Tensions between the appearance data of T2K and NO\(\nu\)A

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Abstract

The long baseline neutrino experiments, T2K and NO\(\nu\)A, have taken significant amount of data in each of the four channels: (a) \(\nu_\mu\) disappearance, (b) \(\bar{\nu}_\mu\) disappearance (c) \(\nu_e\) appearance and (d) \(\bar{\nu}_e\) appearance. There is a mild tension between the disappearance and the appearance data sets of T2K. A more serious tension exists between the \(\nu_e\) appearance data of T2K and the \(\nu_e/\bar{\nu}_e\) appearance data of NO\(\nu\)A. This tension is significant enough that T2K rules out the best-fit point of NO\(\nu\)A at 95% confidence level whereas NO\(\nu\)A rules out T2K best-fit point at 90% confidence level. We explain the reason why these tensions arise. We also do a combined fit of T2K and NO\(\nu\)A data and comment on the results of this fit.

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I. INTRODUCTION

Recently T2K \cite{1} and NO\text{$\nu$}A \cite{2} collaborations have published their data on both neutrino and anti-neutrino runs. The best-fit values of various neutrino oscillations parameters determined by each of these experiments are listed in table I below. In the table, NH refers to normal hierarchy ($\Delta_{32} > 0$) and IH refers to inverted hierarchy ($\Delta_{32} < 0$).

| Parameter                  | NO\text{$\nu$}A | T2K   |
|----------------------------|-----------------|-------|
| $\Delta_{32}/10^{-3}$ eV$^2$ (NH) | 2.51            | 2.463 |
| $\Delta_{32}/10^{-3}$ eV$^2$ (IH) | -2.56           | -2.506|
| $\sin^2 \theta_{23}$ (NH)     | 0.58            | 0.526 |
| $\sin^2 \theta_{23}$ (IH)     | 0.58            | 0.530 |
| $\delta_{\text{CP}}$ (NH)     | 30.6°           | -107.1°|
| $\delta_{\text{CP}}$ (IH)     | -95.4°          | -81.9°|

TABLE I: Best-fit points of T2K [1] and NO\text{$\nu$}A [2] data. The fit is based on the following numbers of protons on target (POT). For NO\text{$\nu$}A POT are $8.85 \times 10^{20}$ ($6.9 \times 10^{20}$) in neutrino (anti-neutrino) modes. For T2K they are $14.7 \times 10^{20}$ ($7.6 \times 10^{20}$) in neutrino (anti-neutrino) modes.

The best-fit values of $\Delta_{32}$, both for NH and for IH, for the two experiments are very close. These two experiments are sensitive to all the three unknown parameters of neutrino oscillations: the neutrino mass hierarchy, the octant of $\theta_{23}$ and the CP violating phase $\delta_{\text{CP}}$. Both experiments prefer NH over IH and the higher octant for $\theta_{23}$. However, T2K prefers $\sin^2 \theta_{23}$ close to the maximal value of 0.5 whereas NO\text{$\nu$}A prefers a higher value which is closer to 0.6. Regarding $\delta_{\text{CP}}$, T2K demands that it should be in the lower half plane (LHP) with a preference for a value close to $-90^\circ$. The best-fit value of $\delta_{\text{CP}}$ for NO\text{$\nu$}A is in the upper half plane (UHP) and it disfavours values close to $-90^\circ$. The results of these experiments are usually given in the form of contours of allowed regions in $\delta_{\text{CP}} - \sin^2 \theta_{23}$ plane, for NH and for IH. Overall, T2K rules out the best-fit point of NO\text{$\nu$}A in this plane at 95% confidence level and NO\text{$\nu$}A rules out the T2K best-fit point at 90% confidence level. This disagreement is the result of the tension between the appearance data of these two experiments. Though both the experiments prefer NH, the possibility of IH is not ruled out. The IH best-fit point
of T2K is allowed only at 2 $\sigma$ while the corresponding point for NO$\nu$A is allowed at 1 $\sigma$. It is interesting to note that the IH best-fit points of the two experiments are reasonably close to each other.

