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New sources of leptonic CP violation at the long baseline experiments

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Many new physics models can bring in the neutrino oscillation probabilities new sources of CP violation. We investigated how Non-Standard-Interactions and sterile neutrinos in the 3+1 model can modify CP-odd observables like the asymmetries $A_{\alpha\beta} \sim P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$. Then, we studied the potential of the DUNE experiment to look for hints of new physics measuring only such asymmetries related to different oscillation channels. We showed that if an high energy flux is used, the $A_{\mu e}$ asymmetry could be very useful for this purpose.

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1. Introduction

Flavor oscillations in the neutrino sector are a well established phenomenon. However, current experiments are able to determine the mixing parameters with uncertainties of the order of few percents, leaving room to possible new physics effects. For example, two appealing and widely studied models are the 3+1 [1] model, which consists in the presence of a fourth sterile neutrino state, and the Non-Standard Interactions (NSI) [2] model, which considers the possibility that when neutrinos propagate through matter, some sort of interactions not included in the standard model can occur [1]. Both models introduce new complex phases in the oscillation probabilities which can be sources of non standard CP violation. The presence of these new phases can modify CP-odd observables such as the asymmetries $A_{\alpha\beta} \sim P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$, which can be directly measured at experiments capable of the discrimination between neutrino and antineutrino events.
In our work, we want to understand if it will be possible to find hints of the presence of new physics only through the measurement of the number of neutrino and antineutrino events at long-baseline experiments. We considered as case study the 1300 km baseline Deep Underground Neutrino Experiment (DUNE) [4].

2. CP asymmetries in the standard model and beyond

From the neutrino oscillation probabilities, we can define the CP-odd asymmetries as:

$$A_{\alpha\beta} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \,. \tag{1}$$

These quantities are very difficult to handle and in order to get readable expressions, we expanded them up to the second order in different small parameters. In particular, we chose the ratio between the mass splittings $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ and the deviations of the mixing angles values from the tribimaximal mixing model predictions r, s and a defined by the relations $\sin\theta_{13} = \frac{r}{\sqrt{2}}$, $\sin\theta_{12} = \frac{1}{\sqrt{3}}(1+s)$ and $\sin\theta_{23} = \frac{1}{\sqrt{2}}(1+a)$. Eventually, we expanded our expressions up to the first order in the matter parameter V_{CC}. At the leading order (for the complete expressions see [5]), the $A_{\mu i}$ asymmetries can be written as

$$\begin{aligned}
A_{\mu e} &= -\frac{4\,\alpha\Delta_{31}\sin\delta}{3r} - 2V_{CC}\left(\Delta_{31}\cot\Delta_{31} - 1\right) \\
A_{\mu\tau} &= \frac{4}{3} r\alpha\Delta_{31}\sin\delta - 2V_{CC}r^2\left(1 - \Delta_{31}\cot\Delta_{31}\right) \\
A_{\mu\mu} &= \frac{4}{3} V_{CC} r\alpha\Delta_{31}\cos\delta\left(\Delta_{31} - \tan\Delta_{31}\right) .
\end{aligned} \tag{2}$$

where $\Delta_{31} = \Delta m^2_{31} L/4E_\nu$. It is clear that, when standard oscillations are considered, the $\mu - e$ asymmetry is of $O(1)$ while the $\mu - \tau$ and the $\mu - \mu$ ones are suppressed by at least two small parameters.
If we include the Non-Standard-Interactions, the matter potential matrix has to be modified introducing five new parameters: ε_{ee}, $\varepsilon_{\tau\tau}$, $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$ and $\varepsilon_{\mu\tau}$. The three off-diagonal parameters are in

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[1] Notice that the sterile neutrino model can in principle be translated into the NSI one (in the case of constant matter density) integrating out the sterile states[3].

general complex and therefore they bring new CP-violating phases δ_{ij} in the oscillation probabilities. The asymmetries are thus modified; the NSI contributions, expanding up to the second order also in the NSI couplings, are, at the leading order,

$$\begin{aligned} A^{NSI}_{\mu e} &= V_{CC}\ \varepsilon_{e\mu} a^{\varepsilon_{e\mu}}_{\mu e}(\delta_{e\mu}) + V_{CC}\ \varepsilon_{e\tau} a^{\varepsilon_{e\tau}}_{\mu e}(\delta_{e\tau}) \\ A^{NSI}_{\mu\tau} &= 8V_{CC}\ \varepsilon_{\mu\tau}\cos\delta_{\mu\tau}\Delta_{31}\cot\Delta_{31} \\ A^{NSI}_{\mu\mu} &= -8V_{CC}\ \varepsilon_{\mu\tau}\Delta_{31}\cos\delta_{\mu\tau}\tan\Delta_{31} - 4r\varepsilon_{e\mu}\Delta_{31}\cos\left(\delta-\delta_{e\mu}\right)\tan\Delta_{31} \end{aligned} \tag{3}$$

where $a_{\mu e}$ and $a_{e\tau}$ are complicated $O(1/r)$ function. The largest corrections appears again in the $\mu - e$ asymmetry.

