Limits on W_R from Meson Decays

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(Received 21 September 2023; revised 8 April 2024; accepted 3 September 2024; published 16 October 2024)

In this Letter we show that pseudoscalar meson leptonic decay data can be used to set stringent limits on the mass m_{W_R} of a right-handed vector boson, such as the one that appears in left-right symmetric models. We have shown that for a heavy neutrino with a mass m_N in the range $50 < m_N/\mathrm{MeV} < 1900$ one can constraint $m_{W_R} \gtrsim (4\text{–}19)$ TeV at 90% CL. This provides the most stringent experimental limits on the W_R mass to date for this heavy neutrino mass range.

DOI: 10.1103/PhysRevLett.133.161802

Introduction—The weak interaction and its left-chiral nature has been connected since its very inception with neutrinos. On the one hand, except for gravity, neutrinos only interact weakly. On the other hand, all neutrinos we have ever observed are left-chiral fermions (ν_L). Furthermore, β decays lead to the understanding that, at low energy, weak interactions are governed by a universal constant, $G_F \sim 1/\Lambda^2 \sim 10^{-5}\ \mathrm{GeV}^{-2}$, the Fermi constant. This, retrospectively, was the first indication of the need for a mediator with mass $\Lambda \sim \mathcal{O}(100\ \mathrm{GeV})$, for couplings of $\mathcal{O}(1)$. So neutrino properties were at the core of building the standard model (SM) of electroweak interactions as a left-chiral gauge theory.

Neutrino oscillation experiments have provided in the last half of century compelling evidence for (tiny) neutrino masses and flavor mixing [1–22]. We may need right-chiral neutrino fields N to explain neutrino masses and mixings, however; these states are uncharged under $SU(2)_L \times U(1)_Y$, the SM symmetry group. This is why we sometimes refer to left (right) chiral neutrinos as active (sterile).

We do not know if there are right-chiral weak charged currents in nature. If so N would be active under them. So low energy weak decays involving neutrinos can be used to test their effective strength G'_F and probe the mass scale of the new mediator W_R.

We will focus here on two body pseudoscalar meson decays $M \to \ell N$, where $M = \pi$, K, and D, $\ell = e, \mu$, and N a right-handed neutrino in the MeV–GeV mass range. In beyond SM models with right-chiral currents and neutrinos, the decay rate $\Gamma(M \to \ell N)$ has two competing contributions [23],

$$\Gamma(M \to \ell N) = (G_F^2 |U_{\ell N}|^2 + G_F'^2) f(m_M, m_\ell, m_N), \qquad (1)$$

the first mediated by W_L, the SM vector boson, and dependent on the active-sterile mixing $U_{\ell N}$, the second mediated by W_R. Here, $f(m_M, m_\ell, m_N)$ is a function that depends on the meson m_M, charged lepton m_ℓ, and right-handed neutrino m_N masses. The low energy effective couplings are related by

$$\left(\frac{G'_F}{G_F}\right)^2 \equiv \left(\frac{m_{W_L} g_R}{m_{W_R} g_L}\right)^4 \sim 7 \times 10^{-8} \left(\frac{5\ \mathrm{TeV}}{m_{W_R}}\right)^4 \left(\frac{g_R}{g_L}\right)^4, \qquad (2)$$

where m_{W_L} and g_L (m_{W_R} and g_R) are the mass and coupling constant associated with the SM (new) interaction. If $|U_{\ell N}|^2 \gg (G'_F/G_F)^2$ the mixing contribution prevails and meson decays constrain the active-sterile mixing [24–31]. However, if $|U_{\ell N}|^2 \ll (G'_F/G_F)^2$ the right current contribution dominates and meson decays can instead constrain m_{W_R}. The best limits on active-sterile mixing are on U_{eN}. In the mass range of interest

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the maximum value allowed by data is $|U_{eN}|^2 \sim 10^{-7}$–10^{-9}; hence, meson decay experiments have a sensitivity to $m_{W_R} \sim (5$–$15)$ TeV.

