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Probing atmospheric mixing and leptonic CP violation in current and future long baseline oscillation experiments

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ABSTRACT

We perform realistic simulations of the current and future long baseline experiments such as T2K, NOνA, DUNE and T2HK in order to determine their ultimate potential in probing neutrino oscillation parameters. We quantify the potential of these experiments to underpin the octant of the atmospheric angle θ_{23} as well as the value and sign of the CP phase δ_{CP}. We do this both in general, as well as within the predictive framework of a previously proposed [1] benchmark theory of neutrino oscillations which tightly correlates θ_{23} and δ_{CP}.

1. Preliminaries: a minimal benchmark theory of neutrino oscillations

The discovery of neutrino oscillations constitutes a major milestone in particle physics [2,3]. While oscillations are a generic expectation in theories of neutrino mass, the corresponding set of oscillation parameters can be extremely rich [4], precluding the possibility of making detailed predictions for the next generation of oscillation experiments [5]. Despite the tremendous experimental progress we have had and which has brought neutrino oscillation physics to the precision age, one still lacks reliable information, for instance, on the octant of the atmospheric angle as well as the value of (Dirac-type) CP phase [6–8], whose determination remains ambiguous. A generic neutrino oscillation pattern would involve in addition a set of non-unitarity parameters [9,10], known to bring in a potentially serious ambiguity in probing CP violation in neutrino oscillations [11].

Here we assume the standard three neutrino paradigm [12] and perform realistic simulations of the current and future long baseline oscillation experiments such as T2K, NOνA, DUNE and T2HK in order to determine their potential in probing neutrino oscillation parameters. For definiteness we focus on the least well-determined ones, namely the atmospheric angle and the (Dirac-type) CP phase.

First we quantify the sensitivity of these experiments to θ_{23} and δ_{CP} in general. We also pose the question within the framework of a simple benchmark theory of neutrino oscillations proposed in Ref. [1]. Such theory has been proposed from first principles, based on a warped flavor model naturally predicting light Dirac neutrinos, so that the lepton mixing matrix has the same structure as the CKM matrix describing quark mixing. A beautiful feature of the model consists in the integration of its extra-dimensional nature, which accounts for the standard model mass hierarchies, with the implementation of a predictive non-Abelian flavor symmetry, in our case $\Delta(27) \otimes \mathcal{Z}_4 \otimes \mathcal{Z}'_4$. The latter leads to the description of all the four neutrino oscillation parameters θ_{ij} and $J_{\rm CP}$, where the latter is the leptonic CP invariant, in terms of just two angles: θ_ν and ϕ_ν according to the following equations,

$$
\begin{aligned}
\sin^2\theta_{12} &= \frac{1}{2-\sin 2\theta_\nu \cos\phi_\nu} \\
\sin^2\theta_{13} &= \frac{1}{3}(1+\sin 2\theta_\nu \cos\phi_\nu) \\
\sin^2\theta_{23} &= \frac{1-\sin 2\theta_\nu \sin(\pi/6-\phi_\nu)}{2-\sin 2\theta_\nu \cos\phi_\nu} \\
J_{\rm CP} &= -\frac{1}{6\sqrt{3}}\cos 2\theta_\nu
\end{aligned}
\tag{1}
$$

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Given the good determination of θ_{13} by reactor experiments, this model is in a sense effectively a one-parameter theory, hence we call it a "minimal" benchmark theory of neutrino oscillations.

Here we explore the potential of current and planned long baseline oscillation experiments in testing the predictions of this model. We perform state-of-the-art simulations of the relevant experiments T2K, NOνA, DUNE and T2HK in order to ascertain how well they can probe the model and compare with the situation in a general unconstrained oscillation scenario.

2. Numerical analysis and experimental setups

In order to quantify the sensitivities of the various experimental setups in testing our benchmark oscillation model, we use GLoBES [13,14] as a numerical simulator. The global (unconstrained) best fit values of the oscillation parameters in the three flavor framework, taken from [6], are given as: $\sin^2\theta_{12} = 0.323$, $\sin^2\theta_{13} = 0.0234$, $\sin^2\theta_{23} = 0.567$ (0.573) for NH (IH), $\delta_{CP} = 1.34\pi$, $\Delta m^2_{21} = 7.5 \times 10^{-5}$ eV^2, $\Delta m^2_{31} = 2.48 \times 10^{-3}$ (-2.38×10^{-3}) eV^2 for NH (IH). If specifically not mentioned something else, all the true data have been generated using the unconstrained best values of the oscillation parameters. Also, we have considered a fixed hierarchy both in true and test data. We are not using any prior on the oscillation parameters because our test oscillation parameters will be predicted by the model [1]. In order to find the sensitivity of this model at a certain confidence level, we are using the following Poissonian χ^2 function [15,16]:

$$\chi^2 = \min_{\{\xi_a,\xi_b\}} \left[2\sum_{i=1}^{n} (y_i - x_i - x_i \ln \frac{y_i}{x_i}) + \xi_a^2 + \xi_b^2 \right] \qquad (2)$$

