Physics Letters B 671 (2009) 77–81

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Testing non-standard CP violation in neutrino propagation

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ARTICLE INFO

Article history:
Received 4 September 2008
Received in revised form 7 November 2008
Accepted 18 November 2008
Available online 20 November 2008
Editor: A. Ringwald

PACS:
14.60.Pq

Keywords:
Neutrino oscillations
Non-standard interactions
CP violation

ABSTRACT

Non-standard physics which can be described by effective four fermion interactions may be an additional source of CP violation in the neutrino propagation. We discuss the detectability of such a CP violation at a neutrino factory. We assume the current baseline setup of the international design study of a neutrino factory (IDS-NF) for the simulation. We find that the CP violation from certain non-standard interactions is, in principle, detectable significantly below their current bounds – even if there is no CP violation in the standard oscillation framework. Therefore, a new physics effect might be mis-interpreted as the canonical Dirac CP violation, and a possibly even more exciting effect might be missed.

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1. Introduction

Physics beyond the Standard Model may introduce non-standard interactions (NSI) [1–5] suppressed by a higher energy scale. In general, such new physics is usually described by effective dimension six [6–8] and eight [9,10] operators. One can describe the effective dimension d Lagrangian as a function of the non-standard physics scale Λ as

$$\mathcal{L}^d = \lambda \frac{\mathcal{O}^d}{\Lambda^{d-4}}, \tag{1}$$

where λ is a dimensionless coupling constant and $\mathcal{O}^d$ is a dimension d operator. Thus, the non-standard physics will be suppressed by $(E_{\mathrm{EWSB}}/\Lambda)^{d-4}$ with respect to the weak interactions, where E_{EWSB} is the electroweak symmetry breaking scale.

In this study, we focus on non-standard propagation effects in standard oscillations (SO). These can be phenomenologically described by neutral current-type NSI of the form

$$\mathcal{L}_{\mathrm{NSI}} = \frac{G_F}{\sqrt{2}} \epsilon^m_{\beta\alpha} (\bar{\nu}_\beta \gamma^\rho L \nu_\alpha)(\bar{f} \gamma_\rho f) + \text{h.c.} \tag{2}$$

with $L = 1 - \gamma^5$, which affect the neutrino propagation in matter for $f \in \{e, u, d\}$. Note that, in general, $\epsilon^m_{\alpha\beta}$ are complex numbers for $\alpha \neq \beta$, and real numbers for $\alpha = \beta$, where we define $\epsilon^m_{\alpha\beta} \equiv |\epsilon^m_{\alpha\beta}| \exp(i\phi^m_{\alpha\beta})$. Thus, $\epsilon^m_{e\mu}$, $\epsilon^m_{\mu\tau}$, $\epsilon^m_{e\tau}$ are possible sources of non-standard CP violation (NSI-CPV).[1]

They enter the propagation Hamiltonian in flavor base proportional to the matter potential $a_{\mathrm{CC}} = 2\sqrt{2} E G_F N_e$ (with N_e the electron density) in the off-diagonal elements. Since $|\epsilon^m_{e\mu}|$ is very well constrained, we focus on $|\epsilon^m_{\mu\tau}|$ and $|\epsilon^m_{e\tau}|$, for which the current bounds are $\mathcal{O}(0.1)$ and $\mathcal{O}(1)$, respectively [10,14,15]. Therefore, the phases $\phi^m_{\mu\tau}$ and $\phi^m_{e\tau}$ might be accessible by future experiments for large enough $|\epsilon^m_{\mu\tau}|$ and $|\epsilon^m_{e\tau}|$. The necessary conditions for an underlying model producing such large NSI are discussed elsewhere [13,16]. Since these interactions will be suppressed by at least a factor of Λ^2 (cf., Eq. (1)), it might be plausible to look for NSI-CPV in the best discussed neutrino oscillation experiments which are sensitive to the highest Λ-scales, such as neutrino factories [17,18].

The measurement of NSIs in neutrino factories has been discussed in Refs. [11,19–25]. As illustrated in Refs. [24,25], the disappearance channels and second "magic" baseline [26] are mandatory for excellent NSI sensitivities. In particular, $\epsilon^m_{\mu\tau}$ is best measured with the disappearance channel, whereas $\epsilon^m_{e\tau}$ is best measured with the appearance channel. Therefore, we expect that the measurement of $\phi^m_{e\tau}$ will be qualitatively similar to that of δ_{CP}, whereas that of $\phi^m_{\mu\tau}$ will have completely new characteristics. We use in

[1] In Refs. [11,12] such NSI-CPV was discussed in the context of source and detection NSI, whereas we focus on the propagation effects. Note that, depending on the model, source and propagation NSI could be related. However, the simplest allowed models to induce $\epsilon^m_{\mu\tau}$ or $\epsilon^m_{e\tau}$ involve two mediator fields (and some cancellation conditions), and propagation NSI are not related to source and detection NSI [13].

