# Constraining BSM Models with Precision Measurements at Future Long-Baseline Neutrino Experiments

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## Abstract

Neutrino oscillations are a very well-established phenomenon, and in the last two decades, we have been able to determine almost all the oscillation parameters with a few percent precision. However, there is still room for the possibility of the presence of new physics effects. In this context, long-baseline (LBL) accelerator experiments provide a great environment to probe BSM (Beyond Standard Model) models. These experiments can look at different oscillation channels at both short (near detectors) and long (far detectors) distances, working with well-controlled focused neutrino beams. Two of the most promising future LBL experiments are DUNE in the USA and T2HK in Japan, which may be part of a bigger experiment (T2HKK) with a second detector in Korea. We studied the performances of these experiments in constraining different models.

*Keywords:* neutrino, oscillation, LBL
*DOI:* 10.31526/LHEP.2023.384

## 1. INTRODUCTION

After the discovery of the third nonvanishing neutrino mixing angle in 2012 [1], the 3-neutrino mixing paradigm has been confirmed. The goal of future oscillation experiments will be to be able to measure with unprecedent precision oscillation parameters. Indeed, there are still a few open questions in the oscillation framework which need to be answered: in which octant the atmospheric mixing angle $\theta_{23}$ lies, which is the neutrino mass hierarchy and which is the amount of CP violation in neutrino oscillation.

However, there exist a large number of new physics models which modify the oscillation probabilities. The astonishing predicted capabilities of the future long-baseline experiments DUNE [2] and T2HK [3] may be able to catch some of the faint effects of new physics in neutrino oscillation; for this reason, we expect that such experiments will be able to probe BSM models. We propose some new approaches that may be used in this context using data from the above-mentioned experiments.

## 2. THE DUNE NC SAMPLE AND THE NEUTRINO DECAY

It is well known that in the standard model neutrinos are stable particles. Moreover, due to their very tiny masses, there are no standard particles which may be involved in their decays. However, there exist some models in which in order to give masses to right-handed neutrinos, massless particles called Majoron [4] $S$ may allow the following neutrino decay:

$$\nu_i \to \nu_j + S. \tag{1}$$

Such a process can obviously modify the oscillation probabilities, since in this case during their flight neutrinos can decay. In presence of a very light sterile neutrino, one of the active neutrino states can decay into a Majoron and a sterile state, both invisible particles. In this framework, called *invisible* decay, in oscillation experiments, we should observe a depletion of the total number of active neutrinos which are observed at the detector. For this reason, oscillation experiments are expected to be sensitive to the neutrino lifetime in the invisible decay model. The $\nu_2$ and $\nu_1$ state lifetimes have already been strongly bounded by solar neutrino experiments; on the other hand, the bounds on $\nu_3$ are still very loose (see [5] for details). In the context of long-baseline experiments, the decay of the third mass eigenstate, in normal ordering, modifies the $\nu_e$ appearance and $\nu_\mu$ disappearance probabilities in the leading order in the following way:

$$P_{\mu e}^{(0)} = \sin^2 2\theta_{13} \sin^2\theta_{23} \left[ e^{-\frac{1}{\beta_3}\frac{L}{2E}} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + \left(\frac{1-e^{-\frac{1}{\beta_3}\frac{L}{2E}}}{2}\right)^2 \right], \tag{2}$$

$$\begin{aligned} P_{\mu\mu}^{(0)} &= 1 + 2\left(e^{-\frac{1}{\beta_3}\frac{L}{2E}} - 1\right)\cos^2\theta_{13}\sin^2\theta_{23} \\ &+ \left(e^{-\frac{1}{\beta_3}\frac{L}{2E}} - 1\right)^2 \cos^4\theta_{13}\sin^4\theta_{23} \\ &- e^{-\frac{1}{\beta_3}\frac{L}{2E}}\left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right) \\ &\times \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right), \end{aligned} \tag{3}$$