In this Letter we reanalyze the results from a number of low energy meson decay experiments assuming right-chiral current dominance, a situation which may manifest in left-right symmetric models (LRSMs) [32–37], to derive the best experimental limits to date on m_{W_R} for this m_N mass range.

Left-right symmetric models—LRSMs remain arguably one of the simplest and best motivated extensions of the SM. Being characterized by the gauge group $SU(2)_L \times SU(2)_R \times U(1)$ and an additional discrete left-right (LR) symmetry [38,39], they forecast the existence of two new gauge bosons: a neutral Z_R and a charged W_R. Fermions are LR symmetric, i.e., $q_{L,R} = (u\,d)^T_{L,R}$ and $\ell_{L,R} = (\nu\,e)^T_{L,R}$, and the $SU(2)_{L,R}$ associated gauge couplings g_L and g_R can be equal or not, depending on the discrete LR symmetry breaking scale [40].

Neutrino masses are natural to these models as three right-chiral neutrinos $N \equiv \nu_R$ have to be introduced to complete the $SU(2)_R$ lepton doublets. Furthermore, the light neutrino masses can be made small via the contributions of type-I and type-II seesaw mechanisms [34,41–43], that is,

$$m_\nu = m_{\rm I} + m_{\rm II}. \quad (3)$$

Note that in a type-I dominant scenario, $m_\nu \sim m_{\rm I} \sim |U_{\ell N}|^2 m_N$, so to fulfill our requirement on subdominant active-sterile mixing, we need

$$m_\nu < 7 \times 10^{-2}\ \text{eV}\left(\frac{m_N}{1\ \text{MeV}}\right)\left(\frac{5\ \text{TeV}}{m_{W_R}}\right)^4\left(\frac{g_R}{g_L}\right)^4, \quad (4)$$

which, in principle, hold for m_N in the MeV–GeV range. As the mixture depends only on $m_{\rm I}$, in a type-II dominant scenario it is naturally suppressed. We will disregard the active-sterile mixing contribution from now on by setting $U_{\ell N} = 0$.

The relevant part of the model Lagrangian for our study is

$$\mathcal{L}_{\rm R}^{\rm cc} = -\frac{g_R}{\sqrt{2}}[\bar{N}U_{RR}^\dagger \not{W}_R E_R + \bar{D}_R V_R^\dagger \not{W}_R U_R] + \text{H.c.}, \quad (5)$$

where the right-chiral fermion fields are grouped as $N = (N_1\,N_2\,N_3)^T$ for neutrinos, $E_R = (e_R\,\mu_R\,\tau_R)^T$ for charged leptons, $D_R = (d_R\,s_R\,b_R)^T$ for down quarks and $U_R = (u_R\,c_R\,t_R)^T$ for up quarks. The Lagrangian is given in the mass basis so U_{RR} and V_R are (approximately) unitary mixing matrices. We will set $V_R = V_{\rm CKM}$, the SM Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix. This relation holds to high degree in the minimal LRSM [44]. Furthermore, to make our analysis as model-independent as possible, we assume all right-handed neutrinos degenerate such that U_{RR} drops out from the calculations.

Relaxing this assumption, the calculations will feature U_{RR} but since U_{RR} involves $\mathcal{O}(1)$ elements, barring specific flavor structure [for example, $(U_{RR})_{\tau i} = 1$], the changes to our results will be of $\mathcal{O}(1)$. Other effect is the three-body decay of a heavier to a lighter N mediated by right-chiral neutral gauge bosons. As the bounds are driven by two-body decays, we expect less than order of 1 differences.

We are working here in the vanishing $W_R - W_L$ mixing limit [45]. Finally, notice that constraining m_{W_R}, we are indirectly limiting the mass of Z_R from the mass relation after breaking the LR symmetry.

Right-handed neutrino searches—The primary production mechanism for N in accelerators are two-body pseudoscalar meson decays. In the limit where the active-sterile mixing is suppressed, this is accomplished via the tree-level process mediated by W_R depicted in Fig. 1, so the rate of this process is like the one in the SM, except for the exchange $G_F \to G_F'$ and the changes in the matrix element and phase space due to a non-negligible m_N. Similarly, for detection, only channels mediated via the charged right-handed current can contribute. There are three types of such searches: visible (with hadrons in the final state), invisible, and meson decay ratios.

