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Non-standard interactions versus non-unitary lepton flavor mixing at a neutrino factory

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Abstract

The impact of heavy mediators on neutrino oscillations is typically described by non-standard interactions (NSIs) or a non-unitary lepton mixing matrix (NU). We focus on dimension-six effective operators, which lead to particular correlations among neutrino production, propagation, and detection non-standard effects. We point out that NSI and NU phenomenologically lead, in fact, to very similar effects for a neutrino factory for completely different fundamental reasons, if the NSIs originate from leptonic operators mediated by bosons at tree level. We discuss how the parameters and probabilities are related in this case, and compare the sensitivities. We demonstrate that NSIs and NU can, in principle, be distinguished for large enough effects at the example of non-standard effects in the μ-τ-sector, which basically corresponds to differentiating between bosons and fermions as heavy mediators as leading order effect. However, we point out that a near detector at superbeams could provide very synergistic information, since the correlation between source and matter NSI is broken for hadronic neutrino production, while NU is a fundamental effect present at any experiment.

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I. INTRODUCTION

During the past decade, experimental studies of neutrino oscillations have provided us with compelling evidence that neutrinos are massive particles and lepton flavors mix. Since an important new window is opened for searching new physics beyond the Standard Model (SM) of particle physics, it is interesting to discuss the impact of potential non-standard effects on neutrino oscillations. In this study, we focus our attention on non-standard effects from heavy mediators, which are integrated out at the scales of the neutrino oscillation experiments.

It is convenient to parameterize the impact of the heavy fields, present in high-energy theory, by adding a tower of effective operators $\mathcal{O}^d$ of dimension $d > 4$ to the Lagrangian. These *non-renormalizable* operators are made out of the SM fields, and invariant under the SM gauge group [1, 2, 3]. They parameterize the effects of the high-energy degrees of freedom on the low-energy theory order by order. In principle, the operator coefficients are weighted by inverse powers of the scale of new physics $\Lambda_{\rm NP}$:

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\rm eff}^{d=5} + \mathscr{L}_{\rm eff}^{d=6} + \cdots\,, \quad \text{with} \quad \mathscr{L}_{\rm eff}^{d} \propto \frac{1}{\Lambda_{\rm NP}^{d-4}}\,\mathcal{O}^d\,. \tag{1}$$

The only possible dimension-five operator, namely, $\mathscr{L}_{\rm eff}^{d=5}$, which violates lepton number by two units, is the famous Weinberg operator [1]

$$\mathcal{O}_W^5 = (\overline{L^c}{\rm i}\tau^2\phi)\,(\phi{\rm i}\tau^2 L)\,, \tag{2}$$

which leads, after electroweak symmetry breaking (EWSB), to Majorana masses for the neutrinos. Here L and ϕ stand for the Standard Model lepton doublets and Higgs field, respectively. At tree level, $\mathcal{O}_W^5$ can only be mediated by a singlet fermion, a triplet scalar, or a triplet fermion, leading to the famous type I [4, 5, 6, 7], type II [8, 9, 10, 11, 12, 13], or type III [14] seesaw mechanism, respectively (see also Ref. [15]). Compared to the electroweak scale, the masses of the neutrinos in all three cases appear suppressed by a factor $v/\Lambda_{\rm NP}$, where $v/\sqrt{2}$ is the vacuum expectation value (VEV) of the Higgs field. Substituting typical values, one obtains that the original seesaw mechanisms point towards the GUT scale.

Except for neutrino masses, the dimension-six operators potentially affecting neutrino oscillations are, for non-standard interactions (NSI), operators of the types

$$\mathcal{O}^{\mathcal{S}} = (\bar{E}E)(\bar{L}L)\,, \quad (\bar{L}L)(\bar{L}L)\,, \tag{3}$$

and, for non-unitarity (NU) coming from heavy singlet fermions, of the type

$$\mathcal{O}^{\mathcal{F}} = \left(\overline{L}\phi\right) \mathrm{i}\not{\partial} \left(\phi^\dagger L\right) \ , \tag{4}$$

where we omitted flavor, spin, and gauge indices. Some of these effective operators result in corrections to the low-energy SM parameters and in exotic couplings. For instance, Eq. (4) implies a correction to the neutrino kinetic energy. After re-diagonalizing and re-normalizing the neutrino kinetic terms [16, 17], a non-unitary lepton mixing matrix appears [15, 18]. On the other hand, Eq. (3) typically leads to lepton-flavor-violating processes.

In ordinary seesaw models, the operators generating neutrino masses [such as Eq. (2)] and non-standard effects [*cf.*, Eqs. (3) and (4)] are connected in general (see, *e.g.*, Refs. [15, 19, 20]). Especially in TeV-scale seesaw models, the smallness of neutrino masses is usually protected by other suppression mechanisms rather than the GUT scale, such as radiative generation, small lepton number breaking, or neutrino masses from a higher than dimension-five effective operator (see, *e.g.*, Ref. [21] and references therein). In these cases, singlet mediators may be introduced at the TeV scale, which typically lead to observable NU effects as well. A very attractive example is the inverse seesaw model [22], in which the light neutrino masses are suppressed by a Majorana mass insertion in the full 9×9 mass matrix. In such a framework, a non-trivial connection between the $\mathcal{O}^5_W$ and $\mathcal{O}^{\mathcal{F}}$ operators exists, which could also be well tested in both the near future colliders and neutrino experiments [23, 24]. As another example, in Table 2 of Ref. [21], a number of possibilities to generate small neutrino masses together with NU is listed, where the neutrino mass originates from a dimension-seven operator. Of course, the heavy seesaw particles may also be directly searched for at future colliders, in particular, at the Large Hadron Collider via the lepton-flavor-violating decays [25].

The NSI operators in Eq. (3) are typically connected to the charged lepton flavor violation by SU(2) gauge invariance, and constrained by lepton universality tests. This implies that stringent bounds exist for the NSIs (we list the current bounds in Sec. III D). On the other hand, if one has a theory for which the (gauge invariant) NSIs in Eq. (3) appear without charged lepton flavor violation and the NSIs involve leptons only, the NSIs present in neutrino production at a neutrino factory and the neutrino propagation are correlated in a particular way, and the flavor structure of the NSIs is strongly constrained [26]. In fact, these correlations increase the experimental sensitivity to NSI parameters dramatically [27], similar to the NU case [28]. Furthermore, it is well known that NU can be re-parameterized in terms of NSIs [29]. In fact, we will demonstrate that for a neutrino factory, the mentioned NSIs are phenomenologically very similar to NU, but for completely different fundamental reasons, which makes it hard to distinguish them. On the other hand, at tree level, the NSIs can be mediated by scalar or vector bosons only (see, *e.g.*, Ref. [26]), whereas the NU is mediated by SM singlet fermions. Therefore, distinguishing between the NSI and NU operators is basically equivalent to differentiating between bosons and fermions as mediators, and therefore theoretically very interesting. Note that, besides leptonic NSIs, there may exist non-standard neutrino-quark interactions stemming from some Grand Unified or R-parity violating supersymmetric theories which could also affect neutrino oscillations. In the current work, we will concentrate on leptonic NSIs, because of their phenomenological similarity to NU.

NSIs and NU have been extensively studied in the literature, from both theoretical and phenomenological point of view. In particular, it has been pointed out that the sub-leading effects generated by NSIs [30, 31, 32, 33] add to the standard matter effect [34, 35] and also introduce new sources of CP violation; then a neutrino factory or a superbeam experiments are adequate places to study their effects [36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51]. Since the sub-leading effects presented in the NU framework are quite similar, the same future facilities can be used to constrain (or measure) the additional rotations and phases [18, 23, 24, 28, 29, 44, 52].

In this work, we are mainly interested in studying the experimental signatures from both types of non-standard operators and trying to understand whether it is possible to disentangle them by using a neutrino factory facility. To this end, we will first present, in Sec. II, the general formalism depicting neutrino oscillations in matter with both source and detector effects being included. These formulas are model-independent, and could be used in theories with both a unitary lepton flavor mixing matrix or a non-unitary one. In Sec. III, we will then classify the higher-dimensional operators according to the mediators, and figure out the NSI effects induced by different non-renormalizable operators. We also summarize the current bounds on the non-standard parameters discussed in this work. In Sec. IV, we briefly discuss several possibilities how to determine the origin of the non-standard effects. Section V is devoted to a detailed analytical discussion of the transition probabilities useful for our analysis, as well as to the presentation of our simulation techniques and the numerical results to show the prospects of searching for the origin of NSIs in a future neutrino factory. Finally, a brief summary is given in Sec. VI.

II. NEUTRINO OSCILLATIONS WITH NON-STANDARD EFFECTS

In this section, we describe neutrino oscillations with non-standard effects from heavy mediators. As we will demonstrate in the next section, both NSIs and NU can be regarded as such non-standard effects, and treated within this unified framework. For this part, however, it will be useful to treat both classes within the NSI framework, since the source, propagation, and detection effects are a *priori* treated independently for NSIs. Therefore, we use the NSI notation in this section.

