

Review Article

Physics Potential of Long-Baseline Experiments

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The discovery of neutrino mixing and oscillations over the past decade provides firm evidence for new physics beyond the Standard Model. Recently, θ_{13} has been determined to be moderately large, quite close to its previous upper bound. This represents a significant milestone in establishing the three-flavor oscillation picture of neutrinos. It has opened up exciting prospects for current and future long-baseline neutrino oscillation experiments towards addressing the remaining fundamental questions, in particular the type of the neutrino mass hierarchy and the possible presence of a CP-violating phase. Another recent and crucial development is the indication of non-maximal 2-3 mixing angle, causing the octant ambiguity of θ_{23} . In this paper, I will review the phenomenology of long-baseline neutrino oscillations with a special emphasis on sub-leading three-flavor effects, which will play a crucial role in resolving these unknowns. First, I will give a brief description of neutrino oscillation phenomenon. Then, I will discuss our present global understanding of the neutrino mass-mixing parameters and will identify the major unknowns in this sector. After that, I will present the physics reach of current generation long-baseline experiments. Finally, I will conclude with a discussion on the physics capabilities of accelerator-driven possible future long-baseline precision oscillation facilities.

1. Introduction and Motivation

We are going through an exciting phase when the light of new findings is breaking apart our long-held understanding of the Standard Model of particle physics. This revolution started in part with the widely confirmed claim that neutrinos have mass, and it will continue to be waged by currently running and upcoming neutrino experiments. Over the last fifteen years or so, fantastic data from world-class experiments involving neutrinos from the sun [1–7], the Earth atmosphere [8, 9], nuclear reactors [10–16], and accelerators [17–22] have firmly established the phenomenon of neutrino flavor oscillations [23, 24]. This implies that neutrinos have mass and they mix with each other, providing an exclusive example of experimental evidence for physics beyond the Standard Model.

The most recent development in the field of neutrinos is the discovery of the smallest lepton mixing angle θ_{13} . Finally, it has been measured to be nonzero with utmost confidence by the reactor neutrino experiments Daya Bay [13] and RENO [14]. They have found a moderately large value of θ_{13} :

$$\sin^2 2\theta_{13}|_{\text{Daya Bay (rate-only)}} = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)} \text{ [13]},$$

$$\sin^2 2\theta_{13}|_{\text{RENO (rate-only)}} = 0.113 \pm 0.013 \text{ (stat)} \pm 0.019 \text{ (syst)} \text{ [14]},$$

which is in perfect agreement with the data provided by the another reactor experiment Double Chooz [15, 16] and the accelerator experiments MINOS [20] and T2K [22]. All the three global fits [25–27] of all the world neutrino oscillation data available indicate a nonzero value of θ_{13} at more than 10σ and suggest a best-fit value of $\sin^2 \theta_{13} \approx 0.023$ with a relative 1σ precision of 10%. Daya Bay experiment is expected to reduce this uncertainty to a level of 5% by 2016 when they will finish collecting all the data [28]. This recent high-precision measurement of a moderately large value of θ_{13} signifies an important breakthrough in validating the standard three-flavor oscillation picture of neutrinos [29]. It has created exciting opportunities for current and future neutrino oscillation experiments to address the remaining fundamental unknowns. This fairly large value of θ_{13} has provided a “golden” avenue to directly probe the neutrino

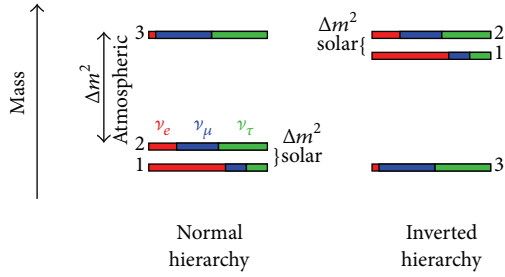


FIGURE 1: The sign of $\Delta m_{31}^2 \equiv m_3^2 - m_1^2$ is unknown. The hierarchy of the neutrino mass spectrum can be normal or inverted.

mass hierarchy (two possibilities are there: it can be either normal (NH) if $\Delta m_{31}^2 \equiv m_3^2 - m_1^2 > 0$ or inverted (IH) if $\Delta m_{31}^2 < 0$, as described in Figure 1) using the Earth matter effects and to search for leptonic CP violation (if the Dirac CP phase, δ_{CP} differs from 0° or 180°) in accelerator-based long-baseline neutrino oscillation experiments [30, 31]. Another recent and important development related to neutrino mixing parameters is the hint of nonmaximal 2-3 mixing by the MINOS accelerator experiment [32, 33]. However, the maximal value of θ_{23} is still favored by the atmospheric neutrino data, dominated by Super-Kamiokande [34]. Combined analyses of all the neutrino oscillation data available [25–27] also prefer the deviation from maximal mixing for θ_{23} ; that is, $(0.5 - \sin^2\theta_{23}) \neq 0$. In ν_μ survival probability, the dominant term mainly depends on $\sin^2 2\theta_{23}$. Now, if $\sin^2 2\theta_{23}$ differs from 1 as indicated by the recent neutrino data, then we get two solutions for θ_{23} : one $< 45^\circ$, named as lower octant (LO) and the other $> 45^\circ$, named as higher octant (HO). In other words, if the quantity $(0.5 - \sin^2\theta_{23})$ is positive (negative), then θ_{23} belongs to LO (HO). This leads to the problem of octant degeneracy of θ_{23} [35] which is a part of the overall eightfold degeneracy [36, 37], where the other two degeneracies are $(\theta_{13}, \delta_{\text{CP}})$ intrinsic degeneracy [38] and the (hierarchy, $\delta_{\text{CP}})$ degeneracy [39]. The resolution of the three fundamental issues in the neutrino sector: neutrino mass hierarchy, octant of θ_{23} , and CP violation is possible only by observing the impact of three-flavor effects in neutrino oscillation experiments [40, 41].

The information on neutrino mass hierarchy is very important in order to settle the structure of neutrino mass matrix which in turn can give crucial piece of information towards the underlying theory of neutrino masses and mixing [42]. This is also a vital ingredient for neutrinoless double beta decay searches investigating the Majorana nature of neutrinos. If $\Delta m_{31}^2 < 0$, and yet no neutrinoless double beta decay is observed even in the very far future experiments, that would be a strong hint that neutrinos are not Majorana particles [43]. Another fundamental missing link that needs to be addressed in long-baseline neutrino oscillation experiments is to measure δ_{CP} and to explore leptonic CP violation. This new source of low-energy CP violation in neutral lepton sector has drawn tremendous interest because of the possibility of leptogenesis is leading to baryogenesis and the observed baryon asymmetry in the universe [44].

Leptogenesis demands the existence of CP violation in the leptonic sector; for a recent review, see [45]. The possible link between leptogenesis and neutrino oscillations has been studied in [46–48]. It is likely that the CP violating phase in neutrino oscillations is not directly responsible to generate the CP violation leading to leptogenesis. But there is no doubt that a demonstration of CP violation in neutrino oscillations will provide a crucial guidepost for models of leptonic CP violation and leptogenesis. Precise measurement of θ_{23} and the determination of its correct octant (if it turns out to be nonmaximal) are also very vital tasks that need to be undertaken by the current- and next-generation neutrino oscillation experiments. These pieces of information will provide crucial inputs to the theories of neutrino masses and mixing [42, 49–51]. A number of excellent ideas, such as $\mu \leftrightarrow \tau$ symmetry [52–59], A_4 flavor symmetry [60–64], quark-lepton complementarity [65–68], and neutrino mixing anarchy [69, 70], have been proposed to explain the observed pattern of one small and two large mixing angles in the neutrino sector. Future ultraprecise measurement of θ_{23} will severely constrain these models leading to a better understanding of the theories of neutrino masses and mixing.

The outline of this review work is as follows. We start in Section 2 by revisiting the phenomenon of neutrino oscillation in the three-neutrino framework. Then, we discuss the importance of matter effect on neutrino oscillation in Section 3. In Section 4, we take a look at our present understanding of neutrino oscillation parameters and we identify the fundamental missing links in the neutrino sector that can be answered in the current- and next-generation long-baseline neutrino oscillation experiments. Section 5 discusses in detail the three-flavor effects in long-baseline neutrino oscillation experiments with the help of $\nu_\mu \rightarrow \nu_e$ oscillation probability, $P_{\mu e}$. Next, in Section 6, we study the physics reach of current-generation long-baseline beam experiments, T2K and NO ν A. In Section 7, we give an overview on the possible options for next-generation accelerator-driven long-baseline oscillation facilities. Finally, in Section 8, we conclude with a summary of the main points.

2. Three-Neutrino Mixing and Oscillation Framework

Bruno Pontecorvo was the pathfinder of neutrino oscillation [74, 75]. In 1957, he gave this concept [76, 77] based on a two-level quantum system. Neutrino oscillation is a simple quantum mechanical phenomenon in which neutrino changes flavor as it travels. This phenomenon arises if neutrinos have nondegenerate masses and there is mixing. First, we consider the fact that neutrinos (ν_e, ν_μ, ν_τ) are produced or detected via weak interactions and therefore they are referred to as weak-eigenstate neutrinos (denoted as ν_α). It means that they are the weak doublet-partners of e^- , μ^- , and τ^- , respectively. In such a case, if neutrinos are assumed to be massive, then in general, it is not mandatory that the mass-matrix of neutrinos written in this weak (flavor) basis will have to be diagonal. So, it follows that the mass eigenstate neutrinos ν_i , $i = 1, 2, 3$

(the basis in which the neutrino mass matrix is diagonal) are not identical to the weak or flavor basis (the charged lepton mass-matrix is diagonal in this basis) and for three light active neutrinos, we have

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i\rangle, \quad (1)$$

where α can be $e, \mu,$ or τ and U is the 3×3 unitary leptonic mixing matrix known as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [23, 78]. This matrix is analogous to the CKM matrix in the quark sector. We use the standard Particle Data Group convention [79] to parametrize the PMNS matrix in terms of the three mixing angles: θ_{12} (solar mixing angle), θ_{23} (atmospheric mixing angle), and θ_{13} (reactor mixing angle) and one Dirac-type CP phase δ_{CP} (ignoring Majorana phases). The mixing matrix U can be parameterized as

$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric mixing}} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor mixing}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar mixing}}, \quad (2)$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. The neutrino mixing matrix finally takes the form

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\text{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{23}c_{13} \end{pmatrix}. \quad (3)$$

It is quite interesting to note that three mixing angles are simply related to the flavor components of the three mass eigenstates as

$$\frac{|U_{e2}|^2}{|U_{e1}|^2} = \tan^2 \theta_{12}, \quad \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} = \tan^2 \theta_{23}, \quad (4)$$

$$|U_{e3}|^2 = \sin^2 \theta_{13}.$$

The transition probability that an initial ν_α of energy E gets converted to a ν_β after traveling a distance L in vacuum is given by

$$P(\nu_\alpha \rightarrow \nu_\beta) = P_{\alpha\beta} = \left| \sum_j U_{\beta j} e^{-im_j^2 L/2E} U_{\alpha j}^* \right|^2, \quad (5)$$

where the last factor arises from the decomposition of ν_α into the mass eigenstates, the phase factor in the middle appears due to the propagation of each mass eigenstate over distance L , and the first factor emerges from their recomposition into the flavor eigenstate ν_β at the end. Equation (5) can also be written as

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \underbrace{\sum_{i>j}^n \text{Re} [U_{\alpha i}^* U_{\beta j}^* U_{\beta i} U_{\alpha j}] \sin^2 X_{ij}}_{\text{CP conserving}} - 2 \underbrace{\sum_{i>j}^n \text{Im} [U_{\alpha i}^* U_{\beta j}^* U_{\beta i} U_{\alpha j}] \sin^2 X_{ij}}_{\text{CP violating}}, \quad (6)$$

where

$$X_{ij} = \frac{(m_i^2 - m_j^2)L}{4E} = 1.27 \frac{\Delta m_{ij}^2}{\text{eV}^2} \frac{L/E}{\text{m/MeV}}. \quad (7)$$

$\Delta m_{ij}^2 = m_i^2 - m_j^2$ is known as the mass splitting and neutrino oscillations are only sensitive to this mass-squared difference but not to the absolute neutrino mass scale. The transition probability (given by (6)) has an oscillatory behaviour with oscillation lengths:

$$L_{ij}^{\text{osc}} = \frac{4\pi E}{\Delta m_{ij}^2} \approx 2.48 \text{ m} \frac{E (\text{MeV})}{\Delta m_{ij}^2 (\text{eV}^2)} \quad (8)$$

$$= 2.48 \text{ km} \frac{E (\text{GeV})}{\Delta m_{ij}^2 (\text{eV}^2)},$$

and the amplitudes are proportional to the elements in the mixing matrix. Since neutrino oscillations can occur only if there is a mass difference between at least two neutrinos, an observation of this effect proves that at least one nonzero neutrino mass exists. In a three-flavor framework, there are two independent mass-squared differences between the three neutrino masses: $\Delta m_{21}^2 = m_2^2 - m_1^2$ (responsible for solar neutrino oscillations) and $\Delta m_{31}^2 = m_3^2 - m_1^2$ (responsible for atmospheric neutrino oscillations). The angle θ_{13} connects the solar sector with the atmospheric one and determines the impact of the three-flavor effects. The last term of (6) accommodates the CP violating part, proportional to $\sin \delta_{\text{CP}}$. This contribution can only be probed in a neutrino oscillation experiment measuring the appearance probability of a new flavor, since for disappearance experiments ($\alpha = \beta$) the last term becomes zero identically. Also, the CP violating term changes sign in going from $P(\nu_\alpha \rightarrow \nu_\beta)$ to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$ (for antineutrino, we have to replace U by U^*). It also changes sign in going from $P(\nu_\alpha \rightarrow \nu_\beta)$ to $P(\nu_\beta \rightarrow \nu_\alpha)$, since the CPT invariance ensures that $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = P(\nu_\beta \rightarrow \nu_\alpha)$.

3. Neutrino Propagation through Matter

Oscillation probability changes dramatically when neutrino passes through matter [80–82]. During propagation through matter, the weak interaction couples the neutrinos to matter.

Besides few hard scattering events, there is also coherent forward elastic scattering of neutrinos with matter particles they encounter along the path. The important fact is that the coherent forward elastic scattering amplitudes are not the same for all neutrino flavors. The ordinary matter consists of electrons, protons, and neutrons but it does not contain any muons or tau-leptons. Neutrinos of all three flavors (ν_e , ν_μ , and ν_τ) interact with the electrons, protons, and neutrons of matter through flavor-independent neutral current interaction mediated by Z^0 bosons. These contributions are the same for neutrinos of all three flavors, leading to an overall phase which can be subtracted. Interestingly, the electron neutrinos have an additional contribution due to their charged current interactions with the ambient electrons of the medium which are mediated by the W^\pm exchange. This extra matter potential appears in the form

$$A = \pm 2\sqrt{2}G_F N_e E, \quad (9)$$

where G_F is the Fermi coupling constant, N_e is the electron number density inside the Earth, and E is the neutrino energy. The + sign refers to neutrinos while the - to antineutrinos. The connection between the electron density (N_e) and the matter density (ρ) is given by

$$V_{CC} = \sqrt{2}G_F N_e \approx 7.6Y_e \frac{\rho}{10^{14} \text{ g/cm}^3} \text{ eV}, \quad (10)$$

where $Y_e = N_e/(N_p + N_n)$ is the relative electron number density. N_p , N_n are the proton and neutron densities in Earth's matter, respectively. In an electrically neutral, isoscalar medium, we have $N_e = N_p = N_n$ and Y_e comes out to be 0.5. If we compare the strength of V_{CC} for the Earth with $\Delta m_{31}^2/2E$, then we can judge the importance of Earth's matter effect on neutrino oscillations. If we consider a neutrino of 5 GeV passing through the core of the Earth ($\rho \sim 10 \text{ g/cm}^3$), then V_{CC} is comparable with $\Delta m_{31}^2/2E$ ($= 2.4 \times 10^{-13} \text{ eV}$ if $\Delta m_{31}^2 = 2.4 \times 10^{-3} \text{ eV}^2$).

