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Non-standard neutrino interactions at DUNE

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Abstract

We explore the effects of non-standard neutrino interactions (NSI) and how they modify neutrino propagation in the Deep Underground Neutrino Experiment (DUNE). We find that NSI can significantly modify the data to be collected by the DUNE experiment as long as the new physics parameters are large enough. For example, if the DUNE data are consistent with the standard three-massive-neutrinos paradigm, order 0.1 (in units of the Fermi constant) NSI effects will be ruled out. On the other hand, if large NSI effects are present, DUNE will be able to not only rule out the standard paradigm but also measure the new physics parameters, sometimes with good precision. We find that, in some cases, DUNE is sensitive to new sources of CP-invariance violation. We also explored whether DUNE data can be used to distinguish different types of new physics beyond nonzero neutrino masses. In more detail, we asked whether NSI can be mimicked, as far as the DUNE setup is concerned, by the hypothesis that there is a new light neutrino state.

1. Introduction

The main goals of next-generation long-baseline neutrino experiments like the Deep Underground Neutrino Experiment (DUNE) (see, for example, Ref. [1]) and Hyper-Kamiokande (HyperK) [2] are to search for leptonic CP-invariance violation and to test the three-massive-neutrinos paradigm (standard paradigm).

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The standard paradigm consists of postulating that the three active neutrinos $\nu_{e,\mu,\tau}$ are linear combination of three neutrino states with well-defined mass $\nu_{1,2,3}$ (masses $m_{1,2,3}$, respectively), and that the mechanism behind the nonzero neutrino masses is such that no accessible interactions or states beyond those prescribed in the standard model of particle physics (SM) are present. In summary, neutrino production, detection, and propagation (including matter effects) are described by the weak interactions, and there are no new light degrees of freedom. While all neutrino data collected so far – with the exception of the short-baseline anomalies [3–7], which we will not consider here – are consistent with the standard paradigm, large deviations are allowed. Candidates for the new physics beyond the standard paradigm include more than three light neutrino mass-eigenstates, new "weaker-than-weak" neutrino–matter interactions, small violations of fundamental physics principles, and couplings between neutrinos and new very light states.

One way to test the standard paradigm is to measure, as precisely as possible, what is interpreted to be the neutrino oscillation probabilities ($\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$, etc.) as a function of the baseline L or the neutrino energy E_ν, and compare the results with the expectations of the standard paradigm. If the observed pattern is not consistent with expectations, one can conclude that there is new physics beyond nonzero neutrino masses.

Here we investigate how well precision measurements of oscillation probabilities at DUNE can be used to probe the existence of non-standard neutrino neutral-current-like interactions (NSI). In more detail, we discuss how much DUNE data, assuming it is consistent with the standard paradigm, can constrain NSI, and discuss, assuming NSI are present, how well DUNE can measure the new physics parameters, including new sources of CP-invariance violation. We also investigate whether DUNE has the ability to differentiate between different types of new phenomena by comparing NSI effects with those expected from the existence of a new neutrino-like state (sterile neutrino).

Studies of the effects of new neutrino–matter interactions on neutrino propagation are not new. Indeed, they were first proposed in Wolfenstein's seminal paper that introduced matter effects [8]. NSI were explored as a solution to the solar neutrino problem [9], and their impact on the oscillations of solar neutrinos [10–15], atmospheric neutrinos [16–28], and accelerator neutrinos [29–38] has been thoroughly explored in the literature in the last twenty years. Some consequences of NSI to DUNE were also explored very recently in Ref. [39]. We add to the discussion in several ways. We consider all relevant NSI parameters when estimating the reach of DUNE, and investigate the capabilities of the experiment to see the new sources of CP-invariance violation. We also perform a detailed simulation of the experiment and deal with the concurrent measurements of the NSI parameters and the standard oscillation parameters. In addition, we address whether and how next-generation long-baseline experiments can distinguish different manifestations of new physics (other than nonzero neutrino masses) in the lepton sector.

This manuscript is organized as follows. In Sec. 2, we discuss NSI and their effects on neutrino oscillations via nonstandard matter effects. We also review, briefly, what is currently known about NSI and discuss some of the assumptions we make implicitly and explicitly. In Sec. 3, we briefly discuss some of the details of our simulations of the DUNE experiment and compute how well DUNE can exclude the various NSI new physics parameters. In Sec. 4, we choose three different NSI scenarios and compute how well DUNE can measure the new physics parameters. Here we also address whether DUNE can distinguish between the existence of NSI and sterile neutrinos. In Sec. 5, we qualitatively discuss potential diagnostic tools beyond DUNE, including future data from HyperK and next-generation measurements of the atmospheric neutrino flux, and offer some concluding remarks.