Impact of non-standard neutrino interactions on future oscillation experiments

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Abstract We study the performance of reactor and superbeam neutrino experiments in the presence of non-standard interactions (NSI). We find that for some non-standard terms, reactor and superbeam experiments would yield conflicting result in the θ_{13} determination, while in other cases, they may agree well with each other, but the resulting value for θ_{13} could be far from the true value. Throughout our discussion, we pay special attention to the impact of the complex phases of the NSI parameters and to the observations at the near detector.

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1 Introduction

In lepton flavour physics, one of the most anticipated upcoming results is the measurement or constraint of the mixing angle θ_{13} by reactor and accelerator neutrino experiments. Within the context of standard oscillations, the physics goals of these types of experiments overlap partly, but if physics beyond the standard model should affect neutrino oscillations, we may obtain independent information from them because they observe the different oscillation channels, and new physics can therefore affect them in differing ways. In this talk, we will study the question of how non-standard effects could modify the results of reactor and superbeam experiments, and will specifically address the following questions:

– What will it mean if reactor and accelerator experiments yield conflicting results?
– If they give consistent results, how rigid is the standard oscillation interpretation?

In order to approach this subject in a model independent way, we will introduce effective four Fermi interactions (usually called non-standard interactions or NSI [1,2]), which are assumed to be induced by physics beyond the standard model at some high energy scale.

For NSI mediated by charged currents, the neutrino states involved in the production and detection processes will not be pure flavour states, but can be described as mixed-flavour states, which we call $|\nu^s\rangle$ for the *source state* and $\langle\nu^d|$ for the *detection state*.

They are defined as [1]

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon_{\alpha\gamma}^s |\nu_\gamma\rangle, \qquad (1)$$

$$\langle\nu_\alpha^d| = \langle\nu_\alpha| + \sum_{\gamma=e,\mu,\tau} \epsilon_{\gamma\alpha}^d \langle\nu_\gamma|. \qquad (2)$$

Here, the index α stands for the flavour of the accompanying charged lepton in the respective process.

We can also introduce NSI mediated by neutral currents, which would create an additional, possibly flavour-violating matter potential of the form [2]

$$(V_{\text{NSI}})_{\beta\alpha} = \sqrt{2} G_F N_e \epsilon_{\beta\alpha}^m. \qquad (3)$$

The ϵ parameters represent the ratio between the NSI amplitude and the standard amplitude. For example, $\epsilon_{\alpha\beta}^s$ and $\epsilon_{\beta\alpha}^d$ are the degrees of "contamination" of the source and detection states with "wrong" flavours, and $\epsilon_{\beta\alpha}^m$ denotes the ratio between the non-standard and standard matter effects in the propagation Hamiltonian. Taking into account the NSI shown in Eqs. (1) – (3), we can calculate the oscillation probability for $\nu_\alpha^s \to \nu_\beta^d$ as

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle\nu_\beta^d| e^{-i(H_{\text{SO}}+V_{\text{NSI}})L} |\nu_\alpha^s\rangle \right|^2. \qquad (4)$$

Here, H_{SO} is the standard neutrino propagation Hamiltonian, which is parameterized by the standard oscillation parameters. Although the Lorentz structure of the effective NSI operators is not fixed by experimental constraints, we will only consider $(V-A)(V-A)$ type interactions in this talk.[1] Under this assumption,

