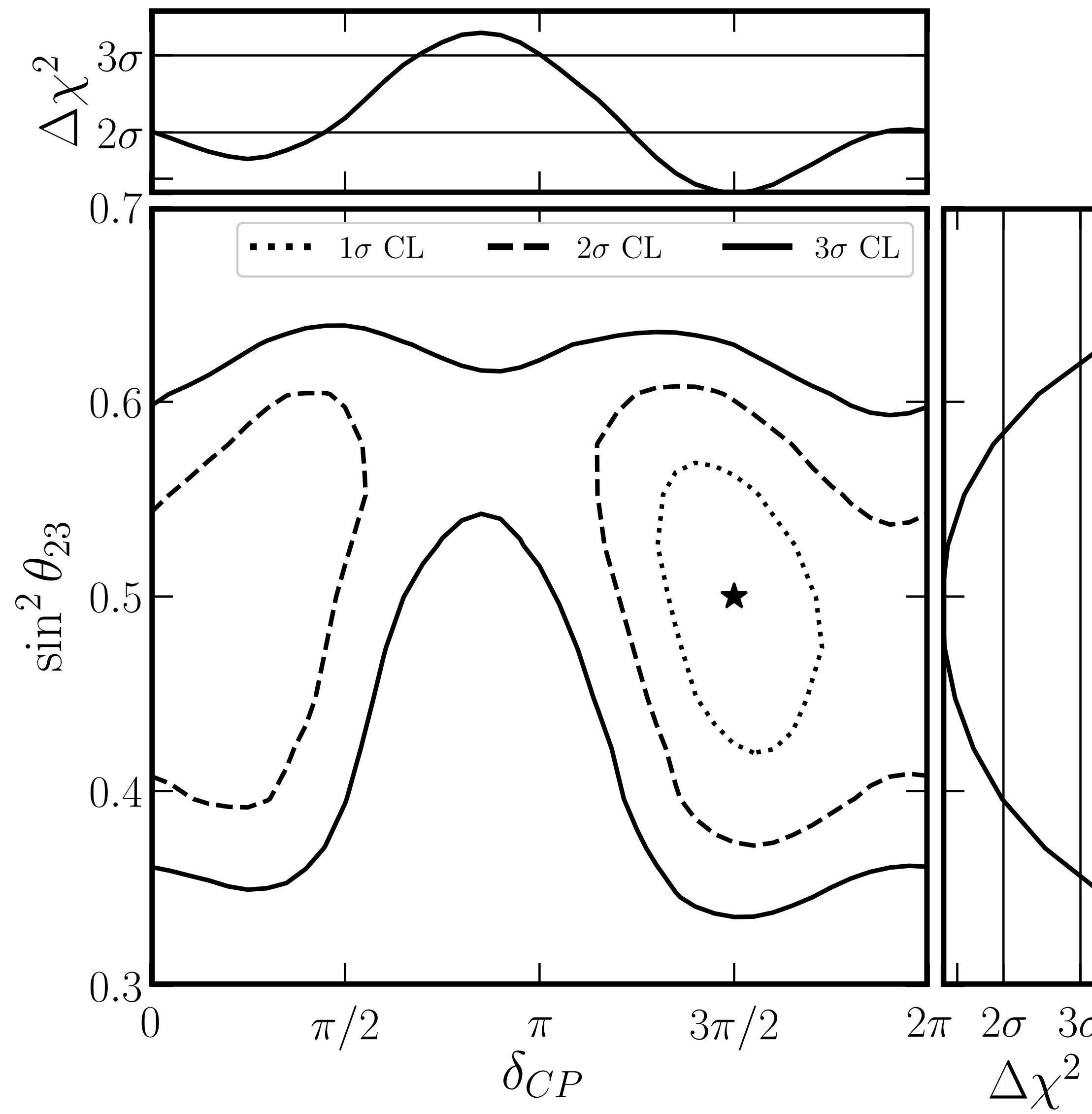
# Conclusions

- **Atmospheric neutrinos** are a unique source for exploring the **neutrino properties**.
- By the end of this decade, **atmospheric neutrinos** will contribute to some of the open questions in neutrino physics: the **mass ordering**, the **octant of  $\theta_{23}$** , and the **CP-violation phase**.
  - For  $\theta_{23}$  it is possible to get more than  $2\sigma$  significance over the octant
  - It is possible to discriminate the mass ordering at  $6\sigma$  using just atmospheric neutrinos
  - $\delta_{cp}$  can be measured at more than  $2\sigma$  thanks to Super-Kamiokande with Gd
- The next generation of experiments will contribute with a precise atmospheric flux measurement. In particular, **DUNE** will be sensitive to some values of  $\delta_{cp}$  at than  $3\sigma$ .