where, n is the total number of bins and

$$y_i(\tilde{f}, \xi_a, \xi_b) = N_i^{pre}(\tilde{f}) \left[1 + \pi^a \xi_a\right] + N_i^b(\tilde{f}) \left[1 + \pi^b \xi_b\right] \qquad (3)$$

where $\tilde{f}$ denotes the oscillation parameters predicted by the model and π^a, π^b denote the systematic errors on signal and background respectively, assumed to be uncorrelated between different channels. On the other hand ξ_a and ξ_b are the pulls due to systematic errors, while N_i^{pre} is the total number of predicted signal events in the ith energy bin and N_i^b is the background events, where the charged current (CC) background depends on $\tilde{f}$. The true data measured by an experiment enter in Eq. (2) through

$$x_i(f) = N_i^{obs}(f) + N_i^b(f) \qquad (4)$$

N_i^{obs} is the number of observed CC signal events in the i-th energy bin and f denotes the standard unconstrained oscillation parameters whose the best fit values are taken from Ref. [6]. Individual contributions coming from the various relevant channels are added together in order to get the total χ^2 as

$$\chi^2_{\text{total}} = \chi^2_{\nu_\mu\to\nu_e} + \chi^2_{\bar{\nu}_\mu\to\bar{\nu}_e} + \chi^2_{\nu_\mu\to\nu_\mu} + \chi^2_{\bar{\nu}_\mu\to\bar{\nu}_\mu} \qquad (5)$$

Finally, this total χ^2 is minimized over the free oscillation parameters. The simulation runs over four possible experimental scenarios, the "current" T2K, NOvA experiments and the "future" T2HK and DUNE proposal setups and this encompass the list of the experiments aimed at improving the θ_{23} measurements and the determination of the CP phase δ_{CP}. For the latter the predicted correlation between θ_{23} and δ_{CP} [1] can be used to significantly shrink down the parameter space of the benchmark model as shown in [17]. In order to sharpen and extend those results we first briefly summarize the procedure used in each of the four setups.

1. **T2K:** To simulate the T2K (Tokai to Kamiokande) experiment, we assumed the configuration in [18] with a full exposure of 7.8×10^{21} protons on target (POT) which produce an off-axis (angle of 2.5^0) neutrino beam with energy peak around 0.6 GeV hitting a 50 kt (fiducial volume 22.5 Kt) water Cerenkov Super-K far detector at Kamioka at a distance of 295 km from the target. In this work, half of the total exposure has been assumed in the neutrino mode and the remaining half of the exposure in the antineutrino mode. We have followed reference [18] in great detail, reproducing their event spectra in all the modes rather well. Following the same reference, we are using an uncorrelated 5% signal normalization error and 10% background normalization error for both neutrino and antineutrino appearance and disappearance channels respectively.
2. **T2HK:** T2HK (Tokai to Hyper-Kamiokande) is also a superbeam accelerator based off-axis experiment which is expected to be operational around 2025 [19]. It uses the same off-axis setup and the same baseline as T2K. It is supposed to be the upgraded version of T2K which also uses a 30 GeV proton beam accelerated by the J-PARC facility, which hits the target and produces an intense neutrino beam. The produced neutrinos at the target will be collected by a 560 kt (fiducial) water Cerenkov far detector placed at Hyper-Kamiokande. Following Ref. [20], we assume an integrated beam with power 7.5 MW $\times\ 10^7$ sec which corresponds to 1.53×10^{21} POT. To make the event number almost equal for both neutrino and antineutrino modes, we have assumed a run time ratio of 1:3 for ν:$\bar{\nu}$ that is 2.5 yrs for neutrino mode and 7.5 yrs for antineutrino mode. As a simplified case, we assume an uncorrelated 5% signal normalization error and 10% background normalization error for both polarities and for both appearance and disappearance channels respectively.
3. **NOνA:** NOνA (NuMI Off-axis ν_e Appearance) [21,22] is an off-axis accelerator based superbeam experiment, consisting of two detectors, one is a near detector at Fermilab and another one is a 14 Kt TASD far detector placed in Ash river, Minnesota at an angle 0.8^0 from the beam direction. Neutrinos from NuMI (Neutrinos at the Main Injector) will pass through 810 km of earth matter before they are detected at the far detector. The off-axis is chosen to get peak energy approximately at 2 GeV. NOνA uses a 120 GeV proton beam with beam power 700 kW to produce the intense neutrino beam. The expected POT is 3.6×10^{21} divided in 50% neutrino mode and 50% anti-neutrino mode, with uncorrelated 5% signal normalization error and 10% background normalization error for both neutrino and antineutrino appearance and disappearance channel respectively. All the relevant information has been taken from [23].
4. **DUNE:** DUNE is a long baseline future generation on-axis superbeam experiment having 1300 km baseline from Fermilab to Sanford Underground Research Laboratory in Lead, South Dakota. DUNE will use a 40 kt LArTPC as its far detector. We have followed the DUNE CDR [24] as reference. It uses a 80 GeV proton beam with beam power 1.07 MW with a total exposure of 300 kt.MW.yrs having neutrino mode running for 3.5 yrs and antineutrino mode running for 3.5 yrs. All other details have been matched to the DUNE design report.

