Left-Right Symmetry: From the LHC to Neutrinoless Double Beta Decay

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The Large Hadron Collider has the potential to probe the scale of left-right symmetry restoration and the associated lepton number violation. Moreover, it offers the hope of measuring the right-handed leptonic mixing matrix. We show how this, together with constraints from lepton flavor violating processes, can be used to make predictions for neutrinoless double beta decay. We illustrate this connection in the case of the type-II seesaw.

More than 70 years ago Majorana [1] raised the question of whether neutrinos are "real" particles. If true, this would allow for neutrinoless double beta decay ($0\nu2\beta$) [2], a violation of lepton number with two electrons created out of "nothing." The transition amplitude is proportional to

$$\mathcal{A}_\nu \propto G_F^2 \frac{m_\nu^{ee}}{p^2}, \tag{1}$$

where m_ν^{ee} is the 1-1 element of the neutrino mass matrix m_ν and $p \approx 100$ MeV a measure of the neutrino virtuality. Present-day neutrinoless double beta experiments are probing the sub-eV region for m_ν^{ee}. There is even a claim of this process being seen, corresponding to $m_\nu^{ee} \approx 0.4$ eV [3]. On the other hand, the upper limits on the sum of neutrino masses from cosmology are rapidly progressing and recently it was argued that the two are incompatible [4]. Whether or not such a conclusion is premature today, we should consider seriously the possibility that this minimal picture will be contradicted by the next round of experiments [5].

This would imply new physics doing the job [6], whose contribution to the transition amplitude can be cast in the natural form

$$\mathcal{A}_{\text{NP}} \propto G_F^2 \frac{M_W^4}{\Lambda^5}, \tag{2}$$

where Λ is the scale of new physics. The new physics enters the game at $\Lambda \sim$ TeV, tailor-made for the Large Hadron Collider (LHC), which provides a strong motivation to pursue this line of thought.

A natural candidate for new physics is the right-handed charged current, as argued [7] in the context of left-right (LR) symmetric theories [8]. It was precisely LR symmetry that led to neutrino masses and, on top, connected them [9] to the scale of parity restoration in the context of the seesaw mechanism [9,10]. This leads to a remarkable signature of lepton number violation in the form of same

sign lepton pairs at colliders [11] in complete analogy with $0\nu2\beta$. Furthermore, with such a low scale one expects sizable rates for lepton flavor violating (LFV) processes, which are being vigorously pursued in the ongoing and planned experiments, yet another encouragement to follow the road of new physics.

Motivated by these considerations, we have performed a detailed study of the relation between the LHC, $0\nu2\beta$, and LFV, in the context of the minimal LR model with type-II seesaw. Our main point is shown in Fig. 1, where the new physics contribution is contrasted with the usual one, due to neutrino mass [12]. Since the standard contribution entails m_ν^{ee}, we use a combination of new physics parameters with the same dimension, denoted hereafter as M_N^{ee}. It depends on the mass of the right-handed charged gauge boson and on masses and mixings of the heavy right-handed neutrinos as displayed below in Eq. (12).

The striking feature which emerges is the reversed role of neutrino mass hierarchies. While in the case of neutrino mass behind neutrinoless double beta decay the normal hierarchy matters less and degeneracy is most promising, in the case of new physics it is normal hierarchy that
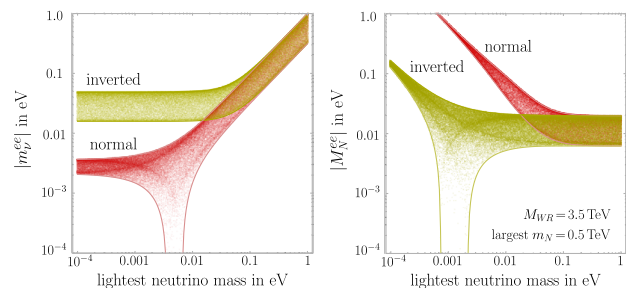

FIG. 1 (color online). The canonical contribution (left) from light neutrino mass and the new physics part (right), with $|M_N^{ee}|$ defined in Eq. (12). The mixing angles are fixed at $\{\theta_{12}, \theta_{23}, \theta_{13}\} = \{35°, 45°, 7°\}$, while the Dirac and Majorana phases vary in the interval $[0, 2\pi]$.

dominates and degeneracy matters less. This conclusion is true when the scale of new physics lies within the LHC reach [13]. In other words, the discovery of LR symmetry at the LHC would provide an additional boost for neutrino-less double beta decay searches. This is the main message of our Letter. In the following we describe the model and analyze its predictions.

