Constraining Sterile Neutrinos Using Decay Width Measurements of SM Bosons

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Abstract

The mixing of right-handed neutrinos with the SM neutrinos contributes to the interactions of these neutrinos with the SM particles. Consequently, they will contribute to the decay widths of the SM W, Z, and Higgs bosons provided that they are kinematically allowed to be produced from these SM gauge bosons. Here, we show that the measured decay widths of Higgs, Z and W bosons can be used to probe sterile neutrinos, if they are kinematically allowed to be produced from these heavy Standard Model (SM) particle decays via the active-sterile neutrino mixing. We analyze the sensitivity of these measured SM quantities to constrain the active-sterile neutrino mixing as a function of the sterile neutrino mass. We make a comparative study of these constraints with other existing constraints from electroweak precision data, beam dump experiments, and peak searches, as well as from big bang nucleosynthesis.

Keywords: left-right symmetric model, seesaw mechanism, sterile neutrino
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1. INTRODUCTION

With the discovery of the Higgs boson at the LHC, all the SM particles except neutrinos achieve their masses through spontaneous symmetry breaking (SSB), known as the Higgs mechanism [1]. Physicists find evidence of the neutrino mass, which is very tiny in nature from the observed neutrino oscillations data in various solar, reactor, atmospheric, and accelerator neutrinos. The seesaw mechanism is one such scenario beyond the SM, which can explain the smallness of neutrino masses. There are various types of the seesaw, but the most widely accepted version of the seesaw is the Type-I seesaw [2]. It requires that the right-handed (RH) neutrinos have Majorana mass in addition to the Dirac mass like other SM-charged fermions. As the seesaw itself represents a ratio, the mass of the SM neutrinos becomes lighter with the increase of the mass of the RH neutrinos. The RH neutrinos could only participate in the SM interactions due to their mixing with the active neutrinos, known as the sterile neutrinos.

The important aspect of the seesaw mechanism is the active-sterile neutrino mixing as well as its Majorana mass, which could be probed experimentally. If the sterile neutrinos are kinematically accessible, the key aspects of the seesaw mechanism could be probed simultaneously through the collider experiments. Despite the large mass range of sterile neutrinos being from the eV scale to the Grand Unified scale, neutrinos of the electroweak mass scale are of great interest. These neutrinos synchronously probe the neutrino mass puzzles, baryon asymmetry, and dark matter. Practically, sterile neutrinos with electroweak mass scale can be verified directly from the constraints of the present colliders like LEP and LHC and from the future colliders like ILC, FCC-ee, and CEPC [3]. But, to date, neutrinos with large mass scale could not be observed experimentally. Therefore, constraints can only be imposed on theoretical parameters. Along with the direct and indirect hunting of the sterile neutrinos, electroweak precision tests like the decay widths of the SM bosons can be used to impose constraints indirectly. Further, the active-sterile neutrino mixing contributes to the interactions of these neutrinos with the SM particles. Henceforth, they will contribute to the decay widths of the SM bosons provided that the SM bosons are kinematically allowed to be produced from these SM gauge bosons.

In the present analysis, we are interested in the phenomenology of active-sterile neutrino mixing parameter space. We analyze in the framework of the left-right symmetric model (LRSM) [4] as an explicit example of the UV-complete model, where the sterile neutrinos and the seesaw mechanism arise naturally from the B-L breaking. The phenomenological study of sterile neutrino parameter space can also be applicable to the minimal extension of the seesaw, i.e., Type-I seesaw [5, 6], which can easily accommodate the sterile neutrino masses scale and the active-sterile neutrino mixing provided that they are experimentally accessible. If the sterile neutrinos are of eV scale or lower, the active neutrino oscillation data are directly affected, which is related to the LSND/MiniBooNE anomaly [7, 8]. However, sterile neutrinos larger than about 10 eV mass suppress the active-sterile neutrino oscillation effects through the large mass splitting. Therefore, we look for other effects like the decay of the sterile itself or the decay of other SM particles involving sterile states. For the existing constraints in the whole parameter space from eV to TeV, one can see [9, 10] and the accompanying website `sterile-neutrino.org` where the constraints are regularly updated. Here, we obtain the upper limits on the active-sterile neutrino mixing from the decay widths of the SM W, Z, and Higgs bosons in the wide mass range of sterile neutrinos and make a comparative study of these constraints.

