Testing partial μ-τ Reflection Symmetry at DUNE and Hyper-Kamiokande

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Neutrino Oscillations and Current Status

Neutrino Oscillations and Current Status

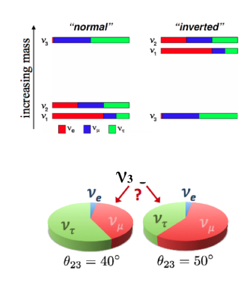
- Neutrino oscillations are well established by phenomenal experiments like **Super-Kamiokande**, **SNO**, KamLAND, K2K, MINOS etc.
- The probability of transition

$$P_{\alpha\beta} = P_{\alpha\beta}(\Delta m^2_{21}, |\Delta m^2_{31}|, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{\rm CP}; E, L, V(x)),$$

[Nufit 4.0 (Nov 2018)]

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
$\delta_{\rm CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

Major Unknowns and Puzzles



- **Unknowns** :
  1. The sign of Δm^2_{31} i.e. whether
     $\Delta m^2_{31} > 0 \implies$ Normal mass ordering.
     $\Delta m^2_{31} < 0 \implies$ Inverted mass ordering.
  2. The octant of θ_{23} i.e. if
     $\theta_{23} > 45^\circ$ Higher Octant (HO).
     $\theta_{23} < 45^\circ$ Lower Octant (HO).
  3. The Dirac CP phase δ_{CP} -$[-180, 180]$
     $\delta_{CP} = 0, \pm 180^\circ$ (CP conserving).
     $\delta_{CP} = \pm 90^\circ$ (maximal CP violation).

- **Flavour Puzzles** : Tiny neutrino masses? Origin of fermion mixing (CKM and PMNS)? Reason for large lepton mixing? Origin of CP violation in the quark (and lepton) sectors?
- Various symmetry based approaches have been successful in predicting the structure of the leptonic mixing matrix and the interrelations among these unknown quantities.

Motivation

Why μ-τ reflection Symmetry?

- In Standard parametrization U_{PMNS}

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix}$$

- $|U_{\mu 1}| \simeq |U_{\tau 1}|\,, \quad |U_{\mu 2}| \simeq |U_{\tau 2}|\,, \quad |U_{\mu 3}| \simeq |U_{\tau 3}|$ to a reasonably good degree of accuracy.

Motivation

- PMNS matrix at the 3σ level :

  For $\Delta m^2_{31} > 0$:

$$|U| \simeq \begin{pmatrix} 0.79 - 0.85 & 0.50 - 0.59 & 0.13 - 0.17 \\ 0.19 - 0.56 & 0.41 - 0.74 & 0.60 - 0.78 \\ 0.19 - 0.56 & 0.41 - 0.74 & 0.60 - 0.78 \end{pmatrix};$$

  For $\Delta m^2_{31} < 0$:

$$|U| \simeq \begin{pmatrix} 0.89 - 0.85 & 0.50 - 0.59 & 0.13 - 0.17 \\ 0.19 - 0.56 & 0.40 - 0.73 & 0.61 - 0.79 \\ 0.20 - 0.56 & 0.41 - 0.74 & 0.59 - 0.78 \end{pmatrix};$$

$\mu - \tau$ reflection Symmetry

- $\mu - \tau$ reflection symmetry : $|U_{\mu i}| = |U_{\tau i}|$ (for all $i = 1, 2, 3$)
- Neutrino mass term is unchanged under the tranformation
  $\nu_e \to \nu_e^c \; , \quad \nu_\mu \to \nu_\tau^c \; , \quad \nu_\tau \to \nu_\mu^c \quad \Longrightarrow \; \mu - \tau$ reflection Symmetry.
- Predictions :

$$|U_{\mu i}| = |U_{\tau i}| \quad \Longleftrightarrow \quad \begin{cases} \theta_{23} = \dfrac{\pi}{4} \; , \quad \theta_{13} = 0 \; ; \\ \qquad \text{or} \\ \theta_{23} = \dfrac{\pi}{4} \; , \quad \delta = \pm\dfrac{\pi}{2} ; . \end{cases}$$

- First condition is ruled out because $\theta_{13} \neq 0$.
- Second condition $\theta_{23} = \frac{\pi}{4}$, $\delta_{CP} = \pm\frac{\pi}{2}$ is still allowed at 3σ.
- Current best fit value of θ_{23} is non-maximal for NH and IH $\Longrightarrow$ deviation from $\mu - \tau$ reflection symmetry.