The model.—The minimal LR symmetric theory is based on the gauge group $\mathcal{G}_{\mathrm{LR}} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ and a symmetry between the left and right sectors [8], which can be taken to be charge conjugation $\mathcal{C}$ (for the advantages of this choice, see [14]). Fermions are LR symmetric, $q_{L,R} = (u,d)_{L,R}$ and $\ell_{L,R} = (\nu,e)_{L,R}$, with $f_L \leftrightarrow (f_R)^c$ under $\mathcal{C}$, and the gauge couplings are $g_L = g_R \equiv g$.

The Higgs sector consists [9] of the $SU(2)_{L,R}$ triplets $\Delta_{L,R} = (\Delta^{++}, \Delta^+, \Delta^0)_{L,R}$, $\Delta_L \in (3,1,2)$, and $\Delta_R \in (1,3,2)$, which under $\mathcal{C}$ transform as $\Delta_L \leftrightarrow \Delta_R^*$. [There is also a bidoublet, which takes the usual role of the standard model (SM) Higgs doublet, and we do not discuss it here. For a recent detailed analysis of its phenomenology and limits on its spectrum, see [14].] The group $\mathcal{G}_{\mathrm{LR}}$ is broken down to the SM gauge group by $\langle \Delta_R \rangle \gg M_W$, and after the SM symmetry breaking, the left-handed triplet develops a tiny $\langle \Delta_L \rangle \ll M_W$. $\langle \Delta_R \rangle$ gives masses not only to the W_R and Z_R gauge bosons but also to the right-handed neutrinos.

The symmetric Yukawa couplings of the triplets relevant for our discussion are

$$\mathcal{L}_Y = \frac{1}{2} \ell_L \frac{M_{\nu_L}}{\langle \Delta_L \rangle} \Delta_L \ell_L + \frac{1}{2} \ell_R \frac{M_{\nu_R}}{\langle \Delta_R \rangle} \Delta_R \ell_R + \mathrm{H.c.}, \quad (3)$$

where M_{ν_L} and M_{ν_R} are Majorana mass matrices of light and heavy neutrinos. In principle, there are also Dirac Yukawa couplings connecting the two. When these tiny couplings play a negligible role, the resulting seesaw is called type II [9(b),15]. Purely for reasons of illustration, the rest of this Letter will be devoted to this appealing case. Because of $\mathcal{C}$, its main characteristic is the connection between the two neutrino mass matrices $M_{\nu_R}/\langle \Delta_R \rangle = M_{\nu_L}^*/\langle \Delta_L \rangle^*$. An immediate consequence is the proportionality of the two mass spectra

$$m_N \propto m_\nu, \quad (4)$$

where m_N stands for the masses of the three heavy right-handed neutrinos N_i, and m_ν for those of the three light left-handed neutrinos ν_i.

In this theory, there are both left- and right-handed charged gauge bosons with their corresponding leptonic interactions in the mass eigenstate basis:

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} (\bar{\nu}_L V_L^\dagger W_L e_L + \bar{N}_R V_R^\dagger W_R e_R) + \mathrm{H.c.} \quad (5)$$