Visible searches—The first class of experiments we will discuss look for visible signals from $N \to \ell^\pm \pi^\mp$ decay in the detector.

We start with the Tokai-to-Kamioka (T2K) experiment [48]. T2K beam is produced mainly by π and K decays from the collision of 30 GeV protons on a graphite target. These mesons are focused and their charge is selected by magnetic horns before they decay in flight producing neutrinos. We say they operate in the neutrino (antineutrino) mode for positive (negative) charged meson selection.

The collaboration used data collected by their off-axis near detector, ND280, to look for N visible decays. They assume N is produced and decay via active-sterile mixing. Their analysis correspond to an exposure to 12.34×10^{20} (6.29×10^{20}) protons on target in the neutrino

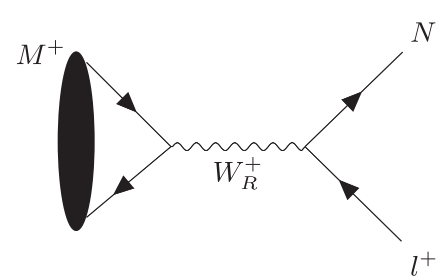

FIG. 1. Production of a right-handed neutrino N by the meson M decay mediated by the right-handed current.

(antineutrino) mode. The ND280 is a detector located 280 m from the proton target with three time projection chambers (TPCs) as their central tracker surrounded by a calorimeter and a muon detector [49]. The main active volume is 6.3 m^3 for the gas TPC. They considered the production modes $K^\pm \to \ell^\pm N$, with N sufficiently long-lived ($\tau \gg 1$ μs) so it can reach ND280 and decay in one of the following modes $N \to \ell^\pm \pi^\mp$, $N \to \ell^\pm \ell'^\mp \nu$, with $\ell, \ell' = e$, μ. The main background is expected from neutrino coherent π production in Ar ($\nu_\mu + \mathrm{Ar} \to \mu^- + \pi^+ + \mathrm{Ar}$), but they also consider other neutrino interactions in and outside the gas TPC. In Table II of [27] we find the background estimated for each production and decay mode (typically < 1 event), as well as the effect of Monte Carlo (MC) statistics, flux, and detector systematics in the background calculation (< 0.5 events). No events were observed in any of these modes.

Only the two-body production and decay modes can be due to W_R under our assumptions: $K^\pm \to e^\pm N$, $N \to e^\pm \pi^\mp$ for $m_\pi + m_e < m_N < m_K - m_e$ (four channels) and $K^\pm \to \mu^\pm N$, $N \to \mu^\pm \pi^\mp$ for $m_\pi + m_\mu < m_N < m_K - m_\mu$ (four channels).

Limits complementary to T2K are provided by the Big European Bubble Chamber (BEBC) [31] search for heavy neutral leptons [50]. Their neutrino beam is originated from a beam dump setup where a flux of 400 GeV protons hit a copper block thick enough to absorb the long-lived mesons produced before they decay. Hence, the expected right-handed neutrino flux predominantly consists of prompt $D^\pm \to \ell^\pm N$ decays, enabling exploration of masses in the range $250 < m_N/\mathrm{MeV} \lesssim 1900$. The bubble chamber detector is positioned 406 m from the copper layer. Analysis of the data collected by the BEBC experiment led to strong constraints on the mixing of heavy neutral leptons with muon and electron neutrinos [50]. The detection channels considered were the same as in T2K. The total amount of data corresponds to $\sim 2 \times 10^{18}$ protons on target. A single event of $N \to \mu^+ \pi^-$ was observed, consistent with the expected background of 0.6 ± 0.2 events.

Unfortunately we cannot profit from the CHARM experiment data [29] because they only consider the three-body final states $N \to \ell \ell' \nu$, forbidden for $U_{\ell N} = 0$.

