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Precision-era neutrino oscillations

How Robust Is the δ_{CP} Measurement?

Cross-section systematics & propagation NSI as threats to leptonic CP violation

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Improving the robustness of the δ_{CP} determination with νSCOPE

Pinheiro, Urrea • arXiv:2604.20956

Diagnosing Unmodeled Neutrino Physics via DUNE and T2HK Complementarity

Pinheiro, Rahaman • arXiv:2603.14215

The question, and the plan

One number, two ways to get it wrong

Measuring δ_{CP} (and the θ_{23} octant) is the flagship goal of **DUNE** and **T2HK**. We ask not *how precisely*, but how **robustly** they can do it.

Two distinct effects can fake or bias the signal:

1 **Detection:** poorly known $\sigma_{\nu_e}, \sigma_{\bar{\nu}_e}$ cross sections.

2 **Propagation:** complex non-standard interactions (NSI).

Outline

1. Why δ_{CP}, and why it is fragile
2. **Threat 1** — the $\sigma_{\nu_e}/\sigma_{\nu_\mu}$–$\delta_{\mathrm{CP}}$ degeneracy
   and how νSCOPE cures it
3. **Threat 2** — propagation NSI
   and the DUNE–T2HK diagnostic
4. Robustness: what it takes

Motivation

Why δ_{CP}, and why worry?

The unknowns are shrinking to two

- JUNO has pinned the **solar parameters** (Abusleme et al., arXiv:2511.14593); combined with global data and cosmology, **normal ordering** is now favoured (Esteban et al., arXiv:2601.09791; Adame et al., arXiv:2404.03002).
- Mixing angles & mass splittings: **percent-level** (Esteban et al., arXiv:2410.05380).
- What is left:
  - the **octant** of θ_{23} ($\theta_{23} \lessgtr 45^\circ$);
  - the **Dirac CP phase** δ_{CP}.
- These are *the* targets of the next decade — and the most systematics-limited of all.

$\theta_{12}, \theta_{13}, \Delta m^2$ ✓

mass ordering (NO)

octant of θ_{23} ?

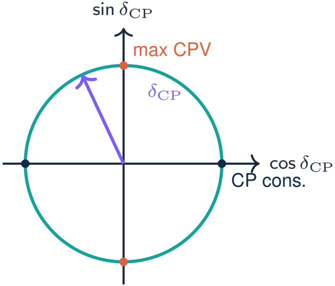
CP phase δ_{CP} ?

δ_{CP} is the gateway to leptonic CP violation

- $\delta_{\mathrm{CP}} \neq 0, \pi$ would be the **first CP violation in the lepton sector**.
- A necessary ingredient (Sakharov) for **leptogenesis** and the baryon asymmetry of the Universe (Sakharov, JETP Lett. 5 (1967); Davidson et al., arXiv:0802.2962).
- The size of CP violation is governed by the **Jarlskog invariant**:

$$J = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \, \sin\delta_{\mathrm{CP}}.$$

- All angles are non-zero ⇒ the whole question is: is $\sin\delta_{\mathrm{CP}} \neq 0$?



CP violation is maximal at $\delta_{\mathrm{CP}} = \pm 90^\circ$.

Two flagships, two baselines

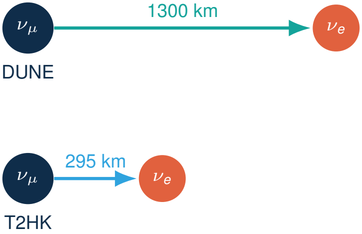
DUNE (Fermilab → SURF)

$L = 1300\,\text{km}$ • wide-band 0.5–8 GeV beam
LArTPC • large matter effects

T2HK (J-PARC → Kamioka)

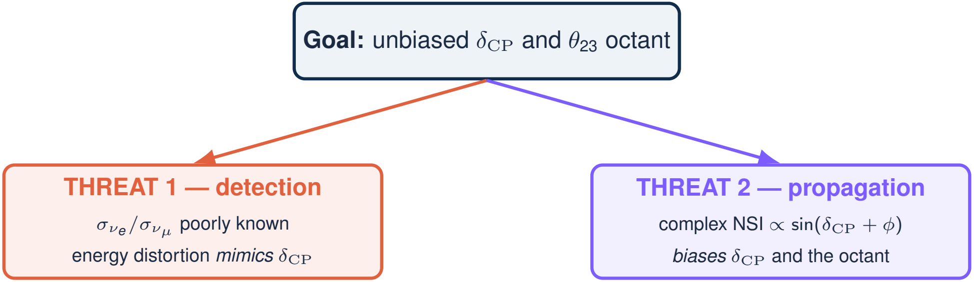
$L = 295\,\text{km}$ • narrow band peaked at 0.6 GeV
Water Cherenkov • small matter effects

