



ESSnuSB COLLABORATION

Atmospheric neutrinos at ESSnuSB

Mass ordering, non-standard interactions and synergy with the super-beam

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INTRODUCTION

Three-flavour oscillations: what is still open

MASS ORDERING

$$\Delta m_{31}^2 > 0 \text{ or } < 0?$$

Normal ordering (NO) or inverted ordering (IO) of m_1, m_2, m_3 .

θ_{23} OCTANT

$$\theta_{23} < 45^\circ \text{ or } > 45^\circ ?$$

Low or high octant, i.e. is ν_3 more muon-like or tau-like.

CP PHASE

$$\sin \delta_{\text{CP}} \neq 0?$$

Is CP violated in the lepton sector, and by how much?

Everything else is known at the 1–5% level (1σ)

$\theta_{12}, \theta_{13}, \theta_{23}, \Delta m_{21}^2$ and $|\Delta m_{31}^2|$ are measured by accelerator, reactor, solar and atmospheric experiments. Precision data also allow tests of new physics such as non-standard interactions.

INTRODUCTION

ESSnuSB: a super-beam and a megaton-class detector

540 kt

fiducial mass in two water-Cherenkov cylinders,
about $2.9 \times$ Hyper-Kamiokande

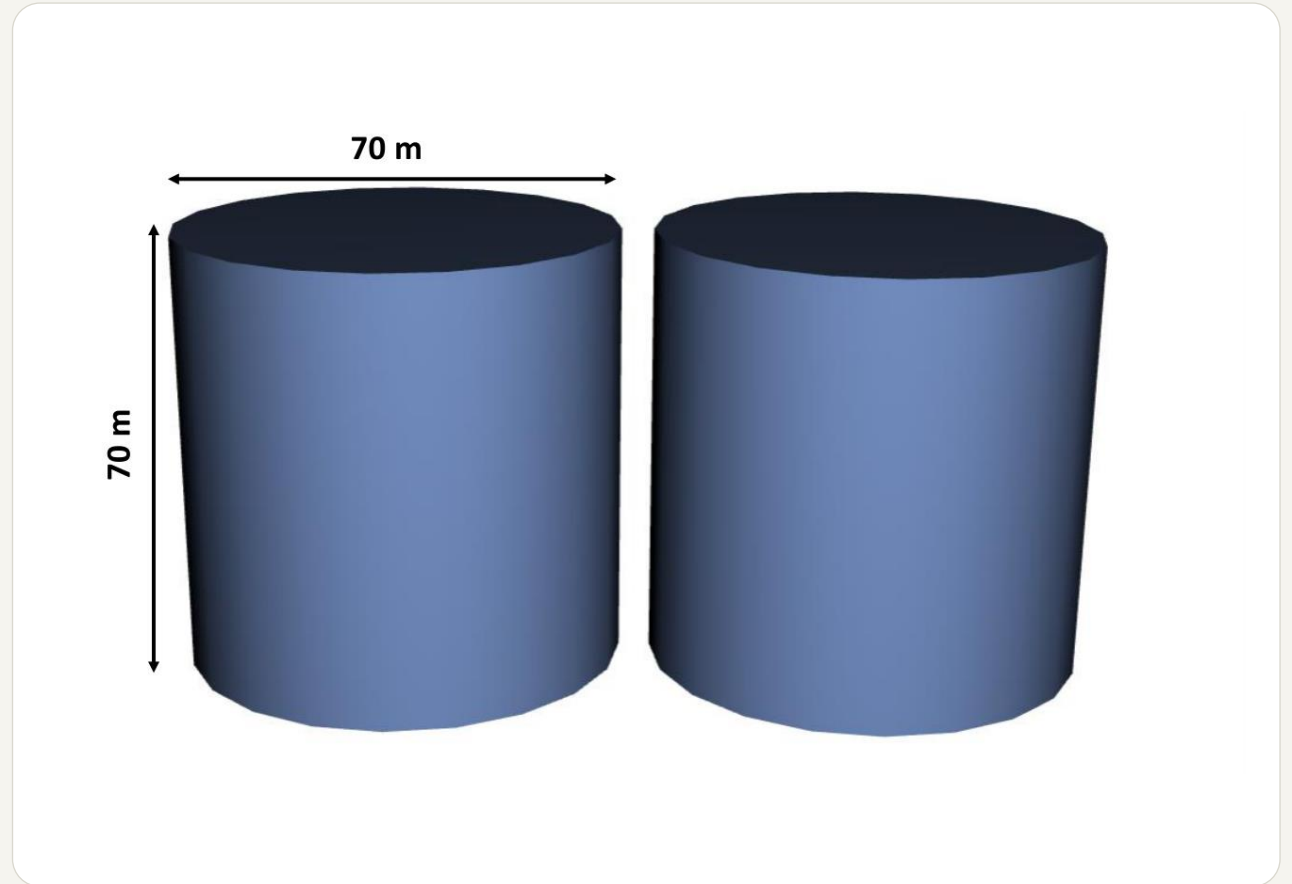
360 km

from the 5 MW ESS linac in Lund to Zinkgruvan,
targeting the second oscillation maximum

~1 km

rock overburden: shields from cosmic muons,
enables non-beam physics such as atmospheric
neutrinos

Far-detector geometry



Atmospheric neutrinos probe Earth matter effects

Wide range: 0.1 MeV to PeV energies, baselines from 15 km to 12,742 km through the Earth (PREM, 81 layers)

Resonance when $\Gamma = \cos 2\theta_{13}$: enhanced ν -osc for NO, enhanced $\bar{\nu}$ -osc for IO

Zinkgruvan flux is high thanks to its proximity to the North Pole; μ/e flavour ratio is about 2:1

EFFECTIVE PARAMETERS IN CONSTANT MATTER

$$\Delta m_{31}^2 \rightarrow \Delta m_{31}^2 \sqrt{(\sin^2 2\theta_{13} + (\Gamma - \cos 2\theta_{13})^2)}$$

$$\sin^2 2\theta_{13} \rightarrow \sin^2 2\theta_{13} / (\sin^2 2\theta_{13} + (\Gamma - \cos 2\theta_{13})^2)$$

$\Gamma = aE/\Delta m_{31}^2$, with $a = \pm \sqrt{2} G_F N_e$ (+ for neutrinos, – for antineutrinos)

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2(L\Delta m_{31}^2/4E)$$

Simulation and analysis chain

1

Events

GENIE on a ROOT geometry of ultra-pure water. Honda fluxes for Pyhäsalmi, 100 years of MC, rescaled to 5.4 Mt·yr (10 years).

2

Oscillation

GLOBES probabilities with the PREM profile. Each MC event is reweighted according to the oscillation probabilities.

3

Detector

e-like and μ -like samples, no charge tag. Energy resolution 30% (sub-GeV) and 10% (multi-GeV), 10° zenith resolution. Efficiencies 62% (ν_μ), 54% (ν_e).

4

Statistics

Poisson χ^2 over 100 energy $\times$ $20 \cos \theta_z$ bins (E from 0 to 100 GeV) for each sample, with five pull-parameter systematics.

Systematic uncertainties and talk roadmap

Systematic error	Uncertainty
Flux normalisation	20%
Cross-section normalisation	10%
Zenith-angle dependence	5% of $\langle \cos \theta_z \rangle$
Energy tilt (δ , $E_0 = 2$ GeV)	5%
Detector efficiency	5%

Each treated with its own pull parameter, separately for e-like and μ -like samples. θ_{23} , Δm^2_{31} and δ_{CP} are free; no priors.

