Impact of light sterile neutrino at the long-baseline experiment options at KM3NeT

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Rudra Majhi
University of Hyderabad, Hyderabad.
Nabarangpur College, Nabarangpur

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NuFACT 2023

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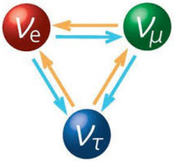
INTRODUCTION

Introduction

- Neutrinos are the most elusive particle postulated by Pauli in 1930.
- In last two decades, several dedicated experiments have observed the flavor transition property of neutrinos while propagating.



  - Neutrino Oscillation confirms the neutrino mass and mixing.
  - Also resolve the Solar and Atmospheric neutrino Anomalies.
  - Neutrino mass states (ν_1, ν_2, ν_3) are related to flavour states by Unitary mixing matrix.

$$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle \quad \alpha = e, \mu, \tau, \;\; i = 1, 2, 3$$

Flavour States   Mass States

- The Mixing Matrix is Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

$$U_{\rm PMNS} = R(\theta_{23})O(\theta_{13},\delta_{13})R(\theta_{12}),$$

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

$$R(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

NuFIT 5.1 (2021)

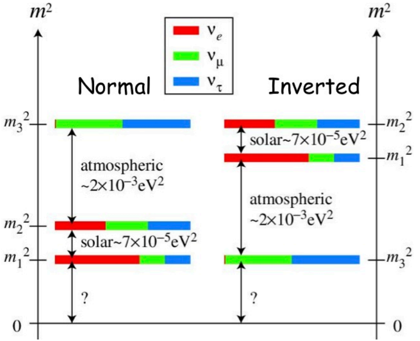
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
		bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
	$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
	$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{\rm CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

- Precise measurement of neutrino oscillation parameters.

* JHEP 09 (2020) 178 [arXiv:2007.14792] & NuFIT 5.1 (2021), www.nu-fit.org.

Unknowns of 3 ν framework

Mass Hierarchy.



- $\Delta m^2_{31} > 0$ (Normal Hierarchy)
  $m_3 >> m_2 > m_1$
- $\Delta m^2_{31} < 0$ (Inverted Hierarchy)
  $m_2 > m_1 >> m_3$

* R. N. Mohapatra et al., arXiv:hep-ph/0510213

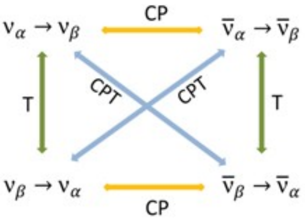
- Absolute scale of neutrino mass is unknown to us.
- Nature of Neutrinos: Dirac or Majorana type?

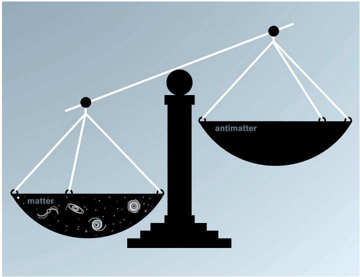
Unknowns of 3 ν framework

CP Violation

C[Particle] = Antiparticle

Parity changes the helicity of a state.





Is $P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$?

- *CP non-invariance comes from δ_{CP} phase in the Leptonic mixing matrix U.*

- CP violation can explain the matter-anti matter asymmetry in universe.

*A. S. Joshipura et al. JHEP 08 (2001), 029

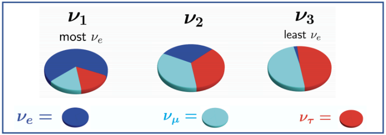
Unknowns of 3 ν framework

Octant of θ_{23}

- Atmospheric mixing angle (θ_{23}) deviates from maximum-mixing value 45°

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

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



Is there more ν_μ or ν_τ in ν_2?

- Are there more than 3 neutrino mass eigenstates? (Do sterile neutrinos exit?)
- Do neutrinos break the CPT and Lorentz invariance?
- Are there Non-Standard Interaction (NSI) effects?

Long-Baseline experiments

- The unknowns in neutrino sector can be studied through Long Baseline neutrino oscillation experiment.
- Earth matter effect in Long Baseline experiment will help to study the unknowns.
- It can give new signals of beyond standard model.

