Lepton number violation in $B_s$ meson decays induced by an on-shell Majorana neutrino

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Lepton-number violation can be induced by the exchange of an on-shell Majorana neutrino $N$ in semileptonic $|\Delta L| = 2$ decays of the $B_s$ meson, $B_s^0 \rightarrow P^- \pi^+ \mu^+ \mu^+$ with $P = K, D_s$. We investigate the production of such a heavy sterile neutrino through these four-body $\mu^+ \mu^+$ channels and explore the sensitivity that can be reached at the LHCb and CMS experiments. For heavy neutrino lifetimes of $\tau_N = [1, 100, 1000]$ ps and integrated luminosities collected of 10 and 50 fb$^{-1}$ at the LHCb and 30, 300, and 3000 fb$^{-1}$ at the CMS, we find a significant sensitivity on branching fractions of the orders $\text{BR}(B_s^0 \rightarrow K^- \pi^+ \mu^+ \mu^+) \lesssim \mathcal{O}(10^{-9} - 10^{-8})$ and $\text{BR}(B_s^0 \rightarrow D_s^- \pi^- \mu^+ \mu^+) \lesssim \mathcal{O}(10^{-8} - 10^{-7})$. In the kinematically allowed mass ranges of $m_N \in [0.25, 3.29]$ GeV and $m_N \in [0.25, 3.29]$ GeV, respectively, we exclude regions on the parameter space $(m_N, |V_{\mu N}|^2)$ associated with the heavy neutrino, which could slightly improve the limits from $B^- \rightarrow \pi^- \mu^- \mu^-$ (LHCb).

I. INTRODUCTION

To discriminate if the light neutrinos are Majorana or Dirac fermions (i.e. if neutrinos are their own antiparticles or not) is one of the most important puzzles in the Standard Model (SM) [1]. To date, it is already well confirmed by a diversity of neutrino oscillation experiments (solar, atmospheric, reactors and accelerators) [2] that light neutrinos are massive particles; however, the responsible underlying mechanism remains unknown, and different new physics (NP) scenarios beyond the SM predict the neutrinos to be Dirac or Majorana massive fermions [3]. If neutrinos are Dirac massive particles, the total lepton number $L$ is a conserved quantity in the nature, while if neutrinos turn out to be Majorana massive particles, $L$ will be not longer conserved and will be violated [1]. The most remarkable searches of lepton-number violating (LNV) signals are by looking for processes with $|\Delta L| = 2$, in which the possible existence of Majorana neutrinos can be tested [1].

The smoking-gun LNV signal is the neutrinoless double-$\beta$ ($0\nu\beta\beta$) decay [4–6]. Searches of this rare nuclear transition have been pursued for several decades by different experiments and up to now no positive signal has been observed [4–6]. Currently, the best limits on their half-lives have been obtained from the nuclei $^{76}$Ge [7] and $^{136}$Xe [8, 9]. Aside from the $0\nu\beta\beta$ decay, low-energy studies of rare semileptonic processes in $|\Delta L| = 2$ decays of pseudoscalar mesons ($K, D, D_s, B, B_s$) and the $\tau$ lepton have been considered as complementary and alternative evidence to prove the Majorana nature of neutrinos $[10–37]$. Since these $|\Delta L| = 2$ decays can be produced (and enhanced) via an intermediate on-shell Majorana neutrino $N$ with a mass in the range $\sim [0.1, 5.0]$ GeV, the phenomenology associated with such a heavy neutrino has been actively studied $[10, 13–37]$. From the experimental side, upper limits on the branching fractions of various LNV processes have been set by different experiments such NA48/2, BABAR, Belle, LHCb, and E791 [38–46]. See also the Particle Data Group [2].

Focusing on the $b$-quark sector, recent attention has been paid to the four-body $|\Delta L| = 2$ decays of $B$ and $B_s$ mesons: $B^0 \rightarrow D^+ \pi^- \mu^- \mu^+$, $B^- \rightarrow D^0 \pi^+ \mu^- \mu^+$ $[23, 25, 34, 35]$, and $B_s^- \rightarrow J/\psi \pi^+ \mu^- \mu^-$ $[20, 21]$. In addition, the $|\Delta L| = 2$ decays of $\Lambda_b$ baryon have been explored as well [47]. As a salient feature, these decay channels are not highly suppressed by Cabibbo-Kobayashi-Maskawa (CKM) factors, and their experimental search is within reach of sensitivity of the LHCb and Belle II $[20, 21, 35]$. So far, the LHCb has reported the upper limit $\text{BR}(B^- \rightarrow D^0 \pi^+ \mu^- \mu^+) < 1.5 \times 10^{-6}$ $[41]$, and improvements are expected in Run 2 and the future upgrade Run 3. On the other hand, the same quark level LNV transition that generates these four-body $|\Delta L| = 2$ channels, can also produce $|\Delta L| = 2$ decays in the $B_s$ meson and their signals may be detected at the LHC, which offers an excellent environment for the $B_s$ physics.

In this work, we will explore the LNV decay channels of the $B_s$ meson, $B_s^0 \rightarrow P^- \pi^+ \mu^+ \mu^+$ with $P = K, D_s$, via an intermediate GeV-scale on-shell Majorana neutrino $N$. To our knowledge, these $|\Delta L| = 2$ decays have not been investigated before from a theoretical nor from an experimental point of view. We will work in a simplified approach in which one heavy neutrino $N$ mixes with one flavor of SM lepton $\ell$ and its interactions are completely determined by the mixing angle $V_{\ell N}$ $[10]$. Since $0\nu\beta\beta$ decay puts stringent limits to the
electron-heavy neutrino mixing $|V_{\mu N}|^2 \lesssim 10^{-8}$ [48], we will focus our attention on the above four-body $\mu^+\mu^+$ modes and explore their expected sensitivities at the LHCb and CMS experiments. We will show that their experimental search allows us to scan the parameter space $(m_N, |V_{\mu N}|^2)$ of the heavy neutrino sector, therefore, an additional test of the existence of Majorana neutrinos.

Let us mention that the presence of a heavy neutrino with a mass of few GeV $[\sim \mathcal{O}(1) \text{ GeV}]$ provides a realistic and falsifiable scenario for a common explanation of the baryon asymmetry of the Universe via leptogenesis [49–52] and the generation of neutrino masses via the GeV-scale seesaw model [53, 54]. This gives us further motivation to study $|\Delta L| = 2$ decays of the $B_s$ meson under consideration.

This work is organized as follows. In Sec. II, we study the $|\Delta L| = 2$ decays of the $B_s$ meson. The expected experimental sensitivities for these channels at the LHCb and CMS is discussed in Sec. III. Based on the results of the previous, in Sec. IV, we discuss the bounds on the parameter space $(m_N, |V_{\mu N}|^2)$ of the heavy neutrino that can be achieved. Our conclusions are given in Sec. V.

