Model-independent way to test the *CPT* violation using *NOvA*, *T2K* and *INO* experiments

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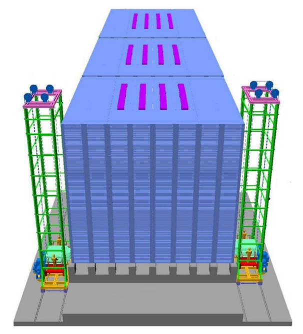
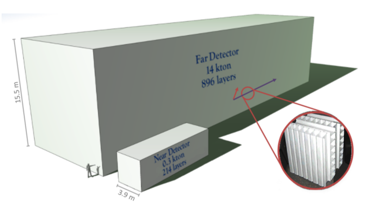
1. Introduction

- Charge-Parity-Time (CPT) symmetry $\rightarrow$ identical oscillation parameters for ν and $\bar{\nu}$
- If different mass and mixing parameters for ν and $\bar{\nu}$ $\rightarrow$ possible hint for CPT violation (Model-independent approach)
- Our focus to find sensitivity for $(\Delta m^2_{32} - \Delta\bar{m}^2_{32})$ and $(\sin^2\theta_{23} - \sin^2\bar{\theta}_{23})$ using long-baseline and atmospheric neutrino experiments in different possible combinations of octant for neutrinos and anti-neutrinos
- We show the joint sensitivity of the T2K, NOvA and INO experiments to such CPT violating observables

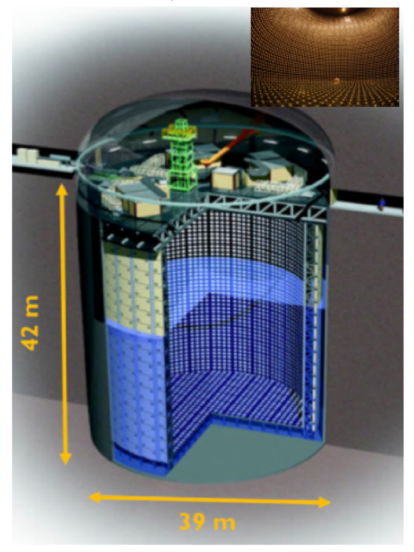
2. Experiments



Iron-Calorimeter(ICAL)-Atmospheric neutrino experiment, Location: Tamilnadu, India



The NOvA (NuMi off-axis ν_e appearance), long-baseline neutrino experiment, Location: Ash River, Minnesota



The T2K (Tokai to Kamioka), long baseline, Location: Tokai, Japan

3. Oscillation Parameters

Osc. parameters	True values	Marginalization range
$\sin^2(2\theta_{12})$	0.86	Fixed
Δm^2_{21} (eV^2)	7.6×10^{-5}	Fixed
$\sin^2(\theta_{13})$	0.0234	Fixed
$\sin^2(\theta_{23})$	varied	0.3-0.7
$\|\Delta m^2_{32}\|$ (eV^2)	varied	(2.0-3.0) $\times 10^{-3}$
δ_{CP}	0.0	Fixed (INO)
δ_{CP}	0.0	$[0 - 360^o]$ (T2K,NOvA)

Table: Oscillation parameters for both ν and $\bar{\nu}$.

Possible combinations of octants for ν and $\bar{\nu}$:

Case 1: ν and $\bar{\nu}$ both in Higher Octant (HO) [$\sin^2\theta_{23}(\sin^2\bar{\theta}_{23})$ in range 0.5-0.7]

Case 2: ν and $\bar{\nu}$ both in Lower Octant (LO) [$\sin^2\theta_{23}(\sin^2\bar{\theta}_{23})$ in range 0.3-0.5]

Case 3: ν in HO and $\bar{\nu}$ in LO

Case 4: ν in LO and $\bar{\nu}$ in HO

$\rightarrow$ The experimental sensitivities for all the octants cases have been shown on a single frame with allowed regions at 1σ,2σ and 3σ Confidence Level (CL) under Normal-Hierarchy assumption.

4. Simulation Inputs

Features	INO
Source	Atmospheric neutrino
Runtime	10 years for ν_μ and $\bar{\nu}_\mu$
Detector	50kton Iron Calorimeter
Charge-id eff.	$\sim 99\%$ for μ^- and μ^+
Direction eff.	1 degree (few GeV muons)
Features	**NOvA**
Baseline	810 km
Run time	3 year ν and 3 year $\bar{\nu}$
Detector	14 kton
Signal eff.	26%(ν_e), 41% ($\bar{\nu}_e$),100% (ν_μ, $\bar{\nu}_\mu$ CC)
Background eff	as in Ref. [1]
Features	**T2K**
Baseline	295 km
Run time	5 year ν and 5year $\bar{\nu}$
Detector	22.5 kton
Signal eff.	87% (ν_e,$\bar{\nu}_e$), 100%(ν_μ, $\bar{\nu}_\mu$CC)
Background eff.	as in Ref. [1]

