HEAVY NEUTRINO MASSES AND MIXINGS AT THE LHC∗

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The $pp \rightarrow lljj$ process is analysed assuming right-handed currents and heavy Majorana neutrinos. We discuss dependence of the cross section $\sigma(pp \rightarrow lljj)$ on the ratio $g_R/g_L$ of right and left gauge couplings. Estimation of the signal strength is given for $\sqrt{s} = 8$ TeV and 14 TeV with $g_R/g_L = 0.6$ and $g_R/g_L = 1$.

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1. Introduction

Recently, several excesses in the invariant mass distributions were reported by the ATLAS and CMS experiments at the $\sqrt{s} = 8$ TeV in $pp \rightarrow jj$ [1–5] and $pp \rightarrow lljj$ [6–8]. Curiously, for all channels, the excesses occurs around similar value of the invariant mass: 1.8–2.2 TeV. Although these data are not statistically significant yet and await verification in the Run 2 of the LHC, they already drew a lot of attention.

One of the attempts to interpret these experimental data within a single framework is to assume a presence of right-handed currents. In such a scenario, an additional heavy gauge boson $W_2^\pm$ is produced in the $pp$ collision. It further decays either to two quarks leading to the dijet signal, or to $WZ/Wh^0$ leading to diboson signal [9–13] or to a charged lepton $l$ and a heavy neutrino $N_a$ [14]. The latter, in turn, decays mainly to a charged lepton and two jets $jj$. The whole process $pp \rightarrow W_2 \rightarrow N_al \rightarrow lljj$ is especially interesting because events with the same-sign (SS) leptons in the final state would clearly signal lepton number violation [15–24].

In this paper, we extend slightly our previous analysis of $pp \rightarrow W_2 \rightarrow N_al \rightarrow lljj$ given in [21] presenting analytical formulae for both neutral and charged gauge boson masses and their mixings matrices for $g_L \neq g_R$. They

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will be used and explored in detail in the forthcoming analysis [25]. We also provide estimations of the cross section \( \sigma(pp \rightarrow eejj) \) for \( \sqrt{s} = 14 \) TeV and \( g_R = g_L \) and \( g_R = 0.6g_L \), not discussed in [21]. Since publishing [21], the process \( pp \rightarrow eejj \) has been discussed e.g. in [9, 12, 13, 22, 26–32].

2. The LHC and \( pp \rightarrow eejj \) in the MLRSM

We focus on the Manifest Left–Right Symmetric Model (MLRSM) based on the SU(2)\(_L\) \( \times \) SU(2)\(_R\) gauge symmetry [33, 34]. Details of the model and more comprehensive list of references can be found e.g. in [35, 36]. The model under consideration contains three heavy neutrinos \( N_a, a = 1, 2, 3 \). We assume that their masses are of the order of 1 TeV and they couple to the charged heavy gauge boson \( W_2^\pm \) in the following way:

\[
L \supset b \frac{g_L}{\sqrt{2}} N_a \gamma^\mu P_R (K_R)_{aj} l_j W_2^{\mu} + \text{h.c.,}
\]

where \( b = g_R/g_L \) is the ratio of the right and left gauge couplings. A direct inspection of matrix elements related to the process \( pp \rightarrow lljj \) shows that beside \( \sqrt{s} \), there are basically three variables that rule the magnitude of the cross section: \( b \), mixing matrix \( K_R \) and mass ratios \( x_a = M^2_{N_a} / M^2_{W_2} \) [21]. As the CMS did not find any excess in the \( pp \rightarrow \mu\mu jj \) channel [7], the first guess is that \( N_e \) practically does not couple to \( \mu \) and \( N_\mu \) is much heavier than \( W_2 \). Such scenario can be described by setting \( M_{N_{1,3}} = 0.925 \text{ TeV}, M_{N_2} = 10 \text{ TeV} \) and choosing the following form of \( K_R \):

\[
K_R = \begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\phi_3} \sin \theta_{13} & 0 & e^{i\phi_3} \cos \theta_{13}
\end{pmatrix}.
\]

Such a form of \( K_R \) seems to be in a good agreement with the data reported by the CMS and ATLAS. The dependence of the cross section for the reaction \( pp \rightarrow eejj \) in the scenario defined by (2) is shown in Fig. 1. Moreover, due to \( K_{R12} = K_{R21} = 0 \), contributions to \( \mu \rightarrow e\gamma \) are negligible in this case.

Let us stress that interferences between degenerate heavy neutrinos have to be carefully treated as they may lead to decreasing of the same-sign signatures in the final state, see Fig. 1. It turns out that the influence of heavy neutrinos \( N_a \), their interferences and mixings, can be conveniently described with the help of two following quantities [21]:

\[
\begin{align*}
r &= \frac{\sigma_{e+e^+} + \sigma_{e^-e^-}}{\sigma_{e+e^-}}, \\
\gamma &= \frac{\sigma_{e+e^+} + \sigma_{e^-e^-} + \sigma_{e+e^-}}{(\sigma_{e+e^+} + \sigma_{e^-e^-} + \sigma_{e+e^-})|b=1,\theta_{13},\phi_3=0}.
\end{align*}
\]
One can check that $\gamma$ depends on $b$ and scales as $\gamma \sim b^2$. On the other hand, $r$ does not depend on the value of $b$ because both numerator and denominator in the definition of $r$ in (3) scales as $b^2$.

It turns out that one can find such values of $\theta_{13}$ and $\phi_3$ that $r = 1/13$ and $\gamma = 0.54$ what reproduces excess in the data related to $pp \to eejj$ reported by the CMS. For example for $\phi_3 = \pi/2$, the value of the angle $\theta_{13}$ has to be $\theta_{13}^{\text{CMS}} = 0.64$.

