OCTANT SENSITIVITY RESTORED

In presence of a light sterile neutrino due to resonant matter effect

arXiv:2212.02949[hep-ph]

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Supriya Pan

Physical Research Laboratory, Ahmedabad
IIT Gandhinagar

OVERVIEW

MOTIVATION

STANDARD NEUTRINO OSCILLATION FRAMEWORK

$|\nu_\alpha\rangle = \sum_i U^\star_{\alpha i}|\nu_i\rangle$, $\iota\partial\nu_\alpha/\partial t = H|\nu_f\rangle$, $H = \frac{1}{2E}UMU^\dagger$, $H_m = H + H_{int}$, $\Delta_{ij} = m_i^2 - m_j^2$

$A = 2\sqrt{2}G_F N_e E$ (CC interaction potential), G_F: Fermi Constant, N_e : e^- density

$$U = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-\iota\delta_{cp}}\\ 0 & 1 & 0\\ -s_{13}e^{\iota\delta_{cp}} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}, M = \begin{bmatrix}m_1^2 & 0 & 0\\ 0 & m_2^2 & 0\\ 0 & 0 & m_3^2\end{bmatrix}, H_{int} = \begin{bmatrix}\frac{A}{2E} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}$$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}^{N} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\frac{1.27\Delta_{ij}L}{E} + 2\sum_{i>j}^{N} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\frac{2*1.27\Delta_{ij}L}{E}$$

Two flavour oscillation

$$P_{e\mu} = \sin^2 2\theta \sin^2\frac{1.27\Delta_{21}L}{E},\; P^m_{e\mu} = \sin^2 2\theta_m \sin^2\frac{1.27\Delta_{21m}L}{E},\; \tan 2\theta_m = \frac{\Delta_{21}\sin 2\theta}{\Delta_{21}\cos 2\theta - A}$$

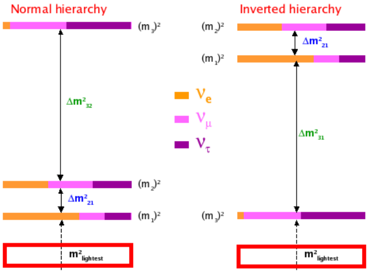
$\theta_m = \pi/4$: $E_{res} = \frac{\Delta_{21}\cos 2\theta}{2V_{cc}}$: MSW Resonance energy (Mikheyev et al., Sov.J.Nucl.Phys. 42, 1985)

CURRENT SCENARIO OF NEUTRINO OSCILLATION

$\theta_{12} = 33.44°$, $\theta_{13} = 8.57°$,$\theta_{23} = 49.20°$, $\Delta_{21} = 7.42e^{-5}eV^2$,$|\Delta_{31}| = 2.52e^{-3}eV^2$ **(JHEP,2020,178)**

Octant of θ_{23}

- $\theta_{23} : 39.6° \rightarrow 51.8° (3\sigma)$
  $\theta_{23} < 45°$: Lower Octant (LO)
  $\theta_{23} > 45°$: Higher Octant (HO)



Mass Hierarchy(antares.in2p3.fr)

CP Sensitivity

- $\delta_{CP} = 0, \pi$: CP Conservation;
  $\frac{\pi}{2}, \frac{3\pi}{2}$: CP Violation

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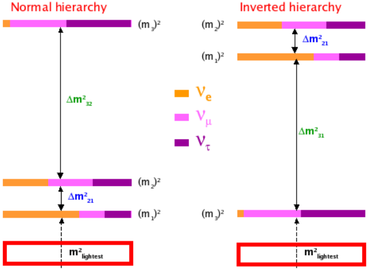

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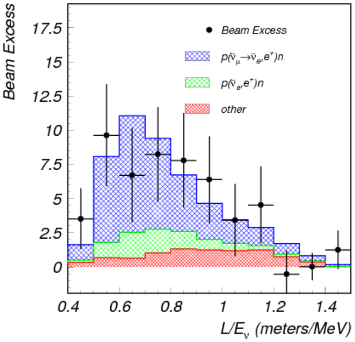
Degeneracies in 3 flavor oscillation paradigm

- **octant-δ_{CP} degeneracy(fixed hierarchy):** $P_{\mu e}(HO, \delta_{CP}) = P_{\mu e}(LO, \delta'_{CP})$
- hierarchy-δ_{CP} degeneracy(fixed octant): $P_{\mu e}(NH, \delta_{CP}) = P_{\mu e}(IH, \delta'_{CP})$.
- Combined hierarchy-$\theta_{23} - \delta_{CP}$ degeneracy: $P_{\mu e}(NH, \theta_{23}, \delta_{CP}) = P_{\mu e}(IH, \theta'_{23}, \delta'_{CP})$.