Both read $\delta_{\rm CP}$ off the **appearance channel** $P(\nu_\mu \to \nu_e)$.



longer baseline ⇒ stronger matter effect
(this asymmetry is the whole story today)

The thesis: precision is not the same as robustness



Goal: unbiased δ_{CP} and θ_{23} octant

THREAT 1 — detection

$\sigma_{\nu_e}/\sigma_{\nu_\mu}$ poorly known

energy distortion *mimics* δ_{CP}

THREAT 2 — propagation

complex NSI $\propto \sin(\delta_{\mathrm{CP}} + \phi)$

biases δ_{CP} and the octant

cure: **external** σ (νSCOPE)

cure: **baseline** complementarity

Same victim — δ_{CP} — attacked from detection and from propagation.

δ_{CP} in oscillations

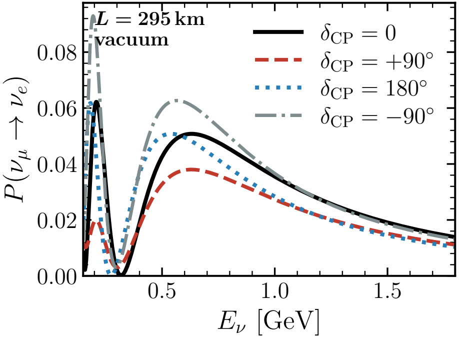
The signal is small and fragile

$\delta_{\rm CP}$ enters only through a sub-leading interference

$$P(\nu_\mu \to \nu_e) \approx \underbrace{4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta}_{\text{leading, CP-even}} + \underbrace{2\alpha\,\sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}\,\sin\Delta\,[\cos\Delta\cos\delta_{\rm CP} - \sin\Delta\sin\delta_{\rm CP}]}_{\text{interference} \propto \alpha} + \mathcal{O}(\alpha^2)$$

$$\Delta \equiv \Delta m_{31}^2 L/(4E), \quad \alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2 \approx 0.03$$

- The CP-odd term is $\sim$30× smaller than the leading one.
- Reading $\delta_{\rm CP}$ means resolving a **tiny energy-dependent modulation** on top of a large rate.
- ⇒ any other process that wiggles the spectrum the same way is dangerous.

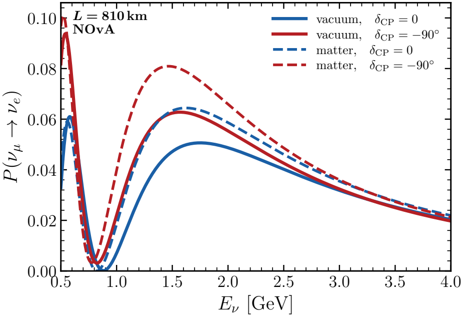


Matter adds a *fake* CP asymmetry — and a way to beat it

$$P \approx 4c_{13}^2 s_{13}^2 s_{23}^2 \frac{\sin^2[(1-A)\Delta]}{(1-A)^2} + 2\alpha\,(\cdots)\,\frac{\sin A\Delta}{A}\,\frac{\sin[(1-A)\Delta]}{1-A}[\cos\Delta\cos\delta_{\rm CP} - \sin\Delta\sin\delta_{\rm CP}], \quad A = \frac{2\sqrt{2}\,G_F N_e E}{\Delta m_{31}^2}$$

$$\Delta \equiv \Delta m_{31}^2 L/(4E), \quad \alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2 \approx 0.03$$

- $A \to -A$ for $\bar{\nu}$: the medium itself breaks $\nu/\bar{\nu}$ symmetry — a CP asymmetry even at $\delta_{\rm CP} = 0$.
- But $A \propto E$ while $\Delta \propto 1/E$: **fake** and **true** asymmetries have *different energy shapes*.
- DUNE's **wide band** separates them spectrally — *provided* the energy dependence of the rate is trustworthy.