Long baseline accelerator neutrino experiments take data in the following four channels:

- $\nu_\mu$ disappearance: The number of events in this channel are the largest because the survival probability is moderately large over a wide energy range and also because the neutrino flux and the cross section are larger. Hence this channel has the highest statistical weight.

- $\bar{\nu}_\mu$ disappearance: This channel has the second highest statistical weight. The survival probability is moderately large but the neutrino flux and the cross section are smaller.

- $\nu_e$ appearance: The statistical weight of this channel is not very high because the oscillation probability is rather small ($\leq 0.05$).

- $\bar{\nu}_e$ appearance: This channel has the least statistical weight because the oscillation probability is low and the anti-neutrino flux and the cross section are smaller.

The tension between the data of the two experiments may well be the result of low statistics and may disappear with more data. However, it is possible to make some predictions regarding the trend along which the tension is likely to be resolved by doing a combined fit.

In this article we study the neutrino and anti-neutrino appearance data of these two experiments using the expressions for $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ in three flavour oscillations including matter effect. The disappearance data is related to the survival probabilities $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$. For the energies and the baselines of T2K and NO$\nu$A, the survival probabilities can be approximated by a two flavour expression with an effective mass-squared difference $\Delta_{\mu\mu}$ [3] and $\sin 2\theta_{23}$. We find that there are mild tensions between the neutrino and anti-neutrino disappearance data of NO$\nu$A [2] and between the neutrino appearance and disappearance data of T2K. These tensions are likely to be resolved with more data. There is, however, a serious tension between the appearance data of the two experiments, which is leading to each experiment ruling out the best-fit point of the other experiment. We explain the cause of this tension. We also do a combined fit of the data from both the experiments and compare the best-fit point to the current best-fit points of the two experiments.
II. $P_{\mu e}$ AND $P_{\bar{\mu} \bar{e}}$ FOR T2K AND NO\nu A

For both T2K and NO\nu A experiments, the expression for $P(\nu_\mu \to \nu_e)$ is [4, 5]

$$P(\nu_\mu \to \nu_e) = P_{\mu e} = \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 \tilde{\Delta}(1 - \tilde{A})}{(1 - A)^2} + \alpha \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\tilde{\Delta} + \delta_{\text{CP}}) \frac{\sin \tilde{\Delta} \tilde{A} \sin \tilde{\Delta}(1 - \tilde{A})}{A} \frac{1}{1 - A}, \quad (1)$$

where $\tilde{\Delta} = 1.27\Delta_{31}L/E$, $\tilde{A} = A/\Delta_{31}$ and $\alpha = \Delta_{21}/\Delta_{31}$. The Wolfenstein matter term $A$ is [6]

$$A \text{ (in eV}^2) = 0.76 \times 10^{-4} \rho \text{ (in gm/cc) E (in GeV)}, \quad (2)$$

where $E$ is the energy of the neutrino and $\rho$ is the density of the matter. For anti-neutrinos, $P(\bar{\nu}_\mu \to \bar{\nu}_e) = P_{\bar{\mu} \bar{e}}$ is given by a similar expression with $\delta_{\text{CP}} \to -\delta_{\text{CP}}$ and $A \to -A$. Since $\alpha \approx 0.03$, the term proportional to $\alpha^2$ in $P_{\mu e}$ is neglected.

The best-fit points of T2K and NO\nu A, for both NH and IH, can be understood by considering the changes induced in $P_{\mu e}$ and $P_{\bar{\mu} \bar{e}}$ by the change in each of the unknowns relative to a common reference set of parameter values. We take this reference set to be vacuum oscillations with $\theta_{23} = 45^\circ$ and $\delta_{\text{CP}} = 0$.