where $\beta_3 = m_3/\tau_3$, in which $m_3$ and $\tau_3$ are the third neutrino eingestate mass and lifetime, respectively. For this reason, several accelerator experiments, like NO$\nu$A, T2K, K2K, and MINOS, were able to set bounds on the decay parameter $\beta_3$, of the order of $10^{-12}$ s/eV [6]. The future DUNE experiment should be able to improve such a limit of an order of magnitude given its great imaging capabilities and its intense muon neutrino beam. However, motivated by the fact that DUNE is expected to recognize not only charged current (CC) events but also neutral current (NC) ones, we studied how the number of NC events is modified by the invisible decay. Indeed, since in such a model some of the neutrinos decay into an invisible state, we expect that the total number of neutrinos is not conserved when the beam reaches the Far Detector, 1300 km away from the neutrino source. Thus, also the NC number of events, which is proportional to the total number of neutrinos, should be affected by the presence of neutrino decay. In particular, we computed that the NC events should be proportional to the quantity

$$\sum_{\alpha}^{e,\mu,\tau} P_{\mu\alpha} = 1 + \left(e^{-\frac{1}{\beta_3}\frac{L}{E}} - 1\right)\cos^2\theta_{13}\sin^2\theta_{23}, \tag{4}$$

which clearly depends on $\beta_3$. We implemented in the DUNE simulations performed using the GLoBES [8] software the NC channel, considering 90% signal efficiency, 10% of the $\nu_\mu$ and $\nu_e$ CC events as background, and 10% normalization error (see [7, 5] for details). Our results for a running time of 3.5 years in neutrino and 3.5 years in antineutrino mode showed that the addition of the NC events will be able to increase the lower bound obtained using only CC channels on $\beta_3$ by roughly 16%. In particular, the lower limit from the CC+NC analysis,

$$\beta_3 > 5.2 \times 10^{-11}\,\mathrm{s/eV}, \tag{5}$$

would be the best world limit set by a single long-baseline experiment.

## 3. THE SOURCE AND DETECTOR NSI AND THE DUNE NEAR DETECTOR

Non Standard Interactions (NSIs) [9, 10] have been widely studied in the literature in the context of neutrino oscillation. They consist in new possible interactions between neutrinos and matter particles; in an effective field theory approach, they can be considered as four fermion interactions of strength $\varepsilon_{\alpha\beta}$ which may occur while neutrinos are produced (*source NSI*), while they propagate through matter (*propagation NSI*) or while neutrinos are detected (*detector NSI*). Long-baseline experiments, since neutrino beams travel through a large amount of Earth matter, are very sensitive to propagation NSI. On the other hand, scattering experiments can be used to probe source and detector NSI. However, we demonstrated how also the Near Detector of long-baseline experiments may be used to exclude large portions of the source and detector parameters space. Indeed, at a very small baseline, we are blind to either oscillation parameters and propagation NSI; on the other hand, we can be sensitive to the source and detector NSI. Indeed, computing the zero-distance oscillation appearance (flavor changing) and disappearance (flavor conserving) probabilities, we obtain, at the leading order,

$$P_{\alpha\beta} = \left|\varepsilon^s_{\alpha\beta}\right|^2 + \left|\varepsilon^d_{\alpha\beta}\right|^2 + 2\left|\varepsilon^s_{\alpha\beta}\right|\left|\varepsilon^d_{\alpha\beta}\right|\cos\left(\Phi^s_{\alpha\beta} - \Phi^d_{\alpha\beta}\right), \tag{6}$$

$$P_{\alpha\alpha} = 1 + 2\left|\varepsilon^s_{\alpha\alpha}\right|\cos\Phi^s_{\alpha\alpha} + 2\left|\varepsilon^d_{\alpha\alpha}\right|\cos\Phi^d_{\alpha\alpha}, \tag{7}$$

where $\varepsilon^{s/d}_{\alpha\beta} = |\varepsilon^{s/d}_{\alpha\beta}|e^{i\Phi^{s/d}_{\alpha\beta}}$ are the source and detector NSI strengths (see [11] for details). Suppose now that we want to exclude a region of the parameter space using a $\chi^2$ function defined as

$$\chi^2 = \frac{(N_{\mathrm{obs}} - N_{\mathrm{fit}})^2}{\sigma^2}, \tag{8}$$

where $\sigma$ represents the statistical uncertainty on the number of events. Assuming vanishing true values of all NSI parameters and writing $N = N_0 P_{\alpha\beta}$ where $N_0$ comes from the flux and the detector features, $\chi^2$ is

$$\chi^2 = \frac{N_0^2}{\sigma^2}\left[\delta_{\alpha\beta} - P_{\alpha\beta}\left(\varepsilon^s_{\mathrm{fit}}, \varepsilon^d_{\mathrm{fit}}\right)\right]^2. \tag{9}$$