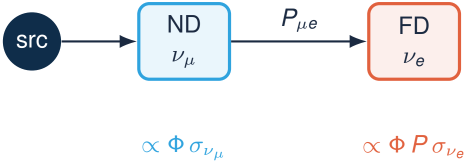


We never measure P — we measure event rates

$$\frac{N^{\mathrm{FD}}_{\nu_e}/dE}{N^{\mathrm{ND}}_{\nu_\mu}/dE} \sim \frac{\Phi^{\mathrm{FD}}_{\nu_\mu}\, P(\nu_\mu \to \nu_e)\, \sigma_{\nu_e}}{\Phi^{\mathrm{ND}}_{\nu_\mu}\, \sigma_{\nu_\mu}}$$

- Near detector sees ν_μ; far-detector signal is ν_e.
- The extrapolation cannot avoid the ratio $\sigma_{\nu_e}/\sigma_{\nu_\mu}$.
- In the SM it is taken known to ~3% — assuming **lepton universality** + accurate **nuclear modelling**.

Both threats live here: a wrong σ ratio *(Threat 1)*; a wrong P from new physics *(Threat 2)*.

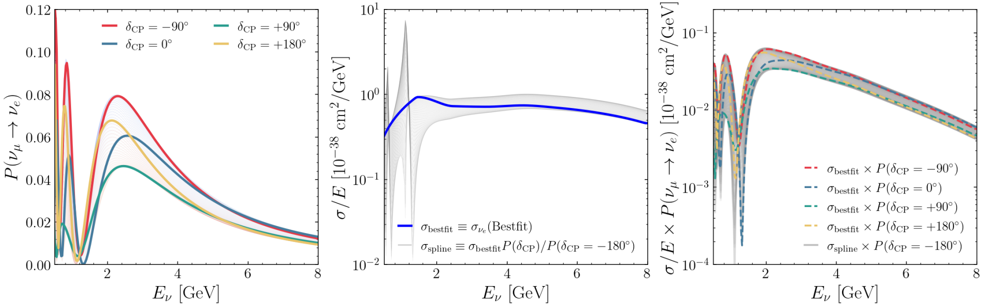


ratio fixes P **only if** $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ is known

Threat 1 — Detection

The $\sigma_{\nu_e}/\sigma_{\nu_\mu}$–$\delta_{\mathrm{CP}}$ degeneracy

The danger, stated precisely



- The CP signal is a **spectral modulation** of $P(\nu_\mu \to \nu_e)$.
- A smooth distortion of $\sigma_{\nu_e}(E)/E$ can imprint the **same modulation** on the measured rate.
- If it looks like the δ_{CP} shape for some phase $\Rightarrow$ degeneracy: the fit cannot tell them apart.
- These curves are smooth, not very wiggly — easy for a cross-section error to fake.

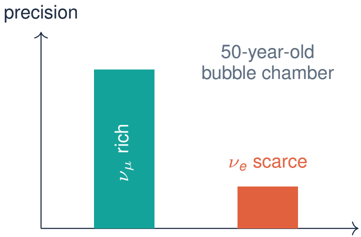
We are trusting 1970s data and an assumption

ν_μ sector — well measured

MINERvA, T2K, NOvA, MicroBooNE, . . .
5–10% per bin across the GeV range.

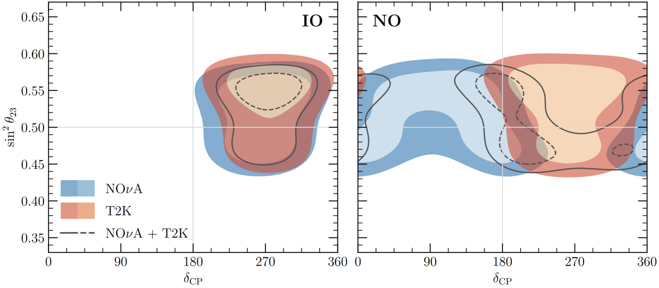
$\nu_e, \bar{\nu}_e$ sector — dramatically worse

World data dominated by Gargamelle (1970s); a few low-statistics modern points (T2K, MicroBooNE).
No percent-level σ_{ν_e}/E exists.



The ν_e flux is a $\sim$1% beam contaminant — hard to isolate from the cross section.