To show the role played by the ratio $b$, we display in Fig. 1 results of numerical simulation in the MadGraph5 (v2.2.2) [37] for $\sqrt{s} = 8, 14$ TeV and two values of $b$: 0.6 and 1. In the left panel of this figure, one can see that the cross section does depend on the value of $b$. Approximately, it is 2.8 times bigger for $b = 1$ than for $b = 0.6$. To generate an UFO file [38], we have used our implementation of the MLRSM in the FeynRules (v2.0.31) [39].
In summary, we have shortly discussed how the ratio $g_R/g_L$ and heavy neutrinos mixing matrix $K_R$ influence cross section for the process $pp \rightarrow lljj$. Hopefully, Run 2 of the LHC will provide enough data to allow to verify the excesses in $pp \rightarrow jj$ and $pp \rightarrow eejj$ reported by the ATLAS and CMS. This would be crucial information for the Beyond Standard Model scenarios involving additional heavy gauge bosons.

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Appendix

Here, we present explicit analytical formulae for masses of the charged and neutral gauge bosons, $M_{W_{1,2}}^2$ and $M_{Z_{1,2}}^2$ respectively, and orthogonal matrices $U_W$, $U_Z$ which relate gauge eigenstates and mass eigenstates in the Manifest Left–Right Symmetric Model with arbitrary $b = g_R/g_L$. For simplicity, we assume that the mass matrices of both charged and neutral gauge bosons, $\tilde{M}_W^2$ and $\tilde{M}_Z^2$ respectively, are real. A Mathematica file $gLgR$ with these formulae altogether with their tests can be downloaded from http://www.tjel.us.edu.pl/tools.html

The mass matrix of the charged gauge bosons is of the following form

$$\tilde{M}_W^2 = \frac{1}{4} g_L^2 v_R^2 \begin{pmatrix} c_+ & -2c_{12}b \\ -2c_{12}b & (2+c_+)b^2 \end{pmatrix}, \quad (5)$$

where $c_+ = (\kappa_1^2 + \kappa_2^2)/v_R^2$ and $c_{12} = \kappa_1 \kappa_2/v_R^2$. The corresponding masses of charged gauge bosons are

$$M_{W_{1,2}}^2 = \frac{g_L^2 v_R^2}{8} \left\{ c_+ + 2b^2 + c_+ b^2 \pm \sqrt{16c_{12}^2 b^2 + [c_+ - (2 + c_+)b^2]^2} \right\}. \quad (6)$$

The gauge eigenstates $W_g = (W_{L}^\pm, W_{R}^\pm)^T$ and mass eigenstates $W_m = (W_1^\pm, W_2^\pm)^T$ are related by the orthogonal transformation $W_g = U_W W_m$, where

$$U_W = \begin{pmatrix} \cos \xi & \sin \xi \\ -\sin \xi & \cos \xi \end{pmatrix}. \quad (7)$$

The mixing angle $\xi$ in (7) is given by the following relation:

$$\tan 2\xi = -\frac{4bc_{12}}{2b^2 - (1 - b^2)c_+}. \quad (8)$$
The mass matrix of the neutral gauge bosons is of the following form

$$\tilde{M}_Z^2 = \frac{1}{2} g_L^2 v_R^2 \begin{pmatrix} \frac{c_+}{2} & \frac{-c_+ b}{2} & 0 \\ -\frac{c_+ b}{2} \frac{1}{2} (4 + c_+) b^2 & 2 b b' & -2 b b' \end{pmatrix},$$ (9)

where \( b' = g'/g_L \). The corresponding masses of neutral gauge bosons are

$$M_{Z_1,2}^2 = \frac{g_L^2 v_R^2}{2} \left\{ b^2 + \frac{1}{4} c_+ (1 + b^2) + b'^2 + \sqrt{\frac{1}{16} \left[ c_+(1 + b^2) + 4(b^2 + b'^2) \right]^2 - c_+ [b^2 + b^2(1 + b'^2)]} \right\}.$$ (10)

The gauge eigenstates \( Z_g = (W^3_L, W^3_R, B)^T \) are related to the mass eigenstates \( Z_m = (Z_1, Z_2, A)^T \) by the orthogonal transformation \( Z_g = U_Z Z_m \). The mixing matrix has the following form:

$$U_Z = \begin{pmatrix} c_W c_\phi & c_W s_\phi & s_W \\ -s_W s_M c_\phi - c_M s_\phi & -s_W s_M s_\phi + c_M c_\phi & c_W s_M \\ -s_W c_M c_\phi + s_M s_\phi & -s_W c_M s_\phi - s_M c_\phi & c_W c_M \end{pmatrix},$$ (11)

where \( s_\phi = \sin \phi, c_\phi = \cos \phi, s_W = \sin \theta_W, c_W = \cos \theta_W, s_M = \tan \theta_W/b, c_M = \sqrt{1 - s_M^2}, g_L = e/\sin \theta_W \) and \( g' = e/\sqrt{\cos 2\theta_W} \). The mixing angle \( \phi \) is defined by the following relation:

$$\sin 2\phi = -\frac{c_+ g_L^2 v_R^2 b^2 \sqrt{b^2 + b'^2 (1 + b'^2)}}{2 (b^2 + b'^2) \left( M_{Z_2}^2 - M_{Z_1}^2 \right)}. \quad (12)$$

Finally, let us note that in the limit \( b \to 1 \), formulae (5)–(12) reduce to (35)–(41) from paper [36].

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