RECEIVED: July 12, 2016

REVISED: August 4, 2016

ACCEPTED: August 5, 2016

PUBLISHED: August 12, 2016

A combined study of source, detector and matter non-standard neutrino interactions at DUNE

Mattias Blennow,^a Sandhya Choubey,^{a,b} Tommy Ohlsson,^a Dipyaman Pramanik^b and Sushant K. Raut^a

^a*Department of Theoretical Physics, School of Engineering Sciences,
KTH Royal Institute of Technology, AlbaNova University Center,
106 91 Stockholm, Sweden*

^b*Harish-Chandra Research Institute,
Chhatnag Road, Jhansi, Allahabad 211 019, India*

E-mail: emb@kth.se, sandhya@hri.res.in, tohlsson@kth.se,
dipyamanpramanik@hri.res.in, raut@kth.se

ABSTRACT: We simultaneously investigate source, detector and matter non-standard neutrino interactions at the proposed DUNE experiment. Our analysis is performed using a Markov Chain Monte Carlo exploring the full parameter space. We find that the sensitivity of DUNE to the standard oscillation parameters is worsened due to the presence of non-standard neutrino interactions. In particular, there are degenerate solutions in the leptonic mixing angle θ_{23} and the Dirac CP-violating phase δ . We also compute the expected sensitivities at DUNE to the non-standard interaction parameters. We find that the sensitivities to the matter non-standard interaction parameters are substantially stronger than the current bounds (up to a factor of about 15). Furthermore, we discuss correlations between the source/detector and matter non-standard interaction parameters and find a degenerate solution in θ_{23} . Finally, we explore the effect of statistics on our results.

KEYWORDS: Neutrino Physics, Beyond Standard Model

ARXIV EPRINT: [1606.08851](https://arxiv.org/abs/1606.08851)

Contents

1	Introduction	1
2	Neutrino oscillations with non-standard interactions	3
3	The DUNE experiment	4
4	Simulation results	6
4.1	Effect on precision measurements at DUNE	7
4.2	Constraining NSI parameters at DUNE	8
4.3	Correlations between source/detector and matter NSIs	10
4.4	Effect of statistics	12
5	Summary and conclusions	12

1 Introduction

Despite its unprecedented success, it is now well established that the Standard Model of elementary particles (SM) needs to be extended. Two of the main observational evidences that cannot be described in the context of the SM are the existence of neutrino masses and mixing and the presence of dark matter in the universe. A plethora of models proposing an extension of SM has been put forth that describe non-zero neutrino mass and mixing and/or dark matter. Some of these new physics models could, in principle, lead to corrections to the effective neutrino interaction vertices through additional (higher-order) terms. All such new charged-current (CC) interactions could therefore lead to modifications in the production and detection of neutrinos, while all neutral-current (NC) interactions could modify the neutrino-matter forward scattering cross-section and hence affect neutrino oscillations in matter. Without going into details of the ultraviolet-complete models, these so-called non-standard interactions (NSIs) involving neutrinos can be parametrised in terms of effective four-fermion operators (see e.g. ref. [1] and references therein). Hence, the NSI parameters are of two kinds: the source/detector NSIs (for CC) and the matter NSIs (for NC), respectively. They have been studied extensively both in the context of existing constraints on the effective NSI parameters as well as in the context of expected constraints coming from future neutrino oscillation experiments. If present, NSIs could also fake expected event spectra due to standard neutrino oscillations, but with a different set of parameter values. This could therefore lead to new degeneracies in the oscillation parameter space. An important challenge for future experiments is thus to find ways to break these degeneracies to obtain maximum sensitivity to oscillation parameters.

Discovery of CP violation in the lepton sector is amongst the most important goals for future neutrino oscillation experiments. The Deep Underground Neutrino Experiment (DUNE) [2–5] is being proposed as a discovery set-up for CP violation. It is expected to have all ingredients needed for precision search of the Dirac CP-violating phase δ , a powerful beam to be built at Fermilab, a large high-end liquid argon detector at Sanford Underground Research Facility (SURF), near detector to control detector systematics, and a long baseline of 1300 km from Fermilab in Illinois, U.S.A. to SURF in South Dakota, U.S.A.. The physics reach of DUNE in the presence of standard oscillations has been studied extensively by the DUNE collaboration [3] and others. Any sizable new physics effect is expected to modify the event spectrum at the DUNE detector, and hence, its physics reach. Effect of matter NSIs on DUNE has been previously studied in refs. [6–10].

It has been established that the presence of matter NSIs in general reduces the sensitivity of DUNE to standard oscillation parameters. The main reason behind this reduction is the interplay between oscillations due to standard and non-standard parameters that give rise to new kinds of degeneracies for long baseline experiments [7, 8]. It has been shown [11] that for sufficiently large values of the NSI parameters one could expect a degeneracy between the sign of Δm_{31}^2 and δ , affecting the sensitivity of DUNE to the neutrino mass ordering [10, 11]. For θ_{23} and CP measurements, studies have revealed that there are two other degeneracies. The first kind is due to an interplay between the oscillation parameter θ_{23} and the NSI parameters. This leads to a reduction of the DUNE sensitivity to θ_{23} and even fake so-called octant solutions [7, 8]. The second kind is due to an interplay between δ and the NSI parameters, opening up the possibility of a reduced expected sensitivity for this parameter at DUNE. Since the NSI paradigm brings in a large number of parameters, the statistical analysis of the projected data at DUNE becomes cumbersome and challenging. The analysis with a full matter NSI parameter scan was performed in refs. [7, 8] for a three years running of the experiment in the neutrino mode and three years in the antineutrino mode. To the best of our knowledge, the impact of source and detector NSIs at DUNE has not been studied before.