ROADMAP

1. Mass ordering

and θ_{23} octant, precision on θ_{23} and Δm^2_{31}

2. Non-standard interactions

bounds and impact on ordering and octant

3. Synergy with the super-beam

δ_{CP} resolution and CP-violation discovery

MASS ORDERING

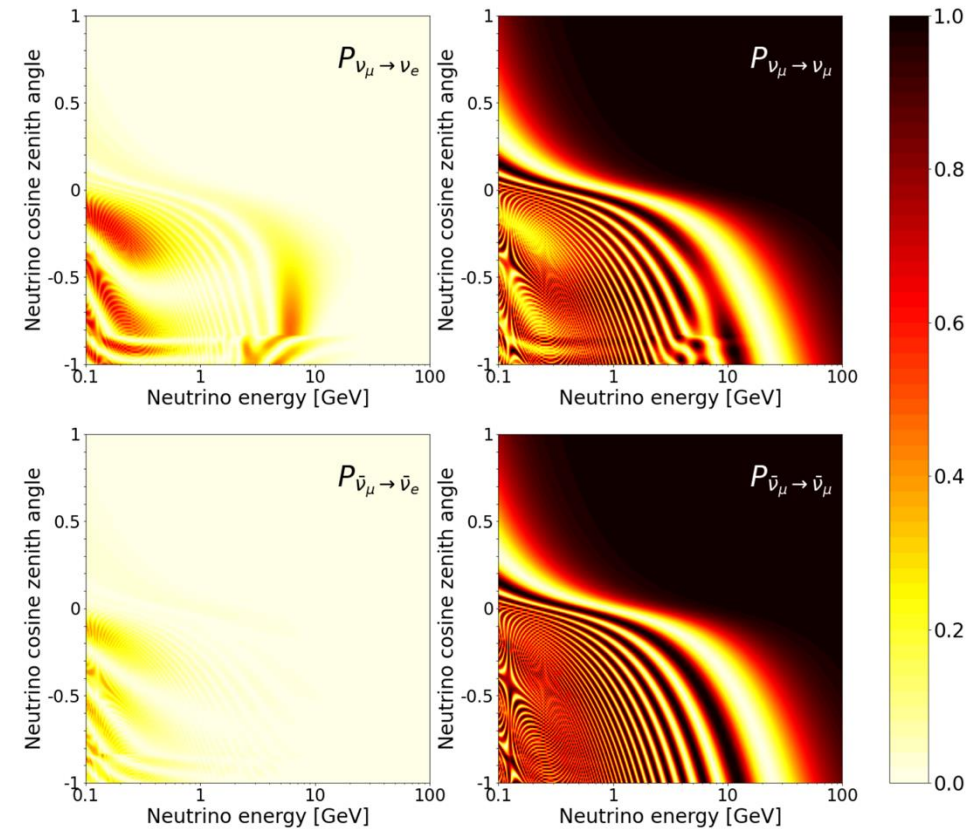
Matter effects separate ν from $\bar{\nu}$

Core-crossing neutrinos ($\cos \theta_z$ from -1 to -0.8): $\nu_\mu \rightarrow \nu_e$ peaks at $E \approx 2$ GeV, but the antineutrino channel shows nothing there (NO). Very strong matter effects at 6-8 GeV for mantle-crossing nu

Disappearance $\nu_\mu \rightarrow \nu_\mu$ is distorted near $E \approx 6$ GeV for neutrinos only (NO).

Flipping the sign of Δm^2_{31} swaps the roles of neutrinos and antineutrinos.

Water Cherenkov cannot tell ν from $\bar{\nu}$, so the signal is the difference in total event rates.



MASS ORDERING

Where the event spectra differ between NO and IO

$\approx 75\%$

NO–IO difference in μ -like events, E in $[1, 2]$ GeV, $\cos \theta_z$ in $[-1, -0.9]$

$\approx 20\%$

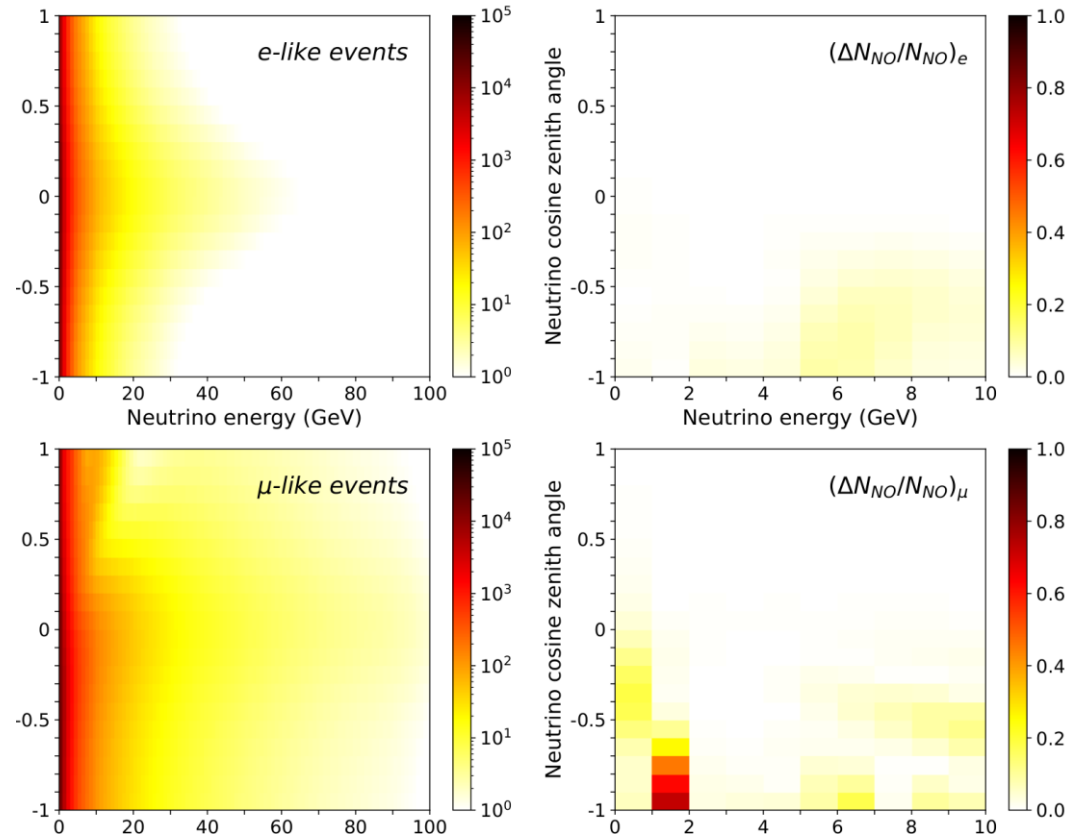
μ -like, E in $[< 1]$ GeV, $\cos \theta_z$ in $[-0.4, -0.3]$

$\approx 10\%$

e-like, E in $[5, 7]$ GeV, $\cos \theta_z$ in $[-1, -0.8]$

The sensitivity is driven mainly by E in $[5, 6]$ GeV; lower energies are limited by systematics.