2. NUMERICAL ANALYSIS

The LRSM is a simple electroweak extension of the SM gauge group and is based on the following gauge symmetry:

$$G_{LR} = SU(3)_C \times SU(2)_R \times SU(2)_L \times U(1)_{B-L}. \qquad (1)$$

In this theory, all the left-handed (LH) fermions must have a RH equivalent and thus removes the left-right asymmetry of the SM. Contrary to the SM, all the fermion fields of this model are grouped as doublets. The LH doublets transform under $SU(2)_L$ while the RH doublets transform under $SU(2)_R$. In addition to this, the model has seven gauge fields (three LH and three RH

W bosons and one photon field) and three scalar Higgs fields (one bidoublet, one LH, and one RH triplet) in the particle spectrum. Here, the electric charge formula is formulated as

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}, \tag{2}$$

where $T_i = \frac{1}{2}\tau_i$, τ_i are the Pauli matrices, and T is the generator of $SU(2)$ gauge group. A detailed study of this model is given in [11].

The LRSM has a higher degree of symmetry than the SM by removing left-right asymmetry and restoring parity conservation, which were previously unachieved in the SM. The spontaneous breaking of parity symmetry can be achieved when the LRSM gauge group is broken down into the SM gauge group. This could be done through the VEV of the Δ_R, which give masses to the two new gauge bosons $W_R^{\pm}$ and $Z^{'}$. The SM gauge group is further broken down into the observed $U(1)_{EM}$ group through the VEV of Higgs field Φ.

The Majorana mass of the RH neutrinos, essential for the seesaw mechanism, appears naturally in this LRSM. These RH neutrinos acquire their masses through the VEV of the neutral component Δ_R at a scale v_R. The Yukawa Lagrangian of this model, which is responsible for the neutrino mass, is

$$\begin{aligned}\mathcal{L}_Y = {} & h\bar{Q}_L\phi\bar{Q}_R + \tilde{h}\bar{Q}_L\tilde{\phi}\bar{Q}_R + h\bar{L}\phi R + \tilde{h}\bar{L}\tilde{\phi}R \\ & + f_L L^T C i\tau_2\Delta_L L + f_R R^T C i\tau_2\Delta_R R + H.C.,\end{aligned} \tag{3}$$

where $\tilde{\phi} = \tau_2\phi^*\tau_2$ and h, $\tilde{h}$, $f_{L,R}$ are the Yukawa couplings. After the symmetry breaking of this Yukawa Lagrangian, the Dirac fermion masses are $M_D = hk + \tilde{h}k'$ where k and k' are the VEVs of the Higgs bidoublet ϕ. Thus, Majorana mass matrix is $M_R = f_R v_R$. This leads to a neutrino mass matrix

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}. \tag{4}$$

Diagonalizing the above mass matrix with the usual seesaw approximation $|M_D| \ll |M_R|$, the mass of the SM neutrinos can be obtained as

$$M_\nu \simeq -M_D M_R^{-1} M_D^T, \tag{5}$$

and the active-sterile neutrino mixing matrix V_{lN} is $M_D M_R^{-1}$.

In this analysis, we have taken into consideration the following decay modes of Higgs, W, and Z bosons:

$$\begin{aligned} h &\longrightarrow N\nu, \\ W &\longrightarrow Nl, \\ Z &\longrightarrow N\nu, \end{aligned} \tag{6}$$

where l stands for e^-, μ^-, and τ^- and ν for ν_e, ν_μ, and ν_τ. The Feynman diagrams are shown in Figure 1. Due to the new Yukawa interaction of the LRSM, the total decay widths of the SM particles are enhanced compared to their SM predicted values. The new decay widths of the above decay processes are listed below where g denotes the coupling constant of weak interactions.

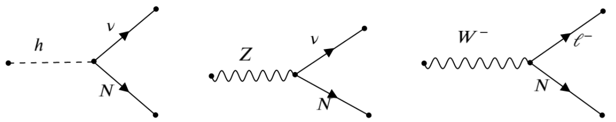

FIGURE 1: Feynman diagrams for the production of sterile neutrinos from Higgs, W, and Z bosons.