Any theory, which gives rise to the matter NSIs, would almost always also give rise to source and detector NSIs, and hence, it is imperative to consider them together in a complete analysis. The neutrino oscillation probabilities in presence of both source/detector and matter NSIs have been calculated before [12] and are seen to depend on these parameters in a correlated way. It is therefore pertinent to ask if these correlation could alter in any way the expected sensitivity of DUNE.

In this paper, we perform a complete analysis of the expected sensitivity of DUNE, allowing for both source/detector and matter NSIs. We study the combined effect of source/detector and matter NSIs and look at possible correlations between them at the level of oscillation probabilities. We point out the importance of the event spectrum in disentangling standard oscillations from oscillations driven by NSI parameters. We next calculate the expected sensitivity of DUNE for standard and NSI parameters from a full scan of the NSI parameter space, including all relevant source/detector and matter NSIs. Finally, we explore the effect of runtime on the precision measurement at DUNE.

2 Neutrino oscillations with non-standard interactions

The presence of flavour off-diagonal operators beyond the SM is manifest in the phenomenon of neutrino oscillations. In the standard picture of neutrino oscillations, a neutrino produced at a source in association with a charged lepton ℓ_α is simply

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle, \quad (2.1)$$

i.e. the weak-interaction eigenstate with isospin $T^3 = +1/2$. Similarly, a neutrino that produces a charged lepton ℓ_β at a detector is

$$\langle\nu_\beta^d| = \langle\nu_\beta|, \quad (2.2)$$

which is also the weak-interaction eigenstate. Between the source and the detector, the propagation of neutrinos with energy E is governed by the time-evolution equation

$$i \frac{d}{dt} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \frac{1}{2E} \left\{ U^\dagger \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{bmatrix} U + \begin{bmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \right\} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}. \quad (2.3)$$

Here, U is the leptonic mixing matrix that is parametrized in terms of three mixing angles θ_{12} , θ_{13} and θ_{23} and one Dirac CP-violating phase δ . The evolution of neutrino states also depends on the two independent mass-squared differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$. When neutrinos propagate through the earth, the coherent forward scattering of ν_e off electrons results in the matter potential $A = 2\sqrt{2}G_F n_e E$, where n_e is the number density of electrons. Thus, standard neutrino oscillation probabilities depend on six oscillation parameters, and are modified by matter effects.

Beyond the SM, it is possible to have CC-like operators that affect the interactions of neutrinos with charged leptons. If these operators are not diagonal in flavour basis, then the production and the detection of neutrinos are affected. The neutrino state produced at the source in association with the charged lepton ℓ_α then also has components of the other flavours

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \varepsilon_{\alpha\gamma}^s |\nu_\gamma\rangle, \quad (2.4)$$

and similarly at the detector,

$$\langle\nu_\beta^d| = \langle\nu_\beta| + \sum_{\gamma=e,\mu,\tau} \varepsilon_{\gamma\beta}^d \langle\nu_\gamma|. \quad (2.5)$$

The matrices $\varepsilon^s = (\varepsilon_{\alpha\gamma}^s)$ and $\varepsilon^d = (\varepsilon_{\gamma\beta}^d)$ that represent the source and the detector NSIs, respectively, are in general complex matrices with 18 real parameters each. These are the nine amplitudes $|\varepsilon_{\alpha\beta}^{s/d}|$ and nine phases $\varphi_{\alpha\beta}^{s/d}$. Note that the definitions of $\varepsilon_{\alpha\gamma}^s$ and $\varepsilon_{\gamma\beta}^d$ follow the convention used in ref. [1].

The NC-like operators affect the propagation of neutrinos through matter, inducing more terms similar to the matter potential. The modified time-evolution equation is

$$i \frac{d}{dt} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \frac{1}{2E} \left\{ U^\dagger \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{bmatrix} U + A \begin{bmatrix} 1 + \varepsilon_{ee}^m & \varepsilon_{e\mu}^m & \varepsilon_{e\tau}^m \\ \varepsilon_{\mu e}^m & \varepsilon_{\mu\mu}^m & \varepsilon_{\mu\tau}^m \\ \varepsilon_{\tau e}^m & \varepsilon_{\tau\mu}^m & \varepsilon_{\tau\tau}^m \end{bmatrix} \right\} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}. \quad (2.6)$$

The entry 1 in the $e - e$ position of the matter effect matrix stands for the standard matter effect, while the parameters $\varepsilon_{\alpha\beta}^m$ represent the matter NSIs. Note that the definitions of $\varepsilon_{\alpha\beta}^m$ also follow the convention used in ref. [1]. Since the Hamiltonian has to be Hermitian, we have the relations $\varepsilon_{\alpha\beta}^m = \varepsilon_{\beta\alpha}^{m*}$. Thus, there are six amplitudes and three phases, i.e. nine real parameters in the matter NSI matrix. Subtracting a constant multiple of the identity matrix does not affect the eigenvectors, and hence, oscillation probabilities. Therefore, we subtract the element $\varepsilon_{\mu\mu}^m$ from all the diagonal elements. We define $\varepsilon_{ee}^{m'} = \varepsilon_{ee}^m - \varepsilon_{\mu\mu}^m$ and $\varepsilon_{\tau\tau}^{m'} = \varepsilon_{\tau\tau}^m - \varepsilon_{\mu\mu}^m$ and treat these two new parameters as the physical parameters of the system.

