PROCEEDINGS OF SCIENCE

Non-standard interactions using the OPERA experiment

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We discuss the interplay of non-standard interactions between neutrinos and charged fermions and their impact on the currently running OPERA experiment. We show that, due to the relatively short distance between CERN and the Gran Sasso laboratory, the neutrino oscillation probabilities can be expanded in the baseline length. This results in a rather simple understanding of numeric simulations, which we perform using the GLoBES software.

10th International Workshop on Neutrino Factories, Super beams and Beta beams
June 30 - July 5 2008
Valencia, Spain

PoS(NuFact08)058

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[†] Based on work done in collaboration with Davide Meloni, Tommy Ohlsson, Francesco Terranova, and Mattias Westerberg [1].

1. Introduction

In recent years, it has been discussed how non-standard interactions (NSIs) between neutrinos and other fermions may affect the precision determination of the neutrino oscillation parameters in upcoming neutrino experiments such as neutrino factories. Several papers have discussed both the impact of the NSIs on the derived standard oscillation parameters, as well as the possible detection of NSIs (see Ref. [2]). Generally, the results of such studies are degeneracies between the standard and non-standard parameters, which cannot be resolved by one single experiment. Here we present the results of a study of the effects of NSIs in the currently running OPERA experiment [3], which is mainly designed to search for $\nu_\mu \to \nu_\tau$ oscillations in the CNGS neutrino beam. The impact of NSIs in the OPERA experiment has also been studied by Esteban-Pretel *et al.* [4,5]. However, their study was focused on the NSI parameter $\varepsilon_{e\tau}$, while our study focuses on $\varepsilon_{\mu\tau}$.

2. Non-standard interactions

We consider NSIs with matter during the propagation phase only. The effective addition to the neutrino oscillation Hamiltonian is given by

$$H_{\rm NSI} = \sqrt{2} G_F N_e \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}, \tag{2.1}$$

where N_e is the local electron number density and the $\varepsilon_{\alpha\beta}$ parametrize the NSI. The fact that there are only six independent εs is based on the requirement of a hermitian Lagrangian, which in turn translates to requiring a hermitian Hamiltonian, resulting in the relation $\varepsilon_{\alpha\beta} = \varepsilon_{\beta\alpha}^*$.

Effects of this type have been thoroughly studied in connection to different types of neutrino experiments, including atmospheric neutrinos, solar neutrinos, and terrestrially produced neutrinos. It should be noted that, while two-flavor analyses of NSIs in the context of atmospheric neutrinos [6,7] imply $\varepsilon_{\mu\tau} < \mathscr{O}(10^{-2})$ and $\varepsilon_{\tau\tau} < \mathscr{O}(10^{-2})$, three-flavor analyses including $\varepsilon_{e\tau}$ and $\varepsilon_{\tau\tau}$ relax the bounds on $\varepsilon_{\tau\tau}$ to be $\mathscr{O}(1)$. Without the two-flavor atmospheric analysis, the bounds on $\varepsilon_{\mu\tau}$ (which has so far not been included in the three-flavor analysis) are $\mathscr{O}(0.3)$, about the same size which we will see that OPERA is sensitive to. Thus, it may be important to include $\varepsilon_{\mu\tau}$ in the atmospheric three-flavor analysis in order to see if the two-flavor atmospheric bound survives the transition to the full three-flavor scheme.

3. The CNGS beam and the OPERA detector

The OPERA experiment is mainly designed for detecting the appearance of ν_τ in a beam initially consisting of almost pure ν_μ. The successful detection of ν_τ would confirm the current picture of the atmospheric ν_μ deficiency being the result of oscillations into ν_τ. This would be the first evidence of neutrino oscillations from an appearance experiment that actually measures the flavor of the final neutrino.

The OPERA detector consists of a massive lead/emulsion target located at LNGS in Gran Sasso, Italy, and recieves the neutrino beam from CERN in Geneva, Switzerland. The resulting baseline length is $L \simeq 732$ km and the average neutrino energy in the beam is $\bar{E}_\nu \simeq 17$ GeV. With the current knowledge of $\Delta m^2_{31} \simeq 2.4 \cdot 10^{-3}$ eV^2 [8], this means that the L/E value of this setup is quite small, resulting in the fact that the neutrino oscillation probability will not be very large.

