On DUNE prospects in the search for sterile neutrinos

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Abstract

Experiments measuring the parameters of active neutrino oscillations can also search for sterile neutrinos in a part of sterile neutrino parameter space. In this paper we analyze the sensitivity of the upcoming experiment DUNE to the active-sterile neutrino mixing for the sterile neutrinos with masses at GeV scale. As it relies on still-undecided design of the Near Detector, we consider several possible configurations. Our most optimistic predictions show that the limit on mixing can be approximately of the same order as the previous estimates made for the LBNE. We present our results as separate plots for sterile neutrino mixing with electron, muon and tau neutrinos. Generally, DUNE has good prospects to probe large region of previously unavailable part of the parameter space before the new projects (like SHiP) join the searches.

1 Introduction

Physics beyond the Standard Model (SM) of particle physics is one of the most rapidly developing fields in theoretical physics. It stems from the discrepancies between SM predictions and some of the experimental data, obtained in last decades. For example, neutrino oscillation phenomena show that the SM is not complete. One way to address this problem is to introduce additional leptons, sterile with respect to the SM gauge interactions $SU(3)_c \times SU(2)_W \times U(1)_Y$ [1]. They are usually called sterile neutrinos and introduced in the following way:

$$\mathcal{L} = i\bar{N}_I \gamma^\mu \partial_\mu N_I - \left( \frac{1}{2} M_I \bar{N}^c_I N_I + Y_{\alpha I} \bar{L}_\alpha \tilde{H} N_I + h.c. \right),$$

(1)

here $N_I$ are sterile neutrinos, $M_I$ are their Majorana masses, and $Y_{\alpha I}$ stand for their Yukawa couplings with lepton doublets $L_\alpha, \alpha = e, \mu, \tau$ and SM Higgs doublet ($\tilde{H}_a = \epsilon_{ab} H_b$). One needs at least two sterile neutrinos to explain active neutrino oscillations, and at least three in the case when all active neutrinos have non-zero masses. It was shown that heavy sterile neutrinos may also provide explanation for leptogenesis (see, for example, Ref. [2]) or serve as a dark matter candidate [3].

Strategy for the searches of such particles depends heavily on their masses. If sterile neutrino mass is at GeV scale, it can appear in heavy hadron decays. Such sterile neutrinos can be searched for in various collider experiments. Experiments measuring the parameters of neutrino oscillations are capable of detecting sterile neutrino decay events as well. Beam energies, as well as specifics of measurement processes, geometry and the relative position of the detector determine the region of sterile neutrino parameter space that can be tested in a given experiment. Experiments such as CHARM [4], NuTeV [5], PS191[6], DELPHI [7], OKA [8], LHCb [9, 10], Belle [10], E949 [11] provide limits on active-sterile neutrino mixing. Many developing projects and upcoming experiments, such as NA62 [12, 13], SHiP [14], MATHUSLA [15], T2K [16] and DUNE [17, 18, 19, 20] declare the search for heavy neutral leptons to be one of their goals.
The search for sterile neutrinos in beam-dump experiments was, for example, considered in Refs. [21, 22]. The process behind the search can be described as follows: the proton beam strikes the target and produces a great number of heavy secondary mesons. Due to active-sterile neutrino mixing part of these mesons would produce sterile neutrinos in their decays. Part of these sterile neutrinos fly towards the detector and decay inside its volume. Such decays can be observed.

The LBNE project provided their estimate of active-sterile neutrino mixing by rescaling the results of existing experimental data using the new experiment specifics in their design report [23]. The DUNE project inherited this estimate as their own predicted sensitivity to active-sterile neutrino mixing without updating the specifics of experiment such as the Near Detector length. Until now there was no update made for the proposed DUNE design [17, 18, 19, 20].

The aim of this paper is to calculate the sensitivity of DUNE to the active-sterile neutrino mixing for sterile neutrinos of masses at GeV scale. As it relies on yet to be decided design of the Near Detector, we consider several possible configurations. We also propose some ideas as to how to reduce the noise of active sterile neutrino events. This paper can be useful for the consideration of the DUNE Near Detector design or its possible additional upgrades.

The paper is organized as follows. In Sec. 2 we present the overall layout of DUNE detector near facilities and the relevant proton beam properties. After that in Sec. 3 we list the experimental features of the search, such as different meson production rates and their momentum distribution. We present in more detail the analysis of sterile neutrino detection specifics and our way to account for it in Sec. 4. We present our estimates in Sec. 5, and conclude in Sec. 6. We also present the various relevant experimental data in Appendix A and the sterile neutrino-related formulae in Appendix B.

## 2 DUNE

Main goal of DUNE is to measure active neutrino parameters with high precision [17, 18, 19, 20]. This will be achieved by creating very intensive high-energy neutrino flux. High energy proton beam (up to 120 GeV) strikes a target, producing a high number of secondary particles (mainly pions and kaons) which produce neutrinos during their decay. To provide enough space for secondary particles to decay, a 221 m long and 4 meters wide decay pipe is planned to be installed behind the target area. At the end of the pipe the absorber is placed to reduce the “noise” from muons. Additionally, natural rock fills the distance between the decay pipe and the detector. The resulting neutrino beam is directed towards the Near Detector at 574 m from the target and the Far Detector at 1300 km, which allows for better prospects of active neutrino parameters measurement.

Important properties of reference proton beam are listed in Tab. 1. Geometrical sizes are listed in Tab. 2.

| Proton beam energy | 120 GeV |
|--------------------|---------|
| Spill duration     | $1.0 \times 10^{-5}$ s |
| Protons on target per year | $1.1 \times 10^{21}$ |
| Cycle time         | 1.2 s |

Table 1: Proton beam properties [19].

| Distance from the target to the Near Detector $L$ | 574 m |
|--------------------------------------------------|-------|
| Decay pipe length $l_{\text{decay pipe}}$        | 194 m |
| Decay pipe radius $r_{\text{decay pipe}}$        | 2 m   |
| Near Detector reference size $\Delta l \times \Delta h \times \Delta h$ [20] | $6.4 \text{ m} \times 3.5 \text{ m} \times 3.5 \text{ m}$ |

Table 2: Geometrical sizes [19].
As the Near Detector is located considerably far from the target, one can notice that the heavy sterile neutrino would reach the detector later than the active neutrinos produced at the same time. But that shift in arrival time is generally less than active neutrino travel time from target to the detector \( t_\nu \approx \frac{374 \text{ km}}{3 \times 10^5 \text{ m/s}} = 1.91 \mu\text{s} \). And the latter time is less than the spill duration of 10 \( \mu\text{s} \). This means that the active neutrino spill would overlap with the possible sterile neutrino arrival, serving as noise for the sterile neutrino search. Timing doesn’t help to get rid of the background from active neutrino interactions in the Near Detector. However a special run with much shorter spill duration can be considered as a solution for this problem.

The Far Detector is simply too far to provide a sufficient number of sterile neutrino decays in the detector volume.

We discuss geometrical restrictions in Sec. 4.

3 Experimental features

We assume that primary 120 GeV proton beam strikes a target and produces mesons that may decay into the sterile neutrinos and SM particles. Sterile neutrino momentum and energy spectra are very important for the further analysis. They are related to the momentum and energy spectra of secondary mesons. The latter can be obtained from experimental data. Longitude momentum distribution obeys the following equation:

\[
\frac{d\sigma}{dx_F} \propto (1 - x_F)^c, \quad x_F = \frac{p_{H_L}}{p_{H_L}^{\text{max}}},
\]

with \( c = 3 \) for the relevant energy \( E = 120 \text{ GeV} \) (see [21, 24, 25]).