A comprehensive study of the bounds on NSI parameters has been carried out by the authors of ref. [13]. The 90% bounds on the source/detector NSI parameters¹ from their study are as follows

$$|\varepsilon_{\alpha\beta}^{s/d}| < \begin{bmatrix} 0.041 & 0.025 & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.12 & 0.018 & 0.13 \end{bmatrix}. \quad (2.7)$$

For the matter NSI parameters, we follow the discussion in ref. [14]. In that paper, the authors have used the bounds from ref. [13] along with more recent results from SK and MINOS [1, 15, 16] to obtain the following bounds

$$|\varepsilon_{\alpha\beta}^m| < \begin{bmatrix} 4.2 & 0.3 & 3.0 \\ 0.3 & - & 0.04 \\ 3.0 & 0.04 & 0.15 \end{bmatrix}. \quad (2.8)$$

Throughout this article, we will refer to the bounds listed above as the ‘current bounds’.

Analytical expressions for the neutrino oscillation probabilities in the presence of source/detector and matter NSIs are given in ref. [12]. The expressions are derived as perturbative expansions in the small parameters $\Delta m_{21}^2/\Delta m_{31}^2$ and $\sin\theta_{13}$ up to linear order in the NSI parameters. In figure 1, we show the change in the $\nu_\mu \rightarrow \nu_e$ oscillation probability $P_{\mu e}$ as the NSI parameters are varied one at a time within their allowed range at 90% C.L. The dark curve within the band corresponds to standard oscillations when the value of the NSI parameter is zero. Since the existing bounds on matter NSIs are weaker, we observe that they affect the probability more, resulting in bands that are much wider. Therefore, we expect them to change the event rates at DUNE and affect the measurement of parameters.

3 The DUNE experiment

DUNE is a proposed long-baseline neutrino oscillation experiment [2–5]. The source of the beam will be at Fermilab, while the liquid argon detector will be located at the SURF. The total distance travelled by the neutrinos will be around 1300 km. In our simulation, we use

¹Strictly speaking, the NSI parameters that affect neutrino oscillations are combinations of the NSI parameters that enter the Lagrangian, depending on the Lorentz structure of the current involved in the process. In this study, we assume for the sake of simplicity that the bounds from ref. [13] apply directly to the oscillation NSI parameters.

Figure 1. Variation in the neutrino oscillation probability $P_{\mu e}$ as a function of neutrino energy E with some of the NSI parameters varied in their allowed range. The central dark curve corresponds to the case of no NSIs. The values of the standard oscillation parameters used in generating these figures are $\theta_{12} = 33.5^\circ$, $\theta_{13} = 8.48^\circ$, $\theta_{23} = 42^\circ$, $\delta = -90^\circ$, $\Delta m_{21}^2 = 7.50 \times 10^{-5} \text{ eV}^2$ and $\Delta m_{31}^2 = 2.45 \times 10^{-3} \text{ eV}^2$.

the neutrino flux corresponding to a 1.2 MW beam with 120 GeV protons. The expected flux at DUNE will have beam power between 1.2 MW and 2.3 MW and proton energy between 80 GeV and 120 GeV. Thus, the configuration we are using gives a conservative estimate of the net statistics that the experiment will accumulate. Unless stated otherwise, we assume that the experiment will run with five years in neutrino mode and five years in antineutrino mode.

The 40 kiloton liquid argon detector is assumed to have an energy resolution of 15% for ν_e and 20% for ν_μ . For NC events, however, the reconstructed energy of the neutrino has a wide spread to lower energies, because of the production of pions and other hadrons. Therefore, we use a smearing matrix to simulate the effect of the reconstruction of these events.

The primary backgrounds to the electron appearance and muon disappearance signal events come from the NC backgrounds and intrinsic ν_e contamination in the flux. In addition, there is a wrong-sign component in the flux. The problem of wrong sign events is more severe for the antineutrino run, since the neutrino component in the antineutrino flux is larger than the antineutrino component in the neutrino flux. We have taken all of these backgrounds into account in our simulation of the experiment. From an experimental point of view, various cuts are imposed on the observed events in order to eliminate as much of the background as possible. Furthermore, in our simulation, the effect of these cuts is to appear as efficiency factors that reduce the number of events. The full specifications of the detector that we have used can be found in ref. [3]. Apart from the usual uncertainties in the flux and the cross-section, the presence of source/detector NSIs can also affect the calibration of the expected number of events. In our analysis, we have included systematic errors in the normalization of the flux at the 5% (20%) level for signal (background) events.

4 Simulation results

For our simulation, we have made use of the GLoBES package [17, 18] along with its auxiliary data files [19, 20]. The scanning of the multi-dimensional parameter space was achieved by a Markov Chain Monte Carlo using the MonteCUBES package [21]. As a result, all of our results are to be interpreted in terms of Bayesian credible regions rather than frequentist confidence levels, i.e. the 90% credible region is the part of parameter space that will contain 90% of the posterior probability as opposed to the 90% C.L. contours that contain the points in parameter space where the simulated result would be within the 90% least extreme experimental outcomes. We have written a GLoBES-compatible probability engine to handle the full parameter space and calculate the oscillation probabilities in the presence of both source/detector and matter NSIs.

Since we are primarily interested in the $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ oscillation probabilities, the relevant source NSI parameters are $\varepsilon_{\mu e}^s$, $\varepsilon_{\mu\mu}^s$ and $\varepsilon_{\mu\tau}^s$, while the relevant detector NSI parameters are ε_{ee}^d , $\varepsilon_{e\mu}^d$, $\varepsilon_{\mu e}^d$, $\varepsilon_{\mu\mu}^d$, $\varepsilon_{\tau e}^d$ and $\varepsilon_{\tau\mu}^d$. The matter NSI parameters affect the propagation of neutrinos and are all relevant, since intermediate states are summed over. Furthermore, based on the analytical expressions and our preliminary simulations, we reduce the set of relevant source/detector parameters to $\varepsilon_{\mu e}^s$, $\varepsilon_{\mu\mu}^s$, $\varepsilon_{\mu\tau}^s$, $\varepsilon_{\mu e}^d$ and $\varepsilon_{\tau e}^d$.

