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Can OPERA help in constraining neutrino non-standard interactions?

A. Esteban-Pretel and J.W.F. Valle
AHEP Group, Institut de Física Corpuscular – C.S.I.C./Universitat de València
Edificio Institutos de Paterna, Apt 22085, E–46071 Valencia, Spain

P. Huber
Theory Division, Department of Physics, CERN
CH-1211 Geneva 23, Switzerland and
Institute for Particle, Nuclear and Astronomical Sciences,
Physics Department, Virgina Tech, Blacksburg, VA 24062, USA

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We study how much the unique ability of the OPERA experiment to directly detect ν_τ can help in probing new, non-standard contact interactions of the third family of neutrinos. We perform a combined analysis of future, high-statistics MINOS and OPERA data. For the case of non-standard interactions in ν_μ to ν_e transitions we also include the impact of possible DoubleCHOOZ data. In all cases we find that the ν_τ sample of OPERA is too small to be statistically significant, even if one doubles the nominal exposure of OPERA to 9×10^{19} pot. OPERA's real benefit for this measurement lies in its very high neutrino energy and hence very different L/E compared to MINOS.

INTRODUCTION

The confirmation of the neutrino oscillation interpretation of solar and atmospheric neutrino data by reactor [1] and accelerator [2, 3] neutrino experiments brings a unique picture of neutrino physics in terms of three-neutrino oscillations [4], leaving little room for other non-standard neutrino properties [5]. Nevertheless, it has long been recognized that any gauge theory of neutrino mass generation inevitably brings in dimension-6 non-standard neutrino interaction (NSI) terms. Such sub-weak strength operators arise in the broad class of seesaw-type models, due to the non-trivial structure of charged and neutral current weak interactions [6]. Similarly, NSI also appear in radiative models of neutrino mass. They can be of two types: flavor-changing (FC) and non-universal (NU) and their strength εG_F is highly model-dependent but may lie within the sensitivities of currently planned experiments. The presence of NSI leads to possibly new resonant effects in the propagation of astrophysical neutrinos [7, 8, 9, 10, 11] and it is interesting to scrutinize their possible role in the propagation of laboratory neutrinos. With neutrino oscillation physics entering the precision age [12, 13] it becomes an important challenge to investigate the role of NSI in future terrestrial neutrino oscillation experiments.

The interplay of oscillation and neutrino non-standard interactions (NSI) was studied in [14] and subsequently it was shown [15, 16] that in the presence of NSI it is very difficult to disentangle genuine oscillation effects from those coming from NSI. The latter may affect production, propagation and detection of neutrinos and in general these three effects need not be correlated. It has been shown that in this case cancellations can occur which make it impossible to separate oscillation from NSI effects. Subsequently it was discovered that the ability to detect ν_τ may be crucial in order to overcome that problem [17], though this method requires sufficiently large beam energies to be applicable. Barring the occurrence of fine-tuned cancellations, NSI and oscillations have very different L/E dependence. Therefore, combining different L/E can be very effective in probing the presence of NSI. The issue of NSI and oscillation in neutrino experiments with terrestrial sources has been studied in a large number of publications [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32]. In [24] it was shown that MINOS [3] on its own is not able to put new constraints on NSI parameters. On the other hand, in [23] the combination of atmospheric data with MINOS was proven to be effective in probing at least some of the NSI parameters. Since matter effects are relatively small in MINOS, its main role in that combination is to constrain the vacuum mixing parameters.

The question we would like to address here is whether the combination of MINOS and OPERA [33] can provide useful information on NSI. OPERA has recently seen the first events in the emulsion cloud chamber [34] and hence it appears timely to ask this question. The idea is that OPERA will be able to detect ν_τ and has a very different L/E than MINOS. Both factors are known to help distinguishing NSI from oscillation effects. Clearly, much larger improvements on existing sensitivities are expected from superbeam experiments like T2K [35] and NOνA [36] especially in combination with reactor neutrino experiments like DoubleCHOOZ [37, 38] or Daya Bay [39], see Ref. [32]. In this letter we will focus on the simple case where NSI only affects neutrino propagation.

