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Measuring CP violation with atmospheric neutrinos

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arXiv:2605.16721

CP violation in the neutrino sector

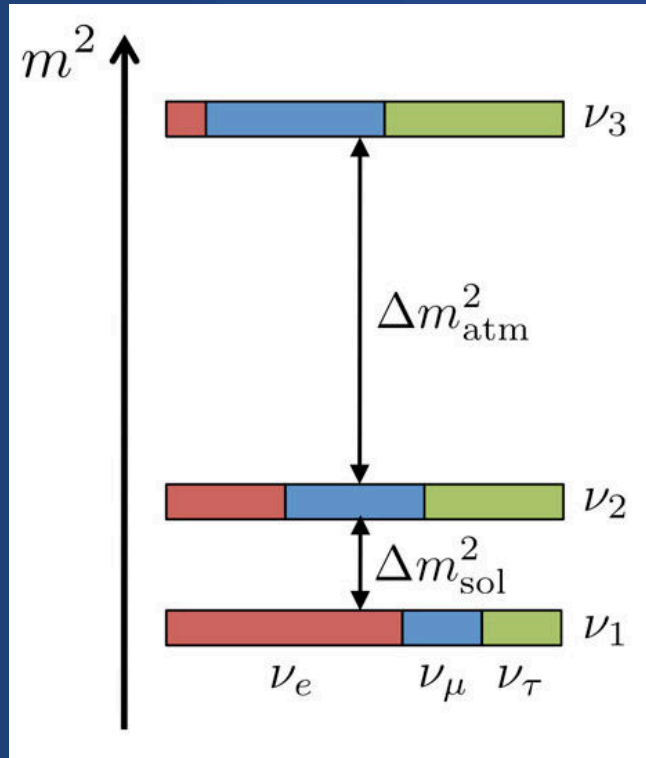
Why does the Universe contain more matter than antimatter?

- Dynamical creation of a matter-antimatter asymmetry requires CP violation
 - CP violation in the SM quark sector too small to explain the observed cosmological baryon asymmetry
- **Essential to test CP violation in the lepton section**

Measuring CP violation in the neutrino sector is a primary aim of accelerator-based long-baseline neutrino oscillation experiments.

- **Is there a viable independent way to measure this parameter?**

Neutrino mixing

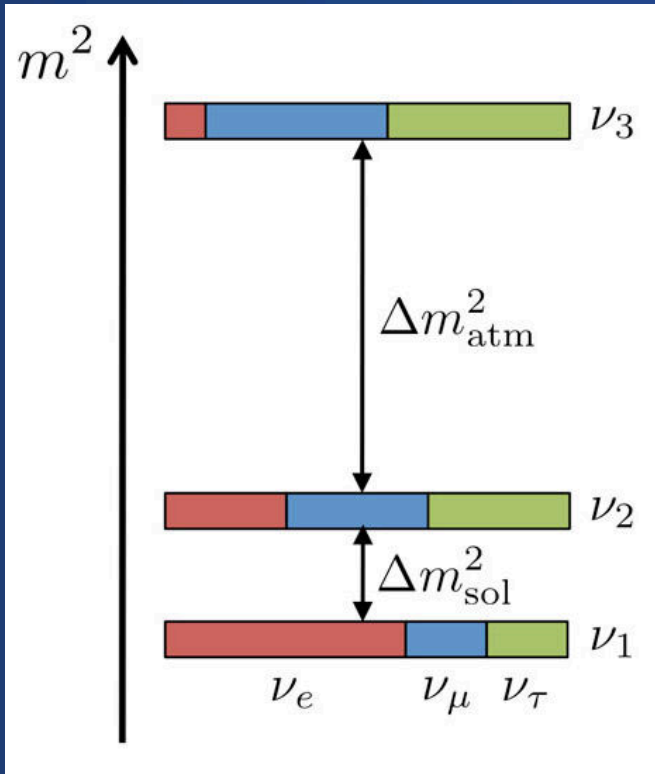


Flavour and mass states related by the neutrino mixing matrix.

Contains three mixing angles & one complex phase.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

CP violation in neutrino mixing



Mixing matrix =

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$

where $c_{12} = \cos \theta_{12}$ etc

The phase δ_{CP} introduces CP-violation

Neutrino oscillation probability

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{k>j} \text{Re}[U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*] \sin^2 \left(\frac{\Delta m_{kj}^2 L}{4E} \right) + 2 \sum_{k>j} \text{Im}[U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*] \sin \left(\frac{\Delta m_{kj}^2 L}{2E} \right)$$

δ_{CP} - even terms

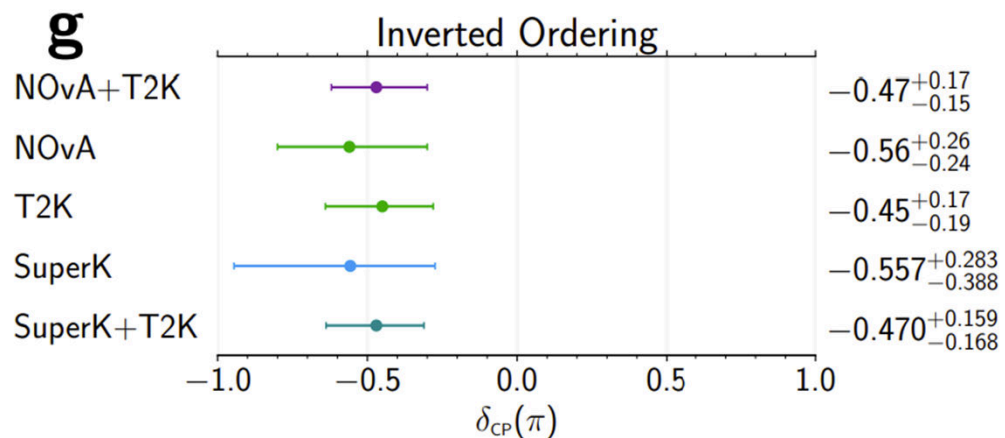
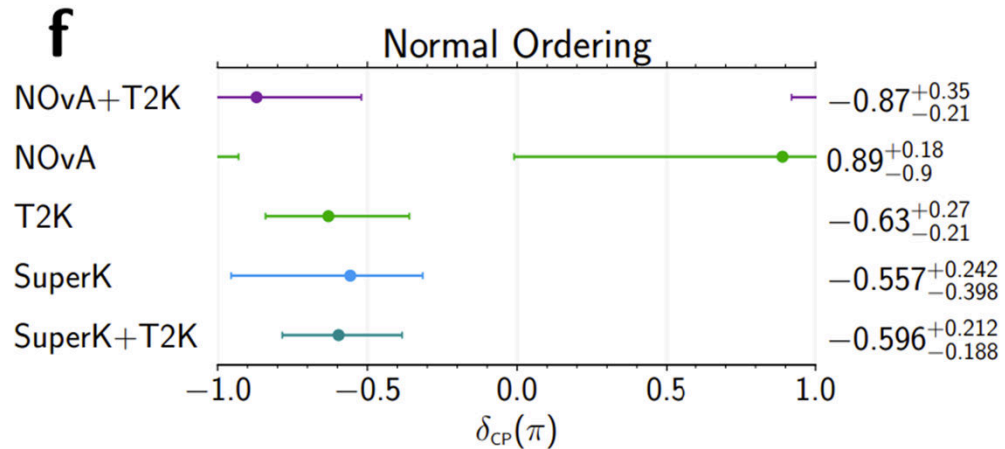
δ_{CP} - odd terms

The task is to extract δ_{CP} -dependent effects in neutrino oscillations.

Need a regime where oscillations are not well approximated by a 2-flavour system.

- Two-flavour mixing is controlled by a single mixing angle and no phase. Genuine 3-flavour effects are needed for the complex phase to enter.
- Need oscillations driven by both mass-splittings Δm_{21}^2 and Δm_{32}^2 to be in play.

Current data



Early indication the phase is non-zero.

Some preference for $\delta_{CP} = 90^\circ, 270^\circ$
(corresponds to maximal CP violation).

Results depends on mass ordering.