STERILE NEUTRINO



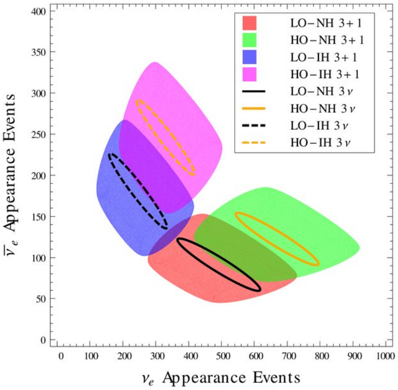
Beam excess at LSND

- LSND observed beam excess 3.8σ, hints $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation(Hill, PRL, 1995).
- Results of MiniBooNE has confirmed in 4.8σ(Aguilar-Arevalo et al, arXiv:2006.16883).
- Observation of ν_e deficit in SAGE and GALLEX (Phys.Rev.C83:065504,2011) has been reinforced with the recent results from BEST at 5σ(Barinov et al., 2021, arXiv:2109.11482.
- To solve these anomalies existence of an extra light sterile neutrino with mass $m_s \sim 1eV$ is proposed leading to 3+1 Oscillation framework,

$$U_s = \tilde{R}_{34}(\theta_{34}, \delta_{34}) R_{24}(\theta_{24}) \tilde{R}_{14}(\theta_{14}, \delta_{14}) R_{23}(\theta_{23}) \tilde{R}_{13}(\theta_{13}, \delta_{13}) R_{12}(\theta_{12})$$

$R_{ij}(\theta_{ij})$: Rotation matrices in i-j plane, $U^{\delta}_{ij} = \text{diag}(1, 1, 1, e^{\iota\delta_{ij}})$, δ_{ij}'s: CP phases.

STERILE NEUTRINO HINDERING THE OCTANT-δ_{CP} DEGENERACY?



Bi-event plot at DUNE

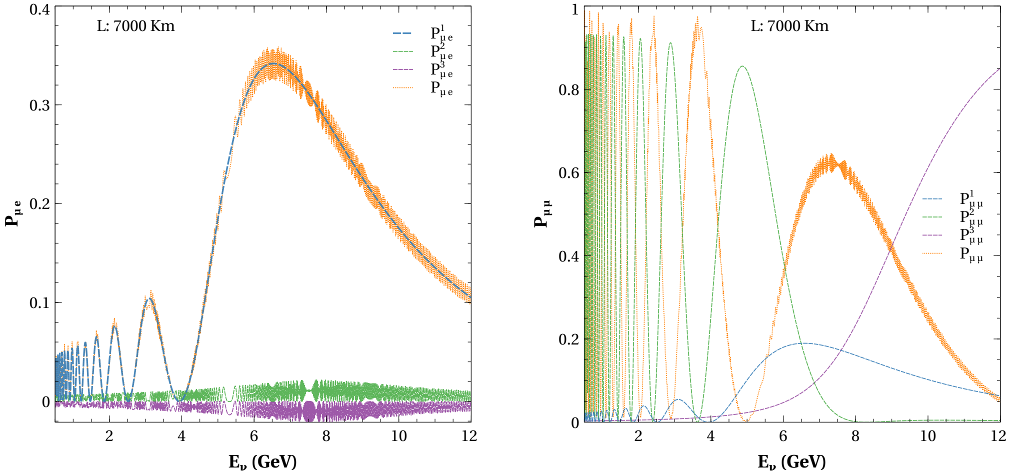
- Agarwalla et al, PRL, 2017 showed the presence of eV scale sterile neutrino jeopardize the octant discovery.
- Their results are for shorter baselines explained through vacuum oscillations.
- **We explore the octant sensitivity at beam+atmospheric baselines with ν_s where matter effect is important.**
- **We have derived the oscillation probabilities in 3+1 framework using: Two Mass Scale Dominance approximation.**

ANALYTICAL STUDY OF PROBABILITIES IN 3+1 FRAMEWORK

THE 3+1 OSCILLATION FRAMEWORK

- $\Delta_{21} << \Delta_{31} << \Delta_{41} \rightarrow \Delta_{21} = 0$: Two Mass Scale Dominance (TMSD) Approx.
- Vacuum Hamiltonian in mass basis: $H_M = \frac{1}{2E}\mathrm{diag}(0, 0, \Delta_{31}, \Delta_{41})$
- Effective mixing matrix: $\tilde{U} = R_{24}(\theta_{24})\tilde{R}_{14}(\theta_{14}, \delta_{14})R_{23}(\theta_{23})U_{\delta 13}R_{13}(\theta_{13})$
- Interaction Hamiltonian: $H_{int} = \mathrm{diag}(V_{CC}, 0, 0, -V_{NC}) = \frac{1}{2E}\mathrm{diag}(A, 0, 0, A/2)$
- Total Hamiltonian: $H = \frac{1}{2E}(UH_M U^\dagger + H_{int}) = (H_0 + H_p)$
- Eigenvalues of H_0 : $\dfrac{\Delta_{41}}{2E}, 0, 0, 0 \rightarrow$ **degenerate perturbation theory**

