

CP violation with LBNE in the presence of a sterile neutrino

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(Based on an ongoing work with Mehedi Masud and Raj Gandhi)

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Oscillation parameters: Current status

NuFIT 2.0 (2014)

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2 \theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \rightarrow 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \rightarrow 0.344$	$0.270 \rightarrow 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \rightarrow 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \rightarrow 35.91$	$31.29 \rightarrow 35.91$
$\sin^2 \theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \rightarrow 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \rightarrow 0.644$	$0.385 \rightarrow 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \rightarrow 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \rightarrow 53.3$	$38.3 \rightarrow 53.3$
$\sin^2 \theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \rightarrow 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \rightarrow 0.0251$	$0.0188 \rightarrow 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \rightarrow 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \rightarrow 9.11$	$7.87 \rightarrow 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \rightarrow 360$	254^{+63}_{-62}	$0 \rightarrow 360$	$0 \rightarrow 360$
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \rightarrow 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \rightarrow 8.09$	$7.02 \rightarrow 8.09$
$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \rightarrow +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \rightarrow -2.307$	$\left[\begin{array}{l} +2.325 \rightarrow +2.599 \\ -2.590 \rightarrow -2.307 \end{array} \right]$

CP violation (CPV)

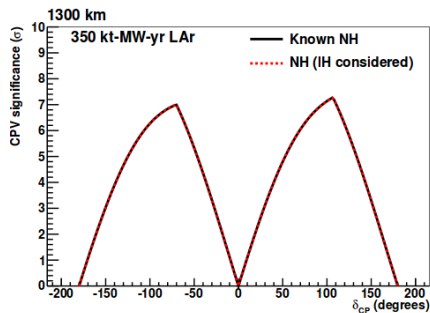
- Establishing whether CP is violated or conserved in the leptonic sector is an important open question in neutrino physics today.
- A possibility of leptogenesis leading to baryogenesis and baryon-asymmetry of the universe was studied by [Fukugita and Yanagida, Phys.Lett. B174 \(1986\) 45](#).
- There may be connections between leptogenesis and neutrino oscillations. [Joshipura, Paschos, and Rodejohan, JHEP 0108 \(2001\) 029](#).
- We will need future facilities for establishing CP violation at a satisfactory level.

Long-Baseline Neutrino Experiment (LBNE)

Characteristic	Long-baseline neutrino experiment (LBNE)
Baseline	1300 km
Location	Fermilab - Homestake
Beam	On-axis
Beam power	0.7 MW
Beam peaks at	~ 2.25 GeV
$P(\nu_\mu \rightarrow \nu_e)$ 1st Osc. Maximum	2.25 GeV
Detector	LArTPC 35kt
Runtime	5 yrs in ν + 5 yrs in $\bar{\nu}$

CPV with LBNE

- LBNE is an extensive effort and will be a very costly experiment.
- Its selling point is the feature that it will be able to prove or disprove existence of CP violation in neutrino oscillations.
- It has been shown in [[arXiv:1311.0212v2](https://arxiv.org/abs/1311.0212v2), M. Bass et. al.] that LBNE can establish CPV at greater than 3σ for 65% of the allowed δ_{CP} values.



Sterile neutrinos

- However, these results and optimisation studies have been performed assuming the usual oscillation framework in which only 3 active neutrino flavors are considered.
- It is but natural to ask whether or not LBNE will be equally sensitive to CP violation within slight extensions of the present model.
- There are several inconclusive positive and negative hints for the existence of **sterile neutrinos**.
- Diverse set of experiments have been planned which aim to prove or refute their existence.
- In this work, we extend the model minimally by assuming the existence of a $\sim 1\text{eV}^2$ sterile neutrino **(3+1)**.

3+1 Model: Phenomenology

- Flavor oscillations will be sensitive to new sterile-mixing angles and additional CP phases. A total of 6 mixing angles and 3 CP phases.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = U^{3+1} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

$$U^{3+1} = O_{34}(\theta_{34})V_{24}(\theta_{24}, \delta_{24})O_{23}(\theta_{23})O_{14}(\theta_{14})V_{13}(\theta_{13}, \delta_{13})V_{12}(\theta_{12}, \delta_{12})$$

- The full algebraic derivation of probabilities in the presence of matter becomes quite arduous. We use the software *GLoBES* for doing analysis.

