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Measuring $\delta_{\rm CP}$ and probing lepton flavour models at ESSnuSB

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ESS NEUTRINO SUPER BEAM

ESS neutrino Super Beam plus

Based on: (i) A. Alekou *et al.*, ESSnuSB CDR, Eur. Phys. J. ST **231** (2022), 3779-3955

(ii) Blennow, **Ghosh**, Ohlsson and Titov, "Testing Lepton Flavor Models at ESSnuSB," JHEP **07** (2020), 014

The ESSnuSB experiment

Accelarator based long-baseline neutrino experiment

- 538 kt Water Cherenkov far detector
- $L = 360$ km (alternative 540 km)
- $E \sim 0.35$ GeV
- $\Delta m^2 \sim 10^{-3}$ eV^2
- Unique: Probes Second oscillation maximum

Neutrino Oscillation

- Neutrino oscillation: transition from one flavor to another
  time=0; time=t;
  ν_e; $\longrightarrow$ distance=L; $\longrightarrow$ ν_e, ν_μ, ν_τ;
- This is because ν_e, ν_μ, ν_τ are combinations of ν_1, ν_2, ν_3;

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

- U is 3×3 matrix
- The transition probability $\nu_\alpha \rightarrow \nu_\beta$:

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

where α, β are e, μ or τ

Neutrino oscillation in 3 generation

Full three flavour vacuum probability formula:

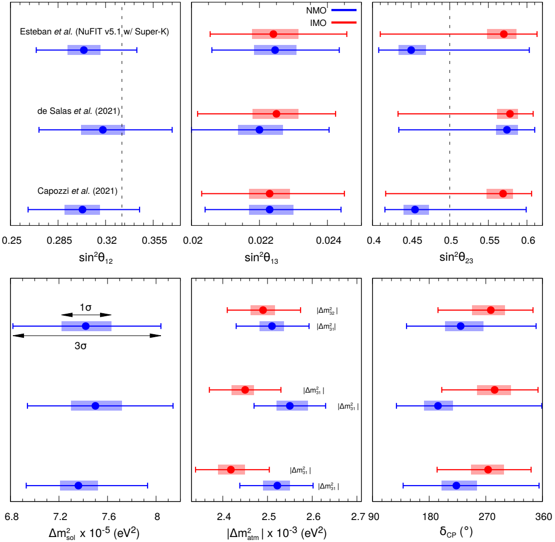
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j} Re[U^*_{\alpha i}U^*_{\beta j}U_{\beta i}U_{\alpha j}]sin^2\frac{\Delta_{ij}L}{4E} + 2\sum_{i<j} Im[U^*_{\alpha i}U^*_{\beta j}U_{\beta i}U_{\alpha j}]sin2\frac{\Delta_{ij}L}{4E}$$

$$\Delta_{ij} = m_i^2 - m_j^2$$

Parameters of neutrino oscillation:

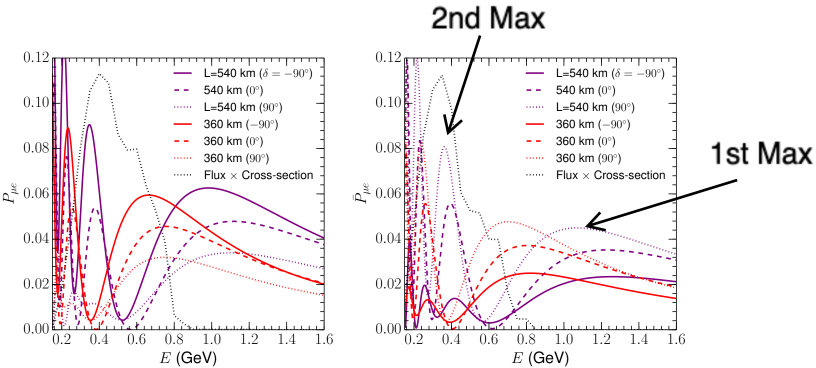
- Elements of U: Three mixing angles and one Dirac phase θ_{12}, θ_{23}, θ_{13}, δ_{CP}
- Two mass squared differences: Appears in $P_{\alpha\beta}$ $\Delta_{21} = m_2^2 - m_1^2$, $\Delta_{31} = m_3^2 - m_1^2$
- L and E

