High precision measurements of oscillation parameters exploiting the complementarity between DUNE and T2HK

Ritam Kundu, Sanjib Kumar Agarwalla, Masoom Singh

Institute of Physics, Bhubaneswar, India

arXiv: 2408.12735

September 20, 2024

Contribution ID:- 130
NuFact 2024 - The 25th International Workshop on Neutrinos from Accelerators

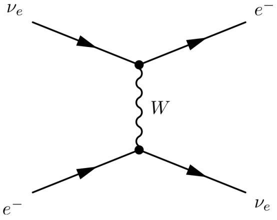
Outline

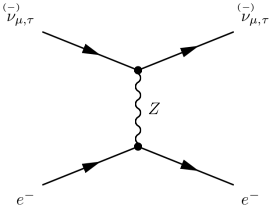
1. Introduction and motivation
    - Status of current oscillation parameters
    - Deviation of θ_{23} from maximal mixing
    - Role of appearance ($\nu_\mu \to \nu_e$) and disappearance ($\nu_\mu \to \nu_\mu$) oscillation channels in probing deviation from maximal mixing

2. Regarding this work
    - Sensitivity of DUNE and T2HK in determining deviation from maximal θ_{23} with variable exposure
    - Precision measurements in atmospheric oscillation parameters - θ_{23} and Δm^2_{31}
    - Wrong θ_{23} octant exclusion
    - Allowed regions in $\sin^2\theta_{23} - \Delta m^2_{31}$ and $\sin^2\theta_{23} - \delta_{\mathrm{CP}}$ plane

3. Summary and Conclusions

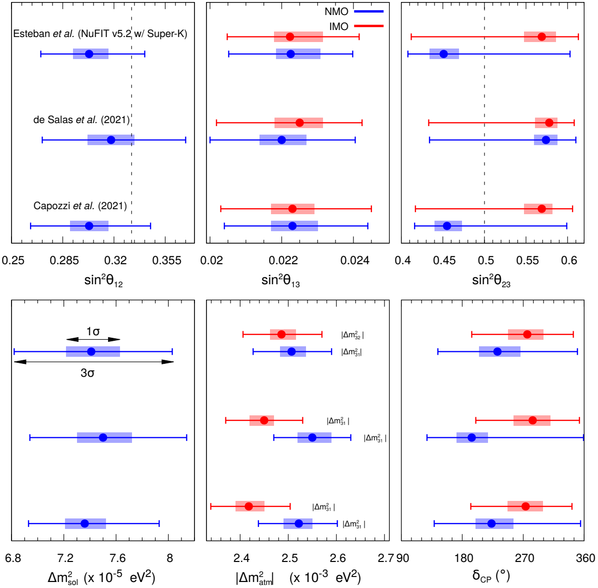
Matter Effect





- Neutrinos interact with matter by coherent forward elastic scattering.
- Charge current interaction of ν_e with electrons creates an extra effective matter term for ν_e, i.e,
  A=$2\sqrt{2}G_F N_e E$.
- Matter term changes sign when we switch from neutrino to anti-neutrino mode.
- Matter term modifies oscillation probability differently depending on the sign of Δm^2.
- The Hamiltonian corresponding to interaction with matter via CC-interaction is,
  H= U$[\frac{1}{2E}\text{diag}(m_1^2,\ m_2^2,\ m_3^2)]U^\dagger + \text{diag}(V_{CC},\ 0,\ 0)$

Present global-fit scenario in 3ν-paradigm

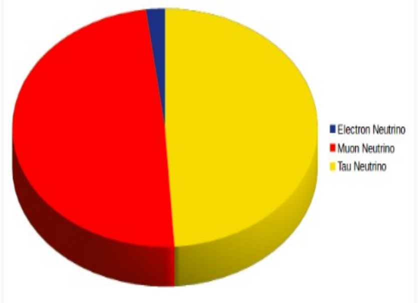


- 3σ (1σ) range of ν oscillation parameters, Esteban *et al*. www.nu-fit.org, de Salas *et al*. arXiv: 2006.11237, and Capozzi *et al*. arXiv: 2107.00532 in NMO and IMO.