Before we go to the result section, it is worth to mention that in the numerical simulation we have used a line-averaged constant matter density of 2.8 gm/cm^3 for T2K, T2HK and NOνA, and 2.95 gm/cm^3 for DUNE following the PREM [25,26] profile.

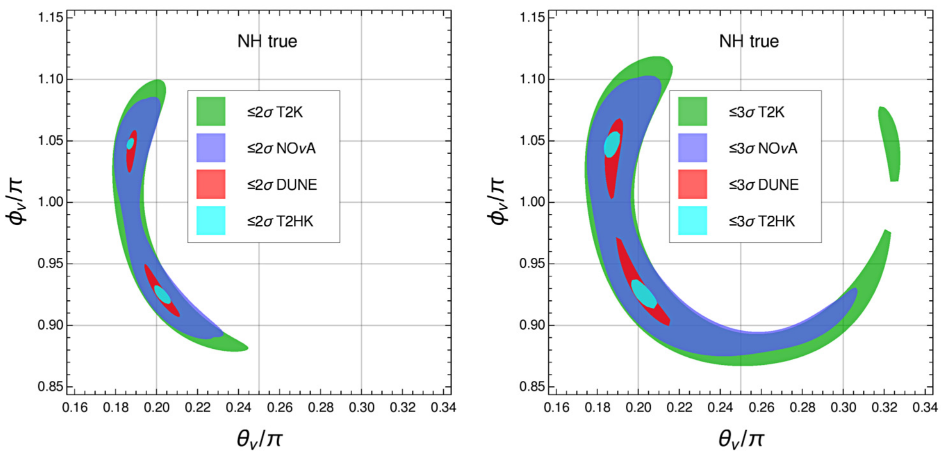

Fig. 1. Allowed regions of the two model parameters θ_ν and ϕ_ν at 2σ (left) and 3σ (right) confidence level at 1 d.o.f. that is ($\Delta\chi^2 = 4$, 9 respectively). The plots assume Normal Hierarchy (NH) as true. The dark green band represents the sensitivity of T2K, while the blue band corresponds to NOνA. The red and cyan bands give the expected sensitivities of the DUNE and T2HK experiments. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Values of the neutrino oscillation parameters corresponding to the χ^2 minima obtained from the benchmark model. The sixth column denotes the standard "unconstrained" three-neutrino best fit values for NH taken from [6]. The number within the parenthesis indicates the minimum value of the χ^2 predicted from the benchmark model for the corresponding experiment.

Parameter	DUNE ($\chi^2_{min} = 0.14$)	T2HK ($\chi^2_{min} = 0.637$)	NOνA ($\chi^2_{min} = 0.016$)	T2K ($\chi^2_{min} = 0.015$)	Unconstrained case
s^2_{12}	0.341	0.341	0.341	0.341	$0.323(\pm 0.016)$
s^2_{13}	0.023	0.023	0.024	0.024	$0.0234(\pm 0.0020)$
s^2_{23}	0.567	0.565	0.565	0.566	$0.567(^{+0.025}_{-0.043})$
δ_{CP}/π	1.30	1.30	1.30	1.30	$1.34(^{+0.64}_{-0.38})$

3. Constraining the benchmark model parameters θ_ν and ϕ_ν from experiment

Equations (1), expressed in terms of two free parameters θ_ν and ϕ_ν suggest that our benchmark model can be tested directly in low energy long baseline (LBL) neutrino oscillation experiments by obtaining the oscillation probability as a function of these two parameters and comparing to experimental data. This will lead to a restriction at a certain confidence level. In this section, we present the allowed region of the two model parameters θ_ν and ϕ_ν implied by the current and future LBL experiments.

Fig. 1 represents the restricted region of the two parameters θ_ν and ϕ_ν at 2σ (left panel) and 3σ (right panel) confidence level at 1 degree of freedom assuming normal hierarchy (NH) as our true choice. The dark green band represents the allowed region given by T2K, the blue band is obtained from NOνA, the red band is the sensitivity region expected for DUNE and the Cyan band corresponds to the sensitivity region of the proposed T2HK experiment. True data set has been generated using the unconstrained values of the oscillation parameters as mentioned in sec. 2 and then fitted to the test data set obtained from each pair of θ_ν and ϕ_ν in order to calculate the minimum $\Delta\chi^2$. Now the same procedure has been followed for all allowed[1] values of θ_ν and ϕ_ν. In order to obtain these sensitivity bands, we only consider those values of the new parameters for which model can be tested at certain confidence level that is $\Delta\chi^2 \leq n\sigma$ (here, $n = 2, 3$).

From Fig. 1, it is quite evident that the T2HK experiment is expected to provide the best sensitivity on the model parameters, followed by DUNE. The performance of T2HK is best because of low baseline and huge statistics which implies a very precise measurement of δ_{CP}, an essential ingredient to constrain our reference benchmark model. Note that for DUNE, the CP sensitivity is somewhat less than T2HK. On the other hand NOνA gives somewhat better sensitivity than T2K.