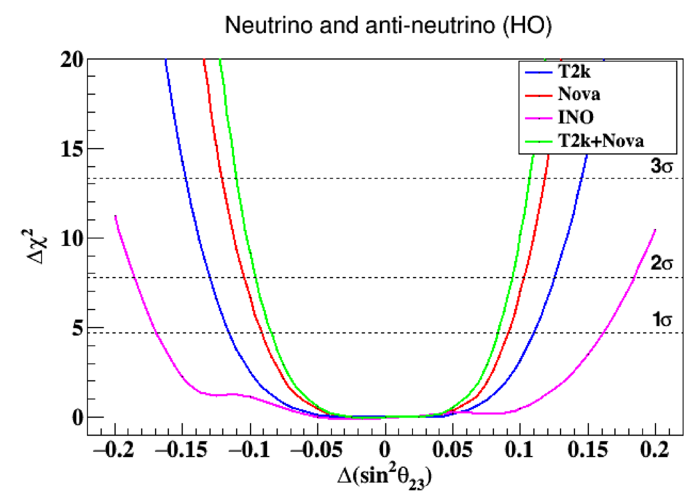
$\rightarrow$ Systematics used in analysis as given in Ref [1]

$\rightarrow$ GLoBES [2] simulation toolkit for long-baseline experiments and a c++ based based code for atmospheric ν experiment.

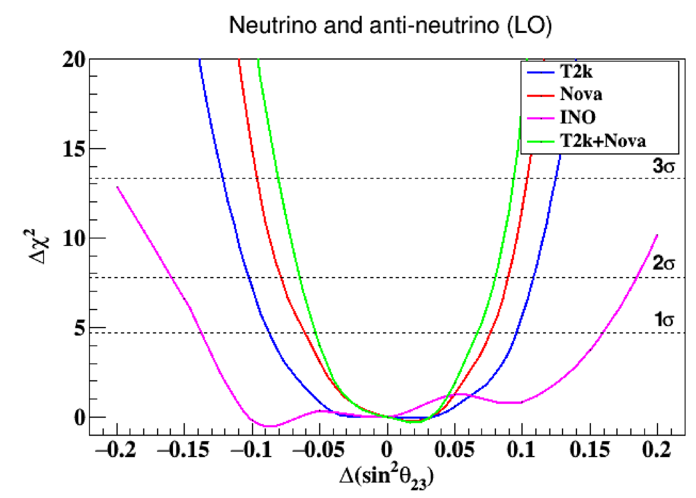
5. Methodology

- Identical oscillation parameters for ν and $\bar{\nu}$ have been considered as null hypothesis(i.e. $[\Delta(\Delta m^2_{32}) = (\Delta m^2_{32} - \Delta\bar{m}^2_{32}) = 0]$, and $[\Delta\sin^2\theta_{23} = (\sin^2\theta_{23} - \sin^2\bar{\theta}_{23}) = 0]$)
- To rule out the null hypothesis, true values of neutrino and anti-neutrino oscillation parameters (Δm^2_{32}, $\sin^2\theta_{23}$, $\Delta\bar{m}^2_{32}$, $\sin^2\bar{\theta}_{23}$) have been varied within marginalisation range and generated true datasets
- A four dimensional grid search is performed for the predicted dataset. χ^2 is calculated between the true datasets and predicted datasets for each set of true values of oscillation parameters
- For each set of difference $\Delta(\Delta m^2_{32})$ or $\Delta\sin^2\theta_{23}$, we calculate $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ including marginalisation and plot it as the functions of desired set of differences