Thus, our final simulations are run over the parameter space spanned by five complex source/detector NSI parameters and three complex and two real matter NSI parameters. As for the standard oscillation parameters, we fix the parameters Δm_{21}^2 and θ_{12} and vary the others.

The best-fit values of the standard parameters are $\theta_{12} = 33.5^\circ$, $\theta_{13} = 8.48^\circ$, $\theta_{23} = 42^\circ$, $\delta = -90^\circ$, $\Delta m_{21}^2 = 7.50 \times 10^{-5} \text{ eV}^2$ and $\Delta m_{31}^2 = 2.45 \times 10^{-3} \text{ eV}^2$ which are consistent with the global fits to neutrino oscillation data [22–24]. These parameters are marginalized over their 3σ ranges allowed by the global fits with the corresponding priors. For the NSI parameters, we use the bounds listed before. The true values of these NSI parameters are either set to zero or to a non-zero value equal to half of the 1σ bounds. The true values of all NSI phases are zero, and they are free to vary in the entire $[-180^\circ, 180^\circ)$ range.

4.1 Effect on precision measurements at DUNE

The current generation of long-baseline neutrino oscillation experiments T2K and NO ν A are already collecting data and have provided a hint of the value of δ [25, 26]. This also gives hints about the neutrino mass ordering and octant of θ_{23} [25, 27]. If the data collected over the next few years do not confirm these hints, then it may be possible for DUNE to make these measurements. At any rate, we expect that data from DUNE will enable us to measure these unknown parameters at a higher confidence level.

It becomes important to question whether the presence of NSIs will adversely affect the precision measurement of these parameters or not. Many recent studies have explored this question for DUNE [6–10] in the context of matter NSIs. In figure 2, we show the effect of NSIs on the precision measurement of θ_{23} and δ when the true values of these parameters are 42° and -90° , respectively. In the left panel, we have set the true values of all NSI parameters to zero. We have then scanned the parameter space for four different cases, where the parameter space consists of (a) only the standard oscillation parameters, (b) standard parameters and source/detector NSI parameters, (c) standard parameters and matter NSI parameters and (d) standard parameters, source/detector NSI parameters and matter NSI parameters. The results are displayed as different contours in the parameter space as the 90% credible regions. This plot shows how the precision in θ_{23} and δ changes as we change our assumption about the parameter space when there are no NSIs in nature. We observe that the sensitivity in θ_{23} is not affected by scanning the extra parameter space. Another significant feature is that the source/detector NSIs do not play much of a role. This is expected, since the current bounds restrict the allowed range of these parameters. There is some worsening of the sensitivity to δ . In the right panel, we have given a similar plot, but with non-zero values of the NSI parameters. This plot shows the successive worsening of precision as more NSIs are introduced. The innermost contour displays the allowed region, where NSIs are present in nature, but we only choose to marginalize over the standard parameters. The sensitivity to the standard parameters obtained from such an analysis would be erroneously optimistic. In order to see the actual worsening of sensitivity because of the presence of NSIs, we compare the dotted black curve of the left panel (zero NSIs, standard oscillation scenario) with the solid red curve of the left panel (non-zero NSIs, all NSI parameters included in the fit). We find that the error in the measurement

Figure 2. Sensitivity of DUNE in the $\theta_{23} - \delta$ plane. The simulated true values of these parameters are 42° and -90° , respectively. The contours enclose the allowed region at 90% credible regions obtained by marginalizing over only the standard parameters, standard parameters and source/detector NSI parameters, standard parameters and matter NSI parameters, and standard parameters and all NSI parameters. In the left (right) panel, the true values of the NSI parameters are taken to be zero (non-zero).

of δ (the size in δ of the 90% credible region) increases from around 90° to almost 180° . In addition, we find a degenerate solution in θ_{23} in the wrong octant. These additional degeneracies have been studied recently in refs. [7, 8].

For completeness, we compute the precision in θ_{13} , θ_{23} , δ and Δm_{31}^2 that DUNE will reach in the presence of NSIs. The results are shown in figure 3, where a striking feature is the appearance of a degenerate solution in θ_{23} .

4.2 Constraining NSI parameters at DUNE

So far, we have discussed the effect of NSIs on the measurement of the standard oscillation parameters. In addition, DUNE can place bounds on the NSI parameters due to its high statistics. In order to estimate these projected bounds from DUNE, we set the true values of the NSI parameters to zero. Varying the fit values, we construct the 90% credible region for the value of the parameter placed by DUNE. These 90% credible regions are obtained by marginalizing over all the other parameters. In table 1, we list the 90% credible upper bounds that DUNE can impose. We have performed the computations for three different cases: (a) the only NSIs are source/detector NSIs, (b) the only NSIs are matter NSIs and (c) all NSIs exist simultaneously.

In general, investigating table 1, we see that in going from the case of (a) only source/detector NSIs or (b) only matter NSIs to the case of (c) both source/detector and matter NSIs, the bounds imposed by DUNE get weaker. This is expected because of the

Figure 3. Precision in the standard oscillation parameters in the presence of NSIs at DUNE. The contours shown correspond to 68% (red), 90% (green) and 95% (blue) credible regions.