A warning already on the table: the T2K–NOνA tension



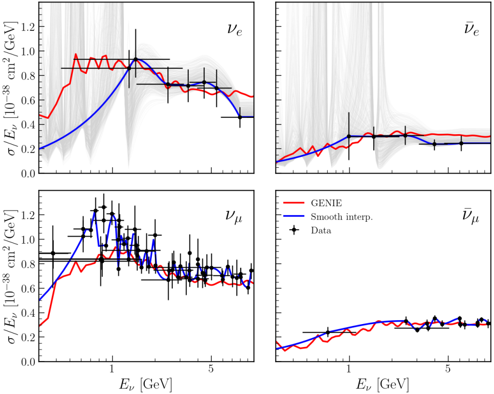
- T2K favours **maximal CPV** ($\delta_{\mathrm{CP}} \simeq -\pi/2$), NO; NO$\nu$A sits **closer to CP conservation**.
- A persistent $\sim 2\sigma$ tension in the δ_{CP}–θ_{23} plane (Abubakar et al., arXiv:2510.19888).
- They differ in generator, target, detector, energy reconstruction — i.e. in exactly the **cross-section / nuclear systematics** at issue here.
- Statistical fluctuation, *or* a preview of what unmodelled systematics can do.

Method: let the data say how bad it can be

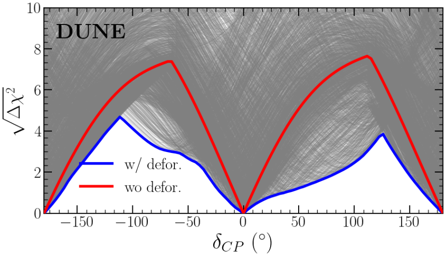
- Build a **data-driven** $\sigma_\alpha(E)$ and allow smooth deformations $\left(\frac{\sigma}{E}\right)^{\mathrm{def}} = [1+f_\alpha(E)]\left(\frac{\sigma}{E}\right)^{\mathrm{interp}}$.
- Keep every $f_e(E)$ **compatible with current data** (χ^2 penalty), agnostic about its origin.
- Propagate through `GLoBES`; marginalize:

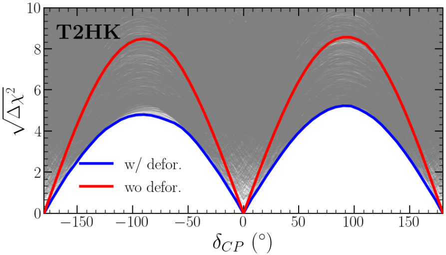
$$\Delta\chi^2 = \min_{f_e}\left[\chi^2_{\mathrm{GLoBES}}(f_e) + \chi^2_e(f_e)\right].$$

- Worst-case envelope = honest, model-independent reach (Pinheiro, Urrea, arXiv:2604.20956).



Result: the CP sensitivity partly evaporates





At maximal CPV

DUNE: $7\sigma \rightarrow 4\sigma$ **T2HK:** $8.6\sigma \rightarrow 4.7\sigma$

- 40–50% relative loss in *both* (Pinheiro, Urrea, arXiv:2604.20956).
- The $\sigma_{\nu_e}/\sigma_{\nu_\mu}$–$\delta_{\rm CP}$ degeneracy is a **leading** limitation.

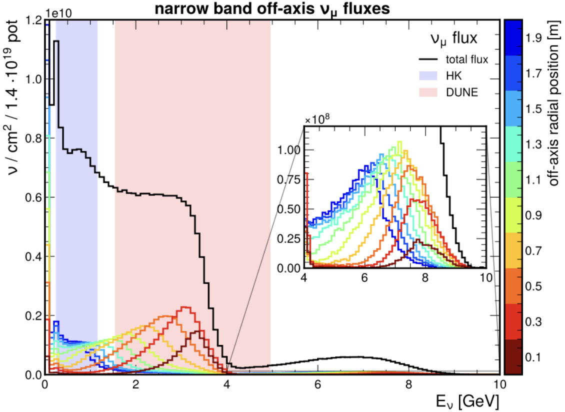
The cure: measure the cross section — νSCOPE @ CERN

- Proposed SPS short-baseline facility with two new handles (nuSCOPE Collab., arXiv:2503.21589):

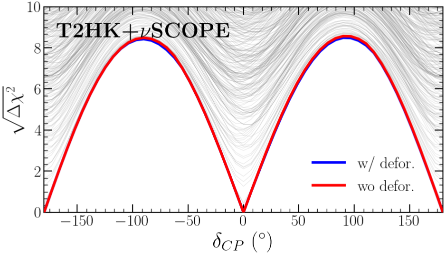
1. **Neutrino tagging:** tag the parent meson, reconstruct $E_\nu = E_{\pi,K} - E_\mu$ — $\sigma_{\nu_\mu}, \sigma_{\bar{\nu}_\mu}$ to $\sim$1%.
2. **Narrow-Band Off-Axis (NBOA):** build a virtual matched flux to measure the ratio directly:

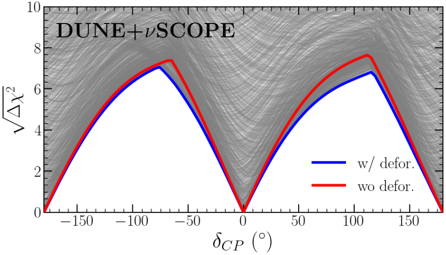
$$R_{\mathrm{NBOA}} \equiv \frac{N^{\nu_e}}{N^{\nu_\mu}_{\mathrm{virtual}}} \simeq \frac{\int \Phi^{\nu_e} \sigma_{\nu_e}}{\int \Phi^{\nu_e} \sigma_{\nu_\mu}}$$

$\Rightarrow$ direct constraint on $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ at $\sim$2%.



Result: νSCOPE restores the reach



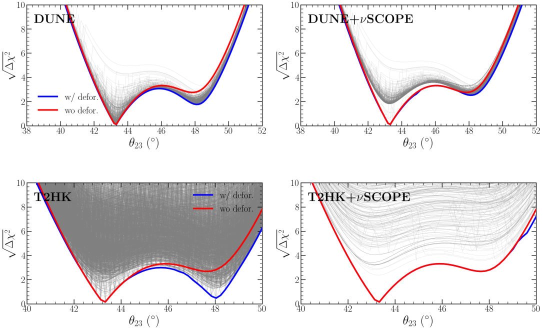


Recovered at maximal CPV

DUNE: $4\sigma \rightarrow 6.5\sigma$ **T2HK:** $4.7\sigma \rightarrow 8.6\sigma$

- A 2% external ratio kills the **most dangerous** distortions.
- External cross sections = insurance for δ_{CP} (Pinheiro, Urrea, arXiv:2604.20956).

The octant is hit too — but more gently



- Octant rests on an *overall* rate, not the fine modulation $\Rightarrow$ fewer distortions can spoil it.
- DUNE $2.6\sigma \to 1.7\sigma \to 2.4\sigma$; T2HK $3\sigma \to 0.3\sigma \to 3\sigma$.
- Milder than the $\sim$ 3–4σ CP loss — and again **recovered** by νSCOPE.

Threat 1 — bottom line

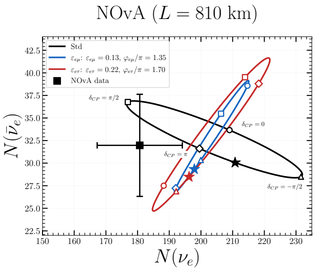
A *model-agnostic* look at how poorly σ_{ν_e} is known shows that 40–50% of the CP-violation sensitivity of DUNE and T2HK rests on **lepton universality** and **nuclear modelling**.

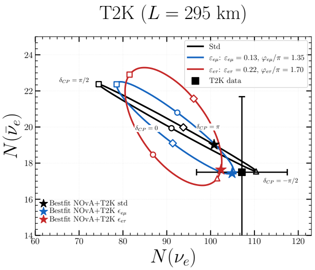
- The $\sigma_{\nu_e}/\sigma_{\nu_\mu}$–$\delta_{\mathrm{CP}}$ degeneracy is a leading systematic in the precision era.
- A percent-level external measurement — ν**SCOPE**'s tagging + NBOA — restores the nominal reach.
- Detection physics must be nailed down *outside* the oscillation fit.

Threat 2 — Propagation

New physics hiding as a degeneracy

Same tension, read as new physics





- The observable is the **matter–antimatter asymmetry** $A_{CP} = P_{\mu e} - \bar{P}_{\mu e}$.
- Under NO, matter *enhances* it more at the longer baseline (NOνA) than at T2K.
- The standard ellipses cannot hit both data points at once $\Rightarrow$ the $\sim 2\sigma$ tension (Pinheiro, Rahaman, arXiv:2603.14215).