II. LNV DECAYS OF $B_s$ MESON

In this section, we study LNV signals in the $|\Delta L| = 2$ decays of the $B_s$ meson $B_s^0 \to P^- \pi^+ \mu^+ \mu^+$, with $P = K, D_s$ denoting a final-state pseudoscalar meson. These processes can occur via intermediate on–shell Majorana neutrino $N$ through the semileptonic decay $B_s^0 \to P^- \mu^+ N$ followed by the subsequent decay $N \to \mu^+ \pi^-$, with a kinematically allowed mass in the ranges

$$B_s^0 \to K^- \pi^- \mu^+ \mu^+: \quad m_N \in [0.25, 4.77] \text{ GeV},$$

$$B_s^0 \to D_s^- \pi^- \mu^+ \mu^+: \quad m_N \in [0.25, 3.29] \text{ GeV}.$$

The $B_s^0 \to P^- \pi^- \mu^+ \mu^+$ decays are then split into two sub-processes and the corresponding branching fraction can be written in the factorized form

$$\text{BR}(B_s^0 \to P^- \pi^- \mu^+ \mu^+) = \text{BR}(B_s^0 \to P^- \mu^+ N) \times \Gamma(N \to \mu^+ \pi^-) \tau_N / \hbar,$$  

(1)

with $\tau_N$ as the lifetime of the Majorana neutrino. The branching ratio of $B_s^0 \to P^- \mu^+ N$ is given by the expression [34]

$$\text{BR}(B_s^0 \to P^- \mu^+ N) = |V_{\mu N}|^2 \int dt \frac{d\text{BR}(B_s^0 \to P^- \mu^+ N)}{dt},$$

(2)

where

$$\frac{d\text{BR}(B_s^0 \to P^- \mu^+ N)}{dt} = \frac{G_F^2 \tau_B |V_{\mu N}|^2}{384 \pi m_B^3 \hbar} \left[ \frac{\lambda(m_{\mu N}^2, m_{\mu \pi}^2, t)}{t^3} \right]^{1/2} \times \left( [C(t)]^2 + [C_0(t)]^2 \right),$$

(3)

is the so-called differential canonical branching ratio [34], where $G_F$ is the Fermi constant; $V_{\mu N}^{CKM}$ denotes the CKM matrix element involved (with $q = u, c$ for $P = K, D_s$); and $F_{\pm}^{B_s N}(t)$ and $F_0^{B_s N}(t)$ are the vector and scalar form factors for the $B_s \to P$ transition, respectively, which are evaluated at the square of the transferred momentum $t = (p_B - p_P)^2$. The usual kinematic Källen function is denoted by $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2(xy + xz + yz)$. The coefficients $C(t)$ and $C_0(t)$ in (3) are defined as

$$C(t) = \lambda(m_{B_s}^2, m_{\mu N}^2 - m_{\mu \pi}^2, t) [t^2 + t(m_{\mu N}^2 + m_{\mu \pi}^2) + (m_{\mu N}^2 - m_{\mu \pi}^2)^2],$$

(4)

$$C_0(t) = 3(m_{B_s}^2 - m_{\mu N}^2)m_{\mu N}^2(t + 2m_{\mu N}^2 - m_{\mu N}^2) + m_{\mu N}^2(t - m_{\mu N}^2),$$

(5)

respectively. The total branching fraction is then obtained by integrating the differential canonical branching ratio over the full $t$ region $[(m_{\mu N} + m_{\mu \pi})^2, (m_{\mu N} - m_{\mu \pi})^2]$.

As mentioned at the Introduction, the coupling of the heavy neutrino (sterile) $N$ to the charged current of lepton flavor $\mu$ is characterized by the quantity $V_{\mu N}$ [10]. Without referring to any NP scenario, we will treat $m_N$ and $V_{\mu N}$ as unknown phenomenological parameters that can be constrained (set) from the experimental non-observation (observation) of $|\Delta L| = 2$ processes [10, 15, 20].

On the other hand, the decay width of $N \to \mu^+ \pi^-$ is given by the expression [10]

$$\Gamma(N \to \mu^+ \pi^-) = |V_{\mu N}|^2 \Gamma(N \to \mu^- \pi^+),$$

(6)

with

$$\Gamma(N \to \mu^+ \pi^-) = \frac{G_F^2 |V_{\mu N}|^2}{16\pi} \int dt \frac{d\text{BR}(B_s^0 \to P^- \mu^+ N)}{dt} \frac{1}{(1 - m_{\mu N}^2/m_N^2)^2 - m_{\mu \pi}^4/m_N^4 \left( 1 + m_{\mu N}^2/m_N^2 \right)},$$

(7)

where $|V_{\mu N}| = 0.97417$ [2] and $f_\pi = 130.2(1.7) \text{ MeV}$ is the pion decay constant [60].

The lifetime of the Majorana neutrino $\tau_N = \hbar / \Gamma_N$ in Eq. (1) can be obtained by summing over all accessible final states that can be opened at the mass $m_N$ [10]. However, in further analysis (Secs. III and IV), we will leave it as a phenomenological parameter accessible to the LHCb and CMS experiments.

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1 We will use the central values $|V_{\mu N}^{CKM}| = 4.09 \times 10^{-3}$ and $|V_{\mu N}^{CKM}| = 40.5 \times 10^{-3}$ [2].
TABLE I. Coefficients \((b_0^+, b_1^+, b_2^+)\) and \((b_0^0, b_1^0, b_2^0)\) of the \(z\) expansion in Eqs. (8) and (9), pole masses \(M_{+}(0)\) and \(t_{+}(0)\).

| Parameter \(B_s \rightarrow D_s\) | \(M_{+}\) (GeV) | \(M_{0}\) (GeV) | \(t_{+}\) (GeV) | \(t_{0}\) (GeV) |
|--------------------------------|----------------|----------------|----------------|--------------|
| \(b_0^+\)                     | 0.858          |                |                |              |
| \(b_1^+\)                     | -3.38          |                |                |              |
| \(b_2^+\)                     | 0.6            |                |                |              |
| \(b_0^0\)                     | 0.658          |                |                |              |
| \(b_1^0\)                     | -0.10          |                |                |              |
| \(b_2^0\)                     | 1.3            |                |                |              |

A. Form factors \(B_s \rightarrow P\) \((P=K, D_s)\)

For the form factors associated with the \(B_s \rightarrow P\) transition, we will use the theoretical predictions provided by the lattice QCD approach [61, 62].

The form factors \(F_{+}^{P, D_s}\) and \(F_{0}^{P, D_s}\) can be represented by the \(z\) expansion through a modification of the Bourrely-Caprini-Zucchini (BCZ) parametrization [61],

\[
F_{+}^{P, D_s}(t) = \frac{1}{(1-t/M_{+}^2)} \sum_{n=0}^{J-1} b_n^+ \left[ z(t)^n - (-1)^n J^z(t)^J \right],
\]

\[
F_{0}^{P, D_s}(t) = \frac{1}{(1-t/M_{0}^2)} \sum_{n=0}^{J-1} b_n^0 \left[ z(t)^n \right],
\]

respectively, where the \(z(t)\) function is defined as

\[
z(t) = \frac{\sqrt{t_+ - t - \sqrt{t_+ - t_0}}}{\sqrt{t_+ - t + \sqrt{t_+ - t_0}}},
\]

In Table I, we show the respective coefficients of the \(z\) expansion in Eqs. (8) and (9) for \(J=3\) as well as additional parameters: pole masses \(M_{+}(0)\) and \(t_{+}(0)\) [61]. The masses of particles involved are taken from the Particle Data Group [2].