Parameter	Only source/detector NSIs	Only matter NSIs	All NSIs	Current bound
$ \varepsilon_{\mu e}^s $	0.017		0.022	0.026
$ \varepsilon_{\mu\mu}^s $	0.070		0.065	0.078
$ \varepsilon_{\mu\tau}^s $	0.009		0.014	0.013
$ \varepsilon_{\mu e}^d $	0.021		0.023	0.025
$ \varepsilon_{\tau e}^d $	0.028		0.035	0.041
$\varepsilon_{ee}^{m'}$		$(-0.7, +0.8)$	$(-0.8, +0.9)$	$(-4.2, +4.2)$
$ \varepsilon_{\mu e}^m $		0.051	0.074	0.330
$ \varepsilon_{\tau e}^m $		0.17	0.19	3.00
$ \varepsilon_{\tau\mu}^m $		0.031	0.038	0.040
$\varepsilon_{\tau\tau}^{m'}$		$(-0.08, +0.08)$	$(-0.08, +0.08)$	$(-0.15, +0.15)$

Table 1. Expected 90% credible regions on NSI parameters from DUNE.

expansion of the parameter space. (For $|\varepsilon_{\mu\mu}^s|$, the precision appears to improve marginally after the inclusion of all NSIs. This is merely an artifact of the randomness inherent in the Monte Carlo simulation and should be taken with a pinch of salt. The relative difference between the two numbers is small enough for them to be practically equal within the precision of our Monte Carlo simulation.) Using all NSIs, we find that all bounds are improved or basically the same as the current bounds. We also see that the most general bounds imposed on the source/detector NSI parameters are only slightly better than the existing bounds. This shows that the main contribution to the sensitivity to these parameters comes from the prior introduced for them. Data from DUNE itself contribute only to the extent of providing more statistics without any significant physics advantage. On the other hand, we find that the bounds on matter NSI parameters are made substantially more stringent than the existing bounds. In particular, the bounds on $\varepsilon_{ee}^{m'}$, $|\varepsilon_{\mu e}^m|$ and $|\varepsilon_{\tau e}^m|$ are improved by a factor of around five to 15, whereas the bounds on $|\varepsilon_{\tau\mu}^m|$ and $\varepsilon_{\tau\tau}^{m'}$ are more or less the same. Our results on the bounds on the matter NSI parameters are consistent with the ones obtained in ref. [8]. It is worth pointing out that the current bounds on the NSI parameters were derived assuming the existence of only one NSI parameter at a time, whereas we have obtained our bounds by allowing all relevant parameters to vary at the same time.

4.3 Correlations between source/detector and matter NSIs

Beyond the SM, CC-like and NC-like NSIs presumably arise from the same model of new physics. Therefore, it is natural to assume that both source/detector and matter NSIs exist. It is interesting to probe the presence of correlations between various kinds of NSI parameters in neutrino oscillations. It is straightforward to pinpoint such correlations from the analytical expressions for the oscillation probabilities given in ref. [12]. The non-standard terms in $P_{\mu e}$ up to linear order in $\sin\theta_{13}$ arising from $\varepsilon_{\tau e}^d$ and $\varepsilon_{\tau e}^m$ are

$$\begin{aligned}
 P_{\mu e} \supset & -4\varepsilon_{\tau e}^d \tilde{s}_{13} s_{23}^2 c_{23} \cos\delta \left[\sin^2 \frac{AL}{4E} - \sin^2 \frac{\Delta m_{31}^2 L}{4E} - \sin^2 \frac{(\Delta m_{31}^2 - A)L}{4E} \right] \\
 & - 2\varepsilon_{\tau e}^d \tilde{s}_{13} s_{23}^2 c_{23} \sin\delta \left[\sin \frac{AL}{2E} - \sin \frac{\Delta m_{31}^2 L}{2E} + \sin \frac{(\Delta m_{31}^2 - A)L}{2E} \right] \\
 & + 4\varepsilon_{\tau e}^m \tilde{s}_{13} s_{23}^2 c_{23} \cos\delta \left[\sin^2 \frac{AL}{4E} - \sin^2 \frac{\Delta m_{31}^2 L}{4E} + \sin^2 \frac{(\Delta m_{31}^2 - A)L}{4E} \right] \\
 & + 2\varepsilon_{\tau e}^m \tilde{s}_{13} s_{23}^2 c_{23} \sin\delta \left[\sin \frac{AL}{2E} - \sin \frac{\Delta m_{31}^2 L}{2E} + \sin \frac{(\Delta m_{31}^2 - A)L}{2E} \right] \\
 & + 8\varepsilon_{\tau e}^m \tilde{s}_{13} s_{23}^2 c_{23} \cos\delta \frac{A}{\Delta m_{31}^2 - A} \sin^2 \frac{(\Delta m_{31}^2 - A)L}{4E}, \tag{4.1}
 \end{aligned}$$

where we have assumed the NSI parameters to be real and used the notation $\tilde{s}_{13} = s_{13}\Delta m_{31}^2/(\Delta m_{31}^2 - A)$. Close to the oscillation maximum, these terms can be combined into one term proportional to $\varepsilon_{\tau e}^m - \varepsilon_{\tau e}^d$. Similarly, the terms involving $\varepsilon_{\tau e}^d$ and $\varepsilon_{\mu e}^m$

Figure 4. Correlations between matter NSI parameters and source/detector NSI parameters at DUNE. The 68% (red), 90% (green) and 95% (blue) credible regions are shown in the $\varepsilon_{\tau e}^m - \varepsilon_{\tau e}^d$ plane in the left panel and in the $\varepsilon_{\mu e}^m - \varepsilon_{\tau e}^d$ plane in the right panel.