Thanks!

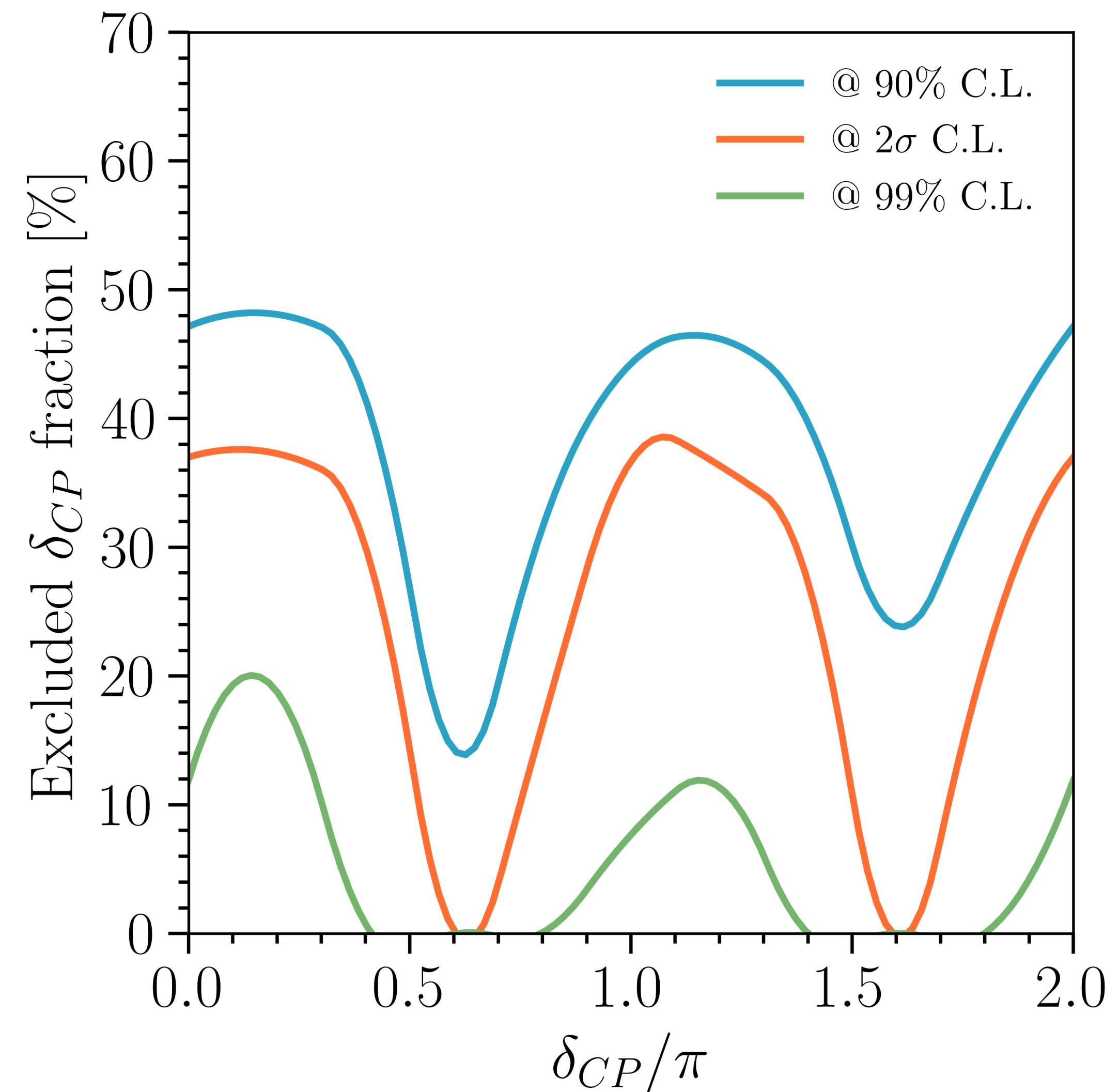
# Backup: DUNE sensitivity to $\theta_{23}$



