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Phenomenology of the right handed lepton mixings at the LHC

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We discuss how the right-handed leptonic mixing in the minimal left-right model may be determined at the LHC. This determination in fundamental in order to determined the Dirac masses of heavy neutrinos and establish experimentally the Left-Right model as a complete theory of neutrino masses and mixings. Then we show that if the the recently CMS diboson excess turns out to be the case and not just an statistical fluctuation, it leads to interesting phenomenological consequences at the LHC and in low energy Lepton Number Violating and Lepton Flavor violating experiments.

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1. Introduction

The minimal left-right model (LR) has been proposed more than four decades ago [1, 2, 3, 4, 5] in order to explain the maximal parity violation observed in weak interactions and more recently established as a complete model of neutrino masses and mixings [6]. In this model the observed parity violation is assumed to be a low energy phenomenon that should be restored at higher energies. The question is whether this restoration occurs at sufficiently low energies so we may discover it directly in the high energy frontier, such as the LHC or future colliders, or indirectly in low energy experiments such as $\mu \to e$ conversion and Neutrinoless Double Beta decay ($0\nu2\beta$) decay. In this talk we consider this possibility and be mainly concerned about the the so called Keung-Senjanović (KS) process [7] and the determination of the right-handed leptonic mixings through it, unlike the quark sector in which the mixings are fixed in terms of the CKM mixings [8, 9, 10]. This process consists in the production of the right-handed parter of the W boson (W_R) at hadron colliders, that decays in one lepton and a heavy Majorana neutrino, giving in the final state two leptons –that may be of the same sign– and two jets. The two same-sign lepton process breaks Lepton number due to the Majorana nature of heavy neutrinos, that may reveal itself through the equality between the branching ratios of same-sign and opposite sign processes [7]. Then we discuss the recently reported CMS diboson excess [11] and some interesting phenomenological predictions that may be derived from it. Several works have been proposed [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22] 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.

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

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L : (2,1,\frac{1}{3}), \quad q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R : (1,2,\frac{1}{3}), \tag{1.1}$$

$$L_L = \begin{pmatrix} \nu \\ l \end{pmatrix}_L : (2,1,-1), \quad L_R = \begin{pmatrix} N \\ l \end{pmatrix}_R : (1,2,-1). \tag{1.2}$$

where N represents the new heavy neutrino states introduced to make explicit the LR symmetry, its presence play a crucial role in explaining the smallness of the neutrino masses on the basis of the see-saw mechanism [23, 24, 25, 26, 27, 28, 29] and $l = \{e, \mu, \tau\}$.

The Higgs sector sector [23, 24] consists in one bidoublet Φ, in the (2,2,0) representation of $\mathscr{G}$ and two scalar triplets Δ_L and Δ_R, belonging to (3,1,2) and (1,3,2) representation respectively

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \quad \Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}. \tag{1.3}$$

In the LR model the charged current Lagrangian is of the form

$$\mathscr{L}_{cc} = \frac{g}{\sqrt{2}}(\bar{\nu}_L V_L^\dagger \not{W} l_L + \bar{N}_R V_R^\dagger \not{W}_R l_R) + h.c., \tag{1.4}$$

where V_R is the right-handed leptonic mixing matrix –the right-handed analogue of the PMNS mixing matrix V_L– the main topic of this work. Throughout this work we choose to use the so called Standard Parametrization [30] of V_R. This matrix V_R has in general 3 different angles and 6 phases that we write it in the form

$$V_R = K_e \hat{V}_R K_N \tag{1.5}$$

where

$$K_e = diag(e^{i\phi_e}, e^{i\phi_\mu}, e^{i\phi_\tau}), \qquad K_N = diag(1, e^{i\phi_2}, e^{i\phi_3}) \tag{1.6}$$

and

$$\hat{V}_R = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13} \\ -s_{12}c_{23}e^{i\delta} - c_{12}s_{13}s_{23} & c_{12}c_{23}e^{i\delta} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23}e^{i\delta} - c_{12}s_{13}c_{23} & -c_{12}s_{23}e^{i\delta} - s_{12}s_{13}c_{23} & c_{13}c_{23} \end{pmatrix}, \tag{1.7}$$

$s_{\alpha\beta}$ is the short-hand notation for $\sin\theta_{\alpha\beta}$ $(\alpha, \beta = 1, 2, 3)$.