In Ref. [62], the form factors for the \(B_s \rightarrow K\) transition are parametrized in a modified BCZ form

\[
F_{+}^{P, K}(t) = \frac{1}{(1-t/M_{+}^2)} \sum_{n=0}^{3} a_n^+ \left[ z(t)^n - (-1)^n J^z(t)^3 \right],
\]

\[
F_{0}^{P, K}(t) = \sum_{n=1}^{3} a_n^0 \left[ z(t)^n - z(0)^n \right]
+ \sum_{n=0}^{2} a_n^+ \left[ z(0)^n - (-1)^n J^z(t)^3 \right],
\]

where the corresponding expansion coefficients \((a_0^+, a_1^+, a_2^+)\) and \((a_0^0, a_0^-, a_1^0)\), pole masses \(M_{+}(0)\) and \(t_{+}(0)\), are displayed in Table II.

III. EXPECTED EXPERIMENTAL SENSITIVITY AT THE LHC

Now, let us provide an estimation of the expected number of events at the LHC, namely, LHCb and CMS experiments, for the \(|\Delta L|=2\) channels of the \(B_s\) meson, \(B_s^0 \rightarrow P^-\pi^-\mu^+\mu^+\) (with \(P=K, D_s\)), discussed above.

A. LHCb experiment

The number of expected events in the LHCb experiment has the form

\[
N_{\text{exp}}^{\text{LHCb}} = \sigma(pp \rightarrow H_b X)_{\text{acc}} f(b \rightarrow B_s) \text{BR}(B_s \rightarrow \Delta L = 2) \times \mathcal{L}_{\text{int}}^{\text{LHCb}} \frac{\mathcal{L}_{\text{int}}^{\text{LHCb}}}{\mathcal{L}_{\text{int}}^{\text{LHCb}}},
\]

where \(\sigma(pp \rightarrow H_b X)_{\text{acc}}\) is the production cross section of \(b\)-hadrons inside the LHCb geometrical acceptance; \(f(b \rightarrow B_s)\) is the hadronization factor of a \(b\)-quark to the \(B_s\) meson; \(\mathcal{L}_{\text{int}}^{\text{LHCb}}\) is the integrated luminosity; \(\text{BR}(B_s \rightarrow \Delta L = 2)\) corresponds to the branching fraction of the given LNV process and \(\mathcal{L}_{\text{int}}^{\text{LHCb}}(B_s \rightarrow \Delta L = 2)\) is its detection efficiency of the LHCb detector involving reconstruction, selection, trigger, particle misidentification, and detection efficiencies. Most of the on-shell neutrinos produced in the decays \(B_s^0 \rightarrow (K^- D_s^+)\mu^+\nu N\) are expected to live a long enough time to travel through the detector and decay \((N \rightarrow \mu^+ \pi^-)\) far from the interaction region. This effect is given by the \(P_{N}^{\text{LHCb}}\) factor (acceptance factor), which accounts for the probability of the on-shell neutrino \(N\) decay products to be inside the LHCb detector acceptance [30]. The reconstruction efficiency will depend on this acceptance factor as well.

The production cross section has been measured to be \(\sigma(pp \rightarrow H_b X)_{\text{acc}} = (75.3 \pm 5.4 \pm 13.0) \mu b\) inside the LHCb acceptance [63]. The world average for the hadronization factor is taken to be \(f(b \rightarrow B_s) = 0.103 \pm 0.005\) [64]. The
Expected events at LHCb experiment

FIG. 1. Number of expected events of the process $B_s^0 \rightarrow K^- \pi^+ \mu^+ \mu^+$ (top) and $B_s^0 \rightarrow D_s^- \pi^- \mu^+ \mu^+$ (bottom) to be observed in the LHCb experiment as a function of their branching fractions for a luminosity of 10 fb$^{-1}$ (red) and 50 fb$^{-1}$ (magenta). The solid black line shows the central value, while the filled area shows the 1-$\sigma$ uncertainty.

proper computation of the detection efficiency requires fully simulated Monte Carlo samples of the exclusive decay, reconstructed in the same way as real LHCb data. Here, we perform a rough estimation of the detection efficiency, based on extrapolation of detection efficiencies already reported by LHCb experiment of similar final states.

The LHCb Collaboration has measured the detection efficiency of the $B_s^0 \rightarrow \phi(K^+K^-)\mu^+\mu^-$ decay mode to be 1.1% [65]. This measurement includes trigger, tracking, reconstruction, particle identification, and selection efficiency. Given the content of final-state charged tracks, we can consider the $B_s^0 \rightarrow K^- \pi^+ \mu^+ \mu^-$ to be the same as for the $B_s^0 \rightarrow \phi(K^+K^-)\mu^+\mu^-$ decay. Regarding the $B_s^0 \rightarrow D_s^- \pi^- \mu^+ \mu^+$ decay, a golden mode to reconstruct the $D_s^+$ meson hadronically is $D_s^+ \rightarrow K^+ K^- \pi^+$, where $\text{BR}(D_s^+ \rightarrow K^+ K^- \pi^+) = (5.45 \pm 0.17) \times 10^{-2}$ [2]. In this situation, there will be two additional charged tracks in the final state; thus, we can multiply previous efficiency by 0.9 for each additional charged track, the approximated single track reconstruction efficiency at LHCb. Finally, in Ref. [66], reconstruction efficiencies for hypothetical long-lived particles inside the LHCb acceptance are given. Here, we can observe that a maximum variation of about 25% is measured in the efficiencies of particles living in the [5 - 50] ps range, with masses up to 200 GeV; however, in our case, long-lived particles can only be produced on-shell, therefore with masses around few GeV. Thus, to account for this effect, we will just add a 25% relative uncertainty to our efficiency prediction, obtaining finally

$$
\epsilon_{\text{LHCb}}^{D}(B_s \rightarrow K^- \pi^+ \mu^+ \mu^+) \mathcal{L}_{\text{int}} \sim (1.10 \pm 0.27)\%,
$$

$$
\epsilon_{\text{LHCb}}^{D}(B_s \rightarrow D_s^- \pi^- \mu^+ \mu^+) \mathcal{L}_{\text{int}} \sim (0.89 \pm 0.22)\%.
$$

With these values, the relative uncertainty on $N_{\text{exp}}$ is of 32% for both LNV modes.

The LHCb experiment performance during LHC-Run1 can be found in Ref. [67]. During LHC-Run2 the expectation is to collect 10 fb$^{-1}$ at the LHC nominal construction energy of a center of mass of 14 TeV. Already some work has been developed for the future LHCb upgrade, LHC-Run3, for which integrated luminosity of the order of 50 fb$^{-1}$ is expected. Assuming the above assumptions on efficiency and cross section, Fig. 1 shows the number of expected events to be observed in the LHCb experiment as a function of branching fraction for $|\Delta L| = 2$ modes of $B_s$ meson. The figure shows red and magenta functions, corresponding to LHC-Run2 and LHC-Run3, respectively. Table III shows the expected signal events at the LHCb experiment for some selected values of the branching ratio, given LHC-Run2 and LHC-Run3 expected integrated luminosities. We can see that values of the branching fractions of the order $\mathcal{O}(10^{-9} - 10^{-8})$ for $B_{s}^{0} \rightarrow K^{-} \pi^{+} \mu^{+} \mu^{-}$ and $\mathcal{O}(10^{-8} - 10^{-7})$ for $B_{s}^{0} \rightarrow D_{s}^{-} \pi^{-} \mu^{+} \mu^{-}$ might be within the experimental sensitivity of the LHCb.