Complex NSI: a phase in the matter potential

$$H = H_{\rm vac} + V_{\rm CC} \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

- Dim-6 NC operators ⇒ extra matter couplings, generally **complex**: $\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| e^{i\phi_{\alpha\beta}}$.
- Off-diagonal $\varepsilon_{e\mu}, \varepsilon_{e\tau}$ add a **new interference term** to $P_{\mu e}$.
- It grows with baseline & energy ⇒ NOνA $>$ T2K — and reconciles the data under NO.

$$P_{\mu e} = P_0 + P_1 + P_2$$

$$P_2 \simeq 8 s_{13} s_{23} \hat{A} |\varepsilon| \left[a f^2 \cos(\delta_{\rm CP} + \phi) + b f g \cos(\hat{\Delta} + \delta_{\rm CP} + \phi) \right]$$

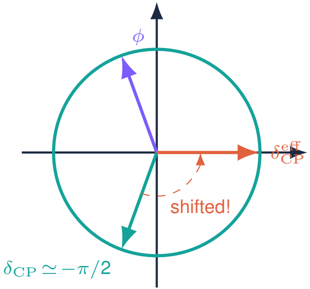
The key object

$$\Delta A_{CP}^{\rm NSI} \propto \hat{A}\, a |\varepsilon| \sin(\delta_{\rm CP} + \phi)$$

⇒ an effective phase $\delta_{\rm CP}^{\rm eff} = \delta_{\rm CP} + \phi$.

Intuition: the fit reads $\delta_{\mathrm{CP}} + \phi$, not δ_{CP}

- A standard 3-ν fit cannot see ϕ — it absorbs it into the inferred phase.
- The NSI term suppresses $\nu_e, \bar{\nu}_e$ appearance for the favoured $\pi < \phi < 2\pi$.
- The fit compensates by shifting δ_{CP} and flipping the octant (HO→LO).
- Both biases come from the *same* P_2 — they are **correlated**.



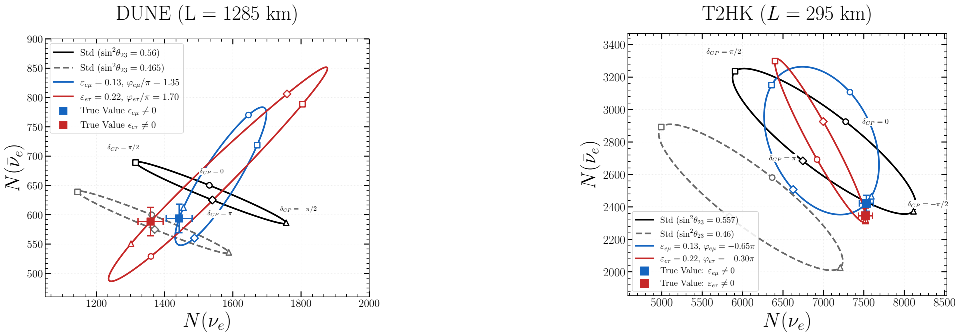
True maximal CPV can be read as nearly CP-conserving.

Benchmarks that fix today's tension

	Benchmark 1	**Benchmark 2**
NSI coupling	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$
$\lvert\varepsilon\rvert$	0.13	0.22
$\phi\,[\pi]$	1.35	1.70
$\sin^2\theta_{23}^{\mathrm{true}}$	0.56 (HO)	0.56 (HO)
$\delta_{\mathrm{CP}}^{\mathrm{true}}\,[\pi]$	-0.56	-0.58

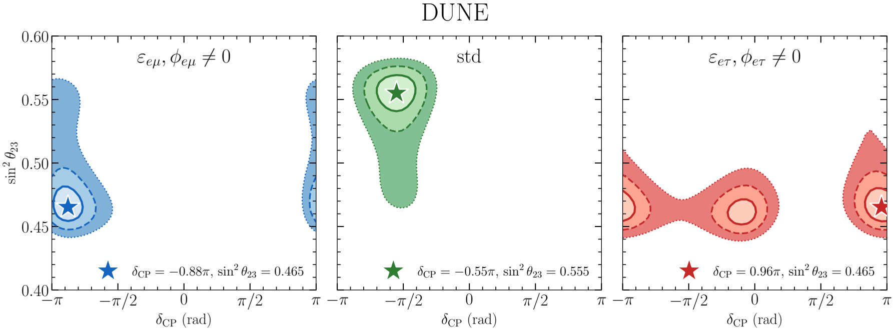
Best fits of a combined NOνA+T2K analysis under NO; both within global NSI bounds. We inject these as truth and fit with standard oscillations (Chatterjee & Palazzo, arXiv:2409.10599).

