

Testing the heavy decaying sterile neutrino hypothesis at the DUNE near detector

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ABSTRACT: One of the most convincing explanations of the LSND and MiniBooNE anomalies relies on a heavy, mostly sterile neutrino with a small muon neutrino component, which decays to an electron neutrino and an invisible light scalar field. We investigate the possibility to test this hypothesis at the near detector complex of the upcoming DUNE experiment. We find that the DUNE liquid argon near detector (ND-LAr) can probe a larger region of the parameter space than the Fermilab SBN program, and may help to confirm or reject a possible hint of ν_e appearance in future MicroBooNE, SBND or ICARUS data. We also argue that it may be possible to distinguish between Dirac and Majorana neutrinos if this scenario is realized in Nature.

KEYWORDS: Sterile or Heavy Neutrinos, Neutrino Interactions, Neutrino Mixing, Non-Standard Neutrino Properties

ARXIV EPRINT: [2508.15888](https://arxiv.org/abs/2508.15888)

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1 Introduction

While most of the large amount of available data from solar, atmospheric, reactor and accelerator neutrino experiments is very successfully interpreted in terms of 3-flavour oscillations [1–3], a few anomalies still persist. Among these, the oldest ones come from the LSND [4] and MiniBooNE [5] short-baseline accelerator experiments. LSND, which ran from 1993 to 1998, observed a 3.8σ excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam that cannot be accounted for by oscillation parameters consistent with the other experiments. This excess was neither confirmed nor excluded by the (less sensitive) KARMEN experiment [6]. The goal of the MiniBooNE experiment was to test the LSND anomaly with a different baseline (541 m vs. 30 m for LSND) but a similar L/E. MiniBooNE ran from 2002 to 2019 with muon neutrinos and antineutrinos and observed an excess of ν_e ($\bar{\nu}_e$) events at low energy in both modes, with a statistical significance of 4.8σ [5] (the overall statistical significance of the LSND and MiniBooNE anomalies is 6.1σ). The MiniBooNE excess can be interpreted in terms of $(\bar{\nu}_\mu^-) \rightarrow (\bar{\nu}_e^-)$ oscillations involving a fourth, mostly sterile neutrino in the eV range, with parameters $\Delta m^2 \gtrsim 0.1 \text{ eV}^2$ and $\sin^2 2\theta \approx (10^{-3} - 10^{-2})$, in good agreement with the LSND allowed region. However, this explanation would imply $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$ disappearance governed by the same Δm^2 , which is not observed by experiments such as MINOS/MINOS+ [7], IceCube DeepCore [8], and the reactor neutrino experiments Bugey [9] and Daya Bay [10]. This tension between appearance and disappearance data has been quantified to be at 4.7σ level in ref. [11]. In addition, a sterile neutrino with parameters consistent with LSND and MiniBooNE is strongly disfavoured by cosmology [12].

Thus, if the LSND and MiniBooNE anomalies are real (i.e., not attributable to misunderstood backgrounds or experimental errors), it appears unlikely that they are due to oscillations driven by light sterile neutrinos, and an alternative, non-oscillation explanation is needed. It is therefore crucial to establish whether these experimental anomalies are real or not. This is the goal of the short-baseline accelerator neutrino program at Fermilab (SBN) [13], which consists of three liquid argon detectors with very good event reconstruction capabilities: SBND [14] (with a baseline of 110 m), MicroBooNE [15] (470 m) and ICARUS [16] (600 m). So far only MicroBooNE has published results, testing various possible origins of the MiniBooNE low-energy excess,¹ such as single electron [17], single photon [18] or e^+e^- pairs [19]. In particular, MicroBooNE recently excluded the MiniBooNE low-energy excess as ν_e at more than 99% C.L. [17].

Still, more data is needed to fully exclude the MiniBooNE anomaly, and it makes sense to investigate the possibility of testing non-oscillation explanations of the LSND and MiniBooNE excesses at SBN or at other experimental facilities [20]. Among the possible new physics explanations (see e.g. ref. [21] for a review), one of the most convincing is the heavy decaying sterile neutrino initially proposed for LSND by the authors of ref. [22], and extended to MiniBooNE in refs. [23] and [24]. In this scenario, a keV/MeV-scale sterile neutrino mixing with ν_μ and decaying to ν_e and a light scalar field is able to mimic the LSND and MiniBooNE excesses even if its mixing angles with ν_μ and ν_e are small, thus avoiding the tension with appearance experiments (for other proposals involving a heavy sterile neutrino decaying to visible or invisible final states, see refs. [25–42]).

The goal of this paper is to investigate the possibility to test the heavy decaying sterile neutrino (HDSN) hypothesis at the DUNE liquid argon near detector (ND-LAr), focusing for definiteness on the scenario of ref. [24]. Our main result is that ND-LAr can probe a larger portion of the HDSN parameter space than the Fermilab SBN program, which might prove crucial to check a possible hint of ν_e appearance in future MicroBooNE, SBND or ICARUS data. We also find that it may be possible, in case of a positive signal, to distinguish between Dirac and Majorana neutrinos.

The paper is organized as follows. In section 2, we introduce the heavy decaying sterile neutrino scenario considered in this paper and provide the main formulae used in our analysis. Section 3 briefly presents the specifications of the DUNE liquid argon near detector and describes the simulations performed in our paper. In section 4, we present our results for the expected sensitivity of ND-LAr to the HDSN parameters, and comment about the possibility to distinguish between Dirac and Majorana neutrinos if this scenario is realized in Nature. Finally, we give our conclusions in section 5.

2 The heavy decaying sterile neutrino (HDSN) scenario

In this work, we consider the heavy decaying sterile neutrino scenario of ref. [24], hereafter referred to as the HDSN scenario. It involves a fourth, mostly sterile neutrino mass eigenstate ν_4 with a mass in the keV–MeV range and a small ν_μ component. This heavy neutrino decays to an electron neutrino and an invisible light scalar field ϕ , thus mimicking the excesses

¹The MiniBooNE detector was not able to efficiently distinguish electrons from photons and collimated e^+e^- pairs.

observed by LSND and MiniBooNE. More specifically, the sterile neutrino is assumed to mix only with the muon neutrino:

$$\nu_{\alpha L} = \sum_{i=1}^4 U_{\alpha i} \nu_{iL}, \quad U_{e4} = U_{\tau 4} = 0, \quad (2.1)$$

where $\alpha = e, \mu, \tau, s$ and U is the 4×4 lepton mixing matrix. The low-energy effective Lagrangian responsible for the decay of ν_4 is taken to be [22, 24]

$$\mathcal{L}_{\text{decay}} = -g \bar{\nu}_{4R} \nu_{eL} \phi + \text{h.c.} \quad (2.2)$$

If neutrinos are Dirac fermions, this corresponds to a maximally parity violating interaction involving only ν_{4R} and ν_{eL} , while in the Majorana case ν_{4R} is the CP conjugate of ν_{4L} (i.e., $\nu_{4R} = C \bar{\nu}_{4L}^T$, with C the charge conjugation matrix). The interaction (2.2) could originate from the non-renormalizable, $\text{SU}(2)_L \times \text{U}(1)_Y$ invariant operator² $g_{se} \bar{\nu}_{sR} L_e H \phi / \Lambda$, where L_e is the lepton doublet containing the left-handed electron and ν_{eL} , H is the Standard Model Higgs doublet, and Λ is a high scale associated with the underlying UV theory.

This scenario can be seen as a simplified model containing only the ingredients needed to explain the LSND and MiniBooNE anomalies (namely, the mixing of the sterile neutrino with the muon neutrino, and the decay of ν_4 to the combination of light mass eigenstates corresponding to the electron neutrino, $\nu_{eL} = \sum_{i=1}^3 U_{ei} \nu_{iL}$). It differs on several points from the model of ref. [23], in which neutrinos are Dirac fermions, parity is conserved, both U_{e4} and $U_{\mu 4}$ are nonvanishing, ν_4 can decay to all active neutrinos, and the light scalar field ϕ is unstable ($\phi \rightarrow \nu_i \bar{\nu}_j$, $i, j = 1, 2, 3$). One could in principle generalize the model of ref. [24] by allowing for a small mixing of the sterile neutrino with ν_e and ν_τ (such that $|U_{e4}|, |U_{\tau 4}| \ll |U_{\mu 4}|$) and subdominant decay modes $\nu_4 \rightarrow \nu_\mu \phi$ and $\nu_4 \rightarrow \nu_\tau \phi$. This would not drastically change its phenomenology, but in order to avoid introducing additional parameters with little impact on the experimental signatures, we will stick to the minimal assumptions (2.1) and (2.2).

The HDSN scenario is constrained by several experimental measurements. Searches for heavy sterile neutrinos in pion, kaon and muon decays constrain $|U_{\mu 4}|^2 \lesssim 10^{-2}$ for $m_4 \gtrsim 1 \text{ MeV}$ (and $|U_{\mu 4}|^2 \ll 10^{-2}$ for m_4 between a few MeV and $\approx 400 \text{ MeV}$) [43, 44]. Below $m_4 \approx 1 \text{ MeV}$, the strongest constraint on $|U_{\mu 4}|^2$ comes from $\nu_\mu / \bar{\nu}_\mu$ disappearance searches at MINOS/MINOS+, which give an upper bound $|U_{\mu 4}|^2 < 2.3 \times 10^{-2}$ (90% C.L.) for $m_4 \gtrsim 10 \text{ eV}$ [7]. The impact of ν_4 decays on this bound is of higher order in $|U_{\mu 4}|^2$, as can be seen from the survival probability (2.6), and can be neglected. The coupling g of the $\nu_4 \nu_e \phi$ interaction is constrained by peak searches in leptonic meson decays, giving $|g U_{\mu 4}|^2 < 1.9 \times 10^{-7}$ (90% C.L.) [45], which translates into $|g| \leq 2.8 \times 10^{-3}$ (respectively $|g| \leq 4.4 \times 10^{-2}$) for $|U_{\mu 4}|^2$ equal to the MINOS upper bound (respectively $|U_{\mu 4}|^2 = 10^{-4}$). We will consider a sterile neutrino mass in the range $1 \text{ keV} \lesssim m_4 \lesssim 1 \text{ MeV}$ and values of g such that $0.01 \text{ eV} \leq |g| m_4 \leq 100 \text{ eV}$, consistent with the above experimental constraints.

²In addition to the interaction (2.2), this operator can also induce $\bar{\nu}_{iR} \nu_{jL} \phi$ ($i, j = 1, 2, 3$), which mediate unwanted invisible decays of the light neutrinos, $\nu_i \rightarrow \nu_j \phi$. To make sure that only the interaction (2.2) is generated, it is enough, in the Dirac case, to assume the absence of active-sterile mixing in the right-handed neutrino sector, such that $\nu_{sR} = \nu_{4R}$. In the Majorana case, one must add the nonrenormalizable operators $g_{\alpha\beta} (L_\alpha H)(L_\beta H) \phi / \Lambda$ ($\alpha, \beta = e, \mu, \tau$) with coefficients $g_{\alpha e} = g_{se} U_{\alpha 4} / U_{s4}^*$ (and $g_{\alpha\beta} = 0$ for $\alpha, \beta \neq e$), such that only the interaction (2.2) arises at low energy [24].