In Table 1, we show a fair comparison between the model independent (unconstrained) oscillation parameters and the one predicted by our simple benchmark model in different experiments. The minimum value of the $\Delta\chi^2$ coming from different experiments is also shown within parenthesis for the corresponding experiment. One should keep in mind that this analysis assumes that the *true values* is the minimum of the current global neutrino oscillation fit. Since the latter assumes the unconstrained scenario with its 4 free parameters, it follows that the true values in the simulation cannot be reproduced by the our benchmark model which has only 2 parameters, lying 2σ away from the minimum [1].

4. Sensitivities on oscillation parameters

Here we examine the sensitivities on neutrino mixing parameters and CP phase, specially focusing to θ_{23} and δ_{CP}, currently the two most poorly determined oscillation parameters. Before presenting our results notice that oscillation studies can be used to probe oscillation parameters in two ways: either in the general unconstrained three-neutrino scenario or within the above minimal benchmark picture of neutrino oscillations. In other words, by assuming the general oscillation picture as the truth, we expect that our available oscillation parameter space will be highly restricted by future experiments in the benchmark scenario. Alternatively, by taking our minimal benchmark picture as true, the real minimum of the oscillation parameters differs from the one obtained by the global oscillation fit, which assumes general χ^2 minimization with four free parameters. These two possible interpretations require a

[1] As pointed out by [1], the model allows both NH (for $\theta_\nu \in [0, \pi/2] \cup [3\pi/2, 2\pi]$) and IH ($\theta_\nu \in [\pi/2, 3\pi/2]$). For definiteness here we consider only NH in the region $\theta_\nu \in [0, \pi/2]$. The angle ϕ_ν can assume any value in between 0 to 2π.

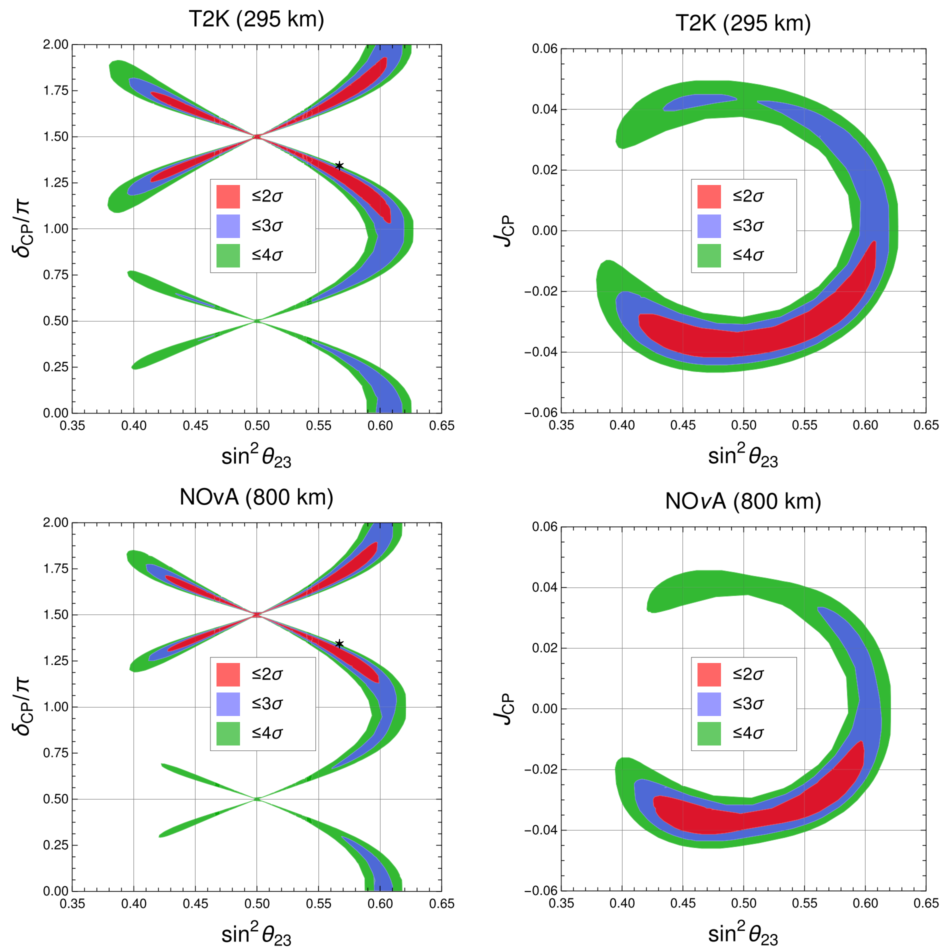

Fig. 2. Precision "measurement" of $\sin^2\theta_{23}$ and δ_{CP} at T2K and NOνA as predicted by the benchmark model when NH is the true hierarchy. The star denotes the unconstrained values from the fifth column of Table 1 and the bands correspond to the 2σ, 3σ, and 4σ C.L uncertainties. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

careful analysis. In order to do that one should analyze and compare both schemes in the same footing for each experiment.