Measuring CP violation with accelerator neutrinos

Accelerator long-baseline experiments – primarily sensitive to $\sin \delta_{CP}$

- For typical parameters ($E_\nu = 0.6$ GeV $L = 300$ km), neglecting matter effects

$$P_{\mu e} \sim 0.04(1 + 0.01 \cos \delta_{CP} - 0.3 \sin \delta_{CP})$$

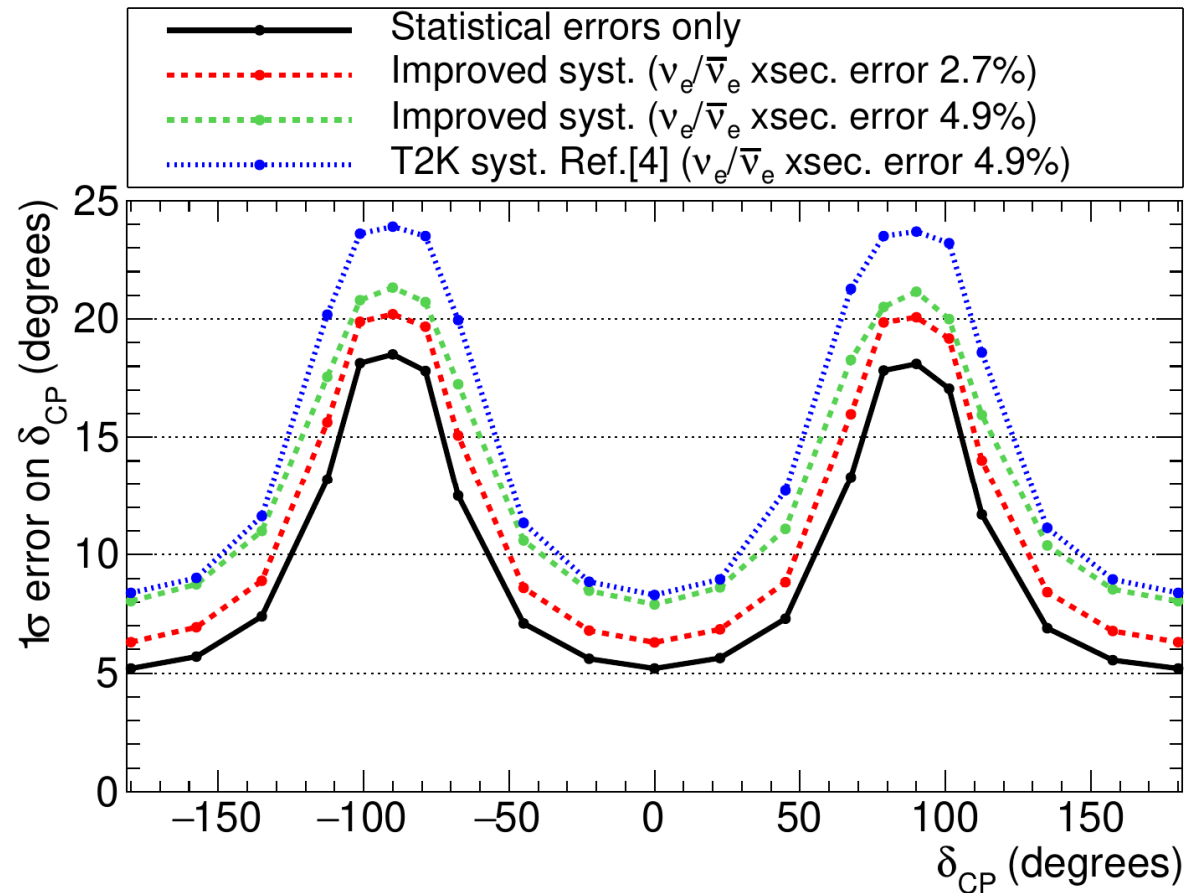
$$\overline{P_{\mu e}} \sim 0.04(1 + 0.01 \cos \delta_{CP} + 0.3 \sin \delta_{CP})$$

- L/E_ν chosen to enhance sensitivity $\sin \delta_{CP}$. Comparing neutrino & antineutrino sensitivity cancels some systematics.

Note: Any manifestly CP violating (neutrino-antineutrino) observable must be proportional to the Jarlskog invariant, thus $\propto \sin \delta_{CP}$

Atmospheric neutrinos – our approach is sensitive to $\cos \delta_{CP}$

Hyper-K sensitivity using accelerator neutrinos



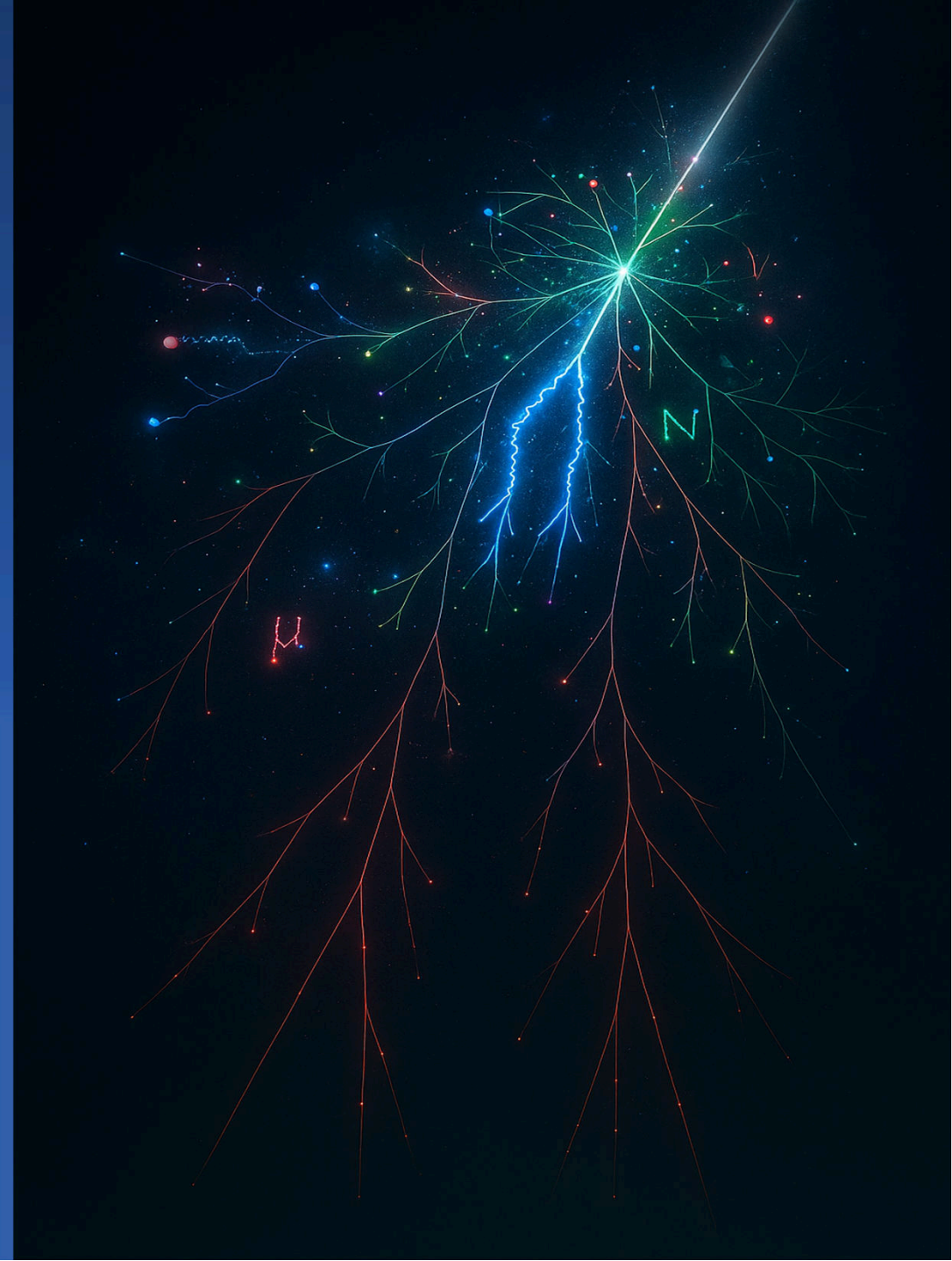
Abe et al. (Hyper-Kamiokande), Eur. Phys. J. C 86, 170 (2026)

T2HK sensitivity to δ_{CP} after 10 years of data taking.