Such a sterile neutrino could affect cosmological observations, and one has to make sure that it is consistent with data. For the considered values of g and m_4 , all ν_4 's present in the early Universe decay well before recombination, leaving no impact on the CMB and structure formation. It could instead affect Big Bang nucleosynthesis, which requires the effective number of relativistic degrees of freedom N_{eff} to be close to 3 around $T = 1$ MeV [46]. However, this constraint can be evaded in the presence of “secret interactions” of the sterile neutrino, e.g. by assuming that ν_s couples to an Abelian gauge boson [47, 48]. These interactions generate an effective, temperature-dependent potential for ν_s which suppresses its mixing with active neutrinos, thus preventing its production in the early Universe until $T \ll 1$ MeV [23]. Finally, the active-sterile mixing can induce ϕ -mediated interactions between the light neutrino mass eigenstates, in conflict with CMB observations, which require neutrinos to be free streaming for redshifts $z \lesssim 10^5$ [49, 50]. However, such interactions do not arise in the scenario considered in this paper, in which no $\nu_i \nu_j \phi$ couplings ($i, j = 1, 2, 3$) are present. For the same reason, the SN 1987A constraint on neutrino self-interactions [51] does not apply either.

Let us now discuss the short-baseline experimental signatures of the HDSN scenario. We consider both the possibilities that neutrinos are Majorana or Dirac fermions. In the Dirac case, the only allowed decay mode for the heavy sterile neutrino is $\nu_4 \rightarrow \nu_e \phi$ (and $\bar{\nu}_4 \rightarrow \bar{\nu}_e \phi$ for the antineutrino). In the Majorana case, the 4-spinor ν_4 satisfies the Majorana condition $\nu_4 = C \bar{\nu}_4^T$, and the heavy neutrino can decay to both $\nu_e \phi$ and $\bar{\nu}_e \phi$ with equal decay rates. Given the energies of the LSND and MiniBooNE beams, the produced ν_4 's are relativistic, and their differential and total decay rates in the lab frame (i.e., including an inverse Lorentz factor $1/\gamma_4 = m_4/E_4$) are given by [22], in the Dirac case,

$$\left. \frac{d\Gamma(\nu_4 \rightarrow \nu_e \phi)}{dE_e} \right|_{\text{Dirac}} = \frac{|g|^2}{16\pi} \frac{m_4^2 E_e}{E_4^3}, \quad \Gamma_4^{\text{D}} \equiv \Gamma(\nu_4 \rightarrow \nu_e \phi)|_{\text{Dirac}} = \frac{|g|^2 m_4^2}{32\pi E_4}, \quad (2.3)$$

where $E_e \equiv E_{\nu_e}$ and $E_4 = E_{\nu_\mu}$ is the energy of ν_4 , which equals the energy of the ν_μ it originates from. The differential $\bar{\nu}_4$ decay rate is given by the same expression. In the Majorana case, one has

$$\left. \frac{d\Gamma(\nu_4 \rightarrow \nu_e \phi)}{dE_e} \right|_{\text{Majorana}} = \left. \frac{d\Gamma(\nu_4 \rightarrow \bar{\nu}_e \phi)}{dE_e} \right|_{\text{Majorana}} = \frac{|g|^2}{16\pi} \frac{m_4^2 E_e}{E_4^3}, \quad (2.4)$$

$$\Gamma_4^{\text{M}} \equiv \Gamma(\nu_4 \rightarrow \nu_e \phi)|_{\text{Majorana}} + \Gamma(\nu_4 \rightarrow \bar{\nu}_e \phi)|_{\text{Majorana}} = \frac{|g|^2 m_4^2}{16\pi E_4}. \quad (2.5)$$

The probability for a ν_μ to be observed as a ν_μ or a ν_e (or a $\bar{\nu}_e$ in the Majorana case) after having travelled a distance L depends on the fraction of ν_4 's in the ν_μ beam, given by $|U_{\mu 4}|^2$, and on the ν_4 decay rate into $\nu_e \phi$ ($\bar{\nu}_e \phi$) in the lab frame. Given the distance between the source and the detector in the LSND and MiniBooNE experiments, standard oscillations between active flavours can safely be neglected.³ This also holds for the DUNE near detector considered in this paper. The probabilities are then given by (denoting $P_{\alpha\beta} \equiv P(\nu_\alpha \rightarrow \nu_\beta)$)

³The averaged active-sterile neutrino oscillations are taken into account in formulae (2.6), and have no impact on eq. (2.7), as $U_{e4} = 0$.

and $P_{\bar{\alpha}\bar{\beta}} \equiv P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$ [22]:

$$P_{\mu\mu} = P_{\bar{\mu}\bar{\mu}} = (1 - |U_{\mu 4}|^2)^2 + |U_{\mu 4}|^4 e^{-\Gamma_4 L}, \quad P_{ee} = P_{\bar{e}\bar{e}} = 1, \quad (2.6)$$

$$P_{\mu e} = P_{\bar{\mu}\bar{e}} = |U_{\mu 4}|^2 (1 - e^{-\Gamma_4 L}). \quad (2.7)$$

The expressions (2.6) for the survival probabilities are valid both in the Dirac and Majorana cases, with the caveat that $\Gamma_4^M = 2\Gamma_4^D$. For the appearance probabilities, one has, in the Majorana case,

$$P_{\mu e} = P_{\bar{\mu}\bar{e}} = P_{\mu\bar{e}} = P_{\bar{\mu}e} = \frac{1}{2} |U_{\mu 4}|^2 (1 - e^{-\Gamma_4^M L}). \quad (2.8)$$

In our analysis, we will also need the dependence of the appearance probability $P_{\mu e}$ on the daughter electron neutrino energy, given by the differential probability

$$\frac{dP_{\mu e}}{dE_e} = \frac{dP_{\bar{\mu}\bar{e}}}{dE_e} = |U_{\mu 4}|^2 (1 - e^{-\Gamma_4^D L}) \frac{2E_e}{E_4^2} \quad (\text{Dirac case}), \quad (2.9)$$

$$\frac{dP_{\mu e}}{dE_e} = \frac{dP_{\bar{\mu}\bar{e}}}{dE_e} = \frac{dP_{\mu\bar{e}}}{dE_e} = \frac{dP_{\bar{\mu}e}}{dE_e} = |U_{\mu 4}|^2 (1 - e^{-\Gamma_4^M L}) \frac{E_e}{E_4^2} \quad (\text{Majorana case}). \quad (2.10)$$

In addition to its impact on the signal (ν_e appearance or ν_μ disappearance), the heavy sterile neutrino also affects the background. Let us consider for definiteness the neutrino mode. The main backgrounds for the appearance signal (ν_e or $\bar{\nu}_e$ scattering on Argon nuclei) are (i) the $\nu_e/\bar{\nu}_e$ contamination of the ν_μ flux (intrinsic background); (ii) the misidentification background (when the μ^-/μ^+ resulting from the scattering of a $\nu_\mu/\bar{\nu}_\mu$ on a nucleus is misidentified as an electron/positron); (iii) the neutral current background. While the intrinsic contamination background does not depend on the physics scenario (Standard Model or heavy decaying sterile neutrino), the misidentification background is proportional to the ν_μ component of the incoming neutrino flux. Since standard neutrino oscillations can be neglected, the misidentification background in the HDSN scenario is suppressed by a factor $P_{\mu\mu}$ with respect to the Standard Model (SM):

$$\frac{N_{\text{mis-ID}}^{\text{HDSN}}}{N_{\text{mis-ID}}^{\text{SM}}} = P_{\mu\mu} = (1 - |U_{\mu 4}|^2)^2 + |U_{\mu 4}|^4 e^{-\Gamma_4 L}, \quad (2.11)$$

with $\Gamma_4 = \Gamma_4^D$ in the Dirac case and $\Gamma_4 = \Gamma_4^M$ in the Majorana case. Since $P_{\bar{\mu}\bar{\mu}} = P_{\mu\mu}$, eq. (2.11) holds both in the neutrino and antineutrino modes. As for the neutral current background, it is proportional to the fraction of active neutrinos in the beam at the detector position, which is equal to 1 in the SM, but depleted by the sterile neutrino component in the HDSN scenario. In the Dirac case, the suppression factor is given by $P_{\mu e} + P_{\mu\mu}$, yielding

$$\frac{N_{\text{NCbckgd}}^{\text{HDSN}}}{N_{\text{NCbckgd}}^{\text{SM}}} = 1 - |U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2) (1 + e^{-\Gamma_4 L}) \quad (\text{Dirac case}), \quad (2.12)$$

which is valid both in the neutrino and antineutrino modes, since $P_{\bar{\mu}\bar{e}} + P_{\bar{\mu}\bar{\mu}} = P_{\mu e} + P_{\mu\mu}$. In the Majorana case, the muon (anti)neutrinos can decay to both ν_e and $\bar{\nu}_e$, which have different

neutral current cross sections $\sigma_{\nu_e}^{\text{NC}}$ and $\sigma_{\bar{\nu}_e}^{\text{NC}}$. One therefore has, in the neutrino mode,

$$\begin{aligned} \frac{N_{\text{NCbckgd}}^{\text{HDSN}}}{N_{\text{NCbckgd}}^{\text{SM}}} &= P_{\mu\mu} + P_{\mu e} + P_{\mu\bar{e}} \frac{\sigma_{\bar{\nu}_e}^{\text{NC}}}{\sigma_{\nu_e}^{\text{NC}}} \quad (\text{Majorana case, neutrino mode}) \\ &\approx 1 - \frac{5}{4} |U_{\mu 4}|^2 \left(1 + \frac{3}{5} e^{-\Gamma_4^M L} \right) + |U_{\mu 4}|^4 (1 + e^{-\Gamma_4^M L}), \end{aligned} \quad (2.13)$$

where we neglected the energy dependence of the ratio $\sigma_{\bar{\nu}_e}^{\text{NC}}/\sigma_{\nu_e}^{\text{NC}}$, and we used $\sigma_{\nu_e}^{\text{NC}} \approx 2\sigma_{\bar{\nu}_e}^{\text{NC}}$ and $\sigma_{\nu_\mu}^{\text{NC}} = \sigma_{\bar{\nu}_\mu}^{\text{NC}}$, while in the antineutrino mode

$$\begin{aligned} \frac{N_{\text{NCbckgd}}^{\text{HDSN}}}{N_{\text{NCbckgd}}^{\text{SM}}} &= P_{\bar{\mu}\bar{\mu}} + P_{\bar{\mu}e} + P_{\bar{\mu}\bar{e}} \frac{\sigma_{\nu_e}^{\text{NC}}}{\sigma_{\bar{\nu}_e}^{\text{NC}}} \quad (\text{Majorana case, antineutrino mode}) \\ &\approx 1 - \frac{1}{2} |U_{\mu 4}|^2 \left(1 + 3 e^{-\Gamma_4^M L} \right) + |U_{\mu 4}|^4 (1 + e^{-\Gamma_4^M L}). \end{aligned} \quad (2.14)$$

Note that, in the limit $e^{-\Gamma_4 L} \rightarrow 1$ (which corresponds to the case where only a negligible fraction of the sterile neutrinos decay before reaching the detector), the right-hand sides of eq. (2.11) to (2.14) all reduce to $1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$.