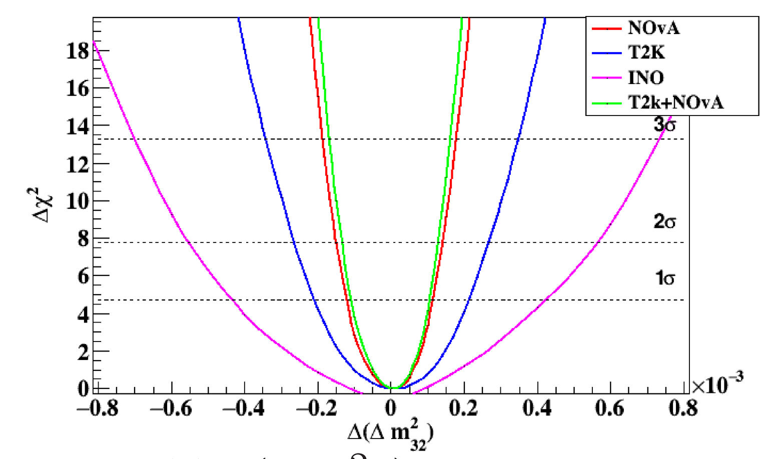
6. Results



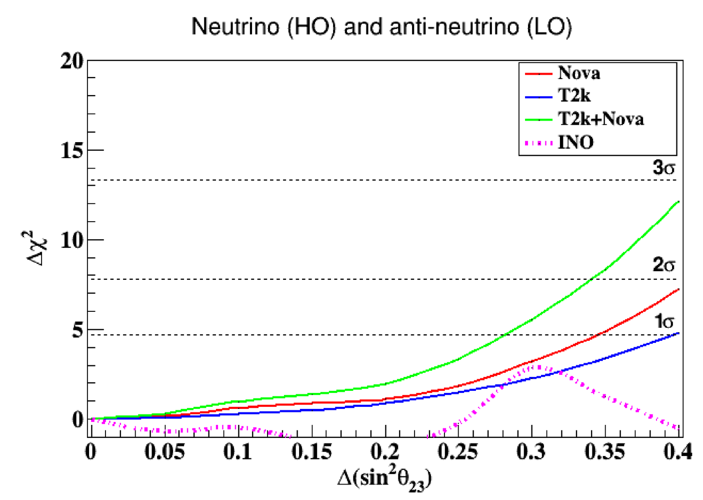
(a)



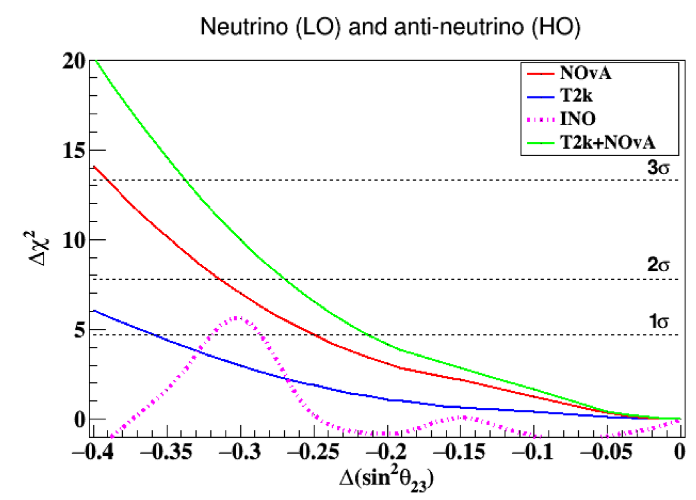
(b)



(e)$\Delta(\Delta m^2_{32})$ sensitivity



(c)



(d)

$\|\Delta(\Delta m^2_{32})\| \times 10^{-3}eV^2$				
Osc.parameter	NOvA	T2K	INO	T2K+NOvA
$\|\Delta(\Delta m^2_{32})\|$	0.10	0.22	0.40	0.10
$\|\Delta\sin^2\theta_{23}\|$				
Octant Case 1	0.1	0.13	0.16	0.07
Octant Case 2	0.08	0.12	0.17	0.09
Octant Case 3	0.34	0.4	$<1\sigma$	0.28
Octant Case 4	0.24	0.36	$<1\sigma$	0.21

f) 1σ sensitivity

Joint sensitivity of NOvA, T2K, INO for $\Delta\sin^2\theta_{23}$ when (a) ν and $\bar{\nu}$ in HO, (b) ν and $\bar{\nu}$ in LO, (c) ν in HO and $\bar{\nu}$ in LO and (d) when ν in LO and $\bar{\nu}$ in HO and (e)for $\Delta(\Delta m^2_{32})eV^2$ which is almost same for all octants

- Measurement of $\Delta\sin^2\theta_{23}$ is largely affected by the existence of ν and $\bar{\nu}$ in particular octant
- All considered experiments are least sensitive for different octant combinations for neutrinos and anti-neutrinos
- For similar octant combinations (either LO or HO) for both ν and $\bar{\nu}$, Precise determination of $\Delta\sin^2\theta_{23}$ for all the experiments
- Each experiment is able to measure $\Delta(\Delta m^2_{32})$ quite significantly irrespective of different octant combinations

References

[1] Phys.Rev.D 101 (2020) 5, 5. DOI: 10.1103/PhysRevD.101.055017
[2] P. Huber et al., Comput. Phys. Commun. 167, 195 (2005)

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7. Conclusions

- With the proposed fiducial volume and run time, the NOvA detector found the best among all the considered experiments for constraining $\Delta(\Delta m^2_{32})$ and $\Delta\sin^2\theta_{23}$
- NOvA+T2k joint results enhances the sensitivities for $\Delta\sin^2\theta_{23}$ if the ν and $\bar{\nu}$ are in different octants. The present CPT bounds at 1σ confidence interval are shown in Table(f)

Publication

This work has been published in: **Phys.Rev.D 101 (2020) 5, 5. DOI: 10.1103/PhysRevD.101.055017**

THANK YOU!!