Effect of sterile phases on degeneracy resolution capabilities of LBL experiments

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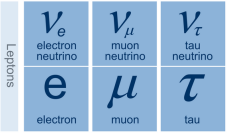
Overview

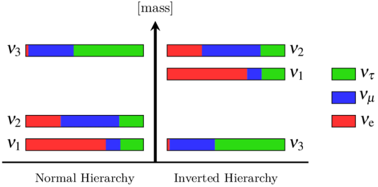
1. Introduction
2. Effect of ν_s on degeneracy resolution
3. Results
4. Conclusion

Neutrinos

- Neutrinos are part of lepton family. They interact only through weak force. ($\sigma_\nu \approx 10^{-38} \frac{cm^2}{GeV}$).



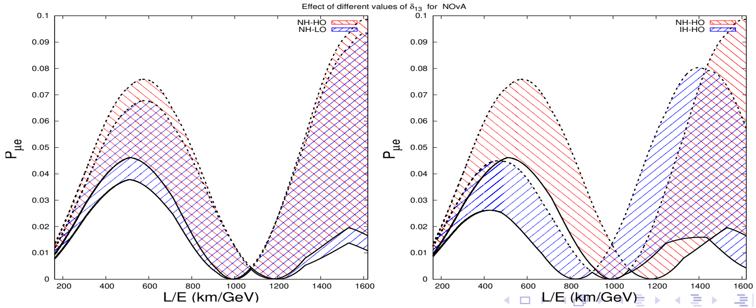
- Neutrinos oscillate between different flavors.



- Study of neutrino oscillations is an important part of neutrino physics.

Neutrino oscillations and degeneracies

- Precise measurement of neutrino oscillation parameters is important.
- Different sets of oscillation parameters may lead to the same value of oscillation probability.
- Due to this true solutions can be mimicked by false solutions causing Parameter degeneracy.
- Octant of θ_{23} and Mass hierarchy (MH) are the 2 degeneracies that are yet to be resolved.
- The true value of the CP violation phase is also yet to be measured.



Sterile Neutrinos

- LSND and MiniBooNE have anomalous experimental results which could be interpreted as due to a new neutrino with a mass $\sim$1 eV.
- As the LEP experiment limits no: of active neutrinos flavors to 3, the new neutrino must be a sterile (No weak interaction) neutrino.
- Sterile neutrino introduces new parameters to be measured.
- This increases the degrees of freedom and will affect degeneracy resolution capabilities of neutrino oscillation experiments.
- We have done a quantitative analysis of how sterile neutrino affects degeneracy resolution of neutrino oscillation experiments.

3+1 sterile neutrino model

- Standard 3 flavor neutrino mixing is given by following 3X3 parameterization

$$U_{PMNS_3} = R_{23}(\theta_{23})\tilde{R_{13}}(\theta_{13}, \delta_{13})R_{12}(\theta_{12}). \quad (1)$$

where R_{ij} and $\tilde{R_{ij}}$ represent real and complex 3×3 rotation in the plane containing the 2×2 sub-block in (i,j) sub-block.

$$R_{ij}^{2\times 2} = \begin{pmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{pmatrix} \text{ and } R_{ij}^{\tilde{2}\times 2} = \begin{pmatrix} c_{ij} & \tilde{s_{ij}} \\ -\tilde{s_{ij}}^* & c_{ij} \end{pmatrix}$$

Where, $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}, \tilde{s_{ij}} = s_{ij}e^{-i\delta_{ij}}$ and δ_{ij} are the CP phases.

- Now addition of sterile neutrino introduces new mixing angles and CP phases. We mainly worked on one sterile neutrino model(3+1). The new parameterization matrix is 4×4 is

$$U_{PMNS_{3+1}} = R_{34}(\theta_{34})\tilde{R_{24}}(\theta_{24}, \delta_{24})\tilde{R_{14}}(\theta_{14}, \delta_{14})U_{PMNS_3}. \quad (2)$$

3+1 sterile neutrino model

- The addition of one sterile neutrino introduces 3 new mixing angles and 2 new CP-phases (properties of 4X4 Unitary matrix).

$$U_{PMNS_{3+1}} = R_{34}(\theta_{34})\tilde{R_{24}}(\theta_{24}, \delta_{24})\tilde{R_{14}}(\theta_{14}, \delta_{14})U_{PMNS_3}. \tag{3}$$

