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Exploring non-unitary mixing of active neutrinos at T2K, T2HK, and T2HKK

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Abstract

- Investigates the capability of long-baseline experiments T2K, T2HK, and T2HKK in establishing the unitarity of active-neutrino mixing by ruling out the non-unitary mixing scheme as a function of true values of CP-violating phase $\delta_{\rm CP}$.
- Obtain the bound on NU parameter in 21 sector
- Determine the sensitivity limit of these experiments in determining NU parameter.

1. Introduction

- The flavor state of neutrino produced in the weak interaction, $|\nu_\alpha\rangle = \sum U_{\alpha i}|\nu_i\rangle$ can change its flavor as it propagates.
- The three flavor neutrino oscillation paradigm has become the most accepted theoretical model to explain the phenomenon of neutrio oscillation.
- In this model, the mixing matrix is unitary and it's standard parametrization is given by $U_{PMNS} = R(\theta_{23})V(\theta_{13},\delta_{CP})R(\theta_{12})$
- Neutrino oscillation implies that neutrinos are massive. To explain massive neutrino, the extended theoretical models require additional sterile neutrinos.
- Short baseline anomalies are also point towards existence of sterile neutrino.
- If such neutrinos exist in nature, then they can mix with active neutrinos.
  - light sterile neutrino (eV scale) : can be probed via Oscillation physics.
  - Heavy sterile neutrino (within TeV scale): can be probed by looking at the deviation from the unitarity of PMNS mixing matrix $\Longrightarrow$ Non-unitary (NU) neutrino mixing. As in presence of such neutrino the active neutrino mixing matrix is no more unitary .
- The goal of this work is to study NU mixing at T2K, T2HK and T2HKK experiment.

2. Neutrino oscillation with non-unitary neutino mixing

- In presence of heavy sterile neutrino, the effective neutrino mixing matrix is of the form

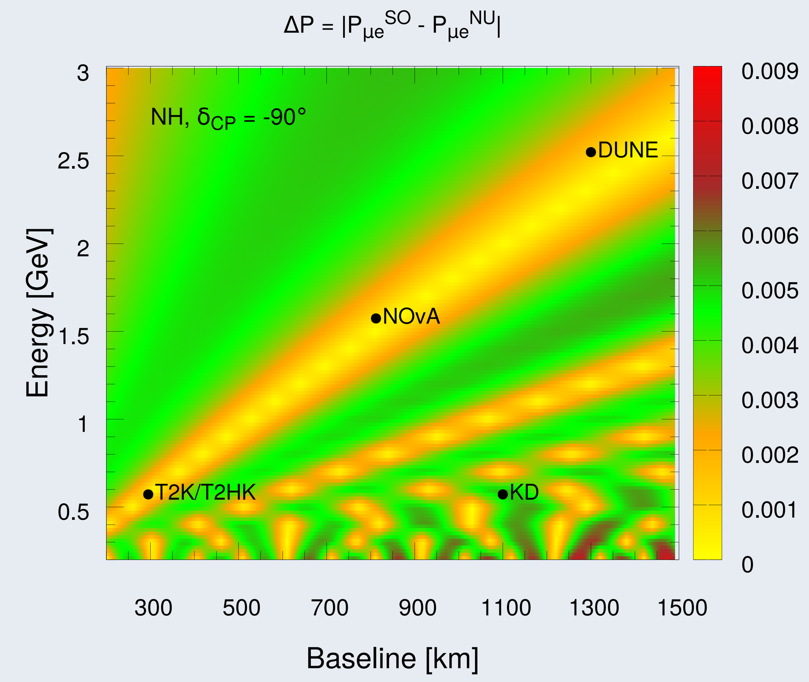
$$U_{eff} = \begin{pmatrix} N_{3\times3} & \Theta \\ R & S \end{pmatrix},$$

where $N_{3\times3}$ is the non-unitary ν_a mixing

$$N = (1 - \frac{1}{2}\Theta^\dagger\Theta)U_{\rm PMNS} = (1-\eta)U_{\rm PMNS},$$

which yields $\eta = \frac{1}{2}\Theta^\dagger\Theta$.

- The Hamiltonian in standard paradigm is given by



$$\mathcal{H}_m = \frac{1}{2E}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31}\end{pmatrix} + U^\dagger_{\rm PMNS}\begin{pmatrix} V_{\rm CC}+V_{\rm NC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC}\end{pmatrix} U_{\rm PMNS}$$

with $\Delta m^2_{ij} = m^2_i - m^2_j$, $V_{\rm CC} = \sqrt{2}G_F n_e$ and $V_{\rm NC} = -G_F n_n/\sqrt{2}$.