The other relevant interactions for our discussion are the ones between the charged leptons and the doubly charged scalars

$$\mathscr{L}_\Delta = \frac{1}{2} l_R^T C Y'_{\Delta_R} \delta_R^{++} l_R + \frac{1}{2} l_L^T C Y'_{\Delta_L} \delta_L^{++} l_L + h.c., \tag{1.8}$$

$$Y'_{\Delta_R} = \frac{g}{m_{W_R}} V_R^* m_N V_R^\dagger, \tag{1.9}$$

where m_{N_α} and m_{W_R} are the heavy neutrino masses and charged gauge boson mass respectively.

It has long been known [31, 32, 33] that for $\mathscr{C}$ as the left-right symmetry $Y'_{\Delta_L} = (Y'_{\Delta_R})^*$ and more recently in [34] is has been shown that a similar result holds for $\mathscr{P}$ as the left-right symmetry, namely $Y'_{\Delta_L} \simeq Y'_{\Delta_R}$ in the interesting portion of the parameter space, namely that for which the Dirac masses are less or equal than the charged lepton masses. As we will see, this observation turns out to be crucial for distinguishing both the left and right doubly charged scalars at the LHC without measuring the polarization of the final leptons coming from their decays.

2. Right-handed leptonic mixings at the LHC: an strategy for determining the mixing angles in the leptonic right mixing matrix

In this section we show how the LHC can be used to completely determined the mixing angles and the Dirac phase in the right-handed leptonic mixing matrix. To this end we consider the Lepton Number violating (LNV) channel of the KS process and the leptonic decays of the doubly charged scalars. Previous LHC Studies have been done for this process assuming one and two heavy neutrino exchange [35], instead here we do it in the generic case without further assumptions, as we will see our approach has the advantage that the hadronic correction cancel redering the determination of the mixing cleaner too and as we will the determination of the Dirac and some Majorana phases is in principle possible. Another obvious advantage is that this approach allow the immediate implementation and testing in Monte Carlo generators such as MadGraph [36] and Pythia [37].

2.1 Keung-Senjanović process

If the W_R boson and the heavy neutrinos are non-degenerate and on-shell (with masses above the pion threshold), the following ratios between production cross sections are simply given by [34]

$$\frac{\sigma(pp \to W_R^+ \to N_\alpha l_i \to l_i^+ l_k^+ jj)}{\sigma(pp \to W_R^+ \to N_{\alpha'} l_r \to l_r^+ l_s^+ jj)} = \frac{\Gamma(W_R^+ \to N_\alpha l_i \to l_i^+ l_k^+ jj)}{\Gamma(W_R^+ \to N_{\alpha'} l_r \to l_r^+ l_s^+ jj)} = \frac{|(V_R^\dagger)_{\alpha i}|^2 |(V_R^\dagger)_{\alpha k}|^2 c^\alpha}{|(V_R^\dagger)_{\alpha' r}|^2 |(V_R^\dagger)_{\alpha' s}|^2 c^{\alpha'}}, \quad (2.1)$$

where $i,k = e,\mu,\tau$ and

$$c^\alpha \equiv |\vec{p}_2^{\,\alpha}|^2 [\frac{|\vec{p}_2^{\,\alpha}|}{3} + E_2^\alpha], \qquad \alpha = 1,2,3 \quad (2.2)$$

E_2^α is the energy of N_α and $\vec{p}_2^{\,\alpha}$ is such that

$$|\vec{p}_2^{\,\alpha}| + \sqrt{|\vec{p}_2^{\,\alpha}|^2 + m_{N_\alpha}^2} = m_{W_R}, \quad (2.3)$$

where m_{N_α} and m_{W_R} are the heavy neutrino masses and charged gauge boson mass respectively.

We see that the in the above ratios all the hadronic dependence cancels and it is independent on the quark mixings too. The main point we want to convey is this: for two and three heavy neutrinos accessible at the LHC (and any future hadron collider), all the three mixings and the Dirac phase in the mixing matrix may be completely determined from the KS process alone.

In what follows we briefly present the mixing angles in V_R as a function of the ratios defined in 2.1 for the one, two and three heavy neutrinos accessible at the LHC.