enter the formula as

$$\begin{aligned}
 P_{\mu e} \supset & -4\varepsilon_{\tau e}^d \tilde{s}_{13} s_{23}^2 c_{23} \cos \delta \left[\sin^2 \frac{AL}{4E} - \sin^2 \frac{\Delta m_{31}^2 L}{4E} - \sin^2 \frac{(\Delta m_{31}^2 - A)L}{4E} \right] \\
 & - 2\varepsilon_{\tau e}^d \tilde{s}_{13} s_{23}^2 c_{23} \sin \delta \left[\sin \frac{AL}{2E} - \sin \frac{\Delta m_{31}^2 L}{2E} + \sin \frac{(\Delta m_{31}^2 - A)L}{2E} \right] \\
 & - 4\varepsilon_{\mu e}^m \tilde{s}_{13} s_{23} c_{23}^2 \cos \delta \left[\sin^2 \frac{AL}{4E} - \sin^2 \frac{\Delta m_{31}^2 L}{4E} + \sin^2 \frac{(\Delta m_{31}^2 - A)L}{4E} \right] \\
 & - 2\varepsilon_{\mu e}^m \tilde{s}_{13} s_{23} c_{23}^2 \sin \delta \left[\sin \frac{AL}{2E} - \sin \frac{\Delta m_{31}^2 L}{2E} + \sin \frac{(\Delta m_{31}^2 - A)L}{2E} \right] \\
 & + 8\varepsilon_{\mu e}^m \tilde{s}_{13} s_{23}^3 \cos \delta \frac{A}{\Delta m_{31}^2 - A} \sin^2 \frac{(\Delta m_{31}^2 - A)L}{4E}.
 \end{aligned} \tag{4.2}$$

These can be combined to give a term proportional to $\varepsilon_{\mu e}^m + \varepsilon_{\tau e}^d$ close to the oscillation maximum. Thus, we expect to have a correlation between $\varepsilon_{\tau e}^d$ and $\varepsilon_{\mu e}^m$ and an anticorrelation between $\varepsilon_{\tau e}^d$ and $\varepsilon_{\mu e}^m$. The current bounds on the source/detector NSI parameters are more stringent than those on the matter NSI parameters. Therefore, in scanning over the parameter space, these correlations get washed out. However, if we make the assumption that these two types of NSI parameters have comparable bounds, then the correlations are visible. This can be observed in the panels of figure 4. In generating these plots, we have made use of the assumptions listed above, and used the (more stringent) priors of the source/detector NSI parameters for the matter NSI parameters as well. The true values assigned to the NSI parameters are half of the bounds used. The correlations appear very weak because (a) the parameter space that has been scanned over is very large, (b) the conditions for the correlation include a very small value of θ_{13} and (c) the signal events

have a spread in energy away from the oscillation maximum. With the current bounds, which are very large for the matter NSI parameters, one does not see any clear correlation between the two types of NSI parameters. In figures 5 and 6, we show the correlations between all the source/detector and matter NSI parameters given their existing bounds.

4.4 Effect of statistics

Finally, we make a note of the effect of statistics on the precision measurements at DUNE in the presence of NSIs and on the measurement of these NSI parameters. In the preceding sections, we have assumed a runtime for DUNE of five years with neutrinos and antineutrinos each (5+5). In this section, we discuss the results with lower statistics. In particular, we have re-run our simulations assuming three years of running in each mode (3+3). Comparing results from the two cases gives an indication of the effect of statistics on the results.

In figure 7, we have shown this comparison for the precision measurements of θ_{23} and δ at DUNE in the presence of all NSIs. The values of the NSI parameters are taken to be the same non-zero values used in generating the right panel of figure 2. Comparing the contours corresponding to the cases of 5+5 and 3+3, we find that the precision in δ is significantly worsened. It has been shown that the combination of neutrino and antineutrino run helps in lifting the $\theta_{23} - \delta$ degeneracy, hence allowing for an accurate measurement of δ [27–31]. Usually, it is sufficient to have a short run in the antineutrino mode that is just adequate to resolve the degeneracy. In this case, however, the presence of NSIs introduces additional sources of CP violation. Therefore, there are additional regions of the parameter space that are allowed owing to the lower statistics.

Furthermore, we have also checked the bounds imposed on the NSI parameters in the case of 3+3. Once again, the experiment is seen to have much better sensitivity to the matter NSI parameters than to the source/detector NSI parameters. We find that the bounds are only slightly worse than those shown in table 1 expected from the case of 5+5. Thus, the main advantage of collecting more data with DUNE is to determine the value of δ with higher precision.

5 Summary and conclusions

The Deep Underground Neutrino Experiment (DUNE) is being proposed as a high precision next-generation neutrino experiment to be built in the U.S.A.. The main physics goals of DUNE are to measure the neutrino mass ordering, the octant of θ_{23} and the Dirac CP-violating phase δ . While the baseline design for DUNE is known to be good for these physics goals in the case of standard oscillations, it is worthwhile to recheck the sensitivities of DUNE in the presence of non-standard neutrino interactions (NSIs). The NSIs are of two kinds — the charged-current-like source/detector NSIs and the neutral-current-like matter NSIs. The source/detector NSIs affect the neutrino fluxes at the production and detection of the neutrinos. On the other hand, the matter NSIs play a role in the coherent scattering of the neutrinos off the ambient matter during neutrino propagation. The role of the matter NSIs on the physics reach of DUNE has been studied. However, it is more likely that if

Figure 5. Correlations between matter NSI parameters and source NSI parameters with current bounds at DUNE. The 68% (red), 90% (green) and 95% (blue) credible regions are shown.

Figure 6. Correlations between matter NSI parameters and detector NSI parameters with current bounds at DUNE. The 68% (red), 90% (green) and 95% (blue) credible regions are shown.

Figure 7. Sensitivity of DUNE in the $\theta_{23} - \delta$ plane with 3+3 years (blue, dashed contours) and 5+5 years (red, solid contours) of data. The simulated true values of these parameters are 42° and -90° , respectively. The contours enclose the 90% credible regions.

NSIs were to exist, they would be both charged- as well as neutral-current-like. Therefore, in this work, we have considered both source/detector and matter NSIs and looked at the expected sensitivity of DUNE to neutrino oscillation parameters as well as NSI parameters. We have performed this analysis by doing a full scan of the entire relevant oscillation and NSI parameter space, which was accomplished by using a Markov Chain Monte Carlo. To the best of our knowledge, a complete phenomenological study of DUNE in the presence of both source/detector and matter NSIs has not been performed before.