* M. Freund, Phys. Rev. D 64 (2001) 053003, arXiv:hep-ph/0103300.

STERILE NEUTRINO

Introduction to Sterile Neutrino

LSND

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

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

* M. A. Acero et al., arXiv:2203.07323.

Reactor Anomaly

- Shows 3% increase in anti neutrino fluxes.
- Overall 6% will increase.
- Neutrino life time will decrease. Increase in cross section for inverse β-decay.
- Compatible for $\Delta m^2 > 1eV^2$.

Gallium Anomaly

- Observed events and cross section is smaller than prediction.
- Explanation:- Electron neutrino disappearance at short baseline oscillations.
- $\Delta m^2, \sin^2(2\theta) = (2.24eV^2, 0.50)$

* Recent result from MicroBooNE, there is no excess of ν_e events coming from the $\nu_\mu$beam.

See talk by

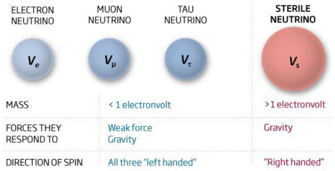
1. WG5: Sterile Neutrino Search at MicroBooNE using both the BNB and NuMI Beams by Meghna Bhattacharya.

- 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.



$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

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

- Sterile neutrino oscillation probability for neutrino detector:

$$P_{\mu e}^{\rm ND} = \sin^2 2\theta_{14} \sin^2 \theta_{24} \sin^2 \left(\frac{\Delta m^2_{41} L}{4E_\nu} \right). \tag{1}$$

- Approximate oscillation probability at far detector in presence of sterile neutrino is

$$\begin{aligned} P_{\mu e}^{\rm FD} &= 4s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\ &+ 8s_{12}c_{12}s_{13}s_{23}c_{23} \sin \Delta_{21} \sin \Delta_{31} \cos\left(\Delta_{31} + \delta_{\rm CP}\right) \\ &+ 4s_{13}s_{14}s_{24}s_{23} \sin \Delta_{31} \sin\left(\Delta_{31} + \delta_{\rm CP} + \delta_{24}\right). \end{aligned} \tag{2}$$

Simulation Details

Simulation Details

- General Long Baseline Experiment Simulator (GLoBES).
- C-library based software package for simulation of experiments.
- we use snu plugin for implementation of sterile neutrino and NSI.

* P. Huber et al., Comput. Phys. Commun. 167, 195 (2005)
* P. Huber et al., Comput. Phys. Commun. 177, 432 (2007)

DUNE

- Baseline of the experiment is 1300 km.
- Near detector (ND) is at a distance of 574 m.
- Beam power 1.2 MW equivalent to 1.1×10^{21} POT per year with a 40 kt LArTPC detector.
- Run-time: 3.5 yrs.(ν)+3.5 yrs.($\overline{\nu}$).

* B. Abi et al., arXiv:2103 .04797.

Possible Long Baseline Facility at KM3NeT

Protvino to ORCA (P2O)

- Neutrinos will be produced at U-70 synchrotron located at Protvino, Russia.
- Beam Power: 90 KW, 0.8×10^{20} POT.
- Neutrinos will be detected at the Mediterranean Sea 40 km offshore Toulon, France.
- FD at 2595 km and ND at 320m.

Upgraded P2O (Up P2O)

- Same configuration as P2O except beam power and POT.
- Beam Power: 450 KW, 4×10^{20} POT

Protvino to Super-ORCA (P2SO)

- Neutrinos will be detected at Super-ORCA detector at distance of 2595 km away.
- Detector will 10 times more dense than ORCA detector.
- Higher energy resolution capability.
- Beam power corresponds to 450 KW (4×10^{20} POT)

• Run time for all the three configuration is 6 years (3 yrs $+$ 3 yrs)

* J. Hofestädt, et al., PoS ICRC2019 (2020) 911, [arXiv:1907.12983]
* A. V. Akindinov et al., Eur. Phys. J. C 79 (2019), no. 9 758, [arXiv:1902.06083].