ANALYTIC PROBABILITIES

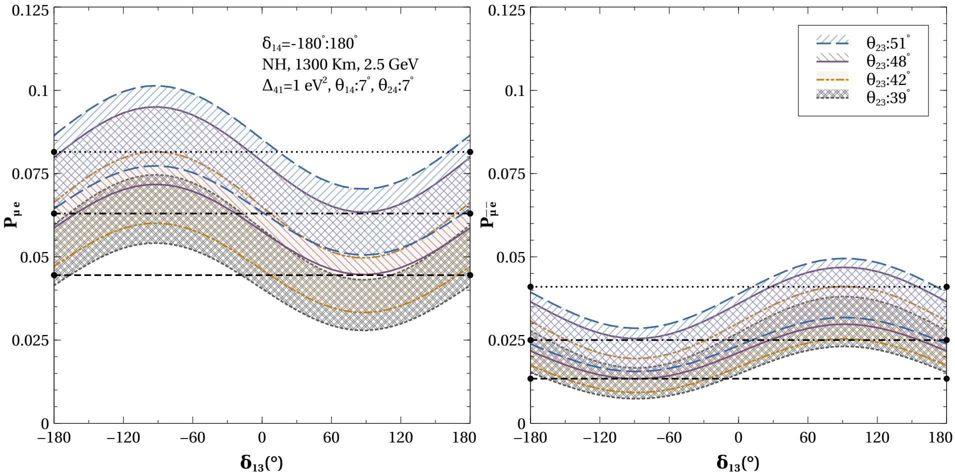


$$P^1_{\mu e} \sim 4\cos^2\theta_{13m}\cos^2\theta_{14m}\sin^2\theta_{13m}\cos^2\theta_{24m}\sin^2\theta_{23}\sin^2\frac{1.27\Delta^m_{31}L}{E}$$

$$P^1_{\mu\mu} \sim \cos^4\theta_{24m}\sin^2 2\theta_{13m}\sin^4\theta_{23}\sin^2\frac{1.27\Delta^m_{31}L}{E}$$

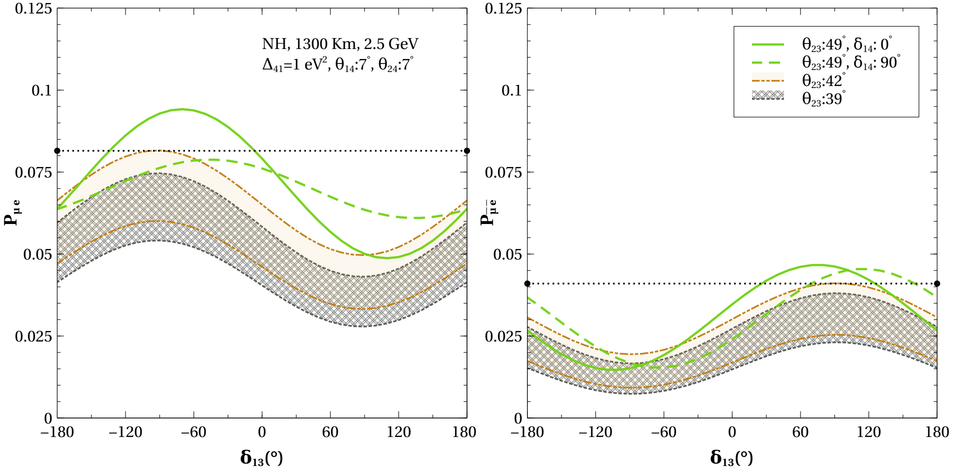
OCTANT DEGENERACY IN 3+1 FRAMEWORK

OCTANT DEGENERACY AT 1300 KM



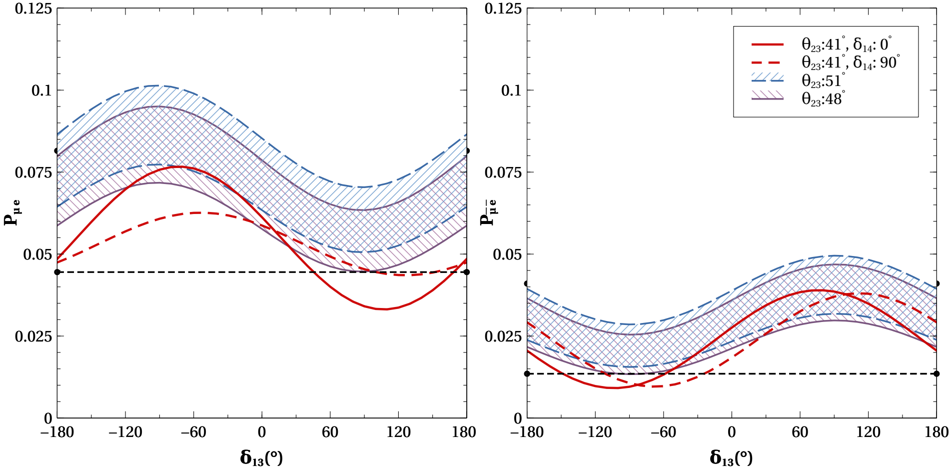
Degenerate solutions are observed for θ_{23}, δ_{14} variation in both octants.

OCTANT DEGENERACY AT 1300 KM



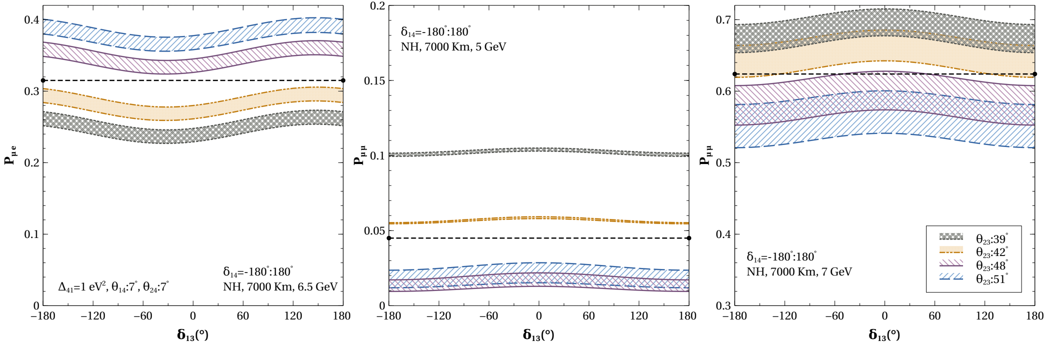
With θ_{23}, δ_{14} being fixed for one octant, the degeneracy gets lifted at certain δ_{13} values.