B. CMS experiment

We also consider the possible sensitivity of the CMS experiment to the LNV signals from $B_s$ meson decays. The expected number of event for the CMS experiment is written as

$$
N_{\text{exp}}^{\text{CMS}} = \sigma(pp \rightarrow B_s X) \text{BR}(B_s \rightarrow \Delta L = 2) \times \epsilon_{\text{CMS}}^{D}(B_s \rightarrow \Delta L = 2) \mathcal{L}_{\text{int}} \mathcal{L}_{\text{CMS}} \mathcal{L}_{\text{exp}}^{\text{CMS}}(B_s \rightarrow \Delta L = 2),
$$

where $\mathcal{L}_{\text{CMS}}$ is the integrated luminosity recorded by the CMS experiment from proton-proton collisions delivered by the LHC; $\sigma(pp \rightarrow B_s X)$ is the $B_s$ meson production cross section in the CMS experiment acceptance; $\epsilon_{\text{CMS}}^{D}(B_s \rightarrow \Delta L = 2)$
is the efficiency to reconstruct and identify the signal events, which includes the trigger efficiency; $\epsilon_N^{CMS}$ is a factor that accounts for the CMS experiment acceptance to the decay of the neutrino; and $BR(B_s \rightarrow \Delta L = 2)$ is the $B_s$ meson branching fraction.

The CMS experiment acceptance to the signal depends on its tracker capabilities to reconstruct charged particles, especially pions and muons. Muons are reconstructed using the tracking system and the muon chambers, while pions are reconstructed by the tracker solely. The decay products from the $B_s$ are not very energetic. For this study, we consider that the muons and pions from signal events have $p_T < 20$ GeV. The CMS experiment has shown to be 90% efficient in reconstructing charged tracks in the mentioned $p_T$ range [68]. However, these studies were performed for a center of mass energy of 7 TeV; we consider that these results also stand for 13 TeV. In addition, we also assume that the reconstruction efficiency of muons is 90%, following the results from Ref. [69].

We use the same techniques as in Ref. [47] to make a rough estimate of the CMS experiment efficiency to reconstruct the signal events. From some analyses performed with the CMS experiment for similar events [70, 71], we can assume that the efficiency for the events from $B^0_s \rightarrow K^- \pi^+ \mu^- \mu^+$ will be approximately the same (1.56 ± 0.05)%.

The CMS experiment has shown that $BR(B^0_s \rightarrow D_s^- \pi^- \mu^+ \mu^+)$ needs to be considered for the further decay of the $D_s^-$ meson. With the CMS experiment, it is not possible to distinguish from a charged track left in the detector by a pion or a kaon. Therefore, we consider all the possible decays of $D_s^-$ into three charged tracks. Considering world averages for $K\pi\pi$ or $KK\pi$ decay branching fractions [2], we can derive that the $BR(D_s^- \rightarrow 3 \text{ charged tracks}) = 13.00 \pm 1.96$. Taking into account this additional branching fraction and the fact that we need to identify two additional charged tracks, we can plug an additional 90% efficiency factor for the track to obtain the total efficiency for the $B^0_s \rightarrow D_s^- \pi^- \mu^+ \mu^+$ channel. We obtain that $\epsilon_D^{CMS}(B^0_s \rightarrow D_s^- \pi^- \mu^+ \mu^+) = (1.26 \pm 0.04)\%$.

## Table III: Number of expected events at the LHCb for some selected values of the branching ratio (BR) of $B^0_s \rightarrow K^- \pi^+ \mu^- \mu^+$ and $B^0_s \rightarrow D_s^- \pi^- \mu^+ \mu^+$.

| Mode                  | $\mathcal{L}^{CMS}_{exp}$ (fb$^{-1}$) | BR   | $\mathcal{L}^{LHCb}_{exp}$ |
|----------------------|----------------------------------|------|-----------------|
| $B^0_s \rightarrow K^- \pi^+ \mu^- \mu^+$ | 10$^{-6}$ | 50   | 8522 ± 2727 | 50 | 852 ± 27 |
|                      | 10$^{-7}$                  | 10   | 1583 ± 506    | 10 | 158 ± 51 |
|                      | 10$^{-8}$                  | 10   | 376 ± 120     | 10 | 37 ± 12 |
|                      | 10$^{-9}$                  | 10   | 70 ± 22       | 10 | 7 ± 2 |
| $B^0_s \rightarrow D_s^- \pi^- \mu^+ \mu^+$ | 10$^{-6}$ | 50   | 376 ± 120 |
|                      | 10$^{-7}$                  | 10   | 37 ± 12       |
|                      | 10$^{-8}$                  | 10   | 4 ± 1         |
|                      | 10$^{-9}$                  | 10   | 7 ± 2         |

Figure 2 shows the results for the expected number of events in the CMS experiment, using the above estimations. Three benchmark luminosities are used: $\mathcal{L}^{int}_{ CMS} = 30, 300, \text{and } 3000 \text{ fb}^{-1}$. Table IV is used to quote explicitly some of the results obtained. We observe that for 30 and 300 fb$^{-1}$ the CMS experiment has sensitivity to branching fractions of the order $\mathcal{O}(10^{-9} - 10^{-8})$ for $B^0_s \rightarrow K^- \pi^+ \mu^- \mu^+$ and $\mathcal{O}(10^{-8} - 10^{-7})$ for $B^0_s \rightarrow D_s^- \pi^- \mu^+ \mu^+$. Such a sensitivity is very similar to the one that can be reached by the LHCb (see Sec. III A). We will consider these values of branching fractions as the most conservative ones to derive limits over the parameters of the heavy sterile neutrino in the next section.
IV. BOUNDS ON THE PARAMETER SPACE \( (m_N, |V_{\mu N}|^2) \)

The experimental non-observation of \( |\Delta L| = 2 \) processes can be reinterpreted as bounds on the parameter space of a heavy sterile neutrino \((m_N, |V_{\mu N}|^2)\), namely, the squared mixing element \( |V_{\mu N}|^2 \) as a function of the mass \(m_N\) [10, 15, 20]. Based on the analysis presented in Sec. III, here, we explore the constraints on the \((m_N, |V_{\mu N}|^2)\) plane that can be achieved from the experimental searches on \(B_s^{0} \rightarrow (K^-, D_s^-) \pi^- \mu^+ \mu^+ \) at the LHC, namely the LHCb and CMS experiments.