At DUNE the effect is amplified into a degeneracy



- $P_2 \propto \hat{A}$, and $\hat{A}_{\mathrm{DUNE}} \simeq 0.22 \gg \hat{A}_{\mathrm{T2HK}}$.
- The **HO+NSI** ellipse overlaps the **LO standard** ellipse: event rates are degenerate (Pinheiro, Rahaman, arXiv:2603.14215).
- Persists from bi-probability to integrated bi-events ⇒ survives the full spectrum.

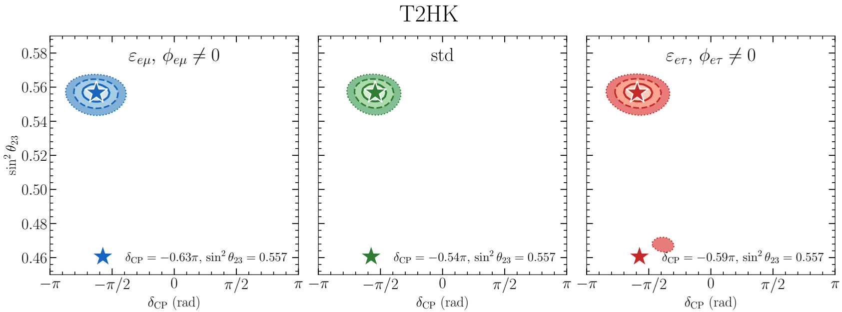
Result: a standard DUNE fit misidentifies $\delta_{\rm CP}$ *and* the octant



$\varepsilon_{e\mu}$**:** $\delta_{\rm CP}$ shifts toward CP conservation; HO disfavoured at $> 2\sigma$ ($a = \sin^2\theta_{23}$ breaks octant symmetry) (Pinheiro, Rahaman, arXiv:2603.14215).

$\varepsilon_{e\tau}$**:** $\delta_{\rm CP}$ flips to the *opposite* half-plane; LO preferred at $> 3\sigma$ ($a = s_{23}c_{23}$ is octant-symmetric).

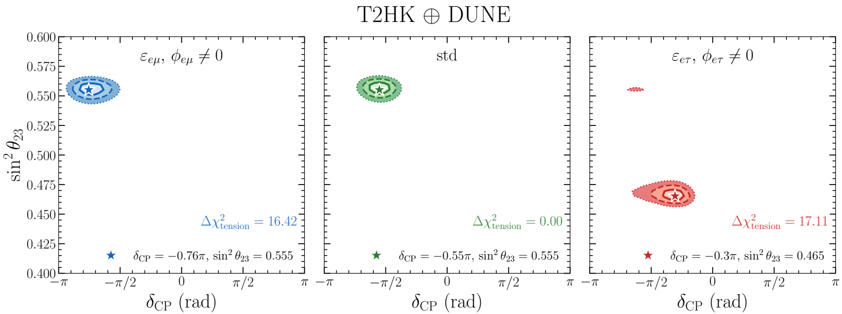
T2HK is the control — short baseline, no bias



- $\hat{A}_{\mathrm{T2HK}} \simeq 0.05$ — about 4× smaller than DUNE.
- $P_2 \propto \hat{A} \Rightarrow$ NSI shift suppressed; ellipses nearly coincide.

- T2HK **recovers** the true octant ($> 2\sigma$) and $\delta_{\mathrm{CP}} \simeq -0.55\pi$ within 1–2σ.
- It sees *essentially the true physics*.

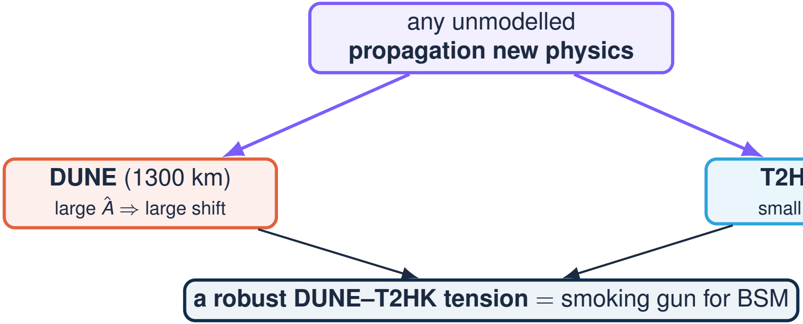
The diagnostic: DUNE and T2HK must then *disagree*



χ^2_{PG} measures how incompatible the two experiments are: penalty for forcing a common fit on top of the individual best fits (Maltoni & Schwetz, arXiv:hep-ph/0304176).