BASIC SETUP

Adding NSI into the propagation of neutrinos yields the following evolution Hamiltonian

$$\mathcal{H} = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \frac{1}{2E} \begin{pmatrix} V & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \frac{V}{2E} \begin{pmatrix} 0 & 0 & \varepsilon_{e\tau} \\ 0 & 0 & 0 \\ \varepsilon_{e\tau} & 0 & \varepsilon_{\tau\tau} \end{pmatrix}, \tag{1}$$

where we have made use of the fact that all $\varepsilon_{x\mu}$ are fairly well constrained and hence are expected not to play a significant role at leading order. The effect of ε_{ee} is a re-scaling of the matter density and all experiments considered here are not expected to be sensitive to matter effects. Hence we will set $\varepsilon_{ee} = 0$. Note, that the ε as defined here, are effective parameters. At the level of the underlying Lagrangian describing the NSI, the NSI coupling of the neutrino can be either to electrons, up or down quarks. From a phenomenological point of view, however, only the (incoherent) sum of all these contributions is relevant. For simplicity, we chose to normalize our NSI to the electron abundance. This introduces a relative factor of 3 compared to the case where one normalizes either to the up or down quark abundance (assuming an isoscalar composition of the Earth), *i.e.* the NSI coupling to only up or down quark would need to be 3 times as strong to produce the same effect in oscillations. Since both conventions can be found in the literature, care is required in making quantitative comparisons.

There are two potential benefits beyond adding statistics from combining the data from MINOS and OPERA: First, OPERA can detect ν_τ which, in principle, allows to directly access any effect from $\varepsilon_{x\tau}$. Moreover, although the baseline is the same, the beam energies are very different $\langle E\rangle \simeq 3\,\mathrm{GeV}$ for MINOS, whereas $\langle E\rangle \simeq 17\,\mathrm{GeV}$ for OPERA.

Experiments

All numerical simulations have been done using the GLoBES software [40, 41]. In order to include the effects of the NSI we have customized the package by adding a new piece to the Hamiltonian as shown in equation 1. We have considered three different experiments: MINOS, OPERA and DoubleCHOOZ, the main characteristics of which are summarized in table I.

MINOS is a long baseline neutrino oscillation experiment using the NuMI neutrino beam, at FNAL. It uses two magnetized iron calorimeters. One serves as near detector and is located at about 1 km from the target, whereas the second, larger one is located at the Soudan Underground Laboratory at a distance of 735 km from the source. The near detector is used to measure the neutrino beam spectrum and composition. The near/far comparison also mitigates the effect of cross section uncertainties and various systematical errors. In our simulations, based on [42, 43, 44], we have used a running time of 5 years with a statistics corresponding to a primary proton beam of 5×10^{20} per year, giving a total of 2.5×10^{21}, the maximum reachable value reported by the MINOS collaboration. The mean energy of the neutrino beam is $\langle E \rangle \simeq 3\,\mathrm{GeV}$.

The OPERA detector is located at Gran Sasso and gets its beam from CERN (CNGS). OPERA consists of two parts: a muon tracker and an emulsion cloud chamber. The latter one is the part which is able to discern a ν_τ charged current interaction by identifying the subsequent τ-decay. The baseline is 732 km. Following [33, 42, 45] we assume a 5 year run with a nominal beam intensity of 4.5×10^{19} pot per year. The CNGS neutrino beam has an average energy of $\langle E \rangle \simeq 17\,\mathrm{GeV}$.

Since both MINOS and OPERA have the same baseline we use the same matter density which we take constant and equal to its value at the Earth's crust, that is $\rho = 2.7$ g/cm^3.

Finally, DoubleCHOOZ is a reactor experiment, to be located in the old site of CHOOZ, in France. The experiment consists of a pair of nearly identical near and far detectors, each with a fiducial mass of 10.16 t of liquid scintillator. The detectors are located at a distance of 0.2 km and 1.05 km respectively. As considered in [46] we assume the thermal power of both reactor cores to be 4.2 GW and a running time of 5 years. The neutrinos mean energy is $\langle E \rangle \simeq 4\,\mathrm{MeV}$.