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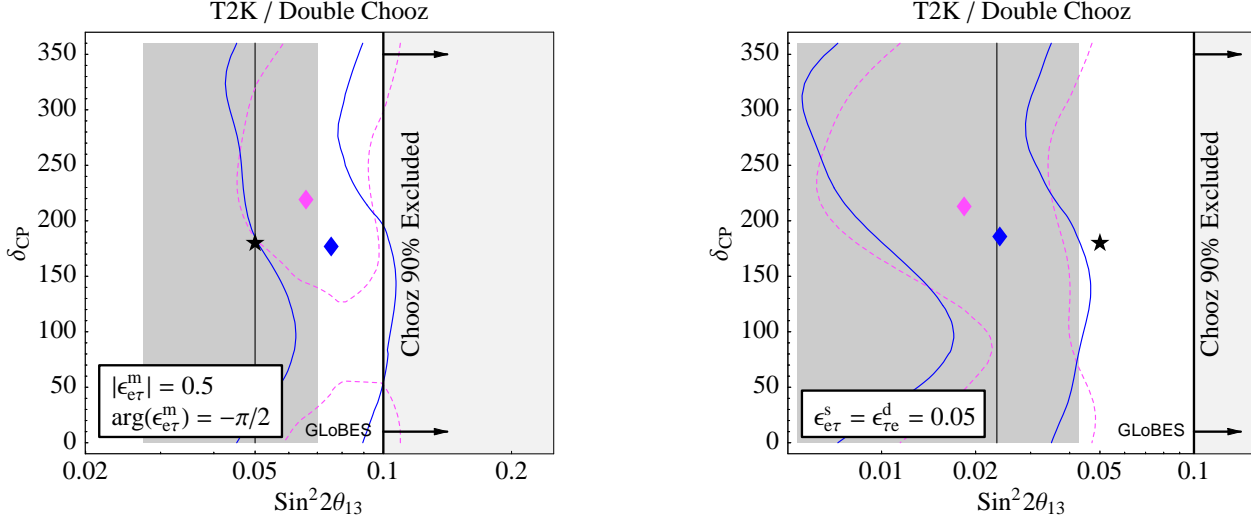[1] The case of NSIs with different Lorentz structures is discussed in Ref. [3].

Figure 1. Examples for a discrepancy (left) and a common offset (right) in the standard oscillation fits for Double Chooz and T2K. In the left panel, corresponding to the NSI parameter $\epsilon_{e\tau}^m$, the best-fit value of Double Chooz (vertical solid line) is located far from the best-fit value of T2K (coloured diamonds). In the right panel, with $\epsilon_{e\tau}^s$ and $\epsilon_{e\tau}^d$, both fits coincide with each other but have a common offset from the true value (denoted by the black star).

we can treat the ϵ parameters as energy-independent. Moreover, the following relation between the NSI in the neutrino beam source and those in the detection process holds:

$$\epsilon_{\alpha\beta}^s = (\epsilon_{\beta\alpha}^d)^*. \tag{5}$$

We will use this relation as a constraint in the numerical simulations which we are going to present in the next section.

2 NSI-induced offsets and discrepancies in θ_{13} fits

To fully assess the high-level consequences of NSI for realistic reactor and superbeam experiments, we have performed numerical simulations using the GLoBES software [4]. In this talk, we will concentrate on only two experiments, namely T2K and Double Chooz. To analyse the simulated data, we define the following χ^2 function

$$\chi^2 = \min_{\lambda} \sum_j^{\text{channel}} \sum_i^{\text{bin}} \frac{|N_{ij}(\lambda^{\text{true}}, \epsilon^{\text{true}}) - N_{ij}(\lambda, \epsilon = 0)|^2}{N_{ij}(\lambda^{\text{true}}, \epsilon^{\text{true}})}$$
$$+ \text{Priors}, \tag{6}$$

where N_{ij} denotes the number of neutrino events in the i-th energy bin for oscillation channel j, the vector $\lambda = (\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}, \Delta m_{21}^2, \Delta m_{31}^2, \boldsymbol{b})$ contains the six standard oscillation parameters and the systematical biases $\boldsymbol{b}$, and ϵ represents the non-standard parameters. For the following plots, χ^2 has been marginalised over all standard oscillation parameters (except, of course, those for which we are interested in confidence regions rather than best-fit points) and over all systematical biases. We keep the NSI parameters fixed at 0 in the fit because we want to study the impact

of NSI on a *standard oscillation* fit. Unless indicated otherwise, we calculate the simulated event rates using the following reference values (*true values*) for the standard oscillation parameters [9],

$$\sin^2 2\theta_{12}^{\text{true}} = 0.84, \qquad \sin^2 2\theta_{23}^{\text{true}} = 1.0,$$
$$\sin^2 2\theta_{13}^{\text{true}} = 0.05, \qquad \delta_{CP}^{\text{true}} = 0,$$
$$(\Delta m_{21}^2)^{\text{true}} = 7.9 \cdot 10^{-5} \text{ eV}^2,$$
$$\left|(\Delta m_{31}^2)^{\text{true}}\right| = 2.5 \cdot 10^{-3} \text{ eV}^2. \tag{7}$$

We assume the true hierarchy to be normal. Although we keep $\delta_{CP}^{\text{true}}$ fixed, this does not limit the generality of our results, because the oscillation probabilities typically depend only on combinations of δ_{CP} and the phases of the NSI parameters. Thus, a variation of δ_{CP} has the same effect as a variation of $\arg(\epsilon)$.