The probability to have non-zero transverse momentum is usually assumed to be exponentially suppressed, the factor of suppression is fitted for each experiment individually. We assume the following momentum distribution for these mesons [21]:

\[
\frac{dN_H}{dp_{H_L} dp_{H_T}} \propto \frac{d\sigma_H}{dp_{H_L} dp_{H_T}} = \int_0^1 dz D(z) \int d^3p_Q \delta(p_Q - z p_H) \frac{d\sigma_Q}{dp_{Q_L} dp_{Q_T}},
\]

where \( d\sigma_Q \) is a differential cross section of direct \( Q \)-quark production obtained from QCD, \( z \) represents a part of hadron momentum \( p_H \) carried by heavy quark \( p_Q \), and a fragmentation function \( D(z) \) describes the details of hadronization. We take PYTHIA distributions i.e. Lund fragmentation function [26]:

\[
D(z) = \frac{(1 - z)^a}{z^{1 + r_{Qbm}}} \exp \left(-\frac{b}{z}(M_H^2 + p_H^2_r)\right),
\]

where the default parameter values (the ones we take) are \( a = 0.68, b = 0.98, r_s = 0, r_c = 1.32, r_b = 0.855 \) [26]. Heavy quark masses are \( m_c = 1.275 \text{ GeV}, m_b = 4.18 \text{ GeV} \) [27]. Equations (3), (4) give us the transverse momentum distribution of secondary mesons.

Different mesons have different chances to be produced in a specific experiment. This is determined by two factors: how many quarks of corresponding type \( \chi_q \) is generated by interactions of the primary beam with the target and the weight of a specific channel in quark hadronization \( Br(q \to H...) \). Basically:

\[
N_H = N_{\text{POT}} \times M_{pp} \times \chi_q \times Br(q \to H),
\]

where \( N_H \) is a number of secondary hadrons and \( N_{\text{POT}} \) is a total number of “protons on target” (we identify it with the total number of proton interactions in the thin target). \( M_{pp} \) is the multiplicity of reaction, i.e. the number of resulting particles in the interaction of primary proton with the target. It is already accounted for for all considered mesons except K-mesons in the value of \( \chi_q \). We take \( M_{pp} = 1 \) for these mesons, for K-mesons the value \( M_{pp} > 1 \) depends on the primary beam energy. For \( E = 120 \text{ GeV} \) \( M_{pp}(K) = 11 \) [21]. We take the following values of \( \chi_q \) [28]:

\[
\chi_s = 10^{-4}, \quad \chi_c = 10^{-4}, \quad \chi_b = 10^{-10}.
\]
Figure 1: Schematic plot of the detector geometry.

For $s$-quark production fractions we take [21]:

$$Br(s \rightarrow K^-) = Br(s \rightarrow K_L^0) = Br(s \rightarrow K_S^0) = 1/3.$$  \hspace{1cm} (7)

For $c$-quark production fractions we take [14]:

$$Br(c \rightarrow D^+) = 0.207, \; Br(c \rightarrow D^0) = 0.632, \; Br(c \rightarrow D_s^+) = 0.088.$$  \hspace{1cm} (8)

For $b$-quark production fractions we take [27]:

$$Br(b \rightarrow B^+) = Br(b \rightarrow B^0) = 0.405, \; Br(b \rightarrow B_s^0) = 0.101.$$  \hspace{1cm} (9)

The production fraction $Br(b \rightarrow B_s^0)$ has only been measured at LHC energies, where it reaches few $\times 10^{-3}$ [29]. At lower energies it is not known. We take:

$$Br(b \rightarrow B_s^0) = 10^{-3}.$$  \hspace{1cm} (10)

Sterile neutrino production fractions from different mesons as well as sterile neutrino decay modes are listed in Appendix B.

4 Algorithm

We simply scan the values of $M_N$ with a 20 MeV step, starting from $M_N = 140$ MeV. For some value of the sterile neutrino mass the number of sterile neutrino decays in the detector volume becomes insufficient to distinguish the sterile neutrino signal from the background (see the description below). At this mass value we abort our scan.

First, we calculate the energy distribution function in each process according to (46), (47) from Appendix B.2. Note that this is an energy in the rest frame of the decaying meson.
H. We also calculate the sterile neutrino mean lifetime \( \tau_N = \sum \frac{1}{\Gamma(N \rightarrow \ldots)} \) according to eqs. (39–45) in Appendix B.1.

After that we randomly chose one of the processes, using corresponding weight \( \chi_q \times Br(q \rightarrow H) \times Br(H \rightarrow N\ldots) \) according to formulae (46), (47), (53), (55) – (57) from Appendix B.2, and values (6) – (10). We randomly choose \( E_N \) from the previously calculated distribution that corresponds to the chosen process. From distributions described by (2), (3) we randomly choose \( p_{HL}, p_{HT}, \vec{p}_H = \vec{p}_H^L + \vec{p}_H^T \).

There is no preference for the direction of sterile neutrino momentum \( p = \{p_x, p_y, p_z\} \) in the rest frame of \( H \), so this direction is also chosen randomly. Its absolute value is \( p = \sqrt{E_N^2 - M_N^2} \). Then we make a Lorentz boost to this momentum to calculate the resulting sterile neutrino momentum \( p_N \) in the laboratory frame. We choose the target as the point of origin, \( z \) axis is directed towards the detector and \( x, y \) axes are chosen so that \( p_{HL} \equiv p_{HL}, p_{HT} \equiv p_{HL}, p_{Hx} = 0 \). For convenience we plot the scheme of the process geometry in Fig. 1. Resulting longitude and transverse components of sterile neutrino momentum in the laboratory frame read:

\[
\begin{align*}
P_{Nx} &= -\frac{E_N}{M_H} p_{HT} - p_z \sqrt{1 + \frac{p_{HT}^2}{M_H^2}}, \\
P_{Ny} &= p_y, \\
P_{Nz} &= \frac{E_N}{M_H} p_{HL} + p_x \sqrt{1 + \frac{p_{HL}^2}{M_H^2}} \equiv p_{NL}. 
\end{align*}
\] (11)

Repeating this process many times (we take \( N_{\text{total}} = 10^7 \) iterations) we obtain the resulting distributions of \( p_{Nx}, p_{Ny}, p_{Nz} \). We note that for the sterile neutrino mixing with tau neutrino a “three stage” processes become important, when heavy meson decays produce taunons, and sterile neutrino is produced in tauon decays. We discuss this case in more detail in Appendix B.2.

Note that according to (13) if decaying meson velocity in the laboratory frame \( v_{H_{\text{tot}}} = \frac{E_N}{M_H} \) is smaller than sterile neutrino longitude velocity in the meson rest frame \( v_{N_{\text{tot}}} = \frac{E_N}{M_N} \): \( v_{H_{\text{tot}}} < v_{N_{\text{tot}}} \), then it is possible that \( p_{Nz} < 0 \), i.e. sterile neutrino flies in the direction opposite of the detector. Obviously such sterile neutrino won’t be registered.