Figure 2. Expected events in the CMS experiment for \(B_s^{0} \rightarrow K^- \pi^- \mu^+ \mu^+ \) (top) and \(B_s^{0} \rightarrow D_s^- \pi^- \mu^+ \mu^+ \) (bottom) as a function of the branching fraction of the final state considered and for three benchmark luminosities: 30 (green), 300 (blue), and 3000 (gray) fb\(^{-1}\). The central value is shown with a solid line. The shaded area represents the associated uncertainty in a 1-\(\sigma\) window.

| Mode \(B_s^{0} \rightarrow K^- \pi^- \mu^+ \mu^+ \) | \(\mathcal{L}^{CMS}_{mt} \) (fb\(^{-1}\)) | \(BR^{CMS}_{exp} \) | \(\mathcal{L}^{CMS}_{exp} \) |
|------------------|-----------------|-----------------|-----------------|
| \(B_s^{0} \rightarrow K^- \pi^- \mu^+ \mu^+ \) | 30 | \(6.2 \times 10^{-6} \) | 6.2 \pm 0.6 |
| | 100 | \(6.2 \times 10^{-7} \) | 6.2 \pm 0.6 |
| | 1000 | \(6.2 \times 10^{-8} \) | 6.2 \pm 0.6 |
| \(B_s^{0} \rightarrow D_s^- \pi^- \mu^+ \mu^+ \) | 30 | \(6.2 \times 10^{-6} \) | 6.2 \pm 0.6 |
| | 100 | \(6.2 \times 10^{-7} \) | 6.2 \pm 0.6 |
| | 1000 | \(6.2 \times 10^{-8} \) | 6.2 \pm 0.6 |

From Eq. (1), it is straightforward to obtain the relation

\[
|V_{\mu N}|^2 = \left[ \frac{\text{BR}(B_s^{0} \rightarrow P^- \pi^- \mu^+ \mu^+)}{\text{BR}(B_s^{0} \rightarrow P^- \mu^+ N) \times \Gamma(N \rightarrow \mu^+ \pi^-) \tau_N} \right]^{1/2},
\]

where \(\text{BR}(B_s^{0} \rightarrow P^- \mu^+ N)\) and \(\Gamma(N \rightarrow \mu^+ \pi^-)\) are given by Eqs. (3) and (7), respectively. As was already discussed in Sec. III and following the analysis of NA48/2 [38] and LHCb [40], we will consider heavy neutrino lifetimes of \(\tau_N = [1, 100, 1000]\) ps as benchmark points in our analysis. This will allow us to extract limits on \(|V_{\mu N}|^2\) without any additional assumption on the relative size of the mixing matrix elements.

From the theoretical point of view, it is worth it to justify heavy neutrino lifetimes within the domain 1 ps \(\leq \tau_N \leq 1000\) ps accessible to the LHCb and CMS experiments (see Figure 3).

Figure 3. Heavy neutrino lifetime \(\tau_N\) as a function of \(m_N\). The blue and red bands correspond to the allowed parameter space for \(|V_{\tau N}|^2 = 10^{-3}\) and \(10^{-2}\), respectively, while \(|V_{\mu N}|^2\) and \(|V_{\mu N}|^2\) vary within the range \([10^{-7}, 10^{-3}]\).
within the range (proximate expression for the neutrino decay width Secs. III A and III B). For that purpose, we will use the approximate expression for the neutrino decay width

\[ \Gamma_N = \frac{G_F m_N^5}{96\pi^3} \left[ 8|V_{eN}|^2 + |V_{\mu N}|^2 \right] + 3|V_{\tau N}|^2, \]

which has been previously considered in the literature [34, 35, 37] for neutrino masses relevant to the \( B_s \) meson decays under consideration. By considering the current bounds on \( |V_{\ell N}|^2 \) \( (\ell = e, \mu, \tau) \) given in Ref. [10], we will vary \( |V_{eN}|^2 \) and \( |V_{\mu N}|^2 \) within the range \([10^{-7}, 10^{-3}]\) and \( |V_{\tau N}|^2 \) from \( 10^{-3} \) to \( 10^{-2} \).

In Fig. 3, we plot the heavy neutrino lifetime \( \tau_N = \hbar / \Gamma_N \) as a function of \( m_N \). The blue and red bands correspond to the allowed parameter space for \( |V_{eN}|^2 = 10^{-3} \) and \( 10^{-2} \), respectively. According to Fig. 3, it is possible to obtain masses at the GeV-scale within the lifetimes domains accessible to the LHCb and CMS experiments.

In Figs. 4(a) and 4(b) we show the exclusions regions on \( |V_{\mu N}|^2 \) as a function of \( m_N \) obtained by taking an expected sensitivity on the branching fractions of the orders

\[ \text{BR}(B_s^0 \to K\gamma \mu\mu) < 10^{-8} \]

and

\[ \text{BR}(B_s^0 \to K^\pm \pi^\mp \mu^+ \mu^-) < 10^{-9}. \]

The black, blue, and gray regions represent the bounds obtained for heavy neutrino lifetimes of \( \tau_N = 1, 100, 1000 \) ps, respectively. Limits provided by \( K^+ \to \pi^+ \mu^- \mu^- \) [38] and \( B^- \to \pi^+ \mu^- \mu^- \) [32] are also included for comparison.

Secs. III A and III B). For that purpose, we will use the approximate expression for the neutrino decay width

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The black, blue, and gray regions represent the bounds obtained for heavy neutrino lifetimes of \( \tau_N = 1, 100, 1000 \) ps, respectively.
For Majorana neutrino masses larger than 0.38 GeV, the $B_s^0 \rightarrow D_s^- \pi^+ \mu^- \mu^+$ channel (CKM-allowed) would be able to exclude a slightly wider region of $|V_{\mu N}|^2$ than $B^- \rightarrow \pi^+ \mu^- \mu^-$. The reason for this is the non-suppression for the CKM elements involved.

Additionally, in Fig. 6, we show the exclusion bounds on the parameter space $(m_N, |V_{\mu N}|^2)$ coming from the Belle [72], DELPHI [73], NA3 [74], CHARMII [75], and NuTeV [76] experiments, in the mass range $[0.5, 5.0] \text{ GeV}$. In comparison, the constraints obtained from the searches on $B_s^0 \rightarrow (K_\pm, D_\pm) \pi^\pm \mu^+ \mu^-$ are represented by the gray and black regions, respectively. In both cases, a lifetime of $\tau_N = 1000 \text{ ps}$ has been taken as a representative value. It is observed that our $|\Delta L| = 2$ channels proposals are less restrictive than the bounds obtained from different search strategies, for instance, Belle [72] and DELPHI [73]. Nevertheless, keeping in mind that we have taken the most conservative values for the branching fractions derived in Secs. III A and III B, it is possible that branching fractions values of the order $BR < 10^{-10}$ might be accessible to the LHCb and CMS experiments (see Figs. 1 and 2), therefore, these $|\Delta L| = 2$ channels would eventually provide complementary bounds.

V. CONCLUDING REMARKS

We have studied the semileptonic $|\Delta L| = 2$ decays of the $B_s$ meson $B_s^0 \rightarrow P^- \pi^+ \mu^+ \mu^+$ via the intermediate GeV-scale on-shell Majorana neutrino $N$, namely, $B_s^0 \rightarrow P^- \mu^+ N (\rightarrow \pi^- \mu^+)$, with $P = K, D_s$. To our knowledge, these LNV decays of the $B_s$ meson have not been investigated before from a theoretical nor from an experimental point of view. We investigated these same-sign $\mu^+ \mu^+$ channels and explored the sensitivity that can be reached at the LHCb and CMS experiments. We considered heavy neutrino lifetimes in the experimental (LHCb and CMS) accessible ranges of $\tau_N = [1, 100, 1000] \text{ ps}$, where the probability for the on-shell neutrino $N$ decay products to be inside the detector (acceptance factor $P_N$) has been taken into account in our analysis. As an outcome, it was found that for integrated luminosities collected of 10 and 50 fb$^{-1}$ by the LHCb experiment and 30, 300, and 3000 fb$^{-1}$ by the CMS experiment one would expect sensitivities on the branching fractions of the orders $BR(B_s^0 \rightarrow K^- \pi^- \mu^+ \mu^+) \lesssim \mathcal{O}(10^{-9} - 10^{-8})$ and $BR(B_s^0 \rightarrow D_s^- \pi^- \mu^+ \mu^+) \lesssim \mathcal{O}(10^{-8} - 10^{-7})$, as conservative values. For masses in the range $m_N \in [0.25, 4.77] \text{ GeV}$ and $m_N \in [0.25, 3.29] \text{ GeV}$, respectively, we extracted bounds on the parameter space $(m_N, |V_{\mu N}|^2)$ that might be obtained from their experimental search. Depending on the $\tau_N$ value, it was found that for $m_N > 0.38 \text{ GeV}$ these four-body channels may be capable of excluding a slightly wider region of $|V_{\mu N}|^2$ than $B^- \rightarrow \pi^+ \mu^- \mu^-$. At the LHCb.