In order to perform more precision measurements on neutrino mixing parameters, an intense high-energy neutrino source together with a long-baseline setup is proved to be the best choice [53]. Similar to the standard matter effects in long-baseline neutrino oscillation experiments, NSIs can affect the neutrino propagation by coherent forward scattering in Earth matter. In the language of effective Hamiltonians, the time evolution of neutrino flavor eigenstates in the presence of NSIs is described by

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_m + \mathcal{H}_{\rm NSI} \,, \tag{5}$$

where

$$\mathcal{H}_0 = \frac{1}{2E} U {\rm diag}(m_1^2, m_2^2, m_3^2) U^\dagger \,, \tag{6}$$

$$\mathcal{H}_m = {\rm diag}(V_{\rm CC}, 0, 0) \,, \tag{7}$$

$$\mathcal{H}_{\rm NSI} = V_{\rm CC} \varepsilon^m \,, \tag{8}$$

with $V_{\rm CC} \simeq \sqrt{2} G_F N_e$ arising from coherent forward scattering and N_e denoting the electron number density along the neutrino trajectory in Earth. The vacuum leptonic mixing matrix U is usually parameterized in the standard form by using three mixing angles and one CP violating phase

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-{\rm i}\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{{\rm i}\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{{\rm i}\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{{\rm i}\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{{\rm i}\delta} & c_{23}c_{13} \end{pmatrix} , \tag{9}$$

where $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$ (for $ij = 12,\ 13,\ 23$), and δ is the Dirac CP-violating phase. In analogy to the vacuum Hamiltonian $\mathcal{H}_0$ in Eq. (6), the effective Hamiltonian $\mathcal{H}$ can also be diagonalized through a unitary transformation

$$\mathcal{H} = \frac{1}{2E}\tilde{U}\mathrm{diag}\left(\tilde{m}_1^2, \tilde{m}_2^2, \tilde{m}_3^2\right)\tilde{U}^\dagger \,, \tag{10}$$

where $\tilde{m}_i^2$ ($i = 1, 2, 3$) denote the effective mass squared eigenvalues of neutrinos and $\tilde{U}$ is the effective leptonic mixing matrix in matter. Note that, in writing down Eq. (10), we have already taken into account the Hermitian property of $\mathcal{H}$. The explicit expressions for $\tilde{U}$ and $\tilde{m}_i^2$ can be found in Ref. [54].

In addition to propagation in matter, production or detection processes can be affected by NSIs. The neutrino states produced in a source and observed at a detector can be treated as superpositions of pure orthonormal flavor states [33, 55, 56]:

$$|\nu_\alpha^s\rangle \ = \ |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon^s_{\alpha\beta}|\nu_\beta\rangle = (1+\varepsilon^s)U|\nu_m\rangle \ , \tag{11}$$

$$\langle\nu_\beta^d| \ = \ \langle\nu_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon^d_{\alpha\beta}\langle\nu_\alpha| = \langle\nu_m|U^\dagger(1+(\varepsilon^d)^\dagger) \ , \tag{12}$$

where the superscripts 's' and 'd' denote the source and the detector, respectively. Note that the two flavor indices follow from the postulate of the coherent contribution to the source or detection effects, and more generally, there could be incoherent contributions, which will not be considered further [55, 57].

For NSIs, the parameters at sources and detectors are not necessarily correlated. Only if the production and the detection are exactly the same process with the same other participating fermions (e.g., beta decay and inverse beta decay), the same quantity enters as $\varepsilon^s_{\alpha\beta} = (\varepsilon^d_{\beta\alpha})^*$ [49]. It is important to keep in mind that these NSI parameters are experiment- and process-dependent quantities. In the following, we will mainly focus on the source and detector NSIs defined for a neutrino factory and specific processes. For NU, however, source, propagation, and detection effects are correlated in a particular way, as we will discuss in the next section.

Including all the NSI effects into the neutrino oscillations, we arrive at the amplitude for the process $\nu_\alpha^s \to \nu_\beta^d$

$$\begin{aligned} \mathcal{A}_{\alpha\beta}(L) \ &= \ \langle\nu_\beta^d|\mathrm{e}^{-\mathrm{i}\mathcal{H}L}|\nu_\alpha^s\rangle = (1+\varepsilon^d)_{\rho\beta}A_{\gamma\rho}\,(1+\varepsilon^s)_{\alpha\gamma} \\ &= \ \left[(1+\varepsilon^d)^T A^T\,(1+\varepsilon^s)^T\right]_{\beta\alpha} = \left[A + \varepsilon^s A + A\varepsilon^d + \varepsilon^s A \varepsilon^d\right]_{\alpha\beta} \ , \end{aligned} \tag{13}$$

where L is the propagation distance and A is a coherent sum over the contributions of all the mass eigenstates ν_i

$$A_{\alpha\beta} = \sum_i \tilde{U}^*_{\alpha i} \tilde{U}_{\beta i} \mathrm{e}^{-\mathrm{i}\frac{\tilde{m}_i^2 L}{2E}} \, . \tag{14}$$

With the above definitions, the oscillation probability is given by [58]

$$\begin{aligned} P(\nu^s_\alpha \to \nu^d_\beta) &= |\mathcal{A}_{\alpha\beta}(L)|^2 \\ &= \sum_{i,j} \mathcal{J}^i_{\alpha\beta} \mathcal{J}^{j*}_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}(\mathcal{J}^i_{\alpha\beta} \mathcal{J}^{j*}_{\alpha\beta}) \sin^2 \frac{\Delta \tilde{m}^2_{ij} L}{4E} \\ &\quad +2 \sum_{i>j} \mathrm{Im}(\mathcal{J}^i_{\alpha\beta} \mathcal{J}^{j*}_{\alpha\beta}) \sin \frac{\Delta \tilde{m}^2_{ij} L}{2E} \, , \end{aligned} \tag{15}$$

where

$$\mathcal{J}^i_{\alpha\beta} = \tilde{U}^*_{\alpha i} \tilde{U}_{\beta i} + \sum_\gamma \varepsilon^s_{\alpha\gamma} \tilde{U}^*_{\gamma i} \tilde{U}_{\beta i} + \sum_\gamma \varepsilon^d_{\gamma\beta} \tilde{U}^*_{\alpha i} \tilde{U}_{\gamma i} + \sum_{\gamma,\rho} \varepsilon^s_{\alpha\gamma} \varepsilon^d_{\rho\beta} \tilde{U}^*_{\gamma i} \tilde{U}_{\rho i} \, . \tag{16}$$

A salient feature of Eq. (15) is that, when $\alpha \neq \beta$, the first term in Eq. (15) is, in general, not vanishing, and therefore, a flavor transition would already happen at the source even before the oscillation process and is known as the zero-distance effect [59]. Although the effective mixing matrix in matter $\tilde{U}$ is still unitary, the presences of NSIs in the source and the detector prevent us from defining a unique CP invariant quantity like the standard Jarlskog invariant [60]. New CP non-conservation terms, which are proportional to the NSI parameters and have different dependences on the quantity L/E, will appear in the oscillation probability. Another peculiar feature in the survival probability is that, in the case of $\alpha = \beta$, CP-violating terms in the last line of Eq. (15) may, in principle, not vanish. Note that Eq. (15) is also valid in the case of a non-unitary lepton flavor mixing matrix. In the minimal unitarity violation scheme, the NU effects are parameterized by using similar ε parameters as in the case of the source and detector NSI effects, but with the relation $\varepsilon^s_{\alpha\beta} = \varepsilon^d_{\alpha\beta} = (\varepsilon^s_{\beta\alpha})^* = (\varepsilon^d_{\beta\alpha})^*$.

In what follows, we will discuss the possible origin of NSIs in Eq. (15) together with the correlations among the NSI parameters.

III. ORIGIN OF NON-STANDARD EFFECTS

As mentioned in the Introduction, non-standard effects naturally emerge from most fundamental theories beyond the SM, and can, in general, be described by a series of higher-dimensional non-renormalizable operators after integrating out the heavy degrees of freedom in the underlying theory. The only dimension-five ($\mathcal{O}^5$) operator is the well-known Weinberg operator in Eq. (2), which gives birth to the masses of light neutrinos. For dimension-six operators ($\mathcal{O}^6$), depending on different mediators, there are, in general, two different kinds of non-renormalizable operators responsible for non-standard effects at tree-level. For scalar or vector boson mediated dimension-six operators $\mathcal{O}^{\mathcal{S}}$, four-fermion interactions are involved, which usually break the lepton flavor (and lepton universality), but conserve the unitarity of the leptonic mixing matrix. On the other hand, fermion mediated dimension-six operators $\mathcal{O}^{\mathcal{F}}$ correct the kinetic energy terms of light neutrinos, which violate the unitarity of the leptonic mixing matrix as a consequence of the mixing between light and heavy neutral fermions. As for dimension-eight or higher operators, both two types of non-standard effects can be induced. In the following, we will discuss the possible non-standard effects stemming from different kinds of higher dimensional operators.

A. Dimension-six operators mediated by scalars or vector bosons

If new scalar or vector bosons are introduced, the (leptonic) dimension-six NSI operators mediated by these at tree level below the EWSB scale are usually given by [3, 61, 62]

$$\mathcal{O}^{\mathcal{S}} = 2\sqrt{2}\, G_F \, (\varepsilon^{L/R})^{\alpha\gamma}_{\beta\delta} \, \left(\bar{\nu}^{\beta}\gamma^{\rho}\mathrm{P}_L\nu_{\alpha}\right) \left(\bar{\ell}^{\delta}\gamma^{\rho}\mathrm{P}_{L/R}\ell_{\gamma}\right) , \tag{17}$$

where ℓ denote the charged leptons. Here G_F is the Fermi coupling constant and P_L and P_R are the left- and right-handed (chiral) projection operators, respectively. Note that, in writing down Eq. (17), we do not require gauge invariance. If SU(2) gauge invariance is imposed at the effective operator level and it is required that all the charged-lepton processes vanish, only the NSI operators of left-handed fields [the second type in Eq. (3)] survive, which are antisymmetric in the flavor indices, i.e., $\alpha \neq \gamma$ and $\beta \neq \delta$. Such operators can be naturally realized in theories with an SM SU(2) singlet singly charged scalar [62, 63, 64, 65, 66]. However, if appropriate cancellation conditions apply, one can also have theories with triplet scalars, and singlet and triplet vectors.[1] Furthermore, if there are no other constraints, the operators may even originate at loop level. However, these are

[1] This can be read off from Table 2 in Ref. [26]: the effective operators generated by the exchange of the different mediators have to be combined such that $\mathcal{C}^{\mathbf{1}}_{LL} = -\mathcal{C}^{\mathbf{3}}_{LL}$.

expected to be smaller than a possible tree-level contribution due to the loop suppression. Therefore, the observation of a dimension-six operator of this type in the neutrino sector may be interpreted in terms of scalar or vector bosons as heavy mediators. Note that, conversely, the consequence of any theory which does not lead to charged-lepton-flavor-violation and produces dimension-six operators is, in general, that the antisymmetric conditions must hold [26].

