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DUNE sensitivities to the mixing between sterile and tau neutrinos

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Most of neutrino events observed from neutrinos produced in the Sun, from interactions in the Earth atmosphere, and neutrinos from artificial sources such as the ones produced in reactor and accelerator-based experiments are well described by neutrino oscillations within the three active neutrino framework. However, the existence of extra light sterile neutrino states, mainly motivated by different anomalies (like LSND and reactor), has not been yet established. In order to reject the light sterile hypothesis (or to discover a new oscillation phase around the eV scale), an enormous effort is being pursued by current and future experimental collaborations. In this talk (based on the work [1]) I will focus on the role of the long-baseline (LBL) neutrino experiments, in particular DUNE, to constrain the tau-sterile mixing angle in the economical framework of having only one extra light sterile neutrino state. As it will be discussed, at LBL experiments the neutral-current data is directly sensitive to the presence of light sterile neutrinos.

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1. Introduction

Neutrino flavor transitions have been observed from different neutrino sources like the Sun and cosmic ray interactions with the Earth atmosphere, and also in neutrinos artificially produced in reactor and accelerator experiments. This wealth of observations have established neutrino oscillations as the mechanism behind the observed neutrino flavor transitions. Another important piece of information is the number of active neutrinos, compatible with three, which comes from the measurement of the invisible Z decay width [2]. Neutrino oscillations with three active neutrinos are not only minimal, but more importantly, successfully accounts for most of the observations. However, extra neutrino flavor states, that do not interact with the Standard Model gauge bosons i.e. have to be sterile, are implied in different neutrino mass models and also motivated by some anomalies. In the first case, extra heavy leptons are needed in seesaw type-I models (including the low-scale seesaw) but they are decoupled from neutrino oscillations and one of their signatures is the unitarity deviation of the effective lepton mixing matrix. Here, we focus in the so called *light sterile* neutrino that is motivated by the short baseline (SBL) anomalies, mainly LSND, MiniBoone, gallium and reactor anomalies. Therefore, SBL anomalies imply an extra oscillation frequency driven by a $\Delta m^2 \sim 1\text{eV}^2$, which is three (four) orders of magnitude larger than the atmospheric (solar) mass squared difference. So far, there is no observation of an extra oscillation frequency in Nature, nevertheless, an important experimental effort is devoted to confirm or rule out the sterile hypothesis. The search for sterile oscillation frequency is perform within a model and the most economical one to accommodate an extra light sterile neutrino state is the so call $3+1$ framework. From the negative observation of an sterile oscillation, several experimental collaborations have reported limits to the active-sterile mixing within the $3+1$ framework [3, 4, 5, 6, 7, 8].

Besides the possibility to test the sterile hypothesis directly in SLB experiments, or by the use of a near detector (ND) of a given long-baseline (LBL) experiment, it is also possible to use the far detector (FD) of a LBL experiment, that can be at the order of hundreds to thousand kilometers away from the production point. At the FD, generally planned to observe neutrino oscillations driven by the atmospheric splitting, it is only possible to study the rapid oscillation (or averaged-out) regime of the sterile oscillations. Otherwise, it is sensitive to lower values of the sterile mass splitting, below $\sim 0.5\text{eV}^2$, making possible to test a complementary Δm^2 parameter space respect to what SBL experiments can probe. In particular, searches for an sterile oscillations at the far detector of LBL experiments have been performed by several collaborations using neutral-current (NC) events in their analysis [3, 4, 6, 8]. Several phenomenological studies have considered the sterile effects at LBL experiments by the use of charge-current events [9, 10, 11, 12, 13, 14, 15]. Here, we summarize the formalism, the main assumptions, and some of the analysis performed in Ref [1] using NC events at the DUNE FD.

2. Formalism

Assuming an extra neutrino flavor state s, flavor and mass eigenstates are connected via:

$$\nu_\alpha = U^*_{\alpha i}\nu_i\,, \tag{2.1}$$

with $\alpha = e, \mu, \tau, s$, and U is the extended lepton mixing matrix. In the simplest case of the $3+1$ framework U can be parametrized adding the three extra rotations related with the fourth mass index. We arbitrarily assumed the following parametrization:

$$U = O_{34} V_{24} V_{14} O_{23} V_{13} O_{12}\,, \tag{2.2}$$

where O_{ij} (V_{ij}) denotes a real (complex) rotation. Therefore we have three new mixing angles $\theta_{\alpha 4}$ and two new Dirac CP phases, δ_{14} and δ_{24}. With one extra mass eigenstate, we also have three Δm^2_{4k} mass squared differences, which can be written using the standard solar and atmospheric splittings in terms of only Δm^2_{41}.

Using probability conservation for the muon neutrino transition we can write $\sum_\alpha P_{\mu\alpha} = 1$ or $\sum_{\beta=e,\mu,\tau} P_{\mu\beta} = 1 - P_{\mu s}$, which implies that a non-zero sterile appearance probability results in $\sum_{\beta=e,\mu,\tau} P_{\mu\beta} < 1$, i.e in a depletion of the sum over the three standard neutrino flavors. This is the main concept that can be exploited by the use of NC events, as we will see later.