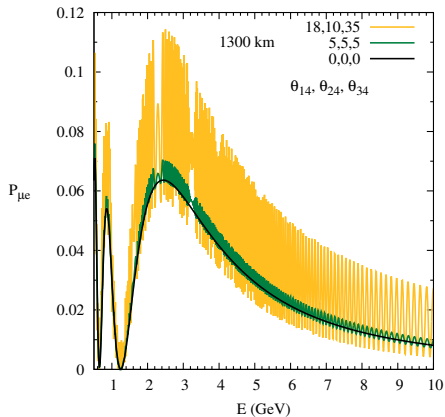
Global constraints on the active-sterile mixings

- [JHEP05\(2013\)050](#), [Kopp et. al.](#) present the constraints on active-sterile mixing parameters from short-baseline oscillations.
- ν_e and $\bar{\nu}_e$ disappearance searches: $|U_{e4}|$.
- $\nu_\mu, \bar{\nu}_\mu$ and NC disappearance searches: $|U_{\mu4}|$ and $|U_{\tau4}|$.
- At 99% C.L., $|U_{e4}|^2 \in [0, 0.1]$, $|U_{\mu4}|^2 \in [0, 0.03]$, $|U_{\tau4}|^2 \in [0, 0.3]$.
- These translate to $\theta_{14} \in [0, 18^\circ]$, $\theta_{24} \in [0, 10^\circ]$, $\theta_{34} \in [0, 35^\circ]$.
- No available information on the three CP phases:
 $\delta_{12}, \delta_{13}, \delta_{24} \in [-\pi, +\pi]$.

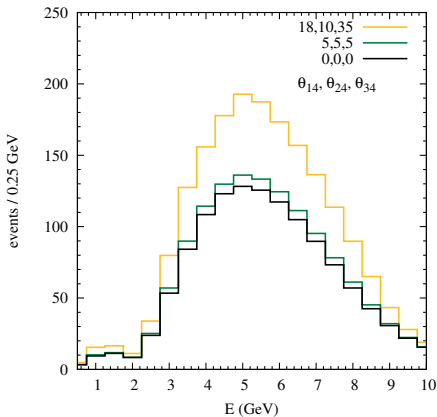
Probability and Events plots

NH, $\theta_{23} = 45^\circ$

neutrino probabilities

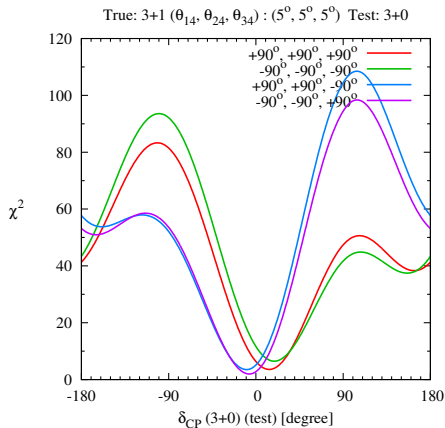
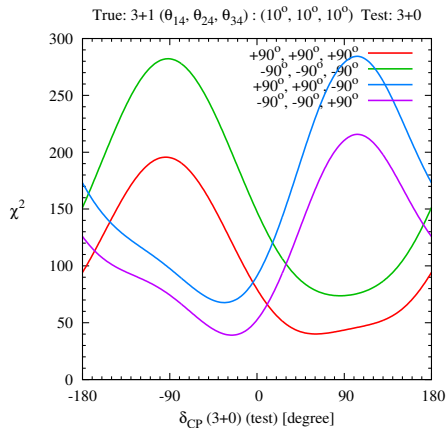


neutrino events



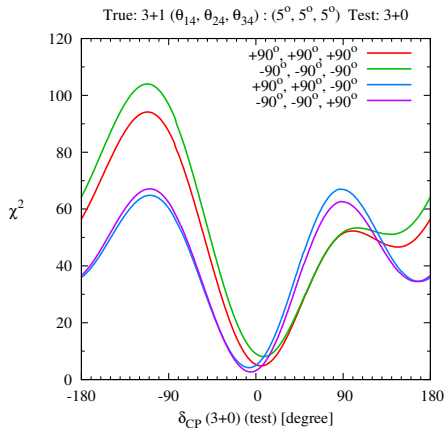
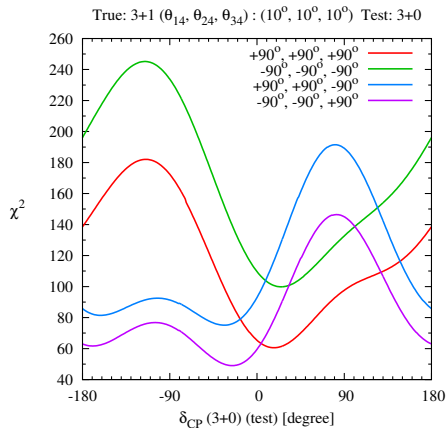
Results: misinterpreting CP violation


True: NH, $\theta_{23} = 45^\circ$



Results: misinterpreting CP violation

True: IH, $\theta_{23} = 45^\circ$





THANK
YOU !