Parameters	Relative 1σ error
$\sin^2\theta_{12}$	4.5%
Δm^2_{21}	2.3%
$\sin^2\theta_{23}$	6.7%
Δm^2_{31}	1.1%
$\sin^2\theta_{13}$	3%
δ_{CP}	16%

- The two most uncertain parameters are θ_{23} and δ_{CP}.
- θ_{23} is in LO (HO) for NMO (IMO) by Esteban *et al*. and Capozzi *et al*.

Deviation of θ_{23} from maximal mixing



- $\mu \rightarrow \tau$ symmetry

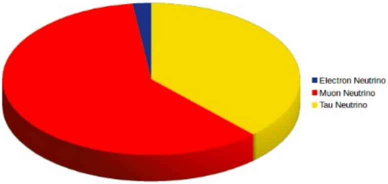
$$|\nu_2\rangle = \cos\theta_{23}\ |\nu_\mu\rangle + \sin\theta_{23}\ |\nu_\tau\rangle$$
$$|\nu_3\rangle = -\sin\theta_{23}\ |\nu_\mu\rangle + \cos\theta_{23}\ |\nu_\tau\rangle$$

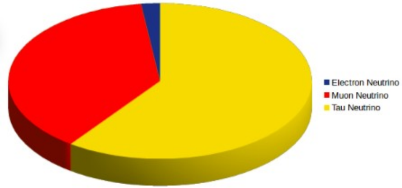
- If $\theta_{23} = 45^\circ$, i.e for MM, ν_2 and ν_3 have equal contributions of ν_μ and ν_τ.

---

https://arxiv.org/abs/hep-ph/9604415

Deviation of θ_{23} from maximal mixing





ν **Mixing Model**	θ_{23}	θ_{13}	θ_{12}
Tri-bimaximal	45°	0°	35°
Bi-maximal	45°	0°	45°
Tri-bimaximal Cabibbo	45°	8.54°	35°
Bi-large	39°	12.12°	39°
Bi-trimaximal	36.23°	12.18°	36.23°

- Deviation from maximal mixing of θ_{23} indicates the exclusion of several theoritical neutrino mixing models.

Considered values of neutrino oscillation parameters in our work

Parameters	Best-fit	1σ range	3σ range	
$\Delta m^2_{21}/10^{-5}\ eV^2$	7.36	7.21-7.52	6.93-7.93	Fixed
$\sin^2\theta_{12}/10^{-1}$	3.03	2.90-3.16	2.63-3.45	Fixed
$\sin^2\theta_{13}/10^{-2}$	2.23	2.17-2.30	2.04-2.44	Fixed
$\sin^2\theta_{23}/10^{-1}$	**4.55**	4.40-4.73	4.16-5.99	Free
$\Delta m^2_{31}/10^{-3}\ eV^2$	**2.522**	2.490-2.545	2.436-2.605	Free
$\delta_{\mathrm{CP}}/^\circ$	**223**	200-256	139-355	Free

Capozzi et al., https://arxiv.org/abs/2107.00532

Roles of different channels in our study

- The appearance probability for $\nu_\mu \to \nu_e$ channel

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2(2\theta_{13})\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

$$-\alpha\sin(2\theta_{13})\zeta\sin\delta_{CP}\sin(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

$$+\alpha\sin(2\theta_{13})\zeta\cos\delta_{CP}\cos(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

- The disappearance probability for $\nu_\mu \to \nu_\mu$ channel

$$P(\nu_\mu \to \nu_\mu) \approx 1-\sin^2(2\theta_{23})\sin^2(\Delta)$$

$$+(\alpha\Delta)c_{12}^2\sin^2(2\theta_{23})\sin(2\Delta)$$

$$-2\alpha\zeta\cos(\delta_{CP})\cos(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(\hat{A}-1)\Delta]}{(\hat{A}-1)}$$

$$+\frac{2}{(\hat{A}-1)}\alpha\zeta\cos(2\theta_{23})\cos(\delta_{CP})\sin(\Delta)[\hat{A}\sin(\Delta)-\frac{\sin(\hat{A}\Delta)}{\hat{A}}\cos((\hat{A}-1)\Delta)]$$

$$\boxed{\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \approx 0.033}$$

$$\boxed{\Delta = \Delta m_{31}^2 L/4E}$$

$$\boxed{\zeta = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}}$$

Appearance channel helps in θ_{23} octant exclusion.