Current status: global



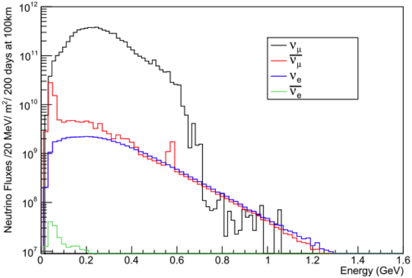
S. K. Agarwalla, R. Kundu, S. Prakash and M. Singh, 2111.11748, N(I)MO: Normal (Inverted) Mass Ordering

Probability and Flux

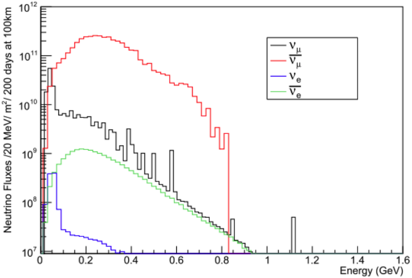


- 360 km: Both 1st and 2nd Maximum
- 540 km: 2nd Maximum
- Separation between the curves are more in 2nd maximum

Flux



(a) Positive polarity

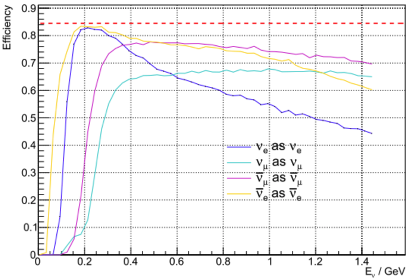


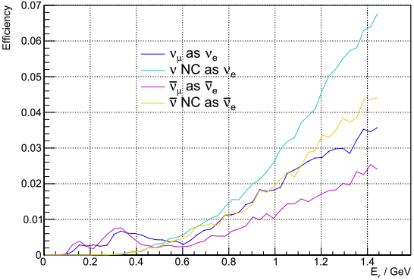
(b) Negative polarity

- Calculated at a distance of 100 km
- Different component of the flux

Calculated by “Flux" group in the collaboration

Far detector "particle selection" efficiency





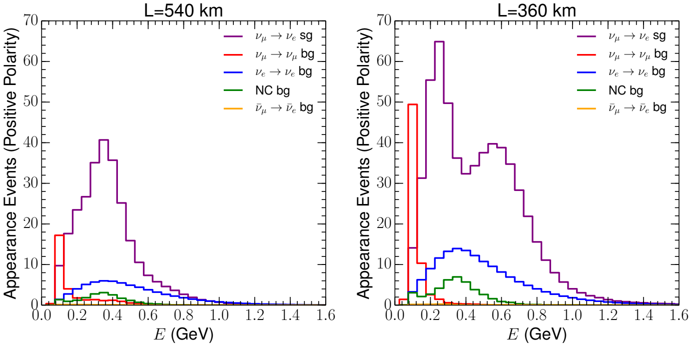
- Overall $> 80\%$ for ν_e selection
- Overall $> 60\%$ for ν_μ selection
- Good background rejection