Concerning the neutrino oscillation parameters used to calculate the simulated event rates, we have taken the current best fit values given in Ref. [4], unless stated otherwise:

$$\begin{array}{rclrclrcl} \sin^2\theta_{12}^{\rm true} &=& 0.32, & \sin^2\theta_{23}^{\rm true} &=& 0.5, & \sin^2\theta_{13}^{\rm true} &=& 0, \\ (\Delta m^2_{21})^{\rm true} &=& +7.6\times10^{-5}\ \mathrm{eV}^2, & (\Delta m^2_{31})^{\rm true} &=& +2.4\times10^{-3}\ \mathrm{eV}^2, & \delta_{CP}^{\rm true} &=& 0\,. \end{array} \tag{2}$$

Note the positive sign assumed for $(\Delta m^2_{31})^{\rm true}$ which corresponds to the case of normal hierarchy. Since, none of the experiments considered here is very sensitive to ordinary matter effects, our results would be very similar when choosing as true hierarchy, the inverted one.

Label	L	$\langle E_\nu \rangle$	power	t_{run}	channel
MINOS$_2$ (M2)	735 km	3 GeV	5×10^{20} pot/yr	5 yr	$\nu_\mu \to \nu_{e,\mu}$
OPERA (O)	732 km	17 GeV	4.5×10^{19} pot/yr	5 yr	$\nu_\mu \to \nu_{e,\mu,\tau}$
DoubleCHOOZ (DC)	0.2 km (near) 1.05 km (far)	4 MeV	8.4 GW	5 yr	$\bar\nu_e \to \bar\nu_e$

TABLE I: Main parameters of the experiments under study.

RESULTS

Disappearance - Probing NU NSI ($\varepsilon_{\tau\tau}$)

As it has been previously shown in [23, 24] the presence of NSI, notably $\varepsilon_{\tau\tau}$, substantially degrades the goodness of the determination of the "atmospheric" neutrino oscillation parameters from experiment. Indeed as shown in figure 1 our calculation confirms the same effect, showing how the allowed region in the $\sin^2\theta_{23}$-Δm^2_{31}-plane increases in the presence of NSI.

This figure is the result of a combined fit to simulated OPERA and MINOS data in terms of the "atmospheric" neutrino oscillation parameters, leaving the mixing angle θ_{13} to vary freely. The inner black dot-dashed curve corresponds to the result obtained in the pure oscillation case (no NSI). As displayed in the figure, allowing for a free nonzero strength for NSI parameters $\varepsilon_{\tau\tau}$ and $\varepsilon_{e\tau}$ the allowed region grows substantially, as seen in the solid, red curve. Intermediate results assuming different upper bounds on $|\varepsilon_{\tau\tau}|$ strengths are also indicated in the figure, and given in the legend. One sees that the NSI effect is dramatic for large NSI magnitudes. However, such large values are in conflict with atmospheric neutrino data [23, 47]. In contrast, for lower NSI strengths allowed by the atmospheric + MINOS data combination [23], say $|\varepsilon_{\tau\tau}| = 1.5$, the NSI effect becomes much smaller. Clearly beam experiments currently can not compete with atmospheric neutrino data in constraining $\varepsilon_{\tau\tau}$. The reason for the good sensitivity of atmospheric data to the presence of NSI is the very large range in L/E, especially the very high energy events are crucial in constraining NSI [47].

In summary, the inclusion of OPERA data helps only for very large values of $\varepsilon_{\tau\tau}$ as can be seen also from the first line of table II. These large values, however are already excluded by the combination of MINOS and atmospheric results [23]. We checked that doubling the OPERA exposure does not change this conclusion. The slight improvement by OPERA is exclusively due the ν_μ sample in the muon tracker and the results do not change if we exclude the ν_τ sample from the analysis. The usefulness of the ν_μ sample stems from the very different value of L/E compared to MINOS. These results are not too surprising, since even a very high energy neutrino factory will not be able to improve the bound on $\varepsilon_{\tau\tau}$ in comparison to atmospheric neutrino data [26].