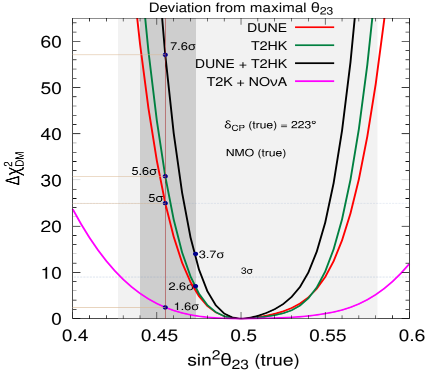
Disappearance channel helps in the precision of θ_{23}.

$$\boxed{\hat{A} = \pm\frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}}$$

Salient features of DUNE and T2HK

Features	**DUNE**	**T2HK**
Baseline length	1300 km (Larger matter effect)	295 km (Smaller matter effect)
Detector Mass	40 kt (Smaller statistics)	187 kt (Larger statistics)
Detection technique	LArTPC	Water Cherenkov
Beam type	Wide-band, on-axis	Narrow-band, off-axis (2.5°)
Beam Power	1.2 MW	1.3 MW
Run time	5 yrs ν + 5 yrs $\bar{\nu}$	2.5 yrs ν + 7.5 yrs $\bar{\nu}$
P.O.T/year	1.1×10^{21}	2.7×10^{21}
Syst. Uncertainty in App. (Disapp.) channel	2% (5%)	5% (3%)

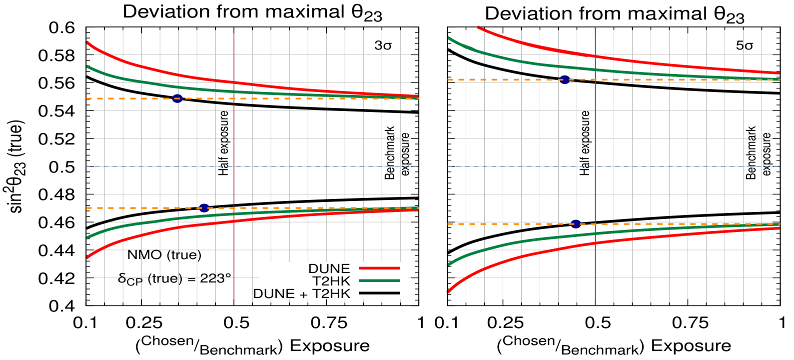
Deviation from maximal θ_{23}



$$\boxed{\Delta\chi^2_{\text{DM}} = \min_{\delta_{\text{CP}},\Delta m^2_{31}} \left\{\chi^2\left(\sin^2\theta_{23}^{\text{test}} = 0.5\right) - \chi^2\left(\sin^2\theta_{23}^{\text{true}} \in [0.4, 0.6]\right)\right\}}$$

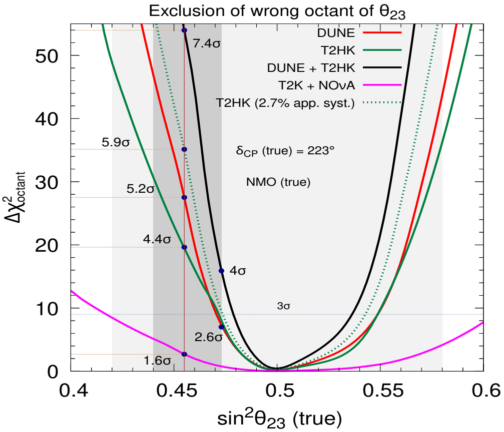
- In Nature, if true $\sin^2\theta_{23}$ attains the lower value of the current 1σ uncertainty (0.473), only DUNE+T2HK can achieve 3σ sensitivity of non-maximal θ_{23} with the present benchmark values.