OCTANT DEGENERACY AT 1300 KM



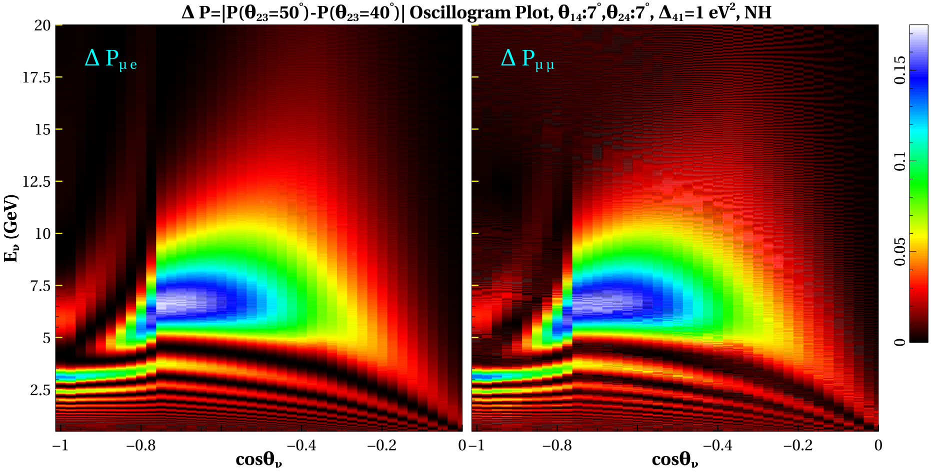
With θ_{23}, δ_{14} being fixed for one octant, the degeneracy gets lifted at certain δ_{13} values.

OCTANT DEGENERACY AT 7000 KM



- Clear removal of degeneracy at both $P_{\mu e}$, $P_{\mu\mu}$ channel.
- Higher baselines show promises of better octant sensitivity.

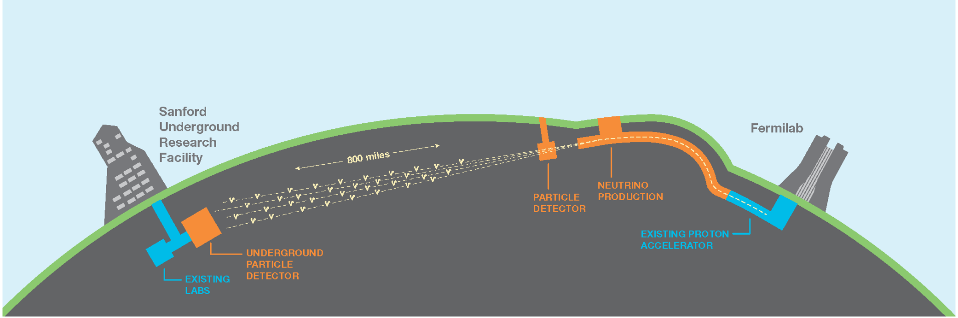
PROBABILITY OSCILLOGRAM SHOWING OCTANT DEGENERACY



Higher baselines of $(5:10) \times 10^3$ km show a significant difference in probabilities.

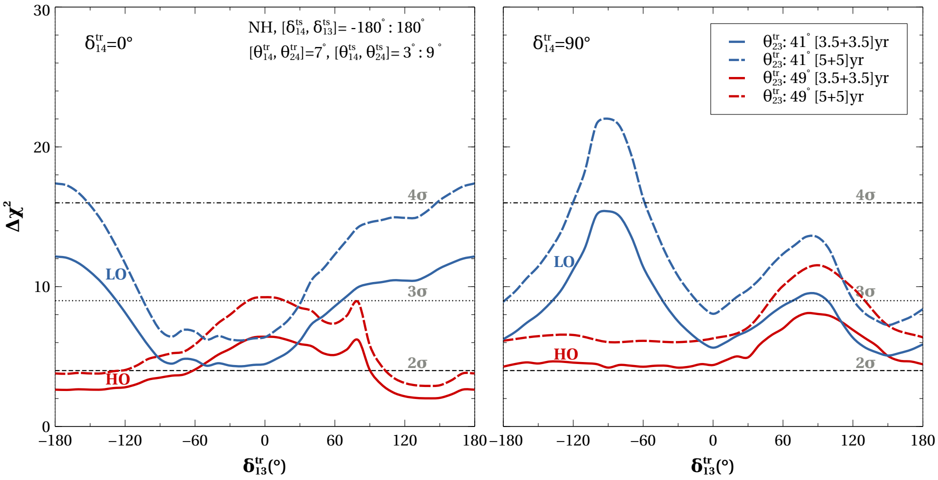
OCTANT SENSITIVITY IN CONTEXT OF DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE)