arXiv:2407.21663, Fig. 3 · 5.4 Mt·yr, true NO



MASS ORDERING

Mass-ordering sensitivity versus true θ_{23}

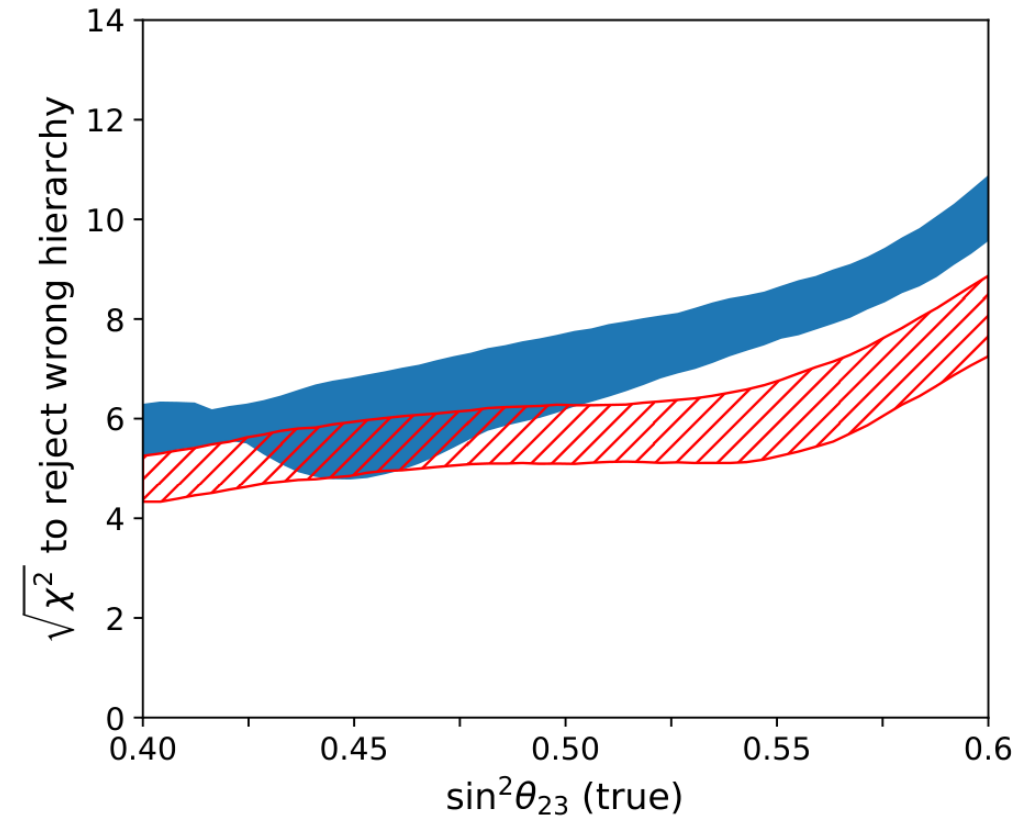
4.8–10.9 σ

to reject IO if NO is true, for $\sin^2\theta_{23}$ in $[0.4, 0.6]$

4.3–8.9 σ

to reject NO if IO is true

Sensitivity rises with $\sin^2\theta_{23}$. Band width shows the δ_{CP} dependence: up to 2.0 σ for NO, about 1 σ for IO.



MASS ORDERING

3σ after 4 years, 5σ after 10 years

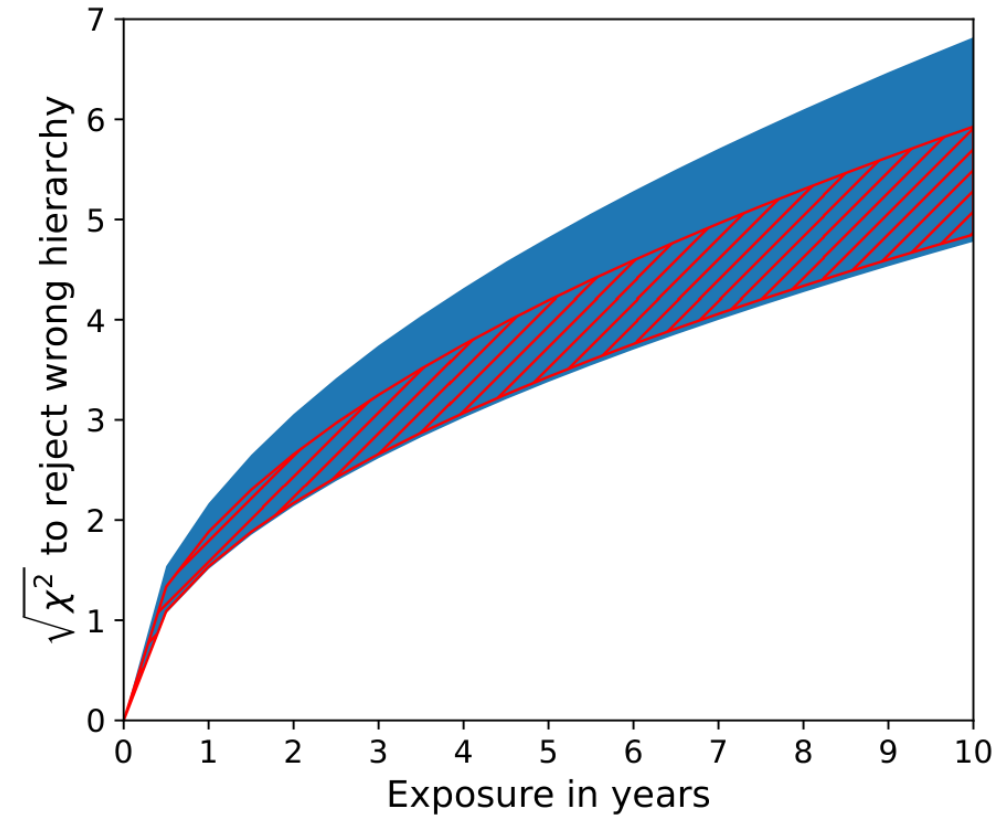
3σ

after about 4 years, whatever the true ordering and δ_{CP}

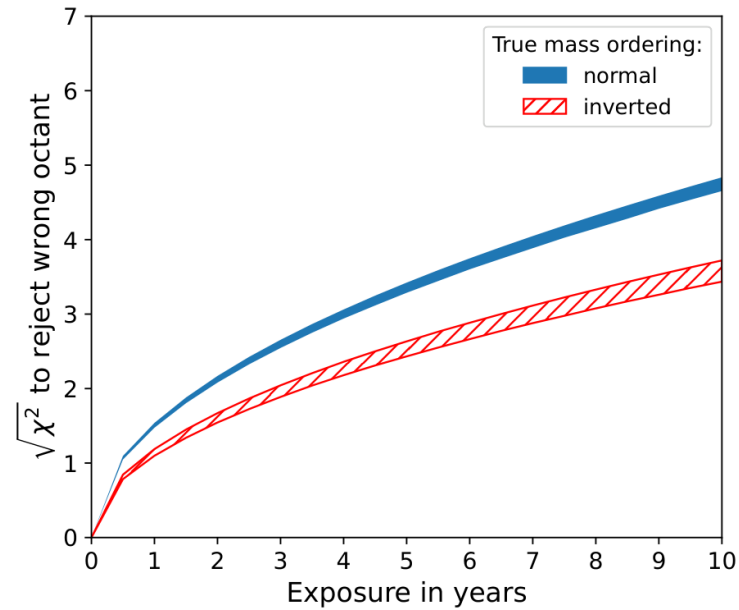
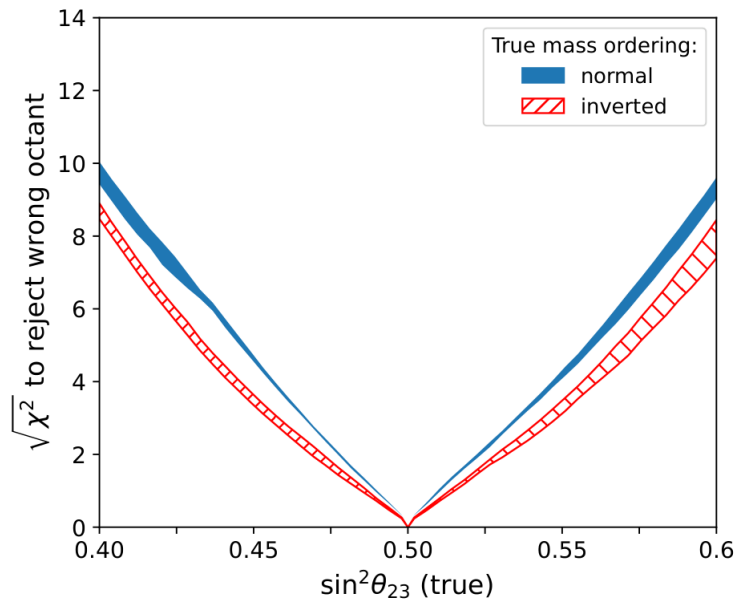
5σ

after 10 years (5.4 Mt·yr), independent of the true ordering

This result is independent of the beam programme and complements it.