In the 3+1 model, we introduce a fourth sterile neutrino heavier than the other three (we considered $\Delta m^2_{41} \sim 1\, eV^2$). In this model, the mixing matrix is a 4×4 unitary matrix, which can be parameterized in terms of six mixing angles and three phases (two more than in the standard case). Considering the parameterization $U = R(\theta_{34})R(\theta_{24})R(\theta_{23},\delta_3)R(\theta_{14})R(\theta_{13},\delta_2)R(\theta_{12},\delta_1)$ in terms of rotation matrices expanding the asymmetries up to the second order in the new mixing angles and averaging out the fast oscillations driven by Δm^2_{41}, we obtain

$$\begin{aligned} A^{3+1}_{\mu e} &= s_{14}s_{24}\ f(\delta_1,\delta_2,\delta_3) \\ A^{3+1}_{\mu\tau} &= 2s_{24}s_{34}\cot\Delta_{31}\left(\sin\delta_3 - 2V_{NC}\Delta_{31}\cos\delta_3\right), \\ A^{3+1}_{\mu\mu} &= 4s_{24}s_{34}V_{NC}\Delta_{31}\cos\delta_3\tan\Delta_{31} \\ A^{3+1}_{\mu s} &= -\frac{2s_{24}s_{34}\sin\delta_3\sin\Delta_{31}\cos\Delta_{31}}{2s^2_{24} + (s^2_{34} - s^2_{24})\sin^2\Delta_{31}}\,. \end{aligned} \tag{4}$$

where f is a $O(1/r)$ function and $s_{ij} = \sin\theta_{ij}$. Notice that the neutral current matter potential V_{NC} must no longer be ignored; moreover, in this model, we also have a fourth asymmetry, related to the fact that muon neutrinos can oscillate in the fourth state. The biggest 3+1 correction to the asymmetries is the one related to the $\mu - s$ transition, followed by the $\mu - e$ one.

3. Searching for new physics effects at DUNE using asymmetries

The DUNE experiment [4] will be a near future long-baseline oscillation experiment based in the USA. The baseline will be 1300 km, and the far detector, located at the Sanford Underground Research Facility (SURF) in South Dakota, will consist of a 40kt LAr-TPC. This experiment is expected to be able to run both in neutrino and antineutrino modes, providing a broad band ν_μ (or $\bar{\nu_\mu}$) on-axis beam at the far site. The proposed flux is peaked at an energy of 2.5 GeV, so to sit at the first atmospheric oscillation maximum at the far detector. However, an even broader high energy flux peaked at roughly 5 GeV [6] is under consideration. As shown in our work, such an high energy flux could be particularly useful for new physics searches. The DUNE experiment will in principle be able to study not only the ν_μ disappearance and the ν_e appearance channels, but also the ν_τ appearance channel [7, 8], and the Neutral Current one [9].

In order to search for new physics effects in the asymmetries, since probabilities are not directly accessible to oscillation experiments, we can define the integrated asymmetries as

$$A_{\alpha\beta} = \frac{N_\beta - \bar{N}_\beta}{N_\beta + \bar{N}_\beta}\,, \tag{5}$$