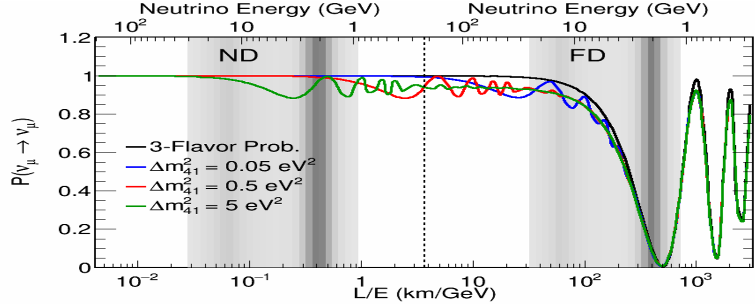
- Measuring the new parameters is important for the study of sterile neutrinos.

	θ_{24}	θ_{34}
NOvA	20.8°	31.2°
MINOS	7.3°	26.6°
SuperK	11.7°	25.1°

Table: The 90% C.L. upper limits on sterile mixing angles for $\Delta m^2_{41} = 0.5$ eV^2 for all experiments.

Search for sterile neutrino

- Short-baseline(SBL) experiments are best place to look for sterile-mixing as they are sensitive to oscillations introduced by new $\Delta \mathrm{m}^2 \simeq 1 \mathrm{eV}^2$, thus the near detector would be the place for it.
- Although Near Detector studies can give good bounds on sterile mixing angles, they are not sensitive to new sterile CP-phases
- Long baseline(LBL) experiments explore complimentary CP phases. Combining both give us better measurements.



G. K. Kafka,FERMILAB-THESIS-2016-27 doi:10.2172/1336405

Oscillation Probability for 3+1 model

- The electron neutrino appearance probability ($P_{\mu e}$) for LBL experiments in 3+1 model in vacuum can be expressed as sum of the four terms

$$P^{4\nu}_{\mu e} \simeq P_1 + P_2(\delta_{13}) + P_3(\delta_{14} - \delta_{24}) + P_4(\delta_{13} - (\delta_{14} - \delta_{24})). \quad (4)$$

- The first two terms give ordinary CP violation.
- The CP phases introduced due to sterile neutrinos persist in the $P_{\mu e}$ even after averaging out Δm^2_{41} lead oscillations.
- Last two terms of equation, give the sterile CP phase dependence terms.
- Thus, We see that LBL experiments are sensitive to sterile phases.

- Expanded form of $P^{4\nu}_{\mu e}$ is as follows:

$$P_1 = \frac{1}{2}\sin^2 2\theta^{4\nu}_{\mu e} + [a^2 \sin^2 2\theta^{3\nu}_{\mu e} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta^{4\nu}_{\mu e}]\sin^2\Delta_{31}$$
$$+ \left[a^2 b^2 - \frac{1}{4}\sin^2 2\theta_{12}(\cos^4\theta_{13}\sin^2 2\theta^{4\nu}_{\mu e} + a^2\sin^2 2\theta^{3\nu}_{\mu e})\right]\sin^2\Delta_{21},$$

$$P_2(\delta_{13}) = a^2 b \sin 2\theta^{3\nu}_{\mu e}(\cos 2\theta_{12}\cos\delta_{13}\sin^2\Delta_{21} - \frac{1}{2}\sin\delta_{13}\sin 2\Delta_{21}),$$

$$P_3(\delta_{14}-\delta_{24}) = ab\sin 2\theta^{4\nu}_{\mu e}\cos^2\theta_{13}\Big[\cos 2\theta_{12}\cos(\delta_{14}-\delta_{24})\sin^2\Delta_{21}$$
$$- \frac{1}{2}\sin(\delta_{14}-\delta_{24})\sin 2\Delta_{21}\Big],$$

$$P_4(\delta_{13}-(\delta_{14}-\delta_{24})) = a\sin 2\theta^{3\nu}_{\mu e}\sin 2\theta^{4\nu}_{\mu e}\Big[\cos 2\theta_{13}\cos(\delta_{13}-(\delta_{14}-\delta_{24}))\sin^2\Delta_{31}$$
$$+ \frac{1}{2}\sin(\delta_{13}-(\delta_{14}-\delta_{24}))\sin 2\Delta_{31} - \frac{1}{4}\sin^2 2\theta_{12}\cos^2\theta_{13}\cos(\delta_{13}-(\delta_{14}-\delta_{24}))\sin^2\Delta_{21}\Big],$$