Finally, the main background for the disappearance signal (ν_μ or $\bar{\nu}_\mu$ scattering on Argon nuclei) is the neutral current background, given by eqs. (2.12) to (2.14).

3 Experimental setup and simulation details

In this section, we briefly discuss the experimental specifications of the DUNE far and near detector facilities, before describing in detail the simulations performed in our analysis.

3.1 Experimental setup

The next generation of long-baseline oscillation experiments will dedicate their main efforts to searching for the Dirac CP-violating phase of the lepton mixing matrix, a fundamental parameter of the Standard Model, and a key observable for a better understanding of the Universe in its first stages. One of these experiments will be the Deep Underground Neutrino Experiment (DUNE) at Fermilab. According to the Technical Design Report configuration [52], DUNE will use a 120 GeV proton beam with a power of 1.2 MW, yielding 1.1×10^{21} protons on target per year. This experiment will have two sets of detectors. The far detector, based on a liquid argon time projection chamber, will be placed approximately 1.5 km underground and 1300 km downstream of the source in the Stanford Underground Research Facility (SURF) in South Dakota. It will have a total mass of 70 kt and a fiducial mass of roughly 40 kt. The near detector complex will be located at Fermilab, approximately 574 m away from the neutrino source. It will consist of three different detectors, two of which will be able to move and collect data at different angles from the on-axis position.

In this work, we consider the 67.2 t movable liquid argon near detector (ND-LAr) proposed by the DUNE Collaboration [53]. Figure 1 represents the muon (anti)neutrino flux as a function of energy for on-axis and different off-axis positions of the detector [53, 54]. As can be seen from the figure, the (anti)neutrino flux becomes smaller and the energy spectrum shifts towards lower energies as the off-axis angle increases.

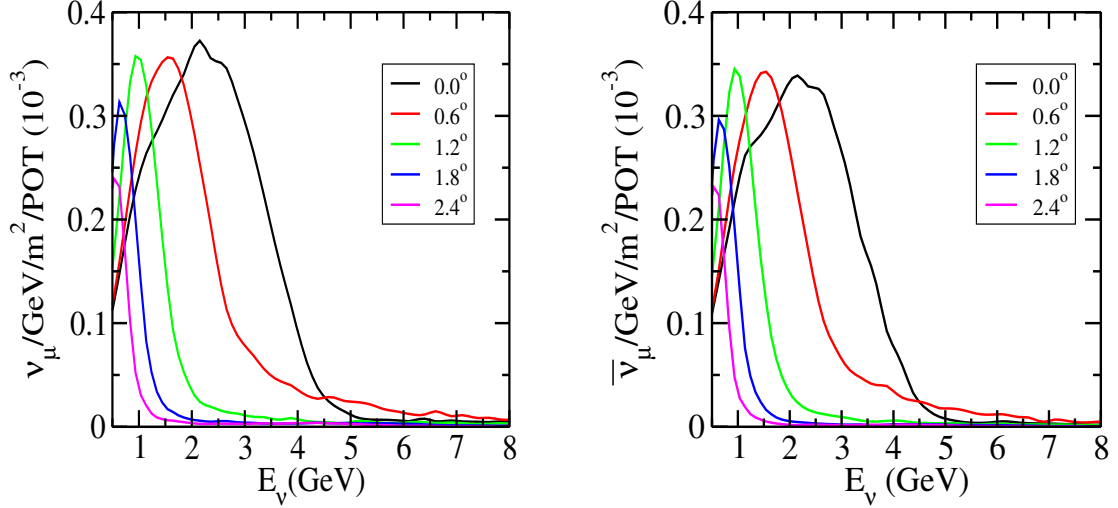


Figure 1. Expected muon neutrino (left) and antineutrino (right) fluxes at the movable DUNE liquid argon near detector (ND-LAr), for on-axis and several off-axis locations.

3.2 Simulation details

Let us now discuss how the appearance and disappearance event spectra at the DUNE liquid argon near detector are calculated, and how the ability of the detector to test the heavy decaying sterile neutrino hypothesis is assessed. In order to estimate the statistical sensitivity of ND-LAr to the HDSN parameters, we assume the standard 3-neutrino framework as the true hypothesis, and we use the Poissonian χ^2 function

$$\chi^2(\kappa) = \min_{\xi} \left[\sum_i 2 \left\{ N_i(\kappa, \xi) - N_i^{\text{obs}} + N_i^{\text{obs}} \ln \left(\frac{N_i^{\text{obs}}}{N_i(\kappa, \xi)} \right) \right\} + \sum_{\xi} \left(\frac{\xi}{\sigma_{\xi}} \right)^2 \right], \quad (3.1)$$

where i labels the different energy bins, N_i^{obs} is the number of events in the i th bin predicted by the SM, and $N_i(\kappa, \xi)$ is the corresponding quantity in the presence of the heavy decaying sterile neutrino. The latter depends on the HDSN parameters, collectively denoted by κ , and on normalization factors for the signal and background, ξ_{sig} and ξ_{bg} . Explicitly,

$$N_i^{\text{obs}} = N_i^{\text{sig}}(SM) + N_i^{bg}(SM), \quad N_i(\kappa, \xi) = N_i^{\text{sig}}(\kappa)(1 + \xi_{\text{sig}}) + N_i^{bg}(\kappa)(1 + \xi_{bg}), \quad (3.2)$$

where $N_i^{\text{sig}}(SM)$ and $N_i^{\text{sig}}(\kappa)$ are the numbers of signal events in the SM and in the HDSN scenario, respectively, and similarly for the background events $N_i^{bg}(SM)$ and $N_i^{bg}(\kappa)$. The normalization factors ξ_{sig} and ξ_{bg} quantify the systematic errors, with associated uncertainties σ_{sig} and σ_{bg} . We assume these systematic uncertainties to be uncorrelated, and conservatively take $\sigma_{\text{sig}} = \sigma_{bg} = 10\%$ across all energy bins.⁴

Let us consider the number of events predicted by the SM in a given signal or background channel. Assuming this channel involves a flavour transition $\nu_{\alpha} \rightarrow \nu_{\beta}$ with probability $P_{\alpha\beta}$ (with $\alpha = \beta$ or $\alpha \neq \beta$), the number of events in the i th reconstructed energy bin $[E_{\text{rec}}^i, E_{\text{rec}}^{i+1}]$

⁴We are assuming energy-independent systematic uncertainties in this analysis, due to the lack of publicly available information about their energy dependence.

Channel	ND-LAr event rates ($\times 10^6$)			
	Signal (CC)	Background		
	Right (wrong) sign component	Intrinsic	Mis-ID	NC
ν mode: $\nu_\mu \rightarrow \nu_e$	$\simeq 0$ ($\simeq 0$)	2.14	0.43	0.65
$\bar{\nu}$ mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\simeq 0$ ($\simeq 0$)	1.2	0.11	0.38
ν mode: $\nu_\mu \rightarrow \nu_\mu$	206 (7.0)	—	—	1.71
$\bar{\nu}$ mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	78 (20)	—	—	0.98

Table 1. Event rates at the DUNE liquid argon near detector (ND-LAr) expected in the Standard Model, assuming 3.5 years of on-axis data taking in either neutrino or antineutrino mode. The first and second rows correspond to the appearance channel in the neutrino and antineutrino modes, respectively, for which the signal from neutrino oscillations is negligible. The last three columns show the number of intrinsic, misidentification, and neutral current background events, as defined in section 2. The third and fourth rows correspond to the disappearance channel in the neutrino and antineutrino modes, respectively, and the number of signal events is given separately for the right sign component (e.g. $\nu_\mu \rightarrow \nu_\mu$ in the neutrino mode) and for the wrong sign component (e.g. $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ in the neutrino mode) of the neutrino beam.

is given by the following formula:

$$N_i^{\nu_\alpha \rightarrow \nu_\beta} = \frac{nT}{4\pi L^2} \int_{E_{\text{rec}}^i}^{E_{\text{rec}}^{i+1}} A(E_{\text{rec}}) dE_{\text{rec}} \int_0^{E_\nu^{\text{max}}} dE_\nu \mathcal{R}(E_\nu, E_{\text{rec}}) \sigma_{\nu_\beta}(E_\nu) \phi_{\nu_\alpha}(E_\nu) P_{\alpha\beta}, \quad (3.3)$$

where E_ν and E_{rec} are the true and reconstructed neutrino energies, respectively, $\phi_{\nu_\alpha}(E_\nu)$ is the flux of the ν_α component of the neutrino beam, $\sigma_{\nu_\beta}(E_\nu)$ the interaction cross-section of ν_β , $\mathcal{R}(E_\nu, E_{\text{rec}})$ the energy resolution function of the detector, and $A(E_{\text{rec}})$ the detector efficiency. The upper limit E_ν^{max} of the second integral corresponds to the maximal energy of the muon (anti)neutrinos in the beam, and the prefactor involves the total running time T , the number n of target Argon nuclei in the detector, and the distance L between the source and the detector. All details regarding the cross sections, energy resolution and efficiency of the detector that we use in our simulations can be found in ref. [55].

Table 1 displays the expected numbers of signal and background events in the appearance and disappearance channels at the DUNE ND-LAr detector, both in the neutrino and antineutrino modes, assuming 3.5 years of on-axis data taking in each mode. For the appearance channel, the numbers of intrinsic, misidentification and neutral current background events are given separately. The negligible appearance signal is due to the fact that neutrino oscillations do not have the time to develop significantly over such a short baseline.