For appearance analysis, equation (6) allows us to write

$$\chi^2 = \frac{N_0^2}{\sigma^2}\left[\left|\varepsilon^s_{\alpha\beta}\right|^2 + \left|\varepsilon^d_{\alpha\beta}\right|^2 + 2\left|\varepsilon^s_{\alpha\beta}\right|\left|\varepsilon^d_{\alpha\beta}\right|\cos\left(\Phi^s_{\alpha\beta} - \Phi^d_{\alpha\beta}\right)\right]^2, \tag{10}$$

which, when minimized, becomes

$$\chi^2_{\mathrm{min}} = \frac{N_0^2}{\sigma^2}\left(\left|\varepsilon^s_{\alpha\beta}\right| - \left|\varepsilon^d_{\alpha\beta}\right|\right)^4. \tag{11}$$

Indicating that $\chi^2_{0,\alpha\beta}$ is the value corresponding to the cut of the $\chi^2$ at a given CL, it is clear that we can exclude the region delimited by

$$\left|\left|\varepsilon^s_{\alpha\beta}\right| - \left|\varepsilon^d_{\alpha\beta}\right|\right| > \sqrt[4]{\frac{\chi^2_{0,\alpha\beta}\sigma^2}{N_0^2}}, \tag{12}$$

which is external to a band in the $(|\varepsilon^s_{\alpha\beta}|, |\varepsilon^d_{\alpha\beta}|)$-plane of width

$$\Delta_{\alpha\beta} = \sqrt[4]{\frac{4\chi^2_{0,\alpha\beta}\sigma^2}{N_0^2}} \tag{13}$$

centered on the line $|\varepsilon^s_{\alpha\beta}| = |\varepsilon^d_{\alpha\beta}|$. Thus, $\Delta_{\alpha\beta}$ provides a measure of the allowed parameter space. It is clear that the excluded region is larger when the uncertainty on the number of events $\sigma$ is smaller and the normalization factor $N_0$ is bigger.

In the disappearance case following the same procedure, we obtain that the excluded region is determined by

$$\left|\Re\left(\varepsilon^s_{\alpha\alpha}\right) + \Re\left(\varepsilon^d_{\alpha\alpha}\right)\right| > \sqrt{\frac{\chi^2_{0,\alpha\alpha}\sigma^2}{4N_0^2}}, \tag{14}$$

where, in this case, the bandwidth is

$$\Delta_{\alpha\alpha} = \sqrt{\frac{\chi^2_{0,\alpha\alpha}\sigma^2}{2N_0^2}}. \tag{15}$$

We take now as an example the DUNE experiment, which will have a LAr-TPC Near Detector of about 50 tons at roughly 500 m from the neutrino source. The high-intensity flux will provide a large number of neutrinos, which in principle could be observed at the Near Detector. Including, in the analysis, the $\nu_e$ and $\nu_\tau$ appearance channels as well as $\nu_\mu$ and $\nu_e$ (from the beam contamination) disappearance, we performed a full simulation of the experiment. Since at the Near Detector the flux is not constrained by any other measurement, we increased the proposed uncertainties for the Far Detector of factor 3. First of all, numerical simulations behave as expected from our analytical discussion. Then, our results for the bandwidth (5+5 years of running time) are the following:

$$\Delta_{\mu\mu} = 0.12, \qquad \Delta_{ee} = 0.11, \tag{16}$$

$$\Delta_{\mu e} = 0.0065, \qquad \Delta_{\mu\tau} = 0.026. \tag{17}$$

Comparing our results with the ones obtained using the DUNE Far Detector, which may be sensitive under some assumptions to some of the source and detector NSI parameters (see [11, 12] for details), our Near Detector results are complementary to the Far Detector ones, excluding different portions of the parameter space.