When the baseline over the energy is such that a given oscillation experiment is sensitive to atmospheric neutrino oscillations one can safely neglect the solar contribution. In this case, the sterile oscillation appearance probability is given by:

$$\begin{aligned} P_{\mu s} \equiv P(\nu_\mu \to \nu_s) = {} & 4|U_{\mu 4}|^2 |U_{s4}|^2 \sin^2\Delta_{41} + 4|U_{\mu 3}|^2|U_{s3}|^2 \sin^2\Delta_{31} \\ & + 8\,\mathrm{Re}\left[U^*_{\mu 4} U_{s4} U_{\mu 3} U^*_{s3}\right] \cos\Delta_{43} \sin\Delta_{41} \sin\Delta_{31} \\ & + 8\,\mathrm{Im}\left[U^*_{\mu 4} U_{s4} U_{\mu 3} U^*_{s3}\right] \sin\Delta_{43} \sin\Delta_{41} \sin\Delta_{31}\,, \end{aligned} \tag{2.3}$$

As usually assumed in previous analysis done by experimental collaborations [3, 4, 6, 8], one can neglect the electron-sterile mixing angle since it is tightly constrain by reactor and solar experiments [16]. Therefore, along this letter we assume $\theta_{14} = 0$. Figure 1 shows the sterile oscillation probability in Eq.(2.3) for a given set of sterile parameters. The purpose of the figure is twofold, it shows the important effect of the δ_{24} Dirac CP phase (three panels) and the behavior of the sterile appearance probability with Δm^2_{41} (three lines). Total cancellation of the oscillation amplitude are shown in left panel for $\delta_{24} = 0$ and $\Delta m^2_{41} = \Delta m^2_{31}$, and also in the right panel for $\delta_{24} = \pi$ and $\Delta m^2_{41} = 10^{-4}\,\mathrm{eV}^2$. This cancellations have a strong impact in the sensitivity results [1].

3. Analysis and results

We assume that no sterile oscillations have taken place at the ND and we study oscillations at the FD. Therefore, at the FD, sensitivity to lower values of the sterile mass splitting, below $\sim 0.5\mathrm{eV}^2$, can be tested and they are complementary to what SBL experiments probes. Following previous analysis, here we make use of the NC events at the FD:

$$\begin{aligned} N_{NC} &= N^e_{NC} + N^\mu_{NC} + N^\tau_{NC} \\ &= \phi_{\nu_\mu}\, \sigma^{NC}_\nu \left\{P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu) + P(\nu_\mu \to \nu_\tau)\right\} \\ &= \phi_{\nu_\mu}\, \sigma^{NC}_\nu \left\{1 - P(\nu_\mu \to \nu_s)\right\}\,, \end{aligned} \tag{3.1}$$

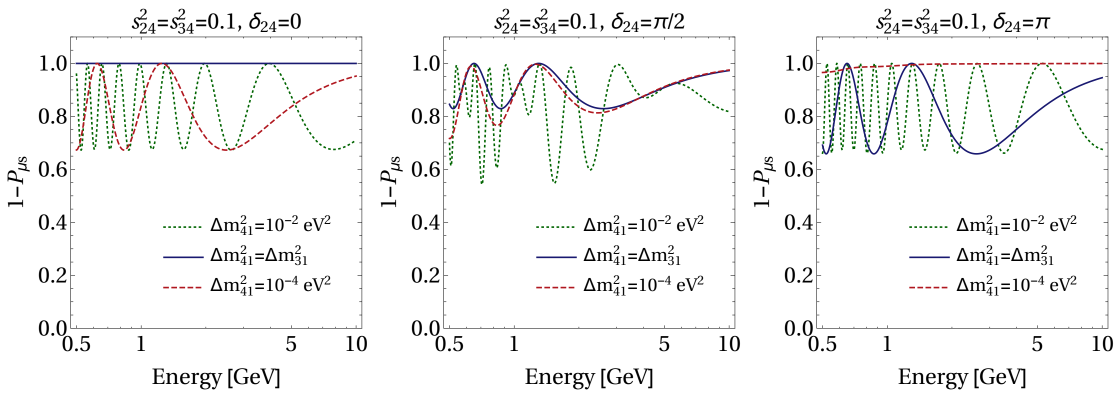

Figure 1: Oscillation probability $1-P_{\mu s}$, in vacuum. The different panels correspond to different values of the new CP-violating phase δ_{24}, while the different lines shown in each panel correspond to different values of the active-sterile mass splitting Δm^2_{41} that define the main oscillation regimes relevant at the FD of a LBL experiment, as indicated in the legend. The rest of the oscillation parameters have been fixed to: $\Delta m^2_{31} = 2.48\times10^{-3}$ eV^2; $\sin^2\theta_{23} = 0.5$; $\sin^2 2\theta_{13} = 0.084$; and $\sin^2\theta_{24} = \sin^2\theta_{34} = 0.1$.