In a two-flavor formalism, the time evolution of the flavor eigenstates in matter is given by the following Schrödinger equation:

$$i \frac{d}{dt} \begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \frac{1}{2E} \left[U \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} U^\dagger + \begin{pmatrix} A(L) & 0 \\ 0 & 0 \end{pmatrix} \right] \begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix}. \quad (11)$$

In case of constant matter density, the problem boils down to a stationary one and a trivial diagonalization of the Hamiltonian can provide the solution. In matter, the vacuum oscillation parameters are connected to the new parameters (the new parameters in matter carry a superscript m) in the following way:

$$\begin{aligned} (\Delta m^2)^m &= \sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2}, \\ \sin 2\theta^m &= \frac{\sin 2\theta \Delta m^2}{(\Delta m^2)^m}. \end{aligned} \quad (12)$$

The famous MSW-resonance [80–83] condition is satisfied at

$$\Delta m^2 \cos 2\theta = A. \quad (13)$$

At MSW-resonance, $\sin 2\theta^m = 1$ (from (12) and (13) which immediately implies that independent of the value of the vacuum mixing angle θ , the mixing in matter is maximal; that is, $\theta^m = \pi/4$). This resonance occurs for neutrinos (antineutrinos) if Δm^2 is positive (negative). It suggests that the matter potential modifies the oscillation probability differently depending on the sign of Δm^2 . Following (13), the resonance energy can be expressed as

$$E_{\text{res}} = 10.83 \text{ GeV} \left[\frac{\Delta m^2}{2.4 \times 10^{-3} \text{ eV}^2} \right] \cdot \left[\frac{\cos 2\theta}{0.96} \right] \cdot \left[\frac{2.8 \text{ g/cm}^3}{\rho} \right]. \quad (14)$$

When neutrino travels through the upper part of the Earth mantle with $\rho = 2.8 \text{ g/cm}^3$, the resonance occurs at roughly 10.8 GeV for positive Δm^2 of $2.4 \times 10^{-3} \text{ eV}^2$. The MSW potential arises due to matter and not antimatter and this fact is responsible for the observed asymmetry between neutrino and antineutrino oscillation probabilities even in the two-neutrino case. In three-flavor scenario, besides the genuine CP asymmetry caused by the CP phase δ_{CP} , we also have fake CP asymmetry induced by matter which causes hindrances in extracting the information on δ_{CP} .

4. Global Status of Oscillation Parameters and Missing Links

Oscillation data cannot predict the lowest neutrino mass. However, it can be probed in tritium beta decay [84] or neutrinoless double beta decay [85] processes. We can also make an estimation of the lowest neutrino mass from the contribution of neutrinos to the energy density of the universe [86]. Very recent measurements from the Planck experiment in combination with the WMAP polarization and baryon acoustic oscillation data have set an upper bound over the sum of all the neutrino mass eigenvalues of $\sum m_i \leq 0.23 \text{ eV}$ at 95% C.L. [87]. But oscillation experiments are sensitive to the values of two independent mass-squared differences: Δm_{21}^2 and Δm_{31}^2 . Recent global fit [27] of all the available neutrino oscillation data in three-flavor framework is given as best-fit $\Delta m_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2$ and $|\Delta m_{31}^2| = 2.4 \times 10^{-3} \text{ eV}^2$ with the relative 1σ precision of 2.4% and 2.8%, respectively. The atmospheric mass splitting is 32 times larger than the solar mass splitting, showing the smallness of the ratio $\alpha = \Delta m_{21}^2/\Delta m_{31}^2 \approx 0.03$. At present, the 3σ allowed range for Δm_{21}^2 is $7.0 \times 10^{-5} \text{ eV}^2 \rightarrow 8.1 \times 10^{-5} \text{ eV}^2$ and the same for $|\Delta m_{31}^2|$ is $2.2 \times 10^{-3} \text{ eV}^2 \rightarrow 2.7 \times 10^{-3} \text{ eV}^2$. Δm_{21}^2 is required to be positive to explain the observed energy dependence of the electron neutrino survival probability in solar neutrino experiments, but Δm_{31}^2 is allowed to be either positive or negative by the present oscillation data. Hence, two patterns of neutrino masses are possible: $m_3 > m_2 > m_1$, called NH where Δm_{31}^2 is positive and $m_2 > m_1 > m_3$, called IH where Δm_{31}^2 is negative. Determining the sign of Δm_{31}^2 is one of the

prime goals of the current- and next-generation long-baseline neutrino oscillation experiments.

As far as the mixing angles are concerned, the solar neutrino mixing angle θ_{12} is now pretty well determined with a best-fit value of $\sin^2\theta_{12} = 0.3$ and the relative 1σ precision on this parameter is 4%. The 3σ allowed range for this parameter is $0.27 \rightarrow 0.35$. The smallest lepton mixing angle θ_{13} has been discovered very recently with a moderately large best-fit value of $\sin^2\theta_{13} = 0.023$. The relative 1σ precision achieved on this parameter is also quite remarkable which is around 10%. The error in the measurement of $\sin^2\theta_{13}$ lies in the range of $0.016 \rightarrow 0.029$ at 3σ confidence level. The uncertainty associated with the choice of reactor $\bar{\nu}_e$ fluxes [88–90] and its impact on the determination of θ_{13} have been discussed in detail in Section 3 of [27]. Here, we would like to emphasize on that fact that the values of θ_{13} measured by the recent reactor and accelerator experiments are consistent with each other within errors, providing an important verification of the framework of three-neutrino mixing. These recent onset of data from reactor and accelerator experiments will also enable us to explore the long expected complementarity between these two independent measurements [40, 91–93]. Our understanding of the 2-3 mixing angle θ_{23} has also been refined a lot in recent years. The best-fit values and ranges of θ_{23} obtained from the three recent global fits [25–27] are listed in Table 1. A common feature that has emerged from all the three global fits is that we now have hint for nonmaximal θ_{23} , giving two degenerate solutions: either θ_{23} belongs to the LO ($\sin^2\theta_{23} \approx 0.4$) or it lies in the HO ($\sin^2\theta_{23} \approx 0.6$). This octant ambiguity of θ_{23} , in principal, can be resolved with the help of $\nu_\mu \leftrightarrow \nu_e$ oscillation data. The preferred value would depend on the choice of the neutrino mass ordering. However, as can be seen from Table 1, the fits of [25] do not agree on which value should be preferred, even when the mass ordering is fixed to be NH. LO is preferred over HO for both NH and IH in [26]. Reference [27] marginalizes over the mass ordering, so the degeneracy remains. The global best-fits in [25, 27] do not see any sensitivity to the octant of θ_{23} unless they add the information from the atmospheric neutrinos. But, in [26], they do find a preference for LO even without adding the atmospheric neutrino data. At present, the relative 1σ precision on $\sin^2\theta_{23}$ is around 11%. Further

improvement in the measurement of θ_{23} and settling the issue of its octant (if it turns out to be nonmaximal) are also the crucial issues that need to be addressed in current- and next-generation long-baseline experiments. Leptonic CP violation can be established if CP violating phase δ_{CP} is shown to differ from 0 and 180° . We have not seen any signal for CP violation in the data so far. Thus, δ_{CP} can have any value in the range $[-180^\circ, 180^\circ]$. Measuring the value of δ_{CP} and establishing the CP violation in the neutral lepton sector would be the top most priorities for the present and future long-baseline experiments.

Due to the fact that both α and θ_{13} are small, so far, it was possible to analyze the data from each neutrino oscillation experiment adopting an appropriate, effective two-flavor oscillation approach. This method has been quite successful in measuring the solar and atmospheric neutrino parameters. The next step must involve probing the full three-flavor effects, including the subleading ones which are proportional to α . These are the key requirements to discover neutrino mass hierarchy, CP violation, and octant of θ_{23} in long-baseline experiments [94, 95].

5. Three-Flavor Effects in $\nu_\mu \rightarrow \nu_e$ Oscillation Channel

To illustrate the impact of three-flavor effects, the most relevant oscillation channels are $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. A study of these oscillation channels at long-baseline super-beam experiments is capable of addressing all the three major issues discussed in the previous section. In particular, the use of an appearance channel in which the neutrino changes flavor between production and detection is mandatory to explore CP violation in neutrino oscillations. Earth's matter effects are also going to play a significant role in probing these fundamental unknowns. The exact expressions of the three-flavor oscillation probabilities including matter effects are very complicated. Therefore, to demonstrate the nature of neutrino oscillations as a function of baseline and/or neutrino energy, it is quite useful to have an approximate analytic expression for $P_{\mu e}$ (the T -conjugate of $P_{e\mu}$) in matter [80, 82, 96], keeping terms only up to second order in the small quantities θ_{13} and α [97–99]:

$$\begin{aligned}
 P_{\mu e} \simeq & \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13} \frac{\sin^2[(1-\widehat{A})\Delta]}{(1-\widehat{A})^2}}_{C_0} \\
 & + \underbrace{\alpha^2 \cos^2\theta_{23}\sin^2 2\theta_{12} \frac{\sin^2(\widehat{A}\Delta)}{\widehat{A}^2}}_{C_1} \\
 & \mp \underbrace{\alpha \sin 2\theta_{13} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\widehat{A}\Delta)}{\widehat{A}} \frac{\sin[(1-\widehat{A})\Delta]}{(1-\widehat{A})}}_{C_-} \sin \delta_{\text{CP}}
 \end{aligned}$$

$$+ \underbrace{\alpha \sin 2\theta_{13} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\widehat{A}\Delta)}{\widehat{A}} \frac{\sin[(1-\widehat{A})\Delta]}{(1-\widehat{A})}}_{C_+} \cos \delta_{\text{CP}}, \quad (15)$$

where

$$\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}, \quad \widehat{A} \equiv \frac{A}{\Delta m_{31}^2}. \quad (16)$$

Equation (15) has been derived under the constant matter density approximation. The matter effect is expressed by the dimensionless quantity \widehat{A} . The “−” sign which precedes the term C_- refers to neutrinos whereas the “+” refers to antineutrinos. In (15), α , Δ , and \widehat{A} are sensitive to the sign of Δm_{31}^2 , that is, the type of the neutrino mass ordering. Note that the sign of \widehat{A} changes with the sign of Δm_{31}^2 as well as in going from neutrino to the corresponding antineutrino mode. The former suggests that the matter effect can be utilized to determine the sign of Δm_{31}^2 , while the latter implies that it can mimic a CP violating effect and hence complicate the extraction of δ_{CP} by comparing neutrino and antineutrino data. For large θ_{13} , the first term of (15) (C_0) dominates and it contains the largest Earth matter effect which can therefore be used to measure the sign of Δm_{31}^2 . This term also depends on $\sin^2 \theta_{23}$ and therefore is sensitive to the octant of θ_{23} . The subdominant terms C_- and C_+ are suppressed by α and provide information on δ_{CP} . The term C_- is the CP-violating part. The term C_+ , although δ_{CP} -dependent, is CP-conserving. The term C_1 is independent of both θ_{13} and δ_{CP} and depends mainly on the solar parameters, Δm_{21}^2 and θ_{12} .

5.1. Hierarchy- δ_{CP} Degeneracy. Since the hierarchy and δ_{CP} are both unknown, the interplay of the terms C_0 , C_- , and C_+ in (15) gives rise to hierarchy- δ_{CP} degeneracy [39]. This degeneracy can be broken completely using the large Earth matter effects provided by the baselines which are >1000 km [41, 100, 101]. For these long baselines, we can also observe both the first and second oscillation maxima quite efficiently using the detectors like Liquid Argon Time Projection Chamber (LArTPC) [102]. It helps to evade the problem of $(\text{sgn}(\Delta m_{31}^2), \delta_{\text{CP}})$ degeneracy [39] and $(\theta_{13}, \delta_{\text{CP}})$ intrinsic degeneracy [38] which can cause the π -transit [103] effect even for large values of $\sin^2 2\theta_{13}$. Adding data from two different experiments with different baselines can also be very useful to resolve this degeneracy [37, 39, 104–107]. Another elegant way to tackle these degeneracies is to kill the spurious clone solutions at the “magic” baseline [36, 73, 108, 109]. When $\sin(\widehat{A}\Delta) = 0$, the last three terms in (15) drop out and the δ_{CP} dependence disappears from the $P_{\mu e}$ channel, which provides a clean ground for θ_{13} and $\text{sgn}(\Delta m_{31}^2)$ measurements. Since $\widehat{A}\Delta = \pm(2\sqrt{2}G_F n_e L)/4$ by definition, the first nontrivial solution for the condition, $\sin(\widehat{A}\Delta) = 0$ reduces to $\rho L = \sqrt{2}\pi/G_F Y_e$. This gives $(\rho/[g/cc])(L/[km]) \approx 32725$,

which for the PREM density profile of the Earth is satisfied for the “magic baseline,” $L_{\text{magic}} \approx 7690$ km. The CERN to India-Based Neutrino Observatory (INO) [110] distance corresponds to $L = 7360$ km, which is tantalizingly close to this “magic” baseline. Performing a long-baseline experiment at “Bimagic” baseline can be also very promising to suppress the effect of these degeneracies [111, 112]. Note that the low-order expansion of the probability $P_{\mu e}$ given by (15) is valid only for values of E and Earth matter density ρ (and hence L) where flavor oscillations are far from resonance; that is, $\widehat{A} \ll 1$. In the limit $\widehat{A} \sim 1$, one can check that even though the analytic expression for $P_{\mu e}$ given by (15) remains finite, the resultant probability obtained is incorrect [113, 114]. While we will use this analytical formula to explain our results in some cases, all the simulations presented in this review article are based on the full three-flavor neutrino oscillation probabilities in matter, using the Preliminary Reference Earth Model (PREM) [115].

The transition probability $P_{\mu e}$ as a function of the neutrino energy is shown in Figure 2. We allow δ_{CP} to vary within the range -180° to 180° and the resultant probability is shown as a band, with the thickness of the band reflecting the effect of δ_{CP} on $P_{\mu e}$. Inside each band, the probability for $\delta_{\text{CP}} = 90^\circ$ ($\delta_{\text{CP}} = -90^\circ$) case is shown explicitly by the solid (dashed) line. In each panel, the blue (red) band is for NH (IH). Left panel (right panel) depicts the probability for neutrino (antineutrino). In upper panels, we take the baseline of 295 km which matches with the distance of Tokai-to-Kamioka (T2K) experiment [116, 117] in Japan. In lower panels, we consider the baseline of 810 km which is the distance between Fermilab and Ash River, chosen for the NuMI Off-Axis Neutrino Appearance (NO ν A) experiment [118–120] in the United States. Matter effect increases $P(\nu_\mu \rightarrow \nu_e)$ for NH and decreases it for IH and vice versa for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$. For δ_{CP} in the lower half-plane ((LHP), $-180^\circ \leq \delta_{\text{CP}} \leq 0$), $P(\nu_\mu \rightarrow \nu_e)$ is larger and for δ_{CP} in the upper half-plane ((UHP), $0 \leq \delta_{\text{CP}} \leq 180^\circ$), $P(\nu_\mu \rightarrow \nu_e)$ is smaller. Hence, for the combination (NH, LHP), the values of $P(\nu_\mu \rightarrow \nu_e)$ are much higher than those for IH (and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ values are much lower). Similarly, for the combination (IH, UHP), the values of $P(\nu_\mu \rightarrow \nu_e)$ are much lower than those of NH (and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ values are much higher). Thus, LHP is the favorable half-plane for NH and UHP is favorable for IH [72, 121]. For T2K baseline, the matter effect is very small and therefore the δ_{CP} bands drawn for NH and IH overlap for almost entire range of δ_{CP} (except for the most favorable combinations like: NH, $\delta_{\text{CP}} = -90^\circ$ and IH, $\delta_{\text{CP}} = 90^\circ$) for almost all the choices of E . NO ν A has better chances to discriminate between NH and IH compared to T2K because of its larger baseline causing larger matter effect.

TABLE 1: 1σ bounds on $\sin^2\theta_{23}$ from the global fits performed in [25–27]. The numbers cited from [27] have been obtained by keeping the reactor fluxes free in the fit and also including the short-baseline reactor data with $L \leq 100$ m, with the mass hierarchy marginalized. This table has been taken from [71].

Reference	Forero et al. [25]	Fogli et al. [26]	Gonzalez-Garcia et al. [27]
$\sin^2\theta_{23}$ (NH)	$0.427^{+0.034}_{-0.027} \oplus 0.613^{+0.022}_{-0.040}$	$0.386^{+0.024}_{-0.021}$	
3σ range	0.36 \rightarrow 0.68	0.331 \rightarrow 0.637	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$
$\sin^2\theta_{23}$ (IH)	$0.600^{+0.026}_{-0.031}$	$0.392^{+0.039}_{-0.022}$	0.34 \rightarrow 0.67
3σ range	0.37 \rightarrow 0.67	0.335 \rightarrow 0.663	

But for the unfavorable combinations like NH, $\delta_{\text{CP}} = 90^\circ$ and IH, $\delta_{\text{CP}} = -90^\circ$, the NH and IH bands still overlap with each other. In the upper panels of Figure 3, we study the same for the Long-Baseline Neutrino experiment (LBNE) [122–125] baseline of 1300 km which is the distance between the Fermilab and the Homestake mine in South Dakota in the United States. The lower panels of Figure 3 depict the hierarchy- δ_{CP} degeneracy pattern for the Long-Baseline Neutrino Oscillation experiment (LBNO) [126–130] baseline of 2290 km which is the distance between the CERN and the Pyhäsalmi mine in Finland. For both the LBNE and LBNO baselines, the matter effects are substantial and they break the hierarchy- δ_{CP} degeneracy completely.