- Inclusion of matter effect increases $P_{\mu e}$ for NH and decreases it for IH. The effect is opposite for $P_{\bar{\mu} \bar{e}}$.
- Both $P_{\mu e}$ and $P_{\bar{\mu} \bar{e}}$ increase if $\theta_{23}$ is in the higher octant (HO) and decrease if it is in the lower octant (LO).
- If $\delta_{\text{CP}}$ is in the lower half plane (LHP) $P_{\mu e}$ increases whereas it decreases for $\delta_{\text{CP}}$ in the upper half plane (UHP). Here again the effect is opposite for $P_{\bar{\mu} \bar{e}}$.

If the hierarchy is NH, the octant is HO and $\delta_{\text{CP}}$ is in LHP, all the three unknowns boost $P_{\mu e}$ and we expect a large excess of $\nu_e$ appearance events. This combination, however, leads to a moderate suppression of $P_{\bar{\mu} \bar{e}}$ because it is reduced due to hierarchy and $\delta_{\text{CP}}$ and increased due to octant. A moderate increase in $P_{\mu e}$, and hence in $\nu_e$ appearance events, occurs when two unknowns boost it and the third suppresses it. Three different combinations can cause this possibility. They are:
• (A) Hierarchy is NH, octant is HO and \(\delta_{\text{CP}}\) is in UHP. For this combination, the effects of hierarchy and \(\delta_{\text{CP}}\) are opposite for both \(P_{\mu e}\) and \(P_{\bar{\mu}e}\). Both these probabilities receive a modest boost due to HO.

• (B) Hierarchy is NH, octant is LO and \(\delta_{\text{CP}}\) is in LHP. Here hierarchy and \(\delta_{\text{CP}}\) both boost \(P_{\mu e}\) and LO lowers it. All three parameters lower \(P_{\bar{\mu}e}\) leading to the lowest expected number of \(\bar{\nu}_e\) appearance events.

• (C) Hierarchy is IH, octant is HO and \(\delta_{\text{CP}}\) is in LHP. Here again, the effects of hierarchy and \(\delta_{\text{CP}}\) are opposite for both \(P_{\mu e}\) and \(P_{\bar{\mu}e}\) and both these probabilities receive a modest boost due to HO.

For the T2K experiment, the peak flux occurs for \(E_\nu \approx 0.6\) GeV. Hence the matter effects are small and lead to a change of about 8% in \(P_{\mu e}\) and \(P_{\bar{\mu}e}\). Maximal values of \(\delta_{\text{CP}}\) can change the probability by about 20%. The change induced by the octant, of course depends on the value of \(\sin^2 \theta_{23}\). For the NO\(\nu\)A experiment, the flux peaks at \(E_\nu \approx 2\) GeV. The corresponding matter effects change probability by about 20%, which is also the change induced by maximal CP violation. The first neutrino data of NO\(\nu\)A had the following features: (a) \(\nu_\mu\) disappearance preferred non-maximal \(\theta_{23}\) and (b) \(\nu_\text{e}\) appearance showed a modest increase relative to the expectation from the reference point [7]. The non-maximal \(\theta_{23}\) values also induced a 20% change in \(P_{\mu e}\) and \(P_{\bar{\mu}e}\). Thus, each of the three unknowns induced change of similar magnitude which lead to three degenerate solutions of the forms (A), (B) and (C) listed above [8].