- In presence of non-unitary lepton mixing, Hamiltonian gets modified as

$$\mathcal{H}^N_m = \frac{1}{2E}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31}\end{pmatrix} + N^\dagger\begin{pmatrix} V_{\rm CC}+V_{\rm NC} & 0 & 0 \\ 0 & V_{\rm NC} & 0 \\ 0 & 0 & V_{\rm NC}\end{pmatrix} N.$$

- Oscillation probability,

$$P_{\alpha\beta}(E,L) = |\langle\nu_\beta|\nu_\alpha(L)\rangle|^2 = \left|\left(N e^{-i\mathcal{H}^N_m L} N^\dagger\right)_{\beta\alpha}\right|^2.$$

4.Results

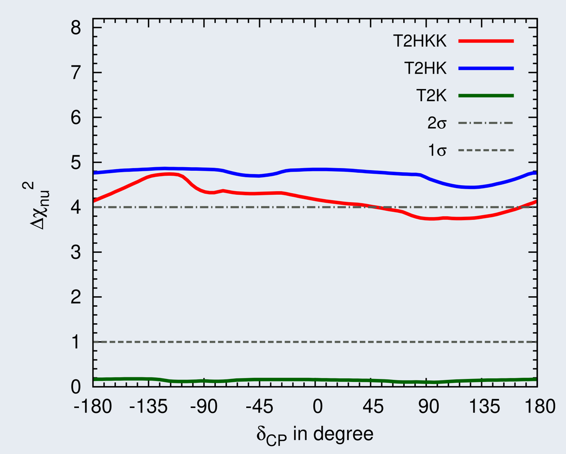


Fig1: Sensitivity to exclude NU mixing

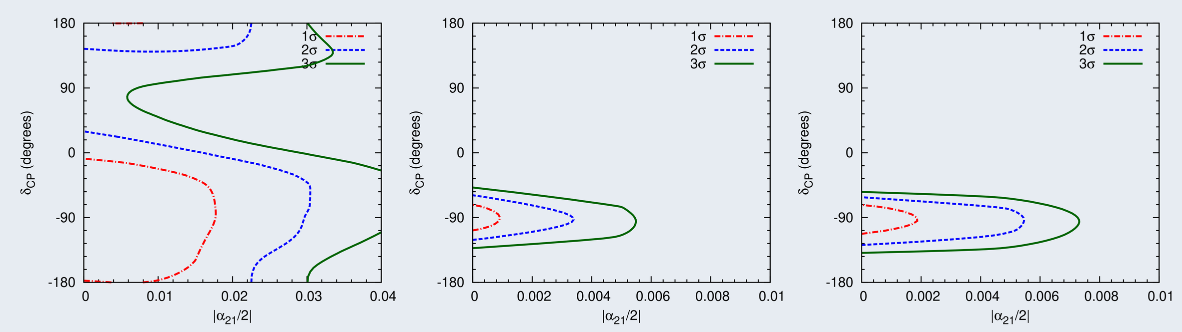


Fig2: The bounds on NU parameter. The left, middle, and right panels are respectively for T2K, T2HK, and T2HKK.

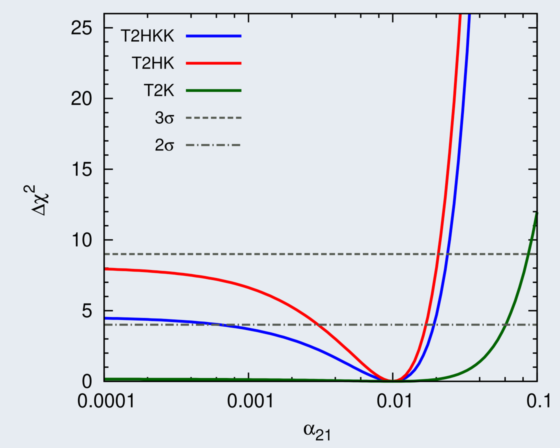


Fig3: Sensitivity limit on NU parameter

3. Simulation details

Expt	L (km)	E (GeV)	Fiducial volume (kt)	POT (10^{21}) (ν:$\bar{\nu}$)	Normalization error
T2K	295	0.6	22.5	7.8 (1:1)	uncorrelated 5% (10%) error on signal (background)
T2HK	295	0.6	187	27 (1:3)	
T2HKK	295 (JD)	0.6	187	27 (1:3)	
	1100 (KD)	0.6	187		

Simulated all the experiments using GLoBES and implemented NU mixing using MonteCUBES

Parameters	$\sin^2\theta_{12}$	$\sin^2 2\theta_{13}$	$\sin^2\theta_{23}$	Δm^2_{21}	Δm^2_{atm} NH (IH)	δ_{CP}
Best fit	0.307	0.085	0.5	7.4×10^{-5} eV^2	$2.5(-2.4)\times10^{-3}$ eV^2	$-90°$

The values of neutrino oscillation parameters used in the analysis[2].

5. Conclusions

- It is found that T2HK can establish unitarity of active neutrino mixing at above 2σ C.L. irrespective of neutrino mass hierarchy and true value of $\delta_{\rm CP}$.
- It is found that the bounds on $(\alpha_{21}/2)$ are 0.028, 0.0026, 0.005 at 2σ C.L. respectively for T2K, T2HK, and T2HKK.
- it is also found that the sensitivity limit of T2HK on NU parameter is far better than that of both T2HKK and T2K.

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