Consequently, the LHCb and CMS experiments have a great chance to look for heavy Majorana neutrinos in the near future, via $|\Delta L| = 2$ decays of the $B_s$ meson. In addition, in the best-case scenario, the experimental search of these LNV channels would complement the bounds given by different search strategies (such as NA3, CHARMII, NuTeV, Belle, and DELPHI).

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2 For recent reviews on the theoretical and experimental status of different GeV-scale heavy neutrino search strategies see Refs. [10, 55–59] and references therein.
[1] A. de Gouvêa and P. Vogel, Lepton flavor and number conserva-
tion, and physics beyond the standard model, Prog. Part. Nucl. 
Phys. 71, 75 (2013) [arXiv:1303.4097 [hep-ph]].

[2] C. Patrignani et al. (Particle Data Group Collaboration), Chin. 
Phys. C 40, 100001 (2016) [http://pdg.lbl.gov].

[3] See, for instance: R. N. Mohapatra et al. [arXiv:1208.5136 [hep-ph]].

[4] H. Päs and W. Rodejohann, Neutrinoless Double Beta Deca-
cy, New J. Phys. 17, 115010 (2015), [arXiv:1507.00170 [hep-ph]]; W. Rodejohann, Neutrinoless Double Beta 
Decay and Particle Physics, Int. J. Mod. Phys. E 20, 1833 (2011) 
[arXiv:1106.1334].

[5] S. Dell’Oro, S. Marcocci, M. Viel, and F. Vissani, Neutrinoless 
double beta decay: 2015 review, Adv. High Energy Phys. 2016, 
2162659 (2016) [arXiv:1601.07512 [hep-ph]].

[6] J. J. Gómez-Cadenas et al., The search for neutrinoless 
double beta decay, Riv. Nuovo Cim. 35, 29 (2012) 
[arXiv:1109.5515 [hep-ph]].

[7] M. Agostini, (GERDA Collaboration), Background free search 
for neutrinoless double beta decay with GERDA, Nature 544, 
47 (2017) [arXiv:1703.00570 [nucl-ex]].

[8] J. B. Albert et al. (EXO-200 Collaboration), Search for Neutri-
noless Double-Beta Decay with the Upgraded EXO-200 Detec-
tor, [arXiv:1707.08707 [hep-ex]]; Search for Majorana neutrinos with the first two years of EXO-200 data, Nature 510, 
229 (2014) [arXiv:1402.6956 [nucl-ex]].

[9] A. Gando et al. (KamLAND-Zen Collaboration), Search for 
Majorana Neutrinos near the Inverted Mass Hierarchy Region 
with KamLAND-Zen, Phys. Rev. Lett. 117, 082503 (2016) 
[arXiv:1605.02889 [hep-ex]].

[10] A. Atre, T. Han, S. Pascoli, and B. Zhang, The search for 
heavy Majorana neutrinos, J. High Energy Phys. 05, 030 (2009) 
[arXiv:0901.3589 [hep-ph]].

[11] L. S. Littenberg and R. Shrock, Upper Bounds on Lepton 
Number Violating Meson Decays, Phys. Rev. Lett. 68, 443 
(1992); C. Dib, V. Gribanov, S. Kovalenko, and I. Schmidt, 
K meson neutrinoless double muon decay as a probe of neu-
trino masses and mixings, Phys. Lett. B 493, 82 (2000) 
[hep-ph/0006277]; L. S. Littenberg and R. Shrock, Impli-
cations of improved upper bounds on |ΔL| = 2 processes, Phys. 
Lett. B 491, 285 (2000) [hep-ph/0005285]; K. Zuber, New 
limits on effective Majorana neutrino masses from rare kaon 
decays, Phys. Lett. B 479, 33 (2000) [hep-ph/0003160].

[12] A. Ali, A. V. Borisov, and N. B. Zamorin, Majorana 
neutrinos and same-sign dilepton production at LHC and in 
heavy meson decays, Eur. Phys. J. C 21, 123 (2001) 
[hep-ph/0104123].

[13] A. Atre, V. Barger, and T. Han, Upper bounds on lepton-
umber violating processes, Phys. Rev. D 71, 113014 (2005) 
[hep-ph/0502163].

[14] M. A. Ivanov, S. G. Kovalenko, Hadronic structure aspects of 
K⁺ → π⁻ + l⁺l⁻ + l⁻l⁺ decays, Phys. Rev. D 71, 053004 (2005) 
[hep-ph/0412198].

[15] J. C. Helo, S. Kovalenko, and I. Schmidt, Sterile neutrinos in 
lepton number and lepton flavor violating decays, Nucl. Phys. 
B853, 80 (2011) [arXiv:1005.1607 [hep-ph]].

[16] G. Cvetic, C. Dib, S. K. Kang, and C. S. Kim, Probing Majorana 
nuclons in rare K and D, D_s, B, B_s meson decays, Phys. Rev. 
D 82, 053010 (2010) [arXiv:1005.4282 [hep-ph]].

[17] J. M. Zhang and G. L. Wang, Lepton-number violating decays 
of heavy mesons, Eur. Phys. J. C 71, 1715 (2011) 
[arXiv:1003.8570 [hep-ph]].

[18] S.-S. Bao, H.-L. Li, Z.-G. Si, and Y.-B. Yang, Search for 
Majorana Neutrino Signal in B_s Meson Rare Decay, Commun. 
Theor. Phys. 59, 472 (2013) [arXiv:1208.5136 [hep-ph]].

[19] Y. Wang, S.-S. Bao, Z.-H. Li, N. Zhu, and Z.-G. Si, Study Majorana 
Neutrino Contribution to B-meson Semi-leptonic Rare 
Decays, Phys. Lett. B 736, 428 (2014) [arXiv:1407.2468 [hep-ph]].

[20] D. Milanès, N. Quintero, and C. E. Vera, Sensitivity to Majorana 
nuclons in ΔL = 2 decays of B_s meson at LHCb, Phys. Rev. D 93, 
094026 (2016), [arXiv:1604.03177 [hep-ph]].

[21] S. Mandal and N. Sinha, Favoured B_s decay modes to search 
for a Majorana neutrino, Phys. Rev. D 94, 033001 (2016), 
[arXiv:1602.09112 [hep-ph]].