One heavy neutrino case: It may well be that only one heavy neutrino mass can be reconstructed and we see from Eq. 2.1 (taking $r = s = \mu$), that there are only two independent quantities including tau leptons in the final state. Furthermore, If only electrons and muons are taken in the final state, is easy to see that there is only one independent quantity within this analysis.

Two heavy neutrinos case: in this case it is clear that in order to probe the elements of V_R, tau leptons must be include in the analysis. Otherwise there is no distinction between the two and three family case and to this end consider $\alpha = \alpha'$ in Eq. 2.1

$$\frac{\Gamma(W_R^+ \to N_\alpha e^+ \to e^+ \mu^+ jj)}{\Gamma(W_R^+ \to N_\alpha \mu^+ \to \mu^+ \mu^+ jj)} = \frac{|(V_R^\dagger)_{\alpha e}|^2}{|(V_R^\dagger)_{\alpha\mu}|^2} \equiv R_\alpha, \quad \alpha = 1,2.$$

There are 4 unknown parameters in $\hat{V}_R$ (θ_{12}, θ_{13}, θ_{23} and δ) and from 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

$$\frac{\Gamma(W_R^+ \to N_1 e^+ \to e^+ e^+ jj)}{\Gamma(W_R^+ \to N_2 e^+ \to e^+ e^+ jj)} \equiv R_4 = \frac{|(V_R^\dagger)_{1e}|^4 c^{(1)}}{|(V_R^\dagger)_{2e}|^4 c^{(2)}}. \quad (2.4)$$

Therefore we see that in order to probe the three mixings angles and the Dirac phase with 2 heavy neutrinos on-shell, tau leptons must be included in the analysis. This may be explicitly seen by considering the relation

$$\frac{\Gamma(W_R^+ \to N_1 e^+ \to e^+ e^+ jj)}{\Gamma(W_R^+ \to N_1 e^+ \to e^+ \tau^+ jj)} = \frac{|(V_R^\dagger)_{1e}|^2}{|(V_R^\dagger)_{1\tau}|^2} \equiv R_\tau \quad (2.5)$$

where it can be readily seen that in this case the mixing angles and the Dirac phase are given by

$$s_{12}^2 = \frac{1}{\sqrt{\frac{c^{(2)}}{c^{(1)}}R_4+1}}, \quad s_{13}^2 = \frac{-\frac{R_\tau R_1}{\sqrt{\frac{c^{(2)}}{c^{(1)}}R_4}}+R_1+R_\tau}{R_\tau R_1+R_1+R_\tau},$$

$$s_{23}^2 = \frac{\left(\frac{1}{R_\tau}+\frac{1}{R_2}+1\right)\sqrt{\frac{c^{(2)}}{c^{(1)}}R_4}}{\sqrt{\frac{c^{(2)}}{c^{(1)}}R_4+1}} - \frac{1}{R_2}, \quad \cos\delta = \frac{c_{13}^2 c_{12}^2 - R_1(c_{23}^2 s_{12}^2 + c_{12}^2 s_{13}^2 s_{23}^2)}{2c_{12}c_{23}s_{12}s_{13}s_{23}R_1} \tag{2.6}$$

The above expressions admits simple interpretation of the three leptonic mixing angles in terms of the final states for the KS process. For instance, from 2.6 we see that θ_{12} is maximal for $R_4 >> 1$ and minimal for $R_4 << 1$. For the θ_{13} angle, we notice that its value is maximal when $R_1 << 1$ or $R_\tau << 1$. Instead it is minimal when $R_1 + R_\tau = R_1 R_\tau / \sqrt{\frac{c^{(2)}}{c^{(1)}}R_4}$. Finally the mixing angle θ_{23} takes its maximal value when $R_4 >> 1$ and $R_\tau >> 1$ and its minimal value when $R_4 << 1$ and $R_2 >> 1$.