Excluding the wrong θ_{23} octant



4.4–4.5 σ

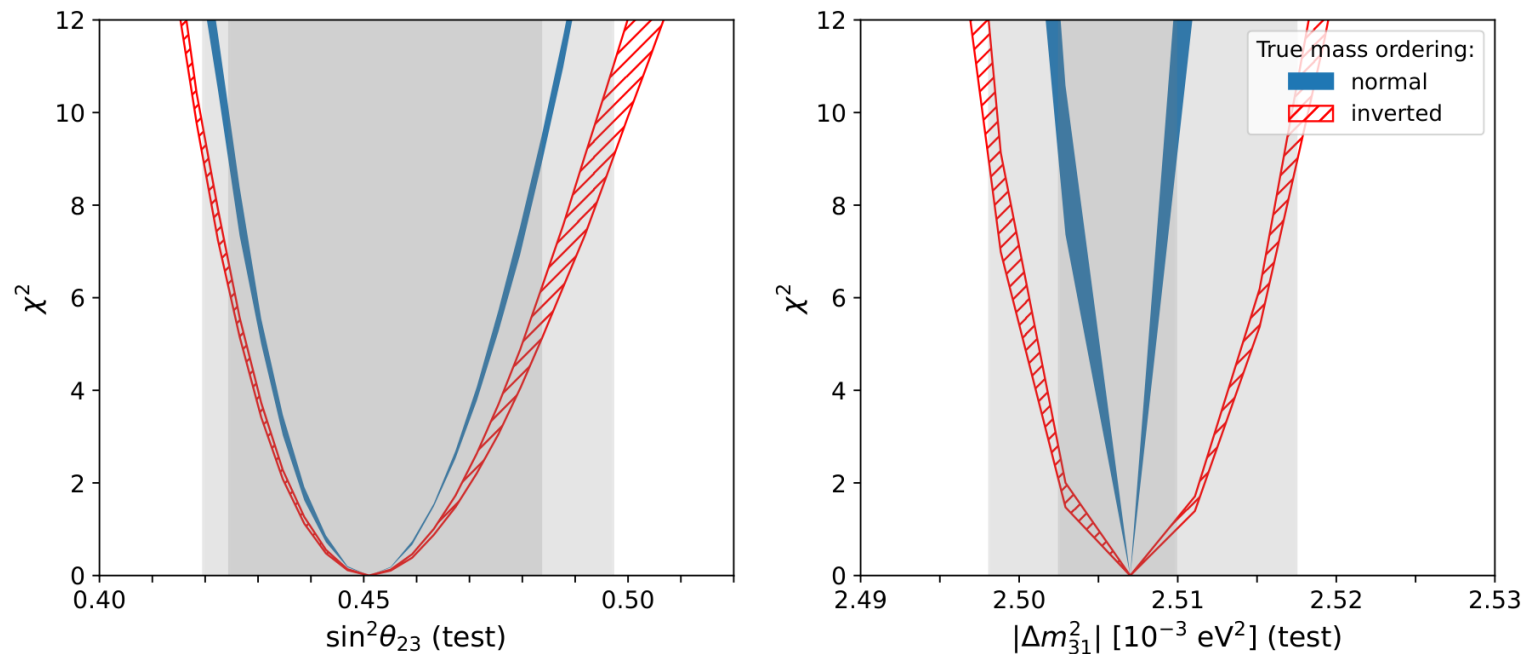
NO true, $\sin^2\theta_{23} = 0.451$, 10 years

3.3–3.5 σ

IO true, same exposure

3 σ after 4 years (NO) or 8 years (IO).
 δ_{CP} matters little: under 0.5 σ (NO),
under 1.1 σ (IO).

Constraining θ_{23} and Δm^2_{31}



$$0.424 < \sin^2 \theta_{23} < 0.484$$

3σ range, true NO (IO: 0.419–0.498)

$$2.502\text{--}2.510$$

$|\Delta m^2_{31}|$ in 10^{-3} eV^2 , 3σ , true NO (IO: 2.498–2.518)

The effect of the unknown δ_{CP} is small on both parameters.

MASS ORDERING

What limits the mass-ordering reach

Loss in sensitivity from each systematic (NO, $\sin^2\theta_{23} = 0.451$, $\delta_{CP} = 1.29\pi$)

0.4 σ

zenith-angle
dependence, the
dominant one

0.2 σ

flux, cross-section and
detector normalisations
together

0.1 σ

energy tilt

0.7 σ

total reduction from all
systematics

Atmospheric neutrinos at ESSnuSB: 3 σ ordering in 4 years, 5 σ in 10 years, octant at 3 σ in 4–8 years.

NON-STANDARD INTERACTIONS

Matter NSI in neutrino propagation

NC-NSI LAGRANGIAN

$$\mathcal{L}_{\text{NC}} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{f,C} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P_C f)$$

Neutral-current interaction of neutrinos with matter fermions f , chirality C

EARTH MATTER

$$\varepsilon_{\alpha\beta}^m \simeq 3\varepsilon_{\alpha\beta}^u + 3\varepsilon_{\alpha\beta}^d + \varepsilon_{\alpha\beta}^e$$

About two nucleons per electron in the Earth

OBSERVABLE IN OSCILLATIONS

$\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$, $\varepsilon_{\mu\tau}$ (complex), and the differences $\varepsilon_{ee} - \varepsilon_{\mu\mu}$ and $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$

MATTER POTENTIAL IN THE HAMILTONIAN

$$H = \frac{1}{2E_\nu} [U \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U^\dagger + A M]$$

$$M = \begin{bmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{bmatrix}$$

$A = 2\sqrt{2} G_F N_e E_\nu$ is the standard matter potential. For antineutrinos, $\delta_{\text{CP}} \rightarrow -\delta_{\text{CP}}$ and $A \rightarrow -A$.

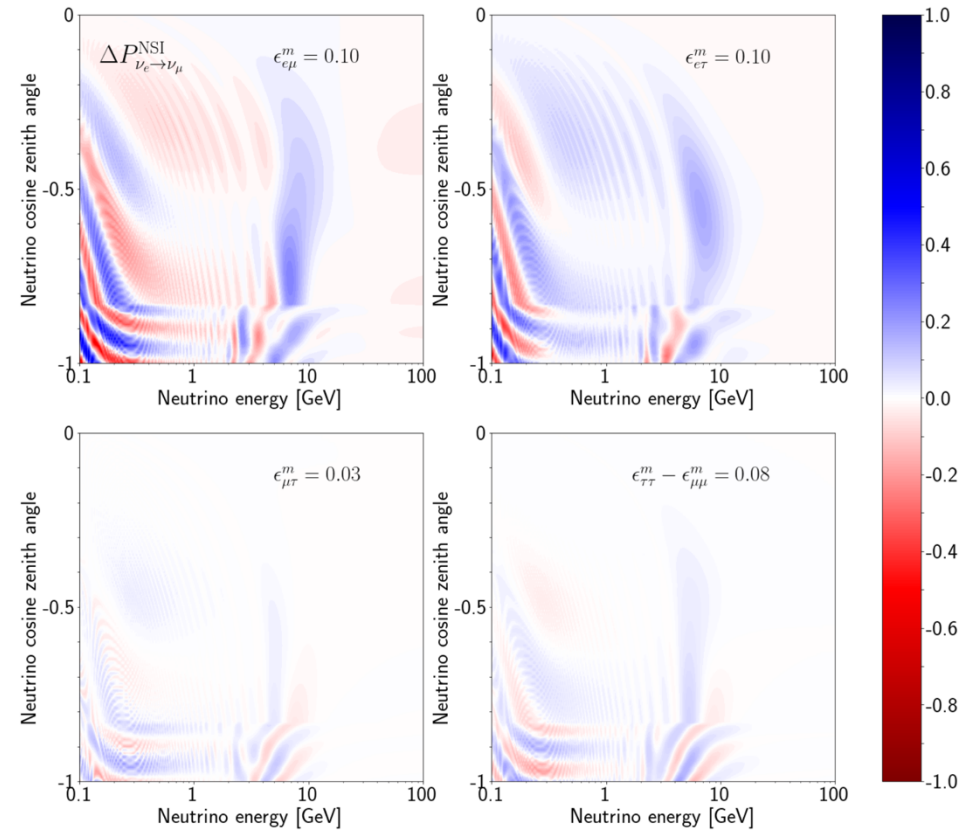
NON-STANDARD INTERACTIONS

Effect on $\nu_e \rightarrow \nu_\mu$ oscillograms

$\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ (0.10) change the probability across the spectrum, most strongly below 1 GeV.

$\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$ have a smaller effect here, at the percent level for E below 10 GeV.

Sub-GeV energy and angle are hard to reconstruct, so multi-GeV sensitivity matters more.



