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Right-handed lepton mixings at the LHC

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Abstract: We study how the elements of the leptonic right-handed mixing matrix can be determined at the LHC in the minimal Left-Right symmetric extension of the standard model. We do it by explicitly relating them with physical quantities of the Keung-Senjanović process and the lepton number violating decays of the right doubly charged scalar. We also point out that the left and right doubly charged scalars can be distinguished at the LHC, without measuring the polarization of the final state leptons coming from their decays.

Keywords: Beyond Standard Model, Neutrino Physics, CP violation

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Contents

1 Introduction

The Left-Right symmetric theory is based on the gauge group $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ [1–5], times a Left-Right symmetry that may be generalized parity ($\mathcal{P}$) or charge conjugation ($\mathcal{C}$) (for reviews see [6–8]). It introduces three new heavy gauge bosons W_R^+, W_R^-, Z_R and the heavy neutrino states N. In this model, the maximally observed parity non conservation is a low energy phenomenon, which ought to disappear at energies above the W_R mass. Furthermore, the smallness of neutrino masses is related to the near maximality of parity violation [9–11], through the seesaw mechanism [9–14].

Theoretical bounds on the Left-Right scale were considered in the past. The small $K_L - K_R$ mass difference gives a lower bound on the Left-Right-scale of around 3 TeV in the minimal model [15].[1] More recently in [18], an updated study and a complete gauge invariant computation of the K_L, K_S and B_d, B_s meson parameters, gives $m_{W_R} > 3.1(2.9)$ TeV for $\mathcal{P}(\mathcal{C})$. In [19] it is claimed that for parity as the Left-Right symmetry, the θ_{QCD} parameter, together with K-meson mass difference Δm_K, push the mass of W_R up to 20 TeV [18, 19]; however this depends on the UV completion of the theory. Direct LHC searches, on the other hand, gives in some channels a lower bound of around 3 TeV [20].

It turns out that there exists [21] an exciting decay of W_R into two charged leptons and two jets ($W_R \to l + N \to ll + jj$). We refer to it as the Keung-Senjanović (KS) process. This process has a small background and no missing energy. It gives a clean signal for the W_R production at LHC, as well as probing the Majorana masses of the heavy neutrinos. Since there is no missing energy in the decay, the reconstruction of the W_R and N invariant masses is possible. If true, the Majorana mass of N will lead to the decay of the heavy

[1] For recent updates see references [16, 17].

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neutrino into a charged lepton and two jets ($N \to l + jj$), with the same probability of decaying into a lepton or antilepton. Recently CMS gives an excess in the ee-channel of 2.8σ for this particular process at $m_{eejj} \approx 2.1$TeV [20]. Several works have been proposed [22–31] in order to explain this excess and the conclusion was that it would need a higher Left-Right symmetry breaking scale, or a more general mixing scenario with pseudo-Dirac heavy neutrinos. Next LHC run will be crucial to establish or discard this excess.

The production of W_R is ensured at the LHC because in the quark sector the left and right mixing matrices are related. For $\mathcal{C}$ as the Left-Right symmetry, the mixing angles are exactly equal, therefore the production rate of W_R is the same as the one of W. For $\mathcal{P}$ the situation is more subtle and needed an in-depth study. Finally in [32] a simple analytic expression valid in the entire parameter space was derived for the right-handed quark mixing matrix. It turns out that despite parity being maximally broken in nature, the Right and Left quark mixing matrices end up being very similar. Moreover the hypothesis of equal mixing angles can be tested at the LHC by studying the hadronic decays of W_R [34].

In the Leptonic sector the connection between the Left and Right leptonic mixing matrices goes away, since light and heavy neutrino masses are different. For $\mathcal{C}$ as the Left-Right symmetry, the Dirac masses of neutrinos are unambiguously determined in terms of the heavy and light neutrino masses [35]. Light neutrino masses are probed by low energy experiments, whereas the ones of the heavy neutrinos can be determined at the LHC. This is why the precise determination of the right-handed leptonic mixing matrix, the main topic of this work, is of fundamental importance.

We focus on the determination of the elements of the leptonic mixing matrix V_R at the LHC, through the KS process and the decays of the doubly-charged scalar δ_R^{++} belonging to the SU$(2)_R$ triplet. We point out that these two processes are not sensitive to three of the phases appearing in V_R, unlike electric dipole moments of charged leptons.

The rest of this paper is organized as follows. In section 2 we give a brief description of the model and the main relevant interactions for our purposes. In section 3 we show the determination of the three mixing angles and the "Dirac" type phase appearing in V_R. We do it in terms of physical observables in the KS process. We also show for $\mathcal{C}$ as the Left-Right symmetry, how the branching ratios of the doubly charged scalar δ_R^{++} into e^+e^+, $e^+\mu^+$ and $\mu^+\mu^+$ can be used to determine the Majorana type phases. We consider for illustration the type II see-saw dominance and put some representative values for the "Dirac" phase, the lightest and the heaviest right-handed neutrino masses. Finally, we also show that the doubly charged scalars δ_L^{++} and δ_R^{++} may be distinguished at the LHC, without measuring the polarization of the charged leptons coming from their decays.

2 The minimal Left-Right symmetric model

The minimal Left-Right symmetric model [1–5] is based on the gauge group $\mathcal{G} = \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$, with an additional discrete symmetry that may be generalized parity ($\mathcal{P}$) or charge conjugation ($\mathcal{C}$). Quarks and leptons are assigned to be doublets in the following irreducible representations of the gauge group:

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L : \left(2, 1, \frac{1}{3}\right), \qquad q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R : \left(1, 2, \frac{1}{3}\right), \tag{2.1}$$

$$L_L = \begin{pmatrix} \nu \\ l \end{pmatrix}_L : (2, 1, -1), \qquad L_R = \begin{pmatrix} N \\ l \end{pmatrix}_R : (1, 2, -1). \tag{2.2}$$

N represents the new heavy neutrino states, whose presence play a crucial role in explaining the smallness of the neutrino masses on the basis of the see-saw mechanism.

The Higgs sector sector [9, 10] consists in one bidoublet Φ, in the (2,2,0) representation of $\mathcal{G}$ and two scalar triplets Δ_L and Δ_R, belonging to (3,1,2) and (1,3,2) representation respectively

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \quad \Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}. \tag{2.3}$$

Under the discrete left-right symmetry the fields transform as follows:

$$\mathcal{P} : \begin{cases} \mathcal{P} f_L \mathcal{P}^{-1} = \gamma_0 f_R \\ \mathcal{P}\Phi\mathcal{P}^{-1} = \Phi^\dagger \\ \mathcal{P}\Delta_{(L,R)}\mathcal{P}^{-1} = -\Delta_{(R,L)} \end{cases} \qquad \mathcal{C} : \begin{cases} \mathcal{C} f_L \mathcal{C}^{-1} = C(\bar{f}_R)^T \\ \mathcal{C}\Phi\mathcal{C}^{-1} = \Phi^T \\ \mathcal{C}\Delta_{(L,R)}\mathcal{C}^{-1} = -\Delta^*_{(R,L)} \end{cases} \tag{2.4}$$

where γ_μ ($\mu = 0, 1, 2, 3.$) are the gamma matrices and C is the charge conjugation operator.

Lepton masses are due to the following Yukawa interactions (once the Higgs fields take their v.e.v along their neutral components)

$$\begin{aligned} \mathcal{L}_Y = {} & \bar{L}_L(Y_\Phi \Phi + \tilde{Y}_\Phi \tilde{\Phi}) L_R + \frac{1}{2}(L_L^T C i\sigma_2 Y_{\Delta_L} \Delta_L L_L \\ & + L_R^T C i\sigma_2 Y_{\Delta_R} \Delta_R L_R) + h.c., \end{aligned} \tag{2.5}$$

where $\tilde{\Phi} = \sigma_2 \Phi^* \sigma_2$, σ_2 being the Pauli matrix.