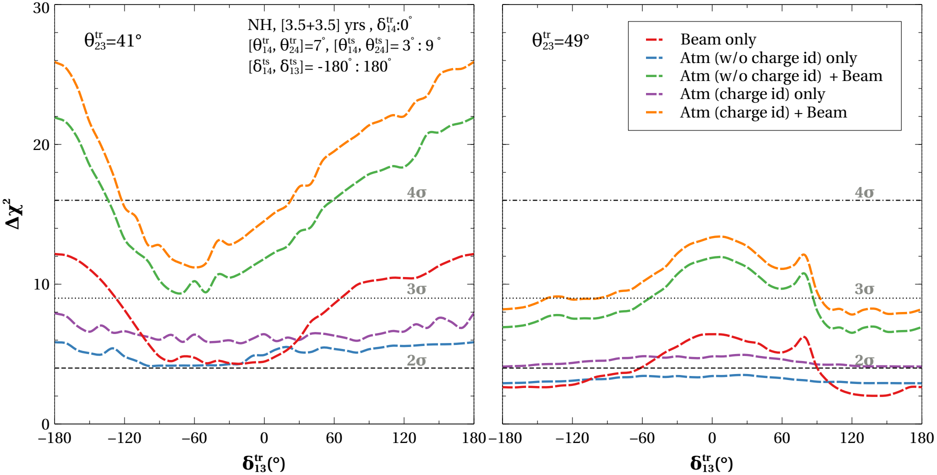
- Primary goals: testing CPV in lepton sector, finding mass hierarchy, θ_{23} octant.
- Long baseline experiment with the far detector at 1300 km with mean neutrino energy around $2 \sim 3$ GeV using liquid argon time projection chamber of 40 kt.
- Anticipating data collection from 2026 for 7 years (3.5 years of $\nu/\bar{\nu}$ beam mode)
- Along with accelerator ν beam DUNE can study atmospheric neutrinos.

OCTANT SENSITIVITY FOR BEAM NEUTRINOS



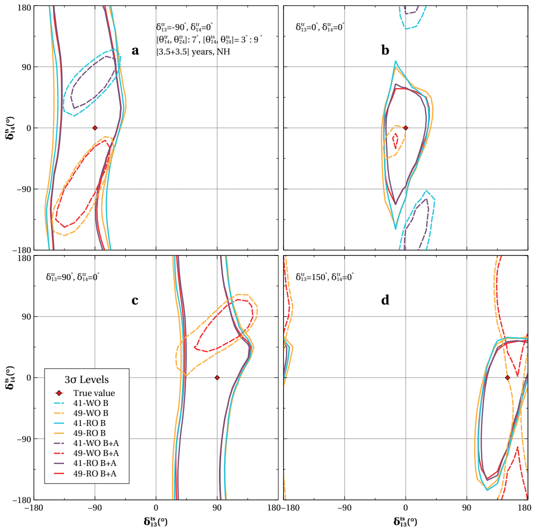
Sensitivity is over 2σ for most the δ_{13} values.

OCTANT SENSITIVITY FOR BEAM AND ATMOSPHERIC NEUTRINOS



The addition of atmospheric analysis lifts sensitivity over 3σ for most of the δ_{13} values.

CONTOUR PLOTS OF SENSITIVITY TO THE OCTANT



δ_{13}	δ_{14}	Present Degeneracies
$-90°$	$0°$	WO-Rδ_{13}-Wδ_{14}
$0°$	$0°$	WO-Rδ_{13}-R$\delta_{14}(49°)$, WO-Rδ_{13}-W$\delta_{14}(41°)$
$90°$	$0°$	WO-Rδ_{13}-W$\delta_{14}(49°)$
$150°$	$0°$	WO-Rδ_{13}-R$\delta_{14}(49°)$, WO-Rδ_{13}-W$\delta_{14}(49°)$

Table: The degeneracies for different true value of δ_{13} with true $\delta_{14} = 0°$

- Inclusion of atmospheric analysis shrinks all the contours improving octant sensitivity.
- The precision of the RO true solutions along with the size and type of WO contours depend on δ_{13}^{true} for fixed δ_{14}^{true}.

OUTLOOK

CONCLUSION

- Analytic probabilities using TMSD approximation shows good fit to the numerical probabilities especially in around the resonance energy.
- Combining the beam and the atmospheric neutrinos, we can obtain 3σ sensitivity in the entire true δ_{13} space for true values of $\theta_{23} = 41^\circ, \delta_{14} = 0^\circ$. In case of true values of $\theta_{23} = 49^\circ, \delta_{14} = 0^\circ$, 3σ sensitivity is achieved for 55% of the δ_{13}^{true} values.
- We also identify the extra degeneracies due to the presence of δ_{14} assuming the normal hierarchy at different true values of phases.