Invisible searches—The second class are peak search experiments. These look for the existence of a heavy neutrino emitted in helicity suppressed meson decays $M^+ \to e^+ \nu_e(N)$. The decays happen either at rest or in flight, for both the signal $M^+ \to e^+ N$ is characterized by a single final state positron. The idea is to search for a subdominant peak in the e^+ spectrum [51,52] from an invisible particle of mass m_N. The peak-search procedure measures the $M^+ \to e^+ N$ decay rate with respect to $M^+ \to e^+ \nu_e$, as a function of m_N. In our scenario these branching ratios are related by

$$\mathcal{B}(M^+ \to e^+ N) = \mathcal{B}^{\mathrm{SM}}(M^+ \to e^+ \nu_e) \rho_e^{MN} \left(\frac{G_F'}{G_F} \right)^2, \quad (6)$$

where $x_e = (m_e/m_M)^2$, $x_N = (m_N/m_M)^2$ with $M = \pi$ or K, and the corresponding kinematical factor is $\rho_e^{MN} = [x_e + x_N - (x_e - x_N)^2] \lambda^{1/2}(1, x_e, x_N)/[x_e(1 - x_e)^2]$ with $\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + bc + ac)$.

We will focus here on experiments PIENU [28] and NA62 [30]. For $M_{W_R} \gtrsim 5$ TeV, N has a lifetime $\tau_N \gg 1$ μs and can be considered stable in these experiments. The PIENU detector at TRIUMF uses a secondary pion beam created by colliding 500 MeV protons into a beryllium target. The positively charged beam (84% π^+, 14% μ^+, and 2% e^+) of momentum 75 MeV is transported to the PIENU apparatus. The π^+ are stopped in a 8 mm thick plastic scintillator and decay at rest. The monochromatic positrons ($E_{e^+} = 69.8$ MeV), are measured in a spectrometer consisting of a large NaI (Tℓ) crystal (48 cm long and 48 cm diameter) surrounded by an array of pure CsI crystals. They collected about 10^7 $\pi^+ \to e^+ \nu_e$ events, which they used to look for N production via active-sterile mixing U_{eN} for $60 < m_N/\mathrm{MeV} < 135$ [53]. Their main background is $\pi^+ \to \mu^+ \nu_\mu$ followed by $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$. They were able to suppress this background by applying cuts on timing, energy, and track information. Their MC simulation was validated with an experimental study [53]. Their background suppressed positron spectrum was fitted with a background and a signal component for $E_{e+} =$ (4–56) MeV in order to search for additional peaks.

The TINA detector [54] is an older TRIUMF experiment similar to PIENU, however with lower sensitivity except in the lower part of the range $50 < m_N/\mathrm{MeV} < 130$ [55].

The NA62 detector at CERN uses a secondary beam (70% π^+, 23% protons, and 6% K^+) created by directing 400 GeV protons from the Super Proton Synchrotron onto a beryllium target. The central beam momentum is 75 GeV, with a momentum spread of 1%. Before entering the long fiducial decay volume of the detector K^+ is tagged by a Cherenkov counter and hadrons from K^+ upstream decays are absorbed by a steel collimator [30]. The momenta of charged particles produced by K^+ decays are measured by a magnetic spectrometer. To maximize signal and avoid background, the e^+ track momentum is restricted to be in the (5–30) GeV range and the reconstructed squared missing mass $m^2_{\mathrm{miss}} = (p_K - p_{e+})^2 < 0.01$ GeV^2, where $p_K(p_{e+})$ is the kaon (positron) four-momentum. Their available data corresponds to 0.79×10^6 Super Proton Synchrotron spills recorded in 2017–2018, at a typical beam intensity of 2.2×10^{12} protons per spill. They looked for N produced by active-sterile mixing with a lifetime exceeding 50 ns. The data analyzed corresponds to $N_K = (3.52 \pm 0.02) \times 10^{12}$ kaon decays in the fiducial volume with 264 mass hypotheses investigated, m_N, with $144 < m_N/\mathrm{MeV} < 462$. The dominant background is

$K^+ \to \mu^+\nu_\mu$ followed by $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decays. This is reduced by requiring compatibility between the e^+ and K^+ tracks. Other backgrounds, including $K^+ \to \mu^+\nu_\mu$ with a misidentified muon, are negligible [30].