For a neutrino factory, the (leptonic) NSI effects induced by Eq. (17) are relevant for the source, but not for the detector, since the detection processes involve quarks. Compared with Eqs. (11) and (12), one can easily read off[2]

$$\varepsilon^{\mathrm{NF}}_{e\beta} = (\varepsilon^L)^{\mu e}_{\beta\mu} \,, \tag{18}$$

$$\varepsilon^{\mathrm{NF}}_{\mu\beta} = (\varepsilon^L)^{e\mu}_{\beta e} \,. \tag{19}$$

Here the dominating effect comes from the left-handed component at the production process due to the helicity suppression of the right-handed component. Note that we use the label "NF" to mark that these NSIs are (production) process dependent quantities only relevant for a neutrino factory, whereas potential NSIs at a superbeam are, in general, completely uncorrelated. In addition, note that by giving up two of the four flavor indices, these parameters violate CP and even CPT explicitly. For instance, $\varepsilon^{\mathrm{NF}}_{\mu\tau}$ may have some interesting effects, while $\varepsilon^{\mathrm{NF}}_{\tau\mu}$ is completely irrelevant, since the beam does not contain any ν_τ.

The leptonic NSI effects in matter are only sensitive to the vector component as

$$\varepsilon^m_{\beta\alpha} = (\varepsilon^L)^{\alpha e}_{\beta e} + (\varepsilon^R)^{\alpha e}_{\beta e} \,, \tag{20}$$

where two charged leptons are restricted to electrons. From Eqs. (17) and (20), we can find that $\varepsilon^m_{\alpha\beta} = (\varepsilon^m_{\beta\alpha})^*$. In addition, since the beam typically transverses ordinary matter consisting of electrons, these parameters are (almost) experiment independent.

Now, if we apply the antisymmetric condition (from gauge invariance and no charged-lepton-flavor-violation), the matter NSI parameters $\varepsilon^m_{e\alpha}$ (for $\alpha = e, \mu, \tau$) and the source NSI parameters $\varepsilon^{\mathrm{NF}}_{e\mu}$ and $\varepsilon^{\mathrm{NF}}_{\mu e}$ are forbidden. In addition, we have the following relations [26]

$$\varepsilon^m_{\mu\mu} = -\varepsilon^{\mathrm{NF}}_{ee} = -\varepsilon^{\mathrm{NF}}_{\mu\mu} \,, \tag{21}$$

$$\varepsilon^m_{\mu\tau} = -(\varepsilon^{\mathrm{NF}}_{\mu\tau})^* \,, \tag{22}$$

[2] Note that there is no standard ν_τ production in a neutrino factory, and hence, there is no corresponding NSI parameter like $\varepsilon^s_{\tau\beta}$.

with both $\varepsilon^m_{\tau\tau}$ and $\varepsilon^{\rm NF}_{e\tau}$ being uncorrelated. Of course, if charged lepton flavor violation is only suppressed, the relations in Eq. (22) only hold to some degree. However, we assume that the underlying theory does not produce charged-lepton-flavor-violation, such as the mentioned singly charged scalar.

B. Dimension-six operators mediated by fermions

In general, gauge invariant theories extended the SM with the tree-level exchange of heavy neutral fermions result in a dimension-six operator in the form of Eq. (4) [15, 18]

$$\mathcal{O}^{\mathcal{F}} = c_{\alpha\beta} \left(\overline{L}_\alpha \tilde{\phi}\right) {\rm i}\partial\!\!\!/ \left(\tilde{\phi}^\dagger L_\beta\right) , \tag{23}$$

with $c_{\alpha\beta}$ being the model dependent coefficients and $\tilde{\phi}$ being related to the Higgs doublet by $\tilde{\phi} = {\rm i}\tau_2\phi^*$. After spontaneous breaking of the SM gauge symmetry, the operator defined in Eq. (23) leads to a correction of the neutrino kinetic energy term, and hence, the leptonic flavor mixing matrix deviates from unitarity. Note that the NU effects only make sense by means of effective theories, while unitarity will be restored once the "full" theory is taken into account.

In the case of a non-unitary lepton flavor mixing matrix, the mass eigenstates (the physical states) of neutrinos are linked to their flavor eigenstates by means of a non-unitary transformation [52]

$$|\nu_f\rangle = N|\nu_m\rangle = (1+\eta)U|\nu_m\rangle , \tag{24}$$

where $\eta \simeq -cv^2/2$ is a Hermitian matrix and U is a unitary matrix diagonalizing the neutrino mass matrix. Note the similarity to Eqs. (11) and (12) with respect to the source and detector effects; however, one can also see the difference compared to NSIs: for both NU and NSI the matter effects are given in terms of $|\nu_m\rangle$, which, however, appear on the left-hand-side of Eq. (24) and implicitly in Eq. (11). In the NU case, the flavor basis, through which the NC and CC interactions are defined, is slightly shifted by η. In the NSI case, additional contributions at source and detector may be present, which do not necessarily affect the properties of the weak interactions in matter (which are still defined with respect to the original flavor eigenstates, and the link between mass and flavor eigenstates remains unitary). The time evolution of neutrino flavor eigenstates is given by

$${\rm i}\frac{\rm d}{{\rm d}t}|\nu_f\rangle = (1+\eta)\,\mathcal{H}\,(1+\eta)^{-1}\,|\nu_f\rangle , \tag{25}$$

where

$$\begin{aligned}\mathcal{H} &= \mathcal{H}_0 + (1+\eta)^\dagger \,\mathrm{diag}\left(V_{\mathrm{CC}} - V_{\mathrm{NC}}, -V_{\mathrm{NC}}, -V_{\mathrm{NC}}\right)(1+\eta) \\ &= \mathcal{H}_0 + \mathcal{H}_m + \mathcal{H}_{\mathrm{NC}} + \left\{\left(\mathcal{H}_m + \mathcal{H}_{\mathrm{NC}}\right), \eta\right\} + \eta(\mathcal{H}_m + \mathcal{H}_{\mathrm{NC}})\eta \\ &\simeq \mathcal{H}_0 + \mathcal{H}_m + \left\{\left(\mathcal{H}_m + \mathcal{H}_{\mathrm{NC}}\right), \eta\right\} + \mathcal{O}(\eta^2)\,. \end{aligned} \tag{26}$$

Here $\mathcal{H}_{\mathrm{NC}} = -\mathrm{diag}\left(V_{\mathrm{NC}}, V_{\mathrm{NC}}, V_{\mathrm{NC}}\right)$ and $V_{\mathrm{NC}} \simeq \sqrt{2} G_F N_n$, with N_n being the number density of neutrons in Earth matter. Since NU effects are sub-leading order effects, one can safely neglect the terms proportional to η^2 in Eq. (26). The pure NC contribution [the third term in the second row of Eq. (26)] is flavor blind, and hence can also be dropped. Then, by comparing Eq. (26) with Eq. (5), we obtain the relations [65]

$$\begin{aligned}\mathcal{H}_{\mathrm{NSI}} &= \left\{\left(\mathcal{H}_m + \mathcal{H}_{\mathrm{NC}}\right), \eta\right\}\,, & (27) \\ \varepsilon^m_{\alpha\beta} &= \eta_{\alpha e}\delta_{\beta e} + \eta_{e\beta}\delta_{\alpha e} - \frac{V_{\mathrm{NC}}}{V_{\mathrm{CC}}}\eta_{\alpha\beta}\,, & (28)\end{aligned}$$

for neutrino propagation in matter, and

$$\varepsilon^s_{\alpha\beta} = \varepsilon^d_{\alpha\beta} = \eta_{\alpha\beta}\,, \tag{29}$$

for the source and detector effects. Note that, for neutrino propagation in realistic Earth matter, $N_e \simeq N_n$ holds to a very good precision. Therefore, we have approximately

$$\varepsilon^m_{ee} \simeq 2\eta_{ee}\,, \quad \varepsilon^m_{\mu\mu} \simeq -\eta_{\mu\mu}\,, \quad \varepsilon^m_{\mu\tau} \simeq -\eta_{\mu\tau}\,, \quad \varepsilon^m_{\tau\tau} \simeq -\eta_{\tau\tau}\,, \tag{30}$$

together with $\varepsilon^m_{e\mu} \simeq \varepsilon^m_{e\tau} = 0$. In practice, these cancellations only hold up to the percentage level, depending on the composition of the material [65]. This implies that $\varepsilon^m_{e\mu}$ and $\varepsilon^m_{e\tau}$ are expected to be suppressed by two orders of magnitude compared to the other parameters.

In comparison with the NSI effects in the previous subsection, a salient feature is that, both the source and detector effects exist, and they are process and experiment independent. In the mean while, they always lead to interferences between the non-standard effects and the standard oscillation effects.