Calculated by "Detector" group in the collaboration

Red dashed line: Fiducial volume cut

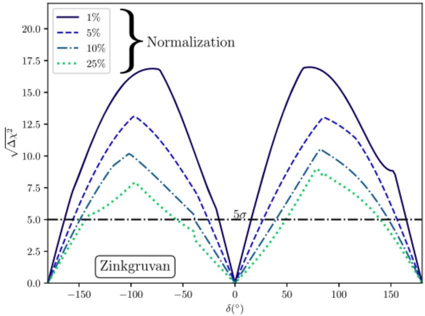
ν_e events

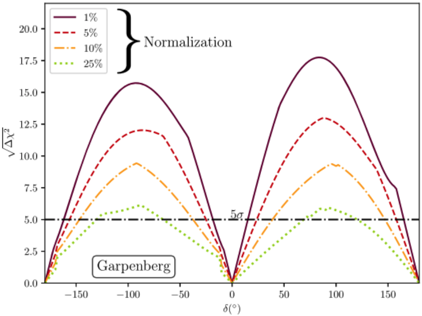
	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)	272.22 (63.75)	578.62 (101.18)
Background	$\nu_\mu \to \nu_\mu$ ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)	31.01 (3.73)	67.23 (11.51)
	$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)	67.49 (7.31)	151.12 (16.66)
	ν_μ NC ($\bar{\nu}_\mu$ NC)	18.57 (2.10)	41.78 (4.73)
	$\bar{\nu}_\mu \to \bar{\nu}_e$ ($\nu_\mu \to \nu_e$)	1.08 (3.08)	1.94 (6.47)



- More events for 360 km
- Major Background: Intrinsic beam background

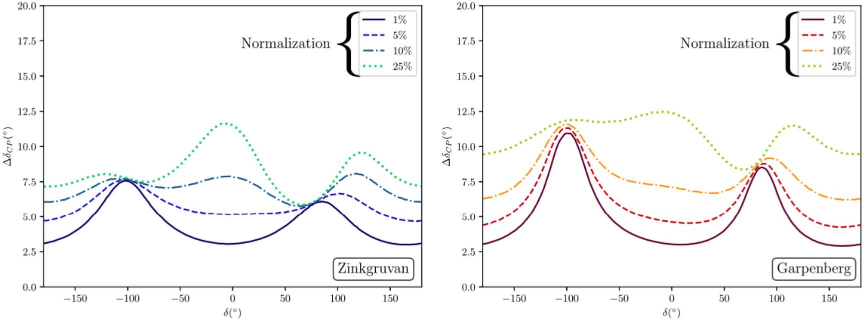
CP violation sensitivity





- 360 km gives better sensitivity than 540 km
- Sensitivity depends on systematic

CP precision sensitivity

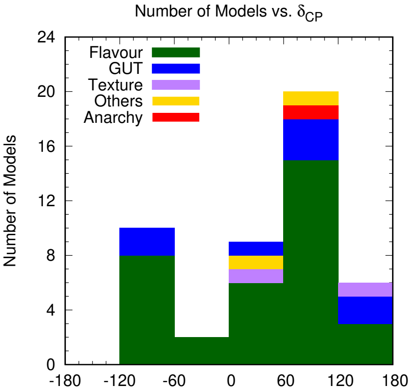


- 360 km gives better precision than 540 km
- Sensitivity depends on systematic

Probing Lepton Flavour Models at ESSnuSB

Why we want to measure $\delta_{\rm CP}$?

The simple answer: To understand the theory



$\delta_{\rm CP}$ (in degrees)

Albright 0905.0146

Our Work

Considered a set of models originating from discrete flavour symmetry

Test the models with ESSnuSB

S_4 Models

$$G_f = S_4 \rtimes CP$$

broken to $G_e = Z_3$ and $G_\nu = Z_2 \times CP$

	I	II	IV	V
$\sin^2\theta_{13}$	$\frac{2}{3}\sin^2\theta$	$\frac{2}{3}\sin^2\theta$	$\frac{1}{3}\sin^2\theta$	$\frac{1}{3}\sin^2\theta$
$\sin^2\theta_{12}$	$\frac{1}{2+\cos 2\theta}$	$\frac{1}{2+\cos 2\theta}$	$\frac{\cos^2\theta}{2+\cos^2\theta}$	$\frac{\cos^2\theta}{2+\cos^2\theta}$
$\sin^2\theta_{23}$	$\frac{1}{2}$	$\frac{1}{2}\left(1-\frac{\sqrt{3}\sin 2\theta}{2+\cos 2\theta}\right)$	$\frac{1}{2}$	$\frac{1}{2}\left(1-\frac{2\sqrt{6}\sin 2\theta}{5+\cos 2\theta}\right)$
$\lvert\sin\delta\rvert$	1	0	1	0

broken to $G_e = Z_4$ $\left(\text{or } Z_2 \times Z_2\right)$ and $G_\nu = Z_2 \times CP$