# 4. CP-ODD ASYMMETRIES AT DUNE AND NEW SOURCES OF LEPTONIC CP VIOLATION

The CP violation in the leptonic sector is caused by the presence of the PMNS mixing matrix phase $\delta$. This parameter appears in the neutrino oscillation probabilities, changing its sign when antineutrino oscillation is considered. However, several new physics models introduce new phases in the neutrino sector, for instance, the already mentioned source and detector NSI phases. There are two other largely studied models which introduce non-standard phases in the oscillations: the propagation NSI [9] and the 3+1 sterile neutrino [13] models. In the former, as discussed, we take into account the possibility of new interactions between neutrinos and matter during neutrino propagation; in the latter, motivated by some long-standing anomalies in neutrino oscillation, we introduce a fourth light sterile state in the game. Both models introduce new complex phases in the oscillation probabilities which can be sources of non standard CP violation. The presence of these new phases can modify CP-odd observables such as the asymmetries

$$A_{\alpha\beta} \equiv \frac{P\left(\nu_\alpha \to \nu_\beta\right) - P\left(\bar{\nu}_\alpha \to \bar{\nu}_\beta\right)}{P\left(\nu_\alpha \to \nu_\beta\right) + P\left(\bar{\nu}_\alpha \to \bar{\nu}_\beta\right)}, \tag{18}$$

which can be directly measured at experiments capable of the discrimination between neutrino and antineutrino events. In particular, a long-baseline experiment, which runs in both neutrino and antineutrino modes, may be able to compute the integrated asymmetries

$$A_{\alpha\beta} = \frac{N_\beta - \bar{N}_\beta}{N_\beta + \bar{N}_\beta}, \tag{19}$$

where $N_\beta$ ($\bar{N}_\beta$) is defined as the number of observed events of a given flavor $\beta$ in neutrino (antineutrino) mode. These quantities are strictly related to the ones defined in terms of probabilities. When a new source of CP violation is introduced in the physics framework, these quantities are modified, since new phases can alter the difference between neutrino and antineutrino oscillation probabilities in a given channel. Taking as a case study the DUNE experiment, whose Far Detector should have access to $\nu_e$ appearance, $\nu_\tau$ appearance, and $\nu_\mu$ disappearance as well as to the Neutral Current channel, we explored the possibility that hints of new physics may be detected via the measurement of the asymmetries. For this purpose, we computed the expected integrated asymmetries for all the transition channels in DUNE, choosing as oscillation parameters the global analysis best fits and varying the standard CP-violating phase $\delta$. Then, we estimated the $1\sigma$ uncertainties on the asymmetries summing statistical and systematic contributions (see [14] for details). Finally, we computed the same asymmetries in the NSI and 3+1 models, varying the NSI couplings in their allowed limits [9] and the sterile neutrino mixing angles in the ranges [0°–10°] for $\theta_{14}$ and $\theta_{24}$, and [0°–30°] for $\theta_{34}$ ($\Delta m^2_{41}$ has been fixed to 1 eV$^2$). We observed that there are no possible values of the asymmetries in the new physics cases, which are outside the standard model asymmetries error bars. For this reason, the measurement of the asymmetries alone is not enough to give hints of the presence of new physics. However, there have been proposals for a high energy flux, peaked at 5 GeV,

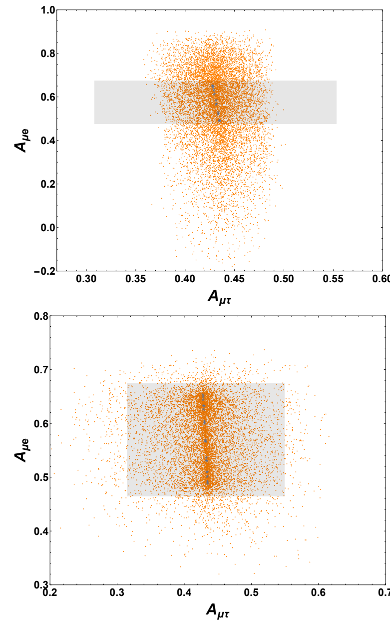


**FIGURE 1:** Integrated asymmetries in the ($A_{\mu\tau}, A_{\mu e}$) plane at DUNE in the NSI (top panel) and 3+1 (bottom panel) cases with the high energy flux. Blue stars represent the asymmetries in the SM case, and the orange dots represent the values obtained with NSI. Grey shadowed region shows the $1\sigma$ error range on the SM asymmetries.

which may be employed at DUNE. We performed the simulations again using such a flux for 3.5+3.5 years, and we could observe that the asymmetry related to the $\nu_e$ appearance channel ($A_{\mu e}$) may be enough to determine at a considerable confidence level the presence of new physics in the form of propagation NSI or sterile neutrinos as shown in Figure 1. Nevertheless, this simple approach does not allow us to determine which is the new physics model that causes the deviation of the asymmetries from the standard ones. For this reason, further analysis should be performed to understand completely the experimental data (see [14] for details).