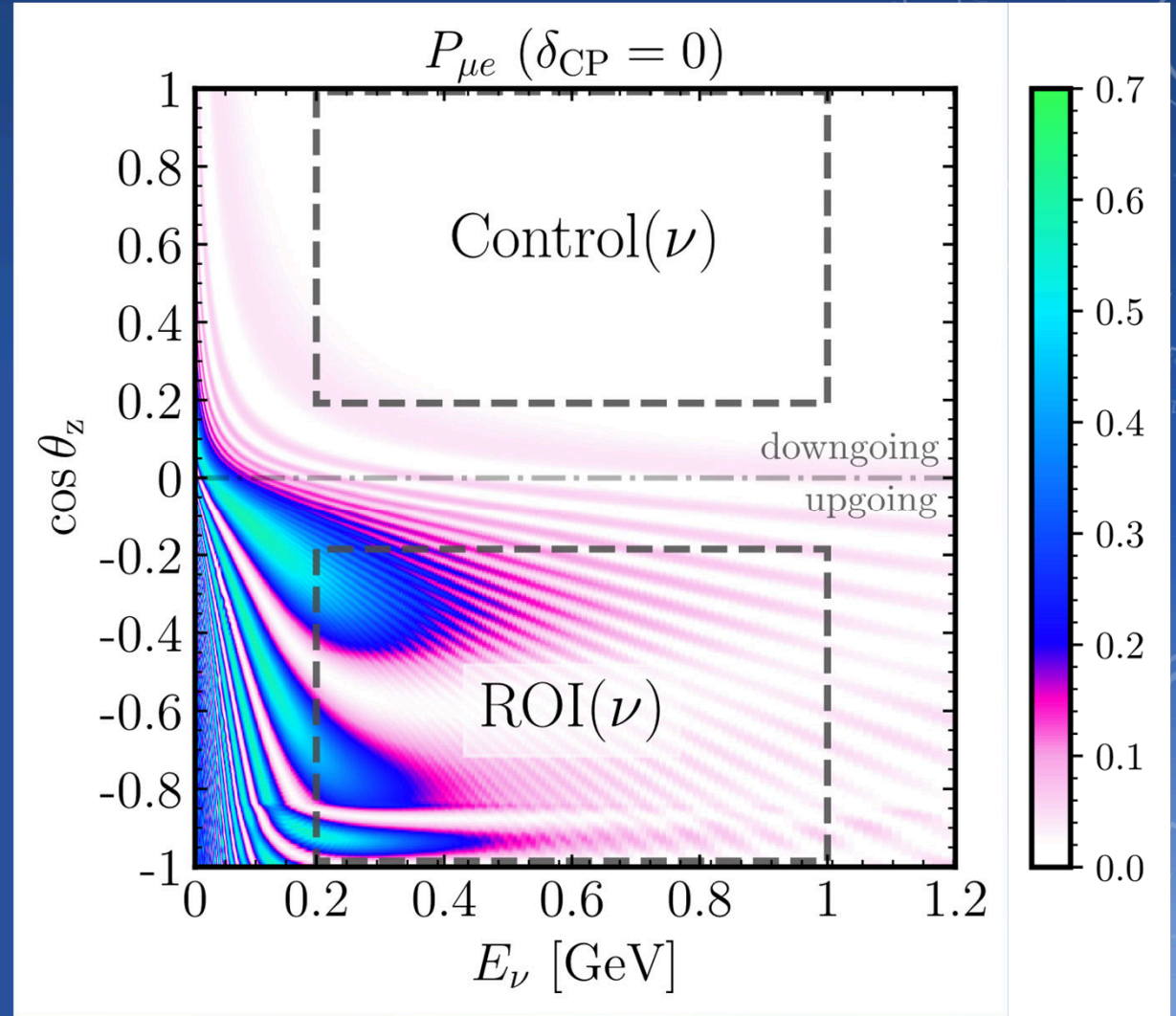
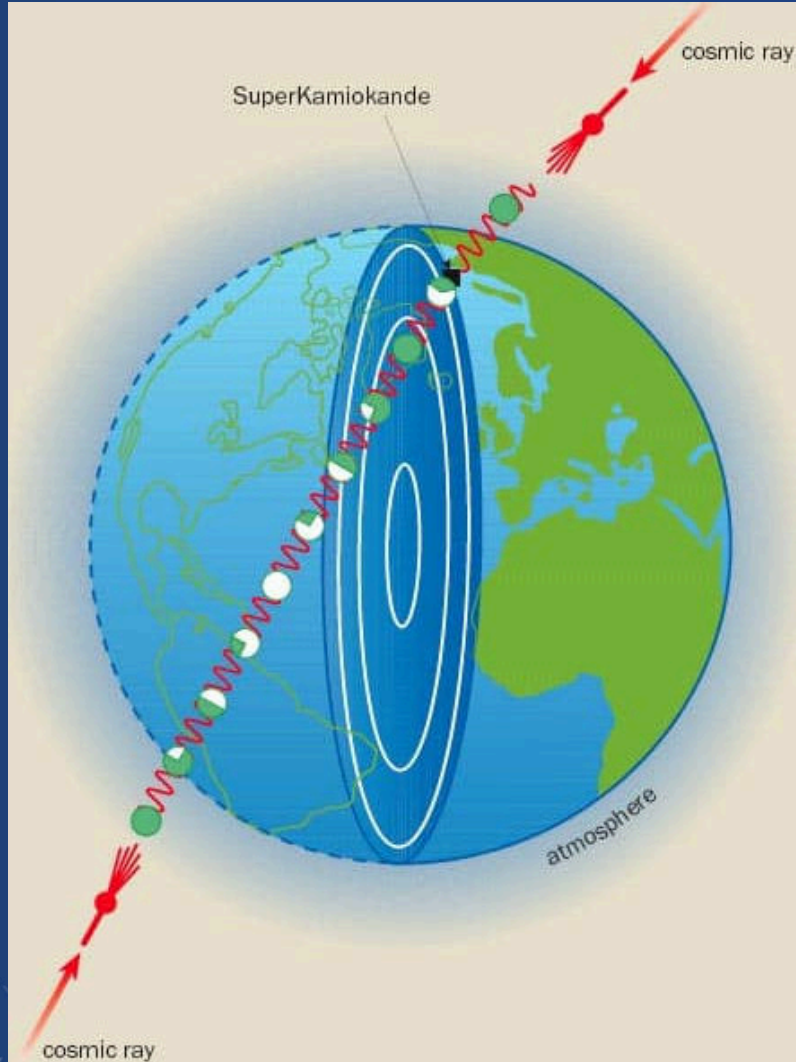
Best sensitivity occurs near the (CP-conserving values) $\delta_{CP} = 0^\circ$ and 180° .