Invariance of the Lagrangian under the Left-Right symmetry requires

$$\mathcal{P} : \begin{cases} Y_{\Delta_{R,L}} = Y_{\Delta_{L,R}} \\ Y_\Phi = Y_\Phi^\dagger \\ \tilde{Y}_\Phi = \tilde{Y}_\Phi^\dagger \end{cases}, \quad \mathcal{C} : \begin{cases} Y_{\Delta_{R,L}} = Y^*_{\Delta_{L,R}} \\ Y_\Phi = Y_\Phi^T \\ \tilde{Y}_\Phi = \tilde{Y}_\Phi^T \end{cases} \tag{2.6}$$

The v.e.v's of the Higgs fields may be written as [11]

$$\langle \Phi \rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix}. \tag{2.7}$$

$$\langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \qquad \langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix} \tag{2.8}$$

where $v_L \ll v_1^2 + v_2^2 \ll v_R^2$ and the neutrino masses take the see-saw form [10]

$$M_N = Y_{\Delta_R}^* v_R, \tag{2.9}$$

$$M_\nu = Y_{\Delta_L} v_L e^{i\theta_L} - M_D^\dagger \frac{1}{M_N} M_D^*, \tag{2.10}$$

$$M_D = v_1 Y_\Phi + \tilde{Y}_\Phi v_2 e^{-i\alpha} \tag{2.11}$$

The charged lepton mass matrix is

$$M_l = Y_\Phi v_2 e^{i\alpha} + \tilde{Y}_\Phi v_1 \tag{2.12}$$

α is called the "spontaneous" CP phase. All the physical effects due to θ_L, can be neglected, since this phase is always accompanied by the small v_L.

As usual, the mass matrices can be diagonalized by the bi-unitary transformations

$$\begin{aligned} M_l &= U_{lL} m_l U_{lR}^\dagger, & M_D &= U_{DL} m_D U_{DR}^\dagger, \\ M_\nu &= U_\nu^* m_\nu U_\nu^\dagger, & M_N &= U_N^* m_N U_N^\dagger, \end{aligned} \tag{2.13}$$

where m_l, m_ν and m_N are diagonal matrices with real, positive eigenvalues.

In the mass eigenstate basis the flavor changing charged current Lagrangian is

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} (\bar{\nu}_L V_L^\dagger \not{W}_L l_L + \bar{N}_R V_R^\dagger \not{W}_R l_R) + h.c., \tag{2.14}$$

V_L and V_R are the left and right leptonic mixing matrices respectively

$$V_L = U_{lL}^\dagger U_\nu, \tag{2.15}$$

$$V_R = U_{lR}^\dagger U_N^*. \tag{2.16}$$

We may use the freedom of rephasing the charged lepton fields to remove three unphysical phases from V_L, which ends up having 3 mixing angles and 3 phases, namely one Dirac and two Majorana phases. On the other hand since the freedom of rephasing the charged lepton is already used for V_L, its right-handed analogue — the leptonic mixing matrix V_R — is a general 3×3 unitary matrix and may be therefore parametrized by 3 mixing angles and 6 phases. As it is well known, the mixing angles of V_L mixing matrix are probed by low energy experiments. Instead we focus in the precise determination of the mixing angles and phases of its right-handed analogue V_R at hadron colliders. This matrix has in general 3 different angles and 6 phases — as discussed above — and we write it in the form $V_R = K_e \hat{V}_R K_N$, where $K_e = \mathrm{diag}(e^{i\phi_e}, e^{i\phi_\mu}, e^{i\phi_\tau})$, $K_N = \mathrm{diag}(1, e^{i\phi_2}, e^{i\phi_3})$ and

$$\hat{V}_R = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13} \\ -s_{12}c_{23}e^{i\delta} - c_{12}s_{13}s_{23} & c_{12}c_{23}e^{i\delta} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23}e^{i\delta} - c_{12}s_{13}c_{23} & -c_{12}s_{23}e^{i\delta} - s_{12}s_{13}c_{23} & c_{13}c_{23} \end{pmatrix}, \tag{2.17}$$

$s_{\alpha\beta}$ is the short-hand notation for $\sin\theta_{\alpha\beta}$ $(\alpha, \beta = 1, 2, 3)$. The next relevant interactions for our discussion are the ones between the charged leptons and the doubly charged scalars

$$\mathcal{L}_\Delta = \frac{1}{2} l_R^T C Y'_{\Delta_R} \delta_R^{++} l_R + \frac{1}{2} l_L^T C Y'_{\Delta_L} \delta_L^{++} l_L + h.c., \tag{2.18}$$

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$$Y'_{\Delta_R} = \frac{g}{m_{W_R}} V_R^* m_N V_R^\dagger. \tag{2.19}$$

If $\mathcal{C}$ is the left-right symmetry, is easy to see from eqs. (2.4) and (2.5) that [6–8]

$$Y'_{\Delta_L} = (Y'_{\Delta_R})^*. \tag{2.20}$$

For parity ($\mathcal{P}$) the situation is different since for a non-zero spontaneous phase the charged lepton masses are not hermitian. Then after the symmetry breaking, one would expect that the left and right Yukawa interactions with the doubly-charged scalar are not the same. It turns out that for right-handed neutrinos masses accessible at the LHC, the charged lepton mass matrices end up being almost hermitian [36]. Let us notice that it implies that Yukawa couplings of the doubly charge scalars must satisfy

$$Y'_{\Delta_L} = S_l Y'_{\Delta_R} S_l + i \tan\beta \sin\alpha (R^* Y'_{\Delta_R} S_l + S_l Y'_{\Delta_R} R^\dagger) + \mathcal{O}\left[(\tan\beta\sin\alpha)^2\right] \tag{2.21}$$

with

$$(R)_{ij} = \frac{(M'_D)_{ij}}{(m_l)_i + (m_l)_j} - \frac{1}{2}\tan\beta e^{-i\alpha}(S_l)_{ij} \tag{2.22}$$

where S_l is a 3×3 matrix with $\pm$ signs in the diagonal entries and zero otherwise, $M'_D = U_{lL}^\dagger M_D U_{lR}$ and $\beta \equiv v_2/v_1$. This is obtained in analogy to the approach used for the quark mixing matrix in [32, 33], where it is also shown that $\tan 2\beta \sin\alpha \lesssim 2m_b/m_t$. Therefore one can safely assume that $Y'_{\Delta_L} \simeq Y'_{\Delta_R}$ as a leading order approximation in the most interesting scenario.

Notice that (2.19) depends on the Majorana phases. Therefore the decay rates of δ_R^{++} into two leptons in the final state depend in a CP-even way on the Dirac and Majorana phases.

3 Determination of the right-handed leptonic mixing matrix

In this section we show how the three angles θ_{12},θ_{23},θ_{13} and the Dirac phase δ, appearing in V_R are all expressed in term of physical observables at the LHC. More precisely, we find analytic expressions relating the elements of $\hat{V}_R$ with some physical branching ratios of the KS process. As for the Majorana phases we point out that they can be obtained through the decays of the doubly charged scalar. Moreover these measurements could serve as a cross-checking for the model.