Since the charged fermion mass matrices are symmetric (due to the symmetry under $\mathcal{C}$), one readily obtains a connection (up to complex phases, irrelevant to our discussion) between the right-handed and the left-handed (PMNS) leptonic mixings matrices

$$V_R = V_L^*. \quad (6)$$

LHC signatures or how to check type II.—The LHC offers an exciting possibility of seeing directly both LR symmetry restoration and lepton number violation. The point is that once produced, W_R can decay into a charged lepton and a right-handed neutrino which in turn decays into a second charged lepton and two jets. Being Majorana particles, they decay into both leptons and antileptons; hence one obtains same sign lepton pairs, signaling the violation of lepton number [11]. It turns out that in this way, the LHC running at 14 TeV can reach $M_{W_R} \lesssim 2.1(4)$ TeV with a luminosity of $0.1(30)$ fb^{-1} [13]. Since in the minimal model there is a rough bound of about $M_{W_R} \gtrsim 2.5$ TeV [14], in order to be conservative in our analysis we choose a representative point $M_{W_R} = 3.5$ TeV together with $m_N^{\mathrm{heaviest}} = 0.5$ TeV.

The flavor dependence of V_R can be determined precisely through these same sign lepton pair channels; thus, Eq. (6) may be falsified in the near future. Furthermore, if the LHC will measure the heavy right-handed masses in the same process, one could perform crucial consistency checks of type-II seesaw, such as

$$\frac{m_{N_2}^2 - m_{N_1}^2}{m_{N_3}^2 - m_{N_1}^2} = \frac{m_{\nu_2}^2 - m_{\nu_1}^2}{m_{\nu_3}^2 - m_{\nu_1}^2} \simeq \pm 0.03. \quad (7)$$

Here, the right-hand side is determined by oscillation data and the $\pm$ sign corresponds to the normal or inverted hierarchy case. Another eloquent relation among the mass scales probed in cosmology, atmospheric neutrino oscillations, and the LHC is

$$m_{\mathrm{cosm}} = \sum_i m_{\nu_i} \simeq 50 \text{ meV} \times \frac{\sum_i m_{N_i}}{\sqrt{|m_{N_3}^2 - m_{N_2}^2|}}. \quad (8)$$

The bottom line is that the LHC can determine the right-handed neutrino masses and mixings and allow one to make predictions studied below. The type-II seesaw chosen here is only a transparent illustration of how these connections take place.

Lepton flavor violation.—Lepton flavor violation in LR symmetric theories has been studied in the past [16]. What is new in our analysis is the connection with the LHC and especially the quantitative implications for $0\nu2\beta$.

There are various LFV processes providing constraints on the masses of right-handed neutrinos and doubly charged scalars illustrated in Fig. 2. It turns out that $\mu \to 3e$, induced by the doubly charged bosons Δ_L^{++} and Δ_R^{++}, provides the most relevant constraint and so we give the corresponding branching ratio

$$\mathrm{BR}_{\mu \to 3e} = \frac{1}{2} \left(\frac{M_W}{M_{W_R}} \right)^4 \left| V_L \frac{m_N}{m_\Delta} V_L^T \right|_{e\mu}^2 \left| V_L \frac{m_N}{m_\Delta} V_L^T \right|_{ee}^2, \quad (9)$$

where $1/m_\Delta^2 \equiv 1/m_{\Delta_L}^2 + 1/m_{\Delta_R}^2$. The current experimental limit is $\mathrm{BR}(\mu \to 3e) < 1.0 \times 10^{-12}$ [17].
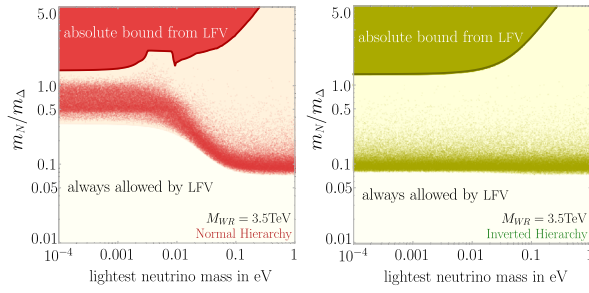
FIG. 2 (color online). Combined bounds on $m_N^{\text{heaviest}}/m_\Delta$ from LFV. The dots show the (most probable) upper bounds resulting for different mixing angles and phases (varied, respectively, in the intervals $\{\theta_{12}, \theta_{23}, \theta_{13}\} = \{31°-39°, 37°-53°, 0°-13°\}$ and $[0, 2\pi]$). The dark line is the absolute upper bound. The plot scales as $M_{W_R}/3.5$ TeV.