Results

Effect at Probability Level

- Probability at far detector will be averaged out for any particular value of Δm^2_{41}.
- Probability at near detector (ND) depends upon the sterile oscillation parameters. ND is the best platform to study sterile neutrino.

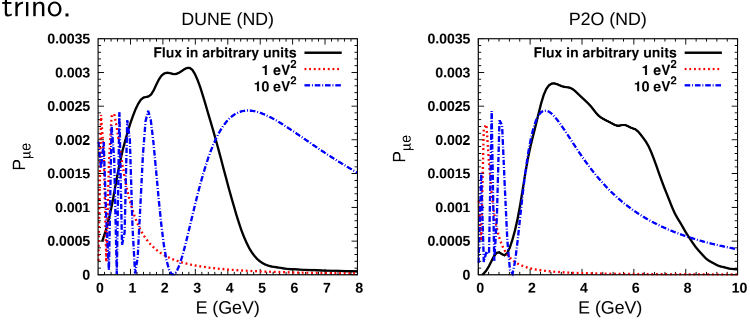


Figure: Probability as a function of energy.

Constration on sterile oscillation parameter

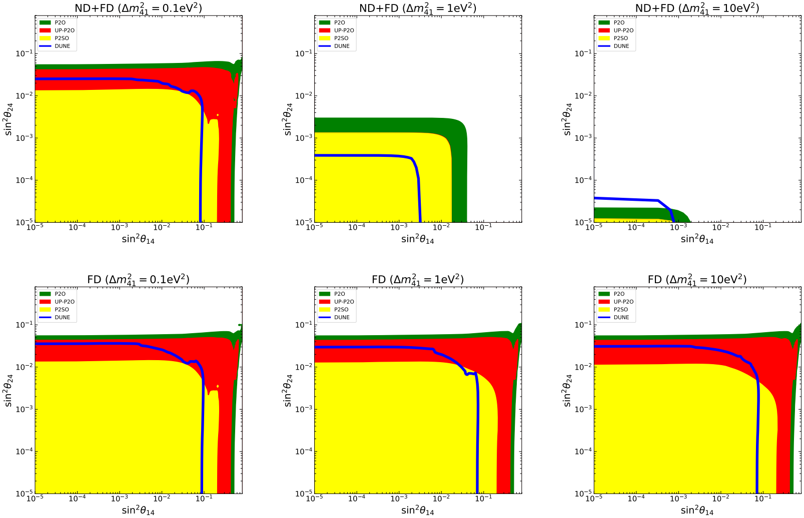


Figure: Allowed region between $\sin^2\theta_{14}$ vs $\sin^2\theta_{24}$ at 95% C.L.

Hierarchy Sensitivity

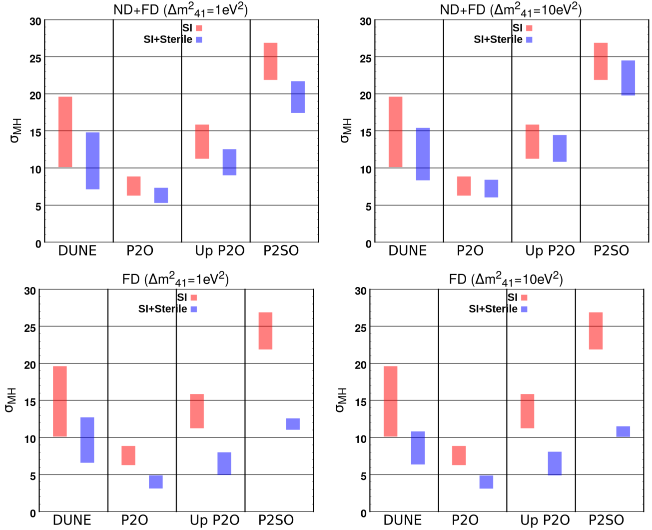


Figure: Range of MH sensitivities of DUNE, P2O, Up P2O and P2SO experiments.

