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New limits on W_R from meson decays

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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 $50 < m_N/\text{MeV} < 1900$ one can constraint $m_{W_R} \lesssim (4-19)$ TeV at 90% CL. This provides the most stringent experimental limits on the W_R mass to date.

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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, $G_F \sim 1/\Lambda^2 \sim 10^{-5}$ GeV^{-2}, the Fermi constant. This, retrospectively, was the first indication of the need for a mediator with mass $\Lambda \sim \mathcal{O}(100$ 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 to us in the last half of century compelling evidences that neutrinos have (tiny) masses and undergo 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 they exist right-chiral neutrinos 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 corresponding 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 extensions of the SM with right-chiral currents and right-chiral neutrinos, the decay rate $\Gamma(M \to \ell N)$ can have two competing contributions [23]

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

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

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

where m_{W_L} and g_L (m_{W_R} and g_R) are the mass and coupling constant associated with the SM (new) weak interaction, and $\kappa \equiv g_R/g_L$. If $|U_{\ell N}|^2 \gg (G'_F/G_F)^2$ the mixing contribution prevails and one can use meson decays to constrain the active-sterile mixing, as has been done by several authors [24–31]. However, if $|U_{\ell N}|^2 \ll (G'_F/G_F)^2$ the right current contribution dominates and one can use these decays instead to constrain m_{W_R}. The best limits on active-sterile mixing are on U_{eN}. While they depend on m_N, in the mass range of interest the maximum value allowed by data is around $|U_{eN}|^2 \sim 10^{-7} - 10^{-9}$, which imply meson decay experiments can have a sensitivity to $m_{W_R} \sim (5-15)$ TeV. Note that this sensitivity is comparable and even surpasses the best limits on m_{W_R} we currently have from the LHC experiments $m_{W_R} < 6.4$ TeV [32, 33].

In this letter we reanalyze the results from a number of low energy meson decay experiments under the assumption of right-chiral current dominance, a situation not considered before in the literature, and that, theoretically, may manifest in left-right symmetric models (LRSM) [34–39], to derive the best experimental limits to date on m_{W_R}.

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Left-right Symmetric Models.— LRSM 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 LR symmetry [40, 41], 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 either be equal or not, depending on the discrete LR symmetry breaking scale [42].

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 [36, 43–45], that is

$$m_\nu \ = \ m_{\rm I} + m_{\rm II}. \tag{3}$$

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

$$m_\nu \ < \ 7\times 10^{-2}\,{\rm eV}\left(\frac{m_N}{1\,{\rm MeV}}\right)\left(\frac{5\,{\rm TeV}}{m_{W_R}}\right)^4 \kappa^4\,, \tag{4}$$

which can, in principle, hold for m_N in the MeV-GeV range. In a type II dominant scenario $m_\nu \sim m_{\rm II}$ since $|U_{\ell N}|^2 \sim m_I/m_N$ the mixture contribution can always be made small. 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

$$\mathcal{L}^{\rm cc}_{\rm R} = -\frac{g_R}{\sqrt{2}}[\overline{N}\, U^\dagger_{RR} \not{W}_R\, E_R + \overline{D}_R\, V^\dagger_R \not{W}_R U_R] + {\rm h.c.}\,, \tag{5}$$

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- 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 unitary mixing matrices. We will set $V_R = V_{\rm CKM}$, the same CKM mixing matrix of the SM. As shown in ref. [46], this relation holds to a very high degree in the minimal left-right model (and is exact for real bidoublet vacuum expectation values) despite the left-right symmetry being badly broken. Furthermore, to make our analysis as model-independent as possible, we will also assume all right-handed neutrinos to have the same mass m_N such that U_{RR} drops out from the calculations. If they are not degenerate in mass, the calculations will involve U_{RR} and there might be new decay channels from heavy N to lighter N, we will leave this model-dependent analysis for future work.