# Backup: Combined analysis: $\delta_{cp}$

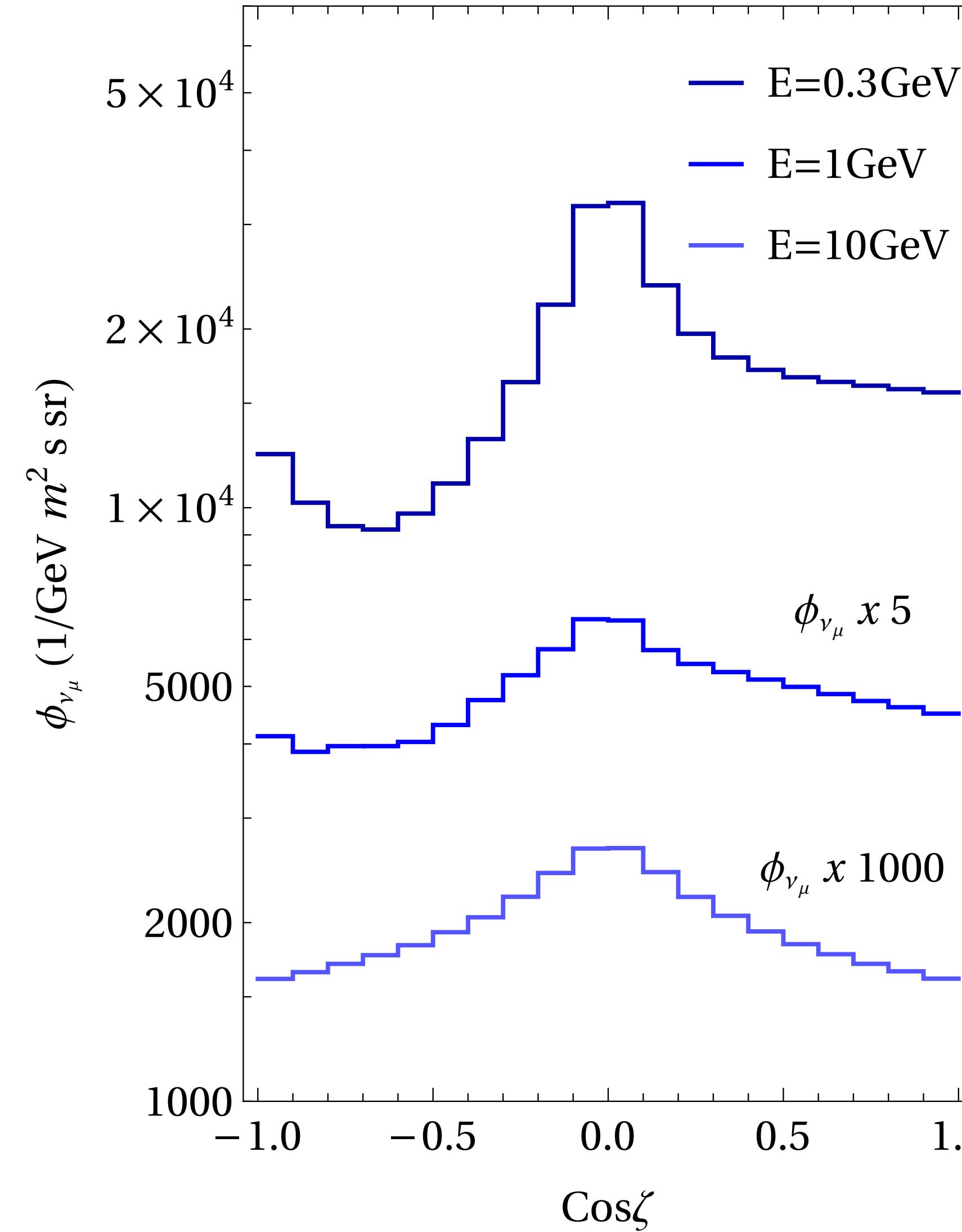
The sensitivity to the CP phase depends on the true value