5.2. *Octant- δ_{CP} Degeneracy.* There is a similar octant- δ_{CP} degeneracy also in the $P_{\mu e}$ channel, which limits our ability to determine the correct octant of θ_{23} [35]. The upper left (right) panel of Figure 4 shows $P_{\mu e}$ versus E_ν ($P_{\mu\bar{e}}$ versus $E_{\bar{\nu}}$) for all possible values of δ_{CP} and for the two different values of $\sin^2\theta_{23}$, assuming NH to be the true hierarchy. These plots are drawn for the T2K experiment. The lower panels show the same for the NO ν A baseline. As can be seen from the upper and lower left panels of Figure 4, for neutrino data, the two octant bands overlap for some values of δ_{CP} and are distinct for other values. The combinations of octant and δ_{CP} which lie farthest from overlap will be favorable combinations for octant determination. For example, LO and δ_{CP} of 90° and HO and δ_{CP} of -90° form the favorable combinations. For the combinations with overlap, HO and δ_{CP} of 90° and LO and δ_{CP} of -90° , it is impossible to determine octant using neutrino data alone. However, as we see from the upper and lower right panels, these unfavorable combinations for neutrino case are the favorable ones for the antineutrino case. Thus, a combination of neutrino and antineutrino data will have a better capability to determine octant compared to neutrino data alone. This is in contrast to the hierarchy- δ_{CP} degeneracy, where for a given hierarchy, the favorable δ_{CP} region is the same for both neutrino and antineutrino. Thus, we draw the conclusion that a balanced neutrino and antineutrino data is imperative for resolving the octant ambiguity of θ_{23} for all values of δ_{CP} [71]. The octant- δ_{CP} degeneracy pattern for the LBNE (LBNO) experiment can be seen from the upper (lower) panels of Figure 5.

6. Present-Generation Beam Experiments: T2K and NO ν A

With the aim to unravel the θ_{13} -driven $\nu_\mu \rightarrow \nu_e$ appearance oscillation, the T2K experiment [116, 117] started its journey in 2010 and the NO ν A experiment [118–120] in the United States is now under construction and will start taking data near the end of this year. The detection of electron neutrino appearance in a ν_μ beam is the prime goal of these experiments and their experimental setups are optimized to achieve this target. Both the T2K and NO ν A experiments use the classic off-axis beam technique [131] that delivers a narrow peak in the energy spectrum, tuned to be at the expected oscillation maximum. Furthermore, this off-axis technology helps to reduce the background coming from the intrinsic ν_e contamination in the beam and a smaller fraction of high-energy tails reduces the background coming from neutral current events. As a result, it improves the signal-to-background ratio a lot. With the recent discovery of a moderately large value of θ_{13} , these current-generation experiments are now poised to probe the impact of full three-flavor effects to discover neutrino mass hierarchy, CP violation, and octant of θ_{23} . But to achieve these goals, they need to have very high proton beam powers of order 1 MW and detectors with huge fiducial masses (of order 10 kilotons) and therefore, these experiments are known as “superbeam” experiments. Next, we briefly describe the main features of the T2K and NO ν A experiments and then we present the physics reach of these experiments in light of the recently discovered moderately large value of θ_{13} .

6.1. *T2K.* T2K uses the 50 kilotons Super-Kamiokande water Cherenkov detector (fiducial volume 22.5 kilotons) as the far detector for the neutrino beam from J-PARC. The detector is at a distance of 295 km from the source at an off-axis angle of 2.5° [116]. The neutrino flux is peaked sharply at the first oscillation maximum of 0.6 GeV. The experiment is scheduled to run for 5 years in the neutrino mode with a power of 0.75 MW. Because of the low energy of the peak flux, the neutral current backgrounds are small and they can be rejected based on energy cut. The signal efficiency is 87%. To estimate the physics sensitivity, the background information and other details are taken from [132, 133].

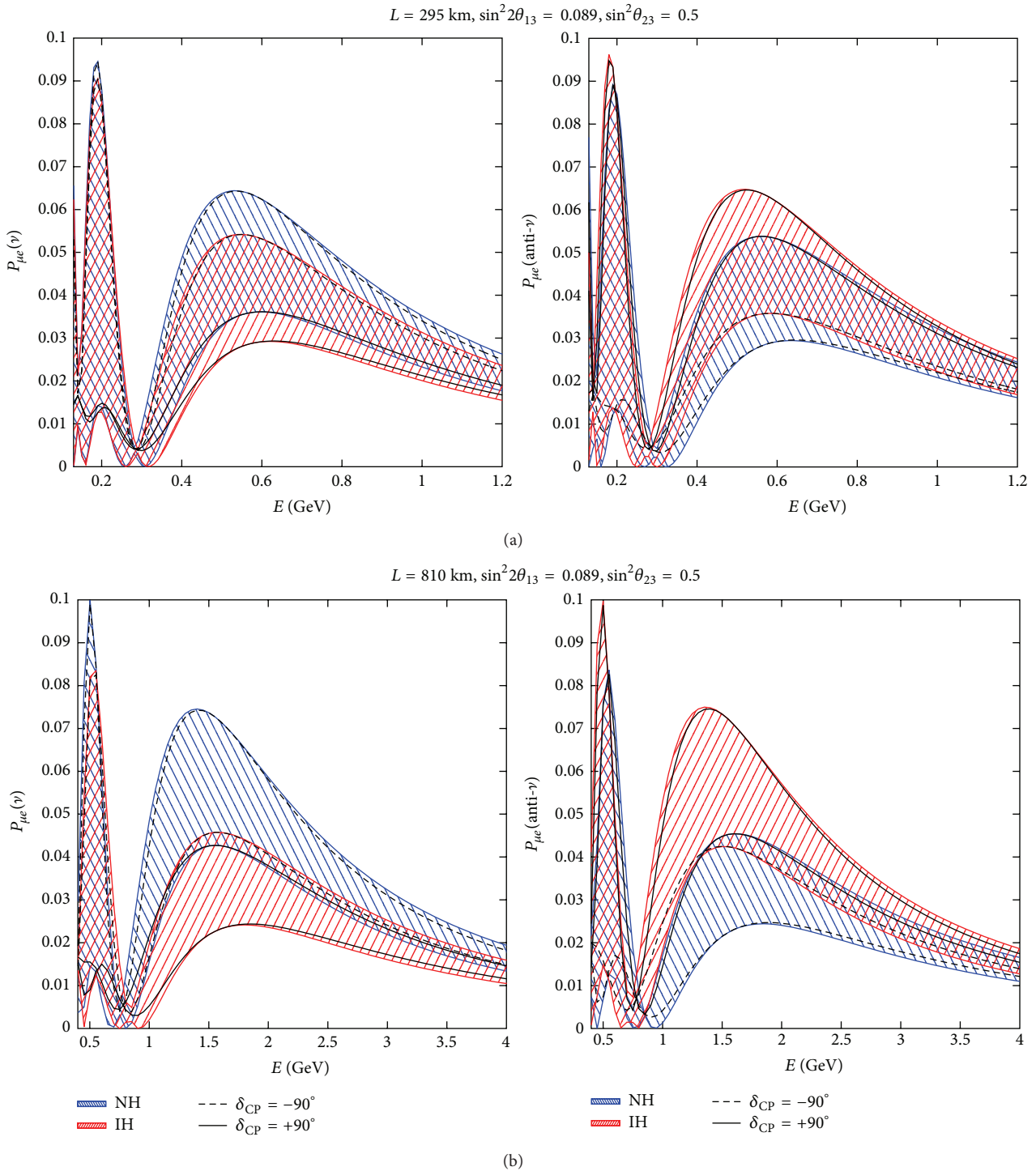


FIGURE 2: The transition probability $P_{\mu e}$ as a function of neutrino energy. The band reflects the effect of unknown δ_{CP} . Inside each band, the probability for $\delta_{\text{CP}} = 90^\circ$ ($\delta_{\text{CP}} = -90^\circ$) case is shown by the solid (dashed) line. The blue (red) band is for NH (IH). The left panel (right panel) is for ν ($\bar{\nu}$). The upper panels are drawn for the T2K baseline of 295 km. The lower panels are for the NO ν A baseline of 810 km. Here, we take $\sin^2 2\theta_{13} = 0.089$ and $\sin^2 \theta_{23} = 0.5$.

6.2. *NO ν A*. NO ν A is a 14 kilotons totally active scintillator detector (TASD) placed at a distance of 810 km from Fermilab, at a location which is 0.8° off-axis from the NuMI beam. Because of the off-axis location, the flux of the neutrinos is

reduced but is sharply peaked around 2 GeV, again close to the first oscillation maximum energy of 1.7 GeV in $P(\nu_\mu \rightarrow \nu_e)$. The most problematic background in NO ν A experiment is neutral current interactions which mostly consist in the

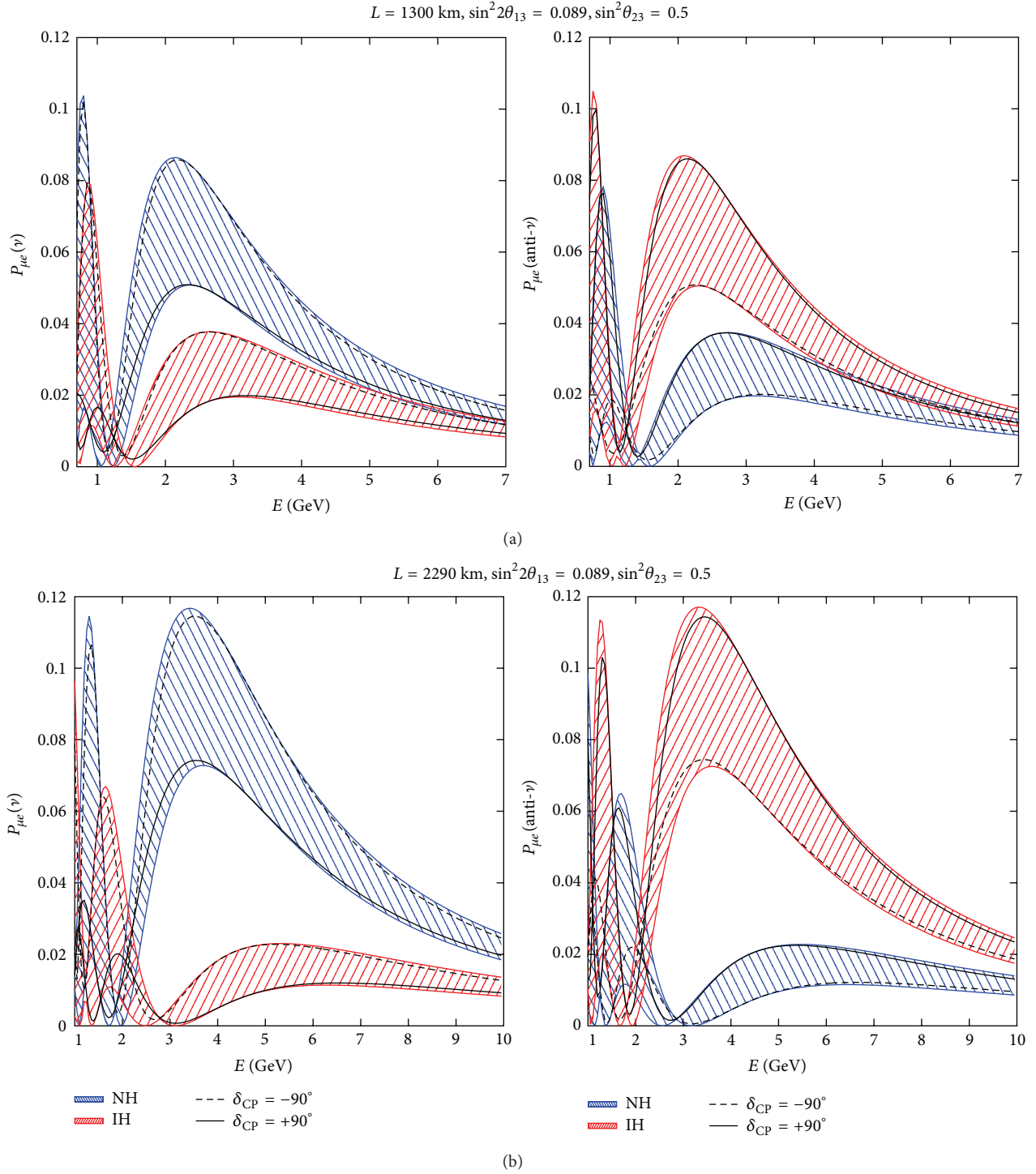


FIGURE 3: $P_{\mu e}$ as a function of neutrino energy. Here, the bands correspond to different values of δ_{CP} from -180° to 180° . Inside each band, the probability for $\delta_{\text{CP}} = 90^\circ$ ($\delta_{\text{CP}} = -90^\circ$) case is shown by the solid (dashed) line. The blue (red) band is for NH (IH). The left panel (right panel) is for ν ($\bar{\nu}$). The upper panels are drawn for the LBNE baseline of 1300 km. The lower panels are for the LBNO baseline of 2290 km. Here, we take $\sin^2 2\theta_{13} = 0.089$ and $\sin^2 \theta_{23} = 0.5$.

single π^0 production. However, the measured energy of this background is shifted to values of energy below the region where the flux is significant. Hence, this background can be rejected using a simple kinematic cut. The experiment is

scheduled to have three-year run in neutrino mode first and then later, three-year run in antineutrino mode as well with a NuMI beam power of 0.7 MW, corresponding to 6×10^{20} protons on target per year. The details of the experiment

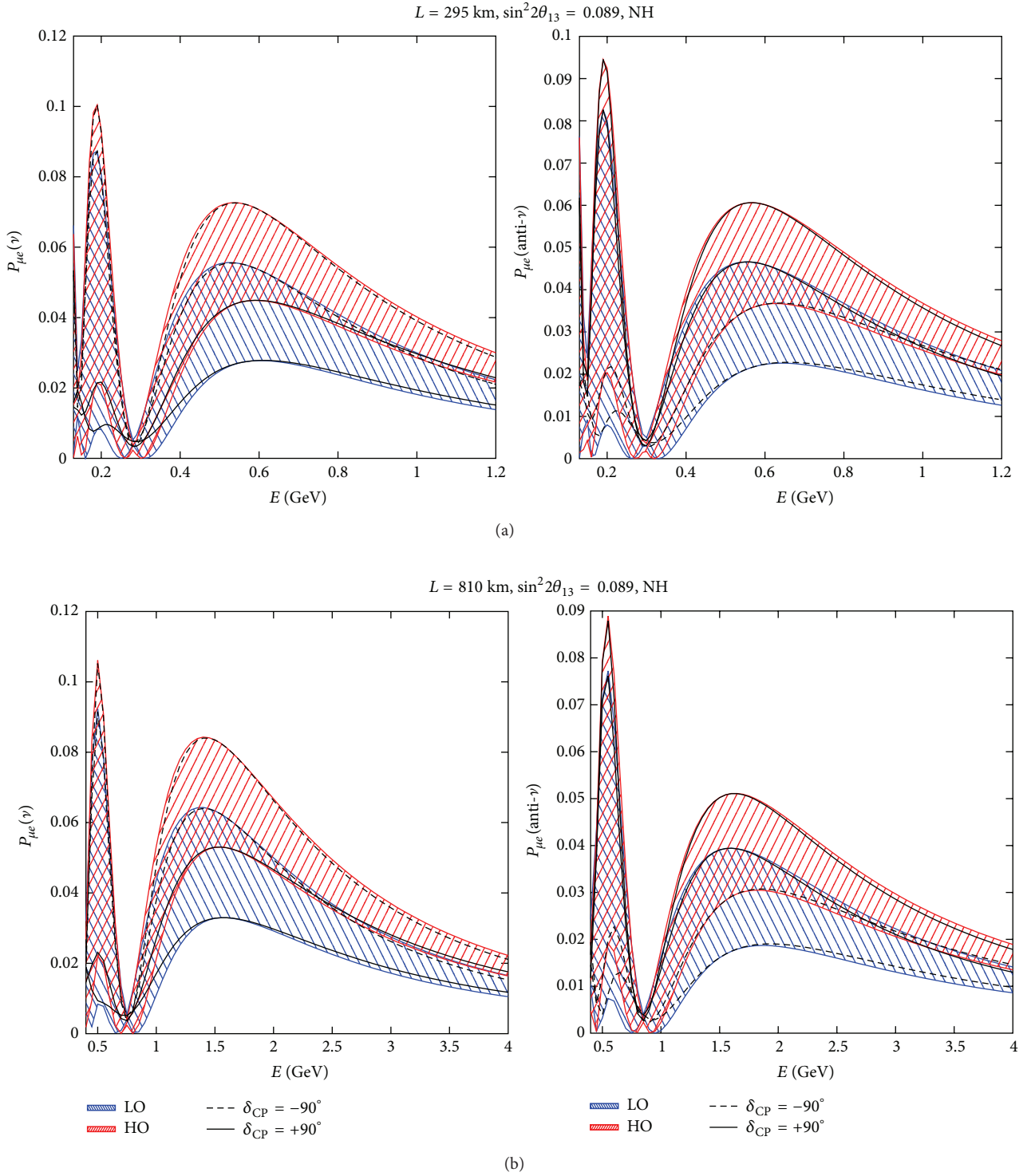


FIGURE 4: $P_{\mu e}$ as a function of neutrino energy. Here, the bands correspond to different values of δ_{CP} ranging from -180° to 180° . Inside each band, the probability for $\delta_{\text{CP}} = 90^\circ$ ($\delta_{\text{CP}} = -90^\circ$) case is shown by the solid (dashed) line. The red (blue) band is for HO with $\sin^2 \theta_{23} = 0.59$ (LO with $\sin^2 \theta_{23} = 0.41$). The left panel (right panel) is for ν ($\bar{\nu}$). The upper panels are drawn for the T2K baseline of 295 km. The lower panels are for the NO ν A baseline of 810 km. Here, we consider $\sin^2 2\theta_{13} = 0.089$ and NH.