C. Other categories of non-standard effects

Apart from purely leptonic NSIs, there could be NSI operators involving quarks, or NSIs from leptonic dimension-six operators, which do lead to charged-lepton-flavor-violation.

Furthermore, NSIs may be induced by dimension-eight or higher operators. For dimension-eight operators at tree level, however, $\mathcal{O}^6$ effects (either NSI or NU or both) are induced as well, or exotic fermions appear, which are strongly constrained by electroweak precision tests [26, 65]. There exists the principle possibility that the dimension-six NSI operators coming from different sources cancel and the leptonic NSI effects originate exclusively from dimension-eight or higher operators [26]. In such a case, the NSI operators might not produce charged lepton flavor violation either. The NSI operators involving four lepton doublets [second category in Eq. (3)] allow then for a connection between source and matter effects, which could be different from the one discussed in Sec. III A. On the other hand, if NSIs come from operators with two lepton doublets and two singlets [first category in Eq. (3)], only matter NSIs will be induced [26].

In summary, there is a third category of non-standard effects, for which the source, detector, and matter interactions may be uncorrelated or correlated in a different way than in the previous subsections. However, these possibilities are either suppressed by higher orders of the new physics scale (dimension-eight operators), or face other constraints. For the sake of simplicity, we do not discuss these categories in detail any further, but we will in some cases point out when observations correspond to this category "Other". One should also keep in mind that data can only be interpreted in certain ways induced by new physics. We mainly discuss the interpretation in terms of dimension-six operators.

D. Bounds on the dimension-six operators

The bounds on the dimension-six operators are, in fact, model dependent. The experimental bounds mainly come from the lepton flavor violating decays $\ell_\alpha \to \ell_\beta \gamma$, the universality test of weak interactions and the invisible decay width of the Z-boson and have been summarized in Ref. [65]. For example, for a scalar mediated $\mathcal{O}^{\mathcal{S}}$ operator, one has

$$|\varepsilon^m_{\mu\mu}| = |\varepsilon^{\rm NF}_{ee}| = |\varepsilon^{\rm NF}_{\mu\mu}| \;<\; 8.2 \times 10^{-4} \,, \tag{31}$$

$$|\varepsilon^m_{\mu\tau}| = |\varepsilon^{\rm NF}_{\mu\tau}| \;<\; 1.9 \times 10^{-3} \,, \tag{32}$$

$$|\varepsilon^m_{\tau\tau}| \;<\; 8.4 \times 10^{-3} \,, \tag{33}$$

$$|\varepsilon^{\rm NF}_{e\tau}| \;<\; 7.5 \times 10^{-2} \,. \tag{34}$$

For the non-unitarity effects induced by the $\mathcal{O}^{\mathcal{F}}$ operator, if the mediators are heavier than the electroweak scale, one has upper bounds on the η parameters[3]

$$|\eta| < \begin{pmatrix} 2.0\times10^{-3} & 6.0\times10^{-5} & 1.6\times10^{-3} \\ \sim & 8.0\times10^{-4} & 1.1\times10^{-3} \\ \sim & \sim & 2.7\times10^{-3} \end{pmatrix} . \tag{35}$$

If the mediators are lighter than the electroweak scale but above a few GeV, the above bounds still apply except $|\eta_{e\mu}| < 9.0\times10^{-4}$ has to be employed because of the restoration of unitarity in the Z-decay. In the case that NSIs come exclusively from $d \geq 8$ NSI operators, the severe constraints from universality test may not apply coherently, and hence, the bounds on NSI parameters are rather loose.

The more general, model independent NSI bounds for a neutrino factory (at 90 % C.L.) are given by [67]

$$|\varepsilon^{\rm NF}_{\alpha\beta}| < \begin{pmatrix} 0.025 & 0.030 & 0.030 \\ 0.025 & 0.030 & 0.030 \\ 0.025 & 0.030 & 0.030 \end{pmatrix} , \tag{36}$$

and

$$|\varepsilon^{mL}_{\alpha\beta}| < \begin{pmatrix} 0.06 & 0.10 & 0.4 \\ \sim & 0.03 & 0.10 \\ \sim & \sim & 0.16 \end{pmatrix} , \qquad |\varepsilon^{mR}_{\alpha\beta}| < \begin{pmatrix} 0.14 & 0.10 & 0.27 \\ \sim & 0.03 & 0.10 \\ \sim & \sim & 0.4 \end{pmatrix} , \tag{37}$$

for left- and right-handed NSIs, respectively.

From this comparison, one can already see one dilemma which could be called the "NSI hierarchy problem". While the model-independent bounds are relatively weak compared to the bounds on the dimension-six operators, the theory leading to such large non-standard effects cannot be that straightforward. For instance, if the NSIs came from dimension-eight operators, they would be naturally expected to be of the order $v^4/\Lambda^4_{\rm NP} \simeq 10^{-4}$ for $\Lambda_{\rm NP} = \mathcal{O}(1)$ TeV (as expected by the hierarchy problem). However, in this case, one cannot use particular correlations between source and matter NSI to enhance the sensitivity. This means that the non-standard effects may in either case be on the edge of the sensitivity of a neutrino factory (see, *e.g.*, Ref. [43] for matter NSIs).

[3] Note that, compared with the bounds on $NN^\dagger$ in Ref. [65], the constraints on η are strengthened by a factor 2, since $NN^\dagger \simeq 1 + 2\eta$ according to Eq. (24).

	ν-factory		SB			ν-factory		SB			ν-factory		SB	
	$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$	$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$		$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$	$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$		$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$	$\mathcal{O}^{\mathcal{S}}$	$\mathcal{O}^{\mathcal{F}}$
ε^m_{ee}		✔		✔	ε^s_{ee}	✔	✔	n/a	n/a					
$\varepsilon^m_{e\mu}$					$\varepsilon^s_{e\mu}$		✔	n/a	n/a					
$\varepsilon^m_{e\tau}$					$\varepsilon^s_{e\tau}$	✔	✔	n/a	n/a	$\varepsilon^d_{\alpha\beta}$		✔		✔
$\varepsilon^m_{\mu\mu}$	✔	✔	✔	✔	$\varepsilon^s_{\mu e}$		✔		✔					
$\varepsilon^m_{\mu\tau}$	✔	✔	✔	✔	$\varepsilon^s_{\mu\mu}$	✔	✔		✔					
$\varepsilon^m_{\tau\tau}$	✔	✔	✔	✔	$\varepsilon^s_{\mu\tau}$	✔	✔		✔					

TABLE I: *Allowed parameters from the discussed dimension-six effective operator classes in a neutrino factory (ν-factory) and a superbeam experiment (SB).*

IV. TESTING THE ORIGIN OF NON-STANDARD EFFECTS

In this section, we qualitatively discuss how the origin of the non-standard effect can be determined. In the rest of this work, we then focus on one particular example – $\varepsilon_{\mu\tau}$ at a neutrino factory.

Obviously, no matter of their possible origin, the non-standard effects can always be re-parameterized in terms of the NSI parameters ε^s, ε^d, and ε^m. Therefore, we have treated them as independent parameters in Sec. II, which can be used for any category. However, for a given experiment (such as a neutrino factory), ε^m will be a particular function of ε^s in different frameworks, and not all the NSI parameters are allowed [*cf.*, discussion around Eqs. (21), (22), and (30)]. We summarize in Tab. I which non-standard effects are allowed for a neutrino factory and a superbeam if the origin are the discussed leptonic dimension-six operators.

At this point, we want to emphasize again that the relationships between source and matter effects in Eqs. (21), (22), and (30) are very similar, especially for the effects easiest to access. Consider, for instance,

$$\varepsilon^m_{\mu\tau} = -(\varepsilon^{\mathrm{NF}}_{\mu\tau})^* \qquad (\mathrm{NSI})\,, \tag{38}$$

$$\varepsilon^m_{\mu\tau} = -\eta_{\mu\tau} = -\varepsilon^s_{\mu\tau} \quad (\mathrm{NU})\,. \tag{39}$$

The origin of these relationships is very different. The NSI relationship relies on the degree that charged lepton flavor violation is suppressed, whereas the NU relationship relies on the equality of the CC and NC potentials in Eq. (28).

If one wants to distinguish the origin of the non-standard effects, it is not sufficient to determine the phase of $\varepsilon^s_{\mu\tau}$, since one can always fit the data with NSI with one phase or NU with minus this phase. In principle, one needs an independent test of ε^s and ε^m (including phases). However, we will demonstrate that the equality between source and detector effects for NU leads to additional differences between the effects.

From the previous discussions, we have qualitatively four possibilities to determine the origin of the non-standard effects (*cf.*, Tab. I):

- Distinguish by appearance of certain parameters. If, for instance, ε^m_{ee} is found, it cannot be interpreted as $\mathcal{O}^{\mathcal{S}}$, but as $\mathcal{O}^{\mathcal{F}}$ (or the category "Other"). If, on the other hand, $\varepsilon^m_{e\tau}$ is found, it has to come from the category "Other", such as a higher-dimensional operator. See, *e.g.*, Ref. [43], for the bounds expected for these parameters at a neutrino factory. While $\varepsilon^m_{e\tau}$ is one of the most discussed NSI parameters in the literature and can be relatively well constrained, ε^m_{ee} adds to the standard matter effect and the bounds are limited by the precision the matter density profile is known [43]. Another such parameter is $\varepsilon^m_{e\mu}$, which can only come from "Other", and is discussed in Ref. [41]. In addition, $\varepsilon^s_{e\mu}$ or $\varepsilon^s_{\mu e}$ could discriminate between $\mathcal{O}^{\mathcal{S}}$ and $\mathcal{O}^{\mathcal{F}}$. At a neutrino factory near detector, this measurement will be limited by charge identification.