[22] V. Gribanov, S. Kovalenko and I. Schmidt, Sterile neutrinos in τ 
lepton decays, Nucl. Phys. B607, 355 (2001), [hep-ph/0102155].

[23] D. Delepine, G. López Castro, and N. Quintero, Lepton number 
violation in top quark and neutral B meson decays, Phys. 
Rev. D 84, 079901 (2011) [ibid D 86, 079905(E) (2012)] 
[arXiv:1108.6009 [hep-ph]].

[24] G. López Castro and N. Quintero, Lepton number violation 
in tau lepton decays, Nucl. Phys. B Proc. Suppl. 253-255, 12 
(2014) [arXiv:1212.0037 [hep-ph]].

[25] G. López Castro and N. Quintero, Bounding resonant Majorana 
nuclons from four-body B and D decays, Phys. Rev. D 87, 
077901 (2013) [arXiv:1302.1504 [hep-ph]].

[26] H.-R. Dong, F. Feng, and H.-B. Li, Lepton number violation 
in D meson decay, Chin. Phys. C 39, 013101 (2015) 
[arXiv:1305.3820 [hep-ph]].

[27] H. Yuan, T. Wang, G.-L. Wang, W.-L. Ju, and J.-M. Zhang, 
Lepton-number violating four-body decays of heavy mesons, 
J. High Energy Phys. 08, 066 (2013) [arXiv:1304.3810 [hep-ph]].

[28] G. López Castro and N. Quintero, Lepton-number-violating 
four-body tau lepton decays, Phys. Rev. D 85, 076006 
(2012) [ibid D 86, 079904(E) (2012)] [arXiv:1203.0537 [hep-ph]].

[29] C. Dib, J. C. Helo, M. Hirsch, S. Kovalenko, and I. Schmidt, 
Heavy sterile neutrinos in tau decays and the 
MiniBooNE anomaly, Phys. Rev. D 85, 011301(R) (2012) 
[arXiv:1110.5400 [hep-ph]].

[30] C. Dib and C. S. Kim, Remarks on the lifetime of ster-
ile neutrinos and the effect on detection of rare meson decays 
M⁻ → M⁻τ⁺τ⁻, Phys. Rev. D 89, 077301 (2014) 
[arXiv:1403.1985 [hep-ph]].
G. Cvetic and C. S. Kim, Rare decays of $B^-$ mesons via on-shell sterile neutrinos, Phys. Rev. D 94, 053001 (2016) [arXiv:1606.01440 [hep-ph]].

G. Cvetic and C. S. Kim, Sensitivity limits on heavy-light mixing $|U_{\mu N}|^2$ from lepton number violating $B$ meson decays, Phys. Rev. D 96, 035025 (2017). [arXiv:1705.09403 [hep-ph]].

G. Moreno and J. Zamora-Saá, Rare meson decays with three pairs of quasi-degenerate heavy neutrinos, Phys. Rev. D 94, 093005 (2016) [arXiv:1606.08820 [hep-ph]]; J. Zamora-Saá, Resonant CP violation in rare tau decay, J. High Energ. Phys. 85, 110 (2017) [arXiv:1612.07656 [hep-ph]].

G. Cvetic, C. Dib, C. S. Kim, and J. Zamora-Sáá, Probing the Majorana neutrinos and their CP violation in decays of charged scalar mesons $\pi, K, D, D_s, B, B_s$, Symmetry 7, 726 (2015) [arXiv:1503.01358 [hep-ph]]; G. Cvetic, C. S. Kim, and J. Zamora-Sáá, CP violation in lepton number violating semihadronic decays of $K, D, D_s, B, B_s$, Phys. Rev. D 89, 093012 (2014) [arXiv:1403.2555 [hep-ph]]; CP violation in $\pi^\pm$ meson decay, J. Phys. G 41, 075004 (2014) [arXiv:1311.7554 [hep-ph]]; C. Dib, M. Campos, and C. S. Kim, CP Violation with Majorana neutrinos in $K$ Meson Decays, I. High Energy Phys. 02, 108 (2015) [arXiv:1403.8009 [hep-ph]].

J. R. Batley et al. (NA48/2 Collaboration), Searches for lepton number violation and resonances in $K^- \to \pi\mu\mu$ decays, Phys. Lett. B 769, 67 (2017) [arXiv:1612.04723 [hep-ex]].

J. P. Lees et al. (BABAR Collaboration), Searches for Rare or Forbidden Semileptonic Charm Decays, Phys. Rev. D 84, 072006 (2011) [arXiv:1107.4465 [hep-ex]]; Search for lepton-number violating processes in $B^+ \to h^-\ell^+\ell^+$ decays, Phys. Rev. D 85, 071103(R) (2012) [arXiv:1202.3650 [hep-ex]].

J. P. Lees et al. (BABAR Collaboration), Search for lepton-number violating $B^+ \to X^-\ell^+\ell^+$ decays, Phys. Rev. D 89, 011102(R) (2014) [arXiv:1310.8238 [hep-ex]].

R. Aaij et al., (LHCb Collaboration), Search for the lepton number violating decays $B^+ \to \pi^-\mu^+\mu^+$ and $B^+ \to K^-\mu^+\mu^+$, Phys. Rev. Lett. 108, 101601 (2012) [arXiv:1110.0730 [hep-ex]]; Searches for Majorana neutrinos in $B^-$ decays, Phys. Rev. D 85, 112004 (2012) [arXiv:1201.5600 [hep-ex]].

R. Aaij et al., (LHCb Collaboration), Search for $D_{s1}^{(*)} \to \pi^-\mu^+\mu^-$ and $D_{s1}^{(*)} \to \pi^-\mu^+\mu^-$ decays, Phys. Lett. B 724, 203 (2013) [arXiv:1304.6365 [hep-ex]].

R. Aaij et al., (LHCb Collaboration), Search for Majorana neutrinos in $B^- \to \pi^-\mu^-\mu^-$ decays, Phys. Rev. Lett. 112, 131802 (2014) [arXiv:1401.5361].

O. Seon et al. (Belle Collaboration), Search for lepton-number-violating $B^+ \to D^-\ell^+\ell^+$ decays, Phys. Rev. D 84, 071106(R) (2011) [arXiv:1107.0642].

Y. Miyazaki et al. (Belle Collaboration), Search for lepton-flavor and lepton-number-violating $\tau \to \ell hh\ell$ decay modes, Phys. Lett. B 719, 346 (2013) [arXiv:1206.5595].

E. Aistal et al. (E791 Collaboration), Search for rare and forbidden charm meson decays $D^0 \to V\ell^+\ell^-$ and $h\ell\ell$, Phys. Rev. Lett. 86, 3696 (2001) [hep-ex/0011077].

J. Mejia-Guisao, D. Milanés, N. Quintero and J. D. Ruiz-Alvarez, Exploring GeV-scale Majorana neutrinos in lepton-number-violating $A_0^\nu$ baryon decays, Phys. Rev. D 96, 015039 (2017) [arXiv:1705.10606 [hep-ph]].

A. Faessler, M. González, S. Kovalenko and F. Šimkovic, Arbitrary mass Majorana neutrinos in neutrinoless double beta decay, Phys. Rev. D 90, 096010 (2014) [arXiv:1408.6077 [hep-ph]]; P. Benes, A. Faessler, F. Simkovic and S. Kovalenko, Sterile neutrinos in neutrinoless double beta decay, Phys. Rev. D 71, 077901 (2005) [arXiv:hep-ph/0501295].

