Physics potential of long-baseline neutrino oscillation experiments in presence of sterile neutrino

Rudra Majhi, Soumya C., Rukmani Mohanta

University of Hyderabad

XXIII DAE-BRNS HIGH ENERGY PHYSICS SYMPOSIUM 2018
IIT Madras

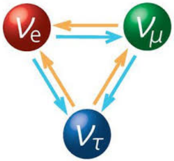
Outline

1. Introduction
2. Introduction to Sterile Neutrino
3. Active-Sterile neutrino mixing
4. Simulation Details
5. Result
    - Degeneracy at Probability Level
    - MH Sensitivity
6. Impact on Neutrino-less double beta decay.
7. Summary

Introduction

- Three types of neutrinos exist in SM.
- Neutrino Oscillation: Flavor transition process of neutrinos.

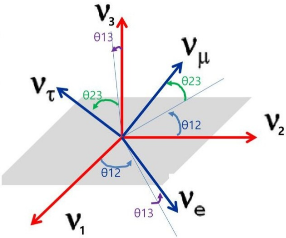
$$|\nu_\alpha\rangle = \sum U_{\alpha i}|\nu_i\rangle$$



- The Mixing Matrix is PMNS Matrix

$$U^3_{\rm PMNS} = R(\theta_{23})O(\theta_{13},\delta_{13})R(\theta_{12}),$$

$$O(\theta_{13},\delta_{13}) = \begin{pmatrix} \cos\theta_{13} & \sin\theta_{13}e^{-i\delta_{13}} \\ -\sin\theta_{13}e^{i\delta_{13}} & \cos\theta_{13} \end{pmatrix}$$



Oscillation Probability:

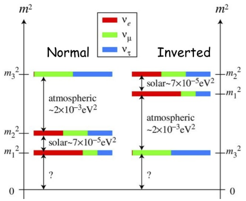
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$+2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})sin^2(\Delta m^2_{ij}\frac{L}{2E})$$

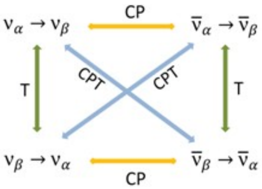
Parameters	θ_{12}/deg.	θ_{23}/deg.	θ_{13}/deg.	δ_{cp}/deg.	$\frac{\Delta m^2_{21}}{10^{-5} eV^2}$	$\frac{\Delta m^2_{31}}{10^{-3} eV^2}$
Values	33.62	47.2	8.5	234	7.4	2.49(−2.46)
3σ Range	$31.42 \to 36.05$	$40.3 \to 51.5$	$8.09 \to 8.98$	$144 \to 374$	$6.80 \to 8.02$	$2.39 \to 2.59$ $-2.54 \to -2.39$

* JHEP 01 (2017) 087 [arXiv:1611.01514]

- Unknowns in Neutrino Sector.



Mass Hierarchy



CP Violation

$\theta_{23} < 45^\circ$(LO)

$\theta_{23} > 45^\circ$(HO)

Octant of θ_{23}

- Standard three flavor framework is able to explain the most of the experimental result.
- There are experimental anomalies can not be explained by SM.

Introduction to Sterile Neutrino

LSND

- Objective:- $\overline{\nu}_\mu \to \overline{\nu}_e$ detection
- Detector was at 30 m. and sensitive to $\Delta m^2 \approx 1.0 eV^2$
  An excess of 3.8σ in $\bar{\nu_e}$ event.
- Best fit Oscillation $(\sin^2(2\theta), \Delta m^2) = (0.003, 1.2 eV^2)$

MiniBooNE

- Baseline:- 500 m.
- Objective:- $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$
- $3.4\sigma(2.8\sigma)$ excess event in $\nu_e(\bar{\nu_e})$ appearance.

Reactor Anomaly

- Shows 3% increase in anti neutrino fluxes.
- Overall 6% will increase.
- Compatible for $\Delta m^2 > 1 eV^2$.

Gallium Anomaly

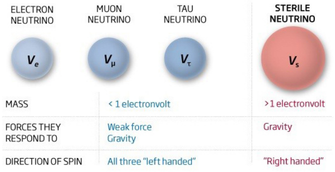
- Observed events and cross section is smaller than prediction (Ratio is $=0.86 \pm 0.05$).
- Explanation:- Electron neutrino disappearance at short baseline oscillations.

K. N. Abazajian et al., arXiv:1204.5379 [hep-ph]

Active-Sterile Neutrino mixing

- LEP Result: Below half of Z Boson mass $N_\nu = 3$

- Sterile neutrinos (ν_s) are neutral lepton, with no ordinary weak interaction except mixing.
- Some experiments predict existence of 1eV scale sterile neutrino.