- Distinguish by bounds (*cf.*, Sec. III D). If large enough effects beyond the dimension-six operator bounds are found, but below the generic bounds, they have to come from the category "Other". If, for instance, $\varepsilon^{\mathrm{NF}}_{e\tau} \sim 10^{-2}$ is measured, it could come from $\mathcal{O}^{\mathcal{S}}$, but is excluded for $\mathcal{O}^{\mathcal{F}}$.

- Distinguish by experiment class. Since the source NSIs are production process-dependent parameters and the NU parameters are fundamental, using a different experiment class can help to disentangle the effects. For instance, if $\varepsilon^{\mathrm{NF}}_{\mu\tau}$ is found at the near detector of a neutrino factory, it may come from $\mathcal{O}^{\mathcal{S}}$ or $\mathcal{O}^{\mathcal{F}}$. If it is a fundamental parameter from $\mathcal{O}^{\mathcal{F}}$, it has to appear at a corresponding superbeam near detector, such as the anticipated Main Injector Non-Standard Interactions Search (MINSIS) project at Fermilab (USA) [68], as well, *i.e.*, $\mathcal{O}^{\mathcal{F}}$ could be excluded if the superbeam does not observe anything. Therefore, in order to disentangle process-dependent NSI from fundamental NU, neutrino factory and superbeam near detectors are complementary.

- Distinguish by correlations. For example, $\varepsilon^s_{\mu\tau} = \varepsilon^d_{\mu\tau} = -\varepsilon^m_{\mu\tau}$ holds for $\mathcal{O}^{\mathcal{F}}$, while $\varepsilon^{\mathrm{NF}}_{\mu\tau} = -\varepsilon^{m*}_{\mu\tau}$ together with $\varepsilon^d_{\mu\tau} = 0$ holds for $\mathcal{O}^{\mathcal{S}}$. The other correlations in Eqs. (21) and (30) will be less accessible at a neutrino factory, since either there are no ν_τ in the beam or the measurement of ε^s_{ee} and $\varepsilon^s_{\mu\mu}$ will be intimately connected to the knowledge of cross sections and fluxes.

Since especially the last category requires some more detailed understanding, we focus on $\varepsilon_{\mu\tau}$ for the rest of this study. In this case, it has been pointed out in the literature that the $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_\mu$ channels provide us with the best sensitivities (see, *e.g.*, Refs. [29, 50, 52, 69, 70, 71, 72, 73], where the phenomenological importance of the $\mu\mu$ and $\mu\tau$ transitions for searching new physics has been stressed. Therefore, we will mostly concentrate on these two channel in the subsequent analysis.

V. NON-STANDARD EFFECTS IN THE μ-τ-SECTOR AT A NEUTRINO FACTORY

Here we focus on the measurement of $\varepsilon_{\mu\tau}$, the differences between the NSI and NU sensitivities, and the ability to determine the origin of the non-standard effects at a neutrino factory.

A. Analytical considerations

In this section, we discuss some of the relevant analytical properties of the transition probabilities useful to understand the output of our numerical simulations. We will concentrate on the appearance probability $P(\nu^s_\mu \to \nu^d_\tau)$ as well as the survival probability $P(\nu^s_\mu \to \nu^d_\mu)$, keeping all $\varepsilon^{s,m,d}_{\alpha\beta}$ but $\varepsilon^{s,m,d}_{\mu\tau}$ vanishing. Note that, since we are only considering neutrino factory setups, we will drop the upper NF label on the non-standard parameters. The expressions for these probabilities can be obtained by applying the general formula given in Eq. (15); to further simplify the results, we consistently expand up to first order in the small quantities θ_{13}, $\Delta m^2_{21}/\Delta m^2_{31}$, and $\varepsilon_{\alpha\beta}$. Keeping all the source, matter, and detector effects, the survival probability reads

$$
\begin{aligned}
P_{\mu\mu} \;=\; & 1-\sin^2 2\theta_{23}\,\sin^2\left(\frac{\Delta L}{4E}\right) - (\mathrm{Re}\,\varepsilon^d_{\tau\mu} + \mathrm{Re}\,\varepsilon^s_{\mu\tau})\sin 4\theta_{23}\,\sin^2\left(\frac{\Delta L}{4E}\right) \\
& + \left(\mathrm{Im}\,\varepsilon^d_{\tau\mu} + \mathrm{Im}\,\varepsilon^s_{\mu\tau}\right)\,\sin 2\theta_{23}\,\sin\left(\frac{\Delta L}{2E}\right) \\
& -\mathrm{Re}\,\varepsilon^m_{\mu\tau}\sin 2\theta_{23}\left[\frac{aL}{2E}\sin^2 2\theta_{23}\,\sin\left(\frac{\Delta L}{2E}\right) + \frac{4a}{\Delta}\cos^2 2\theta_{23}\sin^2\left(\frac{\Delta L}{4E}\right)\right]\,, \qquad (40)
\end{aligned}
$$

where we defined $a = 2EV_{\mathrm{CC}}$ and $\Delta = \Delta m^2_{31}$. This result agrees with Eq. (35) in Ref. [49]. It is now straightforward to obtain the $\nu_\mu \to \nu_\mu$ transitions in the case of scalar and fermion mediated dimension-six operators. In the first case, we need to drop the dependence on $\varepsilon^d_{\mu\tau}$ in Eq. (40) and use the mapping in Eq. (22); choosing the source parameter $\varepsilon^s_{\mu\tau}$ as the relevant parameter, we obtain

$$
\begin{aligned}
P^{\mathcal{S}}_{\mu\mu} \;=\; & 1-\sin^2 2\theta_{23}\,\sin^2\left(\frac{\Delta L}{4E}\right) \\
& -\mathrm{Re}\,\varepsilon^s_{\mu\tau}\sin 4\theta_{23}\,\sin^2\left(\frac{\Delta L}{4E}\right) + \mathrm{Im}\,\varepsilon^s_{\mu\tau}\,\sin 2\theta_{23}\,\sin\left(\frac{\Delta L}{2E}\right) \\
& +\mathrm{Re}\,\varepsilon^s_{\mu\tau}\sin 2\theta_{23}\left[\frac{aL}{2E}\sin^2 2\theta_{23}\,\sin\left(\frac{\Delta L}{2E}\right) + \frac{4a}{\Delta}\cos^2 2\theta_{23}\sin^2\left(\frac{\Delta L}{4E}\right)\right]\,. \qquad (41)
\end{aligned}
$$

In the case of fermion mediated operators $\mathcal{O}^{\mathcal{F}}$, we can use Eqs. (29) and (30) to obtain

$$
\begin{aligned}
P^{\mathcal{F}}_{\mu\mu} \;=\; & 1-\sin^2 2\theta_{23}\,\sin^2\left(\frac{\Delta L}{4E}\right) \\
& -2\,\mathrm{Re}\,\varepsilon^s_{\mu\tau}\sin 4\theta_{23}\,\sin^2\left(\frac{\Delta L}{4E}\right) \\
& +\mathrm{Re}\,\varepsilon^s_{\mu\tau}\sin 2\theta_{23}\left[\frac{aL}{2E}\sin^2 2\theta_{23}\,\sin\left(\frac{\Delta L}{2E}\right) + \frac{4a}{\Delta}\cos^2 2\theta_{23}\sin^2\left(\frac{\Delta L}{4E}\right)\right]\,. \qquad (42)
\end{aligned}
$$

Eqs. (41) and (42) have exactly the same form, except for the second lines, which are different from each other. In Eq. (42), compared to Eq. (40), it is clear that a cancellation between the imaginary parts of the source and detector parameters as well as a sum of their real parts is at work. This is not an accidental fact, but can be proved to happen for any of disappearance probability; in fact, from the general expression in Eq. (15), the true CP violating terms appearing in the last line of Eq. (15) disappear once we use the definition for $\mathcal{J}^i_{\alpha\beta}$ in Eq. (16) computed for the same flavor $\alpha = \beta$ and apply the mapping relations given in Eqs. (29) and (30).

For the numerical simulations to follow, it is useful to adopt a *short baseline* expansion for the $\nu_\mu \to \nu_\tau$ transition, namely up to second order in small $\varepsilon_{\alpha\beta}$ and first in the quantity

$\Delta L/4E$. For the general NSI effects, the transition probability is given by:

$$P_{\mu\tau} = \sin^2 2\theta_{23} \left(\frac{\Delta L}{4E}\right)^2 + |\varepsilon^d_{\mu\tau}|^2 + |\varepsilon^s_{\mu\tau}|^2 - 2\left(\mathrm{Im}\,\varepsilon^d_{\mu\tau} + \mathrm{Im}\,\varepsilon^s_{\mu\tau}\right)\sin 2\theta_{23}\left(\frac{\Delta L}{2E}\right) + 2\,\mathrm{Re}\,(\varepsilon^d_{\mu\tau}\varepsilon^{s*}_{\mu\tau}) \tag{43}$$

and it reduces to the following expressions for the scalar and fermion mediated operators, respectively:

$$P^{\mathcal{S}}_{\mu\tau} = \sin^2 2\theta_{23}\left(\frac{\Delta L}{4E}\right)^2 + |\varepsilon^s_{\mu\tau}|^2 - 2\,\mathrm{Im}\,\varepsilon^s_{\mu\tau}\,\sin 2\theta_{23}\left(\frac{\Delta L}{2E}\right), \tag{44}$$

$$P^{\mathcal{F}}_{\mu\tau} = \sin^2 2\theta_{23}\left(\frac{\Delta L}{4E}\right)^2 + 4\,|\varepsilon^s_{\mu\tau}|^2 - 4\,\mathrm{Im}\,\varepsilon^s_{\mu\tau}\,\sin 2\theta_{23}\left(\frac{\Delta L}{2E}\right). \tag{45}$$

It is noteworthy that, in these two equations, the third term dominates over the second if $\varepsilon^s_{\mu\tau} \lesssim \Delta L/(2E) \simeq 10^{-3}$ at the energy threshold (about 1 GeV) of a neutrino factory for $L \simeq 1\,\mathrm{km}$, whereas the first term is suppressed by L^2. This means that the non-standard CP violation from $\mathrm{Im}\,\varepsilon^s_{\mu\tau}$ is, in principle, measurable in a near detector for large enough statistics. The typical (relative) statistical error for the near detectors considered is about 10^{-5} to 10^{-6}, which is to be compared with $(\varepsilon^s_{\mu\tau})^2$. In conclusion, the currently considered detectors are on the edge of measuring that effect.