Oscillation Probability for 3+1 model

- With the parameters defined as

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4E, \text{ a function of baseline(L) and neutrino energy(E)}$$
$$a = \cos\theta_{14}\cos\theta_{24},$$
$$b = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12},$$
$$\sin 2\theta_{\mu e}^{3\nu} = \sin 2\theta_{13}\sin\theta_{23},$$
$$\sin 2\theta_{\mu e}^{4\nu} = \sin 2\theta_{14}\sin\theta_{24}.$$

$$P_{\mu e}^{4\nu} \simeq P_1 + P_2(\delta_{13}) + P_3(\delta_{14} - \delta_{24}) + P_4(\delta_{13} - (\delta_{14} - \delta_{24})). \quad (5)$$

- We see that δ_{14} and δ_{24} are always together in a linear dependent form.

Details of experiments

- Now, we check whether individual values of δ_{14} and δ_{24} cause any impact on oscillation probabilities after matter effects are introduced.
- GLoBES[1] which is a software package for the simulation of long baseline neutrino oscillation experiments is used for simulating NOvA and DUNE.

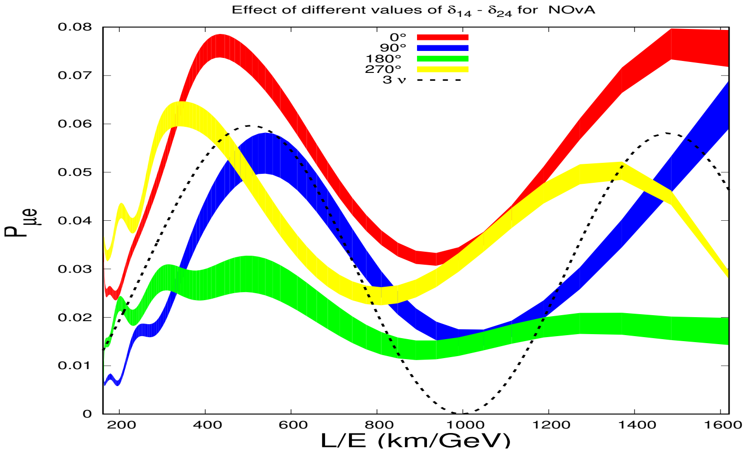
Name of Exp	NOvA [2]	DUNE [3]
Location	Minnesota	South Dakota
POT(yr^{-1})	6.0x10^{20}	1.1x10^{21}
Baseline(Far/Near)	812 km/1km	1300 km/500 m
Target mass(Far/Near)	14 kt/290 t	40 kt/8 t
Exposure(years)	$3+\bar{3}$	$3+\bar{3}$

[1]. P. Huber et al.Comput.Phys.Commun.167,195(2005), arXiv:hep-ph/0407333 [hep-ph]

[2]. P.Adamson et al.[NOvA Collaboration], Phys.Rev.Lett.116,no.15

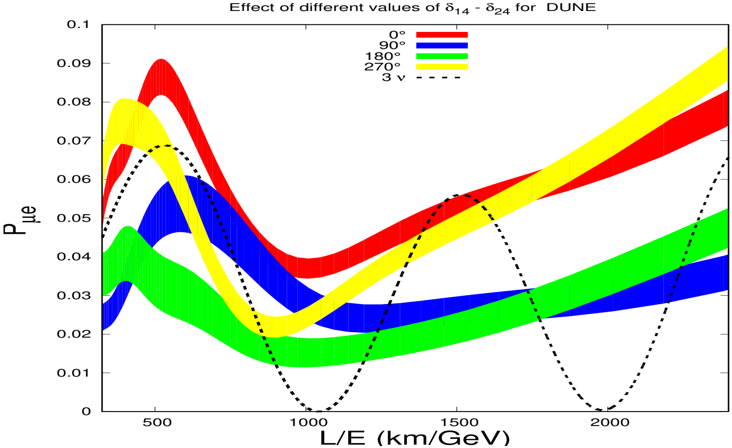
[3]. T.Alion et al.[DUNE Collaboration], arXiv:1606.09550

Effect of different $\delta_{14} - \delta_{24}$ with matter effects for NOvA



- We plotted bands for different $\delta_{14} - \delta_{24}$ values while changing the individual values of δ_{14} and δ_{24} for NOvA.
- We observe small variations due to individual values of δ_{14} and δ_{24} at all energies.