THANK YOU

ENERGIES FOR $\Delta_{21} = 0$ APPROXIMATION WITH ν_s

The modified energies in NH$(E_4^m > E_3^m > E_2^m > E_1^m)$ $[A' = A/2]$

$$\begin{aligned}
E_1^m &: C[\Delta_{31}\sin^2(\theta_{13}-\theta_{13m}) + A'(1+\cos^2\theta_{14}+\cos^2\theta_{14}\sin^2\theta_{24})\cos^2\theta_{13m}]/2E \\
E_2^m &: 0 \\
E_3^m &: C[\Delta_{31}\cos^2(\theta_{13}-\theta_{13m}) + A'(1+\cos^2\theta_{14}+\cos^2\theta_{14}\sin^2\theta_{24})\sin^2\theta_{13m}]/2E \\
E_4^m &: C[\Delta_{41} + A'(1+\sin^2\theta_{14}-\cos^2\theta_{14}\sin^2\theta_{24})]/2E
\end{aligned} \tag{1}$$

$$\sin 2\theta_{13m} = \frac{\Delta_{31}\, s2\theta_{13} + A\cos(\delta_{13}-\delta_{14})\, s\theta_{14}\, s\theta_{23}\, s2\theta_{24}}{f}$$

$$\sin\theta_{24m} = \sin\theta_{24}[1 - \frac{A}{\Delta_{41}} c^2\theta_{14} c^2\theta_{24}], \cos\theta_{24m} = \cos\theta_{24}[1 + \frac{A}{\Delta_{41}} c^2\theta_{14} s^2\theta_{24}],$$

$$\sin\theta_{14m} = \sin\theta_{14}[1 + \frac{A}{\Delta_{41}} c^2\theta_{14}(1+s^2\theta_{24})], \cos\theta_{14m} = \cos\theta_{14}[1 - \frac{A}{\Delta_{41}} s^2\theta_{14}(1+s^2\theta_{24})]$$

OSCILLATION/SURVIVAL PROBABILITIES IN PRESENCE OF STERILE NEUTRINO

$$P^1_{\mu e} = 4\cos^2\theta_{13m}\cos^2\theta_{14m}\sin^2\theta_{13m}(\cos^2\theta_{24m}\sin^2\theta_{23} - \sin^2\theta_{14m}\sin^2\theta_{24m})\sin^2 D^m_{31}$$
$$+ 2\cos^3\theta_{13m}\cos^2\theta_{14m}\sin\theta_{13m}\sin\theta_{14m}\sin 2\theta_{24m}\sin\theta_{23}\sin D^m_{31}\sin(D^m_{31}+\delta)$$
$$- 2\cos\theta_{13m}\cos^2\theta_{14m}\sin^3\theta_{13m}\sin\theta_{14m}\sin 2\theta_{24m}\sin\theta_{23}\sin D^m_{31}\sin(D^m_{31}-\delta),$$
$$P^2_{\mu e} = \cos^2\theta_{14m}\sin 2\theta_{13m}\sin\theta_{14m}\sin\theta_{23}\sin 2\theta_{24m}\sin D^m_{41}\sin(D^m_{41}-\delta) + \sin^2 2\theta_{14m}\sin^2\theta_{24m}\cos^2\theta_{13m}\sin^2 D^m_{41},$$
$$P^3_{\mu e} = -\cos^2\theta_{14m}\sin 2\theta_{13m}\sin\theta_{14m}\sin\theta_{23}\sin 2\theta_{24m}\sin D^m_{43}\sin(D^m_{43}-\delta) + \sin^2 2\theta_{14m}\sin^2\theta_{24m}\sin^2\theta_{13m}\sin^2 D^m_{43}$$
$$P^{4\nu}_{\mu e} = P^1_{\mu e} + P^2_{\mu e} + P^3_{\mu e},\ P^{3\nu}_{\mu e} = \sin^2 2\theta_{13m}\sin^2\theta_{23}\sin^2 D^m_{31}$$
$$P^1_{\mu\mu} = \cos^4\theta_{24m}\sin^2 2\theta_{13m}\sin^4\theta_{23}\sin^2 D^m_{31} + \sin^4\theta_{24m}\sin^4\theta_{14m}\sin^2 2\theta_{13m}\sin^2 D^m_{31}$$
$$+ \sin 2\theta_{24m}\sin\theta_{14m}\sin 4\theta_{13m}\sin\theta_{23}\cos\delta(\cos^2\theta_{24m}\sin^2\theta_{23} - \sin^2\theta_{24m}\sin^2\theta_{13m})\sin^2 D^m_{31}$$
$$+ 4\cos^2\theta_{24m}\sin^2\theta_{24m}\sin^2\theta_{14m}\sin^2\theta_{23}(1 - \frac{\sin^2 2\theta_{13m}}{2} - \sin^2 2\theta_{13m}\cos^2\delta)\sin^2 D^m_{31},$$
$$P^2_{\mu\mu} = \cos^4\theta_{24m}\cos^2\theta_{13m}\sin^2 2\theta_{23}\sin^2 D^m_{32} + 4\cos^2\theta_{24m}\sin^2\theta_{24m}\sin^2\theta_{14m}\sin^2\theta_{13m}\cos^2\theta_{23}\sin^2 D^m_{32}$$
$$- 4\cos^3\theta_{24m}\sin\theta_{24m}\sin\theta_{14m}\sin 2\theta_{13m}\cos^2\theta_{23}\sin\theta_{23}\cos\delta\sin^2 D^m_{32},$$
$$P^3_{\mu\mu} = \cos^4\theta_{24m}\sin^2\theta_{13m}\sin^2 2\theta_{23}\sin^2 D^m_{21} + 4\cos^2\theta_{24m}\sin^2\theta_{24m}\sin^2\theta_{14m}\cos^2\theta_{13m}\cos^2\theta_{23}\sin^2 D^m_{21}$$
$$+ 4\cos^3\theta_{24m}\sin\theta_{24m}\sin\theta_{14m}\sin 2\theta_{13m}\cos^2\theta_{23}\sin\theta_{23}\cos\delta\sin^2 D^m_{21}$$
$$P^{4\nu}_{\mu\mu} = 1 - P^1_{\mu\mu} + P^2_{\mu\mu} + P^3_{\mu\mu},\ P^{3\nu}_{\mu\mu} = 1 - \sin^2 2\theta_{13m}\sin^4\theta_{23}\sin^2 D^m_{31} - \sin^2 2\theta_{23}(\cos^2\theta_{13m}\sin^2 D^m_{32} + \sin^2\theta_{13m}\sin^2 D^m_{21})$$