After the proton beam strikes the target, produced secondary particles travel some distance away from the target before decaying. The distance that \( H \) meson travels down the pipe before decaying at the moment \( t_H \) is \( z_H = \frac{p_H}{M_H} t_H \) (\( t = 0 \) corresponds to the moment when the proton beam strikes the target). Its shift from the axis at this moment is \( x_H = \frac{p_{HT}}{M_H} t_H \). If this meson produces sterile neutrino, its initial coordinates are \( x_N(t_H) = x_H, y_N(t_H) = 0, z_N(t_H) = z_H \). One of the criteria for sterile neutrino to decay in the detector volume is for it to decay when \( L < z_N(t_H + \Delta t) < L + \Delta l \). Here \( L \) is the distance from the target to the detector, \( \Delta l \) is the effective length of the detector and \( \Delta t = \frac{M_N}{p_{Nz}}(L - z_H) \) is a time it takes for sterile neutrino to travel the distance \( L - z_H \). As \( \Delta l \ll L \) then we simply can take \( z_N(t_H + \Delta t) = L \). The other sterile neutrino coordinates \( x_N, y_N \) can be expressed as:

\[
\begin{align*}
x_N &= \frac{p_{HT}}{M_H} t_H + \frac{p_{Nx}}{p_{Nz}} \left( L - \frac{p_{HL} t_H}{M_H} \right), \\
y_N &= \frac{p_{Ny}}{p_{Nz}} \left( L - \frac{p_{HL} t_H}{M_H} \right). 
\end{align*}
\] (14)

(15)

For the on-axis detector we take that the number of sterile neutrinos flying in the direction of the detector \( \mathcal{N}_{\text{forward}} \) is the number of sterile neutrinos for which the following statement is true:

\[
\sqrt{x_N^2 + y_N^2} < \frac{\Delta h}{2}.
\] (16)

Here \( \Delta h \) is the transverse size (height and width) of detector. Equation (16) means that the sterile neutrino won’t fly towards the detector if it deviates too much from the axis \( z \). For short living mesons \( t_H \sim 0, z_H \sim 0 \) equation (16) turns into:

\[
\frac{p_{Nx}}{p_{Nz}} < \frac{\Delta h}{2L}.
\] (17)
where \( p_{N\tau} = \sqrt{p_{N\tau}^2 + p_{N\nu}^2} \) is sterile neutrino transverse momentum.

The moment of decay of the meson \( H \) is another random variable. Probability for meson \( H \) to decay before the moment \( t_H \) in the meson rest frame is:

\[
P(t_H) = 1 - \exp\left(-\frac{t_H}{\tau_H}\right),
\]

where \( \tau_H \) is the meson mean life-time. We choose \( t_H \) according to this law (18).

For long-lived mesons (kaons) we have additional consideration: if the kaon longitude travel distance \( z_H \) exceeds the decay pipe length \( l_{\text{decay pipe}} \), then the kaon reaches the absorber. In pretty much the same way if the kaon transverse travel distance \( x_H = \frac{p_{N\pi}}{\tau_H} t_H \) exceeds the decay pipe radius \( r_{\text{decay pipe}} \), then it collides into the decay pipe walls. When either of these happens, the kaon usually rapidly loses energy. At the moment of its decay it practically stops. From eqs. (14) – (17) it is obvious that sterile neutrinos from such kaons are not very relativistic and have very small probability to reach the detector hundreds of meters away. For that reason we consider the contribution of such kaons negligible and remove them from our estimates the moment they reach the absorber or the walls.

Recall, we simulate \( N_{\text{total}} = 10^7 \) sterile neutrino travel paths to obtain the geometrical restriction for the detector. From distributions (11), (12), (13), the geometry of the detector and its position we obtain the number of sterile neutrino \( N'_{\text{forward}} \) that fly in the direction of the detector using criteria (16), (17). The portion of sterile neutrinos \( \zeta_N \) that fly towards the detector reads:

\[
\zeta_N = \frac{4 N'_{\text{forward}}}{\pi N_{\text{total}}},
\]

where coefficient \( \frac{1}{4} \) represents the fact that the frontal surface of the detector is a square and not a circle, as implied in (16).

In the experiment, the total number of produced sterile neutrinos \( N_N \) depends on the number of mesons of each type \( N_H \) (see eq. (5)) produced at the target and the probability for them to produce the sterile neutrino \( Br(H \rightarrow N...) \) (see Appendix B.2). It can be written as:

\[
N_N = N_{\text{POT}} \times \sum_q M_{pp}(H)\chi_q Br(q \rightarrow H) Br(H \rightarrow N...).
\]

The probability of sterile neutrino decay before the moment \( t_N \) in the sterile neutrino rest frame is described by the usual law (18), where meson \( H \) is replaced by sterile neutrino \( N \):

\[
P(t_N) = 1 - \exp\left(-\frac{t_N}{\tau_N}\right),
\]

where \( \tau_N = \sum_i \frac{1}{\Gamma(N \rightarrow i...)} \) is the sterile neutrino lifetime (see eqs. (39 – 45) in Appendix B.1). In the laboratory frame the sterile neutrino with mass \( M_N \) and longitude momentum \( p_{N\tau} \) travels the distance \( l_N = \frac{p_{N\tau}}{M_N} t_N \) along the beamline before decaying. The probability to decay in the interval \( L < l_N < L + \Delta l \) is:

\[
P(L < l_N < L + \Delta l) = \exp\left(-\frac{L}{\tau_N p_{N\tau}} M_N\right) - \exp\left(-\frac{L + \Delta l}{\tau_N p_{N\tau}} M_N\right).
\]

When sterile neutrino is long lived, i.e. \( \tau_N \gg t_N \), this law (22) has a simple limit:

\[
P(L < l_N < L + \Delta l) \approx \frac{\Delta l}{\tau_N p_{N\tau}} M_N.
\]

Then the number of sterile neutrinos \( N_{\text{decay}} \), that decay inside the detector of the length \( \Delta l \), can be expressed as:

\[
N_{\text{decay}} = N_N \zeta_N \frac{\Delta l}{\tau_N p_{N\tau}} M_N.
\]

For the sterile neutrino with fixed mass and mixing, eq. (24) gives us the total number of the sterile neutrino decays inside the detector volume. Sterile neutrino lifetime depends on the mixing as \( \tau_N \propto |U|^2 \) (see eqs. (39 – 45) in Appendix B.1). The number of produced
sterile neutrinos scales as $N_N \propto |U|^2$ (see (20) and eqs. (46), (47), (53), (55) – (57) in Appendix B.2). Therefore for long-lived sterile neutrino $\tau_N \gg t_N$ we obtain from eq. (24) $N_{\text{decay}} = I \times |U|^4$, where numerical coefficient $I$ doesn’t depend on $|U|^2$.

We want the detector to detect the sterile neutrino decay signals and distinguish them from the background. The main question is: how small the value of $|U|^2$ can be to still allow it? The answer to the question depends heavily on the detector configuration, its efficiency and the methods used to reduce the background noise. We sum up all these effects into one parameter $N_{\text{detector}}$. It represents the minimal number of sterile neutrino decays in the detector volume that would still allow one to distinguish the signal from the background and confirm the existence of the New Physics in the experiment (in Sec. 5 we discuss it in more detail). Hence, DUNE can probe the region of parameter space, obeying $N_{\text{detector}} < N_{\text{decay}}$, that is:

$$|U|^2 \geq \sqrt{\frac{N_{\text{detector}}}{I}}. \quad (25)$$

On the other hand, if sterile neutrino mixes with active neutrinos too strongly, it typically decays before it can reach the detector. The sterile neutrino with the mean lifetime $\tau_N$ has mean decay length $l_N = \tau_N \frac{P_N}{M_N}$. It should exceed the distance $\left(L - \frac{P_{\mu}}{M_H} t_H \right)$ the sterile neutrino has to travel before reaching the detector:

$$l_N = \tau_N \frac{P_N}{M_N} \geq \left(L - \frac{P_{\mu}}{M_H} t_H \right), \quad (26)$$

As we stated before, sterile neutrino lifetime can be expressed as $\tau_N = |U|^{-2} T_N$, where $T_N$ doesn’t depend on $|U|^2$ and can be calculated according to eqs. (39) – (45) in Appendix B.2. That gives us the other limit on active-sterile neutrino mixing:

$$|U|^2 \leq \frac{T_N \frac{P_N}{M_N}}{\left(L - \frac{P_{\mu}}{M_H} t_H \right)}. \quad (27)$$

The DUNE can test the models with mixing obeying eq. (27).