$$\begin{aligned}
\Gamma_{h\longrightarrow N\nu} &= |V_{lN}|^2 \frac{g^2 M_h M_N^2}{32\pi M_W^2}\left(1 - \frac{M_N^2}{M_h^2}\right)^2, \\
\Gamma_{W\longrightarrow Nl} &= |V_{lN}|^2 \frac{g^2 M_W^3}{96\pi M_W^2}\left(1 - \frac{M_N^2}{M_W^2}\right)^2\left(2 + \frac{M_N^2}{M_W^2}\right), \\
\Gamma_{Z\longrightarrow N\nu} &= |V_{lN}|^2 \frac{g^2 M_Z^3}{48\pi M_W^2}\left(1 - \frac{M_N^2}{M_Z^2}\right)^2\left(2 + \frac{M_N^2}{M_Z^2}\right).
\end{aligned} \tag{7}$$

The SM predicted value for Higgs boson decay width is 4.15 MeV [12] whereas the CMS and ATLAS experiments have set constraints as $\Gamma_h = 3.2^{+2.8}_{-2.2}$ MeV [13] at 95% C.L. on the total width of Higgs boson. Similarly, for the W boson decay, the SM value is $\Gamma_W \simeq 2.0932 \pm 0.0022$ GeV [14]. But the preliminary world average value including both Tevatron and LEP2 is $\Gamma_W = 2.085 \pm 0.0042$ GeV [15]. In case of Z boson decay, the SM predicted value [16] is

$$\begin{aligned} \Gamma_Z &= 2.4956 \pm 0.0019\,\text{GeV (SM-Zpole fit)}, \\ \Gamma_Z &= 2.4965 \pm 0.0015\,\text{GeV (SM High-}Q^2\text{ fit)}, \end{aligned} \tag{8}$$

where the accumulated value for the total decay width of Z boson from the ALEPH, DELPHI, L3, and OPAL experiments at LEP and from the SLD experiment is $\Gamma_Z = 2.4952 \pm 0.0023$ GeV [16]. Here, we consider both the theoretical and experimental uncertainties in the decay widths to obtain the maximum possible error, which are listed as follows:

$$\begin{aligned} \Delta\Gamma_h &= 0.00617\,\text{GeV}, \\ \Delta\Gamma_W &= 0.0802\,\text{GeV}, \\ \Delta\Gamma_Z &= 0.00715\,\text{GeV}. \end{aligned} \tag{9}$$

We demand the deviation in these widths from their SM predictions in the LRSM should be less than the uncertainty in their SM values, given in equation (9).

We have used the event generator MadGraph5-aMC@NLO [17] in the present analysis. We calculate the decay widths of Higgs, W, and Z bosons and study the sensitivity of measured decay widths to constrain the active-sterile neutrino mixing parameter as a function of the sterile neutrino mass.

3. RESULTS AND DISCUSSION

We analyze here the constraint region of the active-sterile neutrino mixing in the mass range 1 MeV $\leq M_N \leq$ 500 GeV, which are represented in Figure 2. The W boson decay is represented by the blue line whereas the Higgs boson and Z boson decays are represented by the black line and the red line, respectively, in Figure 2. Higgs decay bound has a different shape compared to W and Z bounds as their decay widths have dissimilar dependencies on mass and mixing of the sterile neutrinos. The

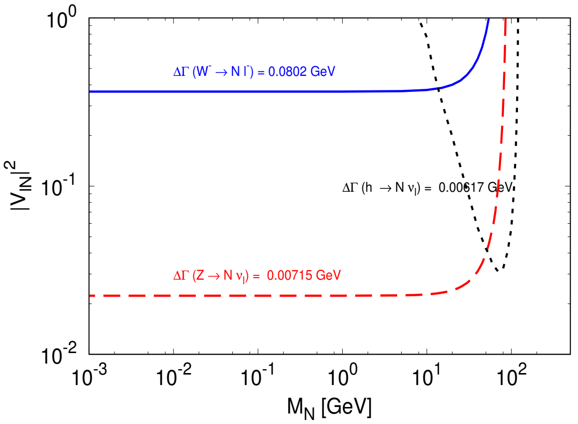

FIGURE 2: Constraints on the active-sterile neutrino parameter space.