T. Asaka, S. Blanchet, and M. Shaposhnikov, The vMSM, dark matter and neutrino masses, Phys. Lett. B 631, 151 (2005) [hep-ph/0503065]; T. Asaka and M. Shaposhnikov, The vMSM, dark matter and baryon asymmetry of the universe, Phys. Lett. B 620, 17 (2005) [hep-ph/0505013].

L. Canetti, M. Drewes, and M. Shaposhnikov, Sterile Neutrinos as the Origin of Dark and Baryonic Matter, Phys. Rev. Lett. 110, 061801 (2013) [arXiv:1204.3902 [hep-ph]]; L. Canetti, M. Drewes, T. Frossard, and M. Shaposhnikov, Dark Matter, Baryogenesis and Neutrino Oscillations from Right Handed Neutrinos, Phys. Rev. D 87, 093006 (2013) [arXiv:1208.4607 [hep-ph]].

L. Canetti, M. Drewes, and B. Garbrecht, Probing leptonogenesis with GeV-scale sterile neutrinos at LHCb and Belle II, Phys. Rev. D 90, 125005 (2014) [arXiv:1404.7114 [hep-ph]].

M. Drewes, B. Garbrecht, D. Gueter and J. Klaric, Testing the low scale seesaw and leptogenesis, JHEP 08, 018 (2017) [arXiv:1609.09069 [hep-ph]]; P. Hernández, M. Kecic, J. Lópe-Pavón, J. Racker and J. Salvado, Testable Baryogenesis in Seesaw Models, J. High Energy Phys. 08, 157 (2016) [arXiv:1606.06719 [hep-ph]]; P. Hernández, M. Kecic, J. Lópe-Pavón, J. Racker and N. Rius, Leptonogenesis in GeV scale seesaw models, J. High Energy Phys. 10, 067 (2015) [arXiv:1508.03676 [hep-ph]]; B. Shuve and I. Yavin, Baryogenesis through Neutrino Oscillations: A Unified Perspective, Phys. Rev. D 89, 075014 (2014) [arXiv:1401.2459 [hep-ph]].

R. W. Rasmussen and W. Winter, Perspectives for tests of neutrino mass generation at the GeV scale: Experimental reach versus theoretical predictions, Phys. Rev. D 94, 073004 (2016) [arXiv:1607.07880 [hep-ph]].

A. de Gouvea, GeV seesaw, accidentally small neutrino masses, and Higgs decays to neutrinos, arXiv:0706.1732 [hep-ph].

M. Drewes, Phenomenology of Right Handed Neutrinos, Int. J. Mod. Phys. E 22, 1330019 (2013) [arXiv:1303.6912].

M. Drewes and B. Garbrecht, Combining experimental and cosmological constraints on heavy neutrinos, Nucl. Phys. B921, 250 (2017) [arXiv:1502.00477 [hep-ph]].
[57] F. F. Deppisch, P. S. Bhupal Dev, and A. Pilaftsis, Neutrinos and Collider Physics, New J. Phys. 17, 075019 (2015) [arXiv:1502.06541].

[58] A. de Gouvêa, and A. Kobach, Global constraints on a heavy neutrino, Phys. Rev. D 93, 033005 (2016) [arXiv:1511.00683].

[59] E. Fernandez-Martinez, J. Hernandez-Garcia and J. Lopez-Favon, Global constraints on heavy neutrino mixing, J. High Energy Phys. 08, 033 (2016) [arXiv:1605.08774].

[60] J. L. Rosner, S. Stone, and R. S. Van de Water, Leptonic Decays of Charged Pseudoscalar Mesons - 2015, [arXiv:1509.02220 [hep-ph]].

[61] C. J. Monahan, H. Na, C. M. Bouchard, G. P. Lepage and J. Shigemitsu (HPQCD Collaboration), Bs → Dsℓν Form Factors and the Fragmentation Fraction Ratio fs/fd, Phys. Rev. D 95, 114506 (2017) [arXiv:1703.09728 [hep-lat]].

[62] C. M. Bouchard, G. P. Lepage, C. Monahan, H. Na and J. Shigemitsu, Bs → Kℓν form factors from lattice QCD, Phys. Rev. D 90, 054506 (2014) [arXiv:1406.2279 [hep-lat]].

[63] R. Aaij et al. (LHCb Collaboration), Measurement of σ(pp → bbX) at √s = 7 TeV in the forward region, Phys. Lett. B 694, 209 (2010) [arXiv:1009.2731 [hep-ex]].

[64] Y. Amhis et al., Heavy Flavor Averaging Group (HFLAV), Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2016, arXiv:1612.07233 [hep-ex].

[65] R. Aaij et al. (LHCb Collaboration), Angular analysis and differential branching fraction of the decay B0s → φμ+μ−, JHEP 1509, 179 (2015) [arXiv:1506.08777 [hep-ex]].

[66] R. Aaij et al. (LHCb Collaboration), Search for massive long-lived particles decaying semileptonically in the LHCb detector, Eur. Phys. J. C 77, 224 (2017) [arXiv:1612.00945 [hep-ex]].

[67] R. Aaij et al., (LHCb Collaboration), LHCb Detector Performance, Int. J. Mod. Phys. A 30, 1530022 (2015) [arXiv:1412.6352 [hep-ex]].

[68] S. Chatrchyan et al. (CMS Collaboration), Description and performance of track and primary-vertex reconstruction with the CMS tracker, JINST 9, P10009 (2014) [arXiv:1405.6569 [physics.ins-det]].

[69] S. Chatrchyan et al. (CMS Collaboration), Muon ID performance: low-pT muon efficiencies, CMS performance note.

[70] S. Chatrchyan et al. (CMS Collaboration), Measurement of the Strange B0 Meson Production Cross Section with J/ψφ Decays in pp Collisions at √s = 7 TeV, Phys. Rev. D 84, 052008 (2011) [arXiv:1106.4048 [hep-ex]].

[71] V. Khachatryan et al. (CMS Collaboration), Angular analysis of the decay B0 → K*0μ+μ− from pp collisions at √s = 8 TeV, Phys. Lett. B 753, 424 (2016) [arXiv:1507.08126 [hep-ex]].

[72] D. Liventsev et al. (Belle Collaboration), Search for heavy neutrinos at Belle, Phys. Rev. D 87, 071102(R) (2013) Erratum:[Phys. Rev. D 95, 099903 (2017)] [arXiv:1301.1105 [hep-ex]].

[73] P. Abreu et al. (DELPHI Collaboration), Search for neutral heavy leptons produced in Z decays, Z. Phys. C74, 57 (1997).

[74] J. Badier et al. (NA3 Collaboration), Mass and lifetime limits on new longlived particles in 300 GeV/c π− interactions, Z. Phys. C 31, 21 (1986).

[75] P. Vilain et al. (CHARM II Collaboration), Search for heavy isosinglet neutrinos, Phys. Lett. B 343, 453 (1995); Phys. Lett. B 351, 387 (1995).

[76] A. Vaitaitis et al. (NuTeV Collaboration), Search for neutral heavy leptons in a high-energy neutrino beam, Phys. Rev. Lett. 83, 4943 (1999) [hep-ex/9908011].