Sterile neutrinos as a source of CP violation

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Abstract. Several anomalous results have been reported at short-baseline neutrino oscillation experiments, which cannot be accommodated in the standard 3-flavor framework. The most popular interpretation of these anomalies entails new light sterile neutrinos (with mass in the eV range) which mix with the three ordinary "active" species. We show that the presence of sterile neutrinos induces new CP violating phenomena and how the the planned LBL experiments will be able to probe them.

1. Introduction

Several anomalous results have been reported in short-baseline (SBL) neutrino oscillation experiments, which cannot be explained in the standard 3-flavor scheme (see [1] for a recent review). The most popular interpretation of these anomalies involves new light sterile neutrinos (with mass in the eV range) which mix with the three ordinary "active" species.

In the simplest scenario, dubbed as 3+1 scheme, only one sterile neutrino species is introduced. The fourth mass eigenstate ν_4 is separated from the standard "triplet" (ν_1, ν_2, ν_3) by a large ($\sim 1\,\mathrm{eV}^2$) squared-mass, giving rise to the hierarchical spectrum $|\Delta m^2_{12}| \ll |\Delta m^2_{13}| \ll |\Delta m^2_{14}|$. The 4×4 mixing matrix can be parametrized as [2]

$$U = \tilde{R}_{34} R_{24} \tilde{R}_{14} R_{23} \tilde{R}_{13} R_{12}\,, \tag{1}$$

where R_{ij} ($\tilde{R}_{ij}$) is a real (complex) 4×4 rotation in the (i, j) plane. The complex rotations depend on the CP-phases δ_{ij}.

By construction, the $3 + 1$ scheme predicts sizable oscillation effects at the short baselines where the new frequency $\Delta_{14} = \Delta m^2_{14} L/4E$ (L being the baseline and E the neutrino energy) is of order one. However, sterile neutrinos may leave their signs also in non-short-baseline experiments. The effects of sterile species have been studied in the context of solar neutrinos [3, 4, 5], atmospheric neutrinos [6], and LBL experiments [2, 7, 8]. In what follows we concisely describe the potential role of LBL experiments in the searches of CP violation (CPV) related to sterile neutrinos.

2. CPV induced by sterile neutrinos at long-baseline experiments

In order to measure any CP phase one must be sensitive to the quantum interference of two distinct oscillation frequencies. In the 3+1 scheme, at SBL setups, only one frequency is

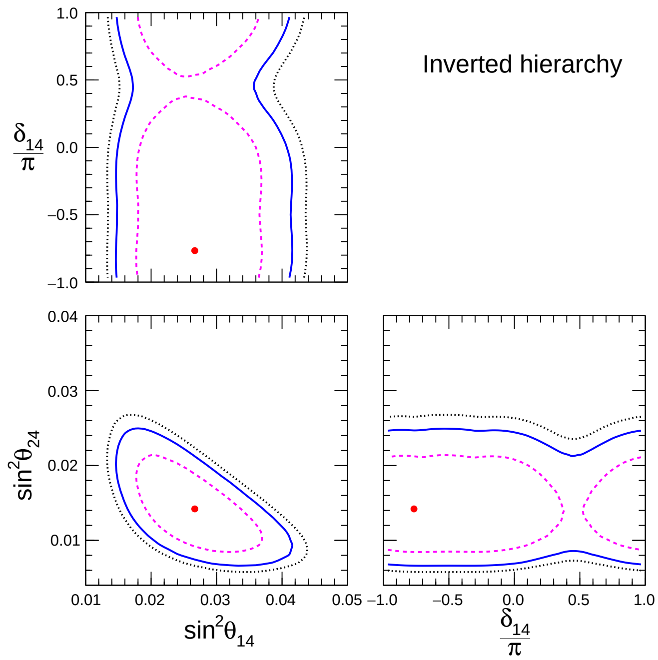

Figure 1. Regions allowed by the combination of the SBL and LBL data (NOνA and T2K) together with the θ_{13}-sensitive reactor results. Figure taken from [13].

observable (the new one) while the atmospheric and solar frequencies have no effect at all. For this reason the SBL setups have no sensitivity to CP violation (both in 3-flavor and 3+1 schemes). As first shown in [2], the situation is different at the long baseline (LBL) experiments, because in these setups the interference between two distinct frequencies becomes observable. In this way the LBL experiments can see both the effects of the standard CP phase and of the new ones. Therefore, the LBL setups are complementary to the SBL experiments in the searches related to the sterile neutrino properties.