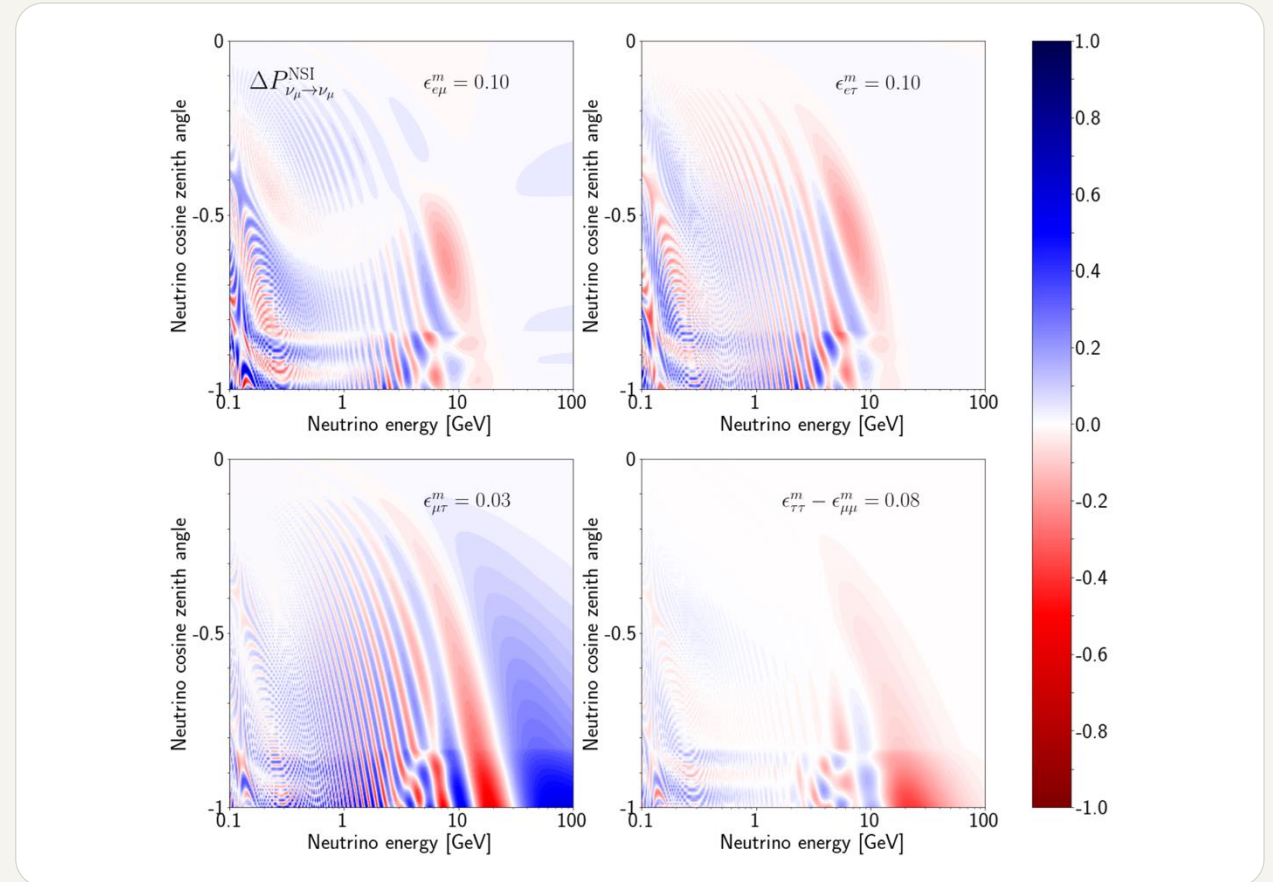
NON-STANDARD INTERACTIONS

Effect on $\nu_\mu \rightarrow \nu_\mu$: the μ - τ sector dominates

$\epsilon_{\mu\tau}$ (0.03) matters most near 100 GeV; $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$ (0.08) peaks around 25 GeV.

Origin: $\nu_\mu \rightarrow \nu_\tau$ conversion enhanced by strong matter effects in the Earth's core.

$\epsilon_{e\mu}$ alters the survival probability at all energies;
 $\epsilon_{e\tau}$ matters below about 10 GeV.



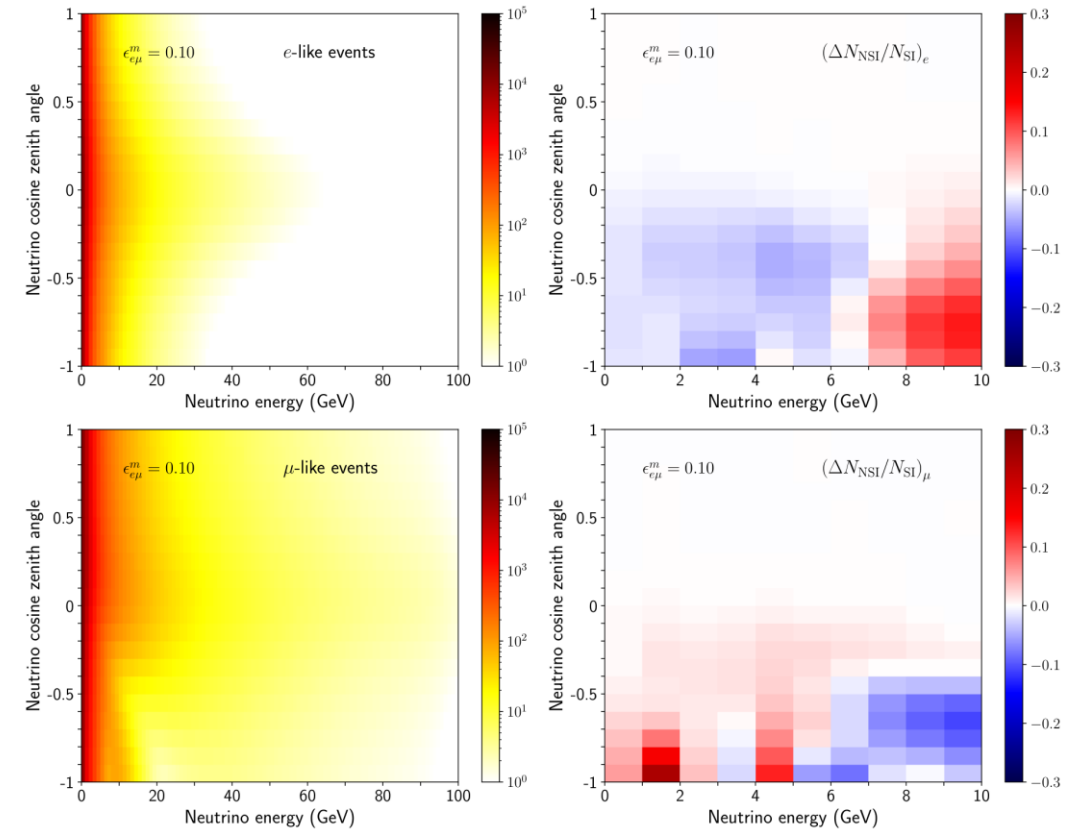
NON-STANDARD INTERACTIONS

What NSI does to the event spectra

Example: $\epsilon_{e\mu}^m = 0.10$ changes e-like and μ -like event numbers by up to tens of per cent in up-going, multi-GeV bins (colour scale $\sim 30\%$).

The effect is largest where the first oscillation maximum for atmospheric neutrinos lies.