Partial $\mu - \tau$ reflection symmetry

Partial $\mu - \tau$ reflection symmetry and its predictions

- Partial $\mu - \tau$ reflection symmetry $\implies$ $|U_{\mu i}| = |U_{\tau i}|$ holds only for a single column.
- Almost all discrete subgroups of SU(3) (few exceptions) having three dimensional irreducable representations, display partial $\mu - \tau$ symmetry. Here for $G_\nu = Z_2$ and $G_\nu = Z_m$
- For $|U_{\mu 1}| = |U_{\tau 1}|$

$$C1: \quad \cos\delta_{CP} = \frac{(c_{23}^2 - s_{23}^2)(c_{12}^2 s_{13}^2 - s_{12}^2)}{4 c_{12} s_{12} c_{23} s_{23} s_{13}}, and \quad \cos^2_{12}\cos^2_{13} = \frac{2}{3} \quad (1)$$

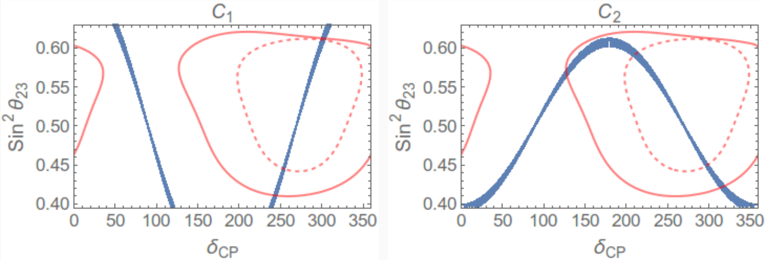
- For $|U_{\mu 2}| = |U_{\tau 2}|$

$$C2: \quad \cos\delta_{CP} = \frac{(c_{23}^2 - s_{23}^2)(c_{12}^2 - s_{12}^2 s_{13}^2)}{4 c_{12} s_{12} c_{23} s_{23} s_{13}}, and \quad \sin^2_{12}\cos^2_{13} = \frac{1}{3}. \quad (2)$$

- $|U_{\mu 3}| = |U_{\tau 3}|$ $\implies$ θ_{23} - maximal and δ_{CP} - unrestricted.

Model Predictions

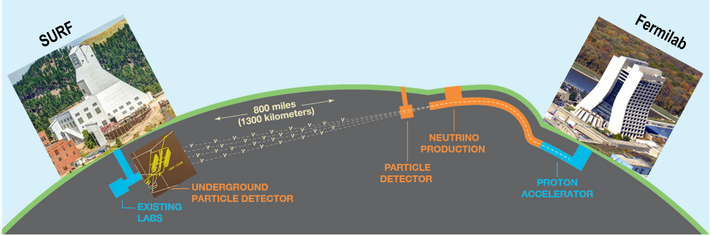
Model predictions



- Red solid(dashed) contours - 3σ regions of global oscillation data for NH (IH).
- Blue - model predictions C1 (left) and C2 (right).
- Each θ_{23} corresponds to two CP phases - δ_{CP}, $(360^\circ - \delta_{CP})$.