4.1. Sensitivity of T2K and NOνA to θ_{23} and δ_{CP} in the minimal benchmark oscillation model

The results from Section 3 can be translated from the two parameters of our benchmark model into the four free parameters θ_{ij} and $\delta_{\rm CP}$ describing oscillations, through Eq. (1), obtaining a χ^2_0,

$$\chi^2_0 \equiv \chi^2(\theta_{ij}(\theta_\nu, \phi_\nu), \delta_{\rm CP}(\theta_\nu, \phi_\nu)) \tag{6}$$

which is the χ^2 function relevant if one assumes the standard picture as true. For definiteness we assume NH to be the true hierarchy. The corresponding two-dimensional 2, 3 and 4σ contours for the T2K and NOνA experiments are presented in Fig. 2. These are the values of the parameters θ_{23} and δ_{CP} which actually contribute to delimit the bands indicated in Fig. 1. The left panels give the $\sin^2\theta_{23}$ vs δ_{CP} contour plot, while the right panels are the $\sin^2\theta_{23}$ versus J_{CP} contour plots, where J_{CP} is the CP invariant. The upper (lower) panels of Fig. 2 correspond to T2K (NOνA). The red band in each plot of Fig. 2 corresponds to the 2σ C.L. allowed region, the blue band corresponds to 3σ C.L. and the green corresponds to the 4σ C.L. allowed region. The star denotes the unconstrained values taken from the fifth column of Table 1.

Notice the clear correlation between θ_{23} and δ_{CP} which is a consequence of Fig. 1. Note also, that a maximal choice of θ_{23} corresponds to the maximal CP violation (up to sign) for T2K and NOνA which is a very important prediction of the benchmark model. Moreover, for non-maximal values of θ_{23}, there is a four fold degeneracy in the CP phase determination in T2K and NOνA. Apart from the θ_{23}–δ_{CP} four-fold degeneracy, there is also degeneracy between the lower octant ($\sin^2\theta_{23} < 0.5$) and higher octant ($\sin^2\theta_{23} > 0.5$), so that, this two parameter model can not distinguish the octant of the atmospheric angle θ_{23}. As expected, in the J_{CP} plots the degeneracy is clearly reduced.

4.2. Sensitivity of T2K and NOνA to θ_{23} and δ_{CP} in the general 3-neutrino oscillation picture

Here we summarize our model independent results for the oscillation parameters θ_{23} and δ_{CP}. They hold in the general 3-neutrino oscillation picture assuming again NH to be the true hierarchy. The precision "measurements" of the oscillation parameters $\sin^2\theta_{23}$ and δ_{CP} in the T2K and NOνA experiments are given in Fig. 3. The star symbol corresponds to the unconstrained Global best-fit values of the oscillation parameters as given in Table 1. The red, blue and dark green bands in each plot correspond to the 2σ, 3σ and 4σ uncertainties respectively in $\sin^2\theta_{23}$ and δ_{CP} plane. Fig. 3 clearly reflects the physics potential of T2K and NOνA in reconstructing the CP phase δ_{CP} and atmospheric mixing angle θ_{23}

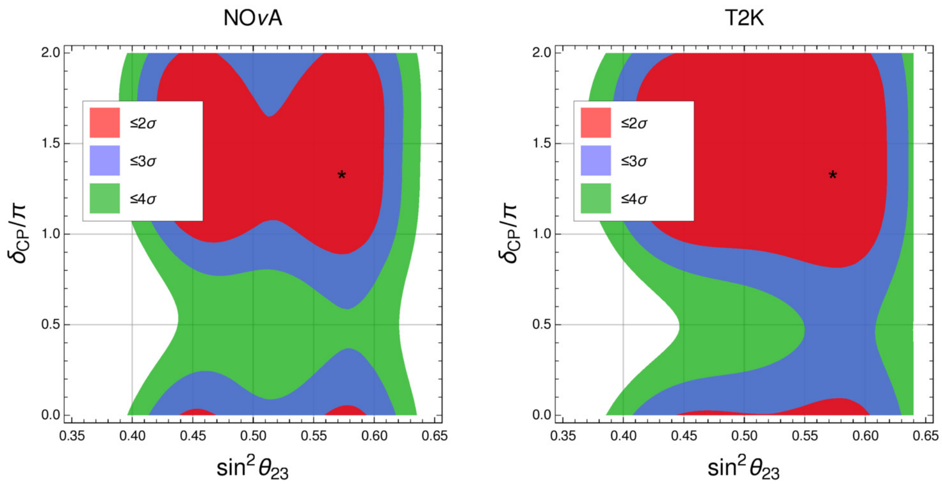

Fig. 3. Precision "measurement" of $\sin^2\theta_{23}$ and δ_{CP} at T2K and NOνA for generic unconstrained 3-neutrino oscillations when NH is the true hierarchy. The star denotes the unconstrained values taken from the fifth column of Table 1 and the bands correspond to the 2σ, 3σ, and 4σ C.L uncertainties. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

corresponding to the point denoted by the symbol "star". Even if for a fixed phase, there is a degeneracy between the two octants of the atmospheric angle θ_{23} at 2σ C.L. for both experiments.