In the HDSN scenario, eq. (3.3) must be modified to take into account the sterile neutrino decays. Let us first consider the case where neutrinos are Dirac fermions and the experiment runs in the neutrino mode. The number of appearance signal events in the i th energy bin is given by eq. (3.4), where the last integral accounts for the fact that the daughter ν_e is less energetic than the parent ν_μ . Eqs. (3.5) and (3.6) correspond to the disappearance signal

and to the neutral current background, respectively.

$$\begin{aligned}
 [N_i^{\nu_\mu \rightarrow \nu_e}]^{D, CC} &= \frac{nT}{4\pi L^2} \int_{E_{\text{rec}}^i}^{E_{\text{rec}}^{i+1}} A(E_{\text{rec}}) dE_{\text{rec}} \int_0^{E_\nu^{\text{max}}} dE_{\nu_e} \mathcal{R}(E_{\nu_e}, E_{\text{rec}}) \sigma_{\nu_e}^{CC}(E_{\nu_e}) \\
 &\quad \times \int_{E_{\nu_e}}^{E_\nu^{\text{max}}} dE_{\nu_\mu} \phi_{\nu_\mu}(E_{\nu_\mu}) \frac{dP_{\mu e}^D}{dE_{\nu_e}}(E_{\nu_\mu}, E_{\nu_e}), \quad (3.4)
 \end{aligned}$$

$$\begin{aligned}
 [N_i^{\nu_\mu \rightarrow \nu_\mu}]^{D, CC} &= \frac{nT}{4\pi L^2} \int_{E_{\text{rec}}^i}^{E_{\text{rec}}^{i+1}} A(E_{\text{rec}}) dE_{\text{rec}} \\
 &\quad \times \int_0^{E_\nu^{\text{max}}} dE_{\nu_\mu} \mathcal{R}(E_{\nu_\mu}, E_{\text{rec}}) \sigma_{\nu_\mu}^{CC}(E_{\nu_\mu}) \phi_{\nu_\mu}(E_{\nu_\mu}) P_{\mu\mu}^D(E_{\nu_\mu}), \quad (3.5)
 \end{aligned}$$

$$\begin{aligned}
 [N_i^{\nu_\mu}]^{D, NC} &= \frac{nT}{4\pi L^2} \int_{E_{\text{rec}}^i}^{E_{\text{rec}}^{i+1}} A(E_{\text{rec}}) dE_{\text{rec}} \\
 &\quad \times \left[\int_0^{E_\nu^{\text{max}}} dE_{\nu_\mu} \mathcal{R}(E_{\nu_\mu}, E_{\text{rec}}) \sigma_\nu^{NC}(E_{\nu_\mu}) \phi_{\nu_\mu}(E_{\nu_\mu}) P_{\mu\mu}^D(E_{\nu_\mu}) \right. \\
 &\quad \left. + \int_0^{E_\nu^{\text{max}}} dE_{\nu_e} \mathcal{R}(E_{\nu_e}, E_{\text{rec}}) \sigma_\nu^{NC}(E_{\nu_e}) \int_{E_{\nu_e}}^{E_\nu^{\text{max}}} dE_{\nu_\mu} \phi_{\nu_\mu}(E_{\nu_\mu}) \frac{dP_{\mu e}^D}{dE_{\nu_e}}(E_{\nu_\mu}, E_{\nu_e}) \right]. \quad (3.6)
 \end{aligned}$$

In the Majorana case, the sterile neutrino can decay either to a ν_e or to a $\bar{\nu}_e$, and eqs. (3.4) to (3.6) are replaced by the following equations:

$$\begin{aligned}
 [N_i^{\nu_\mu \rightarrow \nu_e/\bar{\nu}_e}]^{M, CC} &= \frac{nT}{4\pi L^2} \int_{E_{\text{rec}}^i}^{E_{\text{rec}}^{i+1}} A(E_{\text{rec}}) dE_{\text{rec}} \left[\int_0^{E_\nu^{\text{max}}} dE_{\nu_e} \mathcal{R}(E_{\nu_e}, E_{\text{rec}}) \sigma_{\nu_e}^{CC}(E_{\nu_e}) \right. \\
 &\quad \times \int_{E_{\nu_e}}^{E_\nu^{\text{max}}} dE_{\nu_\mu} \phi_{\nu_\mu}(E_{\nu_\mu}) \frac{dP_{\mu e}^M}{dE_{\nu_e}}(E_{\nu_\mu}, E_{\nu_e}) \\
 &\quad \left. + \int_0^{E_\nu^{\text{max}}} dE_{\bar{\nu}_e} \mathcal{R}(E_{\bar{\nu}_e}, E_{\text{rec}}) \sigma_{\bar{\nu}_e}^{CC}(E_{\bar{\nu}_e}) \int_{E_{\bar{\nu}_e}}^{E_\nu^{\text{max}}} dE_{\nu_\mu} \phi_{\nu_\mu}(E_{\nu_\mu}) \frac{dP_{\mu \bar{e}}^M}{dE_{\bar{\nu}_e}}(E_{\nu_\mu}, E_{\bar{\nu}_e}) \right], \quad (3.7)
 \end{aligned}$$

$$\begin{aligned}
 [N_i^{\nu_\mu \rightarrow \nu_\mu}]^{M, CC} &= \frac{nT}{4\pi L^2} \int_{E_{\text{rec}}^i}^{E_{\text{rec}}^{i+1}} A(E_{\text{rec}}) dE_{\text{rec}} \\
 &\quad \times \int_0^{E_\nu^{\text{max}}} dE_{\nu_\mu} \mathcal{R}(E_{\nu_\mu}, E_{\text{rec}}) \sigma_{\nu_\mu}^{CC}(E_{\nu_\mu}) \phi_{\nu_\mu}(E_{\nu_\mu}) P_{\mu\mu}^M(E_{\nu_\mu}), \quad (3.8)
 \end{aligned}$$

$$\begin{aligned}
 [N_i^{\nu_\mu}]^{M, NC} &= \frac{nT}{4\pi L^2} \int_{E_{\text{rec}}^i}^{E_{\text{rec}}^{i+1}} A(E_{\text{rec}}) dE_{\text{rec}} \\
 &\quad \times \left[\int_0^{E_\nu^{\text{max}}} dE_{\nu_\mu} \mathcal{R}(E_{\nu_\mu}, E_{\text{rec}}) \sigma_\nu^{NC}(E_{\nu_\mu}) \phi_{\nu_\mu}(E_{\nu_\mu}) P_{\mu\mu}^M(E_{\nu_\mu}) \right. \\
 &\quad + \int_0^{E_\nu^{\text{max}}} dE_{\bar{\nu}_e} \mathcal{R}(E_{\bar{\nu}_e}, E_{\text{rec}}) \sigma_{\bar{\nu}}^{NC}(E_{\bar{\nu}_e}) \int_{E_{\bar{\nu}_e}}^{E_\nu^{\text{max}}} dE_{\nu_\mu} \phi_{\nu_\mu}(E_{\nu_\mu}) \frac{dP_{\mu \bar{e}}^M}{dE_{\bar{\nu}_e}}(E_{\nu_\mu}, E_{\bar{\nu}_e}) \\
 &\quad \left. + \int_0^{E_\nu^{\text{max}}} dE_{\nu_e} \mathcal{R}(E_{\nu_e}, E_{\text{rec}}) \sigma_\nu^{NC}(E_{\nu_e}) \int_{E_{\nu_e}}^{E_\nu^{\text{max}}} dE_{\nu_\mu} \phi_{\nu_\mu}(E_{\nu_\mu}) \frac{dP_{\mu e}^M}{dE_{\nu_e}}(E_{\nu_\mu}, E_{\nu_e}) \right]. \quad (3.9)
 \end{aligned}$$

It is straightforward to generalize eqs. (3.4) to (3.9) to the case where the experiment runs in the antineutrino mode. The probabilities appearing in these equations are given

by (see section 2)

$$\frac{dP_{\mu e}^D}{dE_e} = \frac{dP_{\bar{\mu} \bar{e}}^D}{dE_e} = |U_{\mu 4}|^2 (1 - e^{-\Gamma_4^D L}) \frac{2E_e}{E_4^2} \quad (\text{Dirac case}), \quad (3.10)$$

$$\frac{dP_{\mu e}^M}{dE_e} = \frac{dP_{\bar{\mu} \bar{e}}^M}{dE_e} = \frac{dP_{\mu \bar{e}}^M}{dE_e} = \frac{dP_{\bar{\mu} e}^M}{dE_e} = |U_{\mu 4}|^2 (1 - e^{-\Gamma_4^M L}) \frac{E_e}{E_4^2} \quad (\text{Majorana case}), \quad (3.11)$$

where, depending on the case, $E_e = E_{\nu_e}$ or $E_{\bar{\nu}_e}$, $E_4 = E_{\nu_\mu}$ or $E_{\bar{\nu}_\mu}$, and

$$P_{\mu\mu}^D = P_{\bar{\mu}\bar{\mu}}^D = \left(1 - |U_{\mu 4}|^2\right)^2 + |U_{\mu 4}|^4 e^{-\Gamma_4^D L} \quad (\text{Dirac case}), \quad (3.12)$$

$$P_{\mu\mu}^M = P_{\bar{\mu}\bar{\mu}}^M = \left(1 - |U_{\mu 4}|^2\right)^2 + |U_{\mu 4}|^4 e^{-\Gamma_4^M L} \quad (\text{Majorana case}). \quad (3.13)$$

4 ND-LAr sensitivity to the HDSN parameters

In this section, we investigate the possibility to test the heavy decaying sterile neutrino (HDSN) scenario at the DUNE liquid argon near detector (ND-LAr). As we are going to see, ND-LAr has the capability to exclude a large portion of the HDSN parameter space, much bigger than the one consistent with the LSND and MiniBooNE anomalies, which is currently probed by the MicroBooNE experiment at Fermilab.

4.1 Appearance and disappearance spectra in the Standard Model

Let us first consider the charged current signal from neutrino-nucleus scattering and the associated backgrounds. We are interested in both the appearance ($\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and disappearance ($\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$) channels. Since the ND-LAr detector is not magnetized, we assume that muons are not distinguished from antimuons, such that both ν_μ 's and $\bar{\nu}_\mu$'s from the neutrino beam contribute to the disappearance signal, irrespective of whether the experiment runs in the neutrino or antineutrino mode. A similar statement holds for the appearance channel (with the additional subtlety, in the HDSN scenario, that $\nu_\mu \rightarrow \bar{\nu}_e$ and $\bar{\nu}_\mu \rightarrow \nu_e$ transitions are also possible if neutrinos are Majorana fermions).