We recall that the LBL experiments in the $\nu_\mu \to \nu_e$ (and $\bar{\nu}_\mu \to \bar{\nu}_e$) appearance channel are sensitive to the 3-flavor CPV because, at long baselines, the $\nu_\mu \to \nu_e$ transition amplitude contains an interference term between the atmospheric (Δm^2_{13}-driven) and the solar (Δm^2_{12}-driven) oscillations, which depends on the CP-phase δ. As first evidenced in [2], in the presence of sterile neutrinos a new interference term arises, which depends also on the new CP-phase (δ_{14}). In [2] (see also [10]), it has been shown that the transition probability can be approximated as the sum of three terms

$$P^{4\nu}_{\mu e} \simeq P^{\rm ATM} + P^{\rm INT}_{\rm I} + P^{\rm INT}_{\rm II}\,. \tag{2}$$

Remarkably, for typical values of the mixing angles predicted by the current global 3+1 fits [9], the amplitude of the new interference term is almost equal to that of the standard one. As a consequence, one expects some sensitivity of the LBL experiments NOνA [11] and T2K [12] to the non-standard CP-phase δ_{14}. Therefore, these two experiments and their constraints on the CP-phase δ_{14}, should be included in any accurate analysis of the 3+1 scheme. This has been done in the work [13], where a joint analysis of SBL and LBL data has been performed for the first time.

Figure 1, taken from such a work, displays the projections of the $\Delta\chi^2$ for inverted hierarchy (IH). The left-bottom panel reports the projection on the plane of the two mixing angles

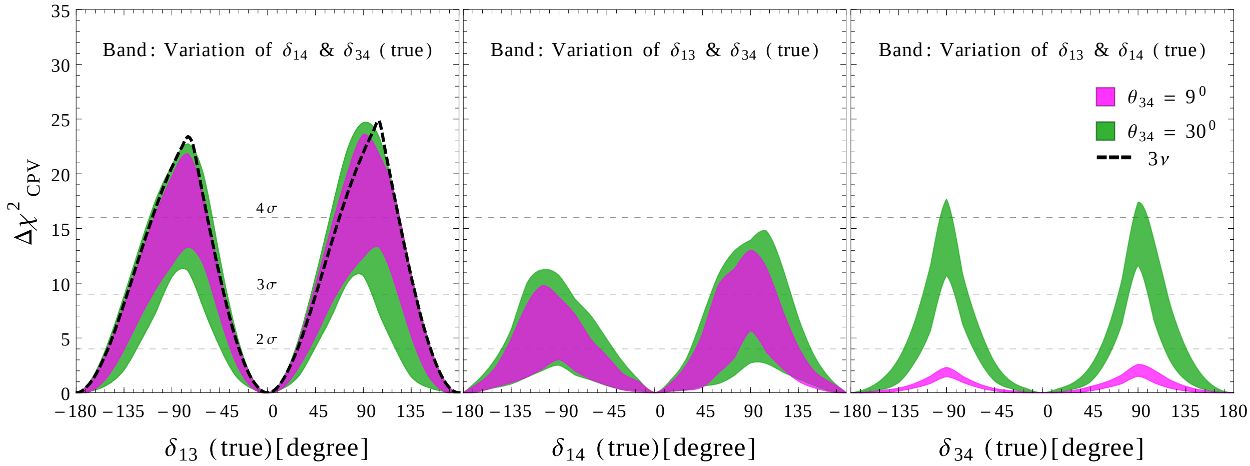

Figure 2. DUNE discovery potential of the CPV induced by the three CP phases involved in the 3+1 scheme. See the text for details. Figure taken from [15].

$(\theta_{14}, \theta_{24})$. The other two panels display the constraints in the plane formed by each one of the two mixing angles and the new CP-phase δ_{14}. Similar results (not shown) are obtained for normal hierarchy (NH). The three contours are drawn for $\Delta\chi^2 = 2.3,\ 4.6,\ 6.0$, corresponding to 68%, 90% and 95% C.L. for 2 d.o.f. The overall goodness of fit is acceptable (GoF = 24%), while the parameter goodness of fit, which measures the statistical compatibility between the appearance and disappearance data sets, is lower (GoF = 7%). This implies that even if the closed contours presented for the two new mixing angles θ_{14} and θ_{24} exclude the 3-flavor case with high significance (slightly more than six standard deviations), one cannot naively interpret this circumstance as an evidence for sterile neutrinos. In addition, we recall that light sterile neutrinos, unless endowed with new properties, are in tension with cosmological data.

Given that NOνA and T2K posses already a weak sensitivity to the new CP-phase δ_{14}, it is very interesting to ask how things will improve at the planned LBL experiments. This issue has been investigated in detail in the works [14, 15, 16, 17] (see also [18, 19]). In Fig. 2, taken from [15], we provide an illustrative example concerning the DUNE experiment. The bands displayed in the left, middle and right panels represent the discovery potential of the CPV induced, respectively, by δ_{13}, δ_{14} and δ_{34}. The thinner (magenta) bands correspond to the case in which all the three new mixing angles have the same value $\theta_{14} = \theta_{24} = \theta_{34} = 9^0$. The thicker (green) bands correspond to the situation in which $\theta_{14} = \theta_{24} = 9^0$ and $\theta_{34} = 30^0$. In each panel, the bands were obtained by varying the true values of the two undisplayed CP-phases in the range $[-\pi, \pi]$. In all cases, marginalization over the hierarchy was performed with NH as true choice. From Fig. 2 we learn that the sensitivity to δ_{14} will substantially increase at DUNE at the price of loosing some information on the standard CP phase δ_{13}.