3.1 Keung-Senjanović process

We begin our analysis by considering the KS process. It has a clean signal with almost no background that consists in two leptons and two jets in the final state. This process has the striking features of no missing energy in the final state and the amplification by the W_R resonance. Measuring the energy and momenta of the final particles it allows the full reconstruction of the masses of the W_R and the heavy neutrino N. Studies of this process were performed in the past [37–41], with the conclusion that W_R can be discovered at the LHC with a mass up to $\simeq 6\,\text{TeV}$, masses for the right-handed neutrinos of the order $m_N \simeq$

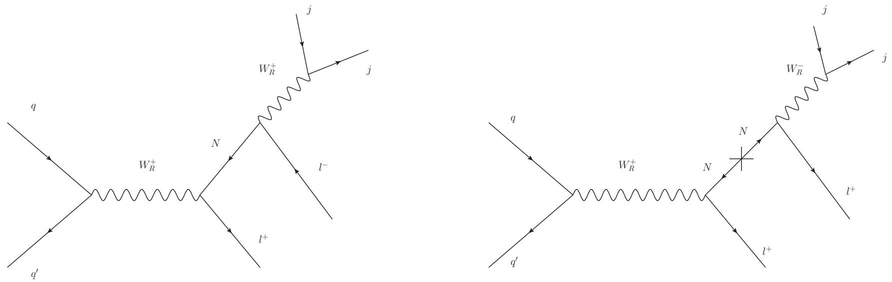

Figure 1. Keung-Senjanović process in both opposite-sign leptons (Left) and the lepton-number-violating same-sign leptons in the final state (Right).

100GeV- 1TeV for 300 fb^{-1} of integrated luminosity. In [42, 43] completed studies of the W_R production and decays at the LHC were done. They gave special emphasis to the chiral couplings of the W_R with initial and final state quarks as well as the final state leptons. They showed that it is possible to determine (by studying angular correlations and asymmetries between the participating particles) the chiral properties of W_R and the fermions.

The KS process offers also the possibility of observing both the restoration of the Left-Right symmetry and the Majorana nature of neutrinos at colliders (see figure 1). The latter implies the equality between the decay rates in the same-sign and the opposite-sign leptons in the final state [21].

Once W_R is produced on-shell, it decays into a lepton and the heavy neutrino N. For W_R boson mass bigger than the masses of the heavy neutrinos N_α (namely, $m_N < m_{W_R}$) where $\alpha = 1, 2, 3$, the decay rate of $W_R \to l_i l_k jj$ is (no summation over repeated indices)

$$\Gamma(W_R^+ \to l_i^+ l_k^+ jj) = \sum_{qq'} \Gamma(W_R^+ \to l_i^+ l_k^+ qq') = \sum_{qq'} \Gamma(W_R^+ \to l_i^+ N_\alpha) \mathrm{Br}(N_\alpha \to l_k^+ qq'), \quad (3.1)$$

where $i, k = e, \mu, \tau$ and "Br" denotes the branching ratio into a given channel. A comment here is in order, we assume that the electron produced together with W_R may be distinguished from the electron coming from the decay of the heavy neutrino N. For instance, in [37, 43] it is shown that this distinction may be done using the appropriate kinematical variable. More precisely in [37] they assumed that the electron with the lowest value of the quantity $m_N^{\rm rec} - m_{\rm inv}(ejj)$ comes from the decay of the heavy neutrino, where $m_N^{\rm rec}$ and $m_{\rm inv}(ejj)$ are the reconstructed mass of the heavy neutrino and the invariant mass of the ejj system respectively. This distinction turns out to be crucial for it allows to measure the polarization effects of the leptonic decays of the W_R boson. Notice that when the heavy neutrino N decays through m_D or into left-handed charged leptons [35] and/or in the form of displaced vertex at the LHC [44] the distinction becomes more apparent. In the case when the two leptons are indistinguishable, there is another diagram that contributes in the amplitude giving a net factor of two in the probability — since the phase space is reduced by a factor of two as well. Conversely for two different leptons there is a factor of two in the probability since both contributions sum up incoherently. The bottom line is that amount to adding a term in eq. (3.1) with $i \leftrightarrow k$. On the other hand, since we shall consider ratios of cross sections, our results are unaffected.

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Notice that if the heavy neutrino masses are not degenerate, in general the KS process is sensitive only to the Dirac type phase δ. In this case both lepton number conserving and lepton number violating channels give the same results. The partonic processes are illustrated in figure 1.

For degenerate heavy neutrino masses, one may easily see from the same-sign leptons in the final state, that there is a CP-even dependence on the phases in K_N. Notice that this channel breaks the total lepton number, then is clear that we should have some dependence on the Majorana phases. In the case of at least two degenerate heavy neutrino masses, it is in principle possible to construct CP-odd, triple-vector-product asymmetries with three momenta or any mixture of momenta and spin for the participating particles.

From eq. (2.14) we find that the decay rate of $W_R^+ \to l_i^+ N_\alpha$ is (in the rest frame of the W_R boson)

$$\Gamma(W_R^+ \to l_i^+ N_\alpha) = \frac{g^2}{8\pi} |(V_R^\dagger)_{\alpha i}|^2 \frac{|\vec{p}_2^{\alpha}|^2}{m_{W_R}^2} \left[\frac{|\vec{p}_2^{\alpha}|}{3} + E_2^\alpha \right], \tag{3.2}$$

$\vec{p}_2^{\alpha}$ is the momentum of the right-handed neutrino N_α. E_2^α is the energy of N_α and $\vec{p}_2^{\alpha}$ is such that

$$|\vec{p}_2^{\alpha}| + \sqrt{|\vec{p}_2^{\alpha}|^2 + m_{N_\alpha}^2} = m_{W_R}. \tag{3.3}$$

the 3-body decay rate of N into one lepton and two jets is given by

$$\Gamma(N_\alpha \to l_k^+ jj) = N_C \frac{g^4}{512\pi^3} |(V_R^\dagger)_{\alpha k}|^2 F\left(\frac{m_N}{m_{W_R}}\right) m_{W_R} \left(\sum_{qq'} |(V_R^Q)^\dagger_{qq'}|^2 \right), \tag{3.4}$$

with,

$$F(x) = -\frac{1}{2} x \left(1 + \frac{x^2}{3}\right) + x^{-3} \left[(1-x^2)\log(1-x^2) + x^2\right], \quad x < 1, \tag{3.5}$$

where V_R^Q is the right-handed quark mixing matrix, N_C is the number of colors and the sum over q, q' includes the kinematically allowed heavy neutrino decays. When $x \ll 1$, $F(x) = x^5/12 + \mathcal{O}(x^7)$ and this corresponds to the decay rate in the limit $m_N \ll m_{W_R}$.

For heavy neutrinos masses above the pion threshold, the dominant decay rate are the hadronic ones and the branching ratio into one charged lepton and two jets is given by

$$\mathrm{Br}(N_\alpha \to l_k^+ jj) = \frac{\Gamma(N_\alpha \to l_k^+ jj)}{\Gamma(\sum_k N_\alpha \to l_k^+ jj)} \simeq |(V_R^\dagger)_{\alpha k}|^2 \tag{3.6}$$

and, according to eq. (3.1), the following the following ratio takes the simple form

$$\frac{\Gamma(W_R^+ \to N_\alpha l_i \to l_i^+ l_k^+ jj)}{\Gamma(W_R^+ \to N_{\alpha'} l_r \to l_r^+ l_s^+ jj)} = \frac{\sigma(pp \to W_R^+ \to N_\alpha l_i \to l_i^+ l_k^+ jj)}{\sigma(pp \to W_R^+ \to N_{\alpha'} l_r \to l_r^+ l_s^+ jj)} = \frac{|(V_R^\dagger)_{\alpha i}|^2 |(V_R^\dagger)_{\alpha k}|^2 c^\alpha}{|(V_R^\dagger)_{\alpha' r}|^2 |(V_R^\dagger)_{\alpha' s}|^2 c^{\alpha'}}, \tag{3.7}$$

where

$$c^\alpha \equiv |\vec{p}_2^{\alpha}|^2 \left[\frac{|\vec{p}_2^{\alpha}|}{3} + E_2^\alpha\right], \tag{3.8}$$

all the hadronic and quark mixing part cancels and we end up having a quantity that depends only on the physical masses and the elements of V_R. When $\alpha = \alpha'$ the expression further simplifies and depends only on the elements of V_R. In what follows we consider the case when one, two or three heavy neutrinos are accessible at the LHC.

