Establishing non-maximal 2-3 mixing with DUNE in light of current neutrino oscillation data

Sanjib Kumar Agarwalla *[1,4,5,6], Ritam Kundu †[1,4], Suprabh Prakash ‡[2], and Masoom Singh §[1,3]

[1]Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India
[2]The Institute of Mathematical Sciences, C.I.T. Campus, Taramani, Chennai 600113, India
[3]Department of Physics, Utkal University, Vani Vihar, Bhubaneswar 751004, India
[4]Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai 400094
[5]International Centre for Theoretical Physics, Strada Costiera 11, Trieste 34151, Italy
[6]Department of Physics & Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin, Madison, WI 53706, U.S.A

Abstract

A discovery of non-maximal θ_{23} at a high confidence level will play a significant role to pinpoint the theories of neutrino masses and mixings and it will certainly play a key role in addressing the long-standing flavor puzzle. Several global analyses of neutrino oscillation data hint towards non-maximal θ_{23}. In this work, we study the performance of the Deep Neutrino Underground Experiment (DUNE) to establish the deviation from maximal θ_{23}. We find that DUNE can establish deviation of θ_{23} from maximal mixing at 4.2σ (5σ) confidence level (C.L.) using 336 (480) kt·MW·yrs exposure and assuming true normal mass ordering (NMO). We also estimate the precision with which DUNE can measure the atmospheric oscillation parameters θ_{23} and Δm^2_{31}. DUNE can improve the relative 1σ precision on Δm^2_{31} $(\sin^2\theta_{23})$ by a factor of 2.8 (4.4) using 336 kt·MW·yrs of exposure as compared to its current precision. Further, we also notice that contribution from both neurino and antineutrino modes are necessary in DUNE to exclude the wrong octant solution and also to improve the precision on θ_{23} and Δm^2_{31}.

* sanjib@iopb.res.in https://orcid.org/0000-0002-9714-8866
† ritam.k@iopb.res.in https://orcid.org/0000-0003-3258-4357
‡ suprabh@imsc.res.in https://orcid.org/0000-0002-1529-4588
§ masoom@iopb.res.in https://orcid.org/0000-0002-8363-7693

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Recent 3ν global fits of oscillation parameters favor NMO at 2.5σ, and provide 90% C.L. hints for lower θ_{23} octant, and leptonic CP-violation. In this work, we explore the prospects of DUNE [1] to establish non-maximal θ_{23}. DUNE is a proposed high-precision long-baseline experiment having a baseline of nearly 1300 km. It is planning to use a new intense on-axis wide-band neutrino beam having an average energy around 2.5 GeV. To simulate the performance of DUNE, we use the following benchmark values of the oscillation parameters: $\sin^2\theta_{23} = 0.455$, $\sin^2\theta_{13} = 0.0223$, $\sin^2\theta_{12} = 0.303$, $\delta_{\rm CP} = 223°$, $\Delta m^2_{21} = 7.36\times10^{-5}$ eV^2, $\Delta m^2_{31} = 2.522\times10^{-3}$ eV^2, and the line-averaged constant Earth matter density of $(\rho_{\rm avg}) = 2.848$ g/cm^3 [2]. We perform all our simulations using the GLoBES software [3]. Now, we briefly describe our main findings.

Establishing non-maximal θ_{23}: We define the sensitivity to establish non-maximal θ_{23} in DUNE in the following fashion

$$\Delta\chi^2_{\rm DM} = \min_{(\vec{\lambda},\,\kappa_s,\kappa_b)} \left\{\chi^2\left(\sin^2\theta_{23}^{\rm true} \in [0.4, 0.6]\right) - \chi^2\left(\sin^2\theta_{23}^{\rm test} = 0.5\right)\right\}. \quad (1)$$

