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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 $pp \rightarrow W_2 \rightarrow N_a l \rightarrow lljj$ 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 $pp \rightarrow W_2 \rightarrow N_a l \rightarrow lljj$ 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:

$$\mathcal{L} \supset b \frac{g_L}{\sqrt{2}} \bar{N}_a \gamma^\mu P_R (K_R)_{aj} l_j W_{2\mu}^+ + \text{h.c.}, \quad (1)$$

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 $x_a = M_{N_a}^2/M_{W_2}^2$ [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 μ and N_μ is much heavier than W_2 . Such scenario can be described by setting $M_{N_{1,3}} = 0.925$ TeV, $M_{N_2} = 10$ TeV and choosing the following form of K_R :

$$K_R = \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\phi_3} \sin \theta_{13} & 0 & e^{i\phi_3} \cos \theta_{13} \end{pmatrix}. \quad (2)$$

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]:

$$r = \frac{\sigma_{e^+e^+} + \sigma_{e^-e^-}}{\sigma_{e^+e^-}}, \quad (3)$$

$$\gamma = \frac{\sigma_{e^+e^+} + \sigma_{e^-e^-} + \sigma_{e^+e^-}}{(\sigma_{e^+e^+} + \sigma_{e^-e^-} + \sigma_{e^+e^-})|_{b=1, \theta_{13}, \phi_3=0}}. \quad (4)$$

One can check that γ 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 .

Fig. 1. Left panel: Cross section for the production of two leptons ee and two jets jj vs. mixing angle θ_{13} calculated within MLRSM model with $b = 1$. The same-sign (SS) and cumulative *i.e.* opposite-sign + same-sign (OS+SS) contributions to the cross section are shown. Horizontal dot-dashed lines represent values of cross sections measured by the CMS. Dashed vertical line corresponds to the value of $\theta_{13}^{\text{CMS}} = 0.64$ for which the cross section has the same value as measured by the CMS. Right panel: Cross section for the process $pp \rightarrow eejj$ vs. mass of charged gauge boson M_{W_2} for $\sqrt{s} = 8, 14$ TeV and $b = 0.6$ (solid lines) and $b = 1$ (dashed lines). Lower dashed line corresponds to $\sqrt{s} = 8$ TeV and $b = 1$, while upper dashed line corresponds to $\sqrt{s} = 14$ TeV and $b = 1$.

It turns out that one can find such values of θ_{13} and ϕ_3 that $r = 1/13$ and $\gamma = 0.54$ what reproduces excess in the data related to $pp \rightarrow eejj$ reported by the CMS. For example for $\phi_3 = \pi/2$, the value of the angle θ_{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, $\widetilde{M}_W^2$ and $\widetilde{M}_Z^2$ 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

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

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

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

The gauge eigenstates $\mathbf{W}_g = (W_L^\pm, W_R^\pm)^T$ and mass eigenstates $\mathbf{W}_m = (W_1^\pm, W_2