<table>
<tr><th></th><th>VI-a</th><th>VI-b</th></tr>
<tr><td>$\sin^2\theta_{13}$</td><td colspan="2">$\frac{1}{4}\left(\sqrt{2}\cos\theta+\sin\theta\right)^2$</td></tr>
<tr><td>$\sin^2\theta_{12}$</td><td colspan="2">$\frac{2}{5-\cos 2\theta-2\sqrt{2}\sin 2\theta}$</td></tr>
<tr><td>$\sin^2\theta_{23}$</td><td>$\frac{4\sin^2\theta}{5-\cos 2\theta-2\sqrt{2}\sin 2\theta}$</td><td>$1-\frac{4\sin^2\theta}{5-\cos 2\theta-2\sqrt{2}\sin 2\theta}$</td></tr>
<tr><td>$\sin\delta$</td><td colspan="2">0</td></tr>
</table>

F. Feruglio, C. Hagedorn and R. Ziegler (2012)

A_5 Models

$$G_f = A_5 \rtimes CP$$

broken to $G_e = Z_3 \ (Z_2 \times Z_2)$ and $G_\nu = Z_2 \times CP$

<table>
<tr><th></th><th>V</th><th>VII-a</th><th>VII-b</th></tr>
<tr><td>$\sin^2\theta_{13}$</td><td>$\frac{1-\sin 2\theta}{3}$</td><td colspan="2">$\frac{(\cos\theta-\varphi\sin\theta)^2}{4\varphi^2}$</td></tr>
<tr><td>$\sin^2\theta_{12}$</td><td>$\frac{1}{2+\sin 2\theta}$</td><td colspan="2">$\frac{(\varphi\cos\theta+\sin\theta)^2}{4\varphi^2-(\cos\theta-\varphi\sin\theta)^2}$</td></tr>
<tr><td>$\sin^2\theta_{23}$</td><td>$\frac{1}{2}$</td><td>$\frac{(\varphi^2\cos\theta-\sin\theta)^2}{4\varphi^2-(\cos\theta-\varphi\sin\theta)^2}$</td><td>$\frac{\varphi^2(\cos\theta+\varphi\sin\theta)^2}{4\varphi^2-(\cos\theta-\varphi\sin\theta)^2}$</td></tr>
<tr><td>$\lvert\sin\delta\rvert$</td><td>1</td><td colspan="2">0</td></tr>
</table>

broken to $G_e = Z_5$ and $G_\nu = Z_2 \times CP$

	II	III	IV
$\sin^2\theta_{13}$	$\frac{3-\varphi}{5}\sin^2\theta$	$\frac{\varphi}{\sqrt{5}}\sin^2\theta$	$\frac{\varphi}{\sqrt{5}}\sin^2\theta$
$\sin^2\theta_{12}$	$\frac{2\cos^2\theta}{3+2\varphi+\cos 2\theta}$	$\frac{4-2\varphi}{5-2\varphi+\cos 2\theta}$	$\frac{4-2\varphi}{5-2\varphi+\cos 2\theta}$
$\sin^2\theta_{23}$	$\frac{1}{2}$	$\frac{1}{2}-\frac{\sqrt{3-\varphi}\sin 2\theta}{3\varphi-2+\varphi\cos 2\theta}$	$\frac{1}{2}$
$\lvert\sin\delta\rvert$	1	0	1

$\varphi = (1+\sqrt{5})/2$ is the golden ratio.

C.-C. Li and G.-J. Ding (2015)

Fitting with current data

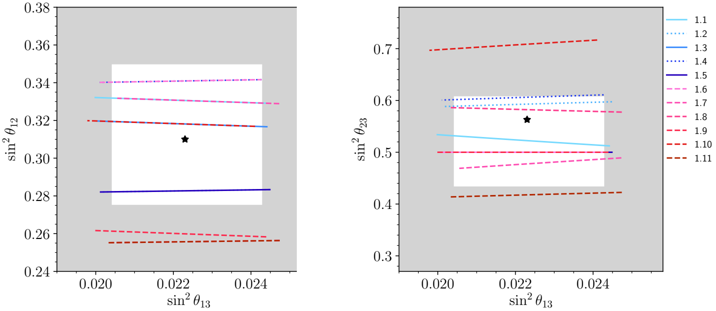
Model → data

$$\chi^2(\theta) = \left[\frac{\sin^2\theta_{12}(\theta) - \sin^2\theta_{12}}{\sigma(\sin^2\theta_{12})}\right]^2 + \left[\frac{\sin^2\theta_{13}(\theta) - \sin^2\theta_{13}}{\sigma(\sin^2\theta_{13})}\right]^2 + \left[\frac{\sin^2\theta_{23}(\theta) - \sin^2\theta_{23}}{\sigma(\sin^2\theta_{23})}\right]^2$$