### III. CURRENT ACCELERATOR NEUTRINO DATA

#### A. T2K

T2K experiment observed maximal disappearance in both \(\nu_\mu\) and \(\bar{\nu}_\mu\) channels. This implies that \(\sin^2 \theta_{23}\) is close to 0.5. We did separate analyses of the disappearance data and the appearance data of T2K. In these analyses, the theoretical expectations are calculated using the software GLoBES [9, 10]. We matched the GLoBES predictions for the expected bin-wise event numbers with those given by the Monte-Carlo simulations of the experiments, quoted in refs. [1] and [2], for the same input parameters. In calculating the theoretical
expectations, the values of $\Delta_{21} = 7.50 \times 10^{-5}$ eV$^2$ and $\sin^2 \theta_{12} = 0.307$ are held fixed. The other mixing angles are varied in the following ranges: $\sin^2 2\theta_{13} = (0.084 \pm 3 \times 0.003)$ and $\sin^2 \theta_{23} = (0.25, 0.75)$. The CP-violating phase is varied over its full range $\delta_{\text{CP}} = (-180^\circ, 180^\circ)$. The effective mass-squared difference, $\Delta_{\mu\mu}$ [3], is varied in the range $(2.32 \pm 3 \times 0.11) \times 10^{-3}$ eV$^2$. The value of $\Delta_{31}$ is determined from the equation [3]

$$\Delta_{31} = \Delta_{\mu\mu} + \Delta_{21}(\cos^2 \theta_{12} - \cos \delta \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23}). \quad (3)$$

For NH, $\Delta_{\mu\mu}$ is positive and for IH it is negative.

The results of the disappearance analysis give the best-fit value of $\sin^2 \theta_{23}$ to be 0.51. The data from both neutrino and anti-neutrino channels are included in this analysis. We also find that this data constrains $\sin^2 \theta_{23}$ to be in the range $(0.43, 0.6)$ at 3 $\sigma$. The disappearance data has no sensitivity to $\delta_{\text{CP}}$. Therefore, the constraints on $\sin^2 \theta_{23}$ are valid for all values of $\delta_{\text{CP}}$.

From table-2 of reference [1] we can estimate that the $\nu_e$ appearance events for the reference point is about 60, for the given neutrino run of T2K. Inclusion of matter effects changes this number by 4 and inclusion of maximal CP violating effects changes it by about 11. Thus, for T2K, the change induced by CP violation is much larger than the change induced by the matter effects. The combined effect of matter effects (assuming NH) and CP violation effects (assuming $\delta_{\text{CP}} = -90^\circ$) increases the estimated number to 80 [1]. Any further increase must necessarily require a value of $\sin^2 \theta_{23}$ larger than 0.5. T2K observes 89 $\nu_e$ appearance events. Hence, the $\nu_e$ appearance data of T2K pulls $\sin^2 \theta_{23}$ to larger values.

An analysis of the $\nu_e$ appearance data is shown in fig 1. It gives the best-fit value of $\sin^2 \theta_{23}$ as 0.63, though 0.5 is allowed within the allowed 1 $\sigma$ range. Thus, we see that there is a mild tension between T2K disappearance data and its $\nu_e$ appearance data. This tension may be due to the limited statistics and may go away with more data. However, the final value of $\sin^2 \theta_{23}$ is likely to be determined by the disappearance data because of its larger statistical weight. The combined analysis done by the T2K collaboration gives the best-fit value $\sin^2 \theta_{23} = 0.53$ [1]. In doing the analysis of the appearance data we have not included the data from the anti-neutrino channel. The number of events observed in this channel are too small for any meaningful analysis.

The observed large excess of $\nu_e$ events requires that $\delta_{\text{CP}}$ must be in the neighbourhood of $-90^\circ$. For values of $\delta_{\text{CP}}$ in the UHP, the expected number of $\nu_e$ appearance events is
FIG. 1: Expected allowed regions in $\sin^2 \theta_{23} - \delta_{CP}$ plane from the current appearance data of T2K in the neutrino channel. In the left panel, the hierarchy is assumed to be NH and in the right panel, the hierarchy is assumed to be IH. The best-fit point has minimum $\chi^2 = 29$ for both NH and IH for 24 energy bins.

smaller than the estimated number for the reference point. Since the observed number is much higher, $\delta_{CP}$ in UHP is strongly disfavoured. This data also disfavours IH because the corresponding matter effects lead to a lower prediction for the number of events. IH with $\delta_{CP} = -90^\circ$ is barely allowed at $2 \sigma$ [1].