Notice that the unconstrained best fit does not coincide with the minimum predicted by the model because the true value cannot be reproduced perfectly within the model. This implies that our benchmark oscillation scheme finds different minimum values for the current/expected oscillation parameters than obtained in an unconstrained fit.

4.3. Sensitivity of future experiments

We now turn to the sensitivity of the future generation of planned long baseline accelerator neutrino oscillation experiments such as DUNE [24] and T2HK [19], for definiteness. Our results are depicted in Figs. 4 and 5. The upper (lower) panel of Fig. 4 corresponds to DUNE (T2HK). Notice that in all plots of Fig. 4, there is an extra cyan band at 5σ C.L. One sees that they will have the potential of severely constraining the parameter space of the model. The most important point to note is that they help to remove the four-fold degeneracy to two-fold degeneracy, due to their fantastic sensitivity to $\delta_{\rm CP}$. It excludes a large part of the parameter space. The allowed region at 4σ corresponds to the 1.10π $(-162°)$ to 1.75π $(-45°)$ for DUNE and for maximal value of θ_{23}, model predicts maximal CP violation that $\delta_{CP} = -90°$. This is a very nice prediction of the benchmark model [1]. Notice that T2HK plays a crucial role in removing the four-fold degeneracy of the CP phase completely for most of the parameter space (for example, if θ_{23} lies in the upper octant) and it improves the sensitivity tremendously which can be attributed to the fact that T2HK has very good sensitivity to the CP phase. For a fixed CP phase, it also removes the octant degeneracy but not at 5σ C.L. and that can be easily verified by placing a horizontal line around the star symbol on the left plot of the lower panel of Fig. 4. Fig. 5 displays the sensitivity region in δ_{CP} versus $\sin^2\theta_{23}$, clearly indicating the capability of T2HK (similar holds for DUNE) in establishing CP violation by rejecting the CP conservation scenario at more than 5σ C.L. The figure gives a quantitative estimate of the precise "measurement" of $\sin^2\theta_{23}$ and δ_{CP} for the generic unconstrained 3-neutrino oscillation scenario, when NH is the true hierarchy. The star denotes the best-fit (unconstrained) values of the two parameters. The true data have been generated with all the best-fit values of the oscillation parameters mentioned in sec. 2 and in the fit we have marginalized on solar and reactor mixing angles θ_{12} and θ_{13} respectively keeping NH fixed. The red, blue and dark green bands correspond to the 2σ, 3σ and 4σ C.L uncertainty respectively at 1 d.o.f. Notice that in this case also the octant would remain unresolved even at 2σ C. L.

Before concluding let us also show the corresponding χ^2 profiles. The plots in Fig. 6 quantify the reconstruction capability for the oscillation parameters θ_{23} (δ_{CP}). The green dot indicates the unconstrained best fit value from [6]. The black dashed curve indicates the current global fit measurement, while the red solid curve gives the T2HK expectation for the general oscillation scheme and the blue solid curve represents the precise measurement by the model.

5. Summary and outlook

We have performed realistic simulations of the current long baseline experiments T2K and NOvA as well as future ones such as DUNE and T2HK in order to determine their potential in probing neutrino oscillation parameters in general, as well as testing our "minimal" benchmark theory of neutrino oscillations. We have seen that the standard unconstrained three-neutrino picture and our benchmark scenario predict different minima for the neutrino oscillation parameters. Nevertheless, current neutrino oscillation experiments cannot exclude our benchmark scenario. In all our considerations we have had to assume a "true" value of the oscillation parameters in order to determine the expected precision of a future "measurement". This "true" value has been taken from [6]. However we could well have taken it from any of the other recent global oscillation fits, namely those in [7,8].

An obvious question arises, namely, what is the sensitivity of the model for any pair of unconstrained value of θ_{23} and δ_{CP}? In other words, what are the values of θ_{23} and δ_{CP} "true" for which the model can be confirmed or excluded at a given confidence? With this in mind, we fix the true values of the currently "best determined" oscillation parameters Δm^2_{ij}, θ_{12} and θ_{13}. Given their current errors their central values are not expected to change significantly in upcoming experiments. We now vary both $\theta_{23}^{\rm TRUE}$ and $\delta_{\rm CP}^{\rm TRUE}$, finding the corresponding minimum of χ^2 within the benchmark scheme by varying the model parameters θ_ν and ϕ_ν. This way we obtain a function $\chi^2_{\rm min}(\theta_{23}^{\rm TRUE}, \delta_{\rm CP}^{\rm TRUE})$,

$$\chi^2_{\rm min}(\theta_{23}^{\rm TRUE}, \delta_{\rm CP}^{\rm TRUE}) = {\rm Min}[\chi^2_{\rm min}(\theta_{23}^{\rm TRUE}, \delta_{\rm CP}^{\rm TRUE}, \theta_\nu, \phi_\nu) \rightarrow {\rm over} \quad \theta_\nu, \phi_\nu] \tag{7}$$