In our simulation of T2K, the Super-Kamiokande far detector and a 1.0 kton water Cerenkov near detector are simulated separately. We introduce a common 10% uncertainty on the neutrino flux and a common 20% error on the number of background events in the ν_e appearance channel. Also for Double Chooz, we simulate the near and far detectors separately. We introduce a 2.8% correlated flux normalization error as well as uncorrelated 0.6% fiducial mass errors, and a bin-to-bin uncertainty of 0.5%. More details on the input parameters of our simulations are given in Ref. [3].

Two exemplary outcomes of the simulation are plotted in Fig. 1. In both panels, we have chosen the "true" parameter values $\sin^2 2\theta_{13} = 0.05$ and $\delta_{CP} = \pi$, as indicated by the black star. The vertical black line and the coloured diamonds represent the best-fit values for Double Chooz and T2K, respectively, while the shaded vertical band and the coloured contours are the corresponding 90% confidence regions. Blue symbols and lines stand for the T2K normal hierarchy fit, and dashed magenta ones are for an inverted hierarchy fit. The NSI contributions are assumed to be
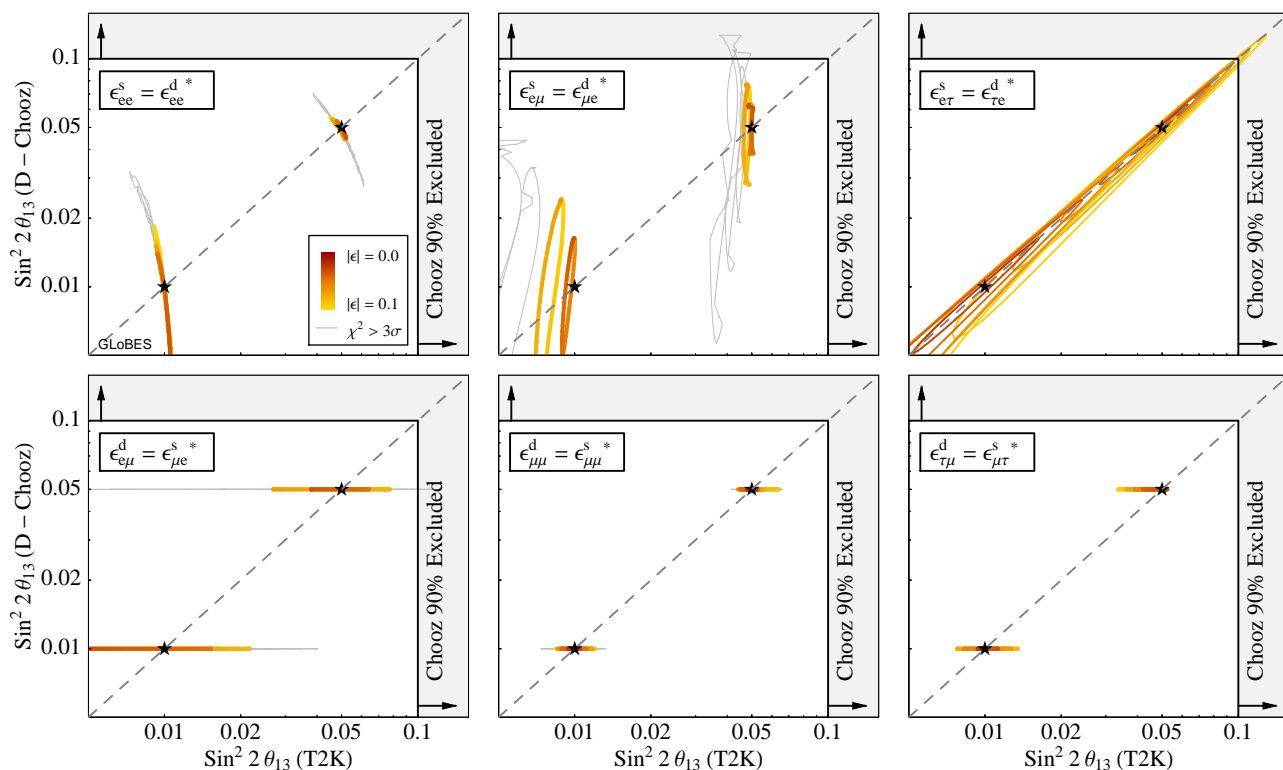
Figure 2. Distribution of the best-fit values for θ_{13} in T2K and Double Chooz in the presence of the NSI parameters $\epsilon_{\alpha\beta}^{s}$ and $(\epsilon_{\beta\alpha}^{d})^{*}$. The black stars indicate the assumed true values of $\sin^{2} 2\theta_{13}$ which are taken to be 0.05 and 0.01.