Through probability plots we have showed the impact of the NSI parameters on the neutrino oscillation probability $P_{\mu e}$. Next, we have presented credible regions in the $\theta_{23} - \delta$ plane for the cases where we have taken in the fit (a) no NSIs, (b) only source/detector NSIs, (c) only matter NSIs and (d) both source/detector and matter NSIs together. The analysis was first performed for the case where the data were generated without the presence of NSIs. This was then repeated for the case where NSIs were present in the generation of the data. In both cases, the effect of source/detector NSIs on the θ_{23} and δ measurements is seen to be marginal, mainly because the source/detector NSIs are already severely constrained by existing data and we have imposed priors in our analysis corresponding to the existing constraints. The effect of matter NSIs is seen to be larger, since the existing constraints on matter NSIs are weaker. Our results, where we have included only matter NSIs, are observed to generally agree with those obtained by others in the recent past, modulo the runtime assumed. The sensitivity to both θ_{23} and δ worsens when matter NSIs are included. The worsening is more severe when the data are generated with NSIs compared to when they are not. Finally, we have presented our results when source/detector and matter NSIs are taken together. For the case where the data are generated with no NSIs, the credible

regions with the inclusion of all NSIs in the fit are not very different from those with only matter NSIs. However, when the data are generated with NSIs, we observe a significant worsening of the precision with the appearance of a fake 90% credible region in the $\theta_{23} - \delta$ plane. We have presented the 68%, 90% and 95% credible regions in the neutrino oscillation parameter space in the presence of NSIs. The correlations between the NSI parameters have been showcased.

We have presented the sensitivities to the NSI parameters expected from DUNE. The 90% credible regions for the source/detector NSIs that we expect are not much better than what we already know from current data. However, the expected sensitivities to the matter NSI parameters are substantially stronger than the existing bounds.

We have presented our main results for a total of ten years of running of DUNE — five years in the neutrino mode and five years in the antineutrino mode (5+5). In order to study the impact of statistics, we have also presented the expected credible regions in the $\theta_{23} - \delta$ plane for a DUNE run plan of three years in the neutrino mode and three years in the antineutrino mode (3+3). Some of the earlier studies on DUNE with a full parameter scan have been done for the case of 3+3 [7, 8]. We have found that for this case, many more degenerate solutions exist in the $\theta_{23} - \delta$ plane. This agrees with the results previously obtained in ref. [8] for the matter NSI only case. However, when the statistics are increased to 5+5, the degenerate solutions for the matter NSI only case disappear.

To conclude, we have performed a complete analysis of the physics reach of DUNE in the presence of both source/detector and matter NSIs, using a full scan of the entire relevant parameter space. DUNE could improve the existing bounds on the matter NSIs, but would not be able to improve the bounds on the source/detector NSIs. Increasing the statistics from 3+3 to 5+5 reduces the negative impact of the matter NSIs on the θ_{23} and δ sensitivities. However, the correlation between the source/detector and matter NSIs result in new degeneracies in the $\theta_{23} - \delta$ plane which remain even in the case of 5+5.

Acknowledgments

This work was supported by the Göran Gustafsson Foundation (M.B.). S.C. acknowledges support from the Neutrino Project under the XII plan of Harish-Chandra Research Institute. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 674896.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] T. Ohlsson, *Status of non-standard neutrino interactions*, *Rept. Prog. Phys.* **76** (2013) 044201 [[arXiv:1209.2710](https://arxiv.org/abs/1209.2710)] [[INSPIRE](#)].
- [2] DUNE collaboration, R. Acciarri et al., *Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE): Volume 1: The LBNF and DUNE Projects*, [arXiv:1601.05471](https://arxiv.org/abs/1601.05471) [[INSPIRE](#)].
- [3] DUNE collaboration, R. Acciarri et al., *Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE): Volume 2: The Physics Program for DUNE at LBNF*, [arXiv:1512.06148](https://arxiv.org/abs/1512.06148) [[INSPIRE](#)].
- [4] DUNE collaboration, J. Strait et al., *Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE): Volume 3: Long-Baseline Neutrino Facility for DUNE June 24, 2015*, [arXiv:1601.05823](https://arxiv.org/abs/1601.05823) [[INSPIRE](#)].
- [5] DUNE collaboration, R. Acciarri et al., *Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE): Volume 4: The DUNE Detectors at LBNF*, [arXiv:1601.02984](https://arxiv.org/abs/1601.02984) [[INSPIRE](#)].
- [6] M. Masud, A. Chatterjee and P. Mehta, *Probing CP-violation signal at DUNE in presence of non-standard neutrino interactions*, [arXiv:1510.08261](https://arxiv.org/abs/1510.08261) [[INSPIRE](#)].
- [7] A. de Gouvêa and K.J. Kelly, *Non-standard Neutrino Interactions at DUNE*, *Nucl. Phys. B* **908** (2016) 318 [[arXiv:1511.05562](https://arxiv.org/abs/1511.05562)] [[INSPIRE](#)].
- [8] P. Coloma, *Non-Standard Interactions in propagation at the Deep Underground Neutrino Experiment*, *JHEP* **03** (2016) 016 [[arXiv:1511.06357](https://arxiv.org/abs/1511.06357)] [[INSPIRE](#)].
- [9] M. Masud and P. Mehta, *Nonstandard interactions spoiling the CP-violation sensitivity at DUNE and other long baseline experiments*, *Phys. Rev. D* **94** (2016) 013014 [[arXiv:1603.01380](https://arxiv.org/abs/1603.01380)] [[INSPIRE](#)].
- [10] M. Masud and P. Mehta, *Non-standard interactions and the resolution of ordering of neutrino masses at DUNE and other long baseline experiments*, [arXiv:1606.05662](https://arxiv.org/abs/1606.05662) [[INSPIRE](#)].
- [11] P. Coloma and T. Schwetz, *Generalized Mass Ordering Degeneracy in Neutrino Oscillation Experiments*, [arXiv:1604.05772](https://arxiv.org/abs/1604.05772) [[INSPIRE](#)].
- [12] J. Kopp, M. Lindner, T. Ota and J. Sato, *Non-standard neutrino interactions in reactor and superbeam experiments*, *Phys. Rev. D* **77** (2008) 013007 [[arXiv:0708.0152](https://arxiv.org/abs/0708.0152)] [[INSPIRE](#)].
- [13] C. Biggio, M. Blennow and E. Fernandez-Martinez, *General bounds on non-standard neutrino interactions*, *JHEP* **08** (2009) 090 [[arXiv:0907.0097](https://arxiv.org/abs/0907.0097)] [[INSPIRE](#)].
- [14] S. Choubey, A. Ghosh, T. Ohlsson and D. Tiwari, *Neutrino Physics with Non-Standard Interactions at INO*, *JHEP* **12** (2015) 126 [[arXiv:1507.02211](https://arxiv.org/abs/1507.02211)] [[INSPIRE](#)].
- [15] SUPER-KAMIOKANDE collaboration, G. Mitsuka et al., *Study of Non-Standard Neutrino Interactions with Atmospheric Neutrino Data in Super-Kamiokande I and II*, *Phys. Rev. D* **84** (2011) 113008 [[arXiv:1109.1889](https://arxiv.org/abs/1109.1889)] [[INSPIRE](#)].