T2K has also observed 7 $\bar{\nu}_e$ appearance events. For $\delta_{CP} = 0$ and NH, they expect to observe 9 events. This number is expected to go down to 8 if $\delta_{CP} = -90^\circ$. Therefore, the number of $\nu_e$ and $\bar{\nu}_e$ appearance events are consistent with each other. Due to the large statistical error in the $\bar{\nu}_e$ appearance events, it is not possible to make any strong comment on the value of $\delta_{CP}$ preferred by this data.

B. NO$\nu$A

The recent neutrino disappearance data of NO$\nu$A is consistent with maximal mixing ($\sin^2 \theta_{23} = 0.5$) whereas the anti-neutrino disappearance data prefers a non-maximal value [2]. Here again there is a mild tension between the different data sets of the same
FIG. 2: Expected allowed regions in $\sin^2 \theta_{23} - \delta_{\text{CP}}$ plane from the appearance data of NO$\nu$A in both neutrino and anti-neutrino channels, as given in [2]. In the left panel, the hierarchy is assumed to be NH and in the right panel, the hierarchy is assumed to be IH. The best-fit point occurs for NH with a minimum $\chi^2 = 6$ for 12 data points. The best-fit point of IH has $\Delta \chi^2 = 0.3$.

experiment. This tension also is not statistically significant because of the limited statistics of the anti-neutrino data. Regarding the appearance events, we expect 39 $\nu_e$ events and 15.5 $\bar{\nu}_e$ events for the reference point [8]. NO$\nu$A experiment observed 58 and 18 events respectively in these channels. That is, there is a moderate excess in both these channels. As mentioned above, each of the three unknowns induce a change of about 20% in the appearance events of NO$\nu$A. A moderate excess in both $\nu_e$ and $\bar{\nu}_e$ appearance events is possible only if the changes induced by the hierarchy and $\delta_{\text{CP}}$ cancel each other and the increase in both channels occurs because $\theta_{23}$ is in HO. That is, the combination of the unknowns must have either form (A) or form (C) listed in section-2. We performed an analysis of NO$\nu$A appearance data in a manner similar to the analysis we did for T2K data.
The results are shown in fig. 2. There are two nearly degenerate best-fit solutions, with the unknown parameter values \((\text{NH}, \sin^2 \theta_{23} = 0.65, \delta_{\text{CP}} = 120^\circ)\) and \((\text{IH}, \sin^2 \theta_{23} = 0.67, \delta_{\text{CP}} = -50^\circ)\) respectively. The first solution is in the form (A) and the second in the form (C).

The analysis done by the NO\(\nu\)A collaboration, of both their disappearance and appearance data, also finds two nearly degenerate best-fit points \([2]\): \((\text{NH}, \sin^2 \theta_{23} = 0.58, \delta_{\text{CP}} = 30.6^\circ)\) and \((\text{IH}, \sin^2 \theta_{23} = 0.58, \delta_{\text{CP}} = -90^\circ)\). Here again, we find two solutions, one in form (A) and the other in form (C). Since the disappearance data also is included in the NO\(\nu\)A analysis, a smaller value of \(\sin^2 \theta_{23}\) is obtained compared to the values shown in fig. 2. The wide difference in the values of \(\delta_{\text{CP}}\) preferred by T2K and by NO\(\nu\)A shows the tension between the data of NO\(\nu\)A and T2K. T2K prefers a large boost of \(P_{\mu e}\) by all the three unknowns whereas NO\(\nu\)A prefers a moderate boost of both \(P_{\mu e}\) and \(P_{\bar{\nu}e}\) due to the combinations mentioned above. This tension is also visible in the fact that T2K rules out the best-fit point of NO\(\nu\)A at 95% C.L. whereas NO\(\nu\)A rules out the best-fit point of T2K at 90% C.L. The appearance events of NO\(\nu\)A, especially in the \(\bar{\nu}_e\) channel, are limited. With more statistics it is possible that the present tension may go away. But the likely resolution of this tension will have \(\delta_{\text{CP}}\) close to \(-90^\circ\) because of the very large excess of \(\nu_e\) appearance events observed by T2K.

