PROCEEDINGS OF SCIENCE

Non-unitarity and sterile neutrinos at the DUNE near detector

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We study the capabilities of the DUNE near detector to probe the 3+1 sterile formalism and the non-unitarity of the leptonic sector. We add to the current analyses in the literature, the use of the charged current events for the ν_τ appearance channel and the consideration of the energy spectral uncertainty (shape uncertainty) for the different channels which plays an important role, especially at the near detector, and has been often overlooked in the literature. We find that even with this more conservative and realistic approach, we still obtain an improvement in the sensitivity with respect to current bounds.

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1. Introduction

The new generation of long-baseline neutrino oscillation experiments such as DUNE are expected to probe the robustness of the three-neutrino oscillation picture to a high level of accuracy. They will also give stronger bounds and/or possibly detect deviations from the standard picture. However, the ability to probe new physics in oscillations is going to be heavily affected by systematic uncertainties coming from our lack of knowledge of the cross sections and fluxes involved. In the case of the near detector (ND), these uncertainties are even larger.

2. Theoretical framework and notation

This proceeding summarizes our results regarding the sensitivity to non-unitarity and light sterile neutrinos in Ref. [1].

A simple way to account for light neutrino masses is to add singlet fermions to the SM field content. The matrix mixing between the mass and flavor basis can be expressed as:

$$\mathcal{U} = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}, \tag{1}$$

Here N is a 3×3 non-unitary matrix corresponding to the PMNS active-light sub-block. The value of the mass of the new states will determine whether they can be produced in the neutrino beam or not, changing the phenomenology we expect to observe. We have two distinct cases: if their mass lies above the production threshold of the neutrino source they cannot be produced, this scenario is usually referred to as Non-unitarity (NU); whereas if the new states are kinematically accessible we call them light sterile neutrinos.

2.1 Parameterization

We will parametrize the deviations from unitarity of the matrix N as follows [2–5]:

$$N = (I - T)U \tag{2}$$

where T is given by:

$$T = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}, \tag{3}$$

and U plays the role of the standard (unitary) PMNS matrix up to small corrections encoded in $\alpha_{\gamma\beta}$.

2.2 Non-Unitarity from new physics above the electroweak scale

In this scenario, the heavy states are integrated out from the low-energy spectrum and are thus not kinematically accessible in the experiment. At very short distances, as the ones in the DUNE ND, the standard oscillations do not have time to develop, yielding the following simple expressions for the oscillations probabilities:

$$\begin{aligned} P_{\mu e}(L = 0) &= |\alpha_{\mu e}|^2, \\ P_{\mu\tau}(L = 0) &= |\alpha_{\tau\mu}|^2. \end{aligned} \tag{4}$$

2.3 Sterile neutrinos & Non-Unitarity from new physics at low scales

As we mentioned, sterile neutrinos are kinematically accesible and we expect a new oscillation frequency. For simplicity, we consider the 3 + 1 scenario in which only one new neutrino is introduced. At very short baselines, the oscillation probabilities read:

$$\begin{aligned} P_{\gamma\beta} = &\quad \sin^2 2\vartheta_{\gamma\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right), &\quad \text{with} \quad \sin^2 2\vartheta_{\gamma\beta} \equiv 4\,|\mathcal{U}_{\beta 4}|^2 |\mathcal{U}_{\gamma 4}|^2, \\ P_{\beta\beta} = &\quad 1 - \sin^2 2\vartheta_{\beta\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right), &\quad \text{with} \quad \sin^2 \vartheta_{\beta\beta} \equiv |\mathcal{U}_{\beta 4}|^2 \,. \end{aligned} \tag{5}$$

In the averaged-out regime they further simplify to:

$$P_{\mu e} = 2\,|\mathcal{U}_{\mu 4}|^2 |\mathcal{U}_{e4}|^2 = 2|\alpha_{\mu e}|^2, P_{\mu\tau} \;=\; 2\,|\mathcal{U}_{\mu 4}|^2 |\mathcal{U}_{\tau 4}|^2 = 2|\alpha_{\tau\mu}|^2 \tag{6}$$

Notice that, barring the factor 2, the new physics effects here are identical to those given in Eq. 4. Thus we can consider this regime as a low-scale source of non-unitarity effects.

3. Results

At the DUNE ND the sensitivity will be dominated by the spectral information, since even for a value of $\alpha_{\gamma\beta}$ that saturates the present bound the signal is much smaller than the background. The sensitivity comes mainly from the differences in energy shape between the background and signal. Shape uncertainties are generally overlooked in the literature.

Comparing Eq. (4) with Eq. (6), we see that in the appearance channels there is only a factor 2 difference, and therefore, the results can be rescaled from one scenario to the other. Even though, in oscillations they only differ by this factor 2, the bounds that apply for to each scenario are different. In the Non-unitarity scenario we have very strong bounds from high-precision measurements of electroweak processes which are not expected to be improved by near future oscillation experiments. However, these constraints do not apply when the sterile neutrinos are kinematically accessible. See [1, 6] for details.

Therefore, our results shown in Fig. 1 for $\alpha_{\mu e}$ (left panel) and $\alpha_{\tau\mu}$ (right panel), respectively, correspond to the averaged-out regime of the steriles. The different lines show the results for different choices of systematic uncertainties as indicated by the labels, as a function of running time.