Measuring CP violation with atmospheric neutrinos

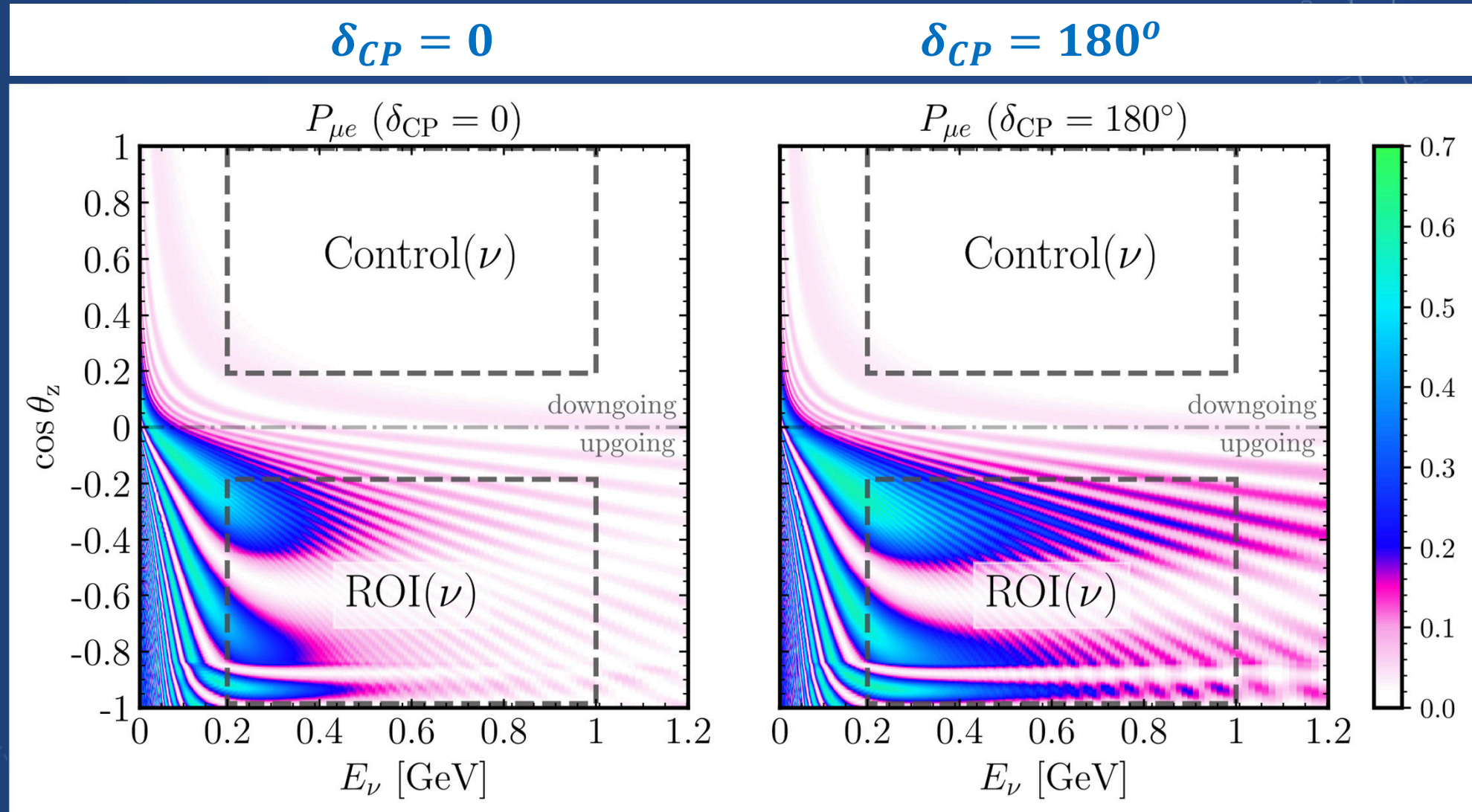
Beacom, NFB, Dolan, Meighen-Berger,
Yim, arXiv:2605.16721



Atmospheric neutrino oscillations



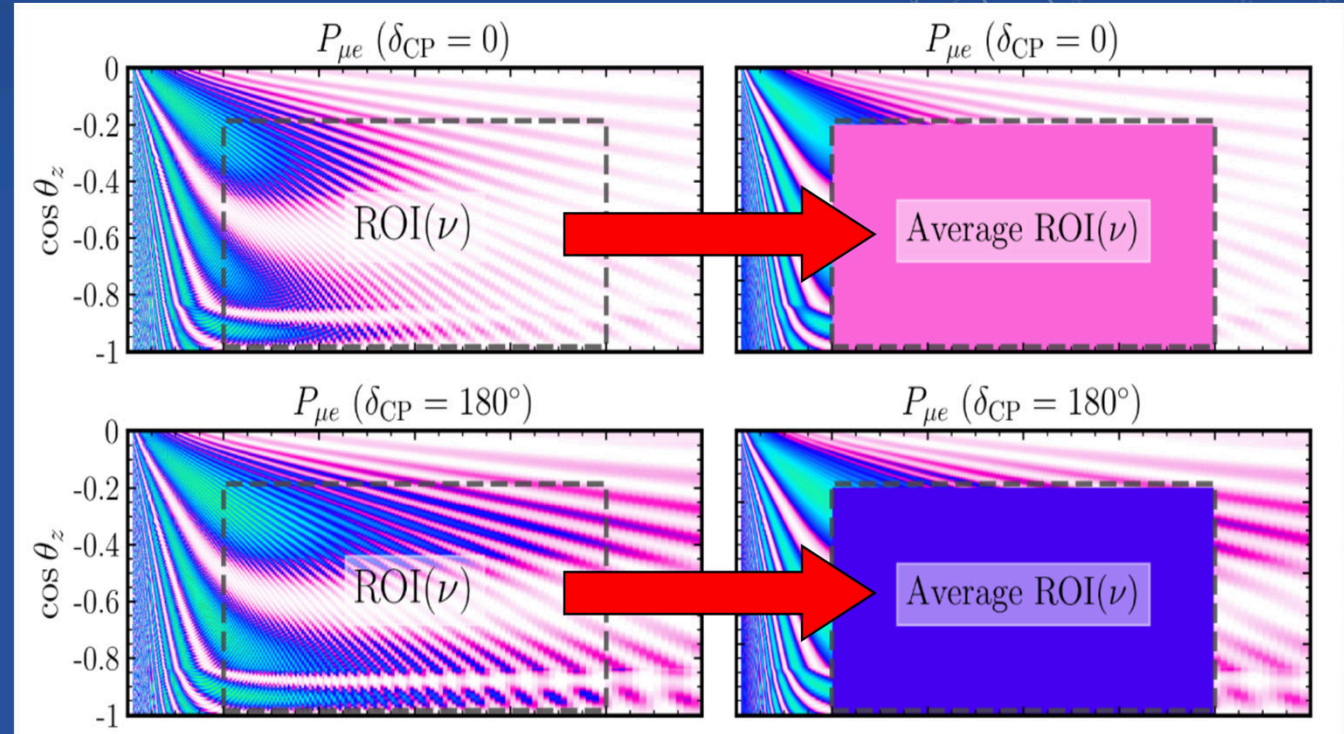
CP violation in atmospheric neutrino oscillations



CP violation in atmospheric neutrino oscillations

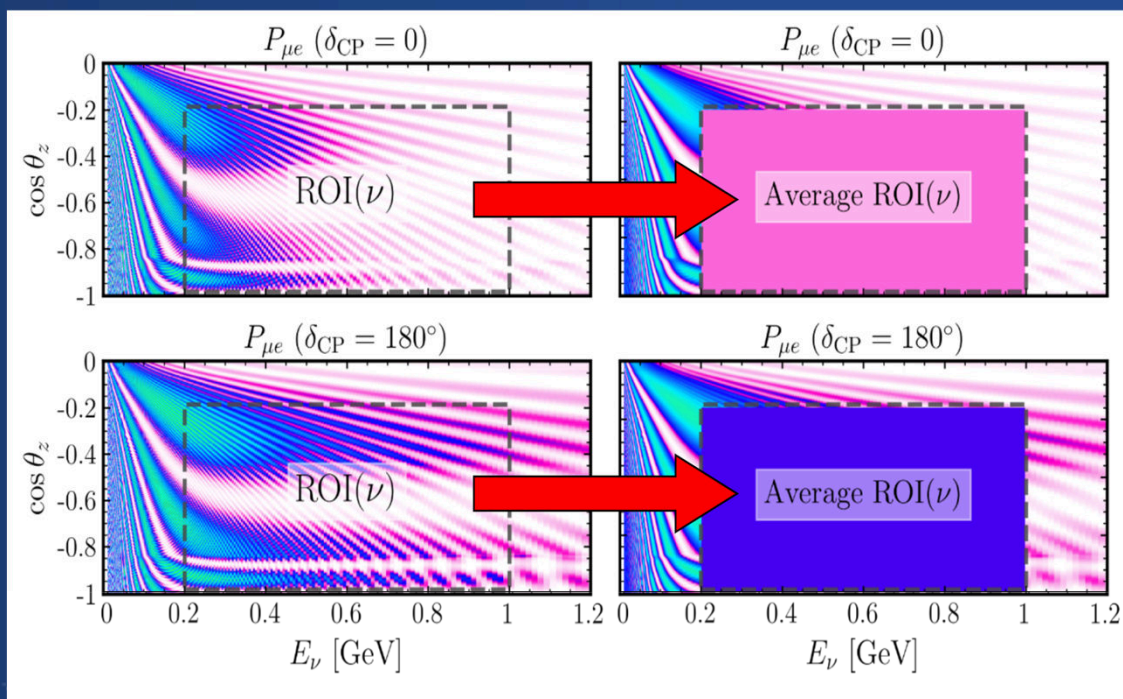
Oscillograms have detailed structure

- ***fine details are unresolvable*** given realistic, unavoidable, energy and angular smearing.
- ***CP-dependent effects survive averaging***