**IV. COMBINED FIT TO T2K AND NO\(\nu\)A DATA**

In this section we present our results of combined fit of the disappearance and the appearance data of T2K and NO\(\nu\)A in both neutrino and anti-neutrino channels. The data of T2K is taken from ref. [1] and that of NO\(\nu\)A from ref. [2]. The theoretical expectations for the two experiments are calculated using the software GLoBES [9, 10], using the procedure that was described in section-3.1 for T2K analyses. There are a total of 182 energy bins, half in neutrino channel and half in anti-neutrino channel. In each case, there are 42 in disappearance data and 24 in appearance data for T2K and 19 in disappearance data and 6 in appearance data for NO\(\nu\)A. In computing the \(\chi^2\) between the data and the theoretical expectations, prior is added for \(\sin^2 2\theta_{13}\) and \(\Delta_{\mu\mu}\). We have also included a 10% overall systematic error for each channel of both the experiments. The results of our fit are shown in figure 3. The best-fit point for NH is \((\sin^2 \theta_{23} = 0.56, \delta_{\text{CP}} = -130^\circ)\) with a \(\chi^2\) of 219 and
FIG. 3: Expected allowed regions in $\delta_{CP} - \sin^2 \theta_{23}$ plane from the combined fit of the neutrino and anti-neutrino data of T2K and NO$\nu$A, as of July 2018. In the left panel, the hierarchy is assumed to be NH and in the right panel, the hierarchy is assumed to be IH. The $\chi^2$ for NH best-fit point is 219 and that for IH best-fit point is 220.5, for 182 data points.

The best-fit point for NH is ($\sin^2 \theta_{23} = 0.56$, $\delta_{CP} = -90^\circ$) with a $\chi^2$ of 220.5. The best-fit point for NH seems to be a compromise between the best-fit points of T2K and NO$\nu$A, especially with regard to choice of $\sin^2 \theta_{23} = 0.56$. On the other hand, the choice of $\delta_{CP} = -130^\circ$ as its best-fit value is enforced by the large excess of $\nu_e$ events observed by T2K. For NH, values of $\delta_{CP}$ in UHP are essentially ruled out at 2 $\sigma$. For IH, the best-fit point in our fit is close to the IH best-fit points of T2K and NO$\nu$A. This is not surprising because those two points are close to each other. For IH, the whole region of $\delta_{CP}$ in upper half plane is ruled out at 3 $\sigma$ because it is disfavoured by both T2K and NO$\nu$A.

Recently NO$\nu$A collaboration published their results with increased anti-neutrino run [11]. The data in this analysis is based on $8.85 \times 10^{20}$ POT in neutrino mode (which is the same for the previous analysis also) and $12.33 \times 10^{20}$ POT in anti-neutrino mode (which is double that of the previous analysis). They have observed 27 $\bar{\nu}_e$ appearance events. The results of this analysis give the best-fit point as (NH, $\sin^2 \theta_{23} = 0.56$, $\delta_{CP} = 0$). The inverted hierarchy is disfavored with its best-fit point (IH, $\sin^2 \theta_{23} = 0.56$, $\delta_{CP} = -90^\circ$) being allowed.
FIG. 4: Expected allowed regions in $\delta_{CP} - \sin^2 \theta_{23}$ plane from the combined fit of the neutrino and anti-neutrino data of T2K and NO$\nu$A, as of July 2019. In the left panel, the hierarchy is assumed to be NH and in the right panel, the hierarchy is assumed to be IH. The $\chi^2$ for NH best-fit point is 209 and that for IH best-fit point is 211.5, for 182 data points.