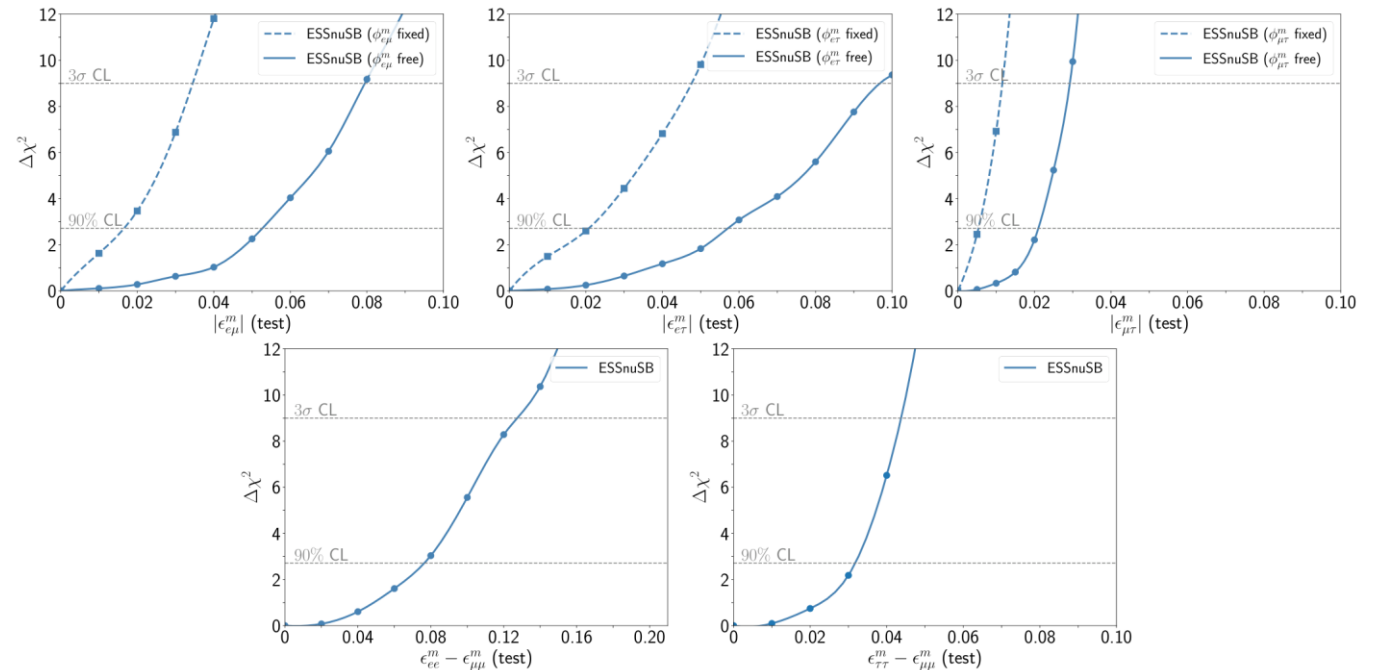
Detector effects included. Other parameters are shown in the appendix of the paper.



Expected sensitivity to matter NSI

$\Delta\chi^2 = \chi^2(\text{NSI}) - \chi^2(\text{SI})$, true NO, 5.4 Mt·yr.
90% and 3σ limits at $\Delta\chi^2 = 2.71$ and 9.

Complex phases matter: letting them float (solid) relaxes the 90% CL bounds by 3.3 ($\epsilon_{e\mu}$), 2.7 ($\epsilon_{e\tau}$) and 4.0 ($\epsilon_{\mu\tau}$).



Projected upper bounds on matter NSI

ESSnuSB bound	$ \epsilon_{e\mu} $	$ \epsilon_{e\tau} $	$ \epsilon_{\mu\tau} $	$\epsilon_{ee}-\epsilon_{\mu\mu}$	$\epsilon_{\tau\tau}-\epsilon_{\mu\mu}$
90% CL, phases free	0.053	0.057	0.021	0.075	0.031
90% CL, phases fixed	0.016	0.021	0.0053	0.075	0.031
3σ , phases free	0.079	0.098	0.029	0.13	0.043
3σ , phases fixed	0.034	0.047	0.011	0.13	0.043

CURRENT LIMITS (90% CL)

$|\epsilon_{e\mu}| < 0.056$, $|\epsilon_{e\tau}| < 0.074$ (ORCA6)

$|\epsilon_{\mu\tau}| < 0.0041$ (IceCube)

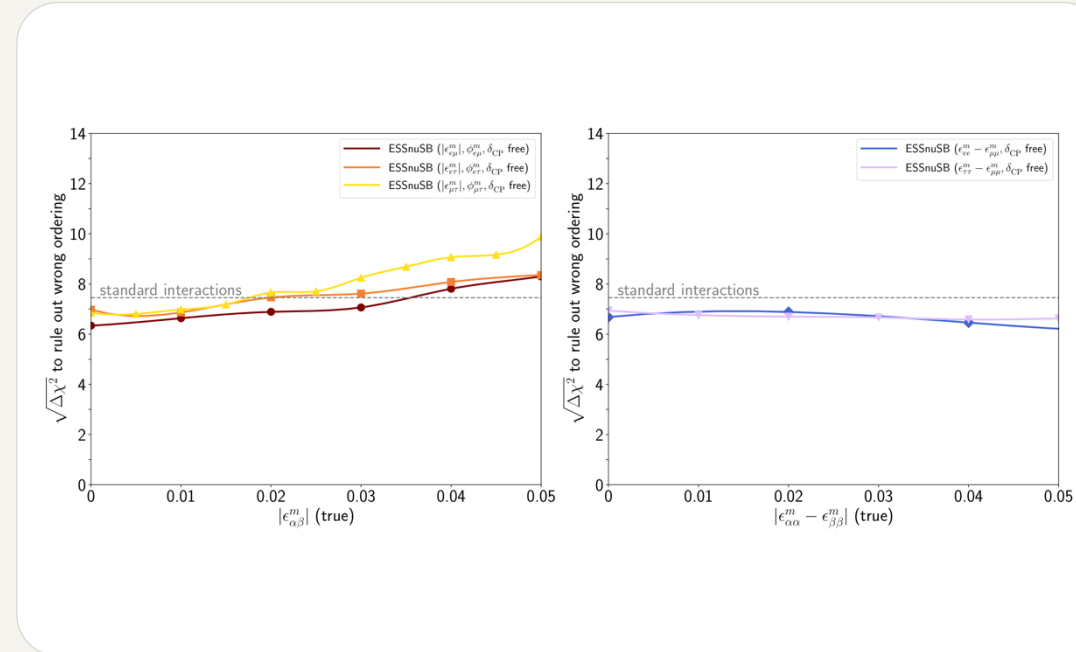
$\epsilon_{\tau\tau}-\epsilon_{\mu\mu} < 0.014$ (DeepCore)

Existing limits assume couplings to down quarks only.

After rescaling to common couplings, ESSnuSB improves $\epsilon_{e\mu}$, $\epsilon_{e\tau}$ and $\epsilon_{\tau\tau}-\epsilon_{\mu\mu}$ by about 3.2, 3.9 and 1.3, and gives the first atmospheric bound on $\epsilon_{ee}-\epsilon_{\mu\mu}$.

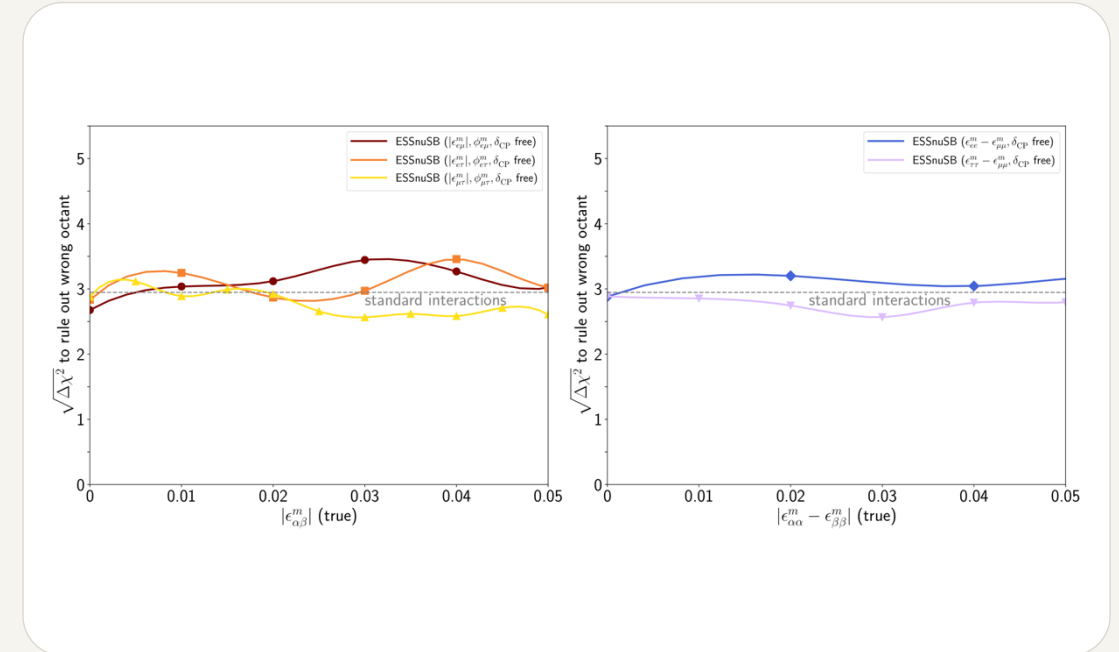
Mass ordering and octant survive NSI

Mass ordering



Freeing one NSI parameter costs 0.6σ – 1.3σ , yet the wrong ordering is still excluded at **6.1σ or better**.