To conclude, the region of active-sterile neutrino mixing to be investigated at DUNE is confined between eqs. (25) and (27).

5 Results

In this Section we present our sensitivity estimates and analysis. We take beam properties and geometrical sizes as described in Ref. [17, 18, 19, 20]: $N_{\text{POT}} = 1.1 \times 10^{22}$ (this corresponds to the total expected number of protons-on-target over ten years), $\Delta h = 3.5\text{m}$, $L = 574\text{m}$, $l_{\text{decay.PIPE}} = 194\text{m}$, $r_{\text{decay.PIPE}} = 2\text{m}$, see Tabs. 1, 2.

For reference we present in Figs. 2, 3 the estimate from LBNE design report [23]. That estimate was made simply by rescaling of the CHARM [4] and CERN PS191 [6] results, taking into account the relevant proton beam and detector geometry parameters of LBNE and CHARM and PS191 experiments. The length of the LBNE Near Detector was taken to be $\Delta l = 30\text{m}$. These lines were calculated for the case when sterile neutrino mixes with every type of active neutrinos, while we present the mixing with a specific type. This results in the difference in the shape of the curve. Due to the difference in masses between electron and muon, decays of kaon into sterile neutrino stop at lower masses of sterile neutrino $M_N$ for the mixing with muon neutrino than for the mixing with electron neutrino. In Figs. 2, 3 one can see these steps at $M_N \sim M_K - m_e$ and $M_N \sim M_K - m_{\mu}$ respectfully. For LBNE line this shift occurs in two steps, as muon part of mixing disappears at lower sterile neutrino mass than electron part. We didn’t found estimates for LBNE limits on mixing with tau neutrino, so in Fig. 4 we present only our estimates.

For simplicity in our analysis we vary only two parameters of the detector: its effective length $\Delta l$ and $N_{\text{detector}}$, which is the number of sterile neutrino decays inside the detector volume, necessary to distinguish the sterile neutrino signal from the background. In the idealistic situation when there is absolutely no noise, according to Poisson distribution $N_{\text{detector}} = 3$ should be enough to place the limit at 95% CL.
Figure 2: Limits on the mixing between the electron neutrino and the sterile neutrino for different configurations of the detector. LBNE (steelblue) line is a previous estimate [23]. Red line is our most optimistic estimate for $\Delta l = 6.4m$ and $N_{detector} = 3$. Blue line is for $\Delta l = 1.0m$ and $N_{detector} = 3$, and green line is for $\Delta l = 6.4m$ and $N_{detector} = 300$.

Figure 3: Limits on the mixing between the muon neutrino and the sterile neutrino for different configurations of the detector. LBNE (steelblue) line is a previous estimate [23]. Red line is our most optimistic estimate for $\Delta l = 6.4m$ and $N_{detector} = 3$. Blue line is for $\Delta l = 1.0m$ and $N_{detector} = 3$, and green line is for $\Delta l = 6.4m$ and $N_{detector} = 300$. 
Figure 4: Limits on the mixing between the tau neutrino and the sterile neutrino for different configurations of the detector. Red line is our most optimistic estimate for $\Delta l = 6.4\text{m}$ and $N_{\text{detector}} = 3$. Blue line is for $\Delta l = 1.0\text{m}$ and $N_{\text{detector}} = 3$, and green line is for $\Delta l = 6.4\text{m}$ and $N_{\text{detector}} = 300$.

Unfortunately, the absence of noise isn’t a realistic assumption for the DUNE Near Detector. The main goal of the Near Detector is to characterize the beam of active neutrinos. Therefore it will be designed in such a way as to increase the probability of neutrino interactions inside the detector. From the point of view of sterile neutrino search, such interactions would serve as a noise.

People search for different sterile neutrino decay modes, the most popular being two body decays. The products of two body decays have a fixed momentum in the decaying particle rest frame. Its value depends only on the decaying particle mass. This fact allows for a more precise reconstruction of the mass of decaying particle than in the case of three-or-more body decays.

Let’s consider a specific example: the decay $N \rightarrow \pi^+ \mu^-$. The Monte-Carlo simulation results for $N_{\text{POT}} = 10^{20}$ presented in Ref. [18] suggest 44 000 events of the $\nu_\mu X \rightarrow \pi^+ \mu^- X$ type, where $X$ is the atom of the target. That means that for $N_{\text{POT}} = 1.1 \times 10^{22}$, adopted in this paper, the number of noise events integrated over the energy easily reaches $4.8 \times 10^6$. For the sterile neutrino two body decay, however, not all of these events serve as the noise. If one reconstructs the energy distribution of the detected $\mu, \pi$, the products of the sterile neutrino decays would form characteristic peaks. Only events for $\mu, \pi$ with the same energy as these peaks would serve as noise for the sterile neutrino signal. Obviously similar considerations apply to other decay modes as well. Unfortunately, the simulation/reconstruction of such energy distribution depends heavily on the detector specifics and is rather hard to perform. A detailed study of detector efficiency will be possible only after the final decision on the design of the Near Detector is made.

Additional possibility is to account for the fact that sterile neutrinos that reach the detector have very small transverse momentum. Therefore the sum of the resulting particles’ transverse momentum should also be close to zero. If one cuts all events for which it doesn’t hold true, one would reduce the amount of noise.

We note that we haven’t considered the effect of horns focusing systems on sterile neutrino momentum distribution. Horns focusing systems affect all charged particles, but particularly...
the charged pions and kaons, as they are relatively long-lived. As the name implies, horns would focus these particles, causing more of them to fly in the direction of detector. Usually horns are specialized to focus pions, as their flux is much higher than the flux of kaons. The usage of horns in other experiments increased the resulting flux of neutrinos by several times. As we have said before, from the point of view of sterile neutrino search, active neutrino events serve as a noise. It should be compensated a little thanks to the focusing of kaons that produce sterile neutrinos, but overall effect of horns is considered to be negative for the sterile neutrino search.

Thus, we present the estimates made for two values of $N_{\text{detector}}$. The first is the most optimistic case $N_{\text{detector}} = 3$ and the second is $N_{\text{detector}} = 300$ which is illustrating a more realistic scenario with some background. According to eq. (25) that would make the limit on mixing $|U_{\alpha}|^2$ to be 10 times higher than in the previous estimate.

We take the currently considered detector length $\Delta l = 6.4m$ from Ref. [20] for these estimates. We present our results for mixing with electron, muon and tau neutrino in Figs. 2, 3 and 4 respectfully. For the red lines we take $N_{\text{detector}} = 3$ and for green lines we take $N_{\text{detector}} = 300$.

The limit (27) represents the fact that sterile neutrino doesn’t decay before reaching the detector. It doesn’t depend on detector specifics, only on sterile neutrino mass $M_N$ and the distance the sterile neutrino has to travel before decaying. For heavier sterile neutrinos less process contribute to their production. Obviously, the sterile neutrinos produced in the decays of lighter particles usually reach the detector more frequently. Our estimates show that for $M_N > 2$ GeV (B-mesons decays) too few sterile neutrinos that reach the detector would be produced to be counted as discovery. Decays from B-mesons are responsible for a tiny feature along the vertical line at $M_N \approx 1.8$ GeV in Fig. 3 for $\Delta l = 6.4m$ and $N_{\text{detector}} = 3$ line. For other lines there is no such feature due to the insufficient number of sterile neutrino events.