B. Simulation techniques

We continue to the numerical simulations of searching for different NSI effects at a neutrino factory. In our analysis, we mostly follow the International Design Study (IDS-NF) [74] baseline setup, which consists of 2.5×10^{20} useful muon decays per polarity and year with the parent muon energy $E_\mu = 25$ GeV. The total running time is assumed to be 10 years. Two magnetized iron calorimeters are assumed at $L = 4000$ km (fiducial mass 100 kton) and $L = 7500$ km (fiducial mass 50 kton), respectively. The description of the neutrino factory is based on Refs. [74, 75, 76, 77]. In addition, we consider in some cases OPERA-inspired (magnetized) Emulsion Cloud Chamber (ECC) near ν_τ-detectors. The $\nu_e \to \nu_\tau$ channel description is based on Refs. [76, 78]. The $\nu_\mu \to \nu_\tau$ channel is assumed to have the same characteristics as in Ref. [78], governed by Refs. [29, 69]. Since we assume that the hadronic decay channels of the τ can be used as well, we assume a factor of five higher signal and background than in Ref. [78], *i.e.*, 48% detection efficiency. Because we are mostly interested in the $\nu_\mu \to \nu_\tau$ channel (for which the $\nu_e \to \nu_\tau$ channel is only a small perturbation in the presence of $\varepsilon_{\mu\tau}$ only), we add the ν_τ and $\bar{\nu}_\tau$ events as a conservative estimate (however, there is little impact of this assumption for the parameters considered). The near detector treatment is based on Ref. [27] with respect to geometric effects of decay straight and detector geometry. For the high-energy neutrino factory, we consider the following near detectors, based on the simulation described above:

ND-L Large (OPERA-like) size, fiducial mass 2 kt, $d = 1$ km (distance to end of decay straight),

ND-M Medium size (*e.g.*, SciBar-sized), fiducial mass 25 t, $d = 80$ m,

ND-S Small size (*e.g.*, silicon vertex-sized), fiducial mass 100 kg, $d = 80$ m,

OND@130km OPERA-like at intermediate baseline $L = 130$ km, as proposed in Refs. [29, 72], in order to improve the sensitivity to the non-standard effects.

Note that is yet unclear if an ECC can be operated as close as 1 km to a neutrino factory because of the high scanning load. Therefore, alternative technologies may be preferable, such as a silicon vertex detector. In this case, other challenges have to be approached, such as the background from anti-neutrino charm production. These issues are currently under discussion within the IDS-NF.

In addition, to a high-energy neutrino factory, we consider a low-energy version of the neutrino factory based upon Refs. [79, 80]. It has $E_\mu = 4.5\,\mathrm{GeV}$ and a magnetized Totally Active Scintillator Detector (TASD) with 20 kt fiducial mass at $L = 1300\,\mathrm{km}$. The total running time is assumed to be ten years with 7×10^{20} useful muon decays per polarity and year. This luminosity is higher by a factor of 2.8 than the one of the standard neutrino factory, since all muons are put in one storage ring (factor two) and the frontend is optimized in a different way, which leads to another 40 % increase of the luminosity [80]. Note that we include two types of backgrounds for the appearance channels, one which scales with the disappearance rates (such as from charge mis-identification), and one which scales with the un-oscillated spectrum (such as from neutral current events), both at the level of 10^{-3} (which is a factor of two higher than in Ref. [80]). We also include the $\nu_\mu \to \nu_e$ channel, based upon Refs. [76, 81]. As near detectors, we consider the above mentioned OPERA-like detector (ND-L), and the small (ND-S) with the same characteristics at a distance of 20 m from the

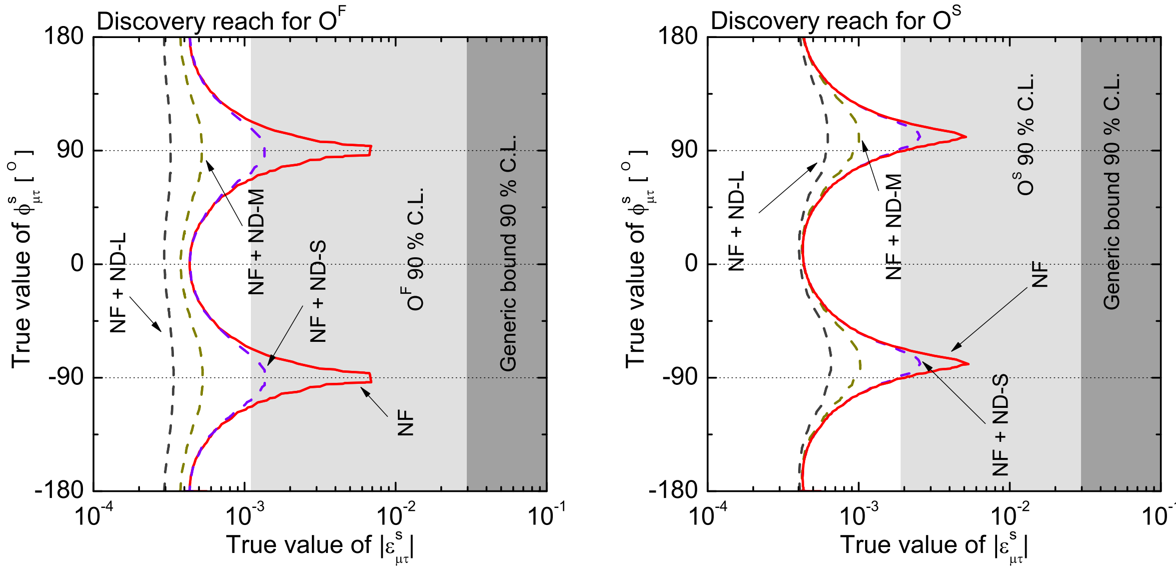

FIG. 1: *The discovery reach of the IDS-NF neutrino factory to $\varepsilon^s_{\mu\tau}$ originating from $\mathcal{O}^{\mathcal{F}}$ (left) or $\mathcal{O}^{\mathcal{S}}$ (right) operators (on right-hand-side of curves, 90 % C.L.). The shadowed areas indicate the current experimental constraints on the corresponding dimension-six operators. In both plot the effects of adding different near detectors are also shown.*

end of the decay straight. For the decay straight, a length of $s = 200$ m is assumed [82] (needed to compute the effective baseline as described in Ref. [27]).

For the experiment simulation, we use the GLoBES software [83, 84] with user-defined systematics. For the oscillation parameters, we use (see, *e.g.*, Refs. [85, 86]) $\sin^2 2\theta_{13} = 0$, $\sin^2\theta_{12} = 0.3$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{21} = 8.0 \times 10^{-5}\,\mathrm{eV}^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3}\,\mathrm{eV}^2$, and a normal mass hierarchy, unless specified otherwise. We impose external errors on Δm^2_{21} and θ_{12} of 3 % each, and we do not include the matter density uncertainty for simplicity.

C. Numerical results

In Fig. 1, we illustrate the *discovery reach* of the IDS-NF neutrino factory to the parameter $\varepsilon^s_{\mu\tau}$ in the two scenarios of fermion (left panel) and scalar mediated (right panel) operators. We define the discovery reach as the values of (true) parameters $|\varepsilon^s_{\mu\tau}|$ and $\phi^s_{\mu\tau}$ [where $\varepsilon^s_{\mu\tau} = |\varepsilon^s_{\mu\tau}|\exp(\mathrm{i}\phi^s_{\mu\tau})$], for which $|\varepsilon^s_{\mu\tau}| = 0$ can be excluded at 90 % C.L. The standard oscillation parameters are thereby marginalized over. As we discussed above, in the case of fermionic operators $\mathcal{O}^{\mathcal{F}}$, the cancellation between the imaginary parts in the survival probability leads to the far detectors being sensitive to the real part of $\varepsilon^s_{\mu\tau}$ only, as it can be clearly seen from Eq. (41). Therefore, there is hardly sensitivity to the corresponding ε parameters in the case of the CP-violating phase $\phi^s_{\mu\tau} = \pm\pi/2$, as shown by the solid (red) curve in the left plot of Fig. 1. In order to increase the sensitivity to the CP-violating phase $\phi^s_{\mu\tau}$, it is useful to include the effects of near detectors capable for τ identification. In fact, as we can see from Eq. (45), an explicit dependence on the imaginary part of $\varepsilon^s_{\mu\tau}$ appears in $P^{\mathcal{F}}_{\mu\tau}$ and, depending on the type of the near detector, this term could be relevant. Note also that the $|\varepsilon^s_{\mu\tau}|^2$ term helps in increasing the sensitivity to the absolute value of $\varepsilon^s_{\mu\tau}$. In this plot, we also compare three different scenarios, in which we combine the IDS-NF neutrino factory setup with the near detectors ND-S, ND-M, and ND-L. The best combination is using the ND-L detector, mainly due to the larger mass. As a rough estimate, a sensitivity 3×10^{-4} to $|\varepsilon^s_{\mu\tau}|$ can be expected in the presence of a near ν_τ-detector. Note also that a short distance ν_τ-detector ($L \simeq 100$ km) does not help much in improving the sensitivity, and hence, we did not include the relative curve in the plot. For a scalar mediated NSI operator, the situation is a bit different, due to the non-vanishing contribution from the imaginary part of $\varepsilon^s_{\mu\tau}$, see Eq. (44). Although this term is dominated by the matter-induced one, its effect is already visible in the right plot of Fig. 1, where the CP violating term is responsible for the asymmetric behavior of the sensitivity curves with respect to $\phi^s_{\mu\tau} = 0$, and better sensitivity for $\phi^s_{\mu\tau} \simeq \pm 90^\circ$. Similar to the $\mathcal{O}^{\mathcal{F}}$ case, a better sensitivity could be expected once the larger near detector is taken into account (the scenario label NF + ND-L in the plot).