θ_{23} octant



Octant sensitivity changes by 0.1σ – 0.4σ and stays at **2.6σ or higher**; for some values it even improves.

The second oscillation maximum is sensitive to δ_{CP}

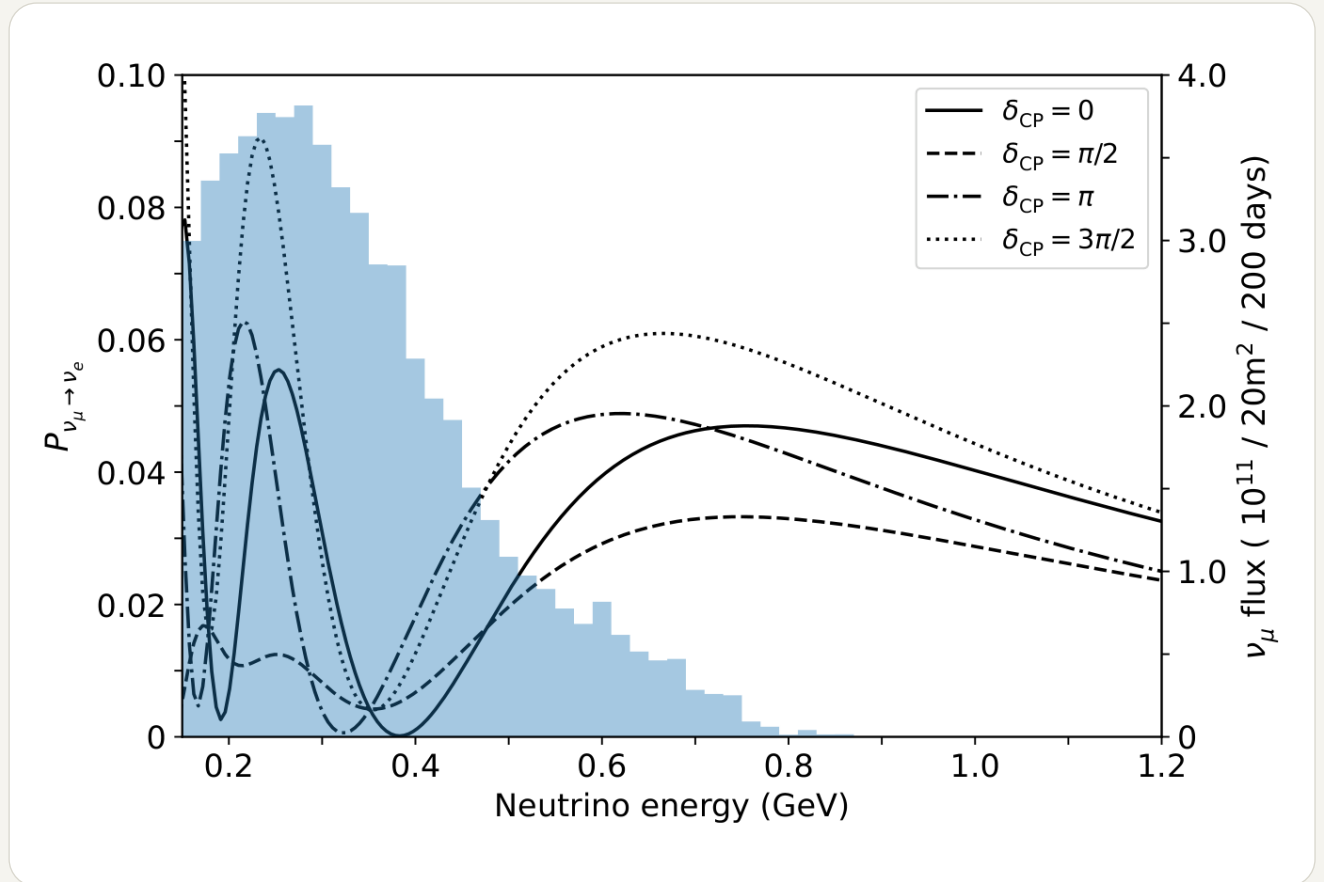
0.08

$\Delta P(\nu_\mu \rightarrow \nu_e)$ between $\delta_{\text{CP}} = 3\pi/2$ and $\pi/2$ at the second maximum ($E \approx 0.25$ GeV)

0.03

at the first maximum ($E \approx 0.65$ GeV)

The interference term dominates at the second maximum, so δ_{CP} is measured with high precision.

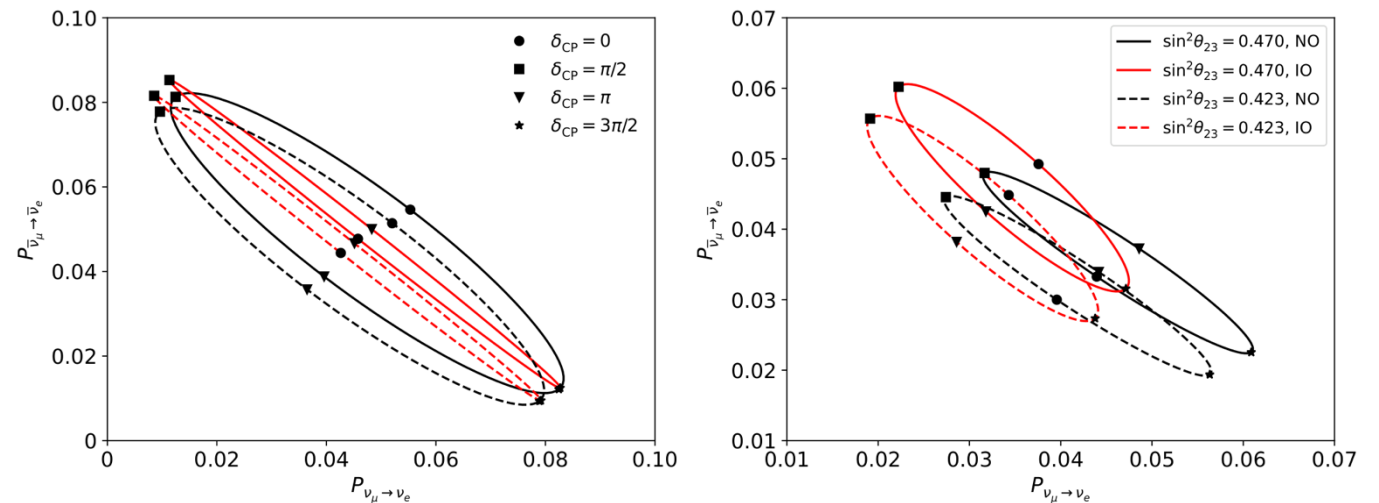


Good for δ_{CP} , weak for the mass ordering

Second maximum (left): ellipses for different θ_{23} shift along a line, so each δ_{CP} is found at the same place. NO and IO ellipses overlap.

First maximum (right): ellipses separate more, but cover smaller ranges, so δ_{CP} is harder.

Baseline of 360 km gives small matter effects: little ordering power in the beam alone.