only at 1.8 $\sigma$. We see that the tension between the T2K data and the NO$\nu$A data persists because the preferred values of $\delta_{CP}$ are widely different. We did a reanalysis of the data from T2K [1] and NO$\nu$A [11]. The results are plotted in fig. 4. Comparing it with fig. 3, we note that the allowed regions have become more constrained though they are very similar to the previously allowed regions. We also note that the best-fit value of $\delta_{CP}$ changed from $-130^\circ$ to $-120^\circ$ and IH is allowed only at 2 $\sigma$. Thus we see that the additional anti-neutrino data of NO$\nu$A leads only to small changes in the combined fit.
V. CONCLUSION

The two long baseline accelerator neutrino experiments, T2K and NOνA, have taken significant amount of data both in the neutrino channel as well as in the anti-neutrino channel. The disappearance data of T2K prefers $\sin^2 \theta_{23}$ close to 0.5 whereas that of NOνA prefers $\sin^2 2\theta_{23}$ to be non-maximal. T2K has observed 89 $\nu_e$ appearance events but the number of $\bar{\nu}_e$ appearance events is not statistically significant. NOνA has observed 58 $\nu_e$ and 18 $\bar{\nu}_e$ appearance events and has established $\bar{\nu}_e$ appearance at 4 $\sigma$.

To understand the constraints imposed by the appearance data on the three unknown parameters of neutrino oscillations, we define a reference point: no matter effects, $\sin^2 \theta_{23} = 0.5$ and $\delta_{CP} = 0$. We consider the change induced in $P_{\mu e}$ and $P_{\bar{\mu} \bar{e}}$ by the inclusion of matter effect due to NH/IH, by the change of $\sin^2 \theta_{23}$ to HO/LO and by the effect of CP-violation with $\delta_{CP}$ in LHP/UHP. Both matter effects and non-zero $\delta_{CP}$ induced opposite deviations in $P_{\mu e}$ and in $P_{\bar{\mu} \bar{e}}$. But the octant of $\theta_{23}$ changes both the probabilities the same way. The observed $\nu_e$ appearance events in T2K are about 50% more than what is expected for the reference point. Such a large excess is possible only if the change in $P_{\mu e}$ is positive due to the changes in all the three unknowns. That is if hierarchy is NH, $\theta_{23}$ is in HO and $\delta_{CP} \approx -90^\circ$. The best-fit point of T2K finds the unknowns to be: hierarchy is NH, $\sin^2 \theta_{23} = 0.53$ and $\delta_{CP} = -107^\circ$. The value of $\sin^2 \theta_{23}$ is a compromise value of the best-fit values of the disappearance and the appearance data. T2K appearance data requires $\delta_{CP}$ to be in the neighbourhood of $-90^\circ$ quite strongly. In the case of NOνA, the observed $\nu_e$ and $\bar{\nu}_e$ appearance events are in moderate excess relative to the reference point. Such an observation can be explained only if the changes induced by hierarchy and $\delta_{CP}$ in $P_{\mu e}$ and $P_{\bar{\mu} \bar{e}}$ nearly cancel each other and the increase is due to $\theta_{23}$ being in HO. This is why NOνA obtains two nearly degenerate solutions: hierarchy is NH, $\theta_{23}$ in HO and $\delta_{CP} \approx 30^\circ$ and hierarchy is IH, $\theta_{23}$ in HO and $\delta_{CP} \approx -90^\circ$. The large excess of $\nu_e$ appearance events in T2K rules out both these points at 95% C.L. On the other hand, the moderate excess of $\nu_e$ and $\bar{\nu}_e$ appearance events in NOνA disfavour enhancement of $P_{\mu e}$ due to both hierarchy and $\delta_{CP}$.