Compared to standard oscillation physics, where the statistics in the far detectors limit the performance, the size of the near detector is very important for non-standard effects.

A meaningful question could be how well the non-standard effects can be measured if they are not vanishing. An example is given in Fig. 2, in which the best-fit contours for the chosen NSI parameter $\varepsilon^s_{\mu\tau} = 0.001 \exp(\mathrm{i}\pi/4)$ are plotted for both type of operators in three different situations, where the IDS-NF neutrino factory setup is alone or accompanied by one or two OPERA-like detectors at different baselines, namely at $L = 1$ km and $L = 130$ km. Using the other two options ND-S and ND-M do not improve the performance. Due to the fact that the far muon-detector is not sensitive to the imaginary part of $\varepsilon^s_{\mu\tau}$ (expect from a small effect for $\mathcal{O}^{\mathcal{S}}$), we observe in both panels that a standard neutrino factory without near detectors has almost no sensitivity to the CP-violating part $\sin\phi^s_{\mu\tau}$. The situation improves a lot in the presence of near detectors, especially when a short-distance detector

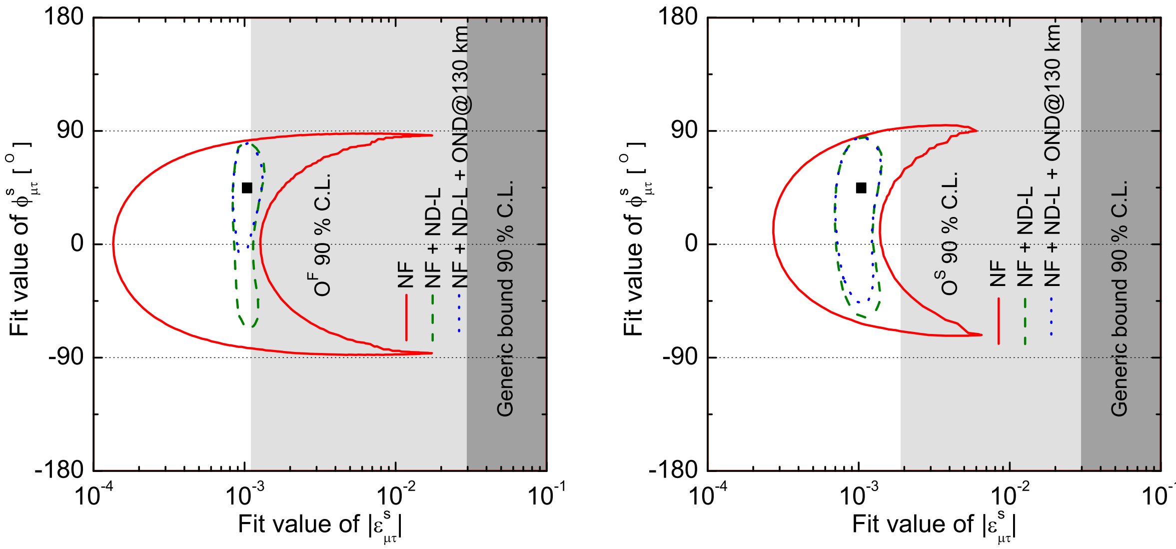

FIG. 2: *The 90 % C.L. contour plot of the NSI parameter $\varepsilon^s_{\mu\tau}$ originating from $\mathcal{O}^\mathcal{F}$ (left plot) or $\mathcal{O}^\mathcal{S}$ (right plot), assuming the true parameter $\varepsilon^s_{\mu\tau} = 0.001\exp(\mathrm{i}\pi/4)$. The analyzed experimental setups consider the IDS-NF neutrino factory alone and in combination with an OPERA-like near detector at a baseline of 1 km and/or 130 km.*

located at $L \simeq 100$ km is taken into account, in which the $\sin\Delta$ terms in Eqs. (44) and (45) contribute to the appearance probability. In particular, the CP-violating phase of $\varepsilon^s_{\mu\tau}$ can be better reconstructed for the $\mathcal{O}^\mathcal{F}$ operator (left panel) because of the additional improving factor of two in the imaginary part term.

Since the phenomenological signatures of $\mathcal{O}^\mathcal{F}$ and $\mathcal{O}^\mathcal{S}$ in terms of discovery potential and parameter measurements are quite similar, it is an important question to see whether a neutrino factory-based setup is able to discriminate $\mathcal{O}^\mathcal{F}$ from $\mathcal{O}^\mathcal{S}$ so as to find hints on the origin of non-standard effects. We answer this question generating events by using the "true" parameters in the case of $\mathcal{O}^\mathcal{F}$ ($\mathcal{O}^\mathcal{S}$), and then fit the data with only $\mathcal{O}^\mathcal{S}$ ($\mathcal{O}^\mathcal{F}$). The results of such an analysis are the exclusion regions (right-hand side of the curves) shown in Fig. 3, where the dimension-six operators can be disentangled. For the IDS-NF neutrino factory combined with several different near detectors, the curves in the left panel show that there is just a very small region beyond the bound at the 90 % C.L. on the $\mathcal{O}^\mathcal{F}$ operators, where the data generated with $\mathcal{O}^\mathcal{F}$ can be distinguished from the $\mathcal{O}^\mathcal{S}$ even if the OPERA-like near detector at the longer baseline is used. If $\mathcal{O}^\mathcal{S}$ is simulated, however, it can be distinguished from $\mathcal{O}^\mathcal{F}$ for a part of the parameter space beyond the current bound with ND-L, as shown in

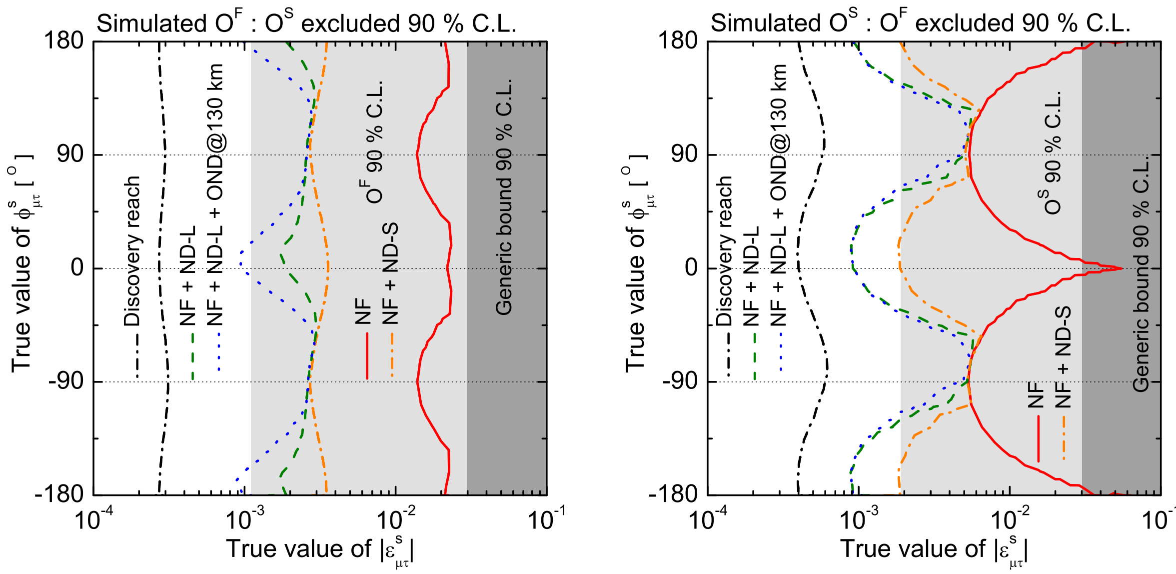

FIG. 3: *Regions in the ($|\varepsilon^s_{\mu\tau}|$-$\phi^s_{\mu\tau}$)-plane where the simulated $\epsilon^s_{\mu\tau}$ induced by one type of operator can be uniquely established, i.e., the other type of operator is excluded at the 90 % C.L. (regions on the right-hand side of the curves). Left panel: the simulated $\varepsilon^s_{\mu\tau}$ is induced by $\mathcal{O}^{\mathcal{F}}$ and fitted with $\mathcal{O}^{\mathcal{S}}$. Right panel: the simulated $\varepsilon^s_{\mu\tau}$ is induced by $\mathcal{O}^{\mathcal{S}}$ and fitted with $\mathcal{O}^{\mathcal{F}}$. In both panels, the discovery reach is also displayed. The experimental setup is the same as Fig. 2.*

the right panel of Fig. 3, especially around the CP-conserving value $\phi^s_{\mu\tau} = 0, \pm\pi$, where the current experimental constraints on $\mathcal{O}^{\mathcal{S}}$ are not as stringent as for $\mathcal{O}^{\mathcal{F}}$. The combinations with other near detectors are illustrated by the ND-S curves, where the sensitivity does not go beyond the current bounds.

