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Long baseline experiments: a new window on sterile neutrinos

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Several anomalies observed in short-baseline neutrino experiments suggest the existence of light sterile neutrinos. Here, we present a brief review of the status of the neutrino oscillations within the 3+1 scheme emphasizing the potential role of LBL experiments in the searches of new CP violating phases related to sterile neutrinos.

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1. Introduction

A long series of experiments performed in the last twenty years has established that neutrinos are massive and mix. A few 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]

$$U = \tilde{R}_{34} R_{24} \tilde{R}_{14} R_{23} \tilde{R}_{13} R_{12}\,, \tag{1.1}$$

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. Sterile neutrinos at long-baseline experiments

The short-baseline experiments are without doubt the best place where to look for sterile neutrinos and certainly, if a breakthrough will come, it will take place at a SBL experiment. However, the SBL experiments have an intrinsic limitation which would impede to further study the properties of the 3+1 scheme. In particular, they are insensitive to the three CP-violation phases involved in such a scheme. In fact, CP-violation is a genuine 3-flavor phenomenon, whose observation requires the sensitivity to the *interference* between at least *two independent* oscillation frequencies. In a SBL experiment only the new largest oscillation frequency ($\Delta_{14} \sim 1$) is visible, while both the atmospheric and the solar splittings are substantially unobservable ($\Delta_{13} \simeq \Delta_{12} \simeq 0$). Therefore, this class of experiments is blind to CP-violation effects.[1] Other kinds of experiments are necessary to access the CP violation induced by sterile neutrinos. We are lucky because these experiments already exist. We are talking of the LBL experiments, both those already operational and the planned ones. As a matter of fact, although such experiments were originally designed to seek the standard CP-phase δ, they are also capable to provide information about other sources of CP violation. This is not obvious a priori and it is true only because, as we will see below, a new interference term

[1] In the $3+N_s$ schemes with $N_s > 1$, CPV could be observed at SBL experiments. However, these setups can probe only a limited number of all the CP phases involved in the model. In contrast, LBL experiments have access to all such phases. For example, in the 3+2 scheme, the SBL experiments are sensitive only to one CP-phase over a total of five observable CP-phases.

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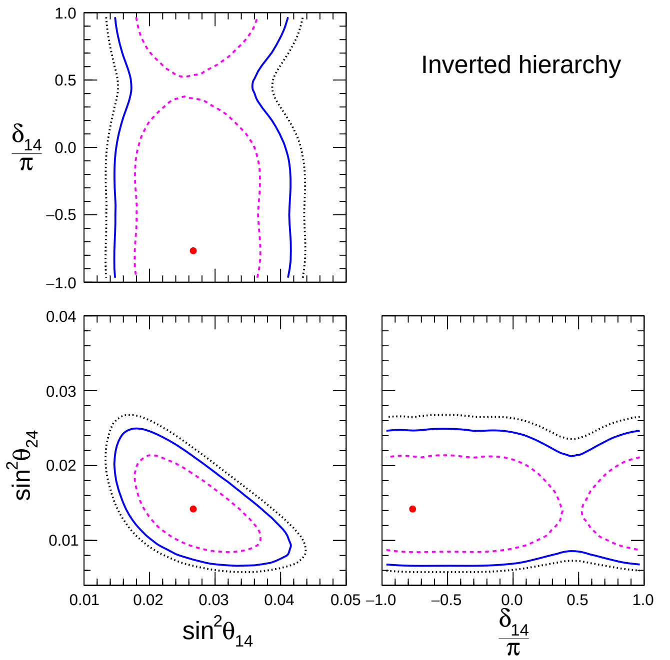

Figure 1: Regions allowed by the combination of the SBL and LBL data (NOνA and T2K) together with the θ_{13}-sensitive reactor results. Figure taken from [13].

arises in the presence of sterile neutrinos, which has exactly the same order of magnitude of the standard 3-flavor interference term.

We recall that the LBL experiments, when working 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 develops 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 not only from $\delta \equiv \delta_{13}$ but also from one new CP-phase (δ_{14}). From the discussion made in [2] (see also [10]), it emerges that the transition probability can be approximated as the sum of three terms

$$P^{4\nu}_{\mu e} \simeq P^{\rm ATM} + P^{\rm INT}_{\rm I} + P^{\rm INT}_{\rm II}\,. \tag{2.1}$$

Remarkably, for typical values of the mixing angles preferred by the current global 3+1 fits [9], the amplitude of the new interference term is almost identical 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 presented 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 $(\theta_{14}, \theta_{24})$. 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

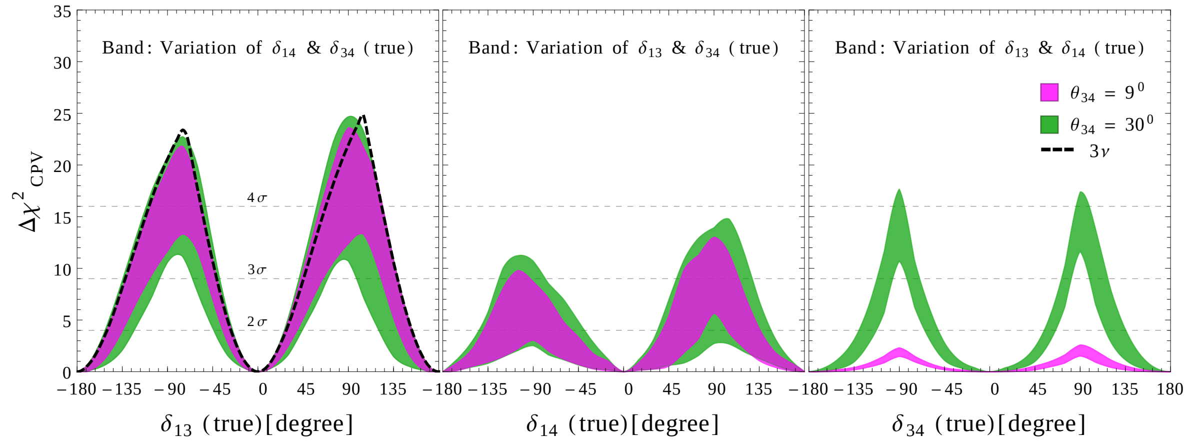

Figure 2: DUNE discovery potential of the CPV induced by the three CP phases involved in the 3+1 scheme. See the text for details. Figure taken from [15].

(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] (see also [17, 18]). 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}.

3. Conclusions

In the case of a discovery 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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