Figure 2 shows the (anti)neutrino spectra (i.e., the number of appearance or disappearance events as a function of the reconstructed (anti)neutrino energy) expected at the DUNE ND-LAr detector in the Standard Model, assuming 3.5 years of running time both in the neutrino and antineutrino modes. The left and right panels display the appearance and disappearance spectra, respectively, while the top and bottom panels correspond to the neutrino and antineutrino modes. In each plot, the signal and the various background events are represented with different colours. Appearance events (red curve in the left panels) refer to electrons or positrons produced from the scattering of a ν_e or a $\bar{\nu}_e$ on an Argon nucleus. The background events that can mimic such a signal are the intrinsic background from the ν_e and $\bar{\nu}_e$ contamination of the neutrino flux (black); the misidentification background due to negative or positive muons misidentified as electrons or positrons (blue); and the neutral current background (green), to which all active neutrinos and antineutrinos contribute. As expected, the SM signal in the appearance channel is extremely small, due to the short baseline of the near detector, which prevents $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations to develop. The observed events are almost exclusively background events. In the disappearance channel

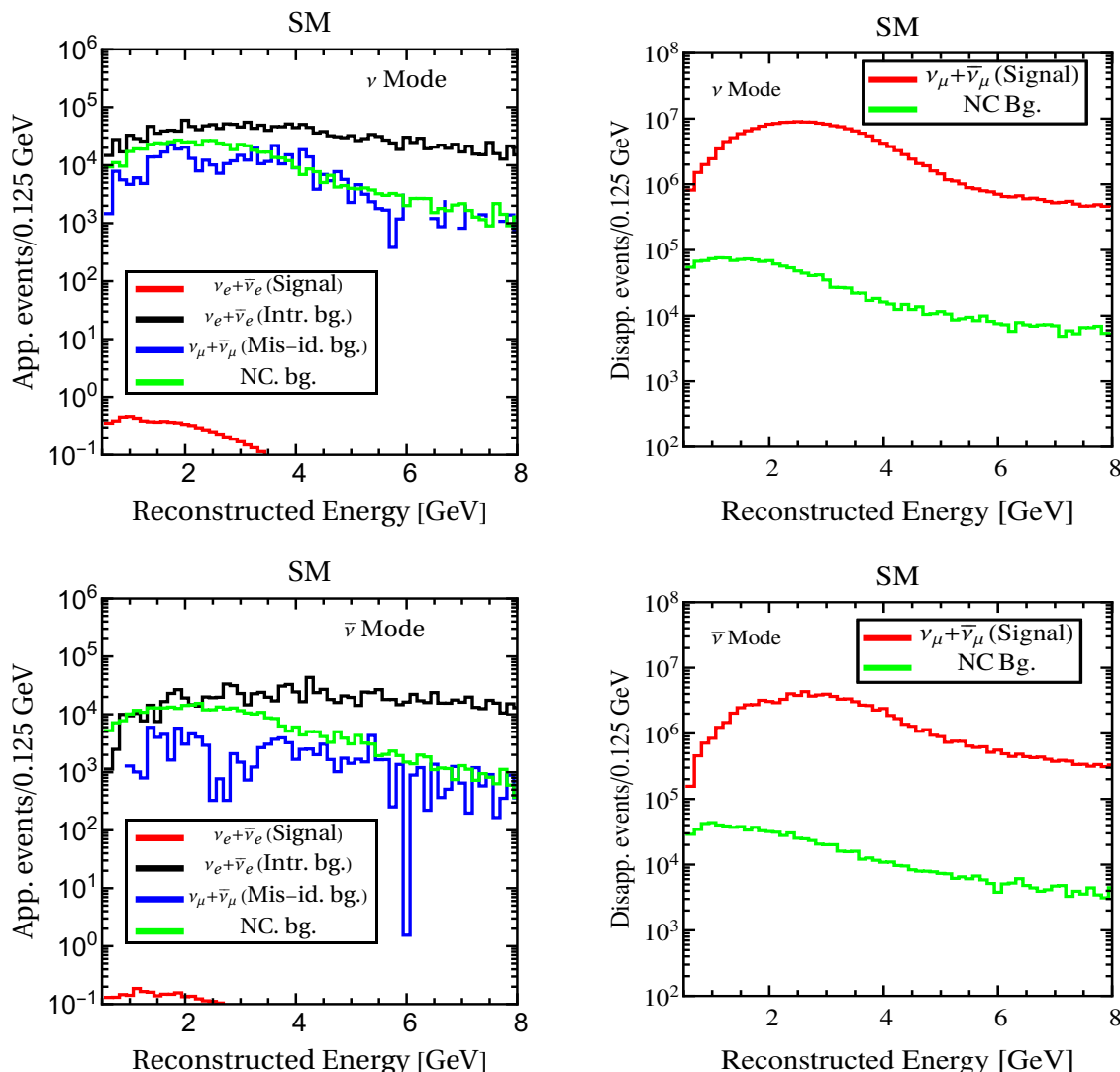


Figure 2. Appearance (left) and disappearance (right) event spectra expected at the DUNE ND-LAr detector in the Standard Model, assuming a running time of 3.5 years on axis in either neutrino or antineutrino mode. The top and bottom panels correspond to the neutrino and antineutrino modes, respectively. In each plot, the signal and the various background events are represented with different colours (see legend).

(right panels), signal events correspond to muons or antimuons produced from the scattering of a ν_μ or a $\bar{\nu}_\mu$ on an Argon nucleus. As can be seen from the plots, the SM signal (red) strongly dominates over the neutral current background (green).

4.2 Appearance and disappearance spectra in the HDSN scenario

Let us now see how the signal and backgrounds are affected by the presence of a heavy decaying sterile neutrino. Figure 3 displays the appearance spectra expected at the DUNE ND-LAr detector for three different choices of the HDSN parameters, assuming neutrinos are Dirac fermions. As in figure 2, a running time of 3.5 years is assumed in both the neutrino (upper panels) and the antineutrino (lower panels) modes. In the left panels, we took

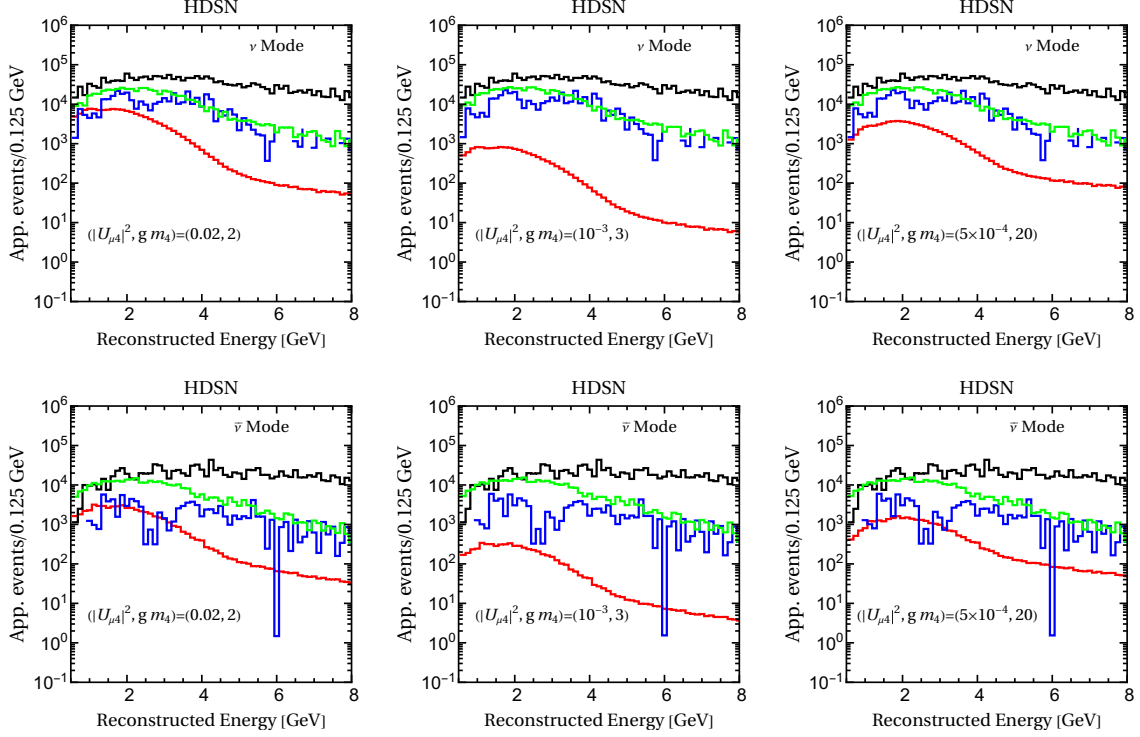


Figure 3. Appearance event spectra expected at the DUNE ND-LAr detector for various choices of the HDSN parameters $|U_{\mu 4}|^2$ and gm_4 (Dirac case), assuming a running time of 3.5 years on axis in either neutrino or antineutrino mode. The top and bottom panels correspond to the neutrino and antineutrino modes, respectively, and the colour code is the same as in the left panels of figure 2.

$(|U_{\mu 4}|^2, gm_4) = (0.02, 2 \text{ eV})$, which can explain the LSND and MiniBooNE anomalies [24] but has been excluded at more than 3σ confidence level by MicroBooNE [56]. In the middle and right panels, we chose the parameter values $(|U_{\mu 4}|^2, gm_4) = (10^{-3}, 3 \text{ eV})$ and $(5 \times 10^{-4}, 20 \text{ eV})$, respectively, which can neither explain the LSND and MiniBooNE anomalies nor be tested by SBN [24], but, as we are going to see later, can be probed at the DUNE near detector. In all three cases, the appearance signal is strongly enhanced with respect to the SM by the decays of the heavy sterile neutrinos, while the misidentification and neutral current backgrounds are only mildly affected.⁵ The number of appearance events depends on the HDSN parameters in a way that is well explained by Formula (2.7): $|U_{\mu 4}|^2$ controls the proportion of heavy sterile neutrinos in the neutrino flux, while the value of gm_4 determines how many of these decay to ν_e 's (the larger gm_4 , the larger the fraction of sterile neutrinos that decay before reaching the detector, since the sterile neutrino decay rate Γ_4 is proportional to $|g|^2 m_4^2$). As a result, the appearance signal increases both with $|U_{\mu 4}|^2$ and gm_4 . As for backgrounds, the numbers of misidentification and neutral current events in the HDSN scenario deviate from the SM prediction by a fraction $2|U_{\mu 4}|^2$ at most,⁶ as can be seen from eqs. (2.11) and (2.12). This explains why these backgrounds are only marginally affected by the presence of the heavy sterile neutrino.

⁵The intrinsic background is independent of the physics scenario, and is therefore unchanged.

⁶This statement also holds in the case of Majorana neutrinos, as can be checked from eqs. (2.13) and (2.14).