# 5. THE NON-UNITARITY OF THE PMNS MATRIX AND THE COMPLEMENTARITY AMONG DUNE AND T2HK

Even though DUNE and T2HK will be two long-baseline experiments both built to measure the standard oscillation parameters with astonishing precision, they will have very different features. For instance, the DUNE baseline (1300 km) will be much larger than the T2HK one (295 km). For this reason, the Japan-based experiment will be almost not affected by matter effects. Then, DUNE will use a broadband on-axis beam, while T2HK a narrow band off-axis beam; finally, DUNE Far Detector will consist in a 40 kt LAr-TPC very performing detector, while T2HK in a gigantic 187 kt Cherenkov detector. All these differences may suggest that the complementarity between the two experiments, data sets may be useful to perform complicated analysis in both standard and BSM oscillation frameworks. In [15], we explored how the two experiments may be able to bound the non-standard parameters that enter in the game when we consider the loss of unitarity of the PMNS ma-

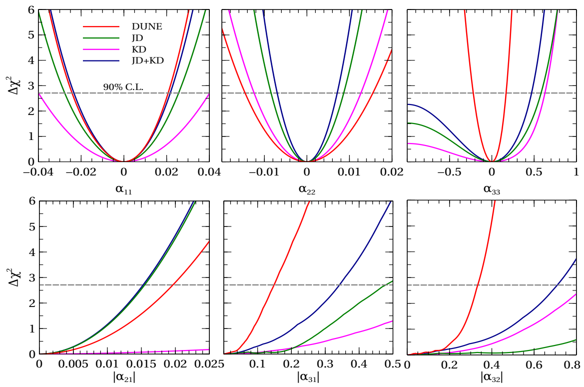


**FIGURE 2:** Sensitivities of the DUNE, T2HK (JD), and T2HK Koreak Detector (KD) to the non-unitarity parameters.

trix [16]. This topic is very interesting since in models that may explain the tiny neutrino masses, new heavy neutral leptons may be included in the Standard Model. These particles can mix with neutrinos and the $3 \times 3$ standard PMNS matrix loses its unitarity requirement. The non-unitarity effects can be parameterized modifying the PMNS matrix in the following way:

$$N = (I + \alpha)U_{\text{PMNS}}, \tag{20}$$

where

$$\alpha = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}|\, e^{i\phi_{21}} & \alpha_{22} & 0 \\ |\alpha_{31}|\, e^{i\phi_{31}} & |\alpha_{32}|\, e^{i\phi_{32}} & \alpha_{33} \end{pmatrix}. \tag{21}$$

As widely studied in the literature, long-baseline experiments are particularly sensitive to the parameters $\alpha_{21}$ and $\alpha_{22}$, which enters in the $\nu_e$ appearance and $\nu_\mu$ disappearance probabilities at the leading order, respectively. However, we performed a full analysis over the whole non-unitarity parameters, space using the GLoBES software, simulating DUNE and T2HK results with a running time of 3.5+3.5 years for DUNE and 2.5+7.5 years for T2HK. We did not use any assumption on the new physics parameters, but we considered them one at a time. We found out that, as shown in Figure 2, while the larger statistics of T2HK may be able to set very stringent bounds on $|\alpha_{21}| < 0.015$ and $|\alpha_{22}| < 0.009$, DUNE, through the matter effects, may be able to bound the three parameters $|\alpha_{3i}|$. Indeed, these parameters, which do not appear in the vacuum probabilities, can have a significant impact on oscillations when matter effects are important, like in the DUNE case. For this reason, we expect that, for the first time, the two experiments may be able to set relatively tight bounds on all the non-unitarity parameters at the same time ($\alpha_{11}$ turned out to be accessible in the same way in both experiments). In [15], we extensively studied the performances of a second T2HK detector in Korea, sitting at the second oscillation maximum. Moreover, we also studied the effects of the Near Detectors, which from one side may have access to some non-unitarity parameters via zero-distance effects in the probabilities; on the other hand, if Near Detectors will be used to constrain the Far Detector flux, their presence may cause the loss of sensitivity in both experiments to the $\alpha_{22}$ parameter. Finally, we studied the inclusion of the $\nu_\tau$ appearance channel in the DUNE analysis, showing that it should be able to improve the bounds on $|\alpha_{32}|$ and $\alpha_{33}$.

## CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

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