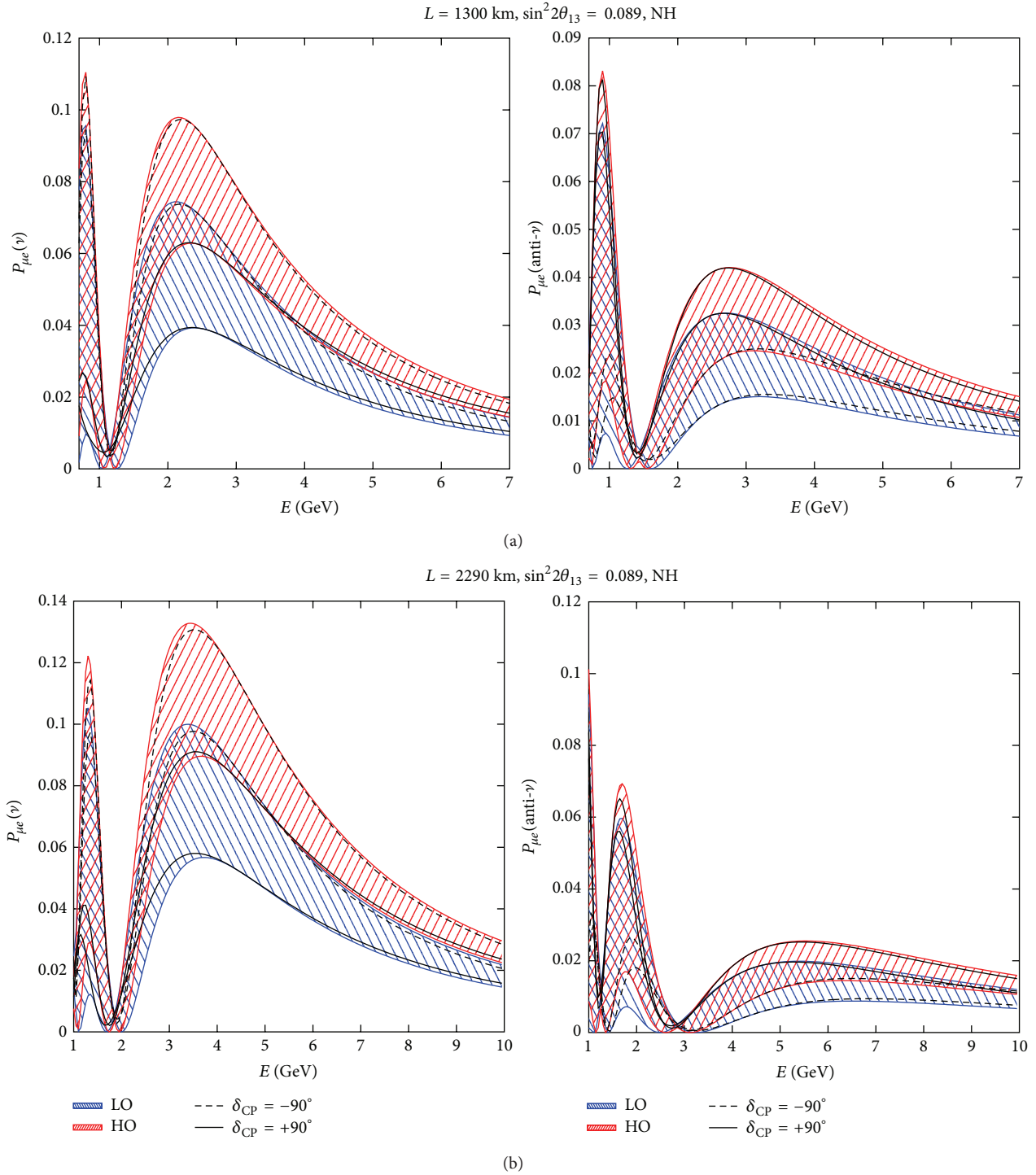


FIGURE 5: $P_{\mu e}$ as a function of neutrino energy. Here, the bands correspond to different values of δ_{CP} ranging from -180° to 180° . Inside each band, the probability for $\delta_{\text{CP}} = 90^\circ$ ($\delta_{\text{CP}} = -90^\circ$) case is shown by the solid (dashed) line. The red (blue) band is for HO with $\sin^2 \theta_{23} = 0.59$ (LO with $\sin^2 \theta_{23} = 0.41$). The left panel (right panel) is for ν ($\bar{\nu}$). The upper panels are drawn for the LBNE baseline of 1300 km. The lower panels are for the LBNO baseline of 2290 km. Here, we consider $\sin^2 2\theta_{13} = 0.089$ and NH.

are given in [120]. In light of the recent measurement of large θ_{13} , NO ν A has reoptimized its event selection criteria. Relaxing the cuts, they now allow more events in both signal and background. Additional neutral current backgrounds are

reconstructed at lower energies and can be managed by a kinematical cut. In our calculations, we use these reoptimized values of signal and background, the details of which are given in [72, 134].

6.3. *Mass Ordering and CP Violation Discovery.* In this section, we describe the capabilities of the T2K and NO ν A experiments for the determination of mass hierarchy and CP violation. We use GLOBES [135, 136] software to simulate the data for these experiments. For the atmospheric/accelerator neutrino parameters, we take the following central (true) values:

$$|\Delta m_{\text{eff}}^2| = 2.4 \cdot 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta_{23} = 1.0, \quad (17)$$

where Δm_{eff}^2 is the effective mass-squared difference measured by the accelerator experiments in $\nu_\mu \rightarrow \nu_\mu$ disappearance channel [32, 33]. It is related to the Δm_{31}^2 (larger) and Δm_{21}^2 (smaller) mass-squared differences through the expression [137, 138]

$$\Delta m_{\text{eff}}^2 = \Delta m_{31}^2 - \Delta m_{21}^2 \times (\cos^2 \theta_{12} - \cos \delta_{\text{CP}} \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23}). \quad (18)$$

The value of Δm_{31}^2 is calculated separately for NH and for IH using this equation where Δm_{eff}^2 is taken to be +ve for NH and -ve for IH. For θ_{23} , we take the maximal mixing as still favored by the Super-Kamiokande atmospheric data [34, 139, 140]. For θ_{13} , we take the best-fit value of $\sin^2 \theta_{13} = 0.026$. The uncertainties in the above parameters are taken to be $\sigma(\sin^2 \theta_{13}) = 13\%$ [25], $\sigma(|\Delta m_{\text{eff}}^2|) = 4\%$, and $\sigma(\sin^2 2\theta_{23}) = 2\%$ [116]. In the calculation, these pieces of information are included in the form of priors. In our χ^2 fit, we marginalize over *all* oscillation parameters within their $\pm 3\sigma$ ranges, as well as the mass hierarchy, by allowing these parameters to vary in the fit and picking the smallest value of the χ^2 function. We take the solar parameters to be

$$\Delta m_{21}^2 = 7.62 \cdot 10^{-5} \text{ eV}^2, \quad \sin^2 \theta_{12} = 0.32. \quad (19)$$

We keep the solar parameters to be fixed throughout the calculation because varying them will have negligible effect. We also take the Earth matter density to be a constant 2.8 g/cm^3 because the variations and the uncertainties in density can be neglected for the T2K and NO ν A baselines. While calculating the sensitivity for T2K, we include a 2% systematic error on appearance signal events and a (uncorrelated) 5% systematic error on backgrounds. For NO ν A, we have assumed 5% systematic error on appearance signal events and a (uncorrelated) 10% systematic error on background events. These pieces of information on the systematic errors are included in the χ^2 function using the pull method as described in, for example, [103, 141]. In our definition of the χ^2 function, we have assumed that the neutrino and antineutrino channels are completely uncorrelated, all the energy bins for a given channel are fully correlated, and the systematic errors on signal and background are fully uncorrelated. We perform the usual χ^2 analysis using a Poissonian likelihood function adding the information coming from ν_e appearance and ν_μ disappearance channels.

For long-baseline experiments, the measurement of the mass hierarchy is easier than a measurement of δ_{CP} because

matter effects enhance the separation between the oscillation spectra, and therefore the event rates, of a NH and an IH. Additionally, this measurement is one that is “discrete” as we only need to differentiate between two possibilities. A “discovery” of the mass hierarchy is defined as the ability to exclude any degenerate solution for the wrong (fit) hierarchy at a given confidence level. A “discovery” of CP violation, if it exists, means being able to exclude the CP-conserving values of $0^\circ, 180^\circ$ at a given confidence level. Clearly, this measurement becomes very difficult for the δ_{CP} values which are closer to $0^\circ, 180^\circ$. Therefore, whilst it is possible to discover the mass hierarchy for *all* possible values of δ_{CP} , the same is not true for CP violation.

In Figure 6, we plot the hierarchy discrimination sensitivity of the old NO ν A, the new NO ν A (with reoptimized event selection criteria for large θ_{13}), and the combined sensitivity of new NO ν A and T2K, as a function of the true value of δ_{CP} . In the left (right) panel, we have assumed NH (IH) to be the true hierarchy. We see that the wrong hierarchy can be ruled out very effectively for δ_{CP} in the favorable half-plane, which is LHP (UHP) for NH (IH). The new event selection criteria of NO ν A make the experiment even more effective in ruling out the wrong hierarchy for δ_{CP} in the favorable half-plane. In the unfavorable half-plane, both the old and the new criteria are equally ineffective. However, the addition of T2K data improves the situation significantly and $\Delta\chi^2$ increases from 0 to ≥ 2 for all the true values of δ_{CP} , thus making it possible to get a 90% CL hint of hierarchy with some additional data. We have checked that a further increment in the exposure of T2K or addition of antineutrino data from T2K does not improve the hierarchy sensitivity much.

The prospects of determining the neutrino mass hierarchy with the combined data from T2K, NO ν A, Double Chooz, RENO, Daya Bay, and the atmospheric neutrino experiment ICAL@INO [110] have been studied in detail in [143]. With 10 years of atmospheric ICAL@INO data collected by 50 kilotons magnetized iron calorimeter detector combined with T2K, NO ν A, and reactor data, a $2.3\sigma - 5.7\sigma$ discovery of the neutrino mass hierarchy could be achieved depending on the true values of $\sin^2 \theta_{23} [0.4-0.6]$, $\sin^2 2\theta_{13} [0.08-0.12]$, and $\delta_{\text{CP}} [0-2\pi]$ [143].

Reoptimization of the event selection criteria of NO ν A has the most dramatic effect on the CP violation discovery potential of the experiment. In Figure 7, we plot the sensitivity to rule out the CP conserving scenarios, as a function of true δ_{CP} in the left (right) panel for NH (IH) being the true hierarchy. We notice that, while in the case of old NO ν A there is no CP violation sensitivity at all at 90% CL, there is such a sensitivity in new NO ν A, for about one-third fraction of the favorable half-plane. Addition of T2K data leads to CP violation sensitivity for about half the region in both favorable half planes at 90% confidence level. It can be shown that, T2K by itself, has no CP violation sensitivity. But the synergistic combination of NO ν A and T2K leads to much better CP violation sensitivity compared to the individual capabilities. Here, we would like to mention that a large value of θ_{13} always does not help for CP violation discovery. As θ_{13} becomes large, the number of electron appearance event

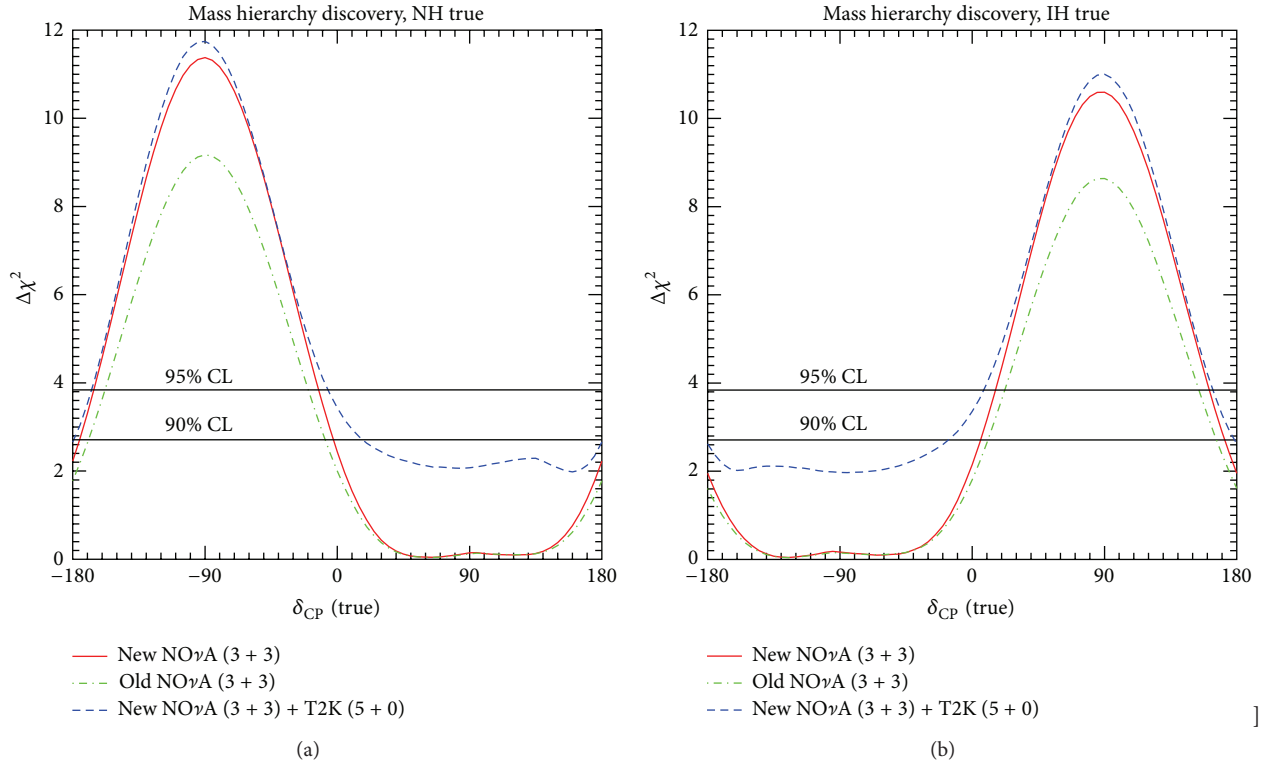


FIGURE 6: Left panel (right panel) shows the $\Delta\chi^2$ for the mass hierarchy discovery as a function of true value of δ_{CP} assuming NH (IH) as true hierarchy. This figure has been taken from [72].