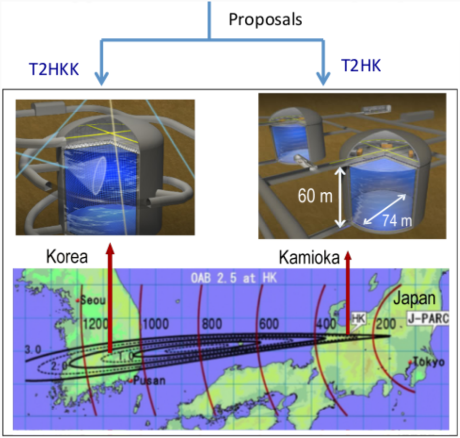
Testing correlations at DUNE and Hyper-K

Deep Underground Neutrino Experiment



- Utilizes Long baseline Neutrino Facility (LBNF) - for high intensity neutrino beam and the infrastructure required for DUNE.
- Baseline(L): 1300 km. Fermilab to the Homestake mine in South Dakota.
- Near neutrino detector (NND): NOMAD-inspired fine grained tracker (FGT), 0.5 km downstream of the target.
- Proposed Far detector (FD): 40 kton LArTPC.
- Initial proton beam power is 1.2 MW (1×10^{21} POT/year), later increased to 2.3 MW.
- Proton beam energy : 120 GeV and ν_μ beam energy : $0.5 < E_\nu < 8$ GeV.
- We assume 5 years of running time in both neutrino and antineutrino beam modes.

Hyper-Kamiokande Experiment



T2HK / 2 x JD

2 tanks of Water Cherenkov detectors @ Kamioka – 295 km
Fiducial volume – 2x187 kt
and 2.5^0 OA

T2HKK / JD+KD

1 WC @ Kamioka – 295 km
+ 1 WC @ Korean – 1100 km)
374 km

Beam OAA – 1.5^0 or 2^0 or 2.5^0

- The proton beam power of 1.3 MW, giving a total of 27×10^{21} POT.
- Total run-time : 10 years.

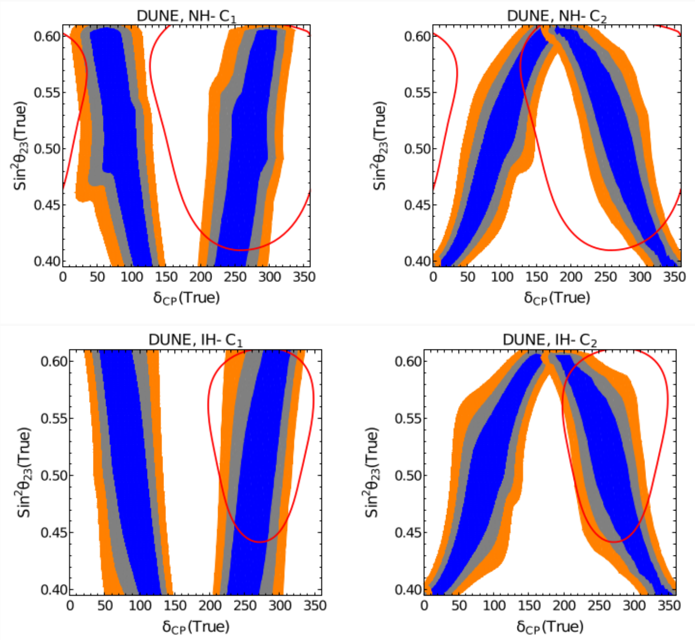
Simulation Details

Osc. param.	True values	Test values
$\sin^2\theta_{13}$	0.0219	0.0197–0.0244
$\sin^2\theta_{12}$	0.306	0.272–0.346
θ_{23}	39°–51°	39°–51°
$\Delta m^2_{21}(\mathrm{eV}^2)$	7.50×10^{-5}	Fixed
$\Delta m^2_{31}(\mathrm{eV}^2)$	2.50×10^{-3}	$(2.35–2.65) \times 10^{-3}$
δ_{CP}	(0–360)°	Symmetry predictions