Effect of different $\delta_{14} - \delta_{24}$ with matter effects for DUNE



- We plotted bands for different $\delta_{14} - \delta_{24}$ values while changing the individual values of δ_{14} and δ_{24} for DUNE.
- We observe small variations due to individual values of δ_{14} and δ_{24} at all energies.

- In this work, we try to see which value of $(\delta_{14} - \delta_{24})$,has the least effect on the parameter degeneracy of resolution of δ_{13}, θ_{23}.
- We use latest NOvA Best fit values as true values for this analysis [4]

$\Delta m^2_{21}/(10^{-5}\ \mathrm{eV}^2/c^4)$	7.53 ± 0.18			
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$			
$\sin^2\theta_{13}$	0.0210 ± 0.0011			
	NH, UO	NH, LO	IH, UO	IH, LO
$\Delta m^2_{32}/(10^{-3}\ \mathrm{eV}^2/c^4)$	$+2.48^{+0.11}_{-0.06}$	$+2.47$	-2.54	-2.53
$\sin^2\theta_{23}$	$0.56^{+0.04}_{-0.03}$	0.48	0.56	0.47
δ_{CP}/π	$0.0^{+1.3}_{-0.4}$	1.9	1.5	1.4
	-	$+1.6\sigma$	$+1.8\sigma$	$+2.0\sigma$

[4].M.A. Acero et al.[NOvA Collaboration],Phys.Rev.Lett. 123 (2019) no.15, 151803

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	-	$+1.6\sigma$	$+1.8\sigma$	$+2.0\sigma$

- For sterile mixing angles, we take upper bounds given in NOvA neutral current analysis paper. [5]

$$\theta_{14} = 10^\circ; \theta_{24} = 20.8^\circ; \theta_{34} = 31.2^\circ$$

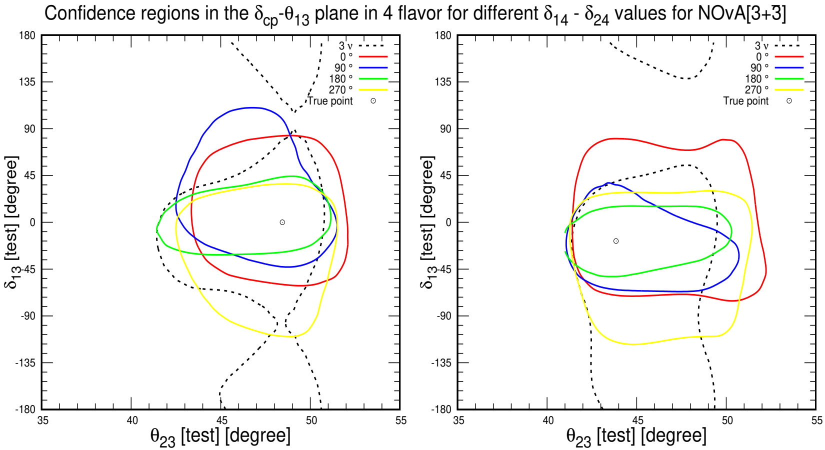
[4].M.A. Acero et al.,Phys.Rev.Lett. 123 (2019) no.15, 151803