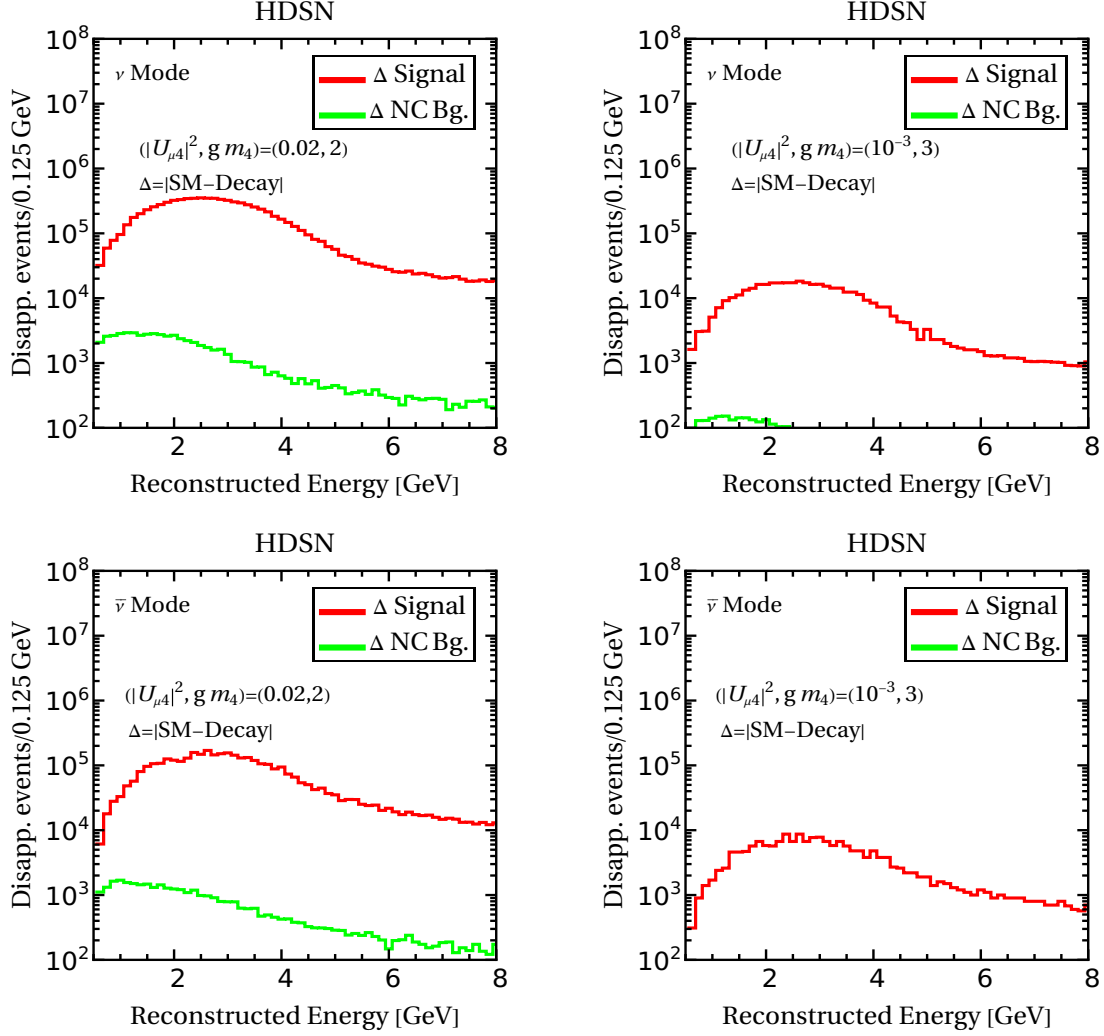


Figure 4. Disappearance event spectra expected at the DUNE ND-LAr detector for various choices of the HDSN parameters $|U_{\mu 4}|^2$ and gm_4 (Dirac case), assuming a running time of 3.5 years on axis in either neutrino or antineutrino mode. The red (green) curves show the difference between the number of signal (background) events predicted in the SM and HDSN scenario as a function of the reconstructed (anti)neutrino energy. The top and bottom panels correspond to the neutrino and antineutrino modes, respectively.

Let us now consider the disappearance channel. The left and right panels of figure 4 show the difference between the predictions of the SM and HDSN scenario for the numbers of signal events (red curves) and neutral current background events (green curves) for two different choices of model parameters, assuming neutrinos are Dirac fermions. As in the previous figures, the upper and lower panels correspond to the neutrino and antineutrino modes, respectively, and a running time of 3.5 years is assumed for each mode. In the left panels, we chose the same parameter values as in the left panels of figure 3, namely $(|U_{\mu 4}|^2, gm_4) = (0.02, 2 \text{ eV})$, while we took $(|U_{\mu 4}|^2, gm_4) = (10^{-3}, 3 \text{ eV})$ in the right panels, as in the middle panels of figure 3. At variance with the appearance signal, the disappearance signal is only mildly affected by the presence of the heavy sterile neutrino (unless one considers

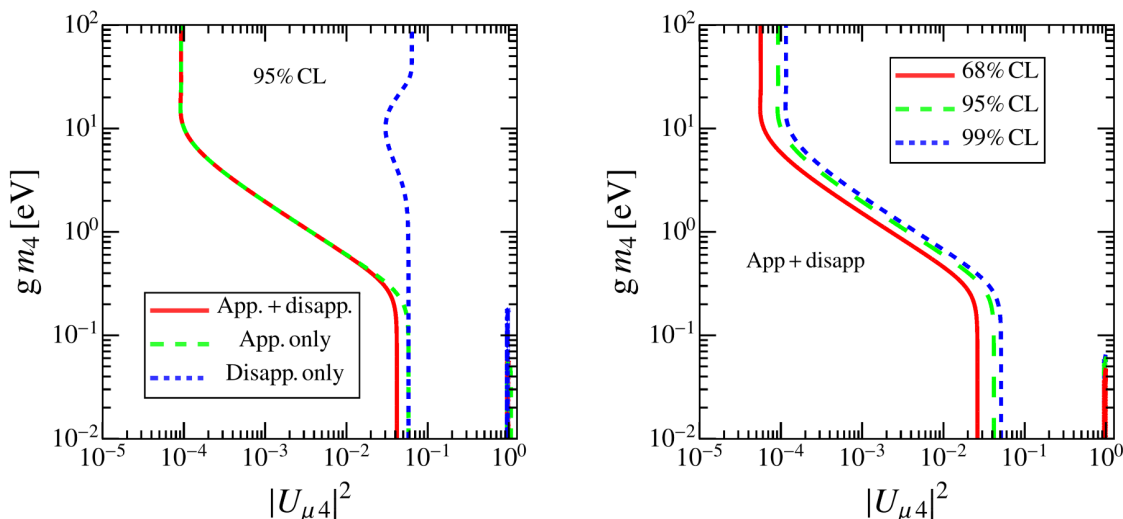


Figure 5. Expected ND-LAr sensitivity to the heavy decaying sterile neutrino parameters $|U_{\mu 4}|^2$ and gm_4 (Dirac case), assuming 3.5 years of on-axis data taking in both neutrino and antineutrino modes, and 10% signal and background uncertainties. The left plot shows the 95% C.L. sensitivities obtained using appearance data only (green long-dashed curve), disappearance data only (blue short-dashed curve), and both appearance and disappearance data (red solid curve). The right plot compares the appearance + disappearance combined sensitivities at various confidence levels. The regions that are expected to be excluded by future data are enclosed within these curves.

values of $|U_{\mu 4}|^2$ larger than the MINOS 90% C.L. upper bound). This can easily be understood from the survival probability (2.6), which deviates from the SM value $P_{\mu\mu}^{\text{SM}} = P_{\bar{\mu}\bar{\mu}}^{\text{SM}} \simeq 1$ by a fraction $2|U_{\mu 4}|^2$ at most. The same holds for the neutral current background, which according to eq. (2.12) is reduced relative to the SM by a factor ranging from $^7 \simeq 1 - 2|U_{\mu 4}|^2$ to $\simeq 1 - |U_{\mu 4}|^2$, depending on the value of gm_4 .

4.3 Sensitivity of ND-LAr to the HDSN parameters

We now move on to assess the ability of the DUNE ND-LAr detector to test the HDSN scenario, focusing first on the case of Dirac neutrinos. The left plot of figure 5 displays the expected 95% C.L. sensitivity regions in the $(|U_{\mu 4}|^2, gm_4)$ plane corresponding to appearance data only (green long-dashed curve), disappearance data only (blue short-dashed curve) and to the combination of appearance and disappearance data (red solid curve). We assumed 3.5 years of on-axis data taking in both the neutrino and antineutrino modes, as well as 10% normalization uncertainties for both signal and background. Comparing the two dashed curves shows that the ND-LAr sensitivity to the mixing parameter $U_{\mu 4}$ is dominated by appearance data, except for values of gm_4 smaller than a few 0.1 eV, where the appearance and disappearance channels are equally efficient in constraining $|U_{\mu 4}|^2$. Combining both channels in this region improves the expected upper bound on $|U_{\mu 4}|^2$, without making it competitive with the MINOS constraint ($|U_{\mu 4}|^2 < 0.023$ at 90% C.L.). Finally, the right

⁷In the case of Majorana neutrinos, this factor ranges from $\approx 1 - 2|U_{\mu 4}|^2$ to $\approx 1 - \frac{5}{4}|U_{\mu 4}|^2$ in the neutrino mode (resp. $\approx 1 - \frac{1}{2}|U_{\mu 4}|^2$ in the antineutrino mode), as can be checked from eqs. (2.13) and (2.14).

plot of figure 5 compares the appearance + disappearance combined sensitivities at different confidence levels (68%, 95% and 99% C.L.).

The different shapes of the appearance and disappearance sensitivity curves in the left plot of figure 5 can be understood from the formulae of section 2. For the disappearance channel, the difference between the predictions of the SM and HDSN scenario for the signal and background scales as $|U_{\mu 4}|^2$, as already noticed, with little dependence on gm_4 (see eqs. (2.6) and (2.12), where the gm_4 dependence is hidden in the sterile neutrino decay rate Γ_4). In fact, the sensitivity to $|U_{\mu 4}|^2$ in the disappearance channel is almost independent of gm_4 , except around $gm_4 \sim 10$ eV. The increased sensitivity to $|U_{\mu 4}|^2$ in this region arises from the energy dependence of the disappearance signal, which is due to the subleading term $|U_{\mu 4}|^4 e^{-\Gamma_4 L}$ in $P_{\mu\mu}$ and is maximal for $gm_4 \sim 10$ eV. For the appearance channel, instead, the signal strongly depends on gm_4 . For large values of this parameter, corresponding to a large Γ_4 , most sterile neutrinos decay before reaching the DUNE near detector and the appearance probability (2.7) reduces to $P_{\mu e} \simeq |U_{\mu 4}|^2$. This explains the upper part of the green long-dashed curve. For smaller values of gm_4 , hence of Γ_4 , only a fraction of the sterile neutrinos decay, leading to a suppression of the appearance probability by a factor $(1 - e^{-\Gamma_4 L})$. As a result, the sensitivity to $|U_{\mu 4}|^2$ decreases with gm_4 . Finally, for gm_4 small enough, most sterile neutrinos reach the near detector before decaying, resulting in a strong suppression of appearance events. The sensitivity to $|U_{\mu 4}|^2$ is then driven by neutral current and misidentification background events, whose number is suppressed relative to the SM by a factor $\simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$ in the low gm_4 region (as can be seen by taking the limit $e^{-\Gamma_4 L} \rightarrow 1$ in eqs. (2.11) and (2.12)). This explains the lower part of the exclusion curve, as well as the narrow allowed region⁸ close to $|U_{\mu 4}|^2 = 1$. However, as already mentioned, the sensitivity of the DUNE ND-LAr detector in the low gm_4 region is not competitive with the MINOS upper bound.