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doi:10.1016/j.physletb.2008.11.042

this study the baseline setup of the international design study for a neutrino factory [27], which includes two baselines, as well as the disappearance channels by the measurement of the wrong-sign muons.

A focus of this Letter is to demonstrate that the discovery of NSI-CPV should be quantified with performance indicators similar to SO-CPV. In addition, the full (relevant) parameter space using a full simulation is discussed. Since there is no model-independent connection between source or detection and propagation NSI [13] and there is not yet any near detector specification for the neutrino factory within the international design study, we do not discuss source and propagation NSI.

2. Method and performance indicator

Our simulations use the GLoBES software [28,29] with the current best-fit values and solar oscillation parameter uncertainties from Ref. [15], as well as a 2% error on the (constant) matter density profile, i.e., we expect the matter density profile to be known with that precision.[2] For the sake of simplicity, we use a normal simulated mass hierarchy. The experimental scenario we consider is the IDS-NF 1.0 setup from Ref. [27], which is the current standard setup for the "International design study of the neutrino factory" (IDS-NF). This setup has been optimized within Refs. [30,31] for the measurement of $\sin^2 2\theta_{13}$, the neutrino mass hierarchy, and leptonic CP violation in the case of standard oscillations. In short, it uses two baselines at about 4000 km and 7500 km with two (identical) magnetized iron neutrino detectors (MIND) with a fiducial mass of 50 kt each. For each baseline, a total of 2.5×10^{21} useful muon decays plus 2.5×10^{21} useful anti-muon decays in the straight of the corresponding storage ring is used, which could be achieved by ten years of operation with 2.5×10^{20} useful muon decays per baseline, year, and polarity. The muon energy E_μ is assumed to be 25 GeV, which is sufficient for a detector with a low enough detection threshold [30]. The detector and systematics specifications can be found in Ref. [27]. Note that there is not yet any near detector specification. We do not simulate the near detector explicitely, because we do not discuss non-standard production or detection effects such as in Ref. [32]. As a small modification of the IDS-NF baseline setup, we do not include the emulsion cloud chamber for ν_τ detection at the short baseline, since it has been demonstrated in Ref. [25] that it hardly contributes to the SO and NSI sensitivities if two baselines are used. We have checked that this also applies for a (hypothetical) $\nu_\mu \to \nu_\tau$ oscillation channel for the effects discussed in this study (which might be different for NSIs in the production process, see Ref. [12]).

We define the sensitivity to NSI-CPV, in the same way as the sensitivity to SO-CPV, as the $\Delta\chi^2$ with which any CP conserving solution can be excluded. That is, we simulate a true $\epsilon^m_{\alpha\beta} = |\epsilon^m_{\alpha\beta}| \exp(i\phi^m_{\alpha\beta})$, where $\phi^m_{\alpha\beta}$ is the CP violating phase $\notin \{0, \pi\}$. In addition, we have a set of simulated values for the SO parameters. Then we compute the $\Delta\chi^2$ for $\phi^m_{\alpha\beta}$ (fit) fixed to 0 and π (CP conservation) and choose the minimum between these two values. All the fit SO parameters and $|\epsilon^m_{\alpha\beta}|$ (fit) are marginalized over. For the sake of simplicity, we do not take into account the mass hierarchy degeneracy.