We note that for mixing with tau neutrino even $N_{\text{detector}} = 300$ can be an overly optimistic prediction. As seen from formulæ (39) – (45) tauon or tau neutrino have to be produced in the decays of such sterile neutrino. Our estimate (see Fig. 4) shows that DUNE Near detector can only restrict the area $M_N < M_\tau$. In this case only processes with tau neutrino production remain. There is almost no hope to detect active neutrinos produced in the detector volume. This greatly hampers the ability to distinguish between the sterile neutrino decays and active neutrino events. We present the same configurations as for mixing with electron neutrino and muon neutrino only for the sake of uniformity.

There is another possibility we point out. If we had additional free space in front of the main detector we could place there a small additional detector, sensitive to sterile neutrino decays. To reduce the active neutrino event noise, as well as to minimize the effect of additional detector on active neutrino study, the additional detector should be almost empty inside. That would allow for detecting of the sterile neutrino decays in this empty space, where are few active neutrino interactions. Depending on the design, it could provide better sensitivity to mixing with active neutrinos than the main detector. In Figs. 2, 3, 4 we show that case with blue lines, for which we take $\Delta l = 1m$ and $N_{\text{detector}} = 3$. From these figures one can see that, depending on its configuration, a small additional detector with good efficiency could provide better limits than the main detector overburdened with active neutrino background.

In Figs. 5, 6, 7 we present current limits on the mixing (and some predictions), which we have taken from [30]. We have removed LBNE estimate (the same as in Figs. 2, 3) and replaced it with our own estimate for DUNE sensitivity. We take $\Delta l = 1m$ and $N_{\text{detector}} = 3$ case as our reference estimate. On the side note, the estimate for $\Delta l = 6.4m$ and $N_{\text{detector}} = 300$ lays near the boundary of the existing limits for mixing with electron or muon neutrino. We note that SHiP experiment has updated its estimate in Ref. [14]. Some other updates can be seen, for example, in Refs. [13, 15, 31].

6 Conclusions

In this paper we calculated the prospects for the sterile neutrino search in the upcoming experiment DUNE. We considered several possibilities for the still-undecided Near Detector
Figure 5: Limits on the mixing between the electron neutrino and the sterile neutrino for different experiments adopted from \cite{30}. Our estimate is a blue “DUNE” line made for $10^{22}$ POT, $\Delta l = 1$ m and $N_{\text{detector}} = 3$.

Figure 6: Limits on the mixing between the muon neutrino and the sterile neutrino for different experiments adopted from \cite{30}. Our estimate is a blue “DUNE” line made for $10^{22}$ POT, $\Delta l = 1$ m and $N_{\text{detector}} = 3$. 

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Figure 7: Limits on the mixing between the tau neutrino and the sterile neutrino for different experiments adopted from [30]. Our estimate is a blue “DUNE” line made for $10^{22}$ POT, $\Delta l = 1 \text{m}$ and $N_{\text{detector}} = 3$.

Our more optimistic predictions are approximately of the same order as the previous estimates, while more conservative ones may lay higher than it, but still lower than the current limits. We point out that for the search of sterile neutrinos an additional small detector, that is almost empty inside, could provide better sensitivity than the main detector. Another possibility to overcome the noise of active neutrino interactions can be a special run with a really short proton spill duration. Overall our estimates show that while DUNE main scientific goal is the measurement of active neutrino parameters, it would still be able to probe currently unavailable part of the sterile neutrino parameter space.

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A Parameters

In this Section we list experimental values of parameters used in our work.

Lepton masses $l \in \{e, \mu, \tau\}$: $M_e = 0.5109989461 \text{ MeV}$, $M_\mu = 105.6583745 \text{ MeV}$, $M_\tau = 1.77686 \text{ GeV}$ [27].

Tauon average lifetime $\tau_\tau = 2.903 \times 10^{-4} \text{ ns}$ [27].

Fermi constant: $G_F = 1.16637877 \times 10^{-5} \text{ GeV}^{-2}$ [27].

Weinberg angle: $\sin^2 \theta_W = 0.23122$ [27].

$\rho$-meson decay constant: $g_\rho = 0.162 \text{ GeV}^2$ [29].

| $V_{ud}$ | $V_{us}$ | $V_{cd}$ | $V_{cs}$ | $V_{ub}$ | $V_{cb}$ |
|---------|---------|---------|---------|---------|---------|
| 0.97420 | 0.2243  | 0.218   | 0.997   | 0.00394 | 0.0422  |

Table 3: CKM-matrix elements [27].
Table 4: Relevant meson decay parameters.

| $H$ | $M_H$, MeV [27] | $\tau_H$, ns [27] | $f_H$, MeV [29] |
|-----|----------------|-----------------|----------------|
| $\pi^+$ | 139.57061 | 26.033 | 130.2 |
| $\pi^0$ | 134.977 | 8.52e-8 | 130.2 |
| $K^+$ | 493.677 | 12.38 | 155.6 |
| $K^0_L$ | 497.611 | 51.16 | |
| $K_S^0$ | 497.611 | 0.089564 | |
| $\eta$ | 547.862 | | 81.7 |
| $\rho$ | 775.26 | | |
| $\eta'$ | 957.78 | -94.7 | |
| $D^+$ | 1869.65 | 1.04e-3 | 212 |
| $D^0$ | 1864.83 | 4.101e-4 | 187 |
| $D^+_s$ | 1968.34 | 5.04e-4 | 249 |
| $B^+$ | 5279.32 | 1.638e-3 | 187 |
| $B^0$ | 5279.63 | 1.52e-3 | |
| $B^0_s$ | 5366.89 | 1.509e-3 | |
| $B^-_s$ | 6274.9 | 5.07e-4 | 434 |

Table 5: Best fit parameters [29] for the form factors of the $K \rightarrow \pi$ transition.

A.1 Form-factors

Basic formula [29]:

$$ f(q^2) = \frac{1}{1 - q^2/M^2_{pole}} \sum_{n=0}^{N-1} a_n \left[ (z(q^2))^n - (-1)^n N (z(q^2))^N \right], \quad (28) $$

where

$$ z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}, \quad (29) $$

with

$$ t_+ = (m_H + m_{H'})^2, \quad t_0 = (m_H + m_{H'}) (\sqrt{m_H - \sqrt{m_{H'}^2}}). \quad (30) $$

A.1.1 K meson form factors

Form factors of $K \rightarrow \pi$ transition are well described by the linear approximation:

$$ f^{K\pi}_{+,0}(q^2) = f^{K\pi}_{+,0}(0) \left( 1 + \lambda_{+,0} \frac{q^2}{m_{\pi^+}^2} \right). \quad (32) $$

| $H, H'$ | $f^{+,0}_{+,0}(0)$ | $\lambda_+$ | $\lambda_0$ |
|---------|-----------------|-------|-------|
| $K^0, \pi^+$ | 0.970 | 0.0267 | 0.0117 |
| $K^+, \pi^0$ | 0.970 | 0.0277 | 0.0183 |

A.1.2 D meson form factors

Form factors of $D \rightarrow K, \pi$:

$$ f(q^2) = \frac{f(0) - c (z(q^2) - z(0)) \left( 1 + \frac{z(q^2) + z(0)}{2} \right)}{1 - Pq^2}, \quad (33) $$

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Table 6: Best fit parameters \([29]\) for the form factors of the \(D \to K, \pi\) transition.

| \(f\) | \(f(0)\) | \(c\) | \(P(\text{GeV}^{-2})\) |
|---|---|---|---|
| \(f_f^{DK}\) | 0.7647 | 0.066 | 0.224 |
| \(f_0^{DK}\) | 0.7647 | 2.084 | 0 |
| \(f_f^{D\pi}\) | 0.6117 | 1.985 | 0.1314 |
| \(f_0^{D\pi}\) | 0.6117 | 1.188 | 0.0342 |

Form factors of \(D \to \eta\):

\[
f_+^{D,\eta}(q^2) = \frac{f_+^{D,\eta}(0)}{\left(1 - \frac{q^2}{M_{D^*}^2}\right)\left(1 - \alpha^{D,\eta}_+ \frac{q^2}{M_{D^*}^2}\right)}, \quad (34)
\]

where \(f_+^{D,\eta}(0) = 0.495, M_{D^*} = 2.112, \alpha^{D,\eta}_+ = 0.198 [29]\).

\[
f_0^{D,\eta}(q^2) = \frac{f_0^{D,\eta}(0)}{1 - \alpha^{D,\eta}_0 \frac{q^2}{M_{D^*}^2}}, \quad (35)
\]

\(f_0^{D,\eta}(q^2)\) is not well constrained by experimental data, so we take \(f_0^{D,\eta}(0) = f_+^{D,\eta}(0)\) and \(\alpha^{D,\eta}_0 = 0 [29]\).