4.4 Dirac versus Majorana neutrinos

So far we assumed that neutrinos were Dirac fermions. The signatures of a heavy decaying sterile Majorana neutrino in the DUNE near detector are qualitatively similar, but not identical, as we discuss below. The differences are mainly due to the fact that sterile Majorana neutrinos have lepton number violating decay modes, resulting in the additional appearance channels $\nu_\mu \rightarrow \bar{\nu}_e$ and $\bar{\nu}_\mu \rightarrow \nu_e$, with the same probabilities as the lepton number conserving transitions $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (the only allowed ones in the Dirac case). Incidentally, this implies that the sterile neutrino decay rate is twice as large in the Majorana case as it is in the Dirac case (i.e., $\Gamma_4^M = 2\Gamma_4^D$).

Figure 6 shows how the expected 95% C.L. sensitivity of ND-LAr to the HDSN parameters depends on the neutrino nature and on the running mode (neutrino vs. antineutrino flux). Each sensitivity curve corresponds to one of the four possibilities: Dirac case, neutrino mode (black solid curve); Dirac case, antineutrino mode (red solid curve); Majorana case, neutrino mode (green dashed curve); Majorana case, antineutrino mode (blue dashed curve). The sensitivities were computed using both appearance and disappearance data, assuming 3.5

⁸This narrow region is also allowed by disappearance data, since both the signal, eq. (2.6), and the background, eq. (2.12), are suppressed by a factor $\simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$ relative to the SM in the limit $e^{-\Gamma_4 L} \rightarrow 1$.

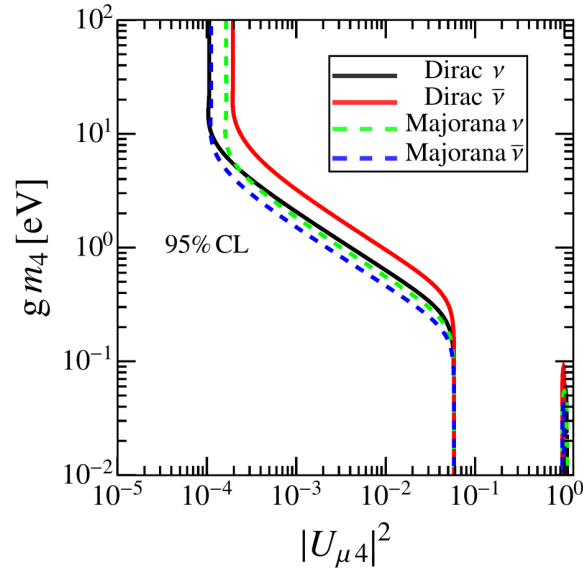


Figure 6. Impact of the neutrino nature and of the running mode (neutrino vs. antineutrino flux) on the expected 95% C.L. (combined appearance and disappearance) sensitivity of ND-LAr to the heavy decaying sterile neutrino parameters $|U_{\mu 4}|^2$ and gm_4 . Black solid curve: Dirac case, neutrino mode. Red solid curve: Dirac case, antineutrino mode. Green dashed curve: Majorana case, neutrino mode. Blue dashed curve: Majorana case, antineutrino mode. Each sensitivity curve assumes 3.5 years of on-axis data taking and 10% signal and background uncertainties.

years of on-axis data taking and 10% normalization uncertainties for signal and background. One can clearly see some differences between the four curves at large and intermediate values of gm_4 . To understand them, it is useful to consider how the signal event rates are affected by the neutrino nature and by the running mode. Let us first consider the large gm_4 region ($gm_4 > 10$ eV), where the sensitivity is dominated by appearance data, and almost all sterile (anti)neutrinos decay before reaching the detector. Given that (i) sterile (anti)neutrinos only decay to electron (anti)neutrinos in the Dirac case; (ii) both sterile neutrinos and antineutrinos decay to ν_e and $\bar{\nu}_e$ with equal probabilities in the Majorana case; and (iii) the charged current cross section is larger for neutrinos than for antineutrinos, one has

$$S_{\bar{\nu}}^D < S_{\bar{\nu}}^M \simeq S_{\nu}^M < S_{\nu}^D, \quad (4.1)$$

where S_{ν}^D (S_{ν}^M) represents the total appearance signal rate in the neutrino mode, assuming neutrinos are Dirac (Majorana) fermions, and analogously for $S_{\bar{\nu}}^D$ ($S_{\bar{\nu}}^M$) in the antineutrino mode. The small difference between S_{ν}^M and $S_{\bar{\nu}}^M$ is due to the fact that the total $\nu_{\mu} + \bar{\nu}_{\mu}$ flux is smaller in the antineutrino mode than in the neutrino mode. Eq. (4.1), together with the fact that the background level is higher in the neutrino mode than in the antineutrino mode, explains the differences in the sensitivity curves that can be observed in the large gm_4 region of figure 6. In particular, in the Dirac case, the neutrino mode can probe smaller values of $|U_{\mu 4}|^2$ than the antineutrino mode. As for the Majorana case, although the signal is roughly the same in the neutrino and antineutrino modes, the antineutrino mode has a significantly better sensitivity to $|U_{\mu 4}|^2$ due to the lower background rate. For the same

reason, the sensitivity to $|U_{\mu 4}|^2$ is practically the same for the Dirac case in the neutrino mode as for the Majorana case in the antineutrino mode, while it is slightly better for the Majorana case in the neutrino mode than for the Dirac case in the antineutrino mode.

In the intermediate gm_4 region ($0.2 \text{ eV} \lesssim gm_4 \lesssim 10 \text{ eV}$), only a fraction $1 - e^{-\Gamma_4 L}$ of the sterile (anti)neutrinos decays before reaching the DUNE near detector. Since $\Gamma_4^M = 2\Gamma_4^D$, there are twice as many decays in the Majorana case as in the Dirac case, resulting in the following hierarchy of signal rates:

$$S_{\bar{\nu}}^D < S_{\nu}^D < S_{\nu}^M \simeq S_{\bar{\nu}}^M. \quad (4.2)$$

One recovers the fact that, in the Dirac case, the sensitivity to $|U_{\mu 4}|^2$ is higher in the neutrino mode than in the antineutrino mode, but now smaller values of the mixing angle can be probed in the Majorana case, especially in the antineutrino mode in which the background level is lower (see figure 6). Finally, in the low gm_4 region ($gm_4 \lesssim 0.1 \text{ eV}$), almost all sterile (anti)neutrinos reach the detector before decaying, and the appearance signal can be neglected. The sensitivity to $|U_{\mu 4}|^2$ is then driven by the disappearance signal, and by the neutral current and misidentification backgrounds in the appearance channel, all of which become independent of the neutrino nature and of the running mode in the low gm_4 region.⁹ As a result, the sensitivity to $|U_{\mu 4}|^2$ in the low gm_4 region does not depend on the neutrino nature nor on the running mode (up to the differences between the neutrino and antineutrino fluxes), as can be seen in figure 6.

The main conclusion one can draw from figure 6 is that it is possible, at least in principle, to distinguish between Dirac and Majorana neutrinos if the HDSN scenario is realized in Nature with $gm_4 \gtrsim \text{few } 0.1 \text{ eV}$. The key observables for this purpose are the numbers of appearance events (or more precisely, the appearance spectra) in the neutrino and antineutrino modes. If neutrinos are Dirac fermions, one expects ND-LAr to observe a larger excess of appearance events in the neutrino mode than in the antineutrino mode, while the opposite is true in the Majorana case. However, telling Dirac from Majorana neutrinos might be challenging in terms of statistics (especially if $|U_{\mu 4}|^2$ is small), and more than 3 years of data taking at ND-LAr would probably be required. A more promising avenue may be to consider a magnetized detector (such as SAND, one of the three near detectors envisaged by the DUNE collaboration) and to reconstruct separately the electron and positron spectra in the neutrino and antineutrino modes. In the Dirac case, only ν_e signal events should be present in the neutrino mode (and $\bar{\nu}_e$ signal events in the antineutrino mode), while both ν_e and $\bar{\nu}_e$ signal events are expected in the Majorana case, in approximately the same proportions in the neutrino and antineutrino modes. We plan a detailed study of the possibility to distinguish between Dirac and Majorana neutrinos in the HDSN scenario in a future work.

⁹Indeed, $P_{\mu\mu} = P_{\bar{\mu}\bar{\mu}}$ and, in the limit where sterile neutrino decays can be neglected (which corresponds to $e^{-\Gamma_4 L} \rightarrow 1$), $P_{\mu\mu}$ becomes independent of Γ_4 , hence of the neutrino nature. The same holds for the ratio $N_{\text{mis-ID}}^{\text{HDSN}}/N_{\text{mis-ID}}^{\text{SM}}$, given by $P_{\mu\mu}$, and for $N_{\text{NCbckgd}}^{\text{HDSN}}/N_{\text{NCbckgd}}^{\text{SM}}$, which reduces to the same expression as $P_{\mu\mu}$ when $e^{-\Gamma_4 L} \rightarrow 1$.

4.5 Comparing the ND-LAr and MicroBooNE/SBN sensitivities to the HDSN parameters

Finally, in figures 7 and 8, we compare the expected ND-LAr sensitivity to the HDSN parameters with the regions consistent with the LSND and MiniBooNE anomalies, and with the current constraint from the MicroBooNE experiment (Dirac case) or the expected sensitivity of the SBN program at Fermilab (Majorana case). For ND-LAr, we considered 3.5 years of on-axis data taking in both neutrino and antineutrino modes. Appearance and disappearance data were combined, and 10% signal and background uncertainties were assumed. Figure 7 corresponds to the Dirac case, with the 95% C.L. and 99% C.L. expected ND-LAr sensitivities shown in the left and right panels, respectively. In ref. [56], an updated fit of MiniBooNE neutrino and antineutrino data within the HDSN scenario was performed, and constraints on the HDSN parameters were derived using recent data from the MicroBooNE experiment. The corresponding 2σ and 3σ regions are shown on the left and right plots, respectively, where the area allowed by MiniBooNE is within the red solid contour, and the region excluded by MicroBooNE lies to the right of the pink long-dashed curve. Also shown is the LSND allowed region, taken from ref. [24]. While the current MicroBooNE data already excludes most of the MiniBooNE allowed region at the 3σ level, ND-LAr will be able to probe a much larger region of the HDSN parameter space, and to fully exclude this scenario as a solution of the LSND and MiniBooNE anomalies. In addition, its sensitivity might prove crucial to confirm or reject a possible hint of ν_e appearance in future MicroBooNE data. Figure 8 corresponds to the Majorana case, which was not considered¹⁰ in ref. [56]. We therefore show the LSND and MiniBooNE allowed regions from ref. [24], as well as the expected sensitivity of the SBN experiment (of which MicroBooNE is one of the three detectors) from the same paper. The same conclusions as in the Dirac case hold. Namely, ND-LAr will be able to probe a much larger region of the HDSN parameter space than SBN, and either to fully exclude this scenario as a solution of the LSND and MiniBooNE anomalies, or to confirm a possible hint of a positive signal in future MicroBooNE, SBND or ICARUS data. Notice that the shape of the MiniBooNE allowed region given by ref. [24] and shown in figure 8 is significantly different from the one of ref. [56], displayed in figure 7. This is due to the fact that only appearance data was considered in ref. [24], while both appearance and disappearance data were included in the fit of ref. [56]. In practice, however, the main difference between the MiniBooNE allowed regions of figures 7 and 8 lies in the part of the parameter space that is already excluded by MINOS/MINOS+. The same comment applies to the sensitivity region of the SBN experiment shown in figure 8, which does not take into account disappearance data, at variance with the region excluded by MicroBooNE in figure 7. One can also notice that, in the large gm_4 region of the parameter space, where the sensitivity

¹⁰The authors of ref. [56] did not consider the Majorana case in order to avoid conflict with the stringent experimental limits on the flux of $\bar{\nu}_e$ from the Sun [57]. However, the constraints discussed in ref. [57] actually apply to the HDSN scenario of ref. [23], in which the electron neutrino contains a ν_4 component and the light scalar field ϕ can decay to a neutrino-antineutrino pair, leading to $\nu_4 \rightarrow \nu_i \phi \rightarrow \nu_i \nu_j \bar{\nu}_k$ ($i, j, k = 1, 2, 3$) in the Sun. In the scenario of ref. [24] considered in this paper, ϕ is extremely light and does not decay to active neutrinos. While decays $\nu_4 \rightarrow \bar{\nu}_e \phi$ are possible in the Majorana case, solar neutrinos are produced in a combination of matter Hamiltonian eigenstates that only very weakly mix with ν_4 , thus evading the constraints on the $\bar{\nu}_e$ flux from the Sun.