Deviation from maximal θ_{23} as the function of exposure



- The range of true values of $\sin^2\theta_{23}$ that can be differentiated from MM choices, by DUNE + T2HK with just ∼ 0.4 of their nominal exposures, cannot be achieved by either of them individually even at their respective full exposures.
- At lower exposure, T2HK always performs better than DUNE irrespective of the values of θ_{23}. At nominal exposure, they perform almost in same way.

Potential of exclusion of the wrong octant of θ_{23}



- At lower confindence, T2HK wins due to larger statistics whereas, at higher confidence DUNE wins due to lesser systematics in appearance channel.
- The combined setup of DUNE and T2HK boosts their individual performances to exclude the wrong octant solution.

Definition of $\Delta\chi^2_{\text{octant}}$

- For $\sin^2\theta_{23}$ (true)<0.5 (LO),

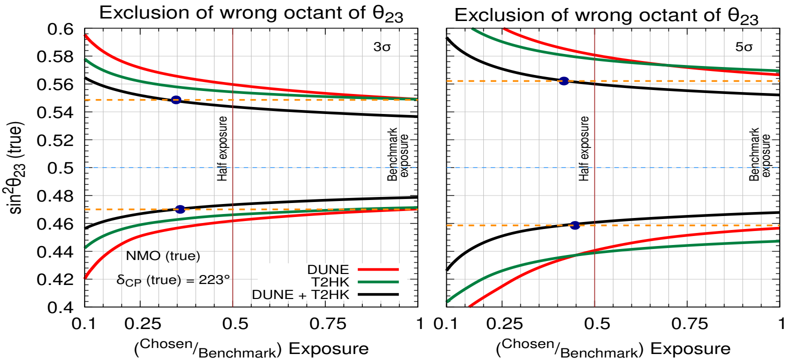
$$\Delta\chi^2_{\text{octant}} = \min_{(\vec{\lambda})}\left\{\chi^2\left(\sin^2\theta_{23}^{\text{true}} = [0.4, 0.5)\right) - \chi^2\left(\sin^2\theta_{23}^{\text{test}} = (0.5, 0.6]\right)\right\}$$

- For $\sin^2\theta_{23}$ (true)>0.5 (HO),

$$\Delta\chi^2_{\text{octant}} = \min_{(\vec{\lambda})}\left\{\chi^2\left(\sin^2\theta_{23}^{\text{true}} = (0.5, 0.6]\right) - \chi^2\left(\sin^2\theta_{23}^{\text{test}} = [0.4, 0.5)\right)\right\}$$

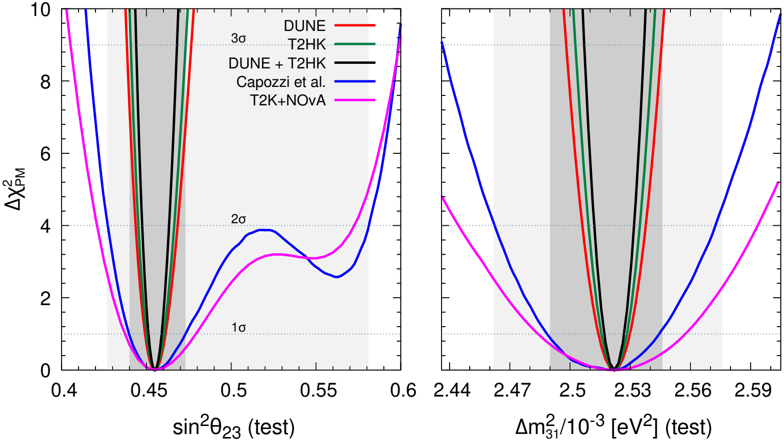
where, $\lambda = \delta_{\text{CP}}$, Δm^2_{31} is the marginalized parameters.

Efficacy of DUNE and T2HK in octant exclusion at various exposures



- With just 0.25 times of the benchmark exposure of the individual experiments, the combined set up can exclude the wrong octant for more than half of the currently allowed $\sin^2\theta_{23}$.

Precision measurement of θ_{23} and Δm^2_{31}



- The combination of DUNE and T2HK outperforms their performances in isolation to the precision measurement of θ_{23} and Δm^2_{31}.