	M2		O		M2+O	
	90% C.L.	95% C.L.	90% C.L.	95% C.L.	90% C.L.	95% C.L.
$\varepsilon_{\tau\tau}$	[-10.8,10.8]	[-11.8,11.8]	[-10.4,10.4]	[-11.0,11.0]	[-8.5,8.5]	[-9.2,9.2]
$\varepsilon_{e\tau}$	[-1.9,0.9]	[-2.3,1.0]	[-2.1,1.4]	[-2.5,1.6]	[-1.6,0.9]	[-2.0,1.0]
Δm^2_{31} [10^{-3} eV^2]	[2.3,4.5]	[2.2,4.9]	[2.0,5.0]	[2.0,5.3]	[2.3,3.8]	[2.2,4.0]
$\sin^2\theta_{23}$	[0.08,0.92]	[0.07,0.93]	[0.08,0.92]	[0.07,0.93]	[0.12,0.88]	[0.11,0.89]

TABLE II: 90% and 95% C.L. allowed regions for $\varepsilon_{\tau\tau}$, $\varepsilon_{e\tau}$, Δm^2_{31} and $\sin^2\theta_{23}$ for different sets of experiments. Each row is obtained marginalizing over the remaining parameters in the table, plus θ_{13}. The true value for $\sin^2 2\theta_{13}$ is 0.

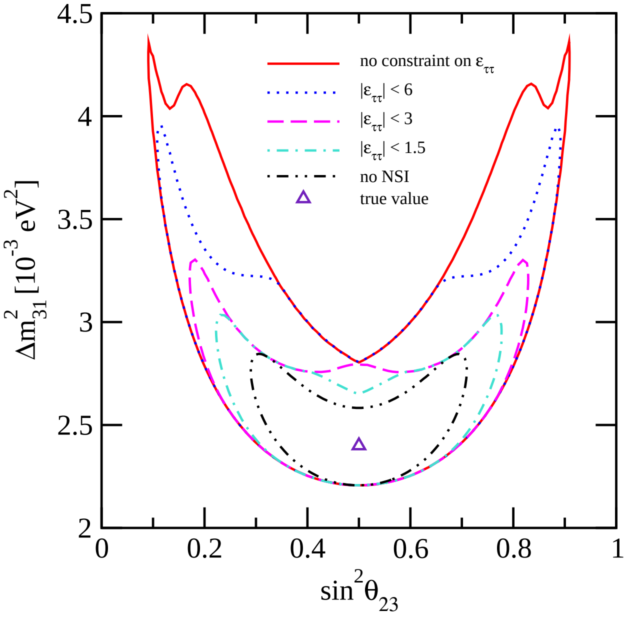

FIG. 1: Shown is the allowed region in the $\sin^2 2\theta_{23}$-Δm^2_{31}-plane at 95% CL (2 dof). In this fit θ_{13}, $\varepsilon_{e\tau}$ and $\varepsilon_{\tau\tau}$ are left free. The different lines correspond to different values for $\varepsilon_{\tau\tau}$ as explained in the legend.

Appearance - probing FC NSI ($\varepsilon_{e\tau}$)

It is well known that, in the presence of NSI, the determination of θ_{13} exhibits a continuous degeneracy [15] between θ_{13} and $\varepsilon_{e\tau}$ which leads to a drastic loss in sensitivity in θ_{13}. A measurement of only $P_{e\mu}$ and $P_{\bar{\mu}\bar{e}}$ at one L/E cannot disentangle the two and will only yield a constraint on a combination of θ_{13} and $\varepsilon_{e\tau}$. In this context, it has been shown in [17], that even a very rudimentary ability to measure $P_{\mu\tau}$ may be sufficient to break this degeneracy. Therefore, it seems natural to ask whether OPERA can improve upon the sensitivity for $\varepsilon_{e\tau}$ that can be reached only with MINOS. The latter has been studied in [23] in combination with atmospheric neutrinos and on its own in Ref. [24]. The result, basically, was that MINOS will not be able to break the degeneracy between θ_{13} and $\varepsilon_{e\tau}$ and hence a possible θ_{13} bound from MINOS will, in reality, be a bound on a combination of $\varepsilon_{e\tau}$ and θ_{13}.