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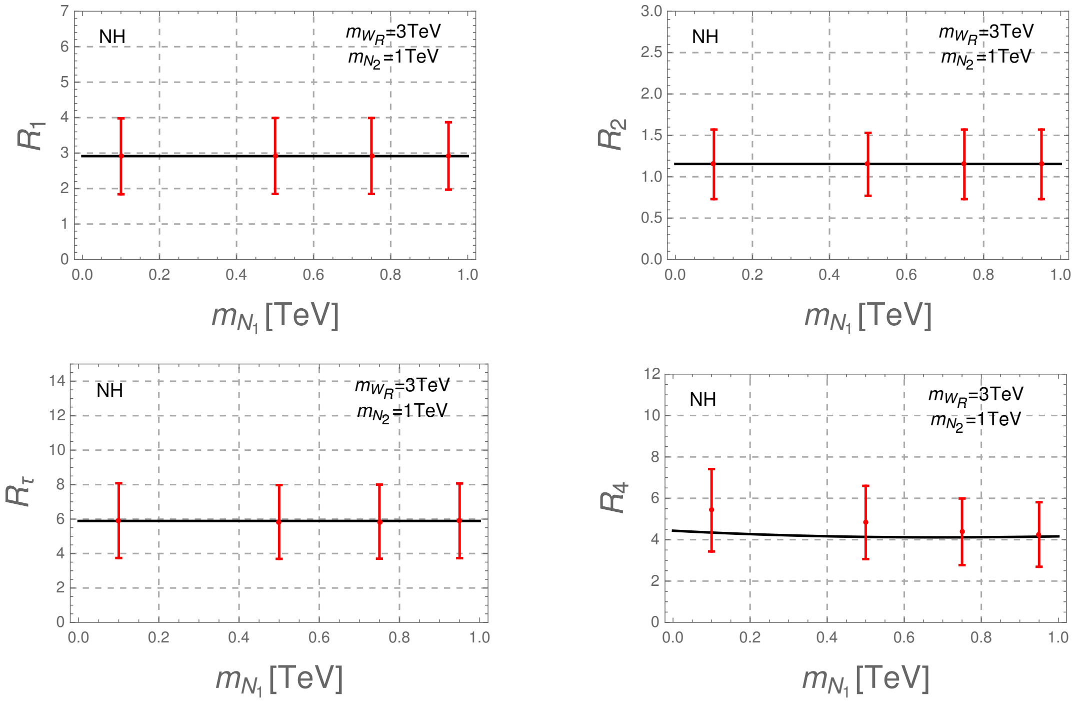

Figure 2. Plots for the quantities R_1,R_2,R_τ and R_4 in the type II see-saw dominance ($V_L \propto V_R^*$) as a function of the lightest neutrino mass eigenstate for 2 heavy neutrinos at the LHC in the NH case. Red dots with errors bars are the results obtained by taking into account the hadronization effects using Pythia 6. We assume the values of the gauge boson $m_{W_R} = 3\,\text{TeV}$ and the heavy neutrino mass $m_{N_2} = 1\,\text{TeV}$.

One heavy neutrino case: it may happen that even if the W_R is found at the LHC, just one of the heavy neutrino mass can be reconstructed. In this case we see from eq. (3.7) (taking $r = s = \mu$) that there are only two independent quantities including tau leptons in the final state, where "independent quantities" refers to the ones that can be measured in the experiment.

If only electrons and muons are considered is easy to see that there is only one independent quantity within this analysis.

Two heavy neutrinos case: one expect for two heavy neutrino at the LHC, that in order to probe all the elements of the mixing matrix V_R the decays of the heavy neutrinos N into electrons, muons and tau leptons must be identified. In fact, in this case analytical solutions for the three mixing angles and the Dirac phase δ can be found in terms of physical quantities at the LHC, this can be seen by considering $\alpha = \alpha'$ in eq. (3.7), namely

$$\frac{\Gamma(W_R^+ \to N_\alpha e^+ \to e^+\mu^+ jj)}{\Gamma(W_R^+ \to N_\alpha \mu^+ \to \mu^+\mu^+ jj)} = \frac{|(V_R^\dagger)_{\alpha e}|^2}{|(V_R^\dagger)_{\alpha\mu}|^2} \equiv R_\alpha \tag{3.9}$$

where

$$\alpha = 1, 2.$$

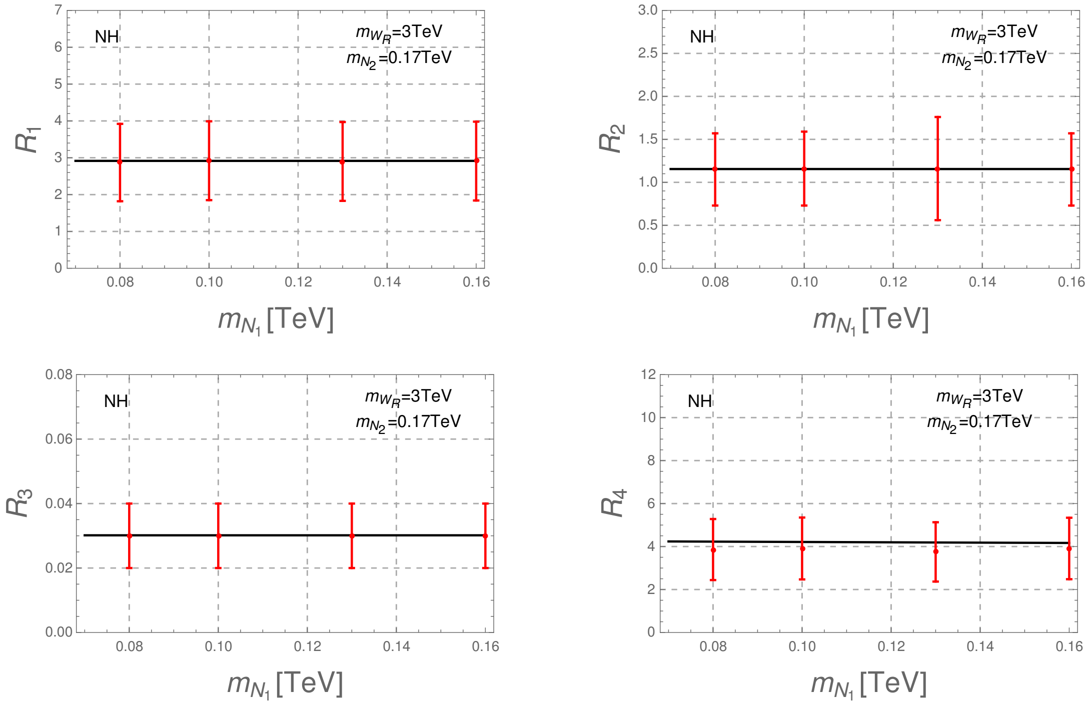

Figure 3. Plots for the quantities R_1,R_2,R_3 and R_4 in the type II see-saw dominance ($V_L \propto V_R^*$) as a function of the lightest neutrino mass eigenstate for 3 heavy neutrinos at the LHC in the NH case. Red dots with errors bars are the results obtained by taking into account the hadronization effects using Pythia 6. We assume the values of the gauge boson $m_{W_R} = 3\,\text{TeV}$ and the heavy neutrino mass $m_{N_2} = 0.17\,\text{TeV}$.