3. Discovery of non-standard CP violation

In the context of NSI-CPV, the most important question might be for which region of the parameter space NSI-CPV will be discovered at a neutrino factory. Since the solar and atmospheric oscillation parameters are very well known, the performance will mainly depend on the true values of $|\epsilon^m_{\alpha\beta}|$, $\phi^m_{\alpha\beta}$, $\sin^2 2\theta_{13}$, and δ_{CP}, where $\phi^m_{\alpha\beta}$ describes the CP violation of interest. Because the absolute value of $\epsilon^m_{\alpha\beta}$ suppresses the phase measurement, the simulated $|\epsilon^m_{\alpha\beta}|$ and $\phi^m_{\alpha\beta}$ will be the most important parameters for the parameter space test, similar to $\sin^2 2\theta_{13}$ and δ_{CP} for the SO-CPV. We illustrate this dependence in Fig. 1 for $\epsilon^m_{e\tau}$ as a function of the true values of $|\epsilon^m_{e\tau}|$ and $\phi^m_{e\tau}$, as well as the true $\sin^2 2\theta_{13} = 0$. This figure looks very similar to the corresponding SO-CPV figure as a function of $\sin^2 2\theta_{13}$ and δ_{CP}: There is a cutoff at small $|\epsilon^m_{e\tau}|$, below which the phase effects are suppressed, and there is no sensitivity close to the CP-conserving solutions $\phi^m_{e\tau} = 0$ and π. Therefore, we adopt an approach similar to that of SO-CPV. We show in Fig. 2 the fraction of $\phi^m_{\mu\tau}$ (left) and $\phi^m_{e\tau}$ (right) for which NSI-CPV will be discovered as a function of the $|\epsilon^m_{\mu\tau}|$ (left) and $|\epsilon^m_{e\tau}|$ (right). In this case, the fraction of $\epsilon^m_{\alpha\beta}$ represents the stacking of all sensitive regions in Fig. 1 along any vertical line corresponding to any fixed $|\epsilon^m_{e\tau}|$. In Fig. 2, the dependence on the true $\sin^2 2\theta_{13}$ and δ_{CP} is indicated by the shaded regions, whereas the curves correspond to the true $\sin^2 2\theta_{13} = 0$ (i.e., the thick curve in the right panel corresponds to the thick curve in Fig. 1).

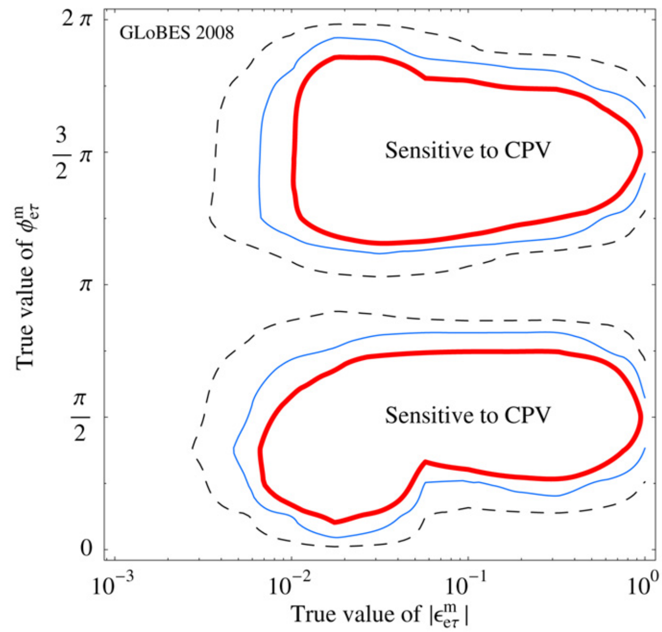

Fig. 1. Sensitivity to NSI-CPV in $\epsilon^m_{e\tau}$ as a function of the true values of $|\epsilon^m_{e\tau}|$ and $\phi^m_{e\tau}$ (for the true $\sin^2 2\theta_{13} = 0$). The different contours correspond to $\Delta\chi^2 = 1$ (dashed), 4 (thin solid), and 9 (thick).

As it is obvious from the analytical and quantitative discussion in Ref. [25], the $\nu_e \to \nu_\mu$ (and $\bar\nu_e \to \bar\nu_\mu$) appearance channels will dominate the determination of $\phi^m_{e\tau}$, whereas the $\nu_\mu \to \nu_\mu$ (and $\bar\nu_\mu \to \bar\nu_\mu$) disappearance channels will dominate the determination of $\phi^m_{\mu\tau}$ (see also Ref. [33] for more analytical discussions). For that reason, we obtain a strong dependence on the simulated $\sin^2 2\theta_{13}$ and δ_{CP} for $\phi^m_{e\tau}$ (right panel of Fig. 2), because the appearance channels are most sensitive to these SO parameters, whereas the CP violation in $\phi^m_{\mu\tau}$ is hardly affected by these parameters. From Fig. 2 (left panel), we can read off that NSI-CPV will be discovered for about 80% of all possible $\phi^m_{\mu\tau}$ for $|\epsilon^m_{\mu\tau}| \sim 0.1$ close to the current bound. The $|\epsilon^m_{\mu\tau}|$ reach is, however, limited to $|\epsilon^m_{\mu\tau}| \gtrsim 0.02$, which means that any significant improvement of the bound will exclude this possibility. For $\phi^m_{e\tau}$ in the right panel, we obtain a picture qualitatively similar to the SO-CPV measurement because of the dominance of the appearance channels. We obtain a large fraction of $\phi^m_{e\tau}$ of up to 80% in an intermediate

[2] In fact, we have checked that the impact of a larger matter density uncertainty on the $\epsilon^m_{e\tau}$ measurement is very small, at the level of a few percent correction.

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