From Fig. 3, we can read off that there are substantial regions of the parameter space between the curves, where $\mathcal{O}^{\mathcal{S}}$ and $\mathcal{O}^{\mathcal{F}}$ can be distinguished at the neutrino factory itself, and the discovery reach of the neutrino factory, for which the neutrino factory will find a non-standard effect, but cannot classify it. These regions go beyond the current bounds. As mentioned before, an interesting discriminator might in this case be a superbeam ν_τ-detector, such as the MINSIS project. Such a detector could tell the fundamental effect $\mathcal{O}^{\mathcal{F}}$ from the process-dependent effect $\mathcal{O}^{\mathcal{S}}$ if the sensitivity is comparable to that of the neutrino factory, *i.e.*, $|\epsilon^s_{\mu\tau}| \ll 10^{-3}$. For instance, if no effect is seen at MINSIS, but some effect is detected at the neutrino factory, it could come from $\mathcal{O}^{\mathcal{S}}$, but not from $\mathcal{O}^{\mathcal{F}}$.

Recently, a low-energy neutrino factory ($E_\mu = 4.5$ GeV) has been attracting some atten-

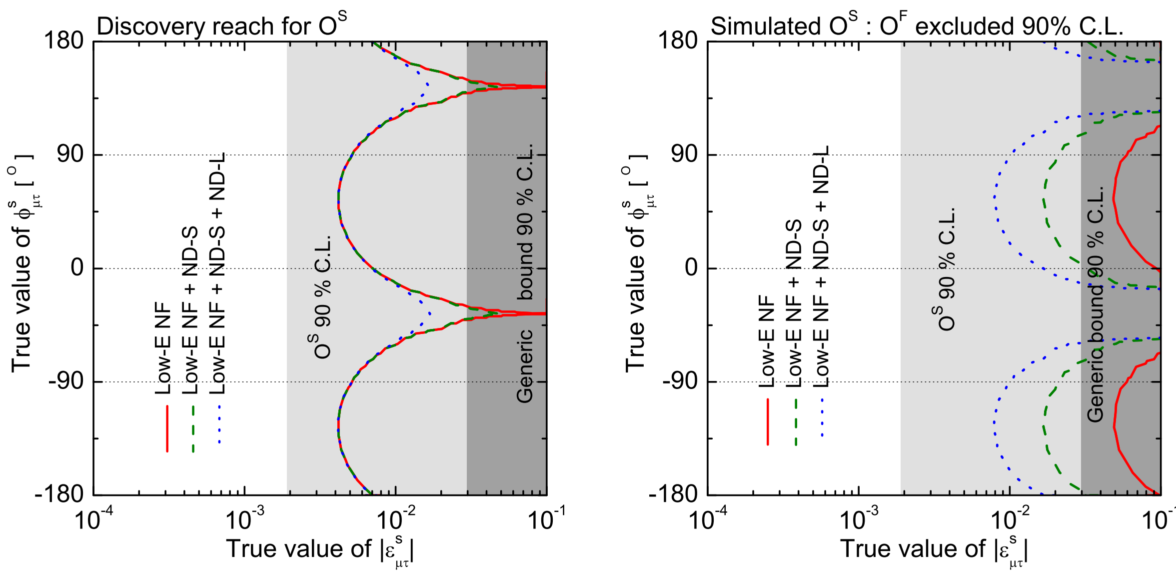

FIG. 4: *Same plots as Fig. 1 (left) and 3 (right), but for a low-energy neutrino factory alone and in combination with the ND-S and ND-S+ND-L.*

tion, for which the same kind of analysis in Figs. 1 and 3 can be repeated. In the left panel of Fig. 4, we show the discovery reach for the $\mathcal{O}^{\mathcal{S}}$ induced NSIs using the low-energy neutrino factory alone and in combination with different combinations of near detectors. We observe that, because of the τ production threshold, there is no hope to search for NSIs originated from $\mathcal{O}^{\mathcal{S}}$ operators below the current experimental limits. Also, in the right plot of Fig. 4 the same combination of experimental facilities is not able to exclude the $\mathcal{O}^{\mathcal{F}}$ operators at 90 % C.L., since the exclusion regions are excluded by current limits already. Finally, in Fig. 5, we plot the CP discovery potential for both $\mathcal{O}^{\mathcal{F}}$ (left panel) and $\mathcal{O}^{\mathcal{S}}$ (right panel) induced CP violations. This is defined as the ensemble of true values of $\phi^s_{\mu\tau}$, which cannot be fitted with the CP-conserving values $\phi^s_{\mu\tau} = 0, \pm\pi$ at 90 % C.L. The combination of the standard IDS-NF neutrino factory with different large enough near detectors may discover CP violation, somewhat beyond the current bounds, especially for $\phi^s_{\mu\tau} \sim \pm\pi/2$. There are no qualitative differences between $\mathcal{O}^{\mathcal{F}}$ and $\mathcal{O}^{\mathcal{S}}$.

VI. SUMMARY

In this work, we have clarified the relationship between NSI and NU effects, where we have focused on non-standard effects coming from dimension-six effective operators when the

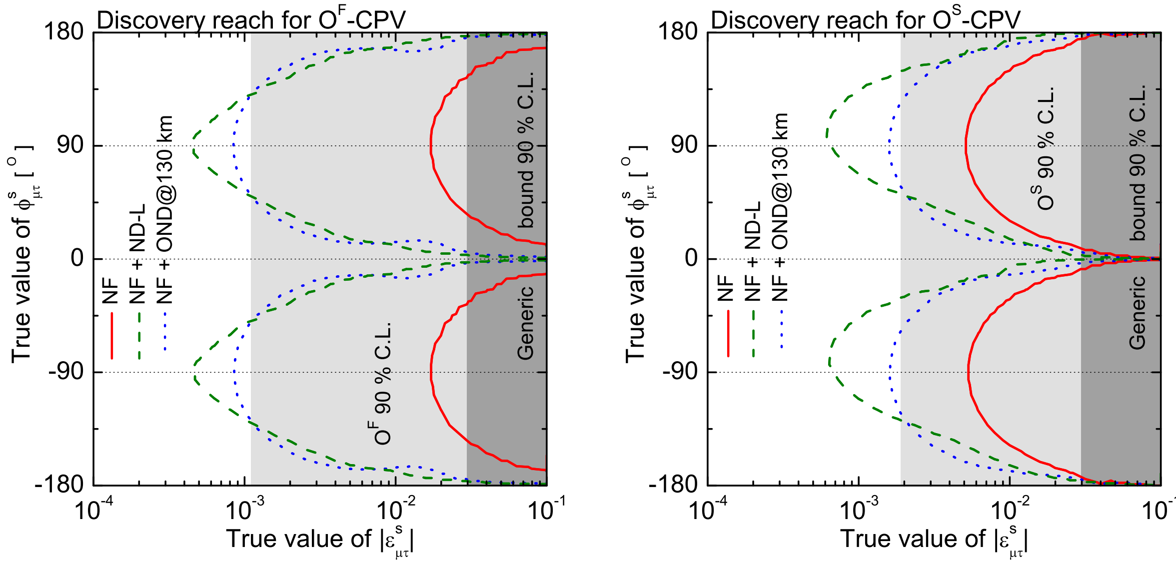

FIG. 5: *The 90 % C.L. of CP discovery potentials in the NU framework (left) and NSI framework (right). The facility combination is the same as Fig. 3.*

heavy fields are integrated out. At tree level, these operators are mediated by bosons (NSIs) or fermions (NU), which means that the discrimination between NSIs and NU is interesting from a theoretical point of view, since it may reveal the nature of the heavy mediator.

From the phenomenological point of view, the assumption of NSIs or NU, together with the assumptions of gauge invariance and vanishing charged lepton flavor violation, has lead to particular correlations between source, propagation, and detector non-standard effects. These correlations can, in some cases, be used to disentangle NSIs from NU, relying on the measurement of individual parameters (such as for ε^m_{ee}). However, for a neutrino factory, NSIs and NU look very similar for some parameters – for entirely different fundamental reasons.

The most interesting case may be $\varepsilon_{\mu\tau}$, which is, in principle, easy to find at the near detector of a neutrino factory (there are no ν_τ in the beam). However, the correlation between source and matter NSIs is basically the same for NSIs and NU. There is some discrimination potential coming from the fact that NU have modified source and detector effects, which, however, hardly exceeds the current bounds. Thus, the easiest way to discriminate NSIs from NU is the comparison with an experiment using a different neutrino production mechanism, such as a superbeam. A possible project in that direction is the MINSIS project. In order to provide complementary information, a similar sensitivity is required, which should be significantly below 10^{-3} for $|\varepsilon^s_{\mu\tau}|$.

We conclude that differentiating between NSIs and NU should be one of the key priorities of searches for new physics effects, since the nature of the non-standard effect points towards the nature of the heavy mediator. The components necessary for this search are ν_τ detection at least in near detectors, both at high-intensity superbeams and a neutrino factory. For the neutrino factory, a high enough muon energy is mandatory for the discussed non-standard effects searches, which means that the high-energy neutrino factory should at least be an upgrade option even for large θ_{13}. In addition, for non-standard effect searches, the size of the near detector is very important, which means that for all applications, large enough detectors are needed.

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