A large fraction of  $\delta_{CP}$  can be excluded at 90% CL for any value of  $\delta_{CP}$  using only atmospheric neutrinos

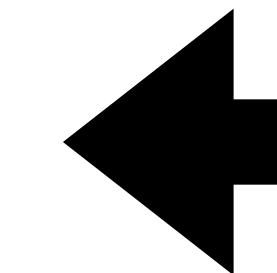


# Backup: Atmospheric neutrinos

The most recent atmospheric neutrino flux estimations are based on 3D-MC simulation



$$\phi_{\nu_i} = \phi_p \otimes R_p \otimes Y_{p \rightarrow \nu_i} + \sum_A \phi_A \otimes R_A \otimes Y_{A \rightarrow \nu_i}$$



The main components in the flux calculations are:

- **Cosmic ray flux ( $\phi_p$ )**
- **Geomagnetic effects (R)**
- **Hadronic interactions (Y)**

Honda, Sajjad Athar, Kajita, Kasahara,  
Midorikawa Phys.Rev.D 92 (2015)

# Backup: $3\nu$ mixing in matter

In matter, the evolution is affected by the matter potential

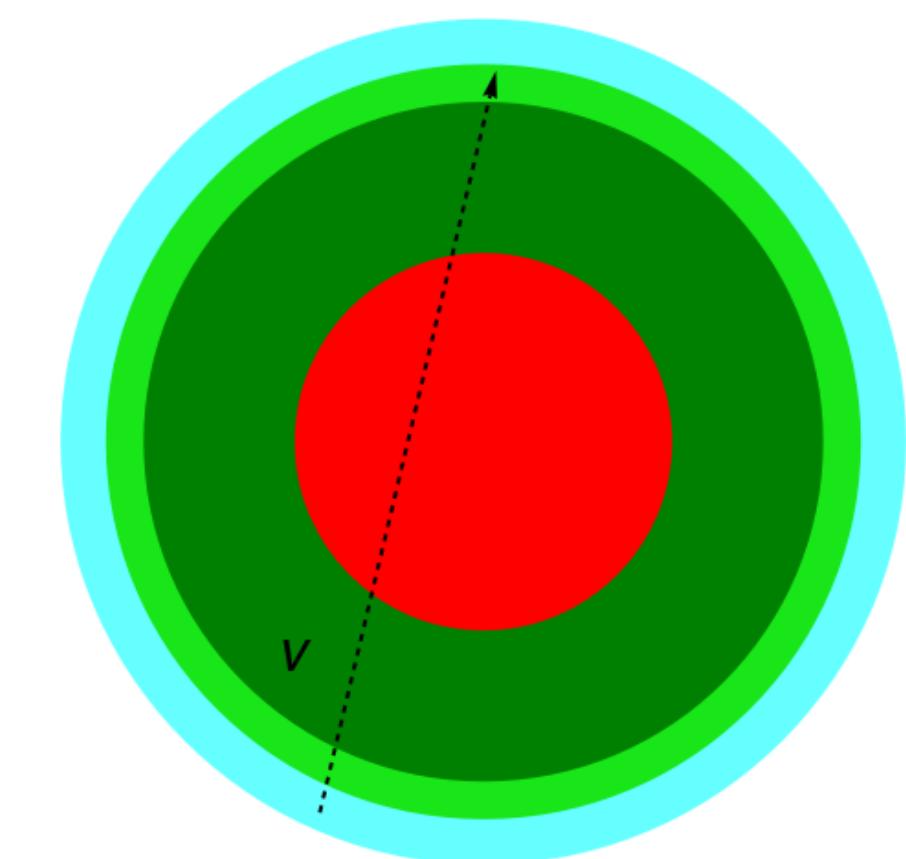
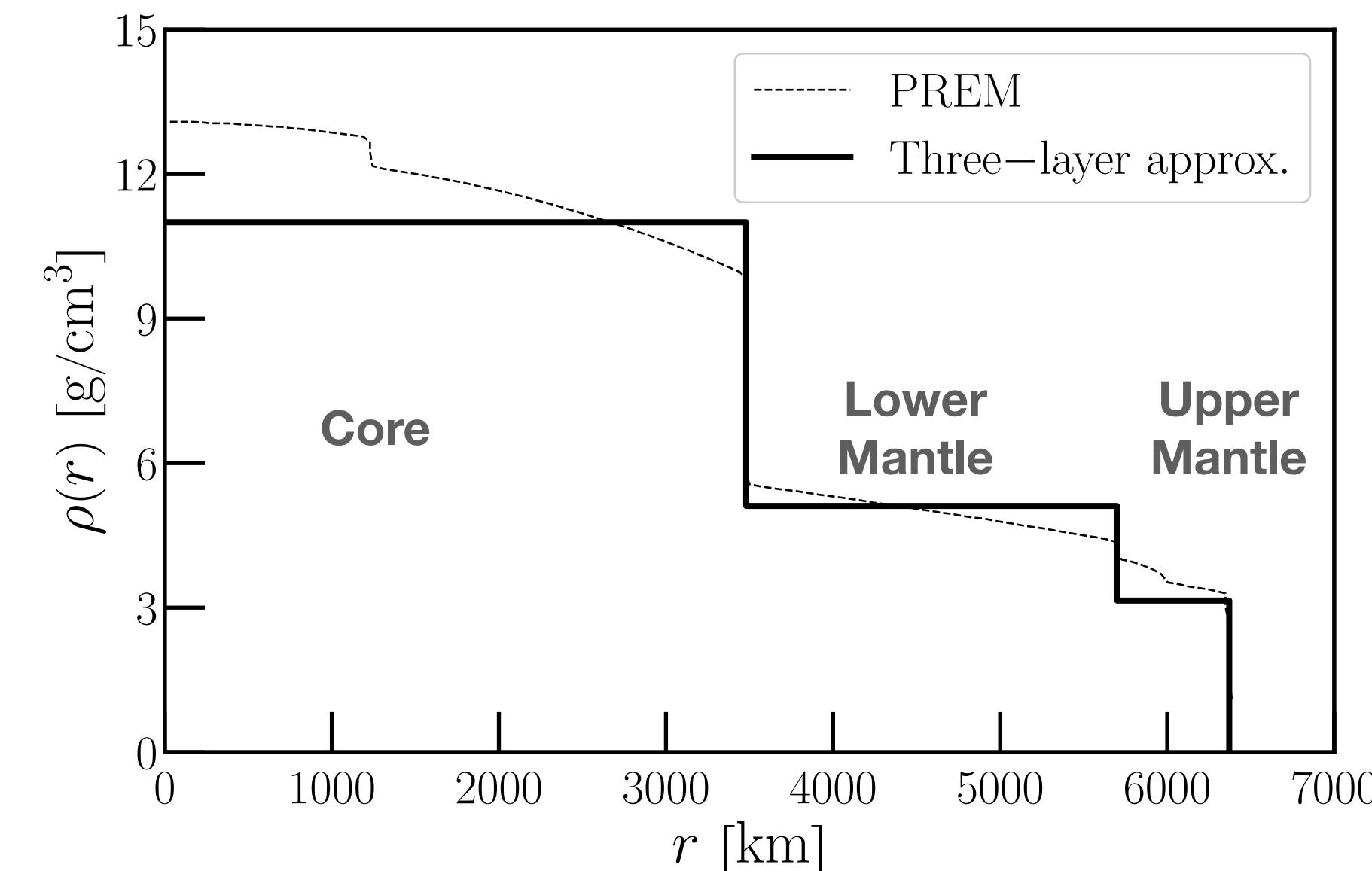
$$i \frac{d\nu}{dE} = \frac{1}{2E} (U^\dagger \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U \pm V_{mat}) \nu$$

For neutrinos crossing the Earth

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



Electron density along the neutrino trajectory



# Backup: Mass ordering

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  $\theta_{13}$ . MSW resonance.

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