Meson decay ratios—The third class of searches investigates the effect of N in the ratio of pseudoscalar meson leptonic decays to e and μ final states [52], constraining the ratio

$$R_{e/\mu}(M) = \frac{1 + R_{N/\nu_e}(M)}{1 + R_{N/\nu_\mu}(M)} R^{\rm SM}_{e/\mu}(M), \tag{7}$$

where $R^{\rm SM}_{e/\mu}(M) \equiv \mathcal{B}^{\rm SM}(M \to e\nu_e)/\mathcal{B}^{\rm SM}(M \to \mu\nu_\mu)$ and $R_{N/\nu_\ell}(M) \equiv \mathcal{B}(M \to \ell N)/\mathcal{B}^{\rm SM}(M \to \ell\nu_\ell)$ with respect to the experimental values $R^{\rm PDG}_{e/\mu}(\pi) = (1.2327 \pm 0.0023) \times 10^{-4}$ and $R^{\rm PDG}_{e/\mu}(K) = (2.488 \pm 0.009) \times 10^{-5}$. Since the leading order radiative corrections do not depend on m_N [24,57] we consider they are the same for $R_{e/\mu}$ [Eq. (7)] and $R^{\rm SM}_{e/\mu}$. We will use the SM predictions $R^{\rm SM}_{e/\mu}(\pi) = (1.2352 \pm 0.0001) \times 10^{-4}$ and $R^{\rm SM}_{e/\mu}(K) = (2.477 \pm 0.001) \times 10^{-5}$ [58]. Note that in calculating R_{N/ν_ℓ} we must take into account which decay channels are available depending on m_N.

Results—Our main results are presented in Fig. 2, where we show the exclusion in the plane (m_N, m_{W_R}) for $g_L = g_R$. The T2K bound for $140 < m_N/\text{MeV} < 493$ was calculated using the public MC simulation of the expected signal after geometrical, kinematical, and efficiency cuts. This is available as a table with the expected number of events in the detector per production and decay modes as a function of m_N assuming 100% selection efficiency and $U_{\ell N} = 1$ [27]. This table was simulated for production and detection via W_L. We checked that polarization effects due to the different Lorentz structure from W_R do not alter detected angular distributions [59]. Furthermore, we benefited from their simulation as it lists separately production and detection processes. These remarks enabled us to use the T2K simulation to compute the events as a function of m_{W_R} and m_N by selecting the relevant channels and weighting the events by $(G'_F/G_F)^2$. Note, however, that processes mediated by W_R are flavor universal in contrast to analysis with $U_{\ell N} \neq 0$. The sensitivity to m_{W_R} increases with m_N until about 388 MeV (for larger m_N the four channels involving the μ cannot contribute anymore), reaching $m_{W_R} \gtrsim 14$ TeV, it remains high up to 493 MeV, partially due to high flux and background suppression [63]. The BEBC limit was obtained as follows. The N flux was inferred from the light neutrino flux, taking into account only the two-body decays of D mesons. To that end we adapted the simulation provided in [26,59] to include only the channels mediated by W_R and rescaling the number of events by $(G'_F/G_F)^2$. We get $m_{W_R} \gtrsim$ (4–5) TeV. These are the best limits in the region $500 < m_N/\text{MeV} < 2000$. There is a region, for small m_{W_R}, not discarded by BEBC. There the N flux is suppressed because most N decay before reaching the detector. In both experiments the exclusion region is incompatible with the expected background at 90% CL.