- Consider the 3+1 framework.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

$$\mathrm{U} = O(\theta_{34}, \delta_{34}) R(\theta_{24}) O(\theta_{14}, \delta_{14}) R(\theta_{23}) O(\theta_{13}, \delta_{13}) R(\theta_{12})$$

$$\begin{aligned} P &\approx 4\sin^2\theta_{23}\sin^2\theta_{13}\sin^2\Delta + 8\sin\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}(\alpha\Delta)\sin\Delta\cos(\Delta+\delta_{13}) \\ &+ 4\sin\theta_{14}\sin\theta_{24}\sin\theta_{13}\sin\theta_{23}\sin\Delta\sin(\Delta+\delta_{13}-\delta_{14}) \,, \end{aligned}$$

where $\Delta \equiv \Delta_{31} L/4E$, $\alpha \equiv \Delta_{21}/\Delta_{31}$, $\Delta_{ij} = m_i^2 - m_j^2$.

Simulation Details

Parameter	θ_{14}	θ_{24}	θ_{34}	δ_{14}	δ_{34}
True Values	$[0^\circ, 20^\circ]$	$[0^\circ, 11^\circ]$	$[0^\circ, 31^\circ]$	$(-180 \to 180)^\circ$	$(-180 \to 180)^\circ$

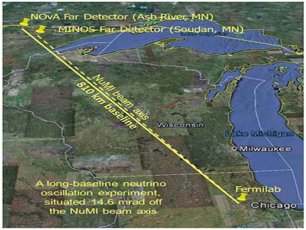
J.Kopp et.al, JHEP 1305, 050 (2013)

GLoBES

- General Long Baseline Experiment Simulator.
- C-library based software package for simulation.
- Use of snu plugin.

T2K		
	Baseline	295 km.
	FD mass	22.5 kt
	Off axial	2.5°

NOνA experiment



Baseline	810 km.
FD mass	14 kt
Off axial	14.6 mrad.
Scheduled run	$3\nu + 3\bar{\nu}$

P. Huber, M. Lindner, and W. Winter, Comput.Phys.Commun. 167, 195 (2005)
P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, Comput. Phys. Commun. 177, 432 (2007)

Simulation Details

Parameter	True Value
$\sin^2\theta_{12}$	0.307
$\sin^2 2\theta_{13}$	0.085
$\sin^2\theta_{23}$	(LO 0.44)
	(HO 0.56)
δ_{CP}	-90^o
Δm^2_{12}	$7.4 \times 10^{-5} eV^2$
$\lvert\Delta m^2_{31}\rvert$	$2.5 \times 10^{-3} eV^2$

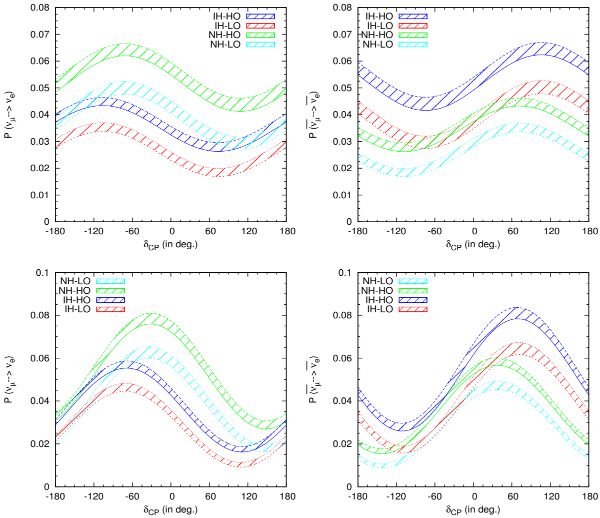
Standard Oscillation Parameter

Parameter	True Value
$\sin^2\theta_{14}$	0.025
$\sin^2\theta_{24}$	0.025
$\sin^2\theta_{34}$	0
δ_{14}	-90^o
δ_{34}	0^o
Δm^2_{14}	$1 eV^2$

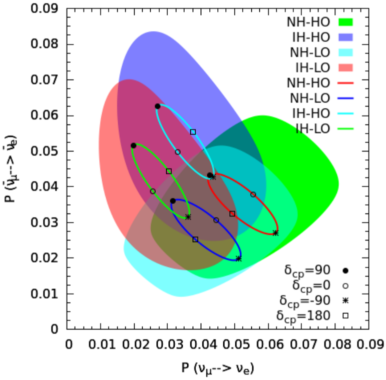
New Oscillation Parameter

- This Sterile Neutrino can have effect on oscillation parameters and on sensitivity of the experiments.
- Can affect to the current unknowns in neutrino sector.