The LFV transition rates become negligible when the masses M_{W_R} and m_Δ become larger than about 100 TeV. We are interested in LHC accessible energies, in which case the smallness of the LFV is governed by the ratio m_N/m_Δ, in addition to mixing angles and phases. In Fig. 2, we plot the upper bound on this quantity varying the mixing angles and phases (LFV plots also take into account $\mu \to e$ conversion in Au nuclei, $\mu \to e\gamma$ and rare τ decays such as $\tau \to 3\mu$, etc. [18]). An immediate rough consequence seems to follow: $m_N^{\text{heaviest}}/m_\Delta < 0.1$ in most of the parameter space. However, the strong dependence on angles and phases allows this mass ratio up to about one in the case of hierarchical neutrino spectra, thus allowing both N and $\Delta_{L,R}$ to be light. This serves as an additional test at colliders of type-II seesaw used here. For degenerate neutrinos, unfortunately, no strict constraint arises: see again Fig. 2.

Neutrinoless double beta decay.—We neglect the small neutrino Dirac Yukawa couplings, the tiny W_L-W_R mixing of $\mathcal{O}(M_W/M_{W_R})^2 \lesssim 10^{-3}$, and contributions coming from the bidoublet through the charged Higgs component, because of its heavy mass of at least 10 TeV [14]. We are left with an effective Hamiltonian with two extra contributions (the one from the left-handed triplet being completely negligible)

$$\mathcal{H}_{\text{NP}} = G_F^2 V_{Rej}^2 \left[\frac{1}{m_{N_j}} + \frac{2m_{N_j}}{m_{\Delta_R^{++}}^2}\right] \frac{M_W^4}{M_{W_R}^4} J_{R\mu} J_R^\mu \bar{e}_R e_R^c, \quad (10)$$

where $J_{R\mu}$ is the right-handed hadronic current. Making use of the LFV constraint $m_N/m_\Delta \ll 1$ one can neglect the Δ_R^{++} contribution and write the total decay rate as

$$\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = G \cdot \left|\frac{\mathcal{M}_\nu}{m_e}\right|^2 \left(|m_\nu^{ee}|^2 + \left|p^2 \frac{M_W^4}{M_{W_R}^4} \frac{V_{Rej}^2}{m_{N_j}}\right|^2\right), \quad (11)$$

where G is a phase space factor, $\mathcal{M}_\nu$ is the nuclear matrix element relevant for the light neutrino exchange, while p measures the neutrino virtuality and accounts also for the ratio of matrix elements of heavy and light neutrinos. These quantities have been calculated and [19,20] are reported in Table I for some interesting nuclei.

To illustrate the impact of the Dirac and Majorana phases on the total decay rate, we plot in the left frame of Fig. 1 the well-known absolute value of m_ν^{ee}, while the corresponding effective right-handed counterpart for the type-II seesaw used here,

$$M_N^{ee} = p^2 \frac{M_W^4}{M_{W_R}^4} \frac{V_{Lej}^2}{m_{N_j}}, \quad (12)$$

is shown in the right frame. The plot was made using Eqs. (4) and (6), with $p = 190$ MeV and taking the entire range of V_L to be allowed by LFV (see Fig. 2.)