Definition of Relative 1σ precision and $\Delta\chi^2_{PM}$

The relative 1σ precision in the measurement of oscillation parameters ζ is estimated as follows:

$$p(\zeta) = \frac{\zeta^{\max} - \zeta^{\min}}{6.0 \times \zeta^{\text{true}}} \times 100\%.$$

$\zeta^{\max}$ and $\zeta^{\min}$ are the allowed 3σ upper and lower bounds, respectively.

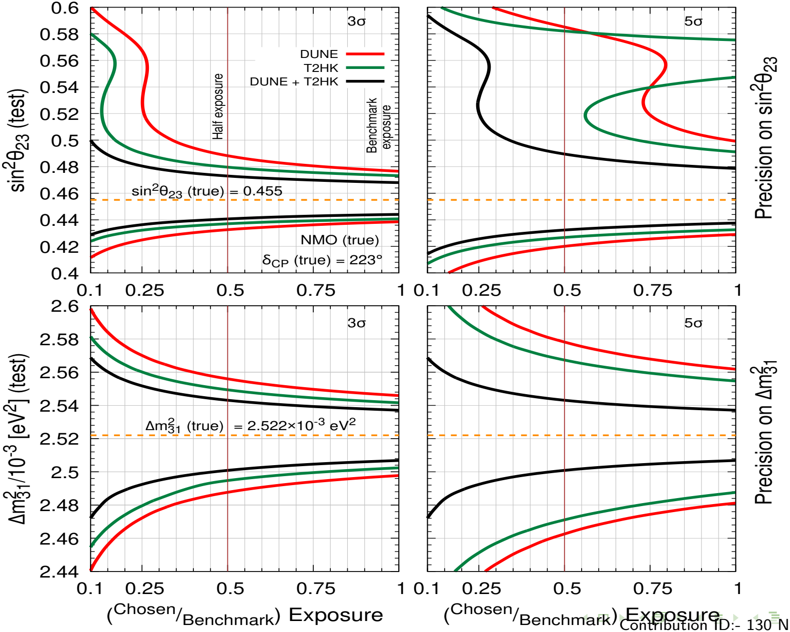
$$\Delta\chi^2_{\text{PM, }\sin^2\theta_{23}} = \min_{(\delta_{CP},\Delta m^2_{31})} \left\{\chi^2\left(\sin^2\theta_{23}^{\text{true}} \in [0.4, 0.6]\right) - \chi^2\left(\sin^2\theta_{23}^{\text{test}} = [0.455]\right)\right\},$$

$$\Delta\chi^2_{\text{PM, }\Delta m^2_{31}} = \min_{(\delta_{CP},\sin^2\theta_{23})} \Big\{\chi^2\Big(\sin^2\theta_{23}^{\text{true}} \in [2.4, 2.6] \times 10^{-3}\Big) - \chi^2\Big(\sin^2\theta_{23}^{\text{test}} = 2.522 \times 10^{-3}\Big)$$

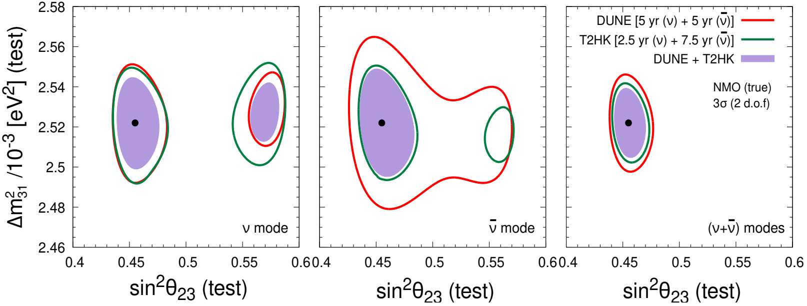
Parameter	Relative 1σ precision (%)					
	T2HK	DUNE	T2HK+DUNE	T2K+NOνA	Capozzi *et al.*	JUNO
$\sin^2\theta_{23}$	1.18	1.40	0.88	7.10	6.72	—
Δm^2_{31}	0.25	0.31	0.20	0.99	1.09	0.2