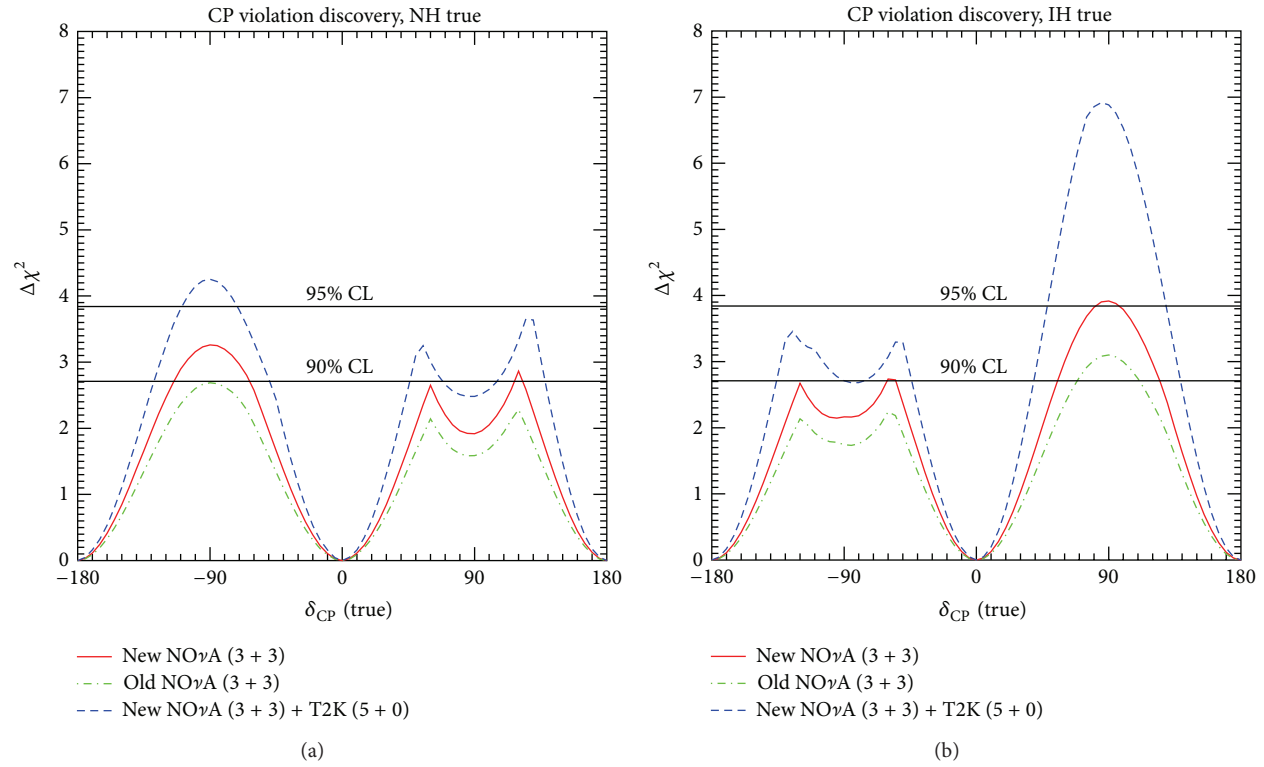


FIGURE 7: Left panel (right panel) shows the $\Delta\chi^2$ for the CP violation discovery as a function of true value of δ_{CP} assuming NH (IH) as true hierarchy. This figure has been taken from [72].

TABLE 2: Fractions of true values of δ_{CP} for which a discovery is possible for mass hierarchy and CP violation. The numbers without (with) parentheses correspond to 90% (95%) CL. Here we take the central values: $\sin^2\theta_{13} = 0.026$ and $\sin^2\theta_{23} = 0.5$. The results are shown for both NH and IH as true hierarchy. This table has been taken from [72].

Setups	Fraction of $\delta_{\text{CP}}(\text{true})$			
	Mass hierarchy		CP violation	
	NH true	IH true	NH true	IH true
NO ν A (3 + 3)	0.48 (0.43)	0.46 (0.41)	0.16 (0)	0.21 (0.04)
NO ν A (3 + 3) + T2K (5 + 0)	0.55 (0.45)	0.54 (0.43)	0.38 (0.11)	0.49 (0.23)

TABLE 3: Fractions of true values of δ_{CP} for which a discovery is possible for mass hierarchy and CP violation. The numbers without (with) parentheses correspond to 90% (95%) CL. Here we take the central value for $\sin^2\theta_{13}$ to be 0.023 as predicted by Daya Bay. For $\sin^2\theta_{23}$, the best-fit value that we consider is 0.413. The results are shown for both NH and IH as true hierarchy. This table has been taken from [72].

Setups	Fraction of $\delta_{\text{CP}}(\text{true})$			
	MH		CPV	
	NH true	IH true	NH true	IH true
NO ν A (3 + 3)	0.39 (0.33)	0.37 (0.31)	0.2 (0.1)	0.22 (0.13)
NO ν A (3 + 3) + T2K (5 + 0)	0.41 (0.34)	0.39 (0.31)	0.28 (0.22)	0.3 (0.25)

increases, reducing the statistical error. However, the large atmospheric term acts as a background in the measurement of CP phase. In fact, the CP asymmetry term is proportional to $1/\sin 2\theta_{13}$ [144, 145]. These two contradictory issues make the measurement of CP phase quite complicated. The systematic uncertainties are also going to play a crucial role for CP violation discovery in light of large θ_{13} [146].

A summary of our results is given in Table 2 in terms of the fraction of δ_{CP} values for which mass hierarchy can be determined/CP violation can be detected. Please note that in deriving the results given in Table 2, we have considered the best-fit value of $\sin^2\theta_{13} = 0.026$ and maximal mixing for θ_{23} . In Table 3, we present the same for the rather conservative choices of neutrino mixing angles: $\sin^2\theta_{13} = 0.023$ (the best-fit value suggested by the Daya Bay experiment) and $\sin^2\theta_{23} = 0.413$ (the LO value of $\sin^2\theta_{23}$ as indicated by the recent MINOS accelerator data).

In [72], we further explore the improvement in the hierarchy and CP violation sensitivities for T2K and NO ν A due to the addition of a 10 kilotons LArTPC placed close to NO ν A site and exposed to the NuMI beam during NO ν A running. It is expected, of course, that such a detector will come on line much later than NO ν A. The capabilities of such a detector are equivalent to those of NO ν A in all aspects. We find that combined data from 10 kilotons LArTPC (3 years of $\nu + 3$ years of $\bar{\nu}$ run), NO ν A (6 years of $\nu + 6$ years of $\bar{\nu}$ run), and T2K (5 years of ν run) can give a close to 2σ hint of hierarchy discovery for all values of δ_{CP} . With this combined data, we can achieve CP violation discovery at 95% CL for roughly 60% values of δ_{CP} . A similar proposal considering 6 kilotons LArTPC has been studied recently in detail in [147].

6.4. Resolving the Octant Ambiguity of θ_{23} . In this section, we study whether the expected appearance data from the ongoing T2K experiment and the upcoming NO ν A experiment can resolve the octant ambiguity of θ_{23} or not.

In Figure 8, we show neutrino events versus antineutrino events for various octant-hierarchy combinations. In each case, with varying values of δ_{CP} , the plot becomes an ellipse. The left panel depicts these ellipses for T2K whereas the right panel shows the same for NO ν A. Here, we assume that T2K will have equal ν and $\bar{\nu}$ runs of 2.5 years each. In the right panel, we see that the ellipses for the two mass orderings overlap whereas the ellipses of LO are well separated from those of HO. Hence, we can expect that NO ν A will have better octant resolution capability than hierarchy discrimination. This situation is even more dramatic in the left panel where there is large overlap between the two hierarchies but clear separation between the octants. Thus, it is very likely that antineutrino data from T2K may play an important role in the determination of octant.

In Figures 9 and 10, we study the behavior of $\Delta\chi^2$ between the true and the wrong octants as a function of true δ_{CP} . Here, the $\Delta\chi^2$ is estimated in the following way. First, we fix the true value of δ_{CP} . We take $\sin^2\theta_{23}$ to be its best-fit value in the true octant: 0.41 for LO and 0.59 for HO. If the LO (HO) is the true octant, the test values of $\sin^2\theta_{23}$ in the HO (LO) are varied within the range [0.5, 0.63] ([0.36, 0.5]), where 0.63 (0.36) is the 2σ upper (lower) limit of the allowed range of $\sin^2\theta_{23}$. The $\Delta\chi^2$ is computed between the spectra with the best-fit $\sin^2\theta_{23}$ of the true octant and that with various test values in the wrong octant and is marginalized over other neutrino parameters, especially the hierarchy, $\sin^2 2\theta_{13}$, and δ_{CP} . Figures 9 and 10 portray the minimum of this $\Delta\chi^2$ versus the true value of δ_{CP} .

From Figure 9, we observe that the NO ν A data by itself can almost rule out the wrong octant at 2σ , if LO is the true octant. If HO is the true octant, then NO ν A data is not sufficient to rule out the wrong octant as can be seen from Figure 10. In fact, the wrong octant can be ruled out only for about half of the true δ_{CP} values. As illustrated in Figures 9 and 10, addition of T2K data improves the octant determination ability significantly. From Figure 9, we

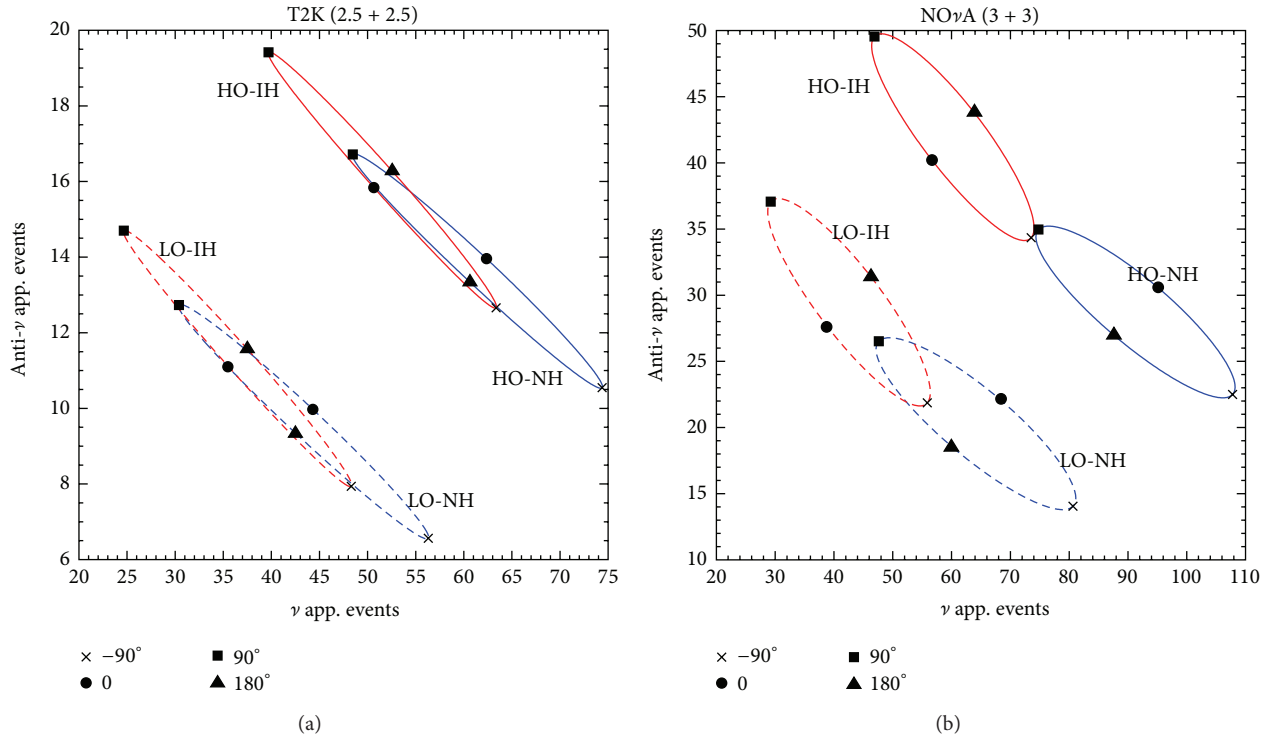


FIGURE 8: Neutrino and antineutrino appearance events for all possible combinations of hierarchy, octant, and δ_{CP} . The left (right) panel is for T2K (NOνA). Here, $\sin^2 2\theta_{13} = 0.089$. For LO (HO), $\sin^2 \theta_{23} = 0.41$ (0.59). Note that for T2K, equal ν and $\bar{\nu}$ runs of 2.5 years each have been assumed. This figure has been taken from [71].

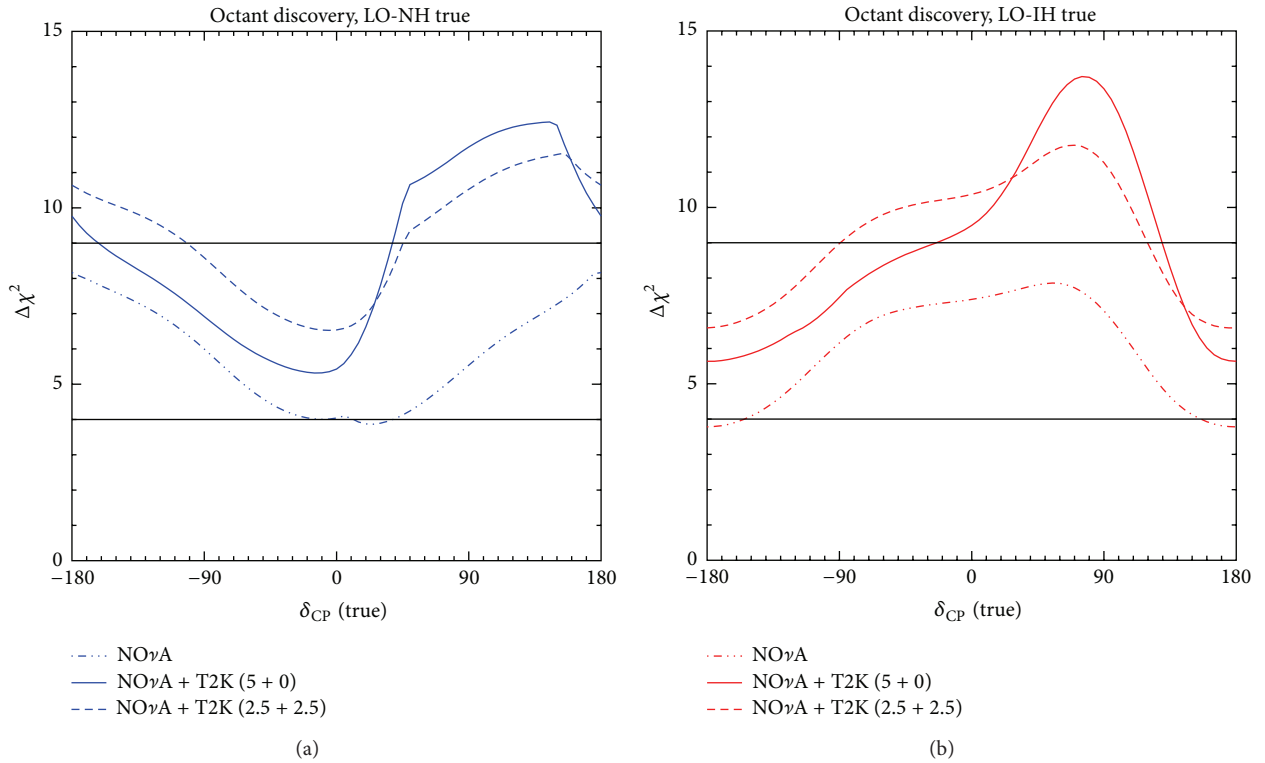


FIGURE 9: Octant resolving capability as a function of true δ_{CP} for various setups. In these plots, LO is assumed to be the true octant. The left (right) panel corresponds to NH (IH) being the true hierarchy. This figure has been taken from [71].