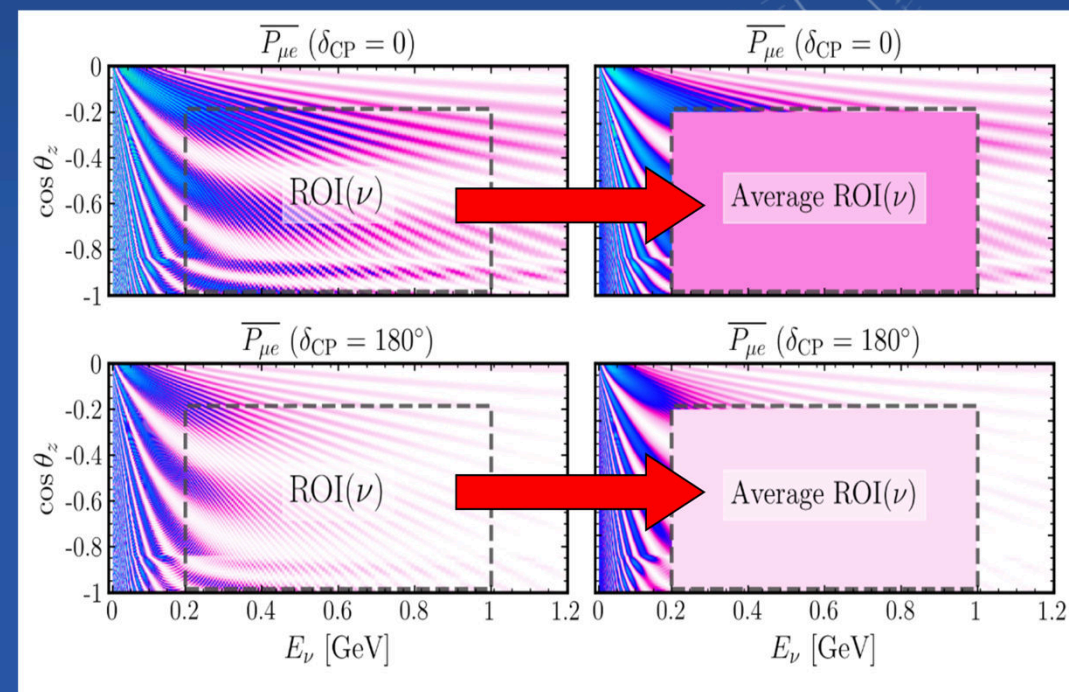


CP violation in atmospheric neutrino oscillations

Neutrinos



Anti Neutrinos



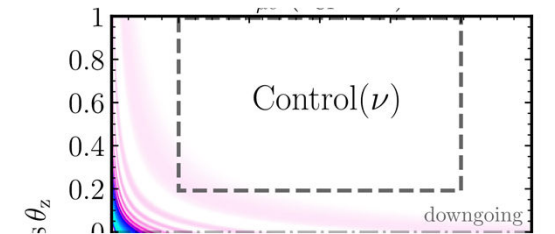
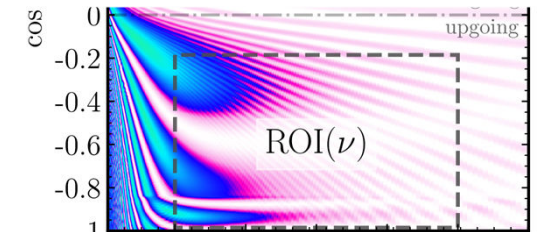
Needed: a robust CP-dependent observable

- Initial (unoscillated) fluxes have: $\phi_e:\phi_\mu:\phi_\tau = 1:2:0$ (from pion decay)

- Rate of electron-type up-going events is δ_{CP} -dependent:

$$\Gamma_{\text{up-going}} \propto \iint_{\text{ROI}} d \cos \theta_z dE_\nu (P_{ee} + 2P_{\mu e})$$

- $\Gamma_{\text{down-going}}$ defined similarly over the **Control** region (and is δ_{CP} -independent)



A robust CP-dependent observable

- **$\cos \delta_{CP}$ -dependent observable:**

- most oscillations average out over the energy-angle region chosen
- This removes $\sin \delta_{CP}$ terms, but not $\cos \delta_{CP}$ terms.

- **Up-down ratio to cancel leading flux & cross section uncertainties:**

$$R_{CP} = \frac{\Gamma_{\text{up-going}}(\delta_{CP})}{\Gamma_{\text{down-going}}} = \frac{\text{ROI}}{\text{Control}} \sim (1 - 0.05 \cos \delta_{CP})$$

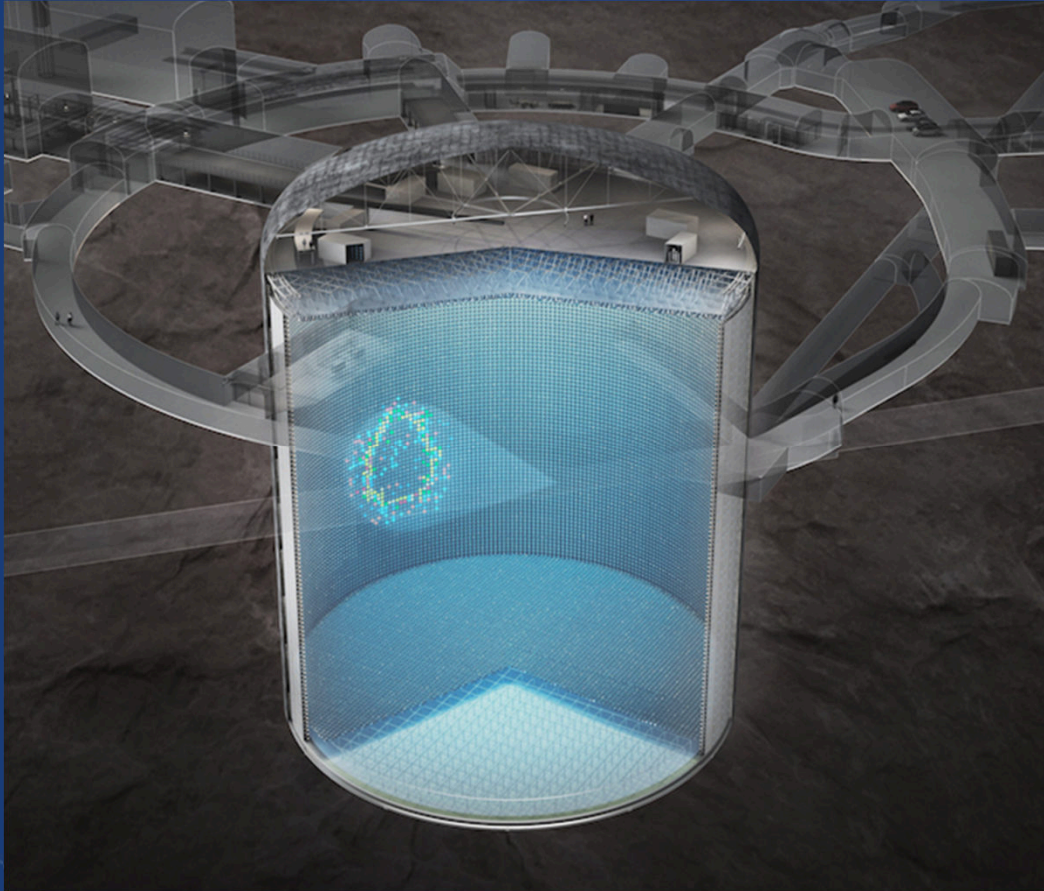
Neutrinos vs antineutrinos

Neutrinos and antineutrinos have opposite-sign δ_{CP} dependence (due to opposite sign matter potential).