There are 4 unknown parameters in $\hat{V}_R$ (θ_{12}, θ_{13}, θ_{23} and δ). By using the above ratios it is possible to probe 2 of them. There is just another independent quantity considering electron and muons in the final state

$$\frac{\Gamma(W_R^+ \to N_1 e^+ \to e^+ e^+ jj)}{\Gamma(W_R^+ \to N_2 e^+ \to e^+ e^+ jj)} \equiv R_4 = \frac{|(V_R^\dagger)_{1e}|^4 c^{(1)}}{|(V_R^\dagger)_{2e}|^4 c^{(2)}}. \tag{3.10}$$

So we conclude that in order to probe the three mixings angles and the Dirac phase with 2 heavy neutrinos on-shell, tau leptons must be included into the analysis and to this end consider the following relation

$$\frac{\Gamma(W_R^+ \to N_1 e^+ \to e^+ e^+ jj)}{\Gamma(W_R^+ \to N_1 e^+ \to e^+ \tau^+ jj)} = \frac{|(V_R^\dagger)_{1e}|^2}{|(V_R^\dagger)_{1\tau}|^2} \equiv R_\tau \tag{3.11}$$

and the mixings angles are given by

$$s_{12}^2 = \frac{1}{\sqrt{\frac{c^{(2)}}{c^{(1)}} R_4} + 1}, \quad s_{13}^2 = \frac{-\frac{R_\tau R_1}{\sqrt{\frac{c^{(2)}}{c^{(1)}} R_4}} + R_1 + R_\tau}{R_\tau R_1 + R_1 + R_\tau}, \quad s_{23}^2 = \frac{\left(\frac{1}{R_\tau} + \frac{1}{R_2} + 1\right)\sqrt{\frac{c^{(2)}}{c^{(1)}} R_4}}{\sqrt{\frac{c^{(2)}}{c^{(1)}} R_4} + 1} - \frac{1}{R_2}. \tag{3.12}$$

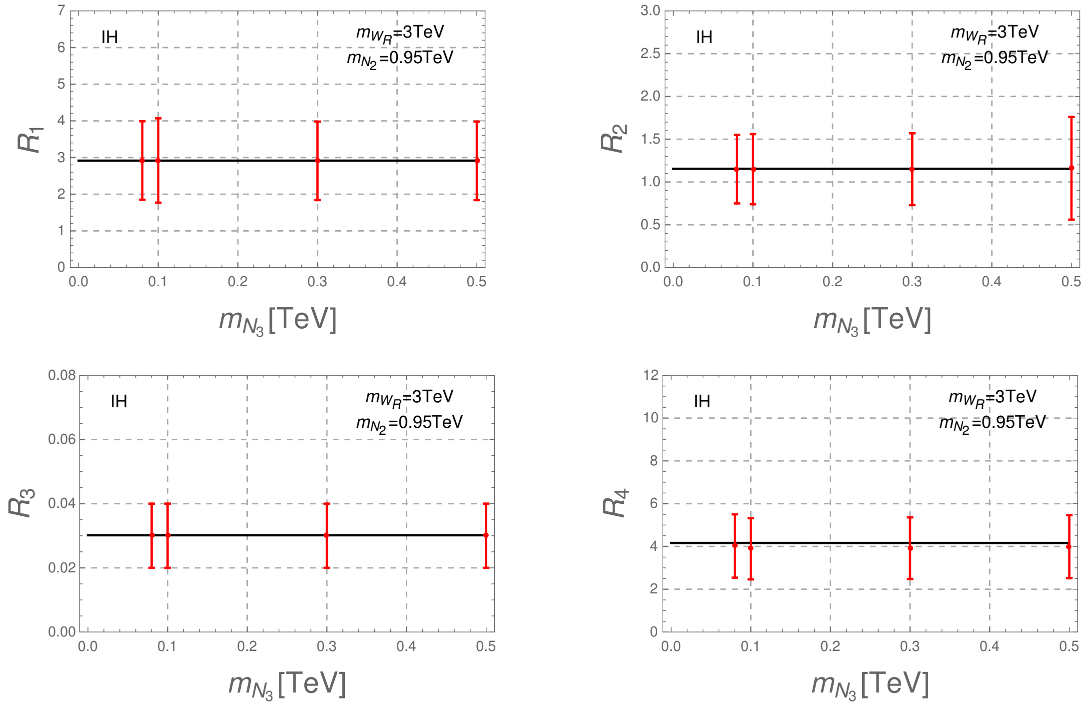

Figure 4. Plots for the quantities R_1,R_2,R_3 and R_4 in the type II see-saw dominance ($V_L \propto V_R^*$) as a function of the lightest neutrino mass eigenstate for 3 heavy neutrinos at the LHC in the IH case. Red dots with errors bars are the results obtained by taking into account the hadronization effects using Pythia 6. We assume the values of the gauge boson $m_{W_R} = 3\,\text{TeV}$ and the heavy neutrino mass $m_{N_2} = 0.95\,\text{TeV}$.

Perhaps the more important advantage of the above expressions is that they allow a simple interpretation of the three leptonic mixing angles in terms of the final states in the KS process. For instance, from (3.12) we may see that θ_{12} is maximal when $R_4 \gg 1$ and minimal when $R_4 \ll 1$. For θ_{13} we notice that its value is maximal whenever $R_1 \ll 1$ or $R_\tau \ll 1$. Instead it is minimal when the relation $R_1 + R_\tau = R_1 R_\tau / \sqrt{\frac{c^{(2)}}{c^{(1)}} R_4}$ is satisfied. Finally θ_{23} takes its maximal value when $R_4 \gg 1$ and $R_\tau \gg 1$ and its minimal value when $R_4 \ll 1$ and $R_2 \gg 1$.

For the sake of simplicity we show the expression for the Dirac phase δ in terms of R_1 and the mixing angles and it is given by

$$\cos\delta = \frac{c_{13}^2 c_{12}^2 - R_1 (c_{23}^2 s_{12}^2 + c_{12}^2 s_{13}^2 s_{23}^2)}{2 c_{12} c_{23} s_{12} s_{13} s_{23} R_1} \tag{3.13}$$

In order to see how the above results are affected once hadronization effects are taken into account, we extent the Feynrules implementation of the mLRSM in [46] to include leptonic mixing in the type II see-saw dominance for $\mathcal{C}$ as the LR symmetry, where it can be shown that $V_R = K_e V_L^*$. The events at the parton level are simulated with Madgraph 5 [47] and hadronization effects with Pythia 6 [48]. We use the same cuts applied in [37–39], namely both jets must have transverse energy grater than 100 GeV and the invariant mass

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of the two final leptons grater than 200 GeV. We take $\theta_{12} = 35^o$, $\theta_{23} = 45^o$, $\theta_{13} = 7^o$ and $\delta = 0$ in this illustrative example.

Furthermore, there is a proportionality between the two neutrino mass matrices

$$\frac{M_N}{\langle \Delta_R \rangle} = \frac{M_\nu^*}{\langle \Delta_L \rangle^*}, \tag{3.14}$$

which implies [57, 58]

$$\frac{m_{N_2}^2 - m_{N_1}^2}{m_{N_3}^2 - m_{N_1}^2} = \frac{m_{\nu_2}^2 - m_{\nu_1}^2}{m_{\nu_3}^2 - m_{\nu_1}^2} \simeq \pm 0.03, \tag{3.15}$$

where the $\pm$ corresponds to normal/inverted (NH/IH) neutrino mass hierarchy respectively. Notice that once the Left-Right symmetry is discovered, this possibility can be verify or falsify by the experiments. We show in figure 2 in the case of normal hierarchy neutrino mass spectrum and for heavy neutrino masses accessible at the LHC, the results obtained from the simulation, where it can be readily seen that our suggested strategy for measuring the right handed mixing angles is feasible at hadron colliders such as the LHC and future ones. Notice that for the IH case, neutrino mass spectra accessible at the LHC would imply that only one or three neutrino masses can be reconstructed. The largest uncertainties in the production cross sections arises from the uncertainties in the parton distribution functions PDF's of the proton and we assume them to be 26% for $m_{W_R} = 3\,\text{TeV}$ as reported in [20] for 7 TeV of the center of mass energy. Although in this paper we consider 13 TeV of center of mass energy, one does not expect this result to change considerably. The assumed theoretical uncertainties of the PDF's imply that the mixing angles $\{\theta_{12}, \theta_{23}, \theta_{13}\}$ may determined with 10%, 20% and 66% accuracy respectively for the values of the mixing angles shown and summing the uncertainties in quadrature. Of course this uncertainties may be diminished in the future and become less important at higher energies as the perturbative QCD computations become more reliable. All this assuming 100% identification of the tau leptons in the final state. This issue and the expected sensitivity to the leptonic mixing angles, CP phases is left for future work.

