Non-Standard ν-Interactions at a Neutrino Factory: Correlation & CP violation effects

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Abstract. The so-called Non-Standard ν-Interactions in propagation is a widely studied topic in the Neutrino Factory literature. However, special attention has not been paid to the possible correlation effects among the whole set of parameters arising in this context (standard and non-standard ones). Here we will focus on these correlation effects analysing the performance of three different Neutrino Factory setups. In addition, we explore the new avenues of CP violation coming from this sort of Non-Standard ν-Interactions with the same perspective, in other words, studying the relation among the several CP-phases involved.

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The so called "Non-Standard neutrino Interactions (NSI)" approach consists in the phenomenological parametrisation of all possible effects of "high energy" new physics (NP)[1], which may affect neutrino oscillation experiments. The idea is to take into account all the four fermion effective operators which can lead to any effect in neutrino oscillations. It consists thus in a completely model independent analysis. Depending on the structure of the operators considered, they can affect neutrino production or detection processes, or modify matter effects in propagation. In this work we will focus on the latter effects[2], which are translated into the following modification of the oscillation Hamiltonian (in the flavour basis):

$$H = H_{free} + A \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix} \qquad (1)$$

where H_{free} is the free Hamiltonian, $A \equiv 2\sqrt{2}G_F n_e$ and $\varepsilon_{\alpha\beta}$ are, basically, the coefficients of the new four fermion effective operators added.

As a result of this model independent approach, the constraints on the NSI parameters are very mild (generically of the order of 10^{-1} or even order one [1]). However it is important to keep in mind that these sort of effects are of the order of $10^{-2} - 10^{-3}$ at most in any realistic neutrino model.

To study the impact of these NSI in propagation we will take advantage of the high energy and strong matter effects which can be achieved in a Neutrino Factory (NF). Three different setups have been considered: (a) IDS25 [2], which consists of two 50 Kton MIND detectors located at $L = 4000$ Km and $L = 7500$ Km exposed to a neutrino flux of 5×10^{20} useful muon decays per year, baseline and polarity and with $E_\mu = 25$ GeV; (b) IDS50, a 50 GeV upgraded version of IDS25; (c) 1B50, a hybrid-MIND detector (50 Kton MIND plus a 4 Kton MECC section) located at $L = 4000$ Km has been considered, exposed to a neutrino flux of 10^{21} useful muon decays per year and polarity (a doubled flux with respect to the previous options is considered since in this setup there is only one baseline), with $E_\mu = 50$ GeV. Five running years per polarity have been considered for the three setups under study.

The fundamental difference between this work [3] and the previous ones in the literature (see for instance Refs. [4, 5, 6]) is that we perform a complete phenomenological analysis considering at once, for the first time, all the NSI parameters which can contribute to propagation in matter. This should be done in order to be consistent with the model independent approach considered here. With that pourpose we have taken advantage of the MonteCUBES software package [7, 8].

We have marginalised over all the parameters which are not shown in the plots. A 10% Gaussian error around the input values for the atmospheric parameters, 4% over the solar ones, and 5% over the PREM density profile have been considered. Gaussian priors have also been considered for the moduli of the NSI parameters around

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[1] In fact, here high energy means $E > M_Z$.
[2] In order to include NSI effects in production/detection we would have to introduce a huge amount of new parameters, so that it becomes hopeless to extract useful physics information from the analysis. We live the issue of NSI effects in production/detection for future analyses using near detectors for which the effects due to propagation are not present.

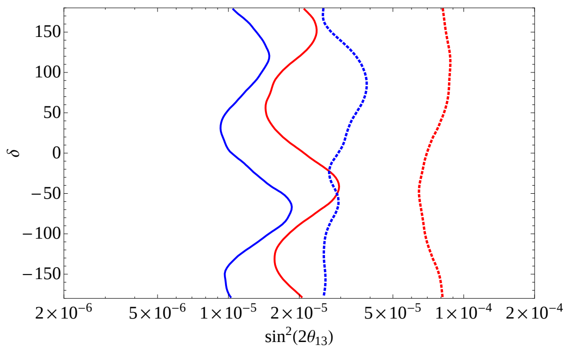

FIGURE 1. Sensitivity to θ_{13} for the IDS50 (blue) and the IDS25 (red) setups as a function of δ, when no NSI are taken into account (solid lines) and after marginalisation over $\varepsilon_{\alpha\alpha}$, $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ (dashed lines). In the regions to the right of the lines, θ_{13} can be distinguished from zero at the 95% CL.

zero, in agreement with their upper bounds [1]. θ_{13}, the standard "Dirac" CP-phase, δ, and the NSI phases have been left completely free during marginalisation.