$D^m_{ij} = \frac{1.27\Delta^m_{ij}L}{E}$, Δ^m_{ij}: modified mass-squared difference, $\delta = \delta_{13} - \delta_{14}$: effective phase, θ_{ijm}: modified angles in matter

ANALYTICAL OVERVIEW OF OCTANT-δ_{CP} DEGENERACY

- $\theta_{23} = \frac{\pi}{4} \pm \eta, \eta \sim 0.1 \lim_{\longrightarrow} \sin^2\theta_{23} \simeq \frac{1}{2} \pm \eta, \sin\theta_{23} \simeq \frac{1}{\sqrt{2}}(1 \pm \eta)$
- $\Delta P \equiv P^{HO}_{\mu e}(\delta^{HO}_{13}, \delta^{HO}_{14}) - P^{LO}_{\mu e}(\delta^{LO}_{13}, \delta^{LO}_{14}) = \Delta P_0 + \Delta P_1 + \Delta P_2 + \Delta P_{fast}$
- $\Delta P < 0$ suggests degeneracy is absent

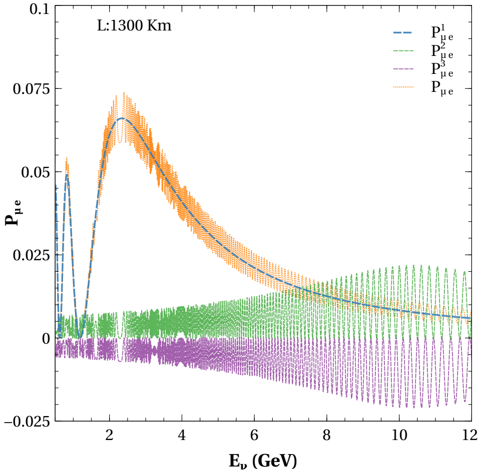
$$\begin{aligned}
\Delta P_0 &= 8\eta \cos^2\theta_{13m} \cos^2\theta_{14m} \cos^2\theta_{24m} \sin^2\theta_{13m} \sin^2 D^m_{31} \\
\Delta P_1 &= X_1(1+\eta)\sin(D^m_{31} + \delta^{HO}) - X_1(1-\eta)\sin(D^m_{31} + \delta^{LO}) \\
\Delta P_2 &= -Y_1(1+\eta)\sin(D^m_{31} - \delta^{HO}) + Y_1(1-\eta)\sin(D^m_{31} - \delta^{LO}) \\
\Delta P_f &= \sum_{k=1,3} Z_k(1+\eta)\sin(D^m_{4k} - \delta^{HO}) - Z_k(1-\eta)\sin(D^m_{4k} - \delta^{LO})
\end{aligned}$$

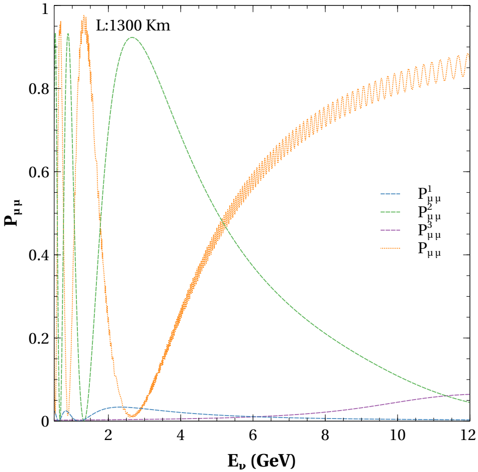
$$\begin{aligned}
X_1 &= \sqrt{2}\cos^3\theta_{13m}\cos^2\theta_{14m}\sin\theta_{13m}\sin\theta_{14m}\sin 2\theta_{24m}\sin D^m_{31} \\
Y_1 &= \sqrt{2}\cos\theta_{13m}\cos^2\theta_{14m}\sin^3\theta_{13m}\sin\theta_{14m}\sin 2\theta_{24m}\sin D^m_{31} \\
Z_1 &= \cos^2\theta_{14m}\sin 2\theta_{13m}\sin\theta_{14m}\sin 2\theta_{24m}\sin D^m_{41}/\sqrt{2}, \\
Z_3 &= -\cos^2\theta_{14m}\sin 2\theta_{13m}\sin\theta_{14m}\sin 2\theta_{24m}\sin D^m_{43}/\sqrt{2}
\end{aligned}$$