NavasNicolas:2023fza

Performance of measuring precision at various exposures



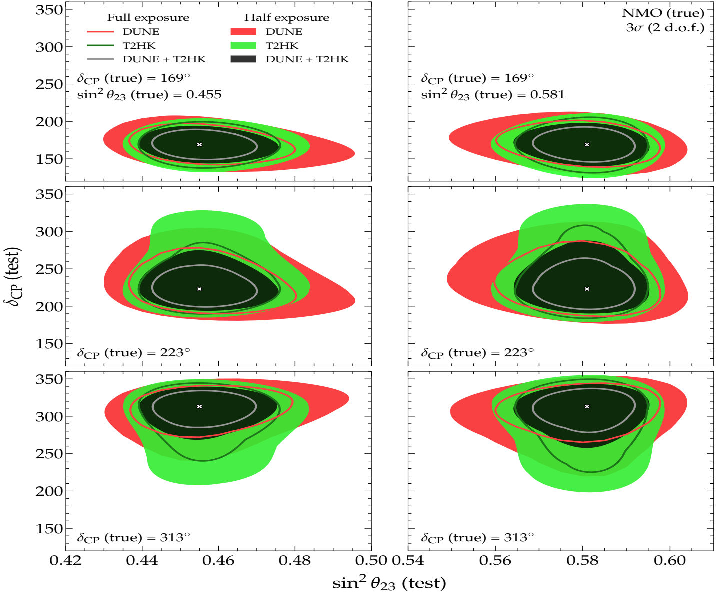
Allowed regions in $\sin^2\theta_{23} - \Delta m^2_{31}$ plane



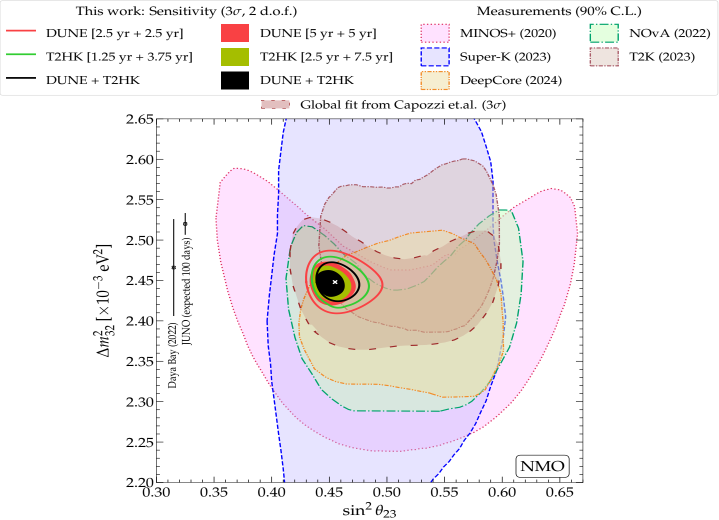
- The combination of DUNE and T2HK can exclude the HO only in antineutrino mode at 3σ C.L. breaking $\sin^2\theta_{23} - \delta_{\rm CP}$ degeneracy due to higher $\bar{\nu}$ statistics in T2HK. So, majority of the appearance events are free from fake (matter-induced) CP-phase.

- HO can be ruled out when both ν and $\bar{\nu}$ modes are considered together.

Allowed regions in $\sin^2\theta_{23} - \delta_{\mathrm{CP}}$ plane



Allowed regions in $\sin^2\theta_{23} - \Delta m^2_{32}$ plane given by the other experiments