In table II we display our results for a true value of $\theta_{13} = 0$ and no NSI. The allowed range for $\varepsilon_{e\tau}$ shrinks only very little by the inclusion of OPERA data. As in the case of $\varepsilon_{\tau\tau}$ we explicitly checked that this result is not due to the ν_τ sample in OPERA but is entirely due to the different L/E compared to MINOS. Also a two-fold increase of the OPERA exposure does not substantially alter the result.

In order to improve the sensitivity to NSI and to break the degeneracy between θ_{13} and $\varepsilon_{e\tau}$ it will be necessary to get independent information on either $\varepsilon_{e\tau}$ or θ_{13}. An improvement of direct bounds on $\varepsilon_{e\tau}$ is in principle possible by using a very high energy ν_e beam and a close detector, but this would require either a neutrino factory or a high γ beta beam. Both these possibilities are far in the future and will therefore not be considered any further in this letter. Thus, we focus on independent information on θ_{13}. Reactor experiments are very sensitive to θ_{13} but do not feel any influence from $\varepsilon_{e\tau}$ since the baseline is very short and the energy very low which leads to negligible matter effects. This is true for standard MSW-like matter effects as well as non-standard matter effects due to NSI [7]. We consider here as new reactor experiment

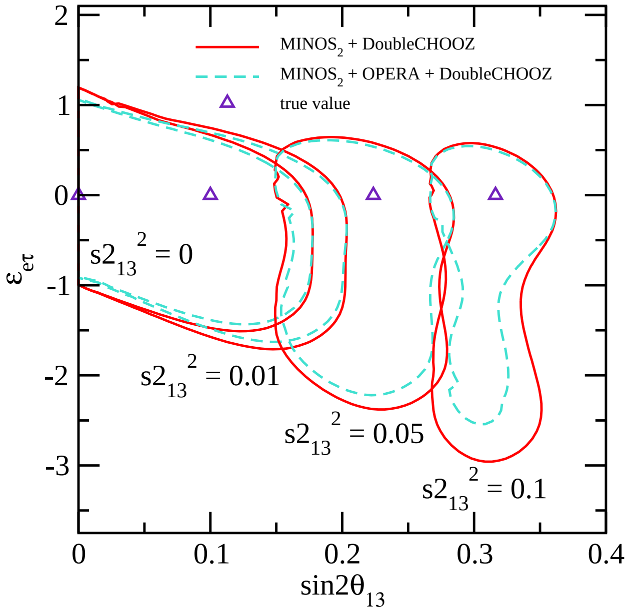

FIG. 2: Shown are the allowed regions in the $\sin 2\theta_{23}$-$\varepsilon_{e\tau}$-plane at 95% CL (2 dof). Δm^2_{31}, θ_{23} and $\varepsilon_{\tau\tau}$ are left free in this fit. The solid lines correspond to the combination of MINOS$_2$ and DoubleCHOOZ while the dashed lines also include OPERA in the analysis. Each set of lines correspond to different true values for $\sin^2 2\theta_{13}$, from left to right: 0, 0.01, 0.05 and 0.1.