$\epsilon_{e\tau}^{m} = 0.5e^{-i\pi/2}$ in the left hand plot and $\epsilon_{e\tau}^{s} = \epsilon_{\tau e}^{d} = 0.05$ in the right hand plot. In the first case, the best-fit value of Double Chooz coincides with the "true" value because reactor experiments are sensitive neither to standard nor to non-standard matter effects. On the other hand, the θ_{13} fit of T2K deviates significantly, indicating that $\epsilon_{e\tau}^{m}$ has a large impact on this experiment, even though *standard* matter effects are only sub-dominant due to the relatively short baseline.[2] The discrepancy is so large, that the best-fit value of T2K is almost ruled out at 90% confidence level by the reactor measurement. In the case shown on the right hand side of Fig. 1, both experiments agree well with each other, but their fits suffer from a common NSI-induced offset, which even leads to an erroneous exclusion of the true θ_{13}.

Let us now proceed to a more systematic analysis, which we present in Figs. 2 and 3. In these figures, we plot the distribution of the best-fit θ_{13} values of both experiments for different values of the NSI parameters. Each curve corresponds to fixed $|\epsilon|$, and varying arg(ϵ), with dark red curves denoting $|\epsilon| \sim 0$, and yellow curves corresponding to $|\epsilon|$ equal to its current upper bound, which is 0.1 for $\epsilon_{\alpha\beta}^{s}$ [6] and 0.7 for $\epsilon_{e\tau}^{m}$ [5]. If the χ^{2} function for one of the experiments exceeds 3σ, the colour of the curves has been changed to grey, regardless of $|\epsilon|$. This indicates that in these

Figure 3. Distribution of the best-fit values for θ_{13} in T2K and Double Chooz in the presence of the NSI parameter $\epsilon_{e\tau}^{m}$.

cases, a 3σ *discovery* of the respective non-standard effect is actually possible. The black stars indicate the chosen "true" θ_{13}. Let us briefly comment on the different cases shown in Figs. 2 and 3. If ϵ_{ee}^{s} and ϵ_{ee}^{d} are introduced (upper left panel of Fig. 2), they modify the $\bar{\nu}_{e}$ flux in Double Chooz, and lead to a wrong measurement of the ν_{e} contamination in the T2K beam by the near detector. Therefore, T2K is affected indirectly. The correct treatment of the near detectors is crucial here to fully assess the impact of NSI. Similarly,

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[2] Standard and non-standard matter effects become more significant at baselines of $\mathcal{O}(10^{3})$ km, which are, for example, considered for a neutrino factory. For recent studies of NSI in this context, see e.g. Refs. [7,8].
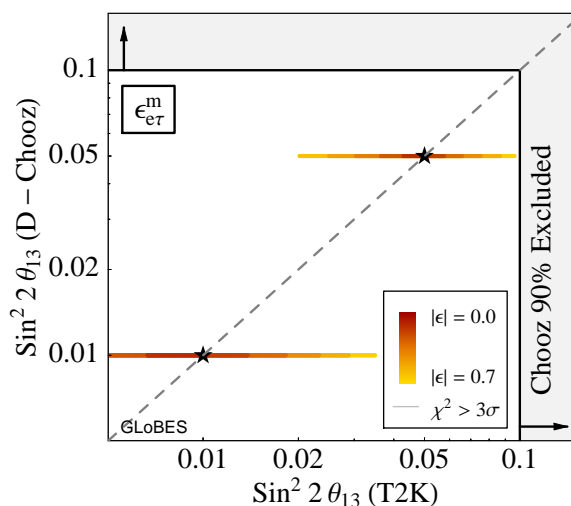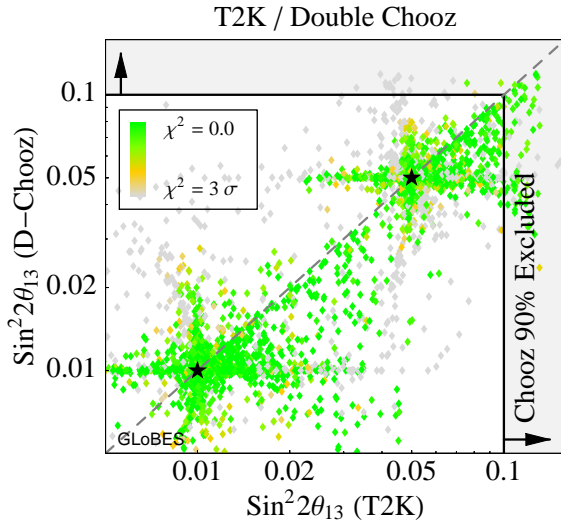
Figure 4. Scatter plot of the θ_{13} best-fit values of T2K and Double Chooz in the presence of random combinations of NSI parameters. It is obvious that NSI can induce ostensible discrepancies between the two experiments (off-diagonal points), or common offsets (close-to-diagonal points) which would lead to consistent, but wrong results.