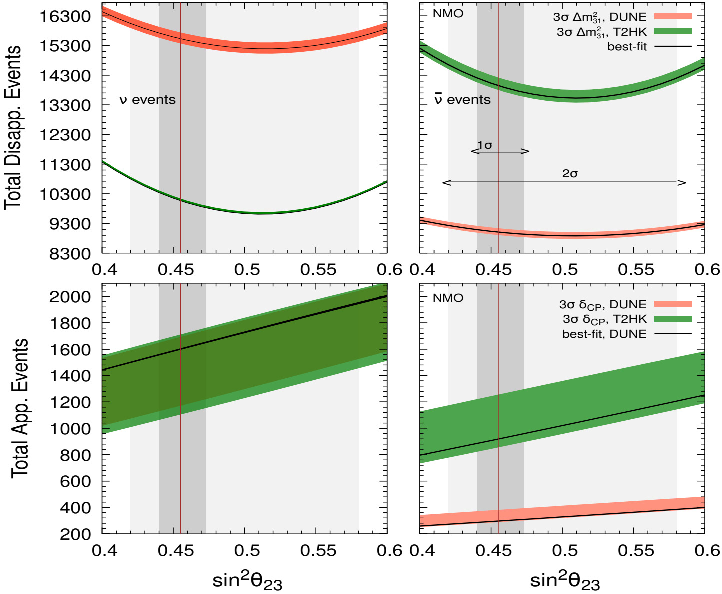


Summary

- Ongoing long-baseline and atmospheric experiments (e.g.- T2K, NOνA, MINOS+, Super-K etc.) strongly suggest deviation from MM of θ_{23}.
- DUNE has large matter effect so is expected to measure Δm^2_{31} precisely. But the larger matter effect induces fake CP-asymmetry which is negligible in T2HK.
- The disappearance statistics of T2HK is larger. So, T2HK is expected measure θ_{23} precisely. But the combined setup improves the present achievable precision of $\sin^2\theta_{23}$ and Δm^2_{31} by a factor of 7 and 5, respectively.
- Combination of DUNE and T2HK outperforms their isolated performances to establish non-maximal θ_{23}. Furthermore, the range of true values of $\sin^2\theta_{23}$ that can be differentiated from MM choices, by DUNE + T2HK with just ~ 0.4 of their nominal exposures, cannot be achieved by either of them individually even at their respective full exposures.
- With only 0.25 times of the benchmark exposure of the standalone experiments, the combination of DUNE and T2HK can exclude the wrong octant of θ_{23} for more than half of the currently allowed $\sin^2\theta_{23}$.
- DUNE+T2HK can exclude the wrong octant solution with only antineutrino mode due to the complementarity between DUNE and T2HK.


Thank you!

Total event rates in DUNE and T2HK



Total number of events in DUNE and T2HK

Channel		LO ($\sin^2\theta_{23} = 0.455$)		MM ($\sin^2\theta_{23} = 0.5$)		HO ($\sin^2\theta_{23} = 0.599$)	
		DUNE	T2HK	DUNE	T2HK	DUNE	T2HK
App.	ν	**1601** [1586]	**1598** [1588]	**1729** [1712]	**1725** [1713]	**2004** [1983]	**1996** [1981]
	$\bar{\nu}$	**297** [187]	**919** [755]	**328** [209]	**1021** [844]	**399** [260]	**1251** [1044]
Disapp.	ν	**15529** [14286]	**10064** [9487]	**15209** [13974]	**9628** [9057]	**15857** [14597]	**10661** [10074]
	$\bar{\nu}$	**9008** [4433]	**13949** [8985]	**8884** [4333]	**13541** [8643]	**9252** [4648]	**14613** [9553]

Table: Total (Signal + Background) appearance and disappearance event rates in DUNE and T2HK assuming 480 kt·MW·years and 2431 kt·MW·years of exposure, respectively. Events in parenthesis does not include the effect of wrong-sign contamination. The events are simulated by General Long Baseline Experiment Simulator (GLoBES).

- Contribution of wrong sign events is more in $\bar{\nu}$ mode than ν due to the cross-section suppression.
- Initially pions or kaons are produced due to pp or pn collision. Positive chaged mesons are abundant than the negative one. Hence, contamination of ν in $\bar{\nu}$ beam is more.

Definition of χ^2 used

$$\chi^2 = \min_{(\vec{\zeta_s},\vec{\zeta_b})} \left\{ 2\sum_{i=1}^{n} (\tilde{y}_i - x_i - x_i ln\frac{\tilde{y}_i}{x_i}) + \zeta_s^2 + \zeta_b^2 \right\},$$

where, n is the total number of bins and

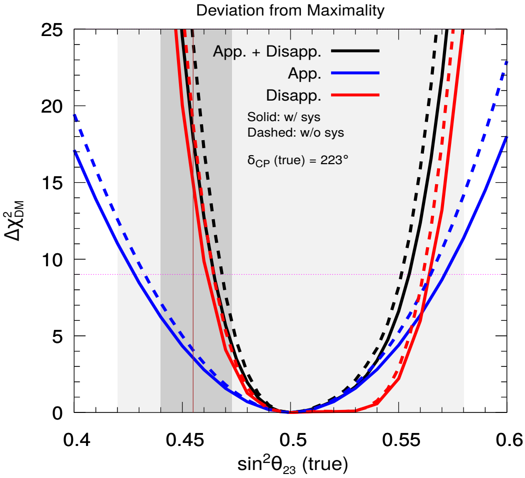
$$\tilde{y}_i(\{\omega, \alpha_{e\mu}\}, \{\zeta_s, \zeta_b\}) = N_i^{th}(\{\omega, \alpha_{e\mu}\})[1 + \pi^s\zeta_s] + N_i^b(\{\omega, \alpha_{e\mu}\})[1 + \pi^b\zeta_b]$$

where,

- $N_i^{th}(\{\omega, \alpha_{e\mu}\}) =$ Predicted no. of events in i-th bin for a set of osc. params. ω and for a given value of $\alpha_{e\mu}$
- $N_i^b(\{\omega, \alpha_{e\mu}\}) =$ No. of background events in the i-th bin where CC background depends on ω and $\alpha_{e\mu}$ but NC does not
- $\pi^s, \pi^b =$ Systematic errors in signal and background
- $\zeta_s, \zeta_b =$'Pulls' due to systematic errors in signal and background respectively
- $x_i = N_i^{ex} + N_i^b$ (where, $N_i^{ex} =$ No. of observed CC signal events in the i-th bin, $N_i^b =$ Same for the background)

https://arxiv.org/pdf/1509.03517.pdf

Effect of Systematics of DUNE in probing non-maximal θ_{23}



Contribution ID:- 130 NuFact 2024 - The 2

Table of systematics in DUNE

True $\sin^2\theta_{23}$	Channels	2%, 5%	0%, 0%	5%, 5%	5%, 10%	10%, 10%
0.455 (Best-fit)	App.+Disapp.	**17.64**	**24.13**	**16.88**	**16.74**	**15.42**
	App.	**3.52**	**4.05**	**2.33**	**2.33**	**1.05**
	Disapp.	**14.31**	**18.79**	**14.31**	**14.16**	**14.16**
0.473 (1σ upper bound)	App.+Disapp.	**4.28**	**5.72**	**3.88**	**3.84**	**3.42**
	App.	**1.27**	**1.47**	**0.84**	**0.84**	**0.38**
	Disapp.	**2.99**	**3.88**	**2.99**	**2.97**	**2.97**

Neutrino mixing in three-flavor oscillation

- Flavor and mass eigen-states are linearly combined as

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \tag{1}$$

- The three flavor neutrino oscillation is given by

$$\begin{aligned}P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j<i} Re(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})\sin^2(1.27\Delta m^2_{ij}L/E)\\ - 2\sum_{j<i} Im(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})\sin(2.54\Delta m^2_{ij}L/E)\end{aligned}$$

where, $\Delta m^2_{ij} = m^2_i - m^2_j$ (in eV^2), L is the baseline length (in km), and E is the energy of the neutrino (in GeV).

Parametrization of PMNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix is parametrized by three independent mixing angles (θ_{23}, θ_{13}, and θ_{12},), two independent mass-squared difference [Solar mass-squared difference (Δm^2_{21}), Atmospheric mass-squared difference (Δm^2_{31})] and one δ_{CP} phase.
- For the non-zero value of θ_{13}, we have got 3ν-paradigm in neutrino oscillation.
- The (3×3) matrices in the red, green, and blue color are called "1-2 sector" or Solar Sector, "1-3 sector" or Reactor Sector, and "2-3 sector" or Atmospheric Sector.

Maki, Z; Nakagawa, M.; Sakata, S. (1962)