The total $0\nu2\beta$ rate is governed by the effective mass parameter

$$|m_{\nu+N}^{ee}| = (|m_\nu^{ee}|^2 + |M_N^{ee}|^2)^{1/2} \quad (13)$$

that supersedes the standard matrix element m_ν^{ee} in the parameter space accessible to the LHC. In Fig. 3, we show $|m_{\nu+N}^{ee}|$ as a function of the lightest neutrino mass. We have already stressed in the introduction the reversed role of the neutrino mass hierarchies. In the case of the right-handed contribution, the normal hierarchy prevails over the inverted in wide regions of the parameter space; for both hierarchies, new physics can win over the neutrino mass as the source of $0\nu2\beta$. Moreover, Fig. 3 shows that there is no more room for a vanishing transition rate, as in Fig. 1. On the upper horizontal axis of Fig. 3 we also display the lightest of the heavy neutrinos. As one can see, the range of m_N^{lightest} is easily below 100 GeV which would lead to interesting displaced vertices at the LHC [14].

In short, $0\nu2\beta$ may be naturally governed by new physics and thus be disjoint from light neutrino masses. This is only in apparent contradiction with the often stated result [21], according to which a nonvanishing $0\nu2\beta$ implies a nonvanishing neutrino Majorana mass. Although true as a generic statement, on a quantitative level it has no practical purpose, as the case exposed here demonstrates explicitly.

TABLE I. Nuclear factors relevant for $0\nu2\beta$.

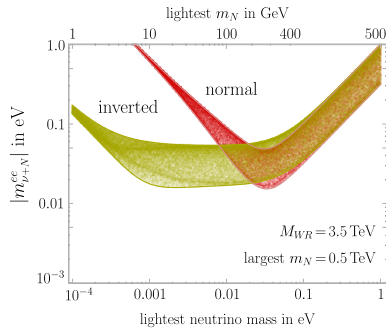| Reference	Nucleus	^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe	^{150}Nd
[19]	$G|\mathcal{M}|^2 \times 10^{13}$ yr	1.1	4.3	2.0	5.3	1.2	75.6
	$p/$MeV	190	186	189	180	280	210
[20]	$G|\mathcal{M}|^2 \times 10^{13}$ yr	2.7	⋯	15.2	12.2	⋯	⋯
	$p/$MeV	184	⋯	193	198	⋯	⋯

FIG. 3 (color online).   Effective $0\nu2\beta$ mass parameter $|m^{ee}_{\nu+N}|$, a measure of the total $0\nu2\beta$ rate including contributions from both left and right currents.

Another example was provided by the minimal supersymmetric standard model [22].

Discussion and outlook.—In this Letter we have shown how the minimal LR symmetric theory offers a deep connection between high energy collider physics and low energy processes such as neutrinoless double beta decay and lepton flavor violation. The crucial point is lepton number violation which at the LHC would reveal itself through same sign dileptons produced from the decay of a heavy right-handed neutrino. The different flavor channels will be a probe of the right-handed mixing matrix, allowing us to test the type-II seesaw hypothesis in the near future.

At the same time, the low scale of LR symmetry implies a sizable contribution to the neutrinoless double beta decay rate. The standard hypothesis that this transition is dominated by the Majorana mass of light neutrinos may lead to a tension between oscillations and measurements of the absolute neutrino mass. Not only does the alternative hypothesis permit wider possibilities, such as small neutrino masses with normal hierarchy ordering and large rate for the neutrinoless double beta decay, but much more interestingly it has a real chance of being tested at the LHC.

Measurements of heavy neutrinos at the LHC can easily invalidate the specific version of the model, requiring, e.g., abandoning $\mathcal{C}$ symmetry and/or type-II seesaw, and replacing our hypotheses on m_N and V_R [Eqs. (4) and (6)] with the experimental results. Whereas this would imply quantitative changes of our results, it would not change our main conclusion that the possible LHC findings will be crucial for the interpretation of the neutrinoless double beta decay.

We are grateful to A. Melfo for help and encouragement throughout this work and collaboration on related issues. We thank B. Bajc, S. T. Petcov, and Y. Zhang for useful discussions, and Y. Zhang for careful reading of the manuscript. F. N. and F. V. thank ICTP for hospitality during the initial stages of this work.