Here, $\vec{\lambda} = \{\delta_{\rm CP},\, \Delta m^2_{31}\}$ are the oscillation parameters over which we marginalize, and κ_s and κ_b are the systematic pulls on signal and background, respectively. From Fig. 1, we observe that establishing non-maximal θ_{23} is mostly independent of the choices of true values of $\delta_{\rm CP}$ because the sensitivity is mainly driven by $\nu_\mu \to \nu_\mu$ survival channel as discussed in detail in Ref [4]. Fig. 1 reveals that DUNE can establish non-maximal θ_{23} at $4.2\sigma\,(5\sigma)$ C.L. in 7 (10) years assuming that the run-time is divided equally in ν and $\bar{\nu}$ modes. With the help of 7 years of data taking, DUNE can determine non-maximal θ_{23} at $3\sigma\,(5\sigma)$ C.L. for any true $\delta_{\rm CP}$ and true NMO, provided true $\sin^2\theta_{23}$ turns out to be $\lesssim 0.465\,(0.450)$ or $\gtrsim 0.554\,(0.572)$ in Nature.

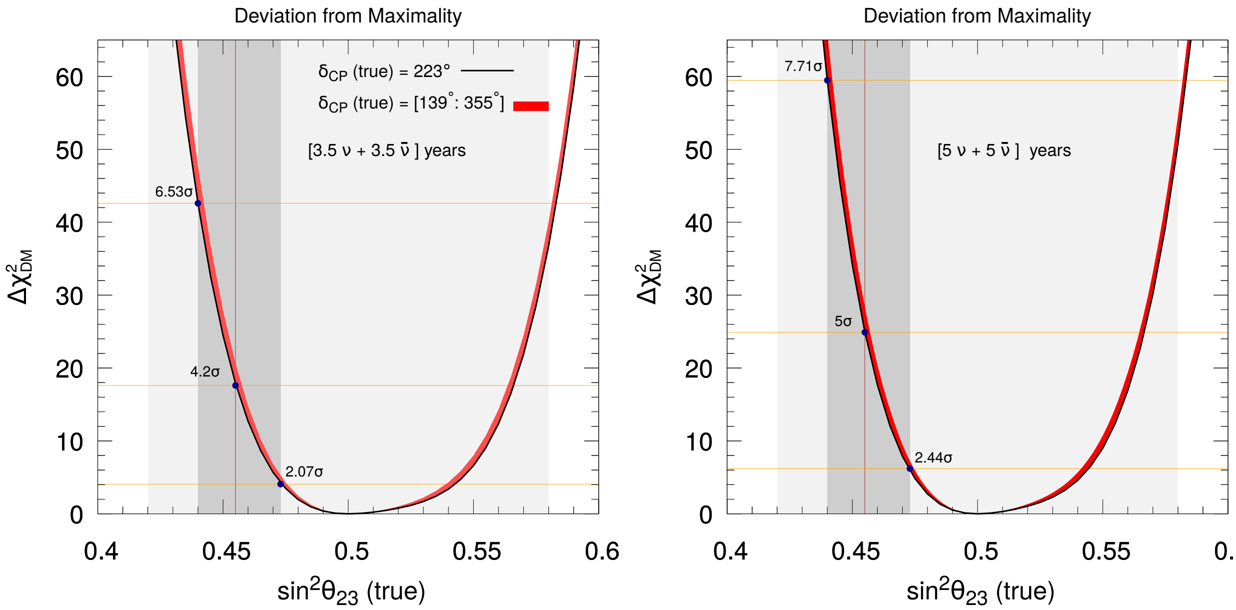

Figure 1: The black line in the left (right) panel depicts the prospects of DUNE to explore the non-maximal θ_{23} as a function of true $\sin^2\theta_{23}$ assuming true NMO and $\delta_{\rm CP}$ (true) = 223° with [3.5 yrs ν + 3.5 yrs $\bar{\nu}$] ([5 yrs ν + 5 yrs $\bar{\nu}$]). The red bands portray the same for true $\delta_{\rm CP}$ between the range of 139° to 355°. In the fit, we marginalize over the current 3σ range of Δm^2_{31} and $\delta_{\rm CP}$, keeping rest of the oscillation parameters fixed to our benchmark choices. The dark (light) - shaded grey region covers the currently allowed 1σ (2σ) region in $\sin^2\theta_{23}$ as obtained in Ref [2] with the vertical brown line depicting the best-fit value of $\sin^2\theta_{23}(0.455)$. The horizontal orange lines show the sensitivity for the current best-fit and 1σ upper and lower bounds of $\sin^2\theta_{23}$. This figure has been taken from Ref [4].