In the case of the peak searches we took Fig. 5 [53], Fig. 3(b) (curve A) [54], and Fig. 5 [30], for PIENU, TINA, and NA62, respectively, and calculated the 90% CL exclusion using the conversion $|U_{eN}|^2 \to (G'_F/G_F)^2$. These searches limit $m_{W_R} <$ (4–19) TeV, depending on m_N. TINA gives the best limit for $50 < m_N/\text{MeV} \lesssim 60$, PIENU for $60 \lesssim m_N/\text{MeV} \lesssim 130$ and NA62 for $144 < m_N/\text{MeV} \lesssim 440$. As a comparison, Refs. [68,69] considered constraints on mass of W_R from lepton-number-violating meson decays mediated by N and the strongest limit obtained is $M_{W_R} > 4.5$ TeV for $M_N \sim 0.38$ GeV.

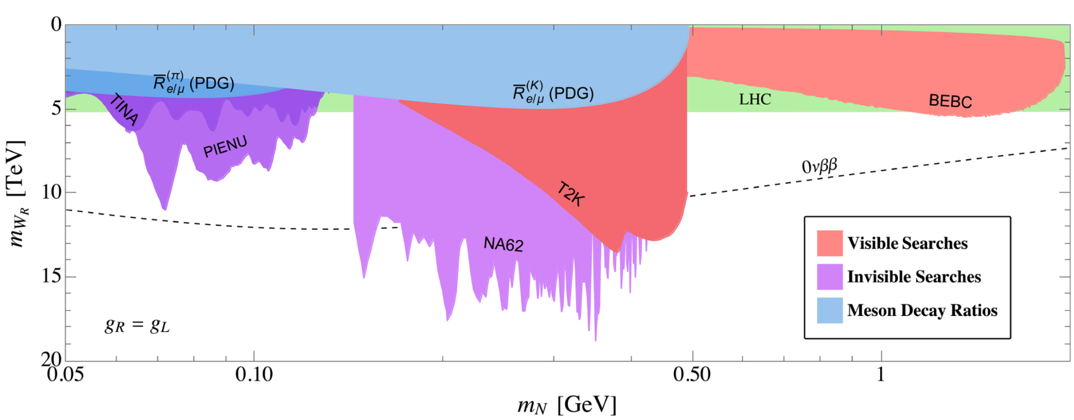

FIG. 2. Bounds on m_{W_R} as a function of m_N from visible searches (red) at T2K [27] and BEBC [31], from invisible peak searches (purple) at PIENU [53], TINA [54], and NA62 [30], as well as from π and K leptonic decay ratios (blue) [64] at 90% CL. We assume $g_R = g_L$. For reference, we also show our estimated limit [59] from the nonobservation of neutrinoless double beta decay ($0\nu\beta\beta$) by KamLAND-Zen [65] and the constraints from the LHC searches (green) for charged lepton plus missing energy [66,67].

Finally, we have used

$$R_{e/\mu}(\pi)/R^{\rm SM}_{e/\mu}(\pi) < \bar{R}^{(\pi)}_{e/\mu}({\rm PDG}) = 1.0017,$$
$$R_{e/\mu}(K)/R^{\rm SM}_{e/\mu}(K) < \bar{R}^{(K)}_{e/\mu}({\rm PDG}) = 1.012, \qquad (8)$$

where $\bar{R}^{(M)}_{e/\mu}({\rm PDG}) \equiv (R^{\rm PDG}_{e/\mu}(M) + 2\sigma)/R^{\rm SM}_{e/\mu}(M)$ to compute the meson decay ratio limits on Fig. 2. The $\bar{R}^{(K)}_{e/\mu}({\rm PDG})$ is dominant in the gap between PIENU and NA62 ($m_N \sim 0.13$ GeV). For $m_N \lesssim 0.05$ GeV, the constraint from meson decay ratios gets weaker starting from $m_{W_R} \sim 4$ TeV for $m_N \sim 0.05$ GeV down to $m_{W_R} \sim 0.5$ TeV for $m_N \sim 1$ MeV.

Other phenomenological constraints—We show in Fig. 2 the limit we estimated from KamLAND-Zen [59,65] nonobservation of neutrinoless double beta decay in ^{136}Xe using the nuclear matrix elements from Ref. [70]. This limit is in agreement with Ref. [71]. However, this may vary by about 50% due to nuclear physics models.