Reconstruction at the detector level becomes more delicate since for low values of the ratio $r = m_N/m_{W_R} \lesssim 0.1$, the decay products of the heavy neutrinos are difficult to separate in the detector, so one would be tempted to conclude that no flavor tagging may be done in this case. This issue was already studied in detail in [37], where it is claimed that for low values of r, one should search for final states with one high p_T isolated lepton and one high p_T jet with large electromagnetic component and matching the high-p_T track in the inner detector for electrons and in the magnetic spectrometer for muons. For instance they found out that for $r = 0.1$ the efficiency is lowered to around 46% [37].

Notice that in the particular example we are considering r could be as low as $r \simeq 0.03$, so that one would expect the efficiency to be lower in this case. In order to assess the efficiency we use the Delphes [59] for detector simulation (with the default Delphes card) and Madanalysis 5 for event counting and cuts [60]. As in [37] we select the events with one isolated electron (or muon) with $\Delta R > 0.5$ and one isolated jet requiring their transverse energies bigger than 1 TeV, with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ where η and ϕ are the pseudo-rapidity and the azimuthal angle respectively. We find that the efficiency gets as low as 35% for one high-p_T electron and one high-p_T jet in the final state and as low as 28% for one high p_T muon and high-p_T jet in the final state. Therefore this rises the required luminosity from 64 fb^{-1} to 223 fb^{-1} for the two heavy neutrino case at LHC in the range of masses considered (all this assuming 100 % of tau lepton identification).

From table 1 in appendix A, we see that the smallest cross sections are the ones of the processes involving two muons in the final state with N_1 as intermediate state. The results obtained are encouraging, we find that for heavy neutrino masses near or below the TeV range, a luminosity of 63 fb^{-1} is sufficient to measure all the three mixing angles at the LHC. We determine this value of the luminosity by requiring at least 10 events, since a ratio of the signal over the background equal to five is reach much faster due to the LNV character of the final states.

Three heavy neutrinos case: once again in this case it is possible to find analytic expressions for the parameters in V_R in terms of the physical quantities defined in eq. (3.7). The novelty is that no tau leptons need to be identified in the final state, hence rendering this scenario ideal for the LHC; to this end consider eqs. (3.9), (3.10) and

$$\frac{\Gamma(W_R^+ \to N_3 e^+ \to e^+\mu^+ jj)}{\Gamma(W_R^+ \to N_3 \mu^+ \to \mu^+\mu^+ jj)} = \frac{|(V_R^\dagger)_{3e}|^2}{|(V_R^\dagger)_{3\mu}|^2} \equiv R_3. \tag{3.16}$$

A straightforward computation gives

$$s_{12}^2 = \frac{1}{1+\sqrt{\frac{c^{(2)}}{c^{(1)}}R_4}}, \quad s_{23}^2 = \frac{R-1}{R_3-1}, \quad s_{13}^2 = \frac{R-1}{R-\frac{1}{R_3}}. \tag{3.17}$$

where

$$R \equiv \frac{1}{\sqrt{\frac{c^{(2)}}{c^{(1)}}R_4}+1}\left[\frac{\sqrt{\frac{c^{(2)}}{c^{(1)}}R_4}}{R_1}+\frac{1}{R_2}\right] \tag{3.18}$$

One striking feature of the above expressions is that both θ_{13} and θ_{23} are near zero whenever R is close to one, and this in turn implies that R_1 is must be close to R_2. Furthermore θ_{23} is nearly maximal when $R_3 \approx R$ and this relation precisely corresponds to the maximal value θ_{13} when $R_3 \approx R$ but its values are close to one.

As it is clear from the above expressions, the elements of $\hat{V}_R$ have in this parametrization simple relations in terms of physical observables at the LHC. The precise form of the Dirac phase δ is shown in (3.13). Notice that for non-degenerate heavy neutrino masses and within this approach one cannot distinguish δ from $-\delta$. In this respect we notice the CP-odd, triple-vector-product asymmetries in $\mu \to e\gamma$ decay and $\mu \to e$ conversion in Nuclei [45] may resolve this ambiguity and could even discriminate in the most interesting portion of the parameter's space, between $\mathcal{C}$ or $\mathcal{P}$ as the Left-Right symmetry.

In figures 3 and 4 we show the theoretical values for the quantities defined above as well as the result obtained using Madgraph 5 and Pythia 6 indicated by the red dots with their respective error bars. We do it for both normal and inverted neutrino mass hierarchies using eq. (3.15) for the heavy neutrino masses not listed in the plots. It is clear from the figures that the hadronic corrections to these quantities are under control and

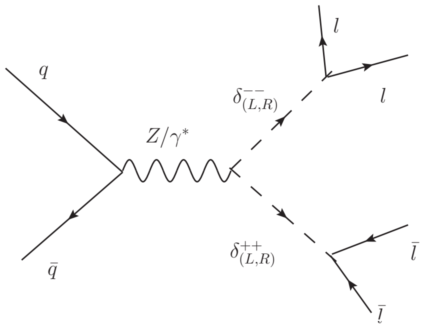

Figure 5. Pair production of the doubly charged scalars with Z/γ^* as intermediate states.

assumed to be 26% as in [20], from which we find that the mixing angles $\{\theta_{12}, \theta_{23}, \theta_{13}\}$ may determined with 10%, 18% and 25% accuracy respectively for the particular values of the mixing angles assumed in this example. We see that despite the value for the mixing angle θ_{13} we used is rather small, it may be determined at the LHC given the present theoretical uncertainties of the PDF's. Future improvements of the perturbative QCD calculations and higher energies may improve the sensitivity.

In this case and from tables 2 and 3 in appendix A, we find that for the range of heavy neutrino masses considered i.e. heavy neutrino masses near or bellow the TeV range, the required luminosity necessary for the determination of the three mixing angles is 417 fb^{-1} and 385 fb^{-1} for the NH and IH cases respectively. The required luminosities rise to 1190 fb^{-1} and 1100 fb^{-1} respectively, when detector simulation is included and with the selection criteria explained in the above section. Notice that in this case the required luminosity bigger than the one for the 2 heavy neutrinos case and this is due to the fact that the mixing of N_3 with the electrons is essentially θ_{13}. Once again and in analogy with the two heavy neutrinos case, we find this value for the luminosity by requiring at least 10 events in the final state, since the ratio of the signal over the background equal to five is reach much faster due to the LNV character of the final states.

3.2 Decays of the doubly-charged scalar δ_R^{++}

In the minimal Left-Right model the other central role at the LHC is played by the doubly charged scalars [49–55]. If light enough they have interesting signatures at colliders through their decays into same-sign leptons in the final state. In particular they can be produced with Z/γ^* as intermediate states, see figure 5. Pair production has the distinctive signature that consists in same-sign dilepton pairs in the final state. Doubly charged scalars belonging to the $\mathrm{SU}(2)_L$ triplet, should be discovered at the LHC in the lepton-lepton channel. For 300fb^{-1} of integrated luminosity the mass reach is around 1 TeV. In the W-W channel is around 700 GeV [54]. In [56] a the lower bound for δ_R^{++} of a few hundred GeV (for $v_R \approx 10$TeV) emerge from the scalar masses assuming $v_1 \ll v_R$.