Three heavy neutrinos case: in this situation and considering only electrons and muons, it is possible to find analytic expressions for the parameters in V_R in terms of the physical quantities defined in Eq. 2.1. The novelty is that no tau leptons need to be identified in the final state, reducing therefore the misidentification and hadronic uncertainties and hence rendering this scenario ideal for the LHC, to this end consider Eqns. 2.4, 2.4 and

$$\frac{\Gamma(W_R^+ \to N_3 e^+ \to e^+\mu^+ jj)}{\Gamma(W_R^+ \to N_3\mu^+ \to \mu^+\mu^+ jj)} = \frac{|(V_R^\dagger)_{3e}|^2}{|(V_R^\dagger)_{3\mu}|^2} \equiv R_3. \tag{2.7}$$

A straightforward computation gives

$$s_{12}^2 = \frac{1}{1+\sqrt{\frac{c^{(2)}}{c^{(1)}}R_4}}, \quad s_{23}^2 = \frac{R-1}{R_3-1}, \quad s_{13}^2 = \frac{R-1}{R-\frac{1}{R_3}}. \tag{2.8}$$

where

$$R \equiv \frac{1}{\sqrt{\frac{c^{(2)}}{c^{(1)}}R_4+1}}\left[\frac{\sqrt{\frac{c^{(2)}}{c^{(1)}}R_4}}{R_1} + \frac{1}{R_2}\right] \tag{2.9}$$

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. Next section we discuss the determination of the Majorana phases at the LHC through the leptonic decays of the doubly charged scalars $\delta_R^{\pm\pm}$.

2.2 Decays of the doubly charged scalar

Notice that so far we have not discussed the determination of the Majorana phases and the question is whether all of some of them may be determined at the LHC. In this respect the central role is played by the decays of the doubly charged scalar δ_R^{++} at the LHC [38, 39, 40, 41, 42, 43, 44, 45], since its leptonic decays depend in the CP even way on some of the Majorana phases appearing in V_R, more precisely these decays are sensitive to two of the Majorana phases in 1.5.

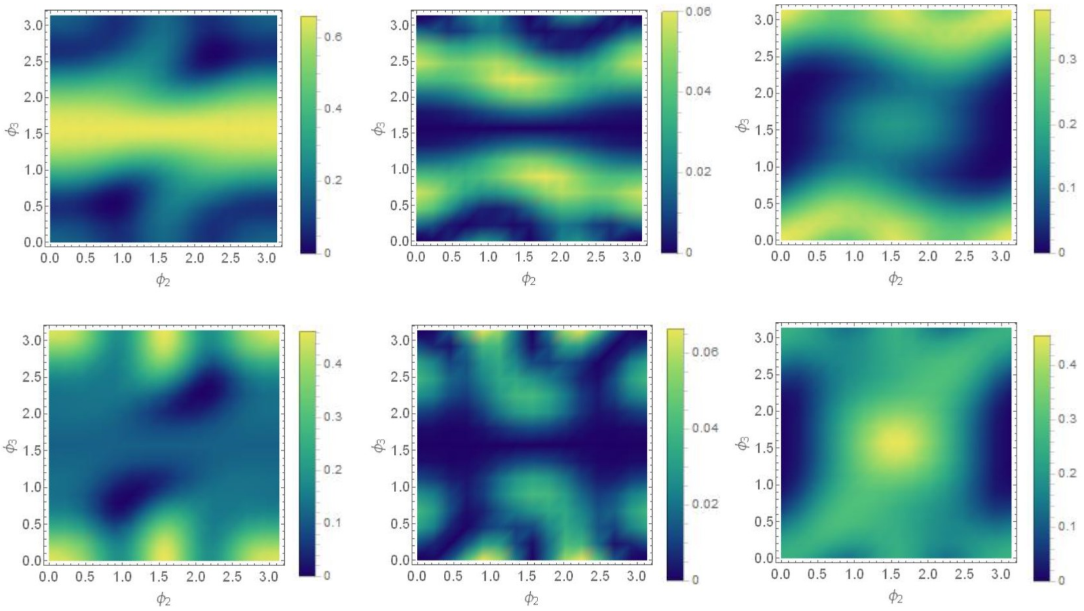

Figure 1: Plots for the branching ratios of δ_R^{++} into leptons in the (ϕ_2, ϕ_3) plane. We assume $\delta = \pi/2$ and the masses for the heaviest and lightest right-handed neutrinos, $m_{heaviest} = 1$TeV and $m_{lightest} = 0.5$TeV in type II dominance. (Left) $Br(\delta_R^{++} \to e^+ e^+)$. (Center)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

The remaining ones may be in principle determined from the electric dipole moment of charged leptons.