Tension reaches 3.3–3.4 σ ($\varepsilon_{e\mu}$ or $\varepsilon_{e\tau}$) after $6+6$ yr — **grows with statistics**. *The disagreement itself is the smoking gun.*

Why this is general: baseline complementarity



any unmodelled **propagation new physics**

DUNE (1300 km)
large $\hat{A} \Rightarrow$ large shift

T2HK (295 km)
small $\hat{A} \Rightarrow$ unbiased

a robust DUNE–T2HK tension $=$ smoking gun for BSM

Different matter effects force different inferred parameters — **the disagreement itself is the signal**.

Synthesis

What robustness actually requires

Two threats, one victim

	Threat 1 — detection	**Threat 2 — propagation**
Origin	$\sigma_{\nu_e}/\sigma_{\nu_\mu}$ poorly known	complex NSI $\propto \sin(\delta_{\rm CP}+\phi)$
Acts on	the *rate* (spectral shape)	the *probability* (matter)
Effect	fakes/degrades $\delta_{\rm CP}$ ($-$40–50%)	biases $\delta_{\rm CP}$ & octant (3.3σ)
Worse at	both (shape degeneracy)	**DUNE** (large $\hat{A}$)
Cure	external σ: ν**SCOPE**	**baseline complementarity**

One is a *systematic* to be measured away; the other is *new physics* to be diagnosed. Both masquerade as $\delta_{\rm CP}$.

The robustness checklist for the precision era

Control detection

Don't *assume* $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ — measure it.

νSCOPE-class tagging + NBOA at the **percent level** recovers the full δ_{CP} reach.

Exploit propagation

Don't read one baseline in isolation — compare them.

A DUNE–T2HK mismatch is a built-in **BSM diagnostic**, not noise to be averaged away.

- Statistics alone will *not* make δ_{CP} robust.
- External cross sections + baseline complementarity are both essential.

Outlook

- **Short & medium baseline precision already here:** JUNO and TAO are collecting data — reactor oscillation parameters entering the precision era.
- **Long-baseline precision still missing:** DUNE and Hyper-K must start taking data for the *first full precision era* to materialise — δ_{CP} and the octant remain unmeasured at the required level.
- ν**SCOPE** **(arXiv:2503.21589)**: a percent-level $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ programme would de-risk every long-baseline CP measurement.
- The two analyses are **complementary safeguards**: one removes a systematic, the other turns a potential confusion into a discovery channel.
- Next: extend the NSI diagnostic beyond NSI (generic propagation operators), and fold νSCOPE priors into the global fit.

Conclusions

- $\delta_{\rm CP}$ is a *small* signal — easy to fake, easy to bias.
- Detection: 40–50% of the reach rests on σ_{ν_e} assumptions; νSCOPE restores it.
- Propagation: NSI bias DUNE, not T2HK — their 3.3σ tension is a BSM diagnostic.
- Robust $\delta_{\rm CP}$ = external σ + baseline complementarity.

Thank you!

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Backup

Supplementary material

Backup — data-driven systematics in `GLoBES`

- Deformations enter at the probability level, channel by channel: $P_{\mu e}(E) \to P_{\mu e}(E)[1 + f_e(E)]$, applied only to ν_e CC.
- Implemented with the extended `GLoBES` of Kopp et al.; the f_e marginalization is external.
- $f_e(E)$ are smooth cubic splines with $f_e \to 0$ at threshold and at high E (DIS scaling).
- Priors: $\chi^2_{e,1}(f_e) \approx \frac{1}{N}\chi^2_e(f_e)$; νSCOPE adds a 2% Gaussian on R_{NBOA}.

Backup — nominal configurations

	DUNE	**T2HK**
Baseline	1300 km	295 km
Exposure	$6.5\nu + 6.5\bar{\nu}$ yr	$2.5\nu + 7.5\bar{\nu}$ yr
Beam peak	0.5–8 GeV (wide)	0.6 GeV (narrow)
Detector	40 kt LArTPC	187 kt Water Cherenkov
$\hat{A}$ at peak	$\simeq 0.22$	$\simeq 0.05$
Nominal CPV ($\pm 90^\circ$)	$\sqrt{\Delta\chi^2} \sim 7$	$\sqrt{\Delta\chi^2} \sim 8.6$