- [16] MINOS collaboration, P. Adamson et al., *Search for flavor-changing non-standard neutrino interactions by MINOS*, *Phys. Rev. D* **88** (2013) 072011 [[arXiv:1303.5314](#)] [[INSPIRE](#)].
- [17] P. Huber, M. Lindner and W. Winter, *Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator)*, *Comput. Phys. Commun.* **167** (2005) 195 [[hep-ph/0407333](#)] [[INSPIRE](#)].
- [18] P. Huber, J. Kopp, M. Lindner, M. Rolinec and W. Winter, *New features in the simulation of neutrino oscillation experiments with GLoBES 3.0: General Long Baseline Experiment Simulator*, *Comput. Phys. Commun.* **177** (2007) 432 [[hep-ph/0701187](#)] [[INSPIRE](#)].
- [19] M.D. Messier, *Evidence for neutrino mass from observations of atmospheric neutrinos with Super-Kamiokande*, Ph.D. Thesis (1999) [[INSPIRE](#)].
- [20] E.A. Paschos and J.Y. Yu, *Neutrino interactions in oscillation experiments*, *Phys. Rev. D* **65** (2002) 033002 [[hep-ph/0107261](#)] [[INSPIRE](#)].
- [21] M. Blennow and E. Fernandez-Martinez, *Neutrino oscillation parameter sampling with MonteCUBES*, *Comput. Phys. Commun.* **181** (2010) 227 [[arXiv:0903.3985](#)] [[INSPIRE](#)].
- [22] F. Capozzi, G.L. Fogli, E. Lisi, A. Marrone, D. Montanino and A. Palazzo, *Status of three-neutrino oscillation parameters, circa 2013*, *Phys. Rev. D* **89** (2014) 093018 [[arXiv:1312.2878](#)] [[INSPIRE](#)].
- [23] D.V. Forero, M. Tortola and J.W.F. Valle, *Neutrino oscillations refitted*, *Phys. Rev. D* **90** (2014) 093006 [[arXiv:1405.7540](#)] [[INSPIRE](#)].
- [24] M.C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, *Updated fit to three neutrino mixing: status of leptonic CP-violation*, *JHEP* **11** (2014) 052 [[arXiv:1409.5439](#)] [[INSPIRE](#)].
- [25] T2K collaboration, K. Abe et al., *Measurements of neutrino oscillation in appearance and disappearance channels by the T2K experiment with 6.6×10^{20} protons on target*, *Phys. Rev. D* **91** (2015) 072010 [[arXiv:1502.01550](#)] [[INSPIRE](#)].
- [26] NOvA collaboration, P. Adamson et al., *First measurement of electron neutrino appearance in NOvA*, *Phys. Rev. Lett.* **116** (2016) 151806 [[arXiv:1601.05022](#)] [[INSPIRE](#)].
- [27] M. Ghosh, S. Goswami and S.K. Raut, *Can the hint of δ_{CP} from T2K also indicate the hierarchy and octant?*, [arXiv:1409.5046](#) [[INSPIRE](#)].
- [28] S.K. Agarwalla, S. Prakash and S.U. Sankar, *Resolving the octant of θ_{23} with T2K and NOvA*, *JHEP* **07** (2013) 131 [[arXiv:1301.2574](#)] [[INSPIRE](#)].
- [29] P. Coloma, H. Minakata and S.J. Parke, *Interplay between appearance and disappearance channels for precision measurements of θ_{23} and δ* , *Phys. Rev. D* **90** (2014) 093003 [[arXiv:1406.2551](#)] [[INSPIRE](#)].
- [30] M. Ghosh, P. Ghoshal, S. Goswami, N. Nath and S.K. Raut, *New look at the degeneracies in the neutrino oscillation parameters and their resolution by T2K, NOvA and ICAL*, *Phys. Rev. D* **93** (2016) 013013 [[arXiv:1504.06283](#)] [[INSPIRE](#)].
- [31] N. Nath, M. Ghosh and S. Goswami, *The physics of antineutrinos in DUNE and determination of octant and δ_{CP}* , [arXiv:1511.07496](#) [[INSPIRE](#)].