[5].P. Adamson et al.[NOvA Collaboration] Phys.Rev. D96 (2017) no.7, 072006

Results

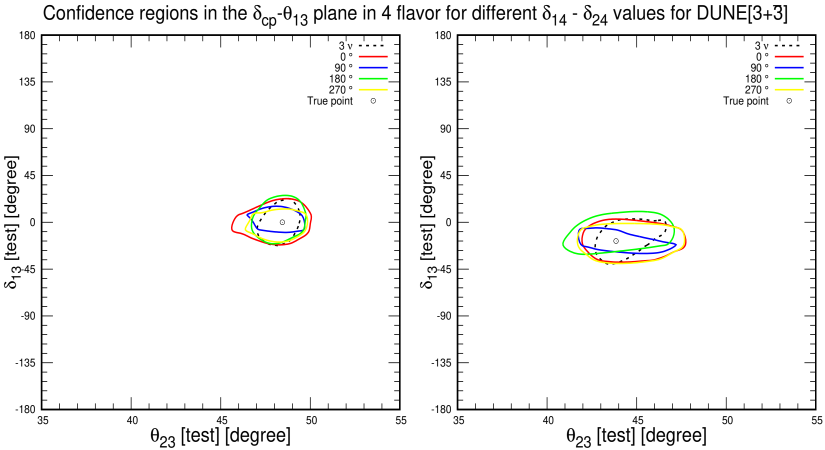
- We explore allowed regions in θ_{23}-δ_{13} plane from NOvA and DUNE simulation data with different values of (δ_{14}- δ_{24}) considering latest NOvA results as true values.
- We plot test values for both NH-HO and NH-LO of 3 and 3+1 neutrino models.

Results



- The contours of this figure are plotted for 90% C.I regions for NOvA. We take NH-HO(NH-LO) as true values for left(right) case.

Results



- The contours of this figure are plotted for 90% C.I regions for DUNE. We take NH-HO(NH-LO) as true values for left(right) case.

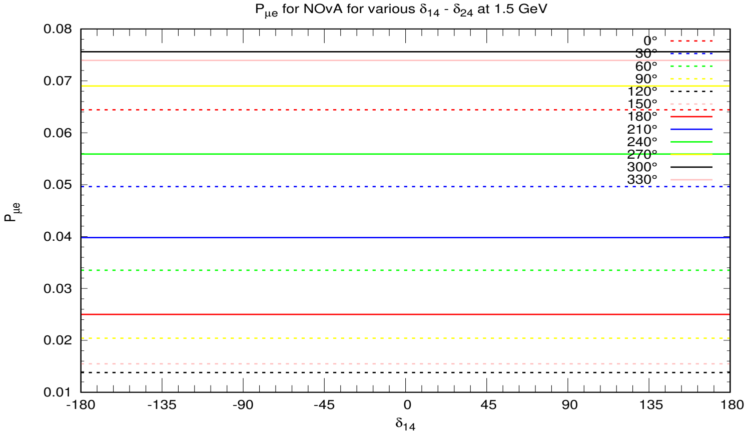
Conclusion

- We see that for both NH-HO and NH-LO case, δ_{14} - $\delta_{24} = 180$ has highest sensitivity to parameter degeneracy for NOvA.
- We see that for both NH-HO and NH-LO case, δ_{14} - $\delta_{24} = 90$ has highest sensitivity to parameter degeneracy for DUNE.
- The difference in the result maybe due to difference in matter effects and statistics between NOvA and DUNE. This is our subject of future investigation.
- More work is needed to be done to include different run-times of NOvA and DUNE experiment

Thank You

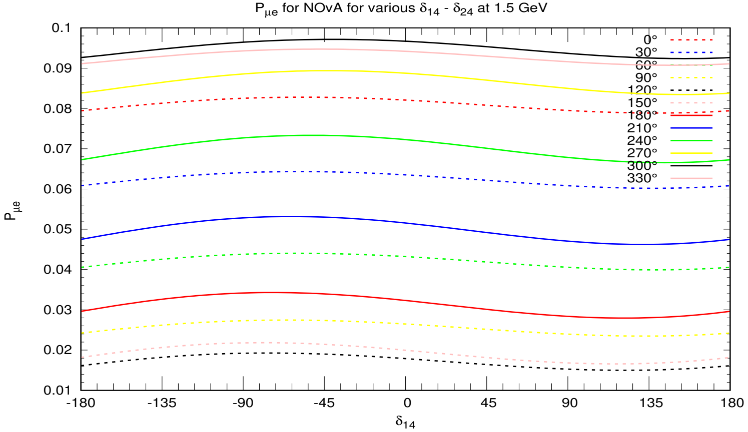
Backup Slides

Effect of different $\delta_{14} - \delta_{24}$ in Vacuum



- We see that individual values of δ_{14} and δ_{24} do not matter in vacuum case.

Effect of different $\delta_{14} - \delta_{24}$ with matter effects



- We see that individual values of δ_{14} and δ_{24} cause small variations with matter effects case.