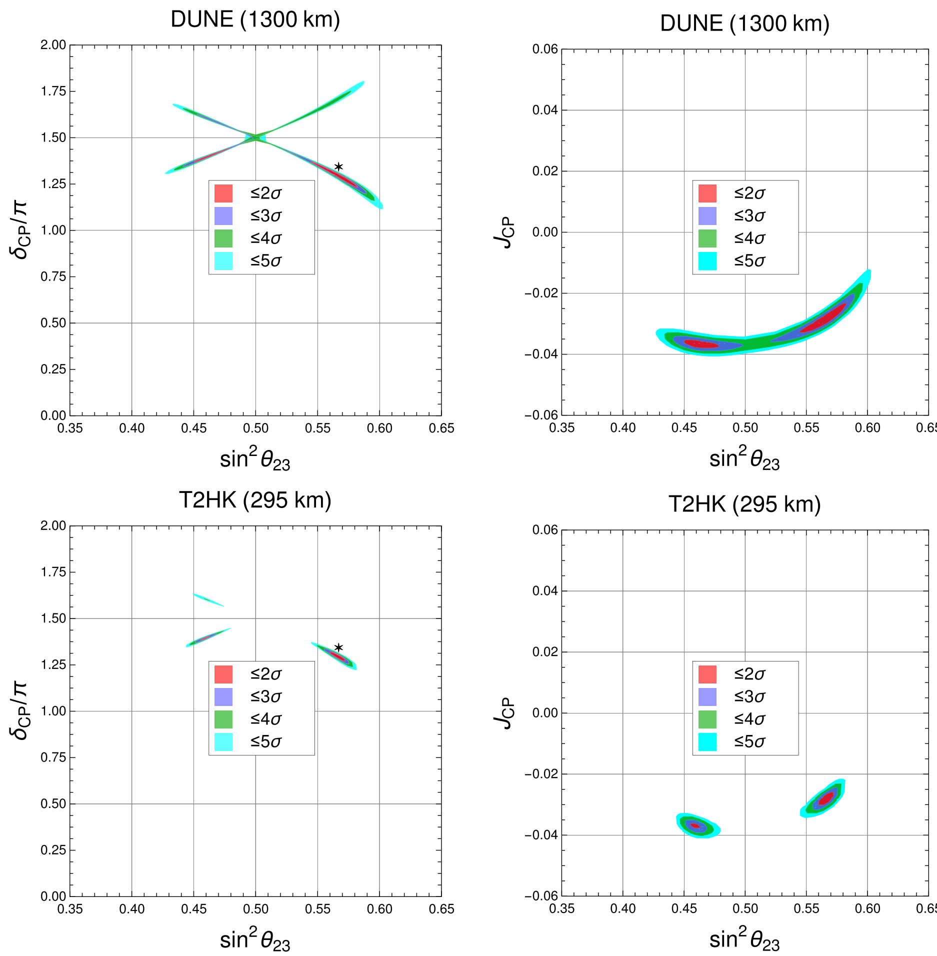

Fig. 4. Precision "measurement" of $\sin^2\theta_{23}$ and δ_{CP} at future LBL experiments DUNE and T2HK when NH is the true hierarchy. The star denotes the unconstrained values taken from the fifth column of Table 1. The bands correspond to the 2, 3, 4 and 5σ C.L uncertainty. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

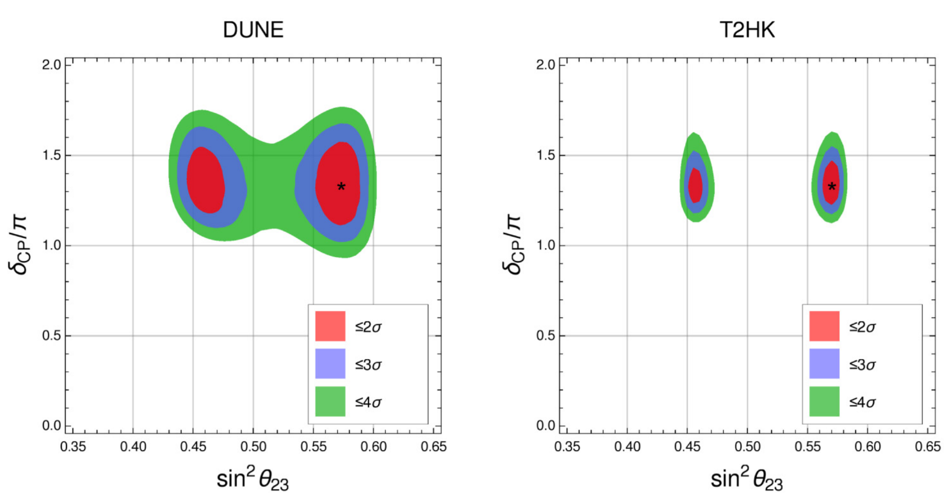

Fig. 5. Precision "measurement" of $\sin^2\theta_{23}$ and δ_{CP} for generic unconstrained 3-neutrino oscillations when NH is the true hierarchy. The star denotes the unconstrained values taken from the fifth column of Table 1. The bands correspond to the 2σ, 3σ and 4σ C.L uncertainty. Notice that in this case the octant would remain unresolved even at 2σ C. L. . (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