The expression for the decay rate of δ_R^{++} into a lepton pair is

$$\Gamma(\delta_R^{++} \to l_i^+ l_k^+) = \frac{1}{16\pi(1+\delta_{ik})} |(Y'_{\Delta_R})_{ik}|^2 m_{\delta_R^{++}}. \tag{3.19}$$

(no summation convention over repeated indices)

It can also decay into $W_R^+ W_R^+$-pair but this decay is kinetically suppressed if $m_{\delta_R^{++}} \ll m_{W_R}$. In this case δ_R^{++} decays mostly into leptons and the branching ratios are

$$\frac{\Gamma(\delta_R^{++} \to l_i^+ l_k^+)}{\Gamma(\delta_R^{++} \to all)} \equiv \mathrm{Br}(\delta_R^{++} \to l_i^+ l_k^+) = \frac{2}{(1+\delta_{ik})} \frac{|(V_R^* m_N V_R^\dagger)_{ik}|^2}{\sum_{k'} m_{N_{k'}}^2}. \tag{3.20}$$

Notice that they are independent of the δ_R^{++} mass and depend in general on the Majorana phases in K_N.

Using the parametrization of eq. (2.17) and eq. (3.20), we compute the branching ratios $\mathrm{Br}(\delta_R^{++} \to e^+ e^+)$, $\mathrm{Br}(\delta_R^{++} \to \mu^+ e^+)$ and $\mathrm{Br}(\delta_R^{++} \to \mu^+ \mu^+)$. In appendix B, we give the explicit formulas for these branching ratios. In figure 6 we show how the branching ratios depend on the Majorana phases assuming type II dominance and $\mathcal{C}$ as the LR symmetry. We do it for the representative values $\delta = \pi/2$, $m_{N_{\text{lightest}}} = 0.5$TeV and $m_{N_{\text{heaviest}}} = 1$ TeV, in both normal and inverted neutrino mass hierarchies.

As we can see from figure 6, the decay rates of δ_R^{++} into electrons and muons are considerably affected by the Majorana phases ϕ_2 and ϕ_3. Notice that when the branching ratio into two electrons and two muons tends to be large, that of one electron and one muon tends to be smaller.

Notice from eq. (3.20) that there are five independent branching ratios into leptons. Taking into account the KS process, we can see that there are more observables than parameters to be fixed by the experiment (three mixing angles, the Dirac phase δ and the Majorana phases ϕ_2 and ϕ_3). For example, by measuring all the elements of $\hat{V}_R$ through the KS process (as we have explicitly shown) and taking let say the decays $\delta_R^{++} \to e^+ e^+$ and $\delta_R^{++} \to \mu^+ \mu^+$, the remaining branching ratios are immediately fixed. This in turn fixes a large number of low-energy experiments, such as the radiative corrections to muon decay and the lepton-flavor-violating decay rates of $\mu \to e\gamma$, $\mu \to eee$ and $\mu \to e$ conversion in nuclei. This is a clear example of the complementary role played by high and low energy experiment in the determination of the left-right symmetric theory [57, 58, 61]. So far we have considered only the decays of δ_R^{++} and not δ_L^{++}. The question is whether one can distinguish them without measuring the polarization of the final leptons. We notice that it can be done at the LHC for $v_L < 10^{-4}$ GeV, i.e in the leptonic decay region for the doubly charged scalar δ_L^{++} (see for instance [53, 55] for detailed studies on this issue). This is due to the relations (2.20) and (2.21) and the fact that the production cross section is a factor 2.5 bigger for δ_L^{++}, than the one for δ_R^{++} [62–64]. Of course it is crucial that the backgrounds are negligible after selection criteria are applied [64, 65]. In [62], the next-to-leading order QCD corrections of the production cross-sections at the LHC are calculated and the total theoretical uncertainties are estimated to be $10 - 15\%$.

At this point the reader may well ask about the physical consequences of the phases appearing in K_e. In this respect we notice that lepton dipole moments and CP-odd asymmetries in LFV decays are in general sensitive to them [45]. Then we can link, in principle, all the parameters appearing in V_R with the experiment.

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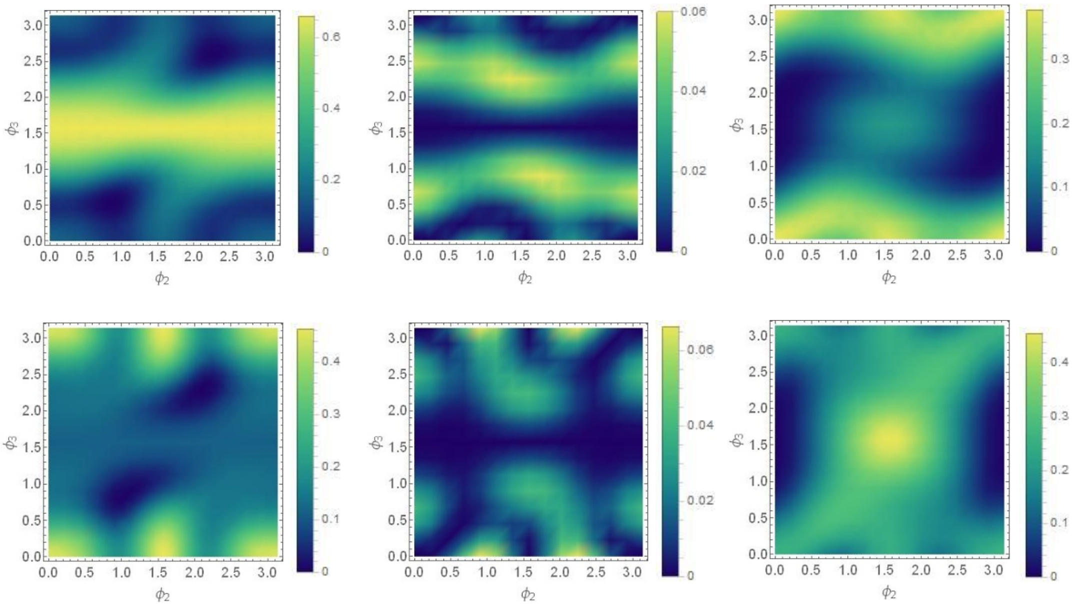

Figure 6. Plots for the branching ratios of δ_R^{++} into leptons in the (ϕ_2, ϕ_3) plane. We assume $\delta = \pi/2$ and the masses for the heaviest and lightest right-handed neutrinos, $m_{\text{heaviest}} = 1$TeV and $m_{\text{lightest}} = 0.5$TeV in type II dominance. (Left) Br($\delta_R^{++} \to e^+e^+$). (Center) Br($\delta_R^{++} \to e^+\mu^+$). (Right) Br($\delta_R^{++} \to \mu^+\mu^+$). (top) Normal hierarchy for neutrino masses. (Bottom) Inverted hierarchy for neutrino masses.

4 Conclusions

In the context of the minimal Left-Right symmetric theory, we studied the determination of the leptonic right-handed mixing matrix V_R at the LHC. We considered the Keung-Senjanović process and the decay of the doubly charged scalar δ_R^{++}.

For non-degenerate heavy neutrino masses, the KS process is sensitive to 3 mixing angles and the Dirac-type phase. We proposed a simple approach in order to determine the three mixing angles and the Dirac phase present in V_R. This determination may be done but at least 2 heavy neutrinos must be produced on-shell, in this case the inclusion of tau-leptons in the analysis is mandatory. For three heavy neutrinos on-shell the three mixing angles and the Dirac phase may be determined by measuring electrons and muons in the final state, rendering the three heavy neutrino case ideal for the LHC. We found exact analytical solutions for the mixing angles and the Dirac phase δ in terms of measurable quantities at the LHC in both two and three heavy neutrino cases. We also show that the hadronization effects for the final jets are under control, thus rendering the proposed strategy feasible at the LHC. Finally we find that for two heavy neutrino at the LHC with masses near or bellow the TeV, an integrated luminosity of 63 fb^{-1} is required in order to measure the three mixing angles that parametrize the right handed leptonic mixing matrix. The required luminosity rises to 223 fb^{-1} once detector simulation is included (assuming 100 % of tau identification). In the case of three heavy neutrinos at the LHC and for the range of heavy neutrino masses considered (near or bellow the TeV) a luminosity of

417 fb^{-1} and 385 fb^{-1} is required for both normal and inverted neutrino mass hierarchy respectively. Finally, these luminosities rise from 417 fb^{-1} to 1190 fb^{-1}, and from 385 fb^{-1} 1100 fb^{-1} once detector simulation is included.