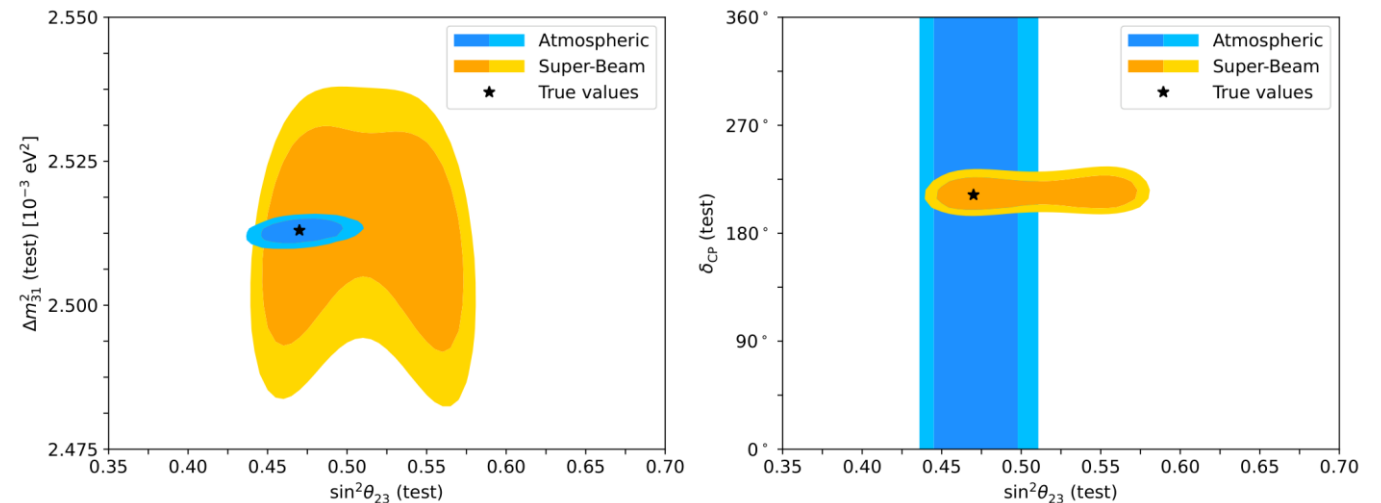


Atmospheric neutrinos tighten θ_{23} and Δm^2_{31}

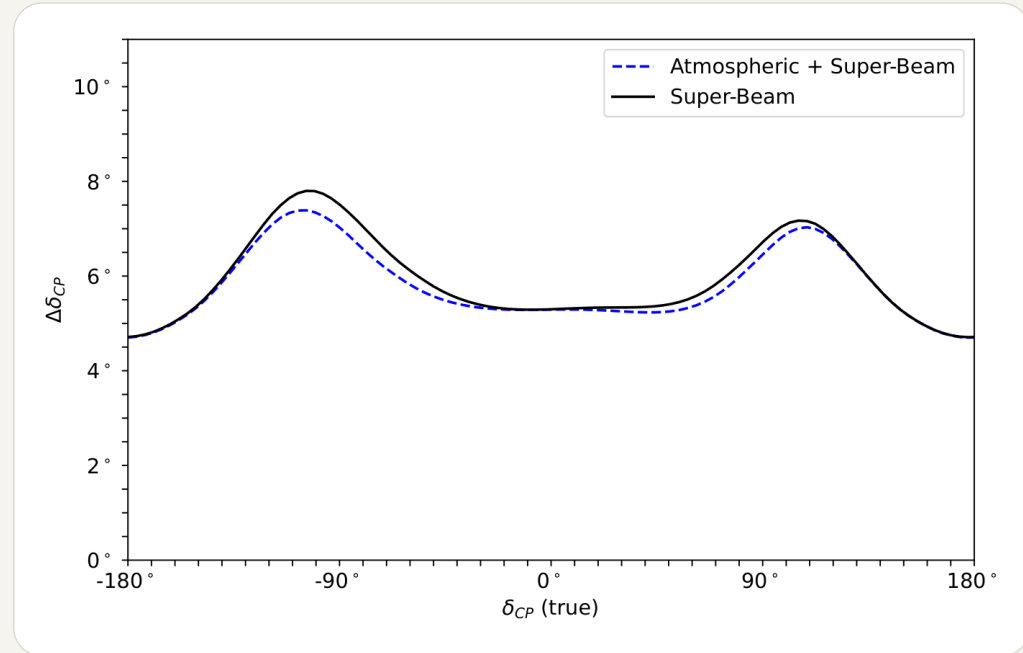
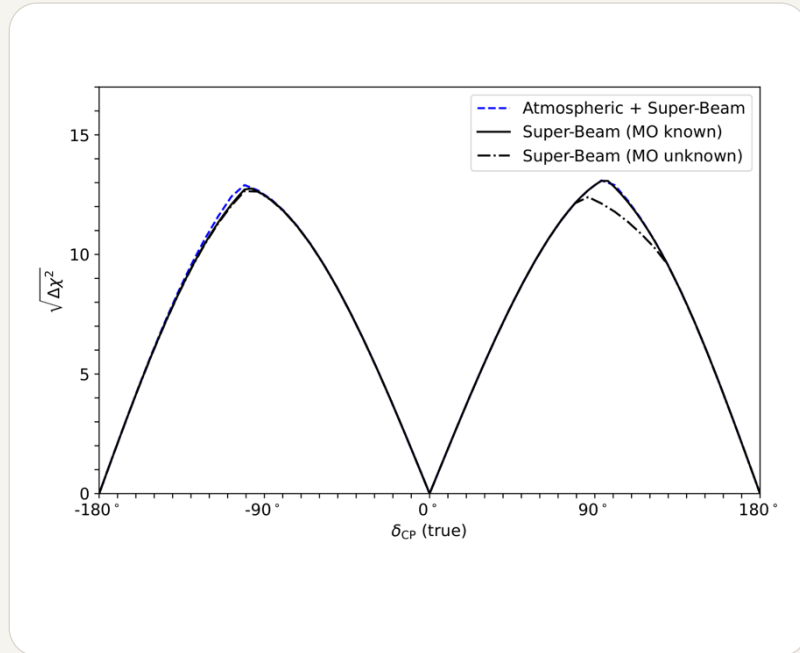
θ_{23} , Δm^2_{31} : atmospheric region (blue) is much smaller than the super-beam one (yellow), thanks to the first oscillation maximum at multi-GeV energies.

δ_{CP} : atmospheric data are flat in δ_{CP} ; the beam constrains it.

Atmospheric 1σ precision: $\sin^2\theta_{23}$ about 3–4%, Δm^2_{31} about 0.04–0.08%, weakly dependent on sub-GeV angular resolution (10° – 30°).



CP violation and δ_{CP} resolution



$\sqrt{\Delta\chi^2} \approx 13$

CPV at $\delta_{CP} = \pm 90^\circ$ from the beam; 5σ for over 70% of δ_{CP}

$7.5^\circ \rightarrow 7.1^\circ$

δ_{CP} resolution (1σ) at -90° with atmospheric data ($6.7^\circ \rightarrow 6.5^\circ$ at $+90^\circ$)

MO unknown?

Atmospheric data restore the CPV reach lost for δ_{CP} between 80° and 130°

SUMMARY

Atmospheric neutrinos complement the ESSnuSB beam

Mass ordering and octant

Ordering at 3σ in 4 years and 5σ in 10 years for either true ordering.

Octant at 3σ in 4 years (NO) or 8 years (IO).

$0.424 < \sin^2\theta_{23} < 0.484$ at 3σ (NO).

Non-standard interactions

90% CL, phases free: $|\varepsilon_{e\mu}| < 0.053$,
 $|\varepsilon_{e\tau}| < 0.057$, $|\varepsilon_{\mu\tau}| < 0.021$.

$\varepsilon_{ee} - \varepsilon_{\mu\mu} < 0.075$ and $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} < 0.031$.

Ordering reach stays at 6.1σ or more;
octant at 2.6σ or more.

Synergy with the beam

Atmospheric data tighten θ_{23} and Δm^2_{31} , which improves the δ_{CP} resolution ($7.5^\circ \rightarrow 7.1^\circ$ at -90°).

They also resolve the ordering and keep CPV discovery intact.

Thank you