We can safely disregard mixing between W_R and W_L [47]. Finally, notice that by setting a limit on m_{W_R}, we are also indirectly constraining 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. Because all right-handed neutrinos of the model are degenerate in mass there is no mixing suppression in the leptonic vertex. So the rate of this process is like the one for $\Gamma(M \to \ell_L\, \nu_{\ell L})$ in the SM, except for the exchange $G_F \to G'_F$ and the correction to 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 must be taken into account. There are three types of such searches: visible (with hadrons in the final state), invisible and meson decay ratios.

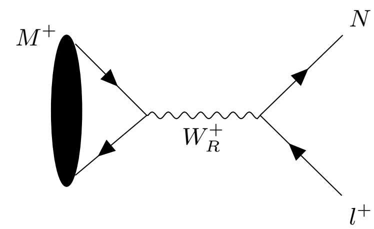

FIG. 1. Production of a right-handed neutrino N by the meson M decay mediated by the right-handed current.

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, a neutrino oscillation experiment in Japan [48]. T2K beam is produced mainly by π and K decays which result 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 has 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} protons on target (POT) in the neutrino mode and 6.29×10^{20} POT in the antineutrino mode. The ND280 is a detector located 280 m from the proton target and having three time projection chambers (TPC) as their central tracker surrounded by a calorimeter and a muon detector [49]. The main active volume is the 6.3 m^3 for gas TPC. They have considered the production modes $K^\pm \to \ell^\pm N$, with N having a lifetime sufficiently long ($\tau \gg 1\,\mu$s) so it can reach ND280, where it will subsequently decay in one of the following modes $N \to \ell^\pm \pi^\mp$, $N \to \ell^\pm \ell'^\mp \nu$, with $\ell, \ell' = e, \mu$. The main background they expected are from neutrino coherent π production in Ar ($\nu_\mu + {\rm Ar} \to \mu^- + \pi^+ + {\rm Ar}$), but they also consider other neutrino interactions in and outside the gas TPC. In Tab. II of [27] we can find the background they have 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 their background calculation (< 0.5 events). They have not observed any events in any of these modes in their data.

Only the two body production and decay modes with the same flavor charged lepton 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 reanalysing the constraints from the Big European Bubble Chamber (BEBC) [31] on heavy neutral leptons [50]. The 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 in the collision before they decay. As a result, 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, followed by other two neutrino detectors, CDHSW and CHARM. Analysis of the data collected by the BEBC experiment has 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 the T2K experiment. The total amount of data corresponds to $\sim 2 \times 10^{18}$ POT. They have observed a single event in the $N \to \mu^+\pi^-$ mode, which is consistent to their expected background of 0.6 ± 0.2 events.

Unfortunately we cannot profit from the CHARM experiment data [29] used to derive limits on active-sterile mixing produced by charm meson decays because they only consider the three body final states $N \to \ell\ell'\nu$, which cannot occur via W_R for $U_{\ell N} = 0$.

Invisible Searches.— The second class are peak search experiments. These experiments look for the existence of a heavy neutrino emitted in two body helicity suppressed meson decays $M^+ \to e^+\nu_e(N)$. The charged meson can decay either at rest or in flight, in both cases the signal $M^+ \to e^+N$ is characterized by a single final state positron, similar to the SM decay. The idea is to search for a subdominant peak in the e^+ spectrum [51, 52] due to the presence of an invisible particle of mass m_N. The peak-search procedure measures the $M^+ \to e^+N$ decay rate with respect to $M^+ \to e^+\nu_e$, the SM rate, as a function of m_N. This approach profits from major cancellations of the residual inefficiencies not fully accounted for in MC simulations but present in both signal and normalization modes. Further corrections can be accounted for by the signal selection acceptance. In the case we are considering these branching ratios are related by

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

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 $\rho_e^{MN} = [x_e + x_N - (x_e - x_N)^2]\lambda^{1/2}(1, x_e^2, x_N^2)/[x_e(1 - x_e)^2]$ 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 $\tau_N \gg 1\ \mu$s so it can be considered stable in these production-search 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 positrons, which are monocromatic ($E_{e^+} = 69.8$ 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 have 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 $E_{e+} = 4$ MeV to $E_{e+} = 56$ MeV in order to search for additional peaks.