For degenerate heavy neutrinos masses, the lepton-number-violating, same-sign lepton channel (figure 1. Bottom) is in general sensitive to two of the Majorana phases of V_R, because in this case there are interference terms between the degenerate right-handed neutrino mass eigenstates.

We point out that the decays of the doubly charged scalar δ_R^{++} into leptons are significantly affected by the same two Majorana phases. In figure 6 we show its branching ratios into e^+e^+,$e^+\mu^+$ and $\mu^+\mu^+$. We did it for $\mathcal{C}$ as the Left-Right symmetry assuming type II see-saw dominance. We considered some representative values of the Dirac phase δ and the right-handed neutrino masses, in both normal and inverted neutrino mass hierarchies.

As a consequence of the near equality of the Yukawa couplings of the doubly charged scalars in both parity or charged conjugation as the Left-Right symmetry, the LHC experiment may distinguish δ_L^{++} from δ_R^{++} without measuring the polarization of the final-state leptons coming from their decays.

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A Cross sections values

In this appendix we present the results for the cross sections obtained from Madgraph 5 [47] and Pythia 6 [48], for different values of the heavy neutrino masses that we used for generation of the relevant processes at the partonic level and the subsequent hadronization effects.

	Cross section σ[fb]			
	$m_{N_2} = 1\,\text{TeV}$			
Processes	$m_{N_1} = 100\text{GeV}$	$m_{N_1} = 500\text{GeV}$	$m_{N_1} = 750\text{GeV}$	$m_{N_1} = 950\text{GeV}$
$pp \to W_R^+ \to N_1 e^+ \to e^+e^+jj$	1.78	1.57	1.44	1.39
$pp \to W_R^+ \to N_1 e^+ \to e^+\mu^+jj$	0.61	0.54	0.50	0.48
$pp \to W_R^+ \to N_1 e^+ \to e^+\tau^+jj$	0.3	0.27	0.25	0.24
$pp \to W_R^+ \to N_1 e^+ \to \mu^+\mu^+jj$	0.21	0.19	0.17	0.16
$pp \to W_R^+ \to N_2 e^+ \to e^+e^+jj$	0.33	0.33	0.32	0.32
$pp \to W_R^+ \to N_2 e^+ \to e^+\mu^+jj$	0.28	0.28	0.28	0.28
$pp \to W_R^+ \to N_2 e^+ \to \mu^+\mu^+jj$	0.25	0.24	0.25	0.25

Table 1. Cross sections for the different processes considered for two heavy neutrinos at the LHC in the normal hierarchy (NH) neutrino mass spectrum and for different values of the lightest heavy neutrino mass.

Processes	Cross section σ[fb] $m_{N_2} = 0.17\,\text{TeV}$ $m_{N_1} = 80\text{GeV}$	$m_{N_1} = 100\text{GeV}$	$m_{N_1} = 130\text{GeV}$	$m_{N_1} = 160\text{GeV}$
$pp \to W_R^+ \to N_1 e^+ \to e^+ e^+ jj$	1.61	1.65	1.63	1.68
$pp \to W_R^+ \to N_1 e^+ \to e^+ \mu^+ jj$	0.55	0.57	0.56	0.58
$pp \to W_R^+ \to N_1 e^+ \to \mu^+ \mu^+ jj$	0.19	0.19	0.19	0.20
$pp \to W_R^+ \to N_2 e^+ \to e^+ e^+ jj$	0.42	0.42	0.43	0.43
$pp \to W_R^+ \to N_2 e^+ \to e^+ \mu^+ jj$	0.36	0.36	0.38	0.37
$pp \to W_R^+ \to N_2 e^+ \to \mu^+ \mu^+ jj$	0.31	0.32	0.33	0.32
$pp \to W_R^+ \to N_3 e^+ \to e^+ \mu^+ jj$	0.048	0.024	0.026	0.027
$pp \to W_R^+ \to N_3 e^+ \to \mu^+ \mu^+ jj$	1.6	0.80	0.85	89

Table 2. Cross sections for the different processes considered for three heavy neutrinos at the LHC in the normal hierarchy (NH) neutrino mass spectrum and for different values of the lightest heavy neutrino mass.

Processes	Cross section σ[fb] $m_{N_2} = 0.95\,\text{TeV}$ $m_{N_3} = 80\text{GeV}$	$m_{N_3} = 100\text{GeV}$	$m_{N_3} = 300\text{GeV}$	$m_{N_3} = 500\text{GeV}$
$pp \to W_R^+ \to N_1 e^+ \to e^+ e^+ jj$	1.35	1.34	1.32	1.36
$pp \to W_R^+ \to N_1 e^+ \to e^+ \mu^+ jj$	0.46	0.46	0.45	0.47
$pp \to W_R^+ \to N_1 e^+ \to \mu^+ \mu^+ jj$	0.16	0.16	0.16	0.16
$pp \to W_R^+ \to N_2 e^+ \to e^+ e^+ jj$	0.34	0.35	0.34	0.34
$pp \to W_R^+ \to N_2 e^+ \to e^+ \mu^+ jj$	0.29	0.30	0.29	0.29
$pp \to W_R^+ \to N_2 e^+ \to \mu^+ \mu^+ jj$	0.25	0.26	0.25	0.26
$pp \to W_R^+ \to N_3 e^+ \to e^+ \mu^+ jj$	0.027	0.028	0.026	0.026
$pp \to W_R^+ \to N_3 e^+ \to \mu^+ \mu^+ jj$	0.92	0.91	0.85	0.86

Table 3. Cross sections for the different processes considered for three heavy neutrinos at the LHC in the inverted hierarchy (IH) neutrino mass spectrum and for different values of the lightest heavy neutrino mass.

B Branching ratio formulas for $\delta_R^{++} \to l^+ l^+$

In this appendix we show the explicit formulas for the branching ratios $\text{Br}(\delta_R^{++} \to e^+ e^+)$, $\text{Br}(\delta_R^{++} \to \mu^+ e^+)$ and $\text{Br}(\delta_R^{++} \to \mu^+ \mu^+)$,

$$\text{Br}(\delta_R^{++} \to e^+ e^+) = \frac{1}{\sum_k m_{N_k}^2} |c_{13}^2 c_{12}^2 m_{N_1} + e^{-2i\phi_2} c_{13}^2 s_{12}^2 m_{N_2} + e^{-2i(\phi_3-\delta)} s_{13}^2 m_{N_3}^2|^2, \quad \text{(B.1)}$$

$$\begin{aligned}\text{Br}(\delta_R^{++} \to e^+ \mu^+) = \frac{2}{\sum_k m_{N_k}^2} |&(-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta})c_{12}c_{13}m_{N_1} + \\ &+ (c_{12}c_{23} - s_{12}s_{23}s_{13}e^{-i\delta})s_{12}c_{13}e^{-2i\phi_2}m_{N_2} + s_{23}c_{13}s_{13}e^{-i(2\phi_3-\delta)}m_{N_3}|^2,\end{aligned} \quad \text{(B.2)}$$

$$\begin{aligned}\text{Br}(\delta_R^{++} \to \mu^+ \mu^+) = \frac{1}{\sum_k m_{N_k}^2} |&(-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta})^2 m_{N_1} + \\ &+ (c_{12}c_{23} - s_{12}s_{23}s_{13}e^{-i\delta})^2 e^{-2i\phi_2} m_{N_2} + s_{23}^2 c_{13}^2 e^{-2i\phi_3} m_{N_3}|^2.\end{aligned} \quad \text{(B.3)}$$

Notice that this branching ratios are independent of the doubly-charged scalar masses and depend only on the masses of the heavy neutrinos

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