In the sterile neutrino scenario, the DUNE ND will be sensitive to different oscillation channels. Figure 2 shows the DUNE ND sensitivity to combination of mixing matrix elements that appear in $P_{\mu e}$. Looking at Eq. 5 we can see that the same parameters are accessible by the combination of P_{ee} and $P_{\mu\mu}$. Therefore, the three channels together will give us the best sensitivity.

4. Conclusions

In this work we have studied the sensitivity to new physics affecting neutrino oscillations in the DUNE ND. We have presented a conservative but realistic approach, including shape uncertainties,

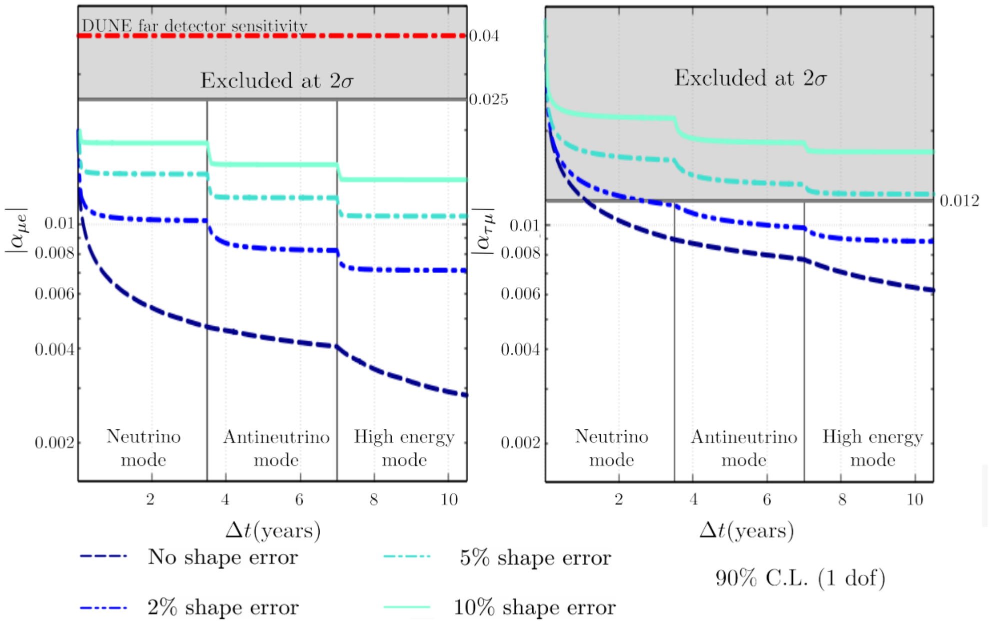

Figure 1: Sensitivity to the off-diagonal NU parameters $\alpha_{\mu e}$ (left panel) and $\alpha_{\tau\mu}$ (right panel). The lines show the sensitivity at 90% CL for 1 degree of freedom (d.o.f.) as a function of the running time Δt. The vertical lines indicate the changes between neutrino and antineutrino running modes (in the nominal beam scenario) as well as the change to the high-energy beam.

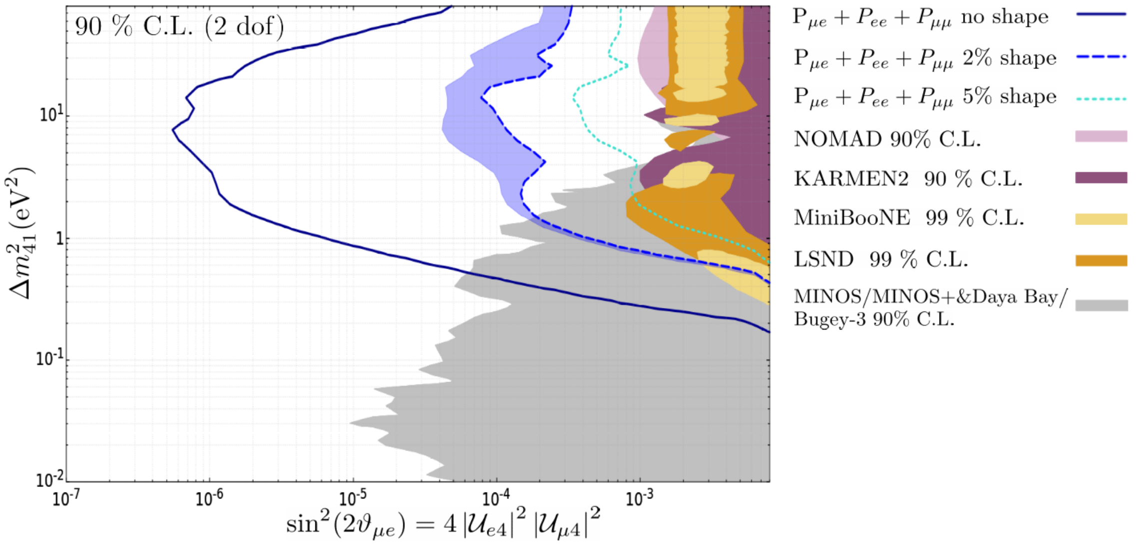

Figure 2: Expected sensitivity to the sterile neutrino scenario, for oscillations in the $P_{\mu e}$ channel. The shaded band to the left of the dashed lines indicate the increase in sensitivity due to the addition of 3.5 years of data taken in the high energy mode.

for different scenarios and channels. Even though, the expected sensitivity is, therefore, reduced we generally expect an improvement over present bounds.

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