For doubly charged scalar masses $m_{\delta_R^{++}} < m_{W_R}/2$, the branching ratio into two same-sign leptons is given by

$$Br(\delta_R^{\pm\pm} \to l_i^\pm l_k^\pm) \equiv \frac{\Gamma(\delta_R^{\pm\pm} \to l_i^\pm l_k^\pm)}{\Gamma(\delta_R^{++} \to all)} = \frac{2}{(1+\delta_{ik})} \frac{|(V_R^* m_N V_R^\dagger)_{ik}|^2}{\sum_{k'} m_{N_{k'}}^2}. \tag{2.10}$$

and it can be seen the dependence on the mixing matrix goes as the elements of V_R squared, hence the dependence on the Majorana phases. In FIG. 1 we show how the branching ratios explicitly depend on the Majorana phases, we do it assuming type II dominance and $\mathscr{C}$ as the LR symmetry, for the representative values $\delta = \pi/2$, $m_{N_{lightest}} = 0.5$TeV and $m_{N_{heaviest}} = 1$ TeV, in both normal and inverted neutrino mass hierarchies. The branching ratios range from 0 up to 0.4 in some cases and this is the main reason that allow us to consider these decays as relevant for the determination of the Majorana phases at the LHC. Notice that in this discussion it is crucial that both $\delta_R^{\pm\pm}$ and $\delta_L^{\pm\pm}$ are distinguishable and this is guaranteed in the most interesting phenomenological situation, since the Yukawa couplings with the leptons in Eq. 1.8 are the same for both $\mathscr{P}$ and $\mathscr{C}$ as the LR symmetries.

3. Left-Right symmetry in the light of the CMS excess (in collaboration with G. Senjanović)

There is a neat way to understand the results presented in [15], in which it is shown that the CMS excess may be perfectly explained within the minimal LR model if two heavy neutrinos, almost generate in mass are accessible at the LHC –the remaining one is assumed to be much heavier and not at the LHC reach. We use the fact that two almost degenerate Majorana fermions maximally mixed, behave as a pseudo-Dirac particle and show that this observation turns out to be crucial in order to understand the reported excess and its phenomenological implications. In particular we noticed that if the CMS excess turn out not to be an statistical fluctuation, then $L_e + L_\tau$ would be violated whereas $L_e - L_\tau$ would be conserved, where L_e and L_τ are the electron and tau lepton number respectively. More recently the interpretation of the excess in terms of pseudo-Dirac neutrinos has also been discussed in [17, 22], where it is also noticed that the tau heavy neutrino may play the role of the Dirac partner for the heavy electron neutrino.

The interaction between the Majorana neutrinos and the leptons consistent with the CMS excess was assumed to be of the form [15]

$$\hat{V}_R^\dagger = \begin{pmatrix} c_\theta & 0 & s_\theta \\ 0 & 1 & 0 \\ -s_\theta e^{i\phi} & 0 & c_\theta e^{i\phi} \end{pmatrix}, \tag{3.1}$$

where θ is the mixing angle, ϕ is the Majorana phase and s_θ is the shorthand notation for $\sin\theta$. For the sake of clarity and in order to better illustrate our ideas, consider $\theta = \frac{\pi}{4}$ and $\phi = \frac{\pi}{2}$, namely maximal maxing and maximal leptonic CP violation. In this case the interaction between the heavy neutrinos and the charged leptons in Eq. 1.4 becomes:

$$\begin{aligned} \mathscr{L}_{cc} \supset \bar{N}_1 \not{W}_R (e+\tau) + i\bar{N}_2 \not{W}_R (\tau - e) + h.c. &= (\bar{N}_1 - i\bar{N}_2)\not{W}_R e + (\bar{N}_1 + i\bar{N}_2)\not{W}_R \tau + h.c. \\ &= \bar{D}_1 \not{W}_R e + \bar{D}_2 \not{W}_R \tau + h.c. \end{aligned} \tag{3.2}$$

where D_1 and D_2 are the Weyl components of the Dirac spinor

$$D = \begin{pmatrix} D_1 \\ D_2 \end{pmatrix}, \tag{3.3}$$

and this may be readily seen by diagonalizing the usual Dirac mass matrix for the D_1, D_2 spinors.