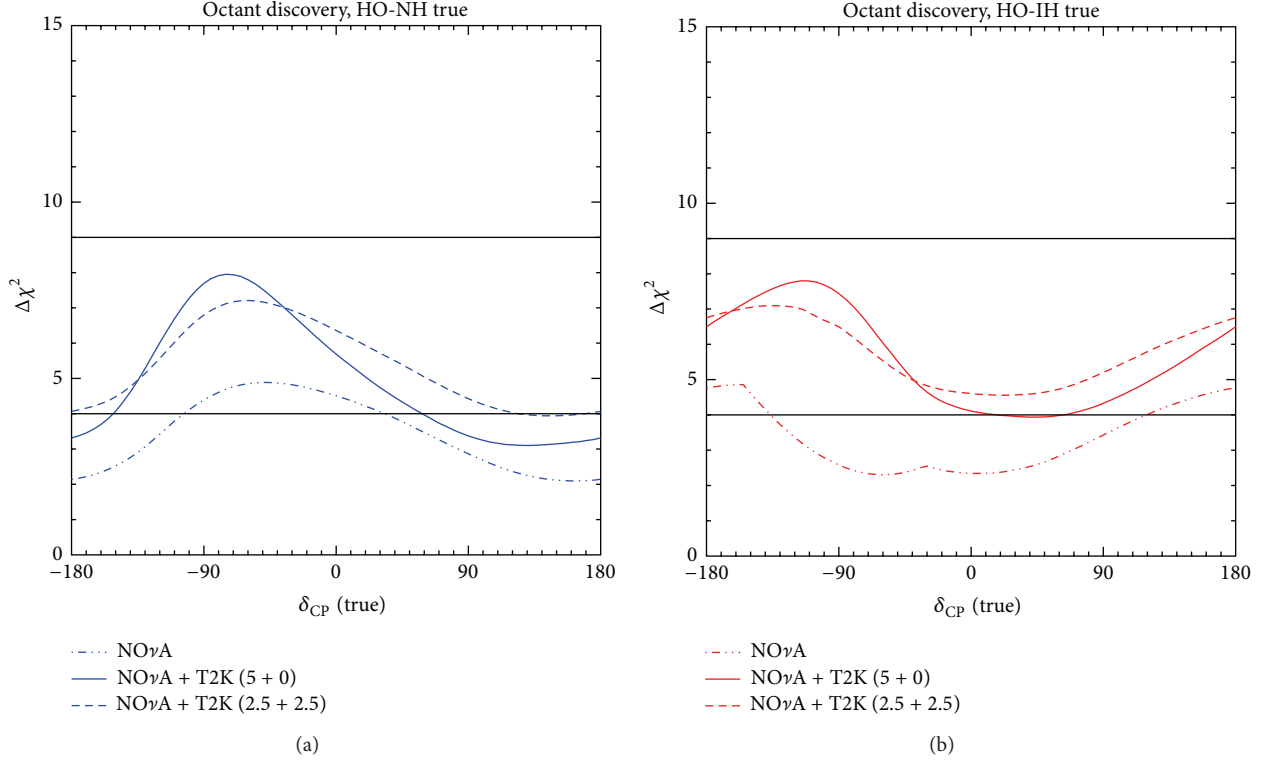


FIGURE 10: Octant resolving capability as a function of true δ_{CP} for various setups. In these plots, HO is assumed to be the true octant. The left (right) panel corresponds to NH (IH) being the true hierarchy. This figure has been taken from [71].

see that the combined data from NO ν A and T2K (5-year ν run) give a 2σ octant resolution for all values of true δ_{CP} if LO is the true octant. From Figure 10, we see that this combined data can rule out the wrong octant at 2σ for HO-IH, but not for HO-NH. The problem of HO-NH can be solved if the T2K has equal ν and $\bar{\nu}$ runs of 2.5 years each. This change improves the octant determination for the unfavorable values of true δ_{CP} (where $\Delta\chi^2$ is minimum) for all four combinations of hierarchy and octant. In particular, for the case of HO-NH, it leads to a complete ruling out of the wrong octant at 2σ for all values of true δ_{CP} . Thus, balanced runs of T2K in $\nu - \bar{\nu}$ mode are preferred over a pure ν run because of better octant determination capability. We observe that this feature of LO being more favorable compared to HO is a consequence of marginalization over the oscillation parameters (mainly δ_{CP}) and the systematic uncertainties. We checked that in the absence of any kind of marginalization $\Delta\chi_{\text{HO}}^2$ is consistently larger than $\Delta\chi_{\text{LO}}^2$.

In the discussion so far, we have assumed the true values of $\sin^2\theta_{23}$ to be 0.41 for LO and 0.59 for HO. These are, of course, the best-fit points from the global analyses. But, we must consider the octant resolution capability for values of true $\sin^2\theta_{23}$ in the full allowed range (0.34 to 0.67). In Figure 11, we plot the 2σ and 3σ octant resolution contours in true $\sin^2\theta_{23}$ -true δ_{CP} plane. Octant resolution is possible only

for points lying outside the contours. These figures clearly show that octant resolution is possible at 2σ for global best-fit points and at 3σ for MINOS best-fit points. The results for the two hierarchies are quite similar. From Figure 11, we can see that if T2K experiment would have equal neutrino and antineutrino runs of 2.5 years each, a 2σ resolution of the octant becomes possible provided $\sin^2\theta_{23} \leq 0.43$ or ≥ 0.58 for any value of δ_{CP} . In [148], the possibility of determining the octant of θ_{23} in the long-baseline experiments T2K and NO ν A in conjunction with future atmospheric neutrino detectors has been studied. The combined data from T2K and NO ν A can provide a $\sim 2\%$ precision on $\sin^2\theta_{23}$ at 2σ using the information coming from the disappearance channel [71].

In this section, we have discussed in detail the physics reach of current generation long-baseline beam experiments: T2K and NO ν A to unravel the neutrino mass hierarchy, CP violation, and octant of θ_{23} . Given their relatively short baselines, narrowband beams, and limited statistics, these experiments suffer a lot from the hierarchy- δ_{CP} and octant- δ_{CP} degeneracies. They can provide a hint for these unknown issues only for favorable ranges of parameters at limited confidence level. Hence, new long-baseline experiments with intense neutrino beam sources and advanced detector technologies are mandatory [100, 149–151] to fathom the hitherto uncharted parameter space of the neutrino mixing matrix well beyond the capabilities of T2K and NO ν A.

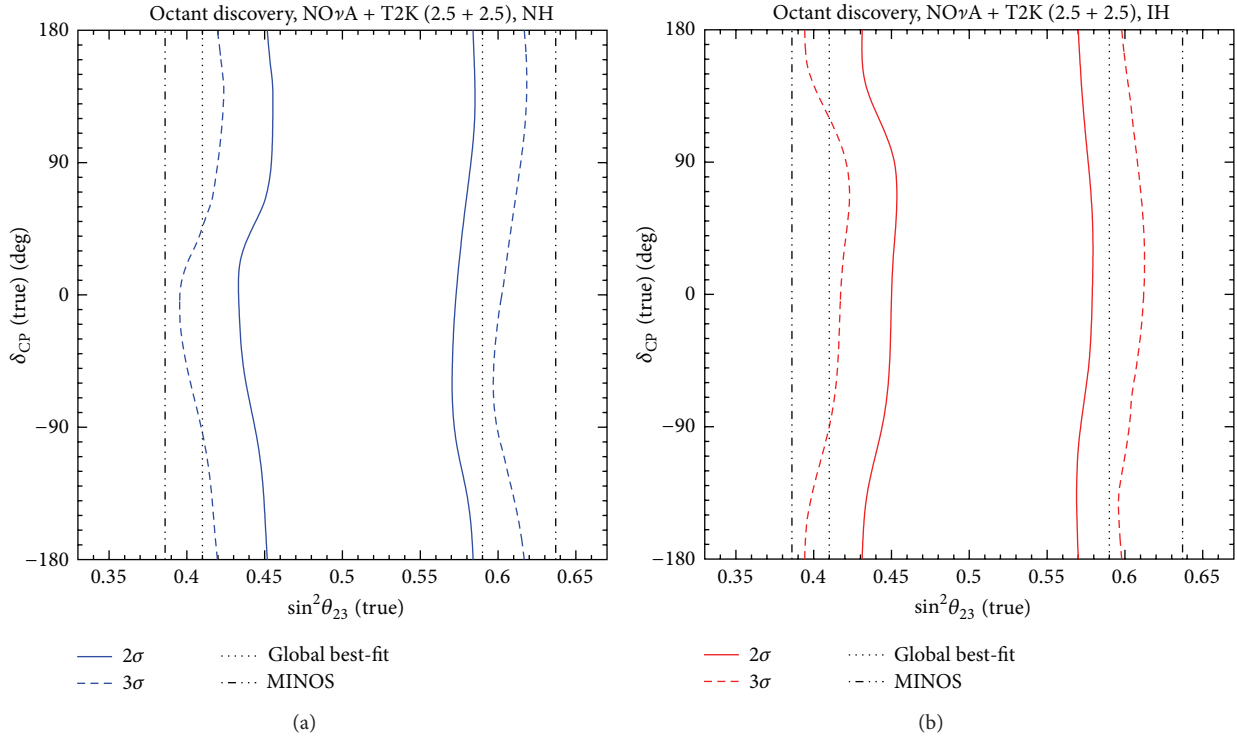


FIGURE 11: Octant resolving capability in the true $\sin^2\theta_{23}$ -true δ_{CP} plane for the combined $3\nu + 3\bar{\nu}$ runs of NO ν A and $2.5\nu + 2.5\bar{\nu}$ runs of T2K. Both 2σ and 3σ CL contours are plotted. The vertical lines correspond to the best-fit values of global data and those of MINOS accelerator data. The left (right) panel corresponds to NH (IH) being the true hierarchy. This figure has been taken from [71].

7. Next Generation Long-Baseline Beam Experiments

In this section, we briefly review the possible options for future high-precision long-baseline beam experiments with a special emphasis on high-power superbeam facilities using liquid argon and water Cherenkov detectors. As discussed in the literature (see, e.g., [149, 152]), the ability of future long-baseline neutrino experiments to discover mass hierarchy, octant of θ_{23} , and CP violation depends on the achievable event statistics and hence strongly on the value of θ_{13} . The fact that θ_{13} is large will have a significant impact on the realization of future long-baseline neutrino oscillation experiments, for which planning till 2011 was focused on a staged approach to achieve sensitivity to increasingly smaller values of θ_{13} . This approach was exemplified in the optimization of the neutrino factory [142, 153] and beta-beam [154, 155] experiments for which it was possible to discover a value of $\sin^2 2\theta_{13}$ as small as 10^{-4} . However, following the recent discovery of a moderately large value of θ_{13} , the focus of future optimizations will be on the possibility to explore mass hierarchy, octant of θ_{23} , and CP violation for a *given* value of θ_{13} . A relatively large value of θ_{13} also allows us to pursue an incremental program, staged in terms of the size of the experiment [100], producing significant new results at each stage. Out of the three major unknowns, the discovery of CP violation is the most toughest goal to achieve. Hence, the determination of mass hierarchy and

octant should be considered as the first step towards the discovery of leptonic CP violation. Future facilities must be developed with the requirements that they should have the capability to determine hierarchy and octant at 3σ confidence level or better for any possible value of δ_{CP} during the first stage and discover CP violation and measure δ_{CP} during the second stage. An incremental approach is also justified in view of the challenges (some of them are unknown) involved in operating very-high-power superbeams and in building giant underground neutrino detectors, which makes such an approach effectively safer and possibly more cost-effective. Both the proposed LBNE and LBNO facilities have adopted this staged approach in light of large θ_{13} . First, we present a comparative study of the physics reach that can be achieved during the first phase of these two proposed experiments. Then, we talk about the proposals of J-PARC to Hyper-Kamiokande (T2HK) long-baseline superbeam experiment [156] and CERN to MEMPHYS (at Fréjus) SPL superbeam experiment [157–160]. We also discuss the possibility to explore leptonic CP violation based on the European Spallation Source (ESS) proton linac which can deliver very intense, cost-effective, and high-performance neutrino beam in parallel with the production of spallation neutron [161, 162]. Megaton-size water Cherenkov detector is one of the key components of these three experimental setups. Next, we discuss the physics prospects of Low-Energy Neutrino Factory (LENF) [163–166] in conjunction with magnetized iron detector (MIND) [142, 167, 168] which seems to be a very

promising setup to explore leptonic CP violation for large θ_{13} . Finally, we mention few proposals based on monoflavor beta-beam concept [154, 155, 169–171].

7.1. Discovery Reach of LBNE and LBNO

LBNE. The Long-Baseline Neutrino Experiment (LBNE) [125] is one of the major components of Fermilab's intensity frontier program. In its first phase (LBNE10), it will have a new, high-intensity, on-axis neutrino beam directed towards a 10 kilotons LArTPC located at Homestake with a baseline of 1300 km. This facility is designed for initial operation at a proton beam power of 708 kW, with proton energy of 120 GeV that will deliver 6×10^{20} protons on target in 230 days per calendar year. In our simulation, we have used the latest fluxes being considered by the collaboration, which have been estimated assuming the smaller decay pipe and the lower horn current compared to the previous studies [172]. We have assumed five years of neutrino run and five years of antineutrino run. The detector characteristics have been taken from Table 1 of [100]. To have the LArTPC cross-sections, we have scaled the inclusive charged current cross-sections of water by 1.06 (0.94) for the ν ($\bar{\nu}$) case [173, 174].

LBNO. The Long-Baseline Neutrino Oscillation experiment (LBNO) [130] plans to use an experimental setup where neutrinos produced in a conventional wide-band beam facility at CERN would be observed in a proposed 20 kilotons (in its first phase) LArTPC housed at the Pyhäsalmi mine in Finland, at a distance of 2290 km. The fluxes have been computed [175] assuming an exposure of 1.5×10^{20} protons on target in 200 days per calendar year from the SPS accelerator at 400 GeV with a beam power of 750 kW. For LBNO also, we consider five years of neutrino run and five years of antineutrino run. We assume the same detector properties as those of LBNE.

Event Spectrum at LBNE10 and LBNO. Figure 12 portrays the expected signal and background event spectra in the ν_e appearance channel as a function of reconstructed neutrino energy including the efficiency and background rejection capabilities for LBNE10 (left panel) and LBNO (right panel) setups. In both panels of Figure 12, one can clearly see a systematic downward bias in the reconstructed energy for neutral current background events due to the final state neutrino included using the migration matrices. The blue dot-dashed and the orange dotted vertical lines display the locations of the first and second oscillation maxima. The green double-dotted-dashed histogram shows the signal event rate. Although, we have some statistics around the second oscillation maximum for both the baselines, its impact is limited due to the fact that the event samples are highly contaminated with neutral current and other backgrounds at lower energies.

Physics with Bievants Plots. In Figure 13, we have plotted ν_e versus $\bar{\nu}_e$ appearance events, for LBNE10 and 0.5*LBNO

for the four possible combinations of hierarchy and octant. Since δ_{CP} is unknown, events are generated for $[-180^\circ, 180^\circ]$, leading to the ellipses. Here, we take $\sin^2 2\theta_{13} = 0.089$. For the lower octant (LO) of θ_{23} , the value $\sin^2 \theta_{23} = 0.41$ is chosen and for higher octant (HO), it is taken to be 0.59. Note that in Figure 13 we have plotted the total number of events, whereas the actual analysis will be done based on the spectral information. Nevertheless, the contours in Figure 13 contain very important information regarding the physics capabilities of the experiments. An experiment can determine both the hierarchy and the octant, if every point on a given ellipse is well separated from every point on each of the other three ellipses. The larger the separation, the better the confidence with which the above parameters can be determined.

For 0.5*LBNO, the two (LO/HO)-IH ellipses are well separated from the two (LO/HO)-NH ellipses, in their number of neutrino events. Hence, 0.5*LBNO has excellent hierarchy determination capability with just neutrino data. However, only neutrino data alone will not be sufficient to determine the octant in case of IH because various points on (LO/HO)-IH ellipses have the same number of neutrino events. Likewise, only antineutrino data cannot determine the octant in case of NH. Therefore, balanced neutrino and antineutrino data is mandatory to make an effective distinction between (LO/HO)-IH ellipses and also between (LO/HO)-NH ellipses.

For LBNE10, ν data alone cannot determine hierarchy because various points on LO-NH and HO-IH ellipses have the same number of ν_e events. Thus, $\bar{\nu}$ data is also needed. Even with $\bar{\nu}$ data, hierarchy determination can be difficult to achieve, if nature chooses LO and one of the two worst-case combinations of hierarchy and δ_{CP} which are (NH, 90°) or (IH, -90°). In such a situation, the ν_e and $\bar{\nu}_e$ events are rather close to each other and it will be very difficult for LBNE10 to reject the wrong combination. Regarding octant determination, the capability of LBNE10 is very similar to that of 0.5*LBNO because the separations between the ellipses, belonging to LO and HO, are very similar for the two experiments.