Until now, we have focused on the discovery potential of the CPV generated by the two CP phases δ_{13} and δ_{14}. Here, we investigate the capability of reconstructing the true values of the two CP phases. With this purpose we consider the four benchmark cases displayed in Fig. 3. The two upper panels represent the CP-conserving scenarios $[0, 0]$ and $[\pi, \pi]$. The third and fourth panels represent two CP-violating cases $[-\pi/2, -\pi/2]$ and $[\pi/2, \pi/2]$. In each panel, we draw the regions reconstructed around the true values of δ_{13} and δ_{14} by the three experiments T2K+NOνA, DUNE and T2HK. In this plot we have taken the NH as the true hierarchy and we have marginalized over the two possible hierarchies in the test model. The confidence levels

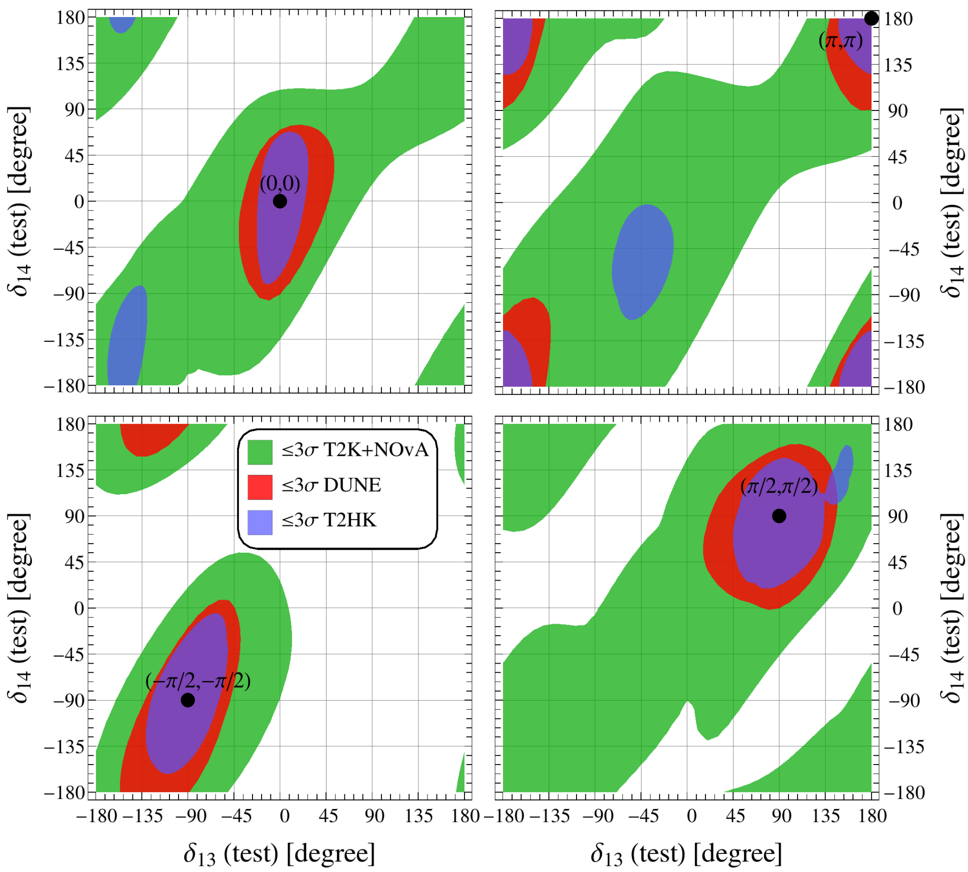

Figure 3. Reconstructed regions for the two CP phases δ_{13} and δ_{14} for three different experimental setups. We have taken the NH as the true hierarchy and we have marginalized over the two possible hierarchies in the test model. The contours correspond to the 3σ level. Figure taken from [17]

correspond to 3σ (1 d.o.f.). The plots clearly show that there is huge gain when going from T2K+NOνA to the new generation experiments DUNE and T2HK. Concerning these two last experiments, the figure shows that T2HK is slightly more precise than DUNE in reconstructing the region around the true values CP phases. However, while in T2HK there are small spurious islands, this does not happen in DUNE. This different behavior is rooted in the fact that the degeneracy between δ_{13} and sgn(Δm^2_{31}) is less pronounced in DUNE. This, in turn, happens because DUNE can neatly separate the two hierarchies thanks to the larger matter effects.

3. Conclusions

In the case of a discovery of a light sterile neutrino at a new short-baseline experiment we will face the challenge of determining all the parameters that govern the extended framework and in particular the new CP-violating phases. In this context LBL experiments can give an important contribution being sensitive to new CP-violation phenomena. Therefore, the two classes of experiments (SBL and LBL) will be synergic in the searches of sterile neutrinos.

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