The analysis of NOνA data picks $\sin^2 \theta_{23} = 0.58$ as the best-fit value [2]. In the combined analysis of the appearance and the disappearance data of the two experiments the best-fit value of $\sin^2 \theta_{23}$ is pulled a little lower by the disappearance data of T2K. The best-fit value
of $\delta_{CP}$ for the NH solution is in the LHP at $-130^\circ$. This value is the result of the large excess of $\nu_e$ appearance events seen by T2K which force $\delta_{CP}$ to take a large value in LHP. Values of $\delta_{CP}$ in UHP, for NH, are ruled out at 2 $\sigma$, even though the best-fit point of NO$\nu$A is in this region. This also is a result of the large excess of $\nu_e$ appearance events observed by T2K. Values of $\delta_{CP}$ in UHP predict the number of $\nu_e$ appearance events for T2K to be close to or below that of the reference point. Such values are strongly disfavoured by T2K because the observed number of events is significantly larger. Even though this region is preferred by NO$\nu$A appearance data, the conflict between its predictions and T2K data is ruling it out at 2 $\sigma$ in the combined fit.

Even though T2K barely allows an IH solution at 2 $\sigma$, the combined fit has a nearly degenerate IH solution which is the common IH solution of each experiment, with $\delta_{CP} = -90^\circ$ and $\sin^2 \theta_{23} = 0.56$. If the hierarchy is IH and $\delta_{CP}$ is in UHP $P_{\mu e}$ is doubly suppressed by matter effects and by $\delta_{CP}$. There is a corresponding double enhancement of $P_{\bar{\mu} \bar{e}}$. Such a feature is not seen by either experiment hence this possibility is ruled out at 3 $\sigma$.

We have redone our analysis where we have included the latest NO$\nu$A data [11]. The combined analysis of T2K plus NO$\nu$A data leads to slightly smaller allowed regions with slightly shifted best-fit parameters. The tension between the T2K data and the NO$\nu$A data still persists because the former prefers $\delta_{CP}$ close to maximal CP violation whereas the latter prefers $\delta_{CP} = 0$. Our best-fit points, for both NH and IH, are close to the corresponding best-fit points obtained by the Nu-fit collaboration [12], in their global neutrino oscillation data analysis, which includes the latest long baseline accelerator neutrino data. Therefore, a simple analysis of the data of T2K and NO$\nu$A experiments leads to reliable information on the values of the unknown parameters.

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IIT Bombay for financial support.

[1] K. Abe et al. (T2K) (2018), 1807.07891.

[2] M. Sanchez (NO\nuA Collaboration) (2018), talk given at the Neutrino 2018 Conference, June 4-9, 2018, Heidelberg, Germany, https://zenodo.org/record/1286758#.W40g9hx9jCI.

[3] H. Nunokawa, S. J. Parke, and R. Zukanovich Funchal, Phys.Rev. D72, 013009 (2005), hep-ph/0503283.

[4] A. Cervera, A. Donini, M. Gavela, J. Gomez Cadenas, P. Hernandez, et al., Nucl.Phys. B579, 17 (2000), hep-ph/0002108.

[5] M. Freund, Phys.Rev. D64, 053003 (2001), hep-ph/0103300.

[6] L. Wolfenstein, Phys. Rev. D17, 2369 (1978).

[7] P. Adamson et al. (NO\nuA), Phys. Rev. Lett. 118, 231801 (2017), 1703.03328.

[8] S. Bharti, S. Prakash, U. Rahaman, and S. Uma Sankar, JHEP 09, 036 (2018), 1805.10182.

[9] P. Huber, M. Lindner, and W. Winter, Comput.Phys.Commun. 167, 195 (2005), hep-ph/0407333.

[10] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, Comput.Phys.Commun. 177, 432 (2007), hep-ph/0701187.

[11] NO\nuA collaboration, M. A. Acero et al., First Measurement of Neutrino Oscillation Parameters using Neutrinos and Antineutrinos by NO\nuA, 1906.04907.

[12] Nu-fit (Nu-fit Collaboration) (2019), http://www.nu-fit.org/?q=node/211.