IMPACT OF NSI ON THE $\theta_{13}-\delta$ MEASUREMENT

The first question we would like to address is if the measurement of the standard CP-violating phase δ can be affected by the presence of NSI. The answer depends on the set of parameters considered in the analysis. We have found that θ_{13}, the key parameter which drives the sensitivity to δ, is not correlated at all with $\varepsilon_{\mu\tau}$ and only shows a very mild correlation with $\varepsilon_{\alpha\alpha}$. However, once $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ are included in the analysis the sensitivity to θ_{13} is worsened as it is shown in Fig. 1. For instance, for the IDS25 setup, the θ_{13}-sensitivity can be one order of magnitude worse due to the correlation with $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ (see red lines in Fig. 1).

SENSITIVITIES TO NSI PARAMETERS

On the other hand, we have studied the sensitivity of the three NF setups mentioned to the whole set of NSI parameters. We can distinguish two different groups of NSI parameters: (i) $\varepsilon_{\alpha\alpha}$ and $\varepsilon_{\mu\tau}$; (ii) $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$. Basically, the sensitivity to (i) comes from the $P_{\mu\mu}$ and $P_{\mu\tau}$ oscillation channels, while the $P_{e\mu}$ and $P_{e\tau}$ channels are mainly sensitive to (ii). This is consistent with the result obtained in the previous section: θ_{13} is correlated only with $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$, and not with the other NSI parameters, because we are sensitive to θ_{13} mainly through $P_{e\mu}$.

Let us first address the sensitivity to (i). First of all, only two combinations of the three diagonal NSI parameters are physical[3]. We choose: $\varepsilon_{ee}-\varepsilon_{\tau\tau}$ and $\varepsilon_{\mu\mu}-\varepsilon_{\tau\tau}$. We found a sensitivity to $\varepsilon_{ee}-\varepsilon_{\tau\tau}$ of the order of 10^{-1}, limited by the matter uncertainty (remember that ε_{ee} appears in Eq. (1) as a perturbation of the standard matter potential). The sensitivity to $\varepsilon_{\mu\mu}-\varepsilon_{\tau\tau}$ turns out to be one order of magnitude stronger, 10^{-2}, since this parameter appears at quadratic order in the oscillation probabilities instead of third order, as it was the case for $\varepsilon_{ee}-\varepsilon_{\tau\tau}$ [9]. We have observed a sizable effect due to a $\theta_{13}\neq 0$ on the sensitivity to $\varepsilon_{ee}-\varepsilon_{\tau\tau}$, while for $\varepsilon_{\mu\mu}-\varepsilon_{\tau\tau}$ the deviation from maximal mixing (of the atmospheric mixing angle) has an important impact on the sensitivity. We have also obtained a sensitivity to the imaginary part of $\varepsilon_{\mu\tau}$ of the same order as for $\varepsilon_{\mu\mu}-\varepsilon_{\tau\tau}$ since it is driven by a similar quadratic dependence in $P_{\mu\mu}$. However, we have found that the sensitivity to the real part of this parameter is roughly one order of magnitude stronger, 10^{-3}, driven by a linear dependence on $Re(\varepsilon_{\mu\tau})$ in $P_{\mu\mu}$. We have checked that there is no correlation among these parameters and the ones given in (ii). Finally, it is remarkable that the same results for (i) are obtained for the three setups under study.

Regarding the sensitivity to the parameters given in (ii), we have found that correlations between $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ can be very important. However, as we have mentioned above, we do not see any significant correlation between (ii) and (i). We found that for $\varepsilon_{e\mu}$ the best sensitivities are achieved for the higher energy setups, IDS50 and 1B50, independently of the number of baselines. On the other hand, in the sensitivity to $\varepsilon_{e\tau}$ the synergy between the two detectors placed at different baselines plays a more important role. This time we obtained that the two baseline setups, IDS50 and IDS25, have the strongest sensitivity to $\varepsilon_{e\tau}$. For both, $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$, the sensitivities are around 10^{-3}.