810 Km: $\Delta P_0 = 0.022, X_1 = 0.013, Y_1 = 0.0004, Z_1 = 0.0001, Z_3 = -0.0164$: ΔP will be zero for some phases

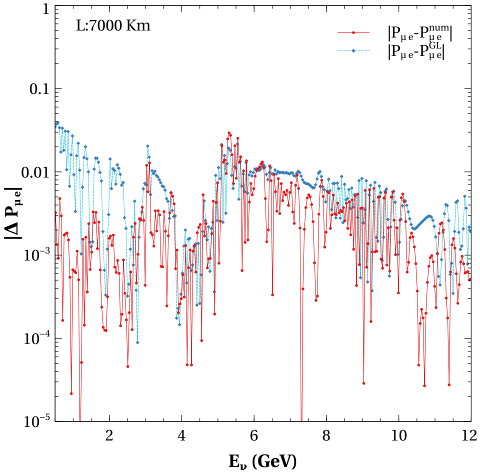
7000 Km:
$\Delta P_0 = 0.136, X_1 = 0.026, Y_1 = 0.007, Z_1 = -0.0056, Z_3 = 0.0064 \equiv \Delta P < 0$: degeneracy removed

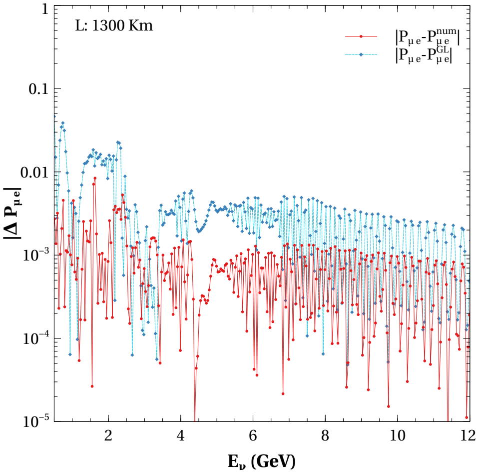
ANALYTIC PROBABILITIES AT 1300 KM



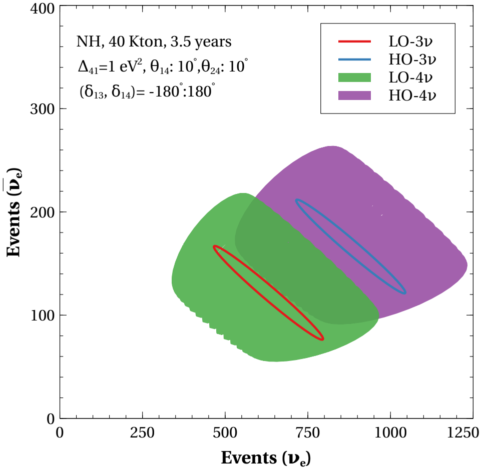


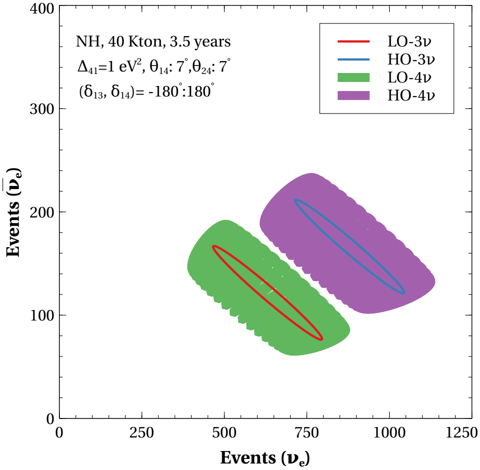
COMPARISONS OF ANALYTIC PROBABILITIES WITH NUMERICAL ONES



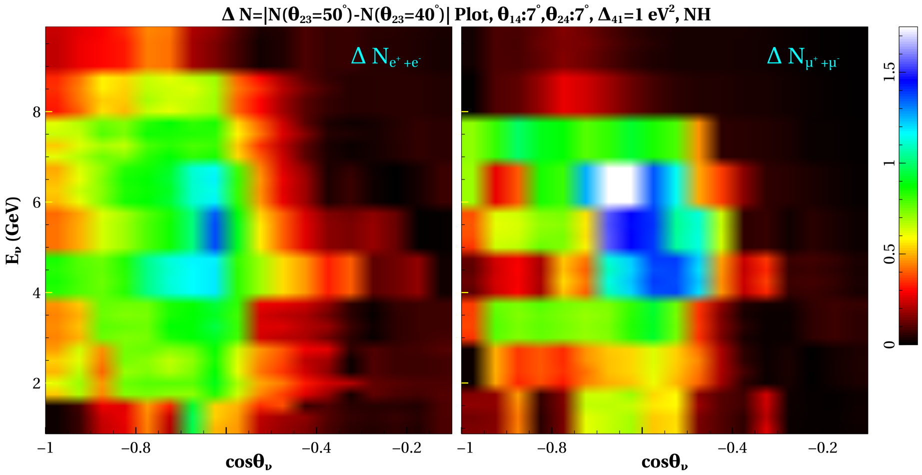


BI-EVENTS PLOT AT 1300 KM





EVENTS AT HIGHER BASELINES



OCTANT DEGENERACY IN $P_{\mu\mu}$ CHANNEL AT 1300 KM