4. Analytic considerations

With both $\Delta m^2_{31} L/(2E) \ll 1$ and $VL \equiv \sqrt{2} G_F N_e \ll 1$, we assume that we are in the region where it is enough to keep the $\mathscr{O}(L)$ terms in the expansion of the neutrino evolution matrix. For the $\nu_\mu \to \nu_\tau$ channel, which is the interesting channel at OPERA, this approximation results in

$$P_{\mu\tau} \simeq \left| c_{13}^2 \sin(2\theta_{23}) \frac{\Delta m^2_{31}}{4E} + \varepsilon^*_{\mu\tau} V \right|^2 L^2. \tag{4.1}$$

This result implies that only the NSI parameter $\varepsilon_{\mu\tau}$ is of importance to this channel as long as the baseline can be considered short in comparison to the vacuum and matter oscillation lengths. Since this is the case in the OPERA experiment, this is very well consistent with the results of Ref. [4,5], where it was shown that OPERA has essentially no sensitivity to $\varepsilon_{e\tau}$ and $\varepsilon_{\tau\tau}$.

From Eq. (4.1), we see that if the coefficient before the L^2 term is close to zero, *i.e.*, if

$$\varepsilon^*_{\mu\tau} \simeq -c_{13}^2 \sin(2\theta_{23}) \frac{\Delta m^2_{31}}{4EV}, \tag{4.2}$$

then the oscillations into ν_τ will be severely suppressed. Inserting the current best-fit values of the standard oscillation parameters, we see that this would occur for $\varepsilon_{\mu\tau} \simeq -0.3$ at the OPERA experiment (assuming normal neutrino mass hierarchy).

5. Numerical results

For our numerical simulations, we use the GLoBES software [9,10] with customized neutrino oscillation routines including the effects of NSIs. We put priors on the standard neutrino oscillation parameters in accordance with the current knowledge (*i.e.*, we used the best-fit values as the simulated values and the current experimental uncertainties as the external errors). For more details on our numerical setup, see Ref. [1].

In Fig. 1, we show the sensitivity of OPERA to the NSI parameter $\varepsilon_{\mu\tau}$. As can be seen from this figure, the sensitivity contours essentially extend along a circle in the complex $\varepsilon_{\mu\tau}$-space centered around $\varepsilon_{\mu\tau} \simeq -0.3$. This is simply the circle indicated by having a constant prefactor of the L^2 term in Eq. (4.1). The reason that the circle is cut off is simply that this prefactor varies with energy, making it possible to slightly resolve the degeneracy by studying the energy distribution of the events. Due to the unknown neutrino mass hierarchy, there is a discrete degeneracy for the sign of $\varepsilon_{\mu\tau}$, since changing the sign of both $\varepsilon_{\mu\tau}$ and Δm^2_{31} in Eq. (4.1) would result in the same neutrino oscillation probability. This is illustrated in the left panel of Fig. 2, where we also show the results for different simulated values of $\varepsilon_{\mu\tau}$. In particular, we note that the sensitivity contours for a simulated $\varepsilon_{\mu\tau} \simeq -0.3$ are essentially discs. This is the case when the prefactor of the L^2 term in Eq. (4.1) is close to zero, meaning that the event rate in the OPERA detector is very low.

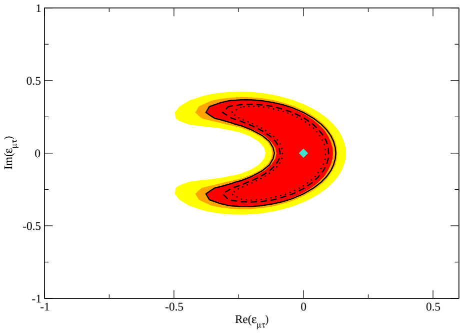

Figure 1: The sensitivity of OPERA to the NSI parameter $\varepsilon_{\mu\tau}$ for 5 (shaded regions) and 10 (black curves) years of running time, respectively. The confidence levels are 90 %, 95 %, and 99 %. Figure from Ref. [1].