A.1.3 B meson form factors

Form factors of \(B \to D, \pi\):

| \(f\) | \(M_{\text{pole}}\) GeV | \(a_0\) | \(a_1\) | \(a_2\) |
|---|---|---|---|---|
| \(f_f^{B_0D(s)}\) | \(\infty\) | 0.909 | -7.11 | 66 |
| \(f_0^{B_0D(s)}\) | \(\infty\) | 0.794 | -2.45 | 33 |
| \(f_f^{B_0\pi}\) | 5.325 | 0.360 | -0.828 | 1.1 |
| \(f_0^{B_0\pi}\) | 5.65 | 0.233 | 0.197 | 0.18 |
| \(f_f^{B_0\pi}\) | 5.325 | 0.404 | -0.68 | -0.86 |
| \(f_0^{B_0\pi}\) | 5.65 | 0.490 | -1.61 | 0.93 |

Table 7: Best fit parameters \([29]\) for the form factors of the \(B \to D, \pi\) transition.

A.1.4 Meson form factors for decay into vector meson

Standard axial form factors \(A_0(q^2), A_1(q^2), A_2(q^2)\) and vector form factor \(V(q^2)\) can be parameterized as:

\[
V(q^2) = \frac{f_{hh'}^{hh'}}{\left(1 - \frac{q^2}{M_V^2}\right)\left(1 - \sigma^{hh'}_{hh'} \frac{q^2}{M_V^2} - \zeta^{hh'}_{hh'} \frac{q^4}{M_V^4}\right)}, \quad (36)
\]

\[
A_0(q^2) = \frac{f_{A_0}^{hh'}}{\left(1 - \frac{q^2}{M_P^2}\right)\left(1 - \sigma_{A_0}^{hh'} \frac{q^2}{M_P^2} - \zeta_{A_0}^{hh'} \frac{q^4}{M_P^4}\right)}, \quad (37)
\]

\[
A_{1,2}(q^2) = \frac{f_{A_{1,2}}^{hh'}}{1 - \sigma_{A_{1,2}}^{hh'} \frac{q^2}{M_P^2} - \zeta_{A_{1,2}}^{hh'} \frac{q^4}{M_P^4}}, \quad (38)
\]
Table 8: Best fit parameters \cite{29} of the meson form factors of the decays into vector meson.

| \( h h' \) | \( D K^* \) | \( B D^* \) | \( B_\rho \) | \( B_s D^* \) | \( B_s K \) |
|-------------|-------|-------|-------|-------|-------|
| \( f_{V}^{h h'} \) | 1.03  | 0.76  | 0.295 | 0.95  | 0.291 |
| \( f_{A_0}^{h h'} \) | 0.76  | 0.69  | 0.231 | 0.67  | 0.289 |
| \( f_{A_1}^{h h'} \) | 0.66  | 0.66  | 0.269 | 0.70  | 0.287 |
| \( f_{A_2}^{h h'} \) | 0.49  | 0.62  | 0.282 | 0.75  | 0.286 |

\( \sigma_{V}^{h h'} \) = 0.27, \( \sigma_{A_1}^{h h'} \) = 0.17, \( \sigma_{A_2}^{h h'} \) = 0.3, \( \sigma_{A_3}^{h h'} \) = 0.67, \( \sigma_{A_4}^{h h'} \) = 0.67, \( \sigma_{A_5}^{h h'} \) = 0.0, \( \sigma_{A_6}^{h h'} \) = 0.17, \( \sigma_{A_7}^{h h'} \) = 0.59, \( \sigma_{A_8}^{h h'} \) = 0.796, \( \sigma_{A_9}^{h h'} \) = 0.350, \( \sigma_{A_{10}}^{h h'} \) = 0.305, \( \sigma_{A_{11}}^{h h'} \) = 0.694, \( \sigma_{A_{12}}^{h h'} \) = 0.798, \( \sigma_{A_{13}}^{h h'} \) = 0.54, \( \sigma_{A_{14}}^{h h'} \) = 0.463, \( \sigma_{A_{15}}^{h h'} \) = 0, \( \sigma_{A_{16}}^{h h'} \) = 0, \( \sigma_{A_{17}}^{h h'} \) = 0, \( \sigma_{A_{18}}^{h h'} \) = 0.055, \( \sigma_{A_{19}}^{h h'} \) = 0.6, \( \sigma_{A_{20}}^{h h'} \) = 0.561, \( \sigma_{A_{21}}^{h h'} \) = 0, \( \sigma_{A_{22}}^{h h'} \) = 2.1, \( \sigma_{A_{23}}^{h h'} \) = 0.510, \( \sigma_{A_{24}}^{h h'} \) = 1.06, \( \sigma_{A_{25}}^{h h'} \) = 0.2, \( \sigma_{A_{26}}^{h h'} \) = 0, \( \sigma_{A_{27}}^{h h'} \) = 0.510, \( \sigma_{A_{28}}^{h h'} \) = 1.06, \( \sigma_{A_{29}}^{h h'} \) = 0.16, \( \sigma_{A_{30}}^{h h'} \) = 0.41, \( \sigma_{A_{31}}^{h h'} \) = -0.21, \( \sigma_{A_{32}}^{h h'} \) = 0.070, \( \sigma_{A_{33}}^{h h'} \) = -0.074.

\( M_{V}^{h h'} \) (GeV) = 1.969, 6.275, 5.279, 6.275, 5.367, \( M_{V}^{h h'} \) (GeV) = 2.112, 6.331, 5.325, 6.331, 5.415.