Model	Case	χ^2_{min}	θ_{bf}	$\theta_{3\sigma}$
1.1	VII-b (A_5)	5.37	17.0°	(16.3°, 17.7°)
1.2	III (A_5)	5.97	169.9°	(169.4°, 170.4°)
1.3	IV (S_4)	7.28	15.0°	(14.3°, 15.7°)
			165.0°	(164.3°, 165.7°)
1.4	II (S_4)	8.91	169.5°	(169.0°, 170.0°)
1.5	IV (A_5)	11.3	10.1°	(9.6°, 10.6°)
			169.9°	(169.4°, 170.4°)
1.6	I (S_4)	12.6	10.5°	(10.0°, 11.1°)
			169.5°	(168.9°, 170.0°)
1.7	VII-a (A_5)	14.8	16.9°	(16.2°, 17.6°)
1.8	VI-b (S_4)	18.1	115.3°	(114.8°, 115.8°)
1.9	II (A_5)	21.8	16.5°	(15.7°, 17.3°)
			163.5°	(162.7°, 164.3°)
1.10	V (S_4)	36.8	165.2°	(164.4°, 165.9°)
1.11	VI-a (S_4)	53.8	115.3°	(114.8°, 115.8°)

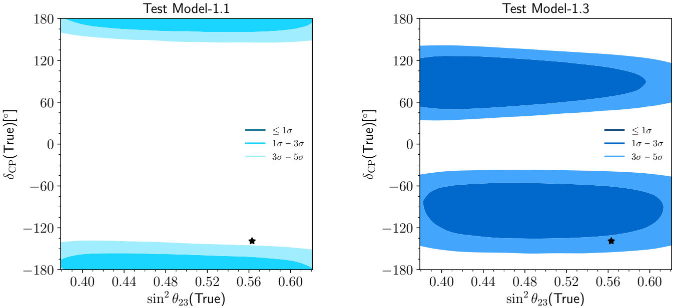
- Models are ordered as they fit the data
- Models 1.6 - 1.11 are disallowed the data by 3σ

Predictions



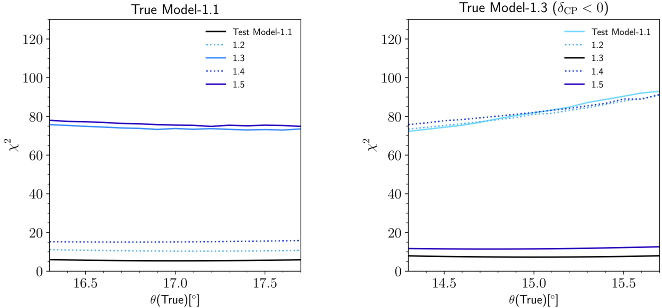
- Grey/White: Disallowed/Allowed region by data
- Prediction of the Models are shown by the horizontal lines
- Models predict very narrow ranges of θ_{23}

Exclusion by ESSnuSB



- Model 1.1 (1.3) predicts $|\sin\delta_{CP}| = 0$ (1)
- If best-fit of δ_{CP} remains close to present best-fit, then Model 1.1 will be excluded
- All θ_{23} values are allowed: Limited θ_{23} sensitivity of ESSnuSB

Testing Two Models with ESSnuSB



- Models 1.3 and 1.5 can be separated from Models 1.1, 1.2 and 1.4
- Because they predict different values of δ_{CP}

Summary

- ESSnuSB: Unique to probe second oscillation maximum
- Good capability to measure δ_{CP}
- Constraint Model parameter space depending on their prediction of δ_{CP}

The Collaboration

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Thank You