	M2		O		M2+O		M2+O+DC	
	90% C.L.	95% C.L.	90% C.L.	95% C.L.	90% C.L.	95% C.L.	90% C.L.	95% C.L.
$\varepsilon_{\tau\tau}$	[-10.1,11.0]	[-11.2,12.0]	[-10.1,10.3]	[-10.8,11.0]	[-7.9,9.0]	[-8.7,9.6]	[-5.1,5.3]	[-5.6,5.8]
$\varepsilon_{e\tau}$	[-4.2,1.3]	[-4.5,1.5]	[-4.3,1.5]	[-5.0,1.8]	[-3.7,1.2]	[-4.1,1.4]	[-0.5,0.4]	[-0.7,0.5]
Δm^2_{31} [10^{-3} eV^2]	[2.3,4.6]	[2.2,5.0]	[2.0,4.8]	[2.0,5.2]	[2.3,4.0]	[2.2,4.2]	[2.3,2.8]	[2.3,2.9]
$\sin^2\theta_{23}$	[0.09,0.92]	[0.08,0.93]	[0.09,0.93]	[0.08,0.94]	[0.13,0.90]	[0.12,0.91]	[0.24,0.78]	[0.22,0.80]

TABLE III: Same as table II with true value $\sin^2 2\theta_{13}$ of 0.1.

DoubleCHOOZ [38], but for our discussion Daya Bay [39] or RENO [48] would work equally well. In figure 2 we show the allowed regions in the $\sin 2\theta_{13}$-$\varepsilon_{e\tau}$ plane for the combinations of MINOS and DoubleCHOOZ (red solid curves) and of MINOS, DoubleCHOOZ and OPERA (blue dashed curves) for four different input values of $\sin^2 2\theta_{13}$ indicated in the plot. As expected, the effect of DoubleCHOOZ in all four cases is to constrain the allowed $\sin 2\theta_{13}$ range. The impact of OPERA, given by the difference between the solid and dashed lines, is absent for very small true values of $\sin 2\theta_{13}$ and increases with increasing true values. For the largest currently permissible values of $\theta_{13} \simeq 0.16$, OPERA can considerably reduce the size of the allowed region and help to resolve the degeneracy. In that parameter region a moderate increase in the OPERA exposure would make it possible to constrain large negative values of $\varepsilon_{e\tau}$. Again, this effect has nothing to do with ν_τ detection and, in this case, is based on the different L/E in ν_e-appearance channel.

CONCLUSION

In this letter we have studied how OPERA can help in improving the sensitivities on neutrino non-standard contact interactions of the third family of neutrinos. In our analysis we considered a combined OPERA fit together with high statistics MINOS data, in order to obtain restrictions on neutrino oscillation parameters in the presence of NSI. Due to its unique ability of detecting ν_τ one would expect that the inclusion of OPERA data would provide new improved limits on the universality violating NSI parameter $\varepsilon_{\tau\tau}$. We found, however, that the ν_τ data sample is too small to be of statistical significance. This holds even if we double the nominal exposure of OPERA to 9×10^{19} pot. OPERA also has a ν_μ sample, which can help constraining NSI. Here the effect is due to the very different L/E of OPERA compared to MINOS. This makes the OPERA ν_μ sample more sensitive to NSI. However, the improvement is small and happens in a part of the NSI parameter space which is essentially excluded by atmospheric neutrino data.

We have also studied the possibility of constraining the FC NSI parameter $\varepsilon_{e\tau}$. For this purpose it is crucial to have a good knowledge of θ_{13}. Therefore, we included future DoubleCHOOZ data, since reactor neutrino experiments are insensitive to the presence of NSI of the type considered here. Therefore, reactor experiments can provide a clean measurement of θ_{13}, which in turn can be used in the analysis of long baseline data to probe the NSI. DoubleCHOOZ is only the first new reactor experiment and more accurate ones like Daya Bay or Reno will follow. Our result would be qualitatively the same if we would have considered those, more precise, experiments, but clearly the numerical values of the obtained bounds would improve. The conclusion for $\varepsilon_{e\tau}$ with respect to the ν_τ sample is the same as before: the sample is very much too small to be of any statistical significance. OPERA's different L/E again proves to be its most important feature and allows to shrink the allowed region on the $\sin^2\theta_{13}$-$\varepsilon_{e\tau}$ plane for large θ_{13} values. Here a modest increase in OPERA exposure would allow to completely lift the θ_{13}-$\varepsilon_{e\tau}$ degeneracy and thus to obtain a unique solution.

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