The LHC searches for visible final states for $m_N \sim$ TeV put a bound of $m_{W_R} > 6.4$ TeV [72,73], while those based on charged leptons and missing energy exclude $m_{W_R} \lesssim 5$ TeV for $m_N \lesssim 40$ GeV [66,67] (see green band in Fig. 2).

Big bang nucleosynthesis can be used to constraint N with lifetime $\tau \gtrsim 0.01$ s and using the limits on $|U_{\ell N}|$ derived in Refs. [74,75] under the assumptions of "thermalized" N and maximal mixing to a particular lepton flavor, we estimate the "allowed" parameter space $m_{W_R} \lesssim$ (5–20) TeV in the mass ranges $m_N \sim$ (0.2–1) GeV [76]. Our new bounds shown in Fig. 2 exclude a significant parameter space still allowed by big bang nucleosynthesis.

For $m_N \lesssim 10$ MeV, supernova cooling bounds become important and constrain $m_{W_R} \gtrsim 4.6$ TeV [77].

It is notable that our bounds are comparable with m_N-independent limits derived from CP violation in $K^0 - \bar{K}^0$ mixing, i.e., $M_{W_R} > 5.5$–17 TeV depending on a physical phase in the minimal LRSM [78].

Finally, while meson decays could in principle be used to perform lepton number and lepton flavor violating searches, this is unrealistic for the experiments considered as the charged lepton produced in the decay is never detected.

Conclusions—Pseudoscalar meson decay experiments have been used in the past to set stringent limits on active-sterile mixing. However, it is conceivable that this mixing could be so tiny that it would be irrelevant for these decays. If right-handed currents exist, as predicted by LRSM, right-handed neutrinos can be produced in meson leptonic decays by a right-handed current, mediated by a vector boson W_R. In this context, we have used low energy pseudoscalar meson leptonic decay data to constrain for the first time the mass m_{W_R}.

Our limits are valid for degenerate right-handed neutrinos with mass in the range $50 < m_N/\text{MeV} < 2000$ and easily adapted for other cases. In this whole mass range they are at least as good as the LHC limits [66,67,72,73], but in the region $60 \lesssim m_N/\text{MeV} \lesssim 500$, they can be significantly more strict, specially due to NA62 and T2K, we get $m_{W_R} \gtrsim$ (12–19) TeV at 90% CL.

Current experiments such as ICARUS [79], MicroBooNE [80], and SBND [81] could perhaps be used to improve these limits for $m_N < m_K$ using the conventional neutrino beam. A new experiment PIONEER [82] is expected to improve in an order of magnitude the PIENU result. Belle II [83] is expected to measure $\sim 10^{11}$ single τ decays. They may be able to use $\tau \to \pi\nu_\tau$ to probe m_{W_R} up to $m_N < m_\tau - m_\pi$. The future DUNE [84,85] experiment may also improve the bounds in the region $m_N > m_K$ using production via prompt D meson and τ decays. The proposed HIKE (high-intensity kaon experiments) [86] at CERN could count with up to 6 times the NA62 beam intensity, being in position, in principle, to increase significantly the sensitivity to m_{W_R}. We intend to investigate whether these experiments can in fact do that in a future publication.

Acknowledgments—R. Z. F. is partially supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) under Contract No. 2019/04837-9, and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). C. S. F. acknowledges the support by FAPESP Contracts No. 2019/11197-6 and No. 2022/00404-3, and CNPq under Contract No. 407149/2021-0. L. P. S. L. and G. F. S. A. are fully financially supported by FAPESP under Contracts No. 2021/02283-6, No. 2022/10894-8, and No. 2020/08096-0. G. F. S. A. would like to acknowledge the hospitality of the Fermilab Theory Group. C. S. F. acknowledges support from the ICTP through the Associates Programme (2023-2028) while this work was being completed. We would like to thank P. A. N. Machado, Robert Shrock, Douglas Bryman, K. S. Babu, Bhupal Dev, and Jordy de Vries for careful reading and useful comments.

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