Where σ^{NC}_{ν} and ϕ_{ν_μ} are the NC cross section and the muon neutrino flux, respectively. Therefore the 'smoking gun' for an sterile appearance is a depletion in the number of NC events at the FD with respect to the three flavor prediction. The background in this case are the $\nu_{e,\mu,\tau}$-CC events potentially misidentified as NC events. Here we study DUNE FD capabilities to constrain the tau-sterile mixing angle with the following details of the analysis:

- Energy reconstruction:
  - Signal: Migration matrix that accounts for the correspondence between a given incident neutrino energy and the amount of visible energy deposited in the detector from Ref. [17].
  - Background: Gaussian energy resolution function, following the DUNE CDR values [18].
- Efficiencies:
  - Signal: A flat 90% efficiency was assumed as a function of the energy reconstruction.
  - Background: Rejection efficiency at the level of 90%, except for taus (irreducible background).
- Systematical errors, implemented as nuisance parameters:
  - Signal: Total normalization (norm) and shape uncertainties.
  - Background: Total normalization (norm).

The nuisance parameters are taken to be uncorrelated between ν and $\bar{\nu}$ channels as well as between the different contributions to the signal and/or background events (see Ref [1] for further details).

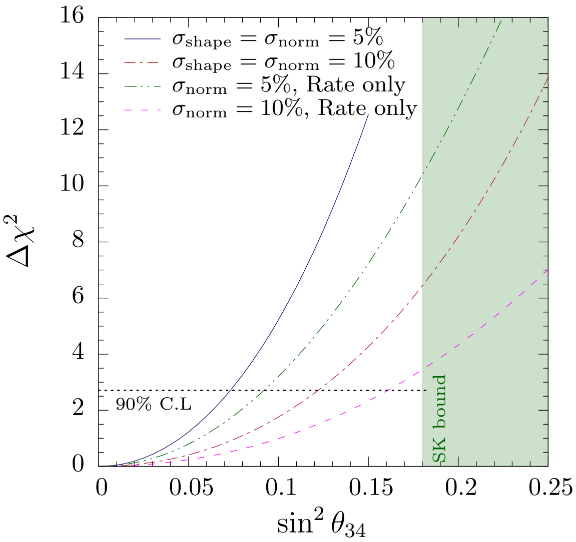

Figure 2: Expected sensitivity to θ_{34} under the assumption $\theta_{14} = \theta_{24} = 0$. The different lines correspond to different assumptions of systematical uncertainties, total normalization of signal and background and shape uncertainties in the signal. The shaded region is disfavored at 90% C.L. from Super-Kamiokande atmospheric data [5] which translates into the constraint $\sin^2\theta_{34} < 0.15$. The horizontal dotted line indicates the value of the $\Delta\chi^2$ corresponding to 90% C.L. for 1 d.o.f..

By the time DUNE will be running, it is expected that pre-DUNE facilities, current and future ones, will tightly constrain the electron and muon sterile-active mixing. Thus, here we additionally assume $\theta_{24} = 0$ and consider the simplest case of having only a non-trivial tau-sterile mixing. In the $\theta_{24} \to 0$ limit, the sterile appearance probability is simply given by $P_{\mu s} = c_{13}^4 \sin^2 2\theta_{23} s_{34}^2 \sin^2\Delta_{31}$, which is Δm_{41}^2-independent and therefore there is no effect on the ND. Additionally, the sterile appearance probability is independent of new Dirac CP phases and thus no prone to amplitude cancellations. So, a clean constraint on θ_{34} can be obtained. In the Fig. 2 we show DUNE constraints to the tau-sterile mixing under benchmark values of the systematical errors. If DUNE collaboration is able to control the systematical errors (total normalization in signal and background and shape uncertainties) of the order of %5, DUNE will constrain $\sin^2\theta_{34} < 0.07$ at the 90% of C.L.

In summary, taking advantage of the excellent capabilities of liquid Argon to discriminate between CC and NC events, we have describe one of the three studies performed in Ref. [1] considering sterile neutrino oscillations (in the 3+1 scheme) at the DUNE FD by the use NC events. Given the current and future limits on the θ_{14}, θ_{24} sterile-active mixing angles, the case $\theta_{24} = \theta_{14} = 0$ becomes relevant by the time DUNE will be running. In this case, the ν_s appearance probability is independent of Δm_{41}^2 and δ_{24}, providing a unique sensitivity to the tau-sterile mixing. Assuming 10% systematics, DUNE will be sensitive to values of $\sin^2\theta_{34} \sim 0.12$ (at 90% CL) improving the current constraints. If systematic errors could be reduced down to 5%, the experimental sensitivity would reach $\sin^2\theta_{34} \sim 0.07$ (at 90% CL).

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