[1] E. Majorana, Nuovo Cimento **14**, 171 (1937).
[2] G. Racah, Nuovo Cimento **14**, 322 (1937); W. H. Furry, Phys. Rev. **56**, 1184 (1939).
[3] H. V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B **586**, 198 (2004); H. V. Klapdor-Kleingrothaus and I. V. Krivosheina, Mod. Phys. Lett. A **21**, 1547 (2006).
[4] G. L. Fogli *et al.*, Phys. Rev. D **78**, 033010 (2008); S. Hannestad *et al.*, J. Cosmol. Astropart. Phys. 08 (2010) 001.
[5] C. Arnaboldi *et al.* (CUORE Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **518**, 775 (2004); S. Schonert *et al.* (GERDA Collaboration), Nucl. Phys. B, Proc. Suppl. **145**, 242 (2005); *Measurements of Neutrino Mass*, Enrico Fermi School Vol. CLXX, edited by C. Brofferio, F. Ferroni, and F. Vissani (IOS Press, Amsterdam, 2009).
[6] G. Feinberg and M. Goldhaber, Proc. Natl. Acad. Sci. U.S.A. **45**, 1301 (1959); B. Pontecorvo, Phys. Lett. **26B**, 630 (1968).
[7] R. Mohapatra and G. Senjanović, Phys. Rev. D **23**, 165 (1981).
[8] J. C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974); R. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 2558 (1975); G. Senjanović and R. Mohapatra, Phys. Rev. D **12**, 1502 (1975); G. Senjanović, Nucl. Phys. **B153**, 334 (1979).
[9] (a) P. Minkowski, Phys. Lett. **67B**, 421 (1977); (b) R. Mohapatra and G. Senjanović, Phys. Rev. Lett. **44**, 912 (1980).
[10] T. Yanagida, *Workshop on Unified Theories and Baryon Number in the Universe*, edited by A. Sawada and A. Sugamoto (KEK, Tsukuba, 1979); S. Glashow, *Quarks and Leptons, Cargèse 1979*, edited by M. Lévy (Plenum, New York, 1980); M. Gell-Mann *et al.*, *Supergravity Stony Brook Workshop, New York, 1979*, edited by P. Van Niewenhuizen and D. Freeman (North Holland, Amsterdam, 1980).
[11] W.-Y. Keung and G. Senjanović, Phys. Rev. Lett. **50**, 1427 (1983).
[12] F. Vissani, J. High Energy Phys. 06 (1999) 022.
[13] A. Ferrari *et al.*, Phys. Rev. D **62**, 013001 (2000); S. Gninenko *et al.*, Phys. At. Nucl. **70**, 441 (2007).
[14] A. Maiezza, M. Nemevšek, F. Nesti, and G. Senjanović, Phys. Rev. D **82**, 055022 (2010); Y. Zhang *et al.*, Nucl. Phys. **B802**, 247 (2008).
[15] M. Magg and C. Wetterich, Phys. Lett. **94B**, 61 (1980); G. Lazarides *et al.*, Nucl. Phys. **B181**, 287 (1981).
[16] V. Cirigliano *et al.*, Phys. Rev. D **70**, 075007 (2004); Phys. Rev. Lett. **93**, 231802 (2004).
[17] U. Bellgardt *et al.* (SINDRUM Collaboration), Nucl. Phys. **B299**, 1 (1988).
[18] W. H. Bertl *et al.* (SINDRUM II Collaboration), Eur. Phys. J. C **47**, 337 (2006); M. L. Brooks *et al.* (MEGA Collaboration), Phys. Rev. Lett. **83**, 1521 (1999); Y. Miyazaki *et al.* (Belle Collaboration), Phys. Lett. B **660**, 154 (2008); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **99**, 251803 (2007).
[19] M. Hirsch *et al.*, Phys. Lett. B **374**, 7 (1996).
[20] F. Šimkovic, J. Vergados, and A. Faessler, Phys. Rev. D **82**, 113015 (2010).
[21] J. Schechter and J. W. F. Valle, Phys. Rev. D **25**, 2951 (1982).
[22] For a recent explicit study, see B. C. Allanach, C. H. Kom, and H. Pas, Phys. Rev. Lett. **103**, 091801 (2009).