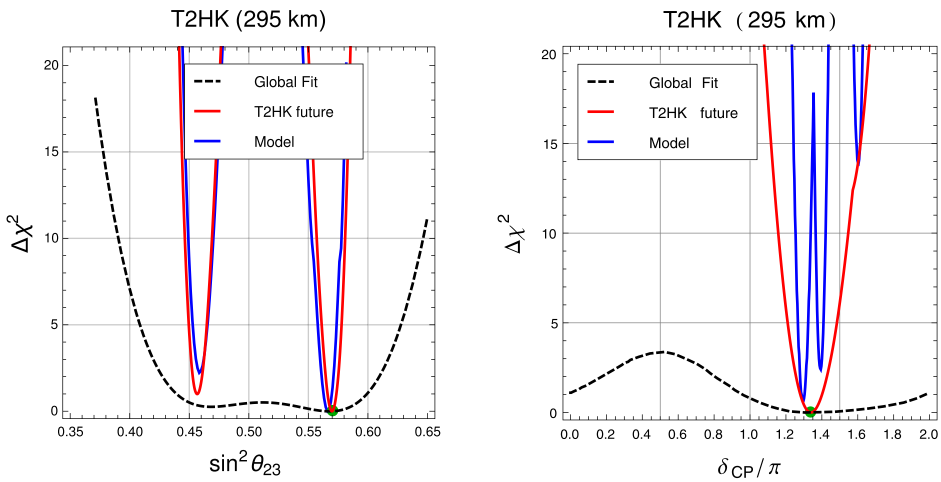

Fig. 6. The left (right) panel indicates the reconstruction of oscillation parameters θ_{23} (δ_{CP}). The green dot indicates the best fit value in the unconstrained oscillation picture, taken from [6]. The black dashed curve indicates the current global fit measurement, the red solid curve indicates the T2HK expectation for the measurement in the generic oscillation scheme, while blue solid curve represents the precise measurement by the model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

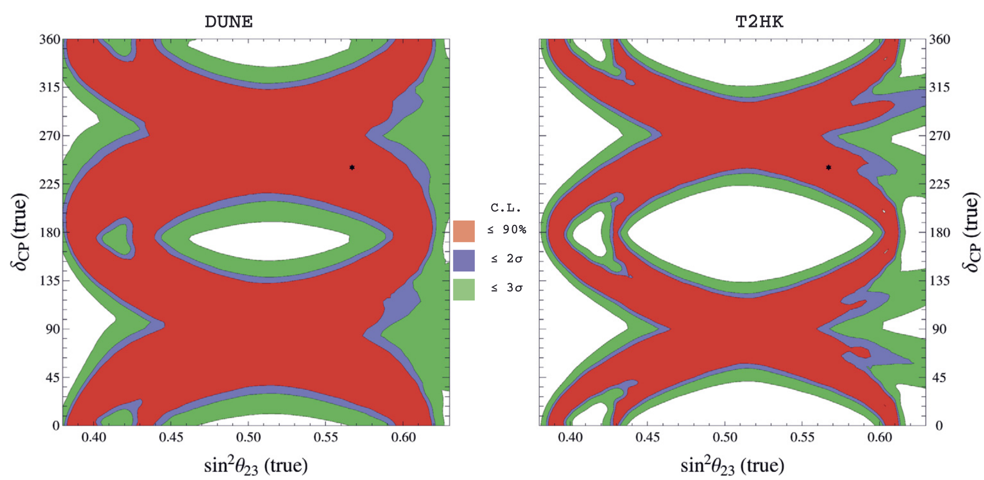

Fig. 7. Probing the model through the true values of $\sin^2\theta_{23}$ and δ_{CP} for normal neutrino mass ordering (NH). The shaded regions denote the confidence level at which DUNE (left) or T2HK (right) would confirm our minimal benchmark oscillation model. The red band corresponds to 90%C.L., the blue band corresponds to 2σ C.L. and the dark green band corresponds to the 3σ C.L. allowed region. The confidence levels are given for 1 d.o.f. ($\Delta\chi^2 = 2.71$, 4 and 9 respectively). The star denotes the unconstrained values taken from the fifth column of Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Now for each true data set the new parameters are marginalized within their allowed values coming from Fig. 1. The resulting χ^2 represents the ability of the experiment to probe the model if it measures a given value of $\theta_{23}^{\text{TRUE}}$ and $\delta_{\text{CP}}^{\text{TRUE}}$ and it has been addressed very nicely in Fig. 7. The light red band corresponds to the 90% C.L. region, the light blue band corresponds to 2σ C.L. region and the green band corresponds to the 3σ C.L region. The blank region indicates the unconstrained parameter space of θ_{23} and δ_{CP} for which the model can be excluded at more than 3σ C.L.. In short, our "minimal" benchmark oscillation model serves to highlight the increased sensitivity of the new planned generation of long baseline oscillation experiments.

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