There are several interesting conclusions one can derive from the interaction 3.2, namely there cannot be for the KS process two same-sign electron or tau in the final state, only final states with one electron and one tau are allowed, breaking therefore the number $L_e + L_\tau$ by two units. Notice that at the same time $L_e - L_\tau$ lepton number is conserved. This observation allow us to conclude that if this particular scenario turns out to be the case, the only Lepton number violation would be in the form of same-sign one electron and one tau in the final state at the LHC, which immediately implies that no $0\nu2\beta$ decay would be observed due to new physics. There is also the LNV meson decay process $K^\pm \to \pi^\mp \tau^\pm e^\pm$ [46], since this process is very similar to the KS process. It is worth mentioning that in this limit no LFV processes such as $\tau \to e\gamma$, $\mu \to e\gamma$ and $\tau \to eee$ would arise, since all this processes explicitly violates $L_e - L_\tau$ lepton number. Therefore we end up having a rather sterile scenario in which no Lepton Flavor Violation (LFV) and the LNV processes occur solely in the form of one electron together with one tau lepton.

In order to explicitly work out the above ideas with one particular example and for the mixing matrix given in 3.1, we compute the partial decay rate for $0\nu2\beta$ decay, this process has been previously studied within the LR model in [47, 48], together with its possible interplay with the LHC. In this case the effective Hamiltonian is of the form [47]

$$\mathscr{H}_{NP} = G_F^2 (V_R^\dagger)^2_{ej} \left[\frac{1}{m_{N_j}} + \frac{2m_{N_j}}{m^2_{\delta_R}} \right] \frac{m_W^2}{m^2_{W_R}} J_{R\mu} J_R^\mu \bar{e}_R e_R^c \tag{3.4}$$

where J_R is the right handed hadronic current, m_{δ_R} the mass of the doubly charged scalar and the the total decay rate is given by [47]

$$\frac{\Gamma_{0\nu2\beta}}{\ln 2} = G. \left| \frac{\mathscr{M}_\nu}{m_e} \right|^2 \left(|m_\nu^{ee}|^2 + |m_{NP}^{ee}|^2 \right) \tag{3.5}$$

where

$$|m_{NP}^{ee}|^2 = \left| p^2 \frac{m_W^4}{m_{W_R}^4} \frac{(V_R^\dagger)^2_{ej}}{m_{N_j}} \right|^2 \tag{3.6}$$

and it parametrizes the new physics contribution to the $0\nu2\beta$ decay rate that using 3.1 takes the simple form

$$m_{NP}^{ee} = p^2 \frac{m_W^4}{m_{W_R}^4} \frac{1}{m_N} \left(\frac{r}{c} \right) \tag{3.7}$$

where r is the ratio between the same-sign over opposite-sign lepton events that should be $r = 1/14$ and c is a pure number of order one –their precise from are given in [15]. We see therefore that the new physics contribution to $0\nu2\beta$ decay is suppressed, as expected from the above discussion. For instance assuming $m_{W_R} = 3$ TeV and $m_N = 100$ GeV one gets $m_{NP}^{ee} \simeq 10^{-2}$ eV, thus ruling out the new physics contribution as the dominant source of $0\nu2\beta$ decay if some signal is detected in the next round of experiments.

4. Conclusions

We have presented within the minimal Left-Right model, an strategy for completely determine the mixing angles, the Dirac phase and some the Majorana phases present in right handed leptoninc mixing matrix V_R –the right handed analogue of the PMNS mixing matrix of light neutrinos– from the Keung-Senjanović (KS) process and the leptonic decays of the right doubly charged scalar $\delta_R^{\pm\pm}$. We have shown that this complete determination may be done in the case of two and three heavy neutrinos accessible at the LHC, being the three neutrino case ideal for the LHC.

Then we discuss the recently reported CMS diboson excess and show that it has the interesting phenomenological prediction, that Lepton Number Violation would be solely in the form of one electron and one tau lepton in the final state. This observation can be understood by noticing that two almost generate Majorana fermions behave as a Pseudo-Dirac particle, we also point out a selection rule in which the lepton number $L_e + L_\tau$ is violated by two units whereas $L_e - L_\tau$ is

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conserved. One immediate prediction of this selection rule is that the decay rates for Lepton Flavor violating processes and Neutrinoless Double Beta decay would be suppressed. Instead the LNV caracter of heavy neutrinos would be manifest at unsuppressed rates, in the form of same-sign electron and tau with two jets at the LHC –KS process– and in the low energy frontier, in the form of the Lepton Number Violating decay of the meson $K^{\pm} \to \pi^{\mp} e^{\pm} \tau^{\pm}$.

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