Constraining CPT violation with Hyper-Kamiokande and ESS $\nu_{SB}$

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Lepton Photon 2021, January 11, 2022
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CPT Symmetry is considered to be an exact symmetry of nature. Briefly, CPT theorem states that particles and anti-particles will have same mass and same life time. There is no evidence of CPT violation in any experiments so far. In case CPT symmetry is violated then for neutrino oscillation case we have to specify neutrinos and anti-neutrinos with different set of oscillation parameters.

\[
|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}) |\nu_i\rangle. \tag{1}
\]

\[
|\bar{\nu}_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}^*(\bar{\theta}_{12}, \bar{\theta}_{13}, \bar{\theta}_{23}, \bar{\delta}_{CP}) |\bar{\nu}_i\rangle. \tag{2}
\]
CPT Asymmetry

- For Neutrino Oscillation case CPT Asymmetry can be defined as

\[ A_{\alpha\beta}^{\text{CPT}} \equiv P_{\alpha\beta} - P_{\beta\alpha}. \]  

(3)

where \( P_{\alpha\beta} \) and \( P_{\beta\alpha} \) are the oscillation probabilities for neutrinos and anti-neutrinos respectively. And \( \alpha, \beta = e, \mu \).

- As we are considering CPT is conserved in nature, \( A_{\alpha\beta}^{\text{CPT}} \) will be zero in vacuum.

- But for long base line experiments this \( A_{\alpha\beta}^{\text{CPT}} \) will be non-zero due to matter effect giving an illusion of CPT violation.
Simulations

- For simulation purpose we have used GLoBES software.
- \( ESS_\nu SB(2\nu + 8\bar{\nu}) \): POT of \(27 \times 10^{22}\) corresponding to 5 MW proton beam, Baseline of 540 km, a water Cherenkov detector of fiducial volume 500 kt, neutrino beam energy of 0.25 GeV.
- \( T2HK(1\nu + 3\bar{\nu}) \): POT of \(27 \times 10^{21}\) corresponding to 1.3 MW proton beam, Baseline of 295 km, two water Cherenkov detector (F.D) of fiducial volume 187 kt \((2 \times 187kt = 374kt)\), neutrino beam energy of 0.56 GeV.
- \( T2HKK(1\nu + 3\bar{\nu}) \): POT of \(27 \times 10^{21}\) corresponding to 1.3 MW proton beam, Baseline of 1100 km, a water Cherenkov detector (F.D) of fiducial volume 187 kt, neutrino beam energy of 0.56 GeV.
- \( DUNE(5\nu + 5\bar{\nu}) \): POT of \(10 \times 10^{21}\) corresponding to 1.2 MW proton beam, Baseline of 1300 km, Liquid argon time projection chamber (LArTPC) of fiducial volume 40 kt, neutrino beam energy 0.5-8 GeV.
we simulate each experiment with $\Delta x = |x - \bar{x}| = 0$, where $x(\bar{x})$ is the oscillation parameter for neutrinos (antineutrinos).

Later, we evaluate the sensitivity of each of the experiments to non-zero $\Delta x$.

In each case, we choose three values for $\theta_{23}$: lower octant ($\sin^2 \theta_{23} = 0.43$), maximal ($\sin^2 \theta_{23} = 0.5$) and higher octant ($\sin^2 \theta_{23} = 0.57$) to study the correlation between the CPT violation sensitivity and the octant of $\theta_{23}$.

In the test values, we marginalize over all the oscillation parameters for both neutrinos and antineutrinos except $x$, $\bar{x}$ and the solar parameters.

$\chi^2(\Delta X) = \chi^2(|x - \bar{x}|) = \chi^2(x) + \chi^2(\bar{x})$

minimum $\chi^2(\Delta X)$ has been calculated over all possible combinations of $|x - \bar{x}|$. 
For our study we have taken $\Delta X$ to be $\Delta(\Delta m^2_{31})$, $\Delta(\delta_{CP})$ and $\Delta(\sin^2 \theta_{23})$.

Furthermore we have analysed neutrino and anti-neutrino data independently assuming nature is invariant under CPT.

We have done this study for combination of DUNE + T2HKK and DUNE + ESS$\nu$SB experiments and scrutinized whether they provide the same oscillation parameters as predicted by CPT symmetry.

Again we have assumed that CPT is violated in nature and estimated the sensitivity of T2HK, T2HKK, ESS$\nu$SB, and DUNE to establish CPT invariance violation individually.
Figure: CPT violation sensitivity for $\Delta m_{31}^2$ and $\sin^2 \theta_{23}$ for long baseline experiments T2HK, T2HKK, ESSnuSB and DUNE
**Results**

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**Figure:** CPT violation sensitivity for $\Delta(\delta_{CP})$ for long baseline experiments T2HK, T2HKK, ESSnuSB and DUNE

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Results

Figure: Allowed parameter space between different neutrino and antineutrino oscillation parameters at 99% C.L. for combination of experiments.
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Results

Figure: Allowed regions between $\delta_{CP}$ and $\bar{\delta}_{CP}$ in the CPT violating scenario.
Conclusion

- T2HKK and ESS$\nu$SB experiments are more sensitive towards $\delta_{CP}$ to obtain the bounds on $\Delta(\delta_{CP})$.
- T2HK, T2HKK and DUNE are sensitive to the atmospheric mixing parameters [$\Delta(\Delta m_{31}^2)$ and $\Delta(sin^2 \theta_{23})$].
- T2HK gives most stringent limits on $\Delta(\Delta m_{31}^2)$ and $\Delta(sin^2 \theta_{23})$.
- T2HKK gives best bound on $\Delta(\delta_{CP})$.
- Both DUNE + T2HKK and DUNE + ESS$\nu$SB experiments are sensitive to CPT violation.
- DUNE + T2HKK can even resolve the octant degeneracy in $\theta_{23}$ and $\overline{\theta}_{23}$ at 99% C.L.
- All the upcoming long-baseline experiments will be able to establish CPT violation individually at 99% C.L. in their proposed run time by demonstrating $\delta_{CP} \neq \overline{\delta}_{CP}$.
Thank You.