Hierarchy and Octant Discovery with LBNE10 and LBNO. Measurement of hierarchy and octant should be considered as a prerequisite for the discovery of leptonic CP violation. To present the results for mass hierarchy and octant discovery, we consider three experimental setups: LBNE10, LBNO, and a possible LBNO configuration with a detector half the mass (10 kilotons), which we denote as 0.5*LBNO. Scaling down the detector size of LBNO by half makes the exposures of these two experiments very similar. Therefore, considering 0.5*LBNO enables us to make a direct comparison between the inherent properties of the two baselines involved. Both LBNE and LBNO will operate at multi-GeV energies with very long baselines. This will lead to a large enough matter effect to break the hierarchy- δ_{CP} degeneracy completely. They are also scheduled to have equal neutrino and antineutrino runs, tackling the octant- δ_{CP} degeneracy. These experiments are planning to use LArTPCs [102, 176] which have excellent kinematic reconstruction capability for all the observed

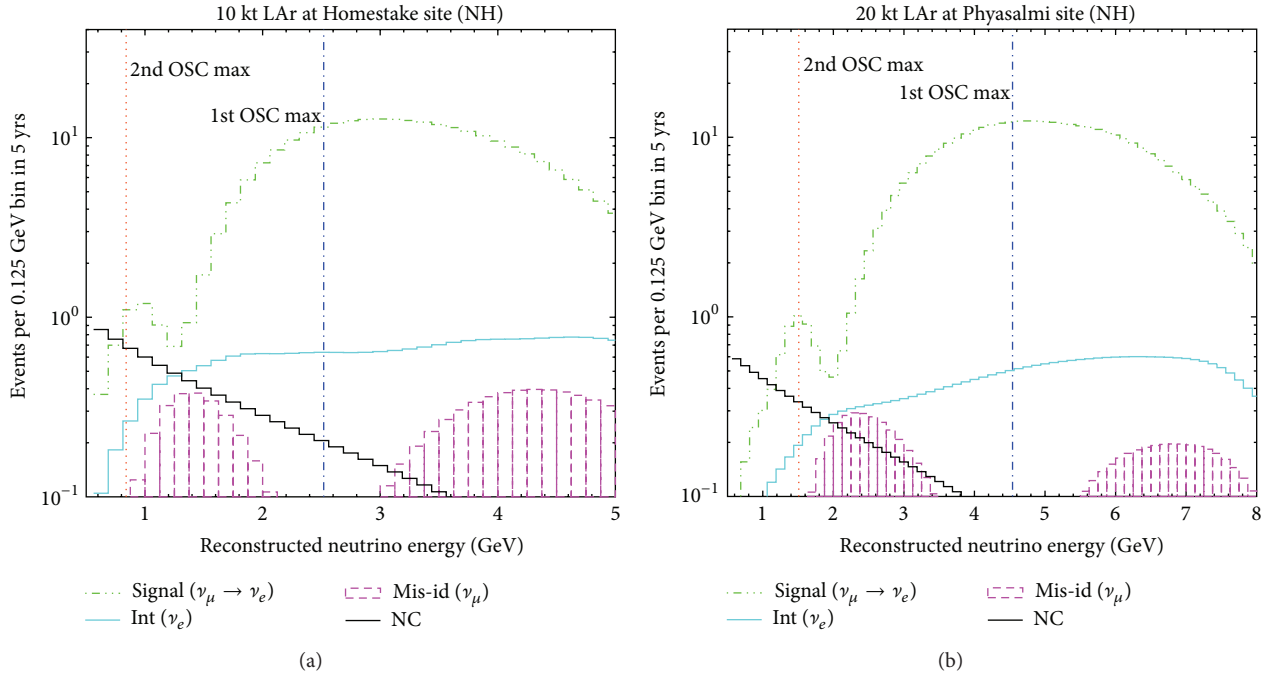


FIGURE 12: Expected signal and background event rates in the ν_e appearance channel as a function of the reconstructed neutrino energy including the efficiency and background rejection capabilities. Here, we consider $\sin^2 2\theta_{13} = 0.0975$ and $\delta_{CP} = 0^\circ$. Left panel (right panel) is for LBNE10 (LBNO). A normal hierarchy has been assumed. In both panels, the blue dot-dashed and the orange dotted vertical lines display the locations of the first and second oscillation maxima.

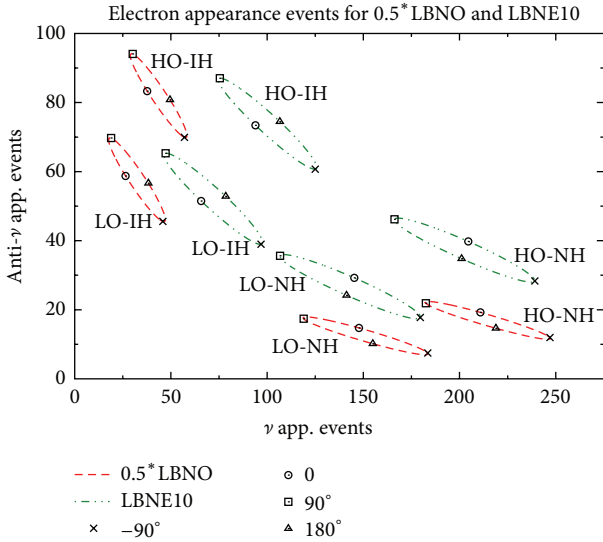


FIGURE 13: Bievts (ν_e and $\bar{\nu}_e$ appearance) plots for the four octant-hierarchy combinations and all possible δ_{CP} values. The experiments considered are LBNE10 and 0.5^*LBNO . Here, $\sin^2 2\theta_{13} = 0.089$. For LO (HO), $\sin^2 \theta_{23} = 0.41$ (0.59). This figure has been taken from [41].

particles. This feature helps in rejecting quite a large fraction of neutral current background.

We study the hierarchy discovery potential for two true values of $\sin^2 \theta_{23}$: 0.41 (LO) and 0.5 (MM). If HO is true,

the results will be better than those for the case of MM. This gives us four true combinations of θ_{23} -hierarchy: LO-NH, LO-IH, MM-NH, and MM-IH. $\Delta\chi^2$ is calculated for each of these four combinations, assuming the opposite hierarchy to be the test hierarchy. In the fit, we marginalize over test $\sin^2 \theta_{23}$ in its 3σ range and Δm_{31}^2 and $\sin^2 2\theta_{13}$ in their 2σ ranges. We considered 5% uncertainty in the matter density, ρ . Priors were added for ρ ($\sigma = 5\%$), Δm_{31}^2 ($\sigma = 4\%$), and $\sin^2 2\theta_{13}$ ($\sigma = 5\%$, as expected by the end of Daya Bay's run). $\Delta\chi^2$ is also marginalized over the uncorrelated systematic uncertainties (5% on signal and 5% on background) in the setups, so as to obtain a $\Delta\chi_{min}^2$ for every δ_{CP} (true).

Figure 14 shows the discovery reach for hierarchy as a function of δ_{CP} (true). We see that even 0.5^*LBNO has $\geq 10\sigma$ hierarchy discovery for all values of δ_{CP} (true) and for all four θ_{23} -hierarchy combinations. The potential of LBNO is even better. The LBNO baseline is close to Bimagic which gives it a particular advantage [111, 112]. For LBNE10, a 5σ discovery of hierarchy is possible for only $\sim 50\%$ of the δ_{CP} (true), irrespective of the true θ_{23} -hierarchy combination. For the unfavorable hierarchy- δ_{CP} combinations, that is, NH with δ_{CP} in the upper half-plane or IH with δ_{CP} in the lower half-plane, the performance of LBNE10 suffers. In particular, for LO and the worst-case combinations ((NH, 90°) and (IH, -90°)), LBNE10 will not be able to provide even a 3σ hierarchy discrimination. Therefore, LBNE10 must increase their statistics, if NO νA data indicate that the unfavorable combinations are true. The discovery potential for all three setups will be better if θ_{23} happens to lie in HO. But, we

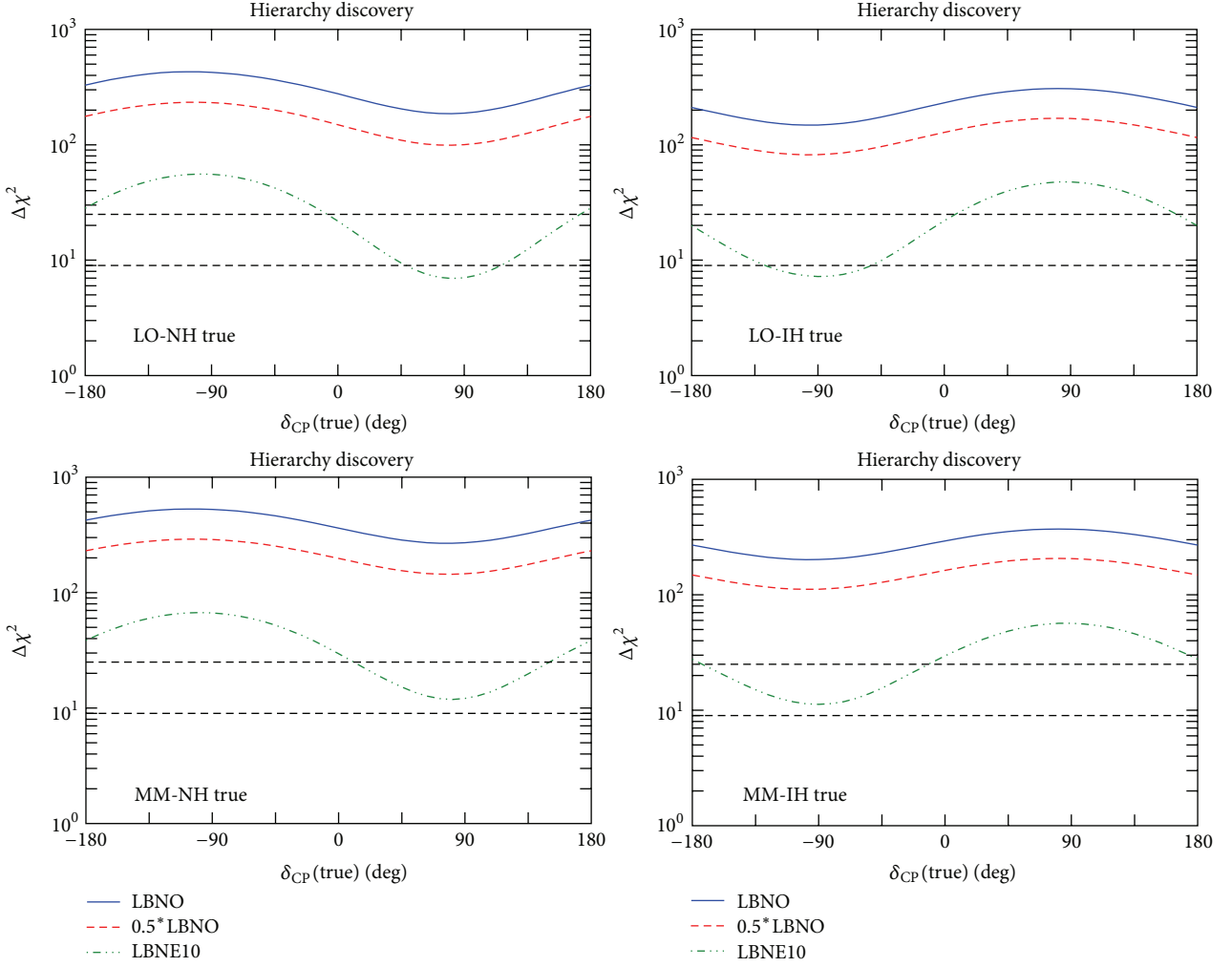


FIGURE 14: Hierarchy discovery reach for LBNO, 0.5*LBNO and LBNE10. Results are shown for the four possible true θ_{23} -hierarchy combinations.

checked that, even then, a 5σ discovery is not possible with LBNE10 for $\sim 30\%$ of the upper half-plane of δ_{CP} for HO-NH true and $\sim 70\%$ of the lower half-plane of δ_{CP} for HO-IH true.

We next consider the discovery reach of the same setups for excluding the wrong octant. We consider the true values of $\sin^2\theta_{23} = 0.41$ (LO) and $\sin^2\theta_{23} = 0.59$ (HO), so that we have the following four true combinations of octant and hierarchy: LO-NH, LO-IH, HO-NH, and HO-IH. $\Delta\chi^2$ is calculated for each of these four combinations, assuming test $\sin^2\theta_{23}$ values from the other octant. For LO (HO) true, we consider the test $\sin^2\theta_{23}$ range from 0.5 to 0.67 (0.34 to 0.5). The rest of the marginalization procedure (over oscillation parameters as well as systematic uncertainties) is the same as that in the case of hierarchy exclusion except with another difference: the final $\Delta\chi^2$ is marginalized over both the hierarchies as the test hierarchy to obtain $\Delta\chi_{\min}^2$.

Figure 15 shows the discovery reach for octant as a function of $\delta_{CP}(\text{true})$. It can be seen that for (LO/HO)-IH

true, the sensitivities of LBNE10 and 0.5*LBNO are quite similar whereas they are somewhat better for 0.5*LBNO if (LO/HO)-NH are the true combinations. For LO-(NH/IH), both LBNE10 and 0.5*LBNO have more than 3σ discovery of octant while for HO-(NH/IH), the $\Delta\chi_{\min}^2$ varies from ~ 6 to ~ 11 . However, with full LBNO, we have more than 3.5σ discovery of octant for all octant-hierarchy combinations. A 5σ discovery of octant is possible only for LO-NH true for $\delta_{CP}(\text{true}) \in (\sim 20^\circ, \sim 150^\circ)$.

CP Violation Discovery with LBNE10 and LBNO. In their first phases, both LBNE10 and LBNO will have very minimal CP violation reach. Figure 16 depicts the CP violation discovery reach for LBNE10 and LBNO. In the left panel (right panel), we have considered NH (IH) as true hierarchy. In Table 4, we mention the fraction of δ_{CP} values for which CP violation can be detected for these two experimental setups. Both LBNE10 and LBNO have CP violation reach for around 50% values of true δ_{CP} at 2σ confidence level. At 3σ , their CP violation reach is quite minimal: only for 10–20% of the entire range.

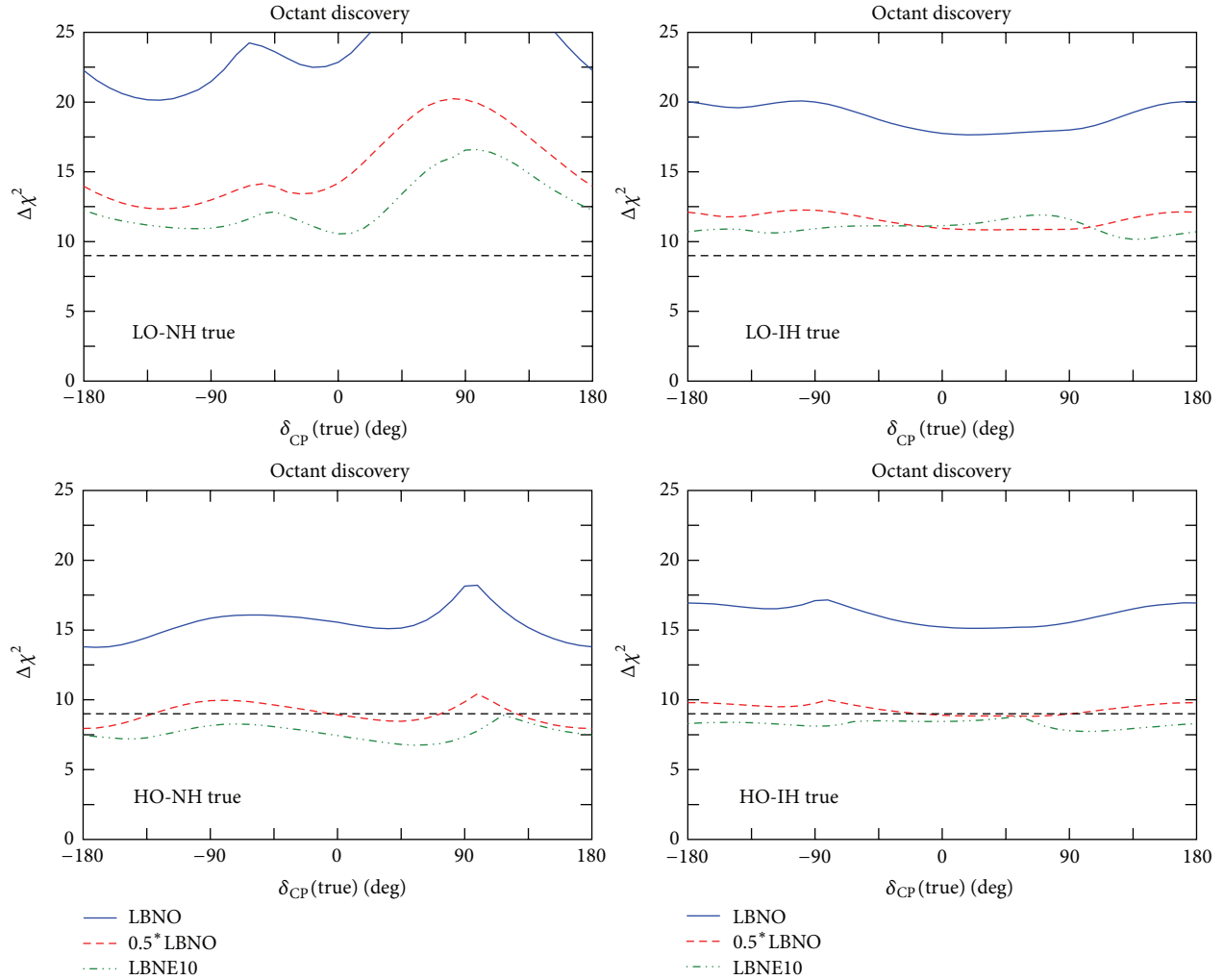


FIGURE 15: Octant resolving capability for LBNO, 0.5^*LBNO , and LBNE10. Results are shown for the four possible true octant-hierarchy combinations.

TABLE 4: Fractions of $\delta_{\text{CP}}(\text{true})$ for which a discovery is possible for CP violation. The numbers without (with) parentheses correspond to NH (IH) as true hierarchy. The results are presented at 2σ and 3σ confidence level.