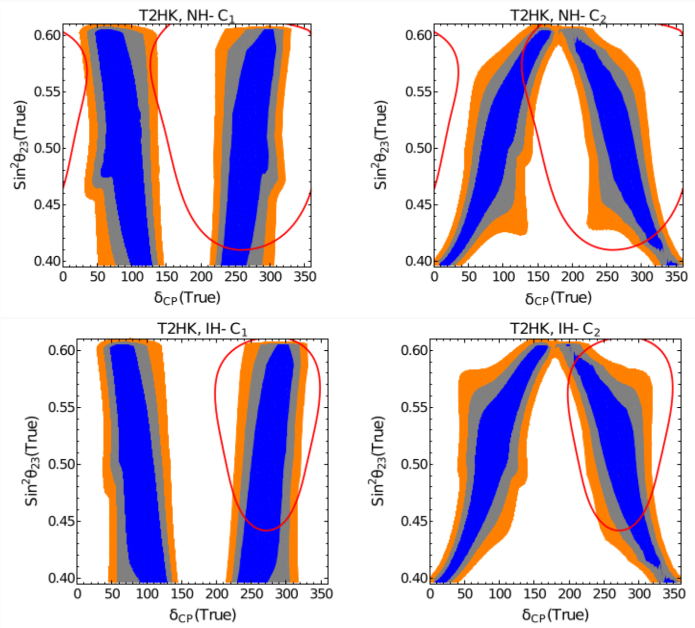
- The data corresponding to each experiment is generated by considering the true values of the oscillation parameters given in the table.
- In theoretical fit, we calculate test events based on model predictions C1 and C2.
- Marginalized over $\sin^2\theta_{13}$, $\sin^2\theta_{23}$, $\sin^2\theta_{12}$, $|\Delta m^2_{31}|$.
- Simulation and analysis using GLoBES package.

Results and Conclusions

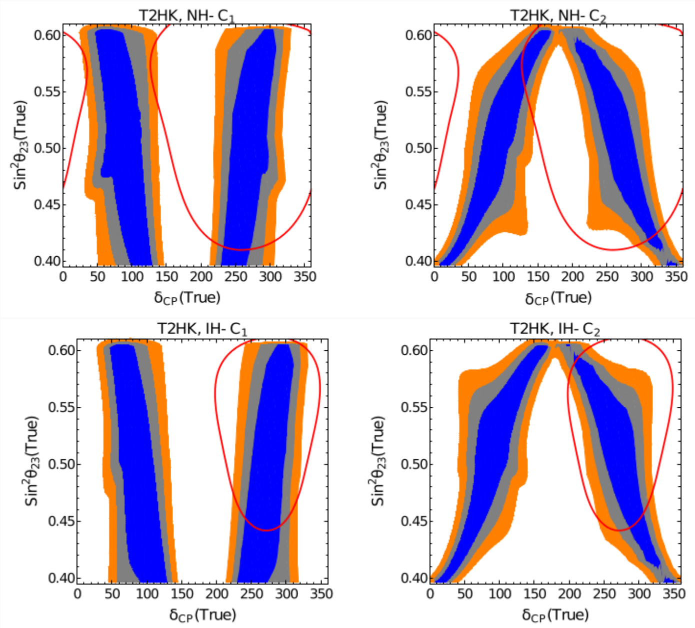
Model predictions



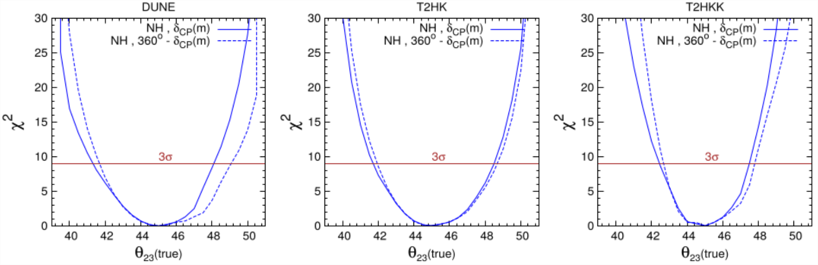
Model predictions



Model predictions



Differentiating C1 and C2 predictions



- True δ_{CP} values are calculated using the correlation C1 and test values - C2.
- Solid blue curves : $0^\circ < \delta_{CP} < 180^\circ$.
- Dashes blue curves : $(360^\circ - \delta_{CP})$ i.e. $180^\circ < \delta_{CP} < 360^\circ$.

Conclusions

- Studied partial reflection symmetry of the leptonic mixing matrix.
- Analysed the correlations among $\sin^2\theta_{23} - \delta_{CP}$ predicted by the symmetries.
- Verified the testability of these symmetries at DUNE and Hyper-K.

Thank you !!!