B. Formulae

B.1 Sterile neutrino decays

2-particle sterile neutrino decays \cite{21, 29}:

\[
\Gamma(N \to H^0 \nu_\alpha) = \frac{|U_{\alpha}|^2}{32\pi} G_F f_H^2 |M_N|^3 \left(1 - \frac{M_N^2}{M_N^2}ight)^2, \tag{39}
\]

\[
\Gamma(N \to H^+ l^-) = \frac{|U_{\alpha}|^2}{16\pi} G_F |V_H|^2 f_H^2 |M_N|^3 \left(1 - \frac{M_N^2}{M_N^2}ight)^2 \times \left(1 - \frac{(M_H - M_l)^2}{M_N^2}ight), \tag{40}
\]

\[
\Gamma(N \to V^+ l^-) = \frac{|U_{\alpha}|^2}{16\pi} G_F |V_V|^2 M_N^3 \times \left(1 - \frac{M_N^2}{M_N^2}ight)^2 + \frac{M_V^2}{M_N^2} \left(1 + \frac{M_V^2 - 2M_V^2}{M_N^2}ight) \times \left(1 - \frac{(M_V - M_l)^2}{M_N^2}\right), \tag{41}
\]

\[
\Gamma(N \to V^0 \nu_\alpha) = \frac{|U_{\alpha}|^2}{32\pi} G_F M_N^2 \left(1 + 2\frac{M_{V^0}}{M_N^2}\right) \left(1 - \frac{M_{V^0}^2}{M_N^2}\right), \tag{42}
\]

where \( H^0 \in \{\pi^0, \eta, \eta', \ldots\}, H^+ \in \{\pi^+, K^+, D^+, \ldots\}, V^0 \in \{\rho^0, \ldots\}, V^+ \in \{\rho^+, \ldots\} \) (see Tab. 4). In this work we use only \( k_\rho = 1 - 2\sin^2 \theta_W \).
3 particle sterile neutrino decays \cite{21, 29}: 

\[
\Gamma\left(N \rightarrow \nu_\alpha \sum_\beta \bar{\nu}_\beta \nu_\beta\right) = \frac{G^2_F M_N^5}{192 \pi^3} |U_\alpha|^2, 
\]

(43)

\[
\Gamma\left(N \rightarrow l^-_{\alpha \neq \beta} l^+_{\beta} \nu_\beta\right) = \frac{G^2_F M_N^5}{192 \pi^3} |U_\alpha|^2 \left(1 - 8x_l^2 + 8x_l^6 - x_l^8 - 12x_l^4 \log x_l^2\right), 
\]

(44)

where

\[
x_l = \max\left(M_{l_\alpha}, M_{l_\beta}\right), \]

\[
L = \log \left[\frac{1 - 3x_l^2 - (1 - x_l^2) \sqrt{1 - 4x_l^2}}{x_l^2 (1 + \sqrt{1 - 4x_l^2})}\right], x_l = \frac{M_l}{M_N},
\]

and

\[
C_1 = \frac{1}{2}(1 - 4 \sin^2 \theta_w + 8 \sin^4 \theta_w), \quad C_2 = \frac{1}{2} \sin^2 \theta_w (2 \sin^2 \theta_w - 1), \]

\[
C_3 = \frac{1}{2}(1 + 4 \sin^2 \theta_w + 8 \sin^4 \theta_w), \quad C_4 = \frac{1}{2} \sin^2 \theta_w (2 \sin^2 \theta_w + 1).
\]

B.2 Sterile neutrino production

2-body meson decays with sterile neutrino production \cite{21}:

\[
\frac{d\mathcal{B}(H^+ \rightarrow l_\alpha^+ N)}{dE_N} = \tau_H \frac{G^2_F M_N^5 M_H f_H^2 |V_{lH}|^2 |U_\alpha|^2 \left(1 - \frac{M_N^2}{M_H^2} + 2 \frac{m^2}{M_H^2} + \frac{m^2}{M_N^2}\right) \times \left(1 - \frac{m^2}{M_H^2}\right) \sqrt{\left(1 + \frac{M_N^2}{M_H^2} - \frac{m^2}{M_H^2}\right)^2 - 4 \frac{M_N^2}{M_H^2} \times \delta \left(E_N - \frac{M_N^2 - M_H^2 + M_N^2}{2 M_H}\right)} }{8 \pi \times \left(1 - \frac{M_H^2}{M_H^2}\right) \sqrt{\left(1 + \frac{M_N^2}{M_H^2} - \frac{m^2}{M_H^2}\right)^2 - 4 \frac{M_N^2}{M_H^2} \times \delta \left(E_N - \frac{M_N^2 - M_H^2 + M_N^2}{2 M_H}\right)}}.
\]

(46)

We take the following decays into two particles: \(K^+ \rightarrow l^+ N, D^+ \rightarrow l^+ N, D_s^+ \rightarrow l^+ N, B^+ \rightarrow l^+ N, B_s^+ \rightarrow l^+ N\).

3-particle scalar meson decays with sterile neutrino production \cite{21}:

\[
\frac{d\mathcal{B}(H \rightarrow H'l_{\alpha} N)}{dE_N} = \tau_H |U_{\alpha}|^2 C_K \frac{G^2_F |V_{HH'}|^2}{64 \pi^3 M_H^2} \int_{q_{\min}}^{q_{\max}} dq^2 \times \]

\[
\times \left(f^2(q^2) (q^2 (M^2_{H'} + M^2_{H'}) - (M^2_N - M^2_{H'})^2) + 2 f_{-}(q^2) f_+(q^2) (M^2_{H'}) (2 M^2_{H'} - 2 M^2_{H'} - 4 E_N M_H - M^2_{H'} + M^2_{H'} + q^2) + M^2_{H} (4 E_N M_H + M^2_{H'} - M^2_{H'} - q^2)) \right) \times \left(2 M^2_{H'} - 2 M^2_{H'} - 4 E_N M_H - M^2_{H'} + M^2_{H'} + q^2\right) - (2 M^2_{H'} + 2 M^2_{H'} - q^2) (q^2 - M^2_N - M^2_{H'})),
\]

(47)
where $C_N = \frac{1}{\sqrt{2}}$ for $H' = \pi^0$, $C_N = 1$ for all other cases [29] and $q^2$ range is [27]:

\[ q^2_{\text{min}} = (E_V^2 + E_q^2) - \left( \sqrt{E_V^2 - M^2} + \sqrt{E_q^2 - M_N^2} \right)^2, \]  
(48)

\[ q^2_{\text{max}} = (E_V^2 + E_q^2) - \left( \sqrt{E_V^2 - M^2} - \sqrt{E_q^2 - M_N^2} \right)^2, \]  
(49)

\[ E_2^* = \frac{M_H^2 + M_N^2 + M^2 - 2M_HE_N}{2m_{12}}, \]  
(50)

\[ E_3^* = \frac{M_HE_N - M_N^2}{m_{12}}, \]  
(51)

\[ m_{12} = \sqrt{M_H^2 + M_N^2 - 2M_HE_N}, \]  
(52)

$q^2$ range depends on $E_N$. [27] provides us with $E_N$ range through equation: $(M_H + M_i)^2 \leq m_{12}^2 \leq (M_H - M_N)^2$. It is equivalent to $M_N \leq E_N \leq \frac{1}{2M_H} (M_H^2 + M_N^2 - (M_H' + M_i)^2)$.

3-particle vector meson decays with sterile neutrino production [21]:

\[ \frac{dBr(H \rightarrow Vl_N)}{dE_N} = \tau_H |U_{\alpha i}|^2 C_K^2 \frac{G_F^2}{32\pi^3 M_H^2} \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \times \]
\[ \times \left( \frac{f_2(q^2)}{2} \left( q^2 - M_N^2 - M^2 + \omega^2 \frac{\Delta q^2}{M_V^2} \right) + \frac{f_4(q^2)}{2} (M_N^2 + M^2)(q^2 - M_N^2 + M^2) \left( \frac{\Delta q^2}{M_V^2} - q^2 \right) + 2f_3(q^2)M_N^4 \left( \frac{\Delta q^2}{M_V^2} - q^2 \right) \left( M_N^2 + M^2 - q^2 + \omega^2 \frac{\Delta q^2}{M_V^2} - q^2 \right) + 2f_3(q^2)f_5(q^2)(q^2(\omega^2 - \omega^2) + \Omega^2(M_N^2 - M^2)) + 2f_2(q^2)f_5(q^2) \left( M_N^2 - M^2 \right) + \Omega^4(q^2 - M_N^2 + M^2) - 2M_V^2(q^2 - M_N^2 + M^2) + 2\omega^2\Omega^2(M_N^2 - q^2 - M^2) + 2\omega^2\Omega^2(M_N^2 - q^2 - M^2) + 2\omega^2\Omega^2(q^2 - M^2) + 2\omega^2\Omega^2(q^2 - M^2) \right), \]
(53)