CP VIOLATION

Finally, in this section we are going to explore the possibility of observing CP violation in the presence of NSI. Since NSI in propagation only introduce new CP-violating terms mainly through the $P_{e\mu}$ and $P_{e\tau}$ channels [9], we have studied the region of the 3-dimensional parameter space, $\{\phi\}=\{\phi_{e\mu},\phi_{e\tau},\delta\}$[4], for which a CP-violating signal can be distinguished from a CP-conserving one. If θ_{13} is measured by the time the NF

[3] We can substract from the Hamiltonian in Eq. (1) the term $\varepsilon_{\tau\tau}\mathbf{1}$, which contributes only to a global phase of the oscillation amplitude, obtaining as a result only two physical parameters.

[4] $\varepsilon_{\alpha\beta}=|\varepsilon_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$.

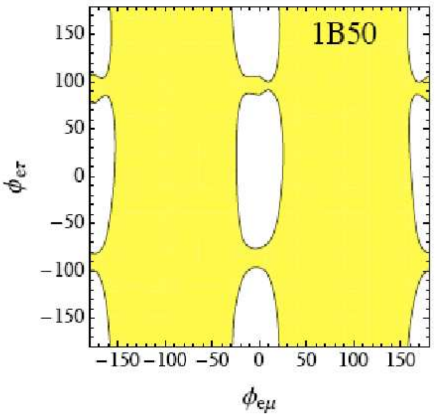

FIGURE 2. CP discovery potential for the 1B50 setup in the $\phi_{e\mu} - \phi_{e\tau}$ plane. The yellow regions show the area of parameter space where CP-violation can be distinguished from CP-conservation at 99% CL, in the $\phi_{e\mu} - \phi_{e\tau}$ plane, for $\theta_{13} = 3^o$, $|\varepsilon_{e\mu}| = |\varepsilon_{e\tau}| = 10^2$ and $\delta = 0$

is built, we can fix θ_{13} in our analysis. On the other hand, if θ_{13} is not known by that time, it is necessary to marginalise over θ_{13} since possible CP-conserving solutions can be found for a given CP-violating input $(\bar{\theta}_{13};\{\bar{\phi}\})$ at a different θ_{13} (what in the standard three-family oscillation scenario is called an "intrinsic degeneracy"). We will analyse only the first possibility[5], fixing thus $\theta_{13} = 3^o$ (the expected sensitivity limit of forthcoming experiments as Double Chooz [10]). In this section, the analysis is not done with MonteCUBES, but following the standard frequentist approach instead.

In Fig. 2 we show the region (yellow) of the parameter space, in the $\phi_{e\mu} - \phi_{e\tau}$ plane, where a CP-violating signal can be distinguished from a CP-conserving one at the 99% C.L for the 1B50 setup. In this figure the parameters not shown in the plot have been fixed during the computations. The regions have been computed for $|\varepsilon_{e\mu}| = |\varepsilon_{e\tau}| = 10^{-2}$ and $\delta = 0$. This figure shows that, for reasonable input values of the NSI parameters, a CP-violating signal could be found in a huge area of the parameter space. Moreover, since in this plot δ is fixed to zero, this CP-violating effect come strictly from New Physics. In fact, the three setups show a similar pattern with two thick vertical lines around $\phi_{e\mu} = \pm 90^o$. In other words, for the input values considered, $\varepsilon_{e\mu}$ dominates over $\varepsilon_{e\tau}$. However, this behaviour becomes more complex when $|\varepsilon_{e\mu}| \ll |\varepsilon_{e\tau}|$, in particular, we have studied the case with $|\varepsilon_{e\mu}| = 10^{-3}$ and $|\varepsilon_{e\tau}| = 10^{-2}$. In such a case both parameters are competitive, showing different patterns in the three setups: the IDS25 setup is not able to see any CP-violating signal; the IDS50 still has a chance in a non-negligible region around $\phi_{e\mu}, \phi_{e\tau} = \pm 90^o$; in the 1B50 setup we found a larger CP-violating region, with two horizontal bands around $\phi_{e\tau} = \pm 90^o$ due to the effect of the $P_{e\tau}$ channel ($\varepsilon_{e\tau}$ dominates [3]). Finally, considering a value of δ different from zero, roughly speaking, leads to an increment of the CP-violating area due to the standard 3 flavour contribution. Notice that, we have found higher energies to be really important in order to observe CP violation coming from NSI in propagation. For a more detailed and complete analysis see Ref. [3].

[5] A more complete analysis including the second possibility can be found in Ref. [3]

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