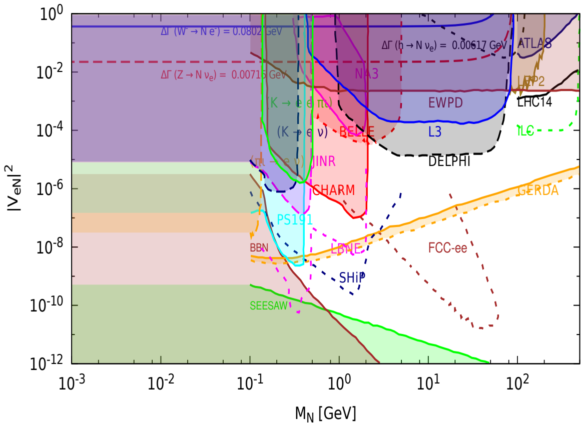

FIGURE 3: Upper bounds on the mixing matrix $|V_{eN}|^2$ in the sterile electron neutrino mass range 1 MeV–500 GeV.

active-sterile neutrino mixings are constrained through various laboratory experiments in a broad mass range of M_N from eV-TeV. We present here the sterile neutrino searches in the mass range 1 MeV–500 GeV, which are consistent for the collider experiments. We have also compared our results with other existing constraints of sterile electron neutrinos, which are displayed in Figure 3. Our results are also comparable with the existing constraints of sterile muon and tau neutrinos. For detailed study, one can see [10].

The BBN constraints for the heavy neutrinos having life time <1 sec [18] are represented by the brown line in Figure 3 and the seesaw, which describes the scale of mixing is identified through the green line. The GERDA experiments [19] represent the yellow line whereas the area between the two yellow lines (solid and dashed) defines the uncertainty due to NMEs [20]. Being heavier compared to the charged leptons, the sterile neutrinos reduces the helicity suppression factor in the leptonic decays, which ultimately increases the sensitivity on $|V_{eN}|^2$ with M_N. The decay channels $\pi \longrightarrow eN$ [21] and $K \longrightarrow eN$ [22] have found the upper limits of the active-sterile neutrino mixing, shown in Figure 3. The Belle experiments [23] put the 90% C.L. limits on $|V_{eN}|^2$ in the mass range of $500\,\text{MeV} \leq M_N \leq 5\,\text{GeV}$, as shown in Figure 3 labeled Belle. As the sterile neutrinos are unstable, they decay to the visible products if kinematically allowed. The search for these visible products is observed by various beam dump experiments. These beam dump experiments such as PS191 [24], NA3 [25], CHARM [26], IHEP-JINR [27], the LBNE [28] are shown in Figure 3, which limits the active-sterile neutrino mixing. The most stringent limit on the active-sterile neutrino mixing comes from $K \longrightarrow ee\pi$ decay mode [29] as shown in Figure 3. The number of events of the sterile neutrino decay process is suppressed by $|V_{eN}|^4$ if the decay width is larger than the detector size. This limitation could be overcome by the proposed fixed target experiments such as SHiP [30] with the increase of the flux of initial hadrons. This is presented in Figure 3 labeled as SHiP. The heavy neutrino production from Z decays limits the neutrino mixing which are shown in Figure 3 as L3 [31], DELPHI [32], and LEP data. Using global fits to the EWPD [33], the 90% C.L. limits on $|V_{eN}|^2$ were obtained and are shown in Figure 3. The L3 collaboration put a 95% C.L. limit on $|V_{eN}|^2$ in a mass range $80\,\text{GeV} \leq M_N \leq 205\,\text{GeV}$ [34], which is shown in Figure 3. Future colliders such as ILC [35] can improve the sensitivity in this mass region with a greater center of mass of energy and larger luminosity, which is shown in Figure 3. The ATLAS collaboration limits the $|V_{eN}|^2 \leq 10^{-2}$–10^{-1} for masses upto 500 GeV [36], which is displayed in Figure 3 (ATLAS).

4. SUMMARY

Though neutrinos are massless in the SM, the observed neutrino oscillations are the conclusive experimental evidence for the existence of neutrino mass. These neutrino mass mechanisms are studied theoretically through various mass models going beyond the SM, which are necessary to be verified experimentally at colliders. Here, we analyze the decay widths of SM W, Z, and Higgs bosons in the framework of LRSM along with the consideration of Type-I seesaw mechanism. We found the constraint region for the active-sterile neutrino parameter space. For this, we assume that the deviation of these decay widths from their SM predicted value is within the errors in the experimentally observed decay widths. Moreover, we compared our results with the existing constraints from different experimental searches. We finally conclude that the measured decay widths from the SM bosons could impose strongest constraints on the active-sterile neutrino mixing as a function of sterile neutrino mass. The results are encouraging and more studies on the production of heavy neutrinos are being planned.

CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

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