where $\omega^2 = M_H^2 - M_V^2 + M_N^2 - M^2 - 2M_HE_N$ and $\Omega^2 = M_H^2 - M_V^2 - q^2$, $C_K = \frac{1}{\sqrt{2}}$ for $H' = \rho^0$, $C_N = 1$ for all other cases [29]; form factors $f_i(q^2)$ can be expressed via standard axial form factors $A_0(q^2), A_1(q^2), A_2(q^2)$ and vector form factor $V(q^2)$ as:

\[ f_1(q^2) = \frac{V(q^2)}{M_H + M_V}, \quad f_2(q^2) = (M_H + M_V)A_1(q^2), \quad f_3(q^2) = \frac{A_2(q^2)}{M_H + M_V}, \]
\[ f_4(q^2) = \frac{V(q^2)(2A_0 - A_1 - A_2)}{M_V}, \quad f_5(q^2) = f_3(q^2) + f_4(q^2), \]  
(54)

| \( \pi^+ \rightarrow l^+N \) | \( K^+ \rightarrow l^+N \) | \( D^+ \rightarrow l^+N \) | \( D_s^+ \rightarrow l^+N \) | \( B^+ \rightarrow l^+N \) | \( B_c^+ \rightarrow l^+N \) |
|---|---|---|---|---|---|
| \( V_H \) | \( V_{ud} \) | \( V_{us} \) | \( V_{cd} \) | \( V_{cs} \) | \( V_{ub} \) | \( V_{cb} \) |

Table 9: 2 particle meson decay CKM-matrix elements.
significant processes are neutrino, but with electron neutrino or muon neutrino as well, then another process to neutrino production have been studied \( \nu \rightarrow \nu \) using the same replacement. Tauon replaces meson \( \tau \rightarrow 0 \), and \( \nu \rightarrow \nu \) becomes available. Tauons are produced in the decays of heavy mesons. The most significant processes are \( D^0 \rightarrow D^+ \rightarrow D^- + \nu \), \( B^0 \rightarrow D^0 \rightarrow D^+ \rightarrow D^- + \nu \), \( B^0 \rightarrow D^0 \rightarrow D^+ \rightarrow D^- + \nu \), and \( B^0 \rightarrow D^0 \rightarrow D^+ \rightarrow D^- + \nu \) [27]. In the leading order they are described by (46), (47), (53), (55) – (57) with sterile neutrino \( N \) replaced by tauon \( \tau \) and lepton \( l \) replaced by active neutrino \( \nu \). We can obtain the resulting tauon momentum and coordinates with formulae (11) – (15) using the same replacement. Tauon replaces meson \( H \) in formulae (11) – (13) of the resulting sterile neutrino momentum spectra. We note that lifetimes of taus and heavy mesons that produce them are very short. Therefore eq. (17) is a sufficient criterion for the sterile neutrino to strike the target.

To obtain \( Br(H \rightarrow N...) \) one needs to integrate (46), (47), (53), (55) – (57) over \( E_N \) from \( M_N \) to \( \infty \) of \( (M_H^2 + M_N^2 - (M_H + M_l)^2)^2 \). Note that other processes that may contribute to neutrino production have been studied [29]. The most important of them is multi-meson

| \( V_{HH} \) | \( V_{us} \) | \( V_{cs} \) | \( V_{cd} \) | \( V_{cb} \) | \( V_{ub} \) |
|---|---|---|---|---|---|
| \( K^0 \rightarrow \pi^+l^-N \) | \( D^0 \rightarrow K^+l^-N \) | \( D^+ \rightarrow K^0l^-N \) | \( B^0 \rightarrow \pi^0l^-N \) | \( B^+ \rightarrow D^0l^-N \) | \( B^0 \rightarrow \rho^0l^-N \) |
| \( K^+ \rightarrow \pi^0l^+N \) | \( D^0 \rightarrow K^+l^-N \) | \( D^+ \rightarrow K^0l^-N \) | \( D^+ \rightarrow \pi^0l^-N \) | \( B^+ \rightarrow D^0l^-N \) | \( B^0 \rightarrow K^+l^-N \) |
| \( B^+ \rightarrow \rho^0l^-N \) | \( B^0 \rightarrow K^+l^-N \) | \( B^0 \rightarrow D^+l^-N \) | \( B^+ \rightarrow D^0l^-N \) | \( B^0 \rightarrow D^+l^-N \) | \( B^0 \rightarrow K^+l^-N \) |

Table 10: 3 particle meson decay CKM-matrix elements.

\[
\frac{d\text{Br}(\tau^+ \rightarrow H^+N)}{dE_N} = \frac{\tau_r[U_{\tau r}]^2 G_F^2 |V_{HH}|^2 f_H^2 M_r^2}{16\pi M^2_{\tau}} \left( 1 - \frac{M_H^2}{M^2_{\tau}} \right) \left( 1 - \frac{M_B^2}{M^2_{\tau}} \right) \times \delta \left( E_N - \frac{M^2_H - M^2_B}{2M_\tau} \right) \tag{55}
\]

\[
\frac{d\text{Br}(\tau^+ \rightarrow \rho^+N)}{dE_N} = \frac{\tau_r[U_{\tau r}]^2 G_F^2 |V_{uu}|^2 f_\rho^2 M_r^2}{8\pi M^2_{\rho}} \left( 1 - \frac{M_\rho^2}{M^2_{\tau}} \right) \left( 1 - \frac{M_B^2}{M^2_{\tau}} \right) \times \delta \left( E_N - \frac{M^2_\rho - M^2_B}{2M_\tau} \right) \tag{56}
\]

\[
\frac{d\text{Br}(\tau^+ \rightarrow \nu_\alpha l^+_\alpha N)}{dE_N} = \frac{\tau_r[U_{\tau r}]^2 G_F^2}{4\pi^3 M_r^2} \left( 1 - \frac{M^2_{\nu_\alpha}}{M^2_{\tau}} \right) \left( 1 - \frac{M^2_B}{M^2_{\tau}} \right) \times \delta \left( E_N - \frac{M^2_{\nu_\alpha} - M^2_B}{2M_\tau} \right) \tag{57}
\]
decay channels. For heavier sterile neutrino their importance becomes more significant. By ignoring these states we can underestimate the total inclusive width \( \frac{1}{m_{\nu}} \times \sum_X Br(H \to NX) \) by about 20\% [29]. On the other hand, as seen from Figs. 2, 3, at \( M_N \gtrsim 2 \text{ GeV} \) too few sterile neutrinos reach Near Detector to be successfully registered. For \( M_N < 2 \text{ GeV} \) the multi-meson channels don’t contribute significantly.

We note that many of the the mentioned processes also prove to be insignificant in the interesting mass range. To determine this we calculate contribution of each process to sterile neutrino production. If the process’ branching value is less than 1% for all considered values of sterile neutrino mass, then it is taken out of consideration. This way the following processes were considered insignificant:

\[ K_S^0 \to \pi^+ \nu - N, \quad B^- \to \pi^0 \nu - N, \quad B^0 \to \rho^+ \nu - N, \quad B_s^0 \to K^+ \nu - N, \quad B_s^0 \to \rho^0 \nu - N, \quad B_s^0 \to K^+ \nu - N. \]

We note that for the case of mixing with tau neutrino only \( D_s \) and heavier mesons can kinematically simultaneously produce the sterile neutrino and tauon in their decays (if \( M_H > M_\tau + M_N \)).

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