electron-type	ν_e :	$R_{CP} \sim (1 - 0.05 \cos \delta_{CP})$	neutrinos
	$\bar{\nu}_e$:	$R_{CP} \sim (1 + 0.04 \cos \delta_{CP})$	antineutrinos
muon-type	ν_μ :	$R_{CP} \sim (1 + 0.02 \cos \delta_{CP})$	
	$\bar{\nu}_\mu$:	$R_{CP} \sim (1 - 0.01 \cos \delta_{CP})$	

- Distinguishing neutrinos from antineutrinos would be powerful.
- However, even a $\nu + \bar{\nu}$ measurement will work, as $\bar{\nu}$ cross sections are smaller in the sub-GeV energy range (hence ν dominate over $\bar{\nu}$ in the event rates).

Can we do this at Hyper-K ?



186 kton fiducial volume

We expect:

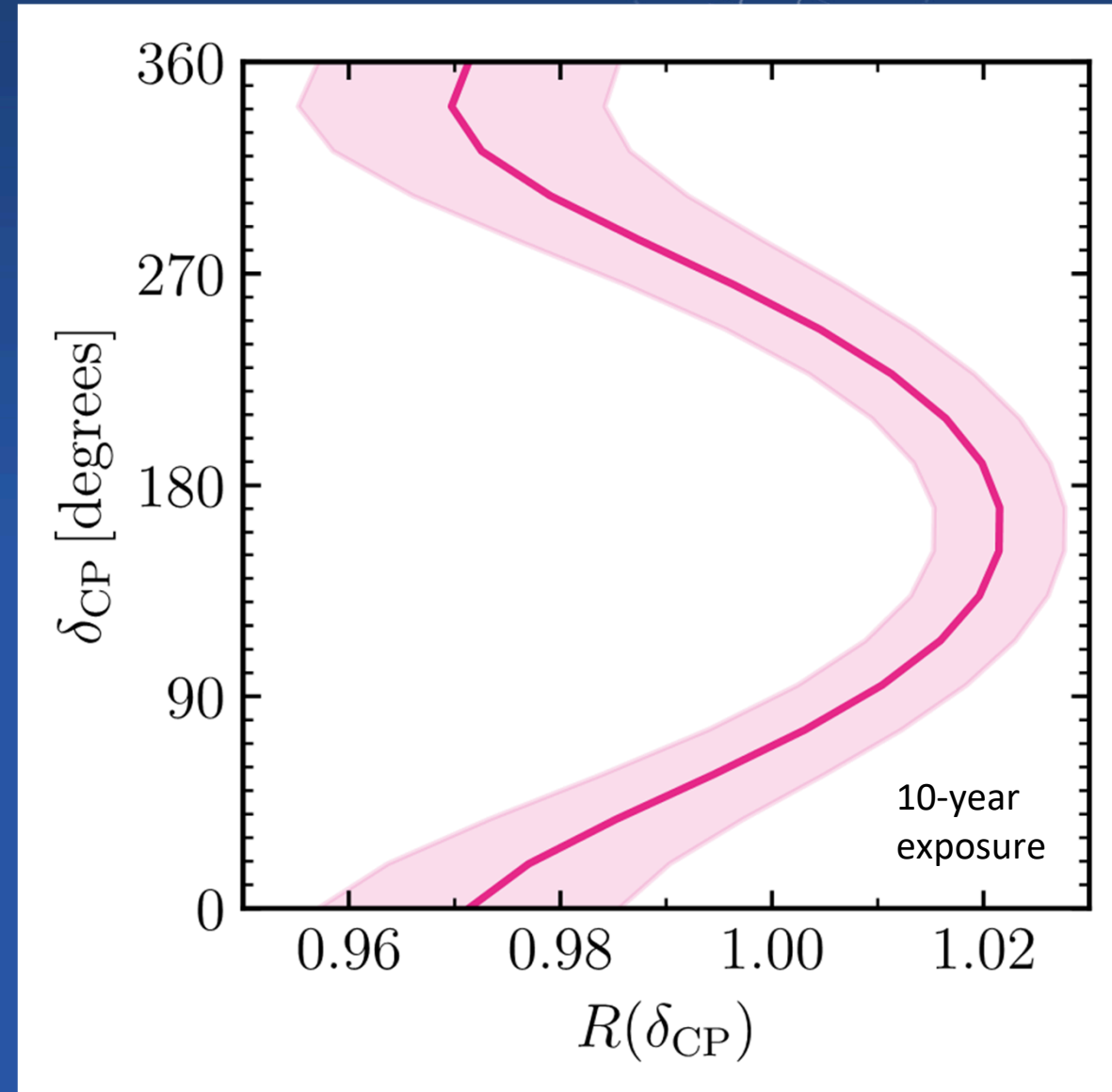
- 2600 sub-GeV e-like events/year
- 2900 sub-GeV μ -like events/year

For a 10-year exposure, the e-like sample alone has a statistical power of $<1\%$

→ good enough to see a 5% effect

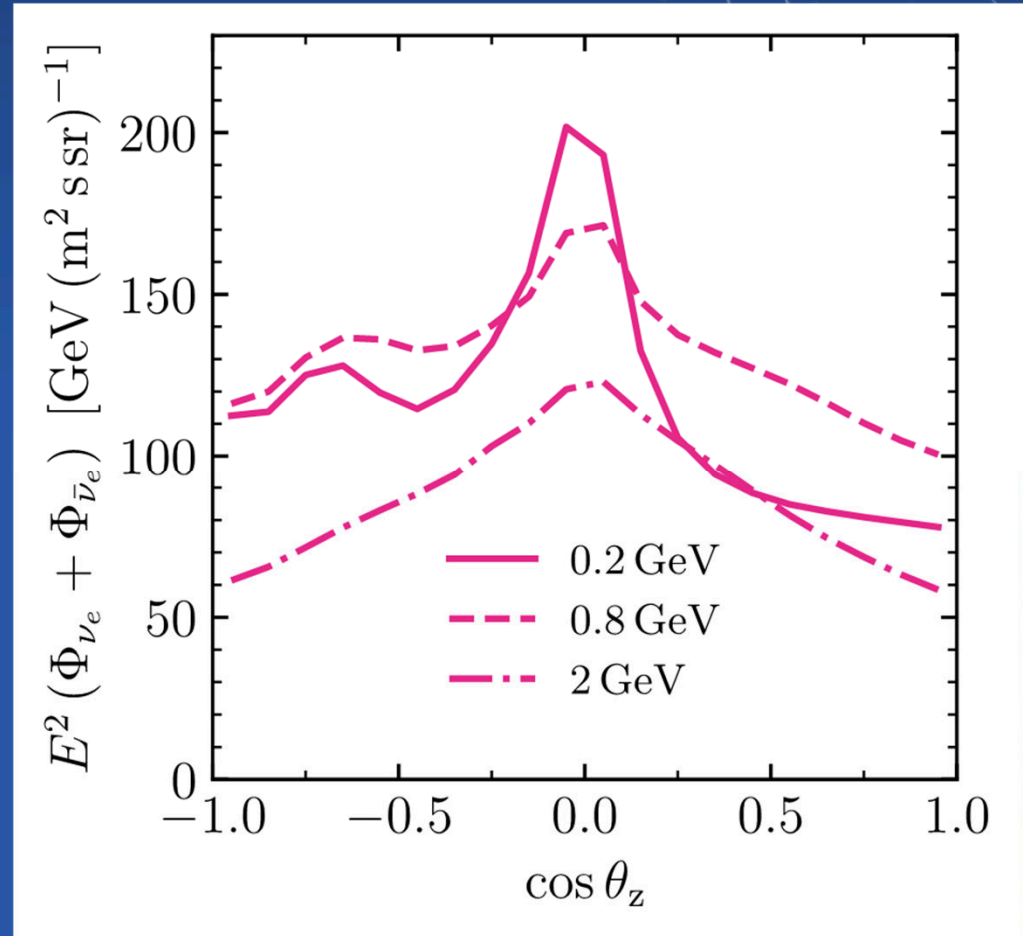
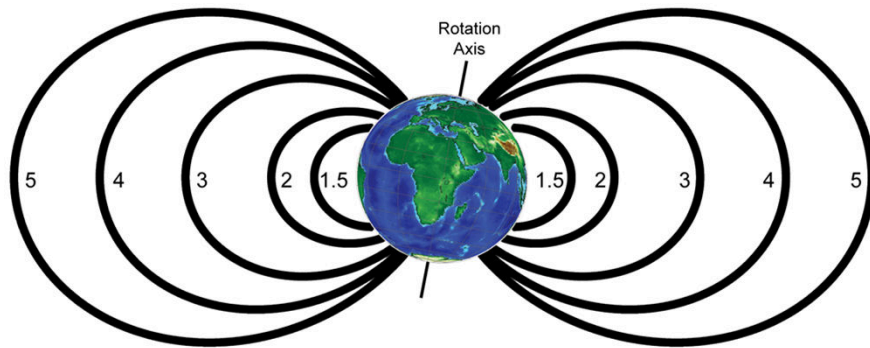
Adding detector effects:

- Detector energy and angular smearing
- Fundamental limitation is the correlation between the charged lepton direction and the true neutrino direction
 - To reduce up/down smearing: zenith-angle cut $|\cos \theta_z| > 0.2$ (i.e. remove the horizon)
- Rate uncertainties (combination of flux and cross section) partially cancel in the ratio.



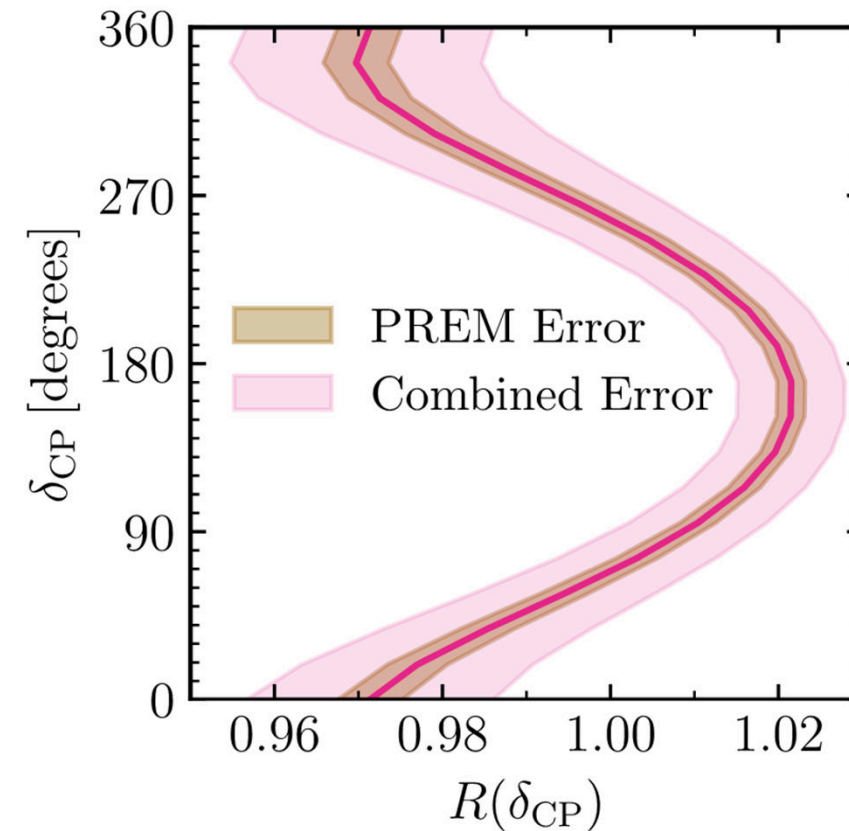
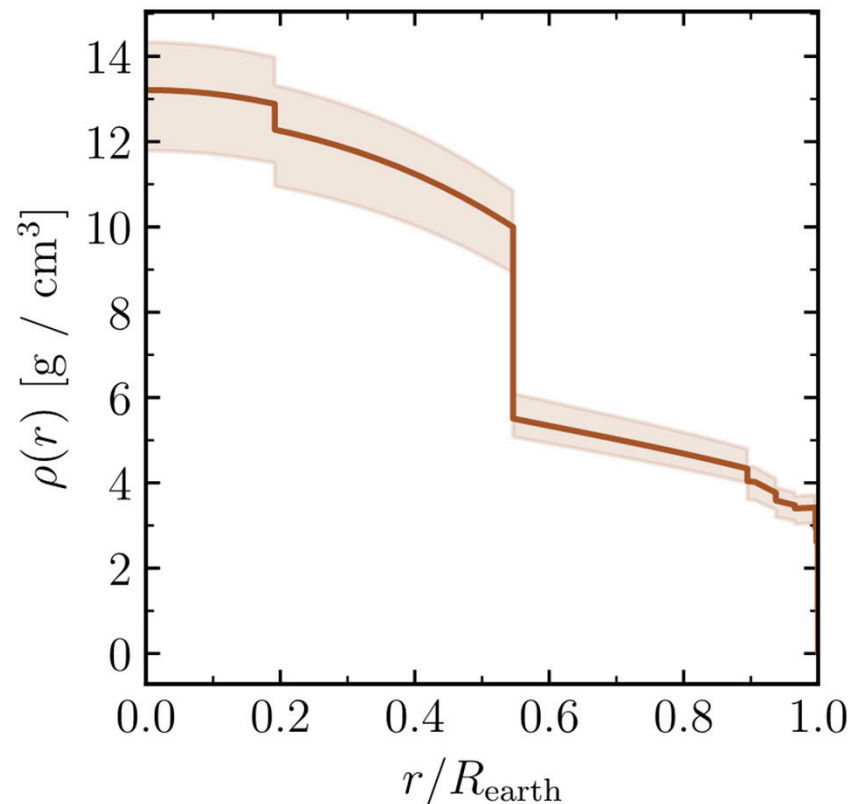
Leading uncertainties:

- The up/down ratio cancels leading flux and cross section uncertainties.
- It is not a perfect cancellation due to flux asymmetries at low energies.
- Arise from geomagnetic effects (Earth's magnetic field imposes location-dependent, low energy cut-off on primary cosmic rays).