The TINA detector [54] is an older TRIUMF experiment very similar to PIENU. It has also looked for peaks in the the positron spectrum from pion decays at rest but using a total of 1.2×10^5 e^+ events. It has lower sensitivity than PIENU, 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 SPS 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^+ are 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 $m^2_{\mathrm{miss}} = (p_K - p_{e+})^2 < 0.01\ \mathrm{GeV}^2$, where $p_K(p_{e+})$ is the kaon (positron) four-momentum. Their available data corresponds to 0.79×10^6 SPS spills recorded during 360 days of operation in 2017–2018, at a typical beam intensity of 2.2×10^{12} protons per spill. They have looked for N produced by active-sterile mixing with a lifetime exceeding 50 ns, and considering that after being produced in $K^+ \to e^+N$ decays they would be boosted by a Lorentz factor of $\mathcal{O}(100)$, so their decay into SM particles in the 156 m long volume between the start of the fiducial volume and the last detector can be neglected. They have analysed data corresponding to $N_K = (3.52 \pm 0.02) \times 10^{12}$ kaon decays in the fiducial volume. They have investigated 264 mass hypotheses, m_N, with $144 < m_N/\text{MeV} < 462$. Their dominant background is due to $K^+ \to \mu^+\nu_\mu$ followed by $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$. 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 according to ref. [30].

Meson Decay Ratios.— The third class of searches investigate the effect of N in the ratio of pseudoscalar meson leptonic decays to e and μ final states [52], constraining the ratio

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

where $R^{\text{SM}}_{e/\mu}(M) \equiv \mathcal{B}^{\text{SM}}(M \to e\,\nu_e)/\mathcal{B}^{\text{SM}}(M \to \mu\,\nu_\mu)$ and $R_{N/\nu_\ell}(M) \equiv \mathcal{B}(M \to \ell\, N)/\mathcal{B}^{\text{SM}}(M \to \ell\,\nu_\ell)$ with respect to the experimental values $R^{\text{PDG}}_{e/\mu}(\pi) = (1.2327 \pm 0.0023) \times 10^{-4}$ and $R^{\text{PDG}}_{e/\mu}(K) = (2.488 \pm 0.009) \times 10^{-5}$. Since the leading order radiative corrections do not depend on m_N [24, 56] we consider they are the same for $R_{e/\mu}$ (eq. (7)) and $R^{\text{SM}}_{e/\mu}$. We will use here the SM predictions $R^{\text{SM}}_{e/\mu}(\pi) = (1.2352 \pm 0.0001) \times 10^{-4}$ and $R^{\text{SM}}_{e/\mu}(K) = (2.477 \pm 0.001) \times 10^{-5}$ [57]. Note that in calculating R_{N/ν_ℓ} we have to take into account which decay channels will be 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 $\kappa = 1$. 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]. We have used this table to compute the expected number of events as a function of m_{W_R} and m_N simply by re-scaling the relevant channels by $(G'_F/G_F)^2$. 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. However, it remains high up to 493 MeV, partially due to high flux and background suppression [58]. 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] to include only the channels mediated by W_R and re-scaling 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 $500 < m_N/\text{MeV} < 2000$. Note, however, that there is a small (white) region for small m_{W_R} which cannot be discarded by BEBC. There the N flux is suppressed because most of these particles 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 have taken Fig. 5 [53], Fig. 3b (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 $144 < m_N/\text{MeV} \lesssim 440$.