the effect of $\epsilon^s_{e\mu}$ and $\epsilon^s_{e\tau}$ can only be fully understood if the near detectors are taken into account [3]. The upper right panel of Fig. 2 shows that $\epsilon^s_{e\tau}$ and $\epsilon^d_{\tau e}$ are particularly dangerous because they lead to a common offset in the reactor and in the superbeam (the best fit values are distributed along the diagonal). We have already seen an example of this effect in Fig. 1. The NSI parameters $\epsilon^s_{\mu\alpha}$ and $\epsilon^d_{\alpha\mu}$ affect only T2K, hence the distribution of the corresponding θ_{13} fits is constrained to horizontal lines in our plots. Among the non-standard matter effects, only $\epsilon^m_{e\tau}$ can give a significant effect, because the other parameters are either subdominant in the oscillation probability, or are already well-constrained experimentally. The effect of $\epsilon^m_{e\tau}$ is a possibly large shift of the θ_{13} fit in T2K, as shown in Fig. 3.

So far, we have only considered situations in which one NSI parameter is dominant, and all the others are negligible. In contrast to this, Fig. 4 shows the distribution of the θ_{13} fits in situations where many NSI parameters are present simultaneously. For each point, the moduli $|\epsilon^{s,d,m}_{\alpha\beta}|$ were chosen randomly on a logarithmic scale between 10^{-8} and the respective experimental upper bounds [5,6], while the phases are linearly distributed between 0 and 2π. The colour coding indicates the χ^2 value for each point. We can see from the plot that, for part of the parameter space, the NSI effect can actually be discovered, i.e. the standard oscillation interpretation does not give a good fit. However, there are also a lot of points with a low χ^2, and among these are many which exhibit a clear discrepancy between the θ_{13} fits of Double Chooz and T2K, and others which correspond to a common offset of the fit values.

3 Conclusion

In this talk, we have discussed the impact of non-standard neutrino interactions on reactor and accelerator experiments, in particular on Double Chooz and T2K. We have introduced flavour violating four-fermion interactions with $(V-A)(V-A)$ type Lorentz structure, and considered the impact of these NSI operators on the neutrino production, propagation, and detection stages. We have performed detailed numerical simulations, taking into account parameter correlations, degeneracies, systematic errors, and a realistic treatment of the near detectors. We have found that NSI can have a sizeable impact on future experiments if the corresponding couplings are close to their current upper bounds, and if the complex phases do not conspire to cancel them. There are scenarios in which a clear discrepancy between Double Chooz and T2K arises, but we have also found situations in which both experiments would agree very well, but the derived θ_{13} has a significant offset from the true value. To detect this kind of problems, a third experiment, complementary to the other two, would be required. Our discussion shows that reactor and superbeam measurements, which might seem to be redundant in the standard oscillation framework, turn out to be highly complementary once non-standard effects are considered.

More details on the impact of non-standard interactions on reactor and superbeam experiments can be found in Ref. [3], in which we also discuss the discovery potential for NSI, paying specific attention to its dependence on the complex phases. Moreover, Ref. [3] provides an intuitive understanding of the impact of the different ϵ parameters, and contains analytic formulae to substantiate the numerical results.

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