Octant Sensitivity

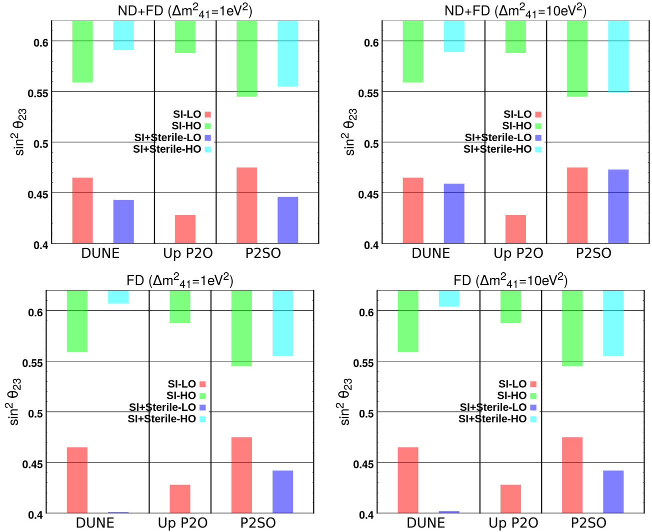


Figure: Region of $\sin^2\theta_{23}$ for which octant sensitivity is above 3σ C.L.

CPV Sensitivities

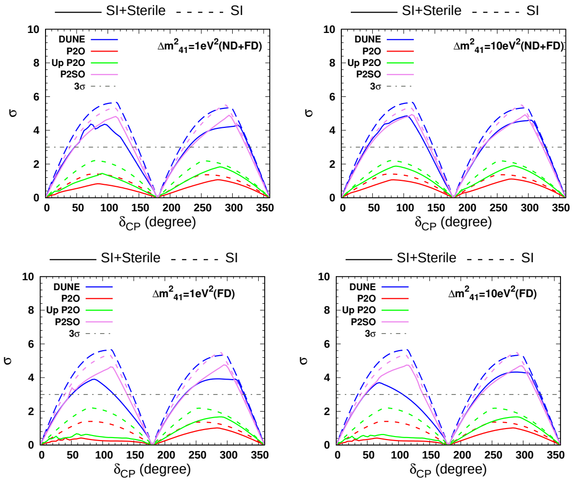


Figure: CPV sensitivities as a function of true δ_{CP} for DUNE, P2O, upgraded P2O (Up P2O), and P2SO experiments.

CP Precision

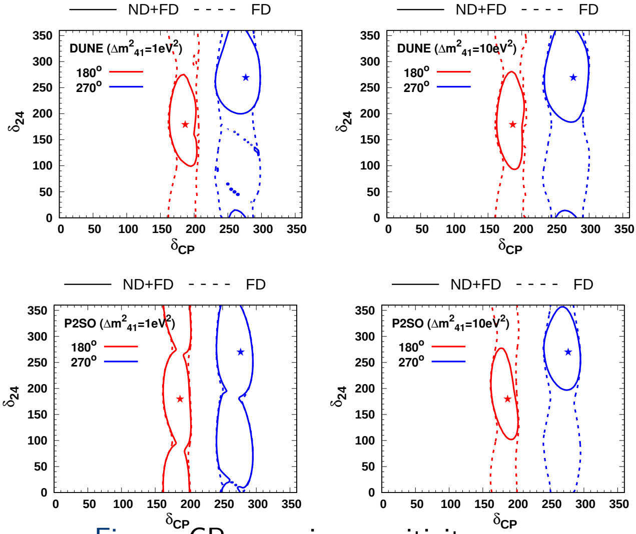


Figure: CP precesion sensitivity.

CONCLUSION

Conclusion

- Options at KM3NeT are more sensitive to the value of Δm^2_{41} is around 10 eV^2.
- DUNE is more sensitive to the value of Δm^2_{41} is around 1 eV^2.
- Inclusion of ND to FD improves the sensitivities for all the long baseline experiment.
- Both P2SO and DUNE have good efficiency to constrain the mixing angles θ_{14} and θ_{24}.
- P2SO gives the best sensitivity for MH.
- Octant and CP sensitivities of P2O and Up P2O are poor compare to DUNE and P2SO.
- DUNE provides slightly better sensitivity than P2SO regarding both CP violation and CP precision.

THANK YOU!