Finally, we have used

$$\begin{aligned} R_{e/\mu}(\pi)/R^{\text{SM}}_{e/\mu}(\pi) &< \overline{R}^{(\pi)}_{e/\mu}(\text{PDG}) = 1.0017\,, \\ R_{e/\mu}(K)/R^{\text{SM}}_{e/\mu}(K) &< \overline{R}^{(K)}_{e/\mu}(\text{PDG}) = 1.012\,, \end{aligned} \tag{8}$$

where $\overline{R}^{(M)}_{e/\mu}(\text{PDG}) \equiv (R^{\text{PDG}}_{e/\mu}(M) + 2\sigma)/R^{\text{SM}}_{e/\mu}(M)$ to compute the meson decay ratio limits on Fig. 2. The $\overline{R}^{(K)}_{e/\mu}(\text{PDG})$ is dominant in the gap between PIENU and NA62 $m_N \sim 0.13$ GeV and for $m_N \lesssim 0.05$ GeV where it is the only bound applicable. In this mass range not shown in the plot, the constraint 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.

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 $50 < m_N/\text{MeV} < 2000$. In this whole mass range they are at least as good as the LHC limits [32, 33], 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% C.L.

Current experiments such as the ones in the Fermilab Short-Baseline Neutrino Program which will collect data produced by typically 10^{21} POT (ICARUS [60], MicroBooNE [61], SBND [62]) could perhaps be used to improve these limits for $m_N < m_K$ using the conventional neutrino beam, i.e. π and K leptonic decays. Belle II [63] at SuperKEKB is expected measure $\sim 10^{11}$ single τ de-

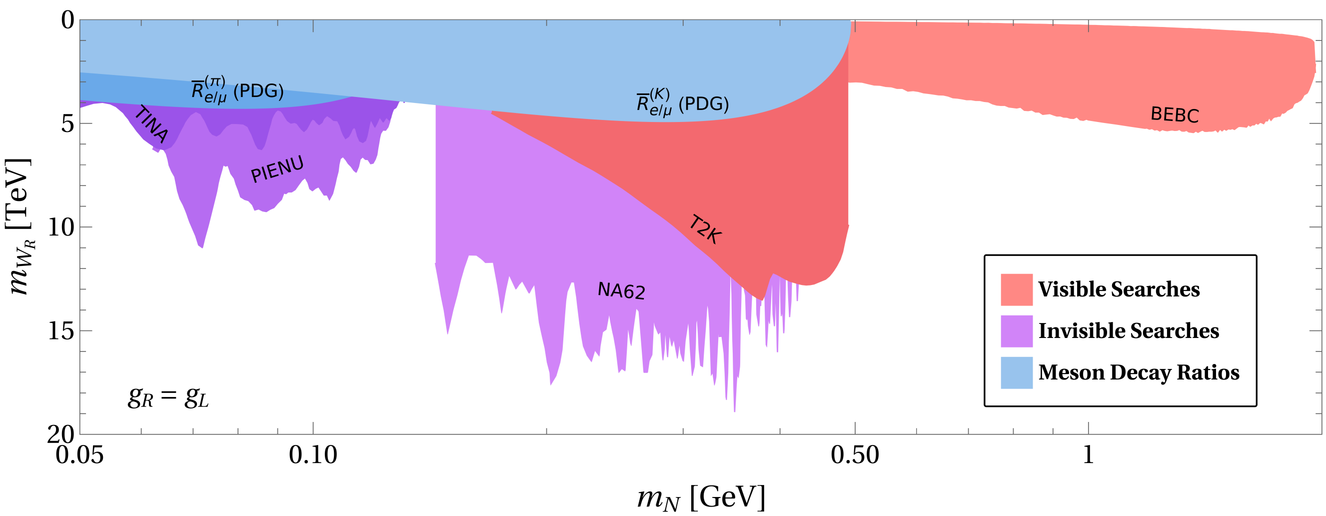

FIG. 2. Bounds on m_W as a function of m_N from visible searches (red) at T2K [27] and BEBC [31], from invisible peak searches (purple) at PIENU [53], TINA [54] and NA62 [30], as well as from π and K leptonic decay ratios (blue) [59] at 90% CL. We assume $\kappa = g_R/g_L = 1$.

cays. 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 [64, 65] neutrino oscillation 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) [66] 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.

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