Precision measurements of atmospheric oscillation parameters: Now, we turn our attention to the precision measurement of atmospheric oscillation parameters. We define the achievable precision on these parameters in the following way

$$\Delta\chi^2_{\rm PM}(\zeta^{\rm test}) = \min_{(\vec{\lambda},\,\kappa_s,\kappa_b)} \left\{\chi^2\left(\zeta^{\rm test}\right) - \chi^2\left(\zeta^{\rm true}\right)\right\}. \tag{2}$$

Here, ζ^{true} represents the best-fit value of the oscillation parameter under consideration and ζ^{test} refers to the same osciilation parameter in its presently allowed 3σ range. The definitions of $\vec{\lambda}$, κ_s ,and κ_b remain the same as mentioned previously in the context of establishing non-maximal θ_{23}. Figure 2 depicts the precision with which DUNE can measure $\sin^2\theta_{23}$ (left panel) and Δm^2_{31} (right panel).

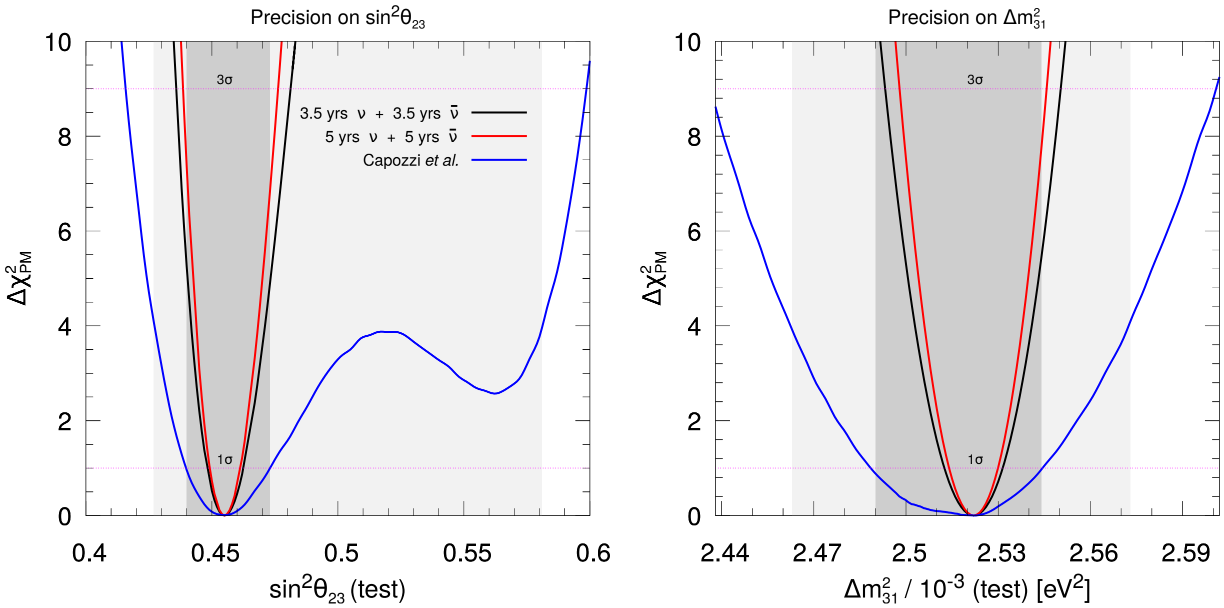

Figure 2: The left figure reveals $\Delta\chi^2_{\rm PM}$ around $\sin^2\theta_{23}\,(\rm true) = 0.455$ and the right one depicts $\Delta\chi^2_{\rm PM}$ for $\Delta m^2_{31}\,(\rm true) = 2.522\times10^{-3}$ eV^2 assuming true NMO and $\delta_{\rm CP}\,(\rm true) = 223°$. The black (red) lines indicate the precision with $[3.5\nu + 3.5\bar{\nu}]$ yrs ($[5\nu+5\bar{\nu}]$ yrs). Blue lines portray the present precision from the global fit study [2]. In the fit, we marginalize over the current 3σ range of Δm^2_{31} ($\sin^2\theta_{23}$), and $\delta_{\rm CP}$ in the left (right) figure keeping rest of the oscillation parameters fixed at our benchmark values. The dark (light) - shaded grey portion gives the currently allowed 1σ (2σ) region in $\sin^2\theta_{23}$ (Δm^2_{31}) in the left (right) panel as obtained in the global fit study [2] assuming NMO. This figure has been taken from Ref [4].

It is clearly visible from Fig. 2 that DUNE has the potential to significantly improve the precision on these parameters as compared to their present measurements. To quantify this, we define the achievable relative 1σ precision on these parameters (ζ) as follows