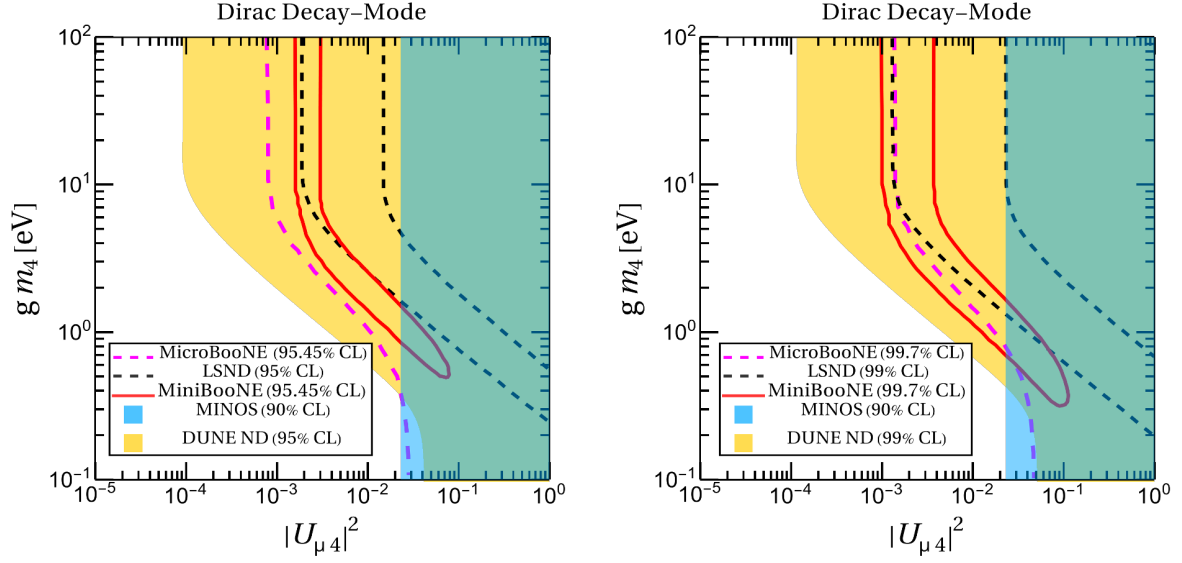


Figure 7. Comparison of the 95% C.L. (left) and 99% C.L. (right) expected sensitivity of ND-LAr to the HDSN parameters $|U_{\mu 4}|^2$ and $g m_4$ (Dirac case) with the regions consistent with the LSND [24] and MiniBooNE [56] anomalies, and with the region excluded by the MicroBooNE experiment [56]. For ND-LAr, we assumed 3.5 years of on-axis data taking in both neutrino and antineutrino modes, as well as 10% signal and background uncertainties. The confidence levels for the MiniBooNE and MicroBooNE regions, taken from ref. [56], are 2σ in the left plot and 3σ in the right plot. Also shown is the 90% C.L. MINOS/MINOS+ upper bound on $|U_{\mu 4}|^2$ [7].

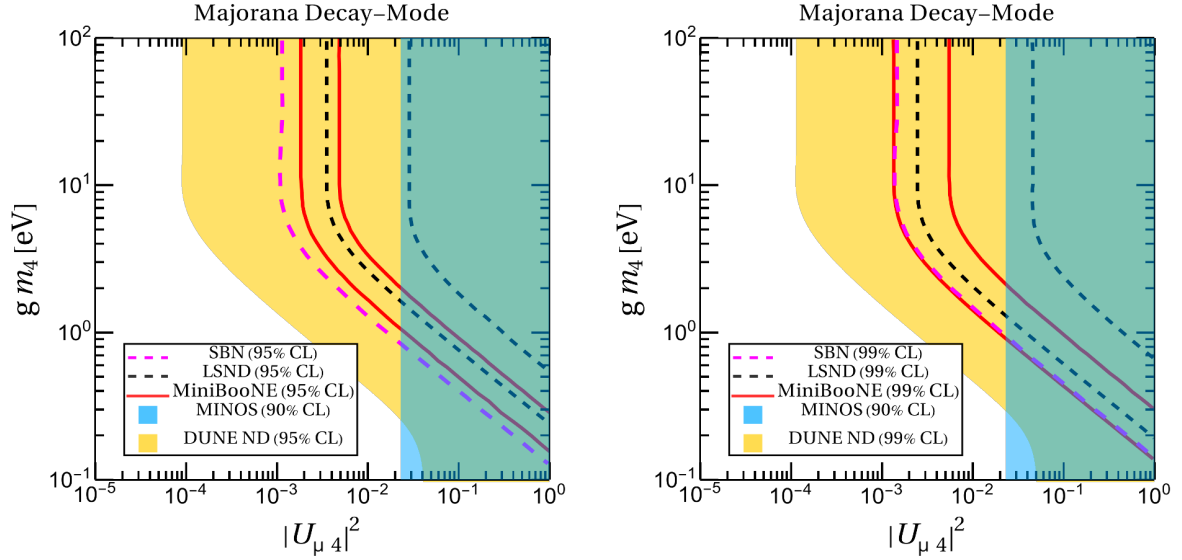


Figure 8. Comparison of the 95% C.L. (left) and 99% C.L. (right) expected sensitivity of ND-LAr to the HDSN parameters $|U_{\mu 4}|^2$ and $g m_4$ (Majorana case) with the regions consistent with the LSND and MiniBooNE anomalies, and with the expected sensitivity of the SBN experiment. For ND-LAr, we assumed 3.5 years of on-axis data taking in both neutrino and antineutrino modes, as well as 10% signal and background uncertainties. The LSND, MiniBooNE and SBN regions are taken from ref. [24]. Also shown is the 90% C.L. MINOS/MINOS+ upper bound on $|U_{\mu 4}|^2$ [7].

to $|U_{\mu 4}|^2$ is driven by appearance data, the MicroBooNE constraint is already as good as the expected sensitivity of the SBN program reported in ref. [24]. This suggests that the final sensitivity of SBN will be better than indicated by the pink long-dashed curve of figure 8.

Throughout this paper, we assumed that ND-LAr was located on the beam axis, although it will be a movable detector, able to collect data at different angles from the on-axis position. As discussed in section 3.1 and illustrated in figure 1, the value of the off-axis angle strongly affects the neutrino flux at the near detector. Namely, the intensity of the flux decreases as the off-axis angle increases, and its peak is shifted towards lower energies. We have checked that this flux reduction weakens the sensitivity of ND-LAr to $|U_{\mu 4}|^2$, as could have been anticipated. This is the reason why we did not present any results for off-axis locations of the DUNE ND-LAr detector. On the other hand, future off-axis data may help to constrain the energy dependence of the flux and cross section uncertainties, and make it possible to check how our results are affected by this energy dependence.

5 Conclusions

In this paper, we investigated the possibility to test the heavy decaying sterile neutrino hypothesis at the DUNE liquid argon near detector (ND-LAr). More specifically, we considered the scenario of refs. [22, 24], in which a fourth, mostly sterile neutrino with a mass in the keV-MeV range and a small muon neutrino component decays to an electron neutrino and an invisible light scalar field, thus mimicking the excesses observed by the LSND and MiniBooNE experiments. We showed that ND-LAr can probe a larger region of the heavy decaying sterile neutrino parameter space than the Fermilab SBN program, and will be able to fully exclude this scenario as a solution to the LSND and MiniBooNE anomalies. For instance, ND-LAr can exclude $|U_{\mu 4}|^2 \gtrsim 10^{-4}$ for $gm_4 \geq 10$ eV at more than 95% C.L. with 3.5 years of on-axis data taking in both neutrino and antineutrino modes. This sensitivity might prove crucial to confirm or reject a possible hint of ν_e appearance in future MicroBooNE, SBND or ICARUS data.

We also showed that it may be possible, in case of a positive signal, to distinguish between Dirac and Majorana neutrinos by exploiting the differences in the appearance spectra of the neutrino and antineutrino modes, provided that $gm_4 \gtrsim \text{few } 0.1$ eV. This might however be challenging for ND-LAr in terms of statistics, especially if $|U_{\mu 4}|^2$ is small. A more promising avenue may be to consider a magnetized detector (such as SAND, one of the three near detectors proposed by the DUNE collaboration) and to reconstruct separately the electron and positron spectra in the neutrino and antineutrino modes.

Finally, while we focused in this work on the scenario of refs. [22, 24], our results suggest that the DUNE ND-LAr detector can also efficiently probe other heavy decaying neutrino models predicting similar signatures, such as the one of ref. [23].

Acknowledgments

We thank Guadalupe Moreno-Granados for collaboration at an early stage of this project. The work of S.S.C. is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Project No. 510963981. S.S.C. also acknowledges financial support

from the LabEx P2IO (ANR-10-LABX-0038 — Project “BSMNu”) in the framework of the “Investissements d’Avenir” (ANR-11-IDEX-0003-01) managed by the Agence Nationale de la Recherche (ANR), France. The work of S.L. is supported in part by the European Union’s Horizon Europe research and innovation programme under the Marie Skłodowska-Curie Staff Exchange grant agreement No. 101086085 — ASYMMETRY. S.L. also acknowledges the hospitality of the Kavli IPMU while working on this project. O.G.M. was supported by the CONAHCyT Grant 23238 and by SNII-Mexico. O.G.M. would like to thank Luis Delgadillo for useful discussions.

This paper represents the views of the authors and should not be considered a DUNE collaboration paper.

Data Availability Statement. This article has no associated data or the data will not be deposited.

Code Availability Statement. This article has no associated code or the code will not be deposited.

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