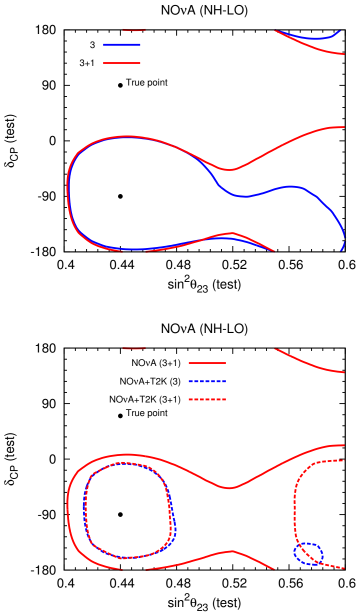
Degeneracy at Probability Level



Probability as a function of δ_{CP}

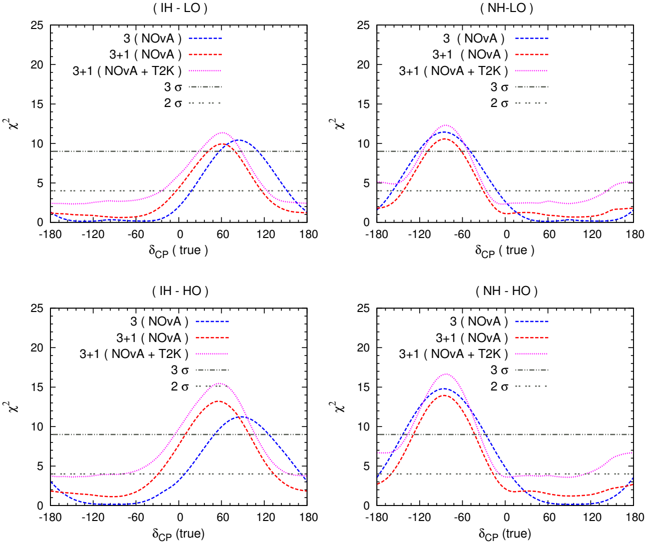


Bi-probability plot



Parameter Space in $\theta_{23} - \delta_{CP}$ Plane

MH Sensitivity

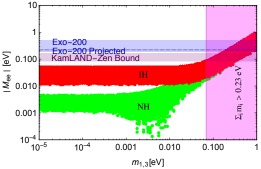


Mass Hierarchy Analysis

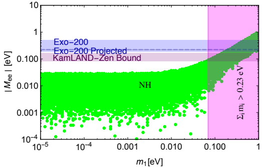
Neutrino-Less Double Beta Decay

- $0\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^-$
- Can explain Majorana nature neutrinos and absolute mass scale . $|M_{ee}| = \left| U_{e1}^2\, m_1 + U_{e2}^2\, m_2 e^{i\alpha} + U_{e3}^2\, m_3 e^{i\beta} \right|$
- KamLAND-Zen: $|M_{ee}| < (0.061 - 0.165)$ eV (A. Gando et al, [KamLAND-Zen Collaboration], Phys. Rev. Lett. 117, 082503 (2016))
- With sterile eV scale sterile neutrino: $|M_{ee}| = \left| U_{e1}^2\, m_1 + U_{e2}^2\, m_2 e^{i\alpha} + U_{e3}^2\, m_3 e^{i\beta} + U_{e4}^2\, m_4 e^{i\gamma} \right|$.

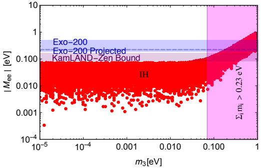
Standard 3 generation ν



NH with eV scale ν_s



eV scale ν_s in IH case



Summary

- eV scale sterile neutrino can exists.
- Sterile neutrino increases the degeneracy between the oscillation parameters.
- The mass hierarchy sensitivity of NOνA is getting worse in presence of sterile neutrino.
- T2K along with NOνA shows a significant increase in sensitivity.

$$|M_{ee}|_{\rm NH} = \left| U_{e1}^2 \, m_l + U_{e2}^2 \sqrt{\Delta m^2_{\rm sol} + m_l^2} \; e^{i\alpha} + U_{e3}^2 \sqrt{\Delta m^2_{\rm atm} + m_l^2} \, e^{i\beta} \right|, \quad (1)$$

and

$$|M_{ee}|_{\rm IH} = \left| U_{e1}^2 \sqrt{\Delta m^2_{\rm atm} - \Delta m^2_{\rm sol} + m_l^2} + U_{e2}^2 \sqrt{\Delta m^2_{\rm atm} + m_l^2} \; e^{i\alpha} + U_{e3}^2 \; m_l \, e^{i\beta} \right|. \quad (2)$$