where N_β ($\bar{N}_\beta$) is defined as the number of observed events of a given flavor β in neutrino (antineutrino) mode. These quantities are strictly related to the ones defined in terms of probabilities. DUNE is expected to be able to measure $A_{\mu e}$, $A_{\mu\mu}$ and $A_{\mu\tau}$ via the three Charged Current channels and $A_{\mu s}$ (in the 3+1 scenario) indirectly using the Neutral Current channel, being $N_{NC} \propto 1 - P(\nu_\mu \to \nu_s)$. Using the GLoBES software [10], we computed the expected integrated asymmetries for all the transition channels in DUNE considering both the standard and the high energy fluxes in the standard model, choosing as oscillation parameters their best fits and varying the standard CP-violating phase δ. Then, we estimated the 1σ uncertainties on the asymmetries summing statistical and systematic contributions (see [5] for details). Eventually, we computed the same asymmetries in the NSI and 3+1 models, varying the magnitude of the NSI couplings in their allowed limits [2] and the sterile neutrino mixing angles in the ranges [0°-10°] for θ_{14} and θ_{24}, [0°-30°] for θ_{34} (Δm^2_{41} has been fixed to 1 eV^2). Our simulations showed that with the standard DUNE flux, there are no possible values of the asymmetries in the new physics cases, which are outside the standard model asymmetries error bars. For this reason, the measurement of the asymmetries alone is not enough to give hints of the presence of new physics. On the other hand, with the high energy flux our results are more interesting.

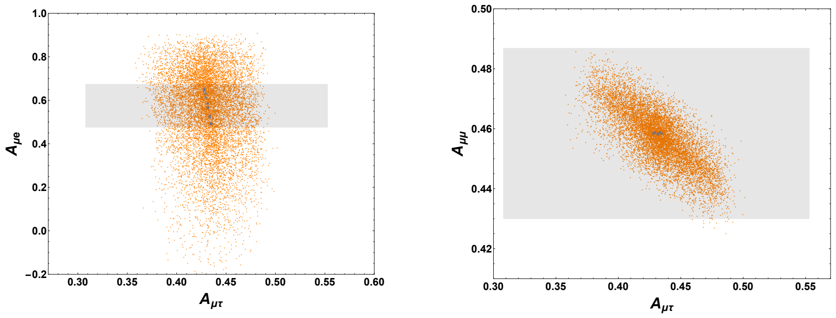

Figure 1: Integrated asymmetries in the ($A_{\mu\tau}, A_{\mu e}$) (left) and ($A_{\mu\tau}, A_{\mu\mu}$) planes (right) at DUNE with the high energy flux. Blue stars represent the asymmetries in the SM case and the orange dots represents the values obtained with NSI. Grey shadowed region shows the 1σ error range on the SM asymmetries.

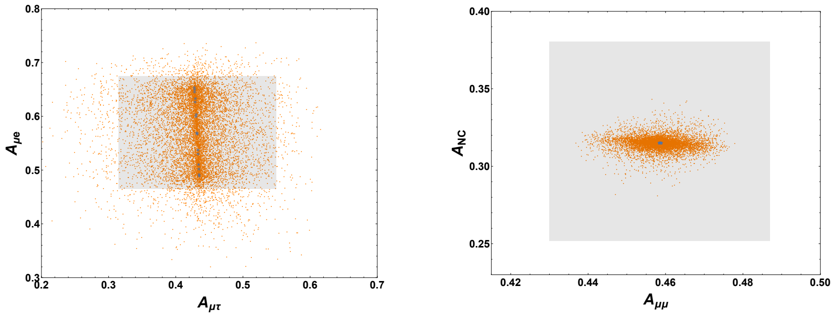

Figure 2: Same as Fig. 1 but for the 3+1 model in the ($A_{\mu\tau}, A_{\mu e}$) (left) and ($A_{NC}, A_{\mu\mu}$) planes (right).

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In Figs. 1 (for the NSI case) and 2 (for the 3+1 case) the standard values of the asymmetries obtained considering the high energy flux are represented by blue stars, their uncertainties by grey shadowed regions and the possible values of the asymmetries in the new physics scenarios by orange dots. It is evident that for $A_{\mu\mu}$ and A_{NC} there are no orange dots outside the standard error bars. In the $A_{\mu\tau}$ case, there are several non standard parameters combinations which produce asymmetries outside the error bars in the 3+1 case, even though they are never more than 2σ away from the standard values. However, the most interesting asymmetry, as expected from our analytical discussion, is $A_{\mu e}$. Indeed, the presence of NSI or sterile neutrinos can generate observed asymmetries which are up to 4σ away from the standard model values. Thus, a simple measurement based only on the number of events at DUNE, if performed with an high energy flux, could reveal at a certain confidence of level the presence of new physics. This analysis could be performed also considering other long-baseline experiments or other new physics models which introduce new sources of CP-violation in neutrino oscillation. Nevertheless, this simple approach does not allow us to determine which is the new physics model that causes the deviation of the asymmetries from the standard ones. For this reason, further analysis should be performed to understand completely the experimental data.

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