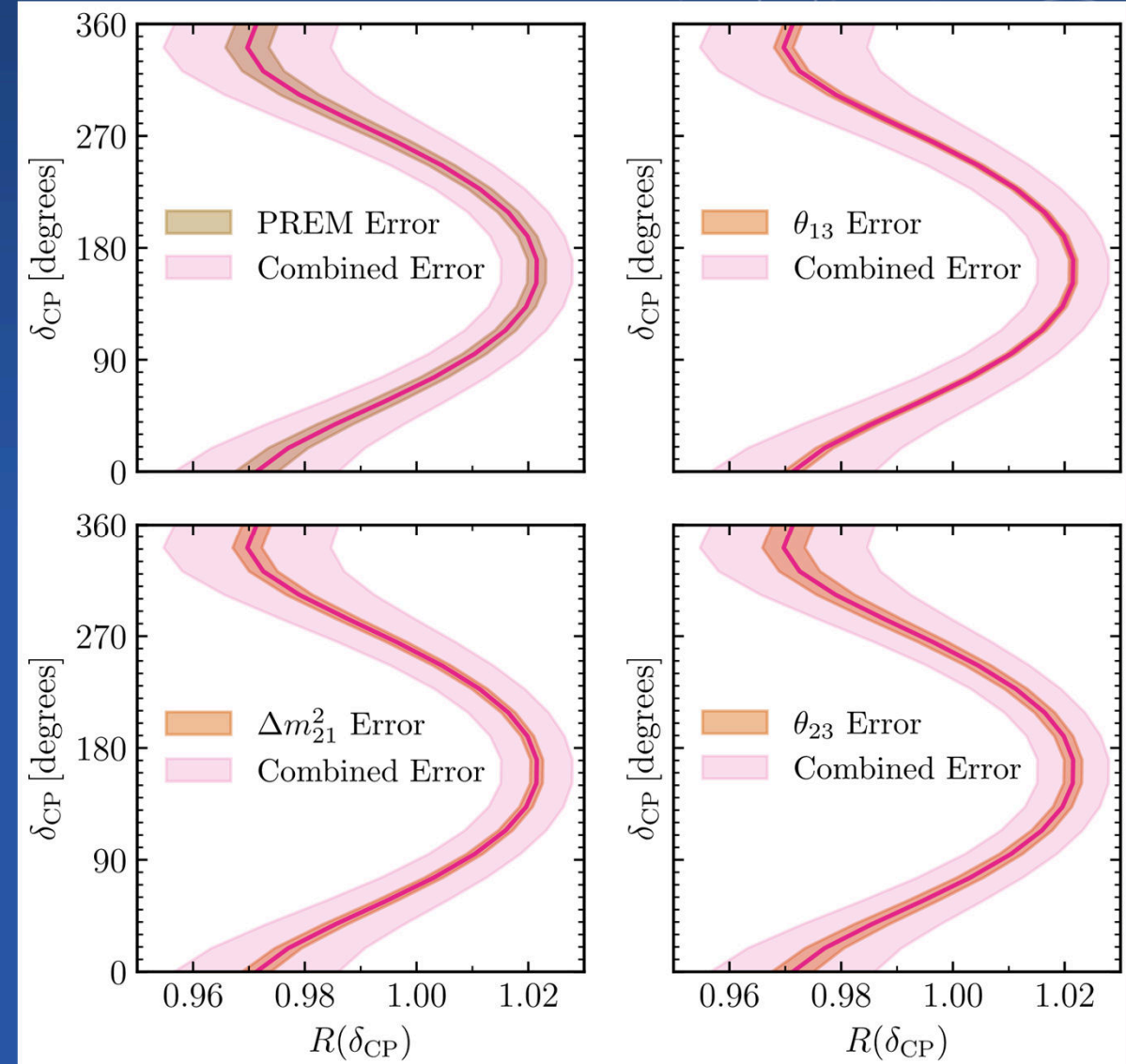
Subdominant uncertainties

- Largely insensitive to uncertainties in the Earth's density profile.
(Ensemble of density profiles; each layer varied up to 10%; with the total mass fixed.)



Subdominant uncertainties

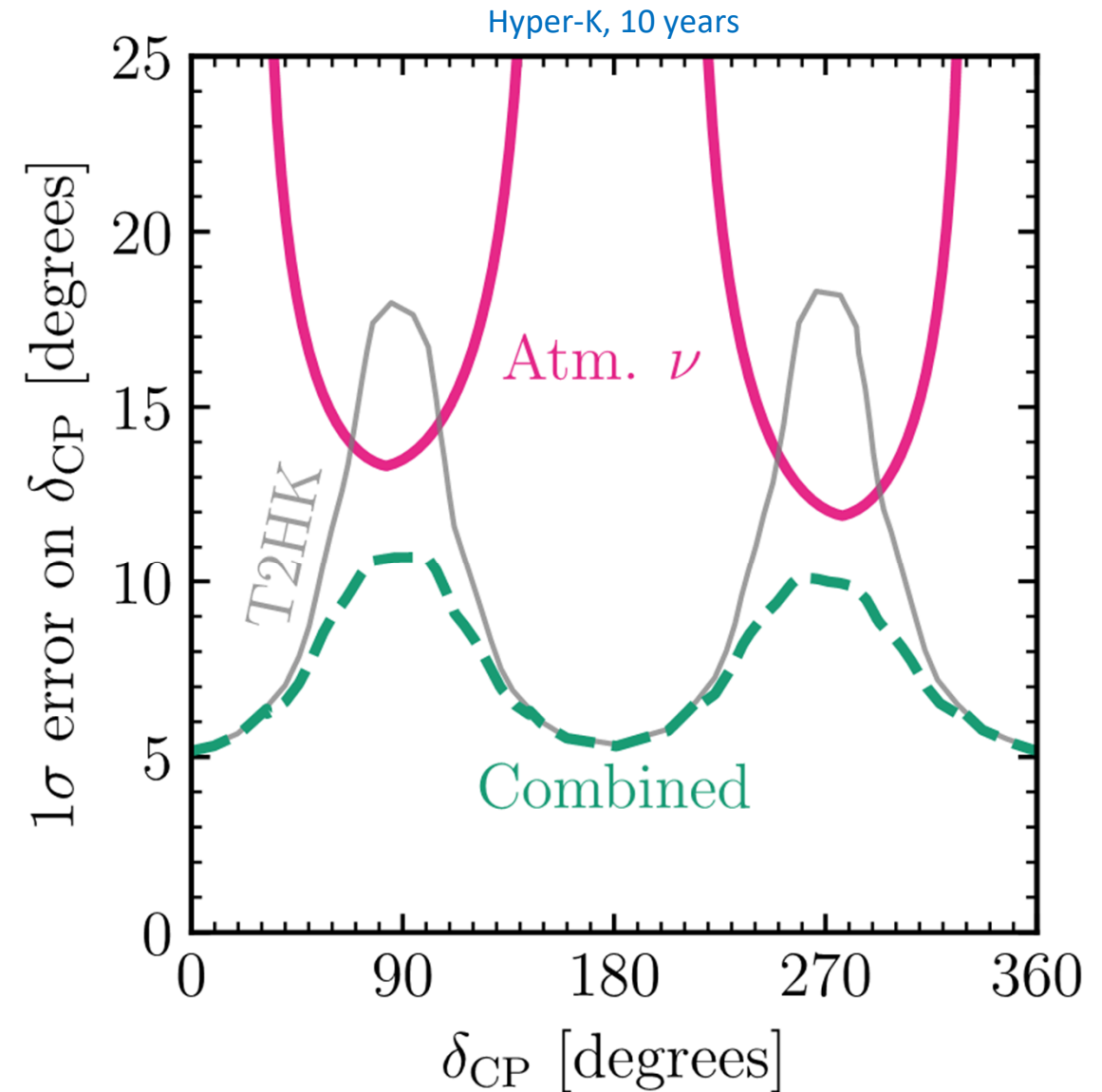
- Also largely insensitive to current neutrino mixing parameter uncertainties.
- Greatest (but still small) contribution from θ_{23} , θ_{13} and m_{21}^2 .
- Future precision measurements of the mixing parameters will further reduce these errors.
- (Averaging over the region of interest reduces the sensitivity to the other oscillation parameters.)



Projected resolution

- **Atmospheric approach** most sensitive where the **long-baseline approach** is least sensitive.
(due to $\cos \delta_{CP}$ vs $\sin \delta_{CP}$ dependence)
- Excellent complementarity
- **Combined sensitivity** is excellent across the full parameter range

Atmospheric approach optimal near 90° & 270°
(maximal CP-violation; favoured by current data)



Beacom, NFB, Dolan, Meighen-Berger, Yim, arXiv:2605.16721

Summary

Measuring CP violation in the neutrino sector

- Standard approach = accelerator long-baseline experiments
- Only known alternative = atmospheric neutrinos

Atmospheric neutrinos

- Sensitive to $\cos \delta_{CP}$ rather than $\sin \delta_{CP}$
- Most sensitive near $\delta_{CP} = 90^\circ, 270^\circ$ (maximal CP violation; currently favoured)
- A combination of atmospheric & accelerator neutrino measurements will get us there faster!

Beacom, NFB, Dolan, Meighen-Berger, Yim, arXiv:2605.16721