Setups	Fraction of $\delta_{\text{CP}}(\text{true})$	
	2σ	3σ
LBNE10 (5 years ν + 5 years $\bar{\nu}$)	0.52 (0.56)	0.09 (0.26)
LBNO (5 years ν + 5 years $\bar{\nu}$)	0.51 (0.54)	0.17 (0.19)

7.2. T2HK, CERN-MEMPHYS, and ESS LINAC Proposals.

The T2HK proposal [156] plans to use a 1.66 MW superbeam from the upgraded J-PARC proton synchrotron facility directed to a 1 megaton water Cherenkov detector (with fiducial mass of 560 kilotons) located at a distance of 295 km from the source at an off-axis angle of 2.5° . A proposed location for this detector is about 8 km south of Super-Kamiokande at an underground depth of 1,750 meters water equivalent. The main purpose of this experiment is to achieve an unprecedented discovery reach for CP violation. The water

Cherenkov detector provides an excellent energy resolution for sub-GeV low-multiplicity final-state events. Both the high-power narrowband beam and the megaton-size detector play an important role to have large numbers of ν_e and $\bar{\nu}_e$ appearance events at the first oscillation maximum. This experiment plans to have 1.5 years of neutrino run and 3.5 years of antineutrino run with one year given by 10^7 seconds. The baseline of this experiment is too short to have any matter effect. Therefore, its mass hierarchy discovery reach is very limited. The expected accuracy in the determination of CP phase is better than 20° at 1σ confidence level assuming that mass hierarchy is known. For $\sin^2 2\theta_{13} = 0.1$, the CP violation can be established at 3σ CL for 74% of the δ_{CP} values provided that we fix the hierarchy in the fit. This CP coverage reduces to 55% if we marginalize over both the choices of hierarchy in the fit [156].

Like T2HK proposal, there is a superbeam configuration which is under consideration in Europe [157, 159, 160] using the CERN to Fréjus baseline of 130 km. The aim of this proposal is to send a 4 MW high-power superbeam from

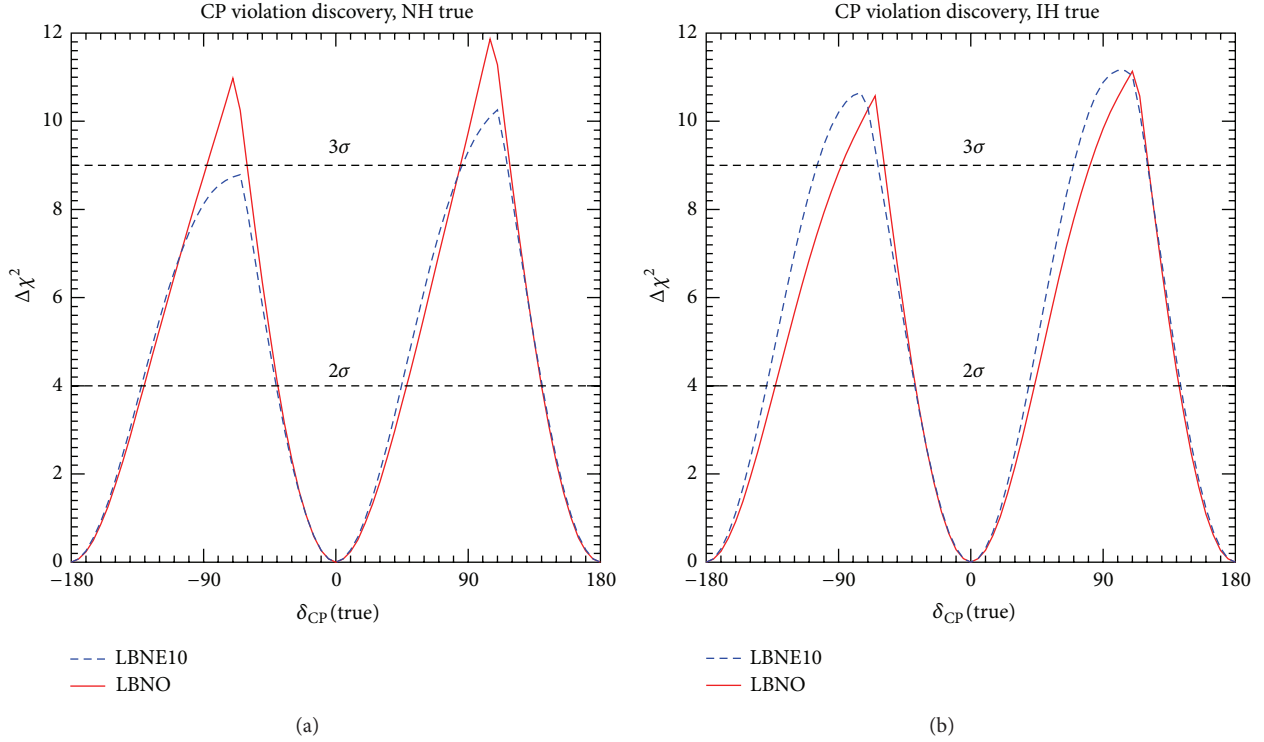


FIGURE 16: Left panel (right panel) shows the $\Delta\chi^2$ for the CP violation discovery as a function of true value of δ_{CP} assuming NH (IH) as true hierarchy.

CERN towards a 440 kilotons MEMPHYS water Cherenkov detector [158] located 130 km away at Fréjus. Using this setup, CP violation can be established for roughly 60% values of δ_{CP} at 3σ confidence level [158] assuming two years of neutrino run and eight years of antineutrino run, with uncorrelated systematic uncertainties of 5% on signal and 10% on background.

Another interesting possibility to explore leptonic CP violation using a very intense, cost-effective, and high-performance neutrino beam from the proton linac of the ESS facility currently under construction in Lund, Sweden, has been studied recently in detail in [161, 162]. A high-power superbeam from this proton linac in conjunction with a megaton-size water Cherenkov detector located in the existing mines at a distance of 300 to 600 km from the ESS facility can discover leptonic CP violation at 5σ confidence level for 50% of the δ_{CP} values [162].

7.3. Neutrino Factory. The term “Neutrino Factory” [149, 150, 177, 178] has been associated to describe neutrino beams created by the decays of high-energy muons (obtained via pion decay) which are circulated in a storage ring with long straight sections. The decay of muons in these straight sections produces an intense, well-known, and pure beam of ν_μ and $\bar{\nu}_e$. If μ^+ are stored, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ decays generate a beam consisting of equal numbers of ν_e and $\bar{\nu}_\mu$. The most promising avenue to explore CP violation, neutrino mass hierarchy, and octant of θ_{23} at a neutrino factory is the

subdominant $\nu_e \rightarrow \nu_\mu$ oscillation channel which produces muons of the opposite charge (wrong-sign muons) to those stored in the storage ring and these can be detected with the help of the charge identification capability of a magnetized iron neutrino detector (MIND) [97, 167]. In the most recent analysis [167] of MIND, low-energy neutrino signal events down to 1 GeV were selected with an efficiency plateau of $\sim 60\%$ for ν_μ and $\sim 80\%$ for $\bar{\nu}_\mu$ events starting at ~ 5 GeV, while maintaining the background level at or below 10^{-4} . For the neutral current background, the impact of migration is nonnegligible and it is peaked at lower energies. This feed-down is the strongest effect of migration and thus has potential impact on the energy optimization, since it penalizes neutrino flux at high energies, where there is little oscillation but a large increase in feed-down background.

In light of recently discovered moderately large value of θ_{13} , shorter baselines and lower energies are preferred to achieve high performance in exploring CP violation. Even E_μ as low as 5 to 8 GeV at the Fermilab-Homestake baseline of about 1300 km is quite close to the optimal choice (see upper left panel of Figure 17), which means that the MIND detector approaches the magnetized totally active scintillator detector performance of the Low-Energy Neutrino Factory (LENF) [163]. With the present baseline choice of the Neutrino Factory ($E_\mu = 10$ GeV and $L = 2000$ km) and a 50 kilotons MIND detector, CP violation can be established for around 80% values of δ_{CP} at 3σ CL considering 5×10^{21} useful muon decays in total.

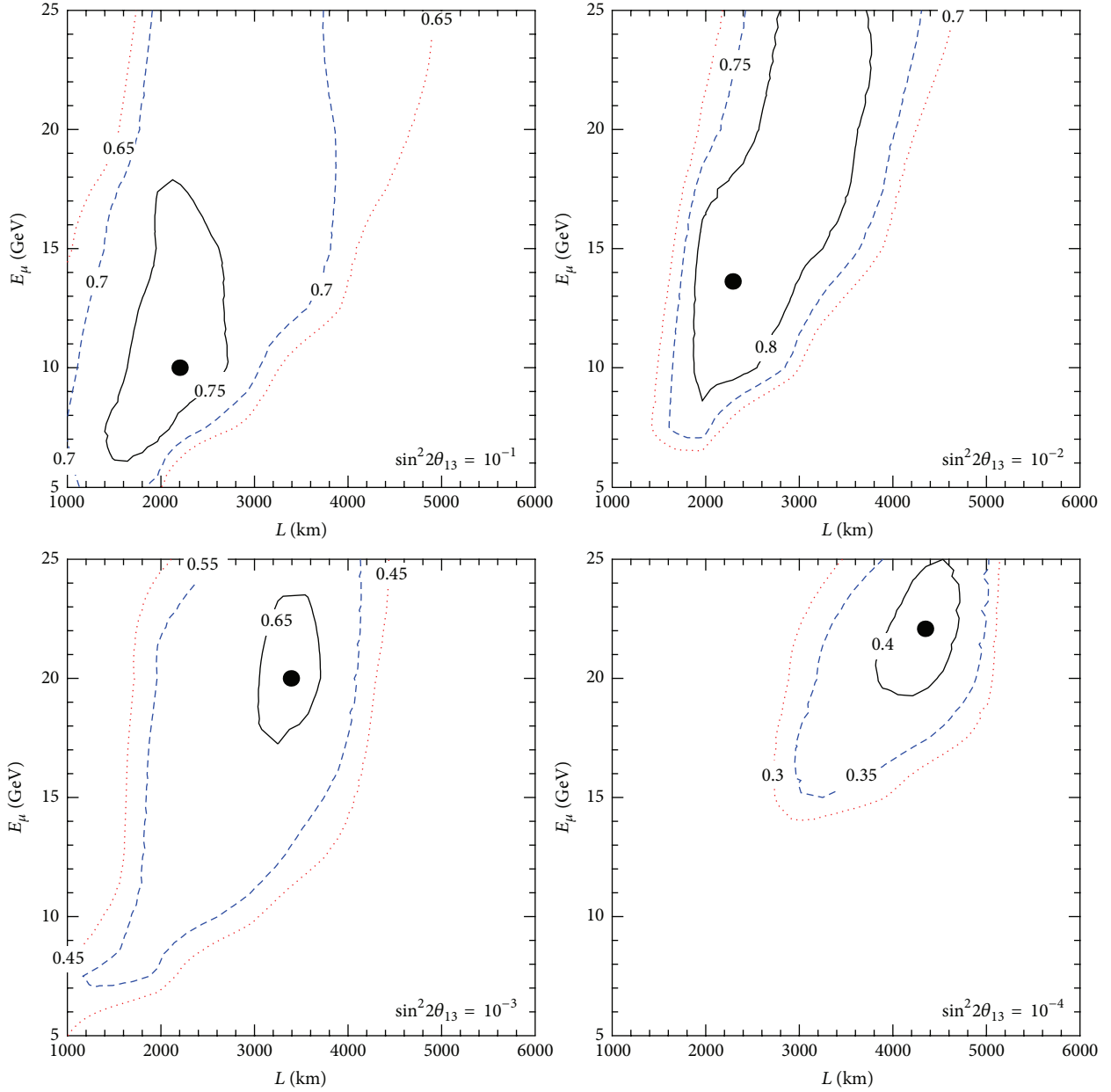


FIGURE 17: Fraction of $\delta_{\text{CP}}(\text{true})$ for which CP violation will be discovered at 3σ CL as a function of L and E_μ for the single-baseline Neutrino Factory. The different panels correspond to different true values of $\sin^2 2\theta_{13}$, as given there. Here, we consider 5×10^{21} useful muon decays in total with a 50 kilotons MIND detector. The optimal performance is marked by a dot: (2200, 10.00), (2288, 13.62), (3390, 20.00), and (4345, 22.08) with regard to their best reaches of the fraction of $\delta_{\text{CP}}(\text{true})$ at 0.77, 0.84, 0.67, and 0.42. This figure has been taken from [142].

7.4. Beta-Beams. Zucchelli [169] put forward the novel idea of a beta-beam [73, 170, 171, 179], which is based on the concept of creating a pure, well-understood, intense, collimated beam of ν_e or $\bar{\nu}_e$ through the beta-decay of completely ionized radioactive ions. Firstly, radioactive nuclides are created by impinging a target by accelerated protons. These unstable nuclides are collected, fully ionized, bunched, accelerated, and then stored in a decay ring. The decay of these highly boosted ions in the straight sections of the decay ring produces the so-called beta-beam. It has been proposed to

produce ν_e beams through the decay of highly accelerated ^{18}Ne ions ($^{18}_{10}\text{Ne} \rightarrow ^{18}_9\text{F} + e^+ + \nu_e$) and $\bar{\nu}_e$ from ^6He ($^6_2\text{He} \rightarrow ^6_3\text{Li} + e^- + \bar{\nu}_e$) [169]. More recently, ^8B ($^8_5\text{B} \rightarrow ^8_4\text{Be} + e^+ + \nu_e$) and ^8Li ($^8_3\text{Li} \rightarrow ^8_4\text{Be} + e^- + \bar{\nu}_e$) [180–182] with much larger endpoint energy have been suggested as alternate sources since these ions can yield higher energy ν_e and $\bar{\nu}_e$, respectively, with lower values of the Lorentz boost γ [154, 183–186]. Details of the four beta-beam candidate ions can be found in Table 5. It may be possible to store radioactive ions producing beams with both polarities in the same ring. This will enable running

TABLE 5: Beta decay parameters: lifetime τ , electron total end-point energy E_0 , f -value, and decay fraction for various ions. This table has been taken from [73].

Ion	τ (s)	E_0 (MeV)	f	Decay fraction	Beam
$^{18}_{10}\text{Ne}$	2.41	3.92	820.37	92.1%	ν_e
^6_2He	1.17	4.02	934.53	100%	$\bar{\nu}_e$
^8_5B	1.11	14.43	600872.07	100%	ν_e
^8_3Li	1.20	13.47	425355.16	100%	$\bar{\nu}_e$

the experiment in the ν_e and $\bar{\nu}_e$ modes simultaneously. In the low γ design of beta-beams, the standard luminosity taken for the ^{18}Ne and ^6He is 1.1×10^{18} (ν_e) and 2.9×10^{18} ($\bar{\nu}_e$) useful decays per year, respectively.

Within the EURISOL Design Study [171], the $\gamma = 100$ option with ^6He and ^{18}Ne ions has been studied quite extensively. The energy spectrum of the emitted neutrinos from these radioactive ions with $\gamma = 100$ suits well the CERN to Fréjus baseline of 130 km. Compared to superbeam, the main advantage of using beta-beam is that it is an extremely pure beam with no beam contamination occurs at the source. Combining beta-beam with superbeam, we can study the T-conjugated oscillation channels [187, 188] and this combined setup can provide an excellent reach for CP violation discovery.

8. Summary and Conclusions

The discovery of neutrino mixing and oscillations provides strong evidence that neutrinos are massive and leptons flavors are mixed with each other which leads to physics beyond the Standard Model of particle physics. With the recent determination of θ_{13} , for the first time, a clear and comprehensive picture of the three-flavor leptonic mixing matrix has been established. This impressive discovery has crucial consequences for future theoretical and experimental efforts. It has opened up exciting prospects for current and future long-baseline neutrino oscillation experiments towards addressing the remaining fundamental questions, in particular the type of the neutrino mass hierarchy, the possible presence of a CP-violating phase in the neutrino sector, and the correct octant of θ_{23} (if it turns out to be nonmaximal establishing the recent claims). In this paper, we have made an attempt to review the phenomenology of long-baseline neutrino oscillations with a special emphasis on subleading three-flavor effects, which will play a crucial role in resolving these unknowns in light of recent measurement of a moderately large value of θ_{13} . We have discussed in detail the physics reach of current-generation long-baseline experiments: T2K and NO ν A which have very limited reach in addressing these unknowns for only favorable ranges of parameters. Hence, future facilities are indispensable to cover the entire parameter space at unprecedented confidence level. A number of high-precision long-baseline neutrino oscillation experiments have been planned/proposed to sharpen our understanding about these tiny particles. In this review, we have discussed in detail the physics capabilities of few of

such proposals based on superbeams, neutrino factory, and beta-beam.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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