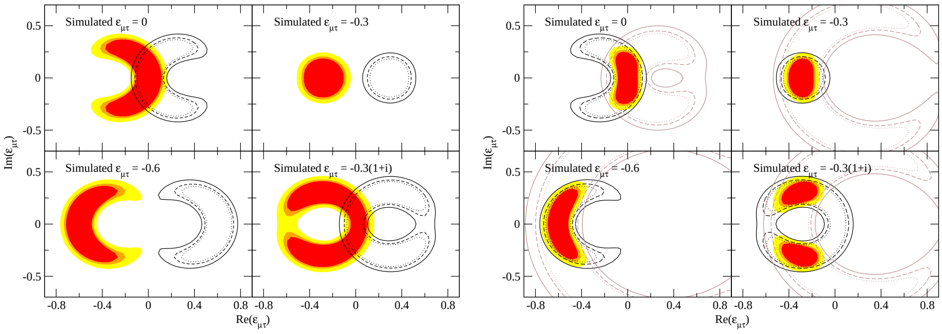

Figure 2: *Left panel:* The discrete degeneracy in $\varepsilon_{\mu\tau}$ induced by the unknown sign of Δm^2_{31}. The sensitivity contours in this figure are produced for five years of running. The shaded areas correspond to the normal mass hierarchy while the black curves correspond to the inverted mass hierarchy. The data was simulated for normal mass hierarchy and different values of $\varepsilon_{\mu\tau}$, as shown in the figure. *Right panel:* The results of running OPERA for five years with neutrinos (black curves) and anti-neutrinos (light curves), respectively, as well as the combined result (shaded regions). Figures from Ref. [1].

As is shown in the right panel of Fig. 2, the degeneracy between $\varepsilon_{\mu\tau}$ and the standard neutrino oscillation parameters can be partly resolved. If OPERA would run for five years with neutrinos and five years with anti-neutrinos, then the degeneracy is resolved in a significantly better way than if one simply increases the running time in neutrinos to ten years (*c.f.*, Fig. 1). The reason for this is that changing to anti-neutrinos would imply that $\varepsilon_{\mu\tau}V \to -\varepsilon^*_{\mu\tau}V$, which can alter the neutrino oscillation probability presented in Eq. (4.1), something that would not be the case in the absence of the NSI term.

6. Summary

We have seen that the appearance channel $\nu_\mu \to \nu_\tau$ at the OPERA experiment would be sensitive to real $\varepsilon_{\mu\tau} \sim \mathscr{O}(0.1)$, while an imaginary component of $\varepsilon_{\mu\tau}$ would complicate the situation by introducing an additional degeneracy, essentially being a circle centered around $\varepsilon_{\mu\tau} \simeq \mp 0.3$ (depending on the neutrino mass hierarchy). If $|\varepsilon_{\mu\tau}|$ would be close to 0.3, then there could be a significant suppression of the number of ν_τ events in the OPERA detector. In addition, the degeneracy introduced by including complex values of $\varepsilon_{\mu\tau}$ can be partly resolved by running OPERA for five years with neutrinos and five years with anti-neutrinos.

In conclusion, we note that the possible bounds on $\varepsilon_{\mu\tau}$ from the OPERA experiment are less restrictive than the bounds coming from the two-flavor analysis of atmospheric neutrino experiments. However, since three-flavor analysis is known to relax the two-flavor atmospheric bounds on $\varepsilon_{\tau\tau}$, it is possible that such an effect could also relax the bounds on $\varepsilon_{\mu\tau}$, meaning that the bounds from OPERA could still be of interest. Including $\varepsilon_{\mu\tau}$ into the full three-flavor analysis would resolve this issue. If the two-flavor bounds are found to survive the transition to three flavors, then it is fair to say that NSIs would not play any role in the OPERA experiment (see also Ref. [4, 5]).

Acknowledgments

The author would like to thank the other authors of Ref. [1] for fruitful collaboration. This work was supported by the Swedish Research Council (Vetenskapsrådet) through Contract No. 623-2007-8066.

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