$$p(\zeta) = \frac{\zeta^{\rm max} - \zeta^{\rm min}}{6.0\times\zeta^{\rm true}} \times 100\% \,. \tag{3}$$

Here, $\zeta^{\rm max}$ and $\zeta^{\rm min}$ represent the allowed 3σ upper and lower bounds of a given oscillation parameter in DUNE for a true choice of the same oscillation parameter ($\zeta^{\rm true}$). We quote the achievable precision in DUNE on $\sin^2\theta_{23}$ and Δm^2_{31} in Table 1. It is remarkable to see that DUNE with 3.5 years of neutrino and 3.5 years of antineutrino data, can provide much better precision on θ_{23} and Δm^2_{31} (see second column) as compared to the precision achieved by the current global neutrino oscillation data (see fourth column). As far as the precision on Δm^2_{31} is concerned, DUNE can provide slightly better measurement of Δm^2_{31} as compared to

Parameter	Relative 1σ precision (%)			
	DUNE $(3.5\,\nu + 3.5\,\bar{\nu})$ yrs	DUNE $(5\,\nu + 5\,\bar{\nu})$ yrs	Capozzi *et al.* [2]	JUNO [5]
$\sin^2\theta_{23}$	1.53	1.31	6.72	—
Δm^2_{31}	0.39	0.31	1.09	0.50

Table 1: Relative 1σ precision on $\sin^2\theta_{23}$ and Δm^2_{31} around the true choices of $\sin^2\theta_{23} = 0.455$ and $\Delta m^2_{31} = 2.522\times 10^{-3}$ eV^2. The second and third columns are exhibiting DUNE's capability with $[3.5\nu{+}3.5\bar{\nu}]$ yrs ($[5\nu{+}5\bar{\nu}]$ yrs). The fourth coulumn reveals the current relative 1σ precision on these parameters from the global fit study [2]. The reachable precision on Δm^2_{31} from the upcoming JUNO experiment [5] is being shown in the fifth column. This Table has been taken from Ref [4].

what we expect from the upcoming JUNO experiment (see fifth column). The third column shows that DUNE can further improve the precision on $\sin^2\theta_{23}$ and Δm^2_{31} if we increase the run-time from 7 years to 10 years.

Allowed regions in test ($\sin^2\theta_{23} - \Delta m^2_{31}$) plane: Next in Fig. 3, we show the allowed regions

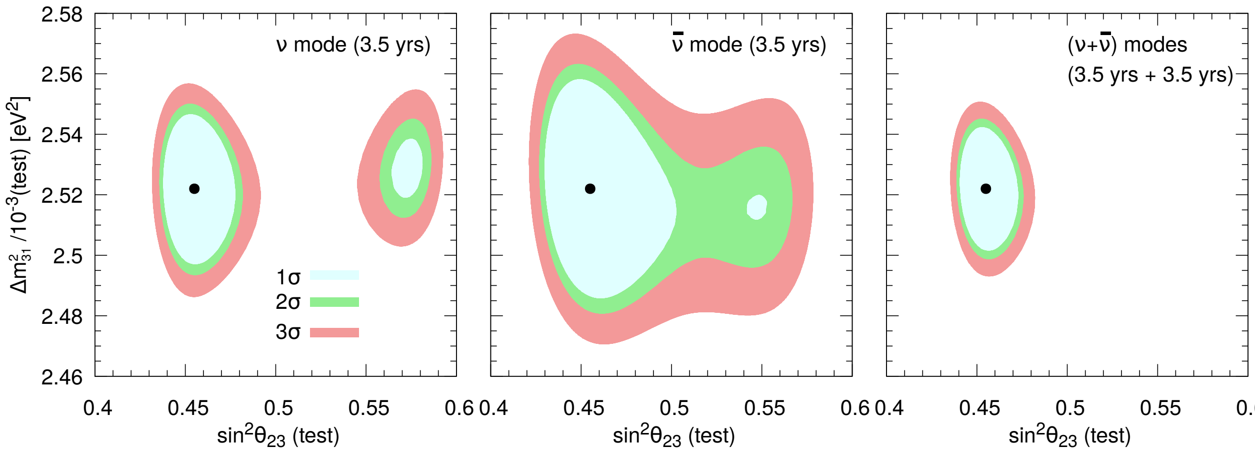

Figure 3: Allowed regions in the test ($\sin^2\theta_{23}$ - Δm^2_{31}) plane at 1σ (blue), 2σ (green), and 3σ (red) C.L. combining appearance and disappearance data in DUNE. Left (Middle) figure is for 3.5 years of neutrino (antineutrino) run. The right panel shows the performance of combined neutrino (3.5 years) and antineutrino (3.5 years) runs. The solid black point indicates the true choices of $\sin^2\theta_{23} = 0.455$ and $\Delta m^2_{31} = 2.522\times 10^{-3}$ eV^2 for true NMO and true $\delta_{\rm CP}$ = 223°. In the fit, we marginalize over the current 3σ range of $\delta_{\rm CP} = [139^\circ : 355^\circ]$ keeping rest of the oscillation parameters fixed at their present best-fit values. This figure has been taken from Ref [4].

in the test ($\sin^2\theta_{23} - \Delta m^2_{31}$) plane around the current best-fit values of $\sin^2\theta_{23} = 0.455$ and $\Delta m^2_{31} = 2.522\times 10^{-3}$ eV^2 for true NMO and true $\delta_{\rm CP}$ = 223°. The left (middle) panel depicts the performance of only 3.5 years of neutrino (antineutrino) run whereas the right panel shows the performance of the combined 3.5 years of neutrino and 3.5 years of antineutrino run. By comparing these panels, we come to the following important conclusions: (i) the data from only ν or $\bar{\nu}$ mode is not sufficient to rule out the wrong octant solution even at 1σ C.L., (ii) the maximal mixing solution is also allowed at 2σ with only antineutrino data, (iii) the combined data from ν and $\bar{\nu}$ modes help to kill the clone solutions due to octant of θ_{23} and $\delta_{\rm CP}$ degeneracy, and establish the right octant solution even at 3σ C.L., and (iv) the enhancement in statistics due to the combined ν and $\bar{\nu}$ data, turns out to be also very useful to reduce the uncertainties around these parameters.

Summary and Conclusions: We demonstrate in detail that DUNE is capable to shed light on the pressing issues related to 2-3 mixing, which plays a crucial role to address the unsolved isuues, such as neutrino mass ordering, leptonic CP violation, and precision measurement of oscillation parameters. With the current best-fit values of oscillation parameters, we find that DUNE has the ability to exclude maximal mixing solutions of $\sin^2\theta_{23}$ at 4.2σ assuming true NMO. This sensitivity decreases (increases) further to 2.07σ (6.53σ) if we consider the true value of $\sin^2\theta_{23} = 0.473$ (0.44), which are the current 1σ upper (lower) bound from the global fit study. We notice that DUNE can improve the current relative 1σ precision on $\sin^2\theta_{23}$ (Δm^2_{31}) by a factor of 4.4 (2.8) using 336 kt·MW·yrs of exposure. We further observe that both neutrino and antineutrino data are necessary to exclude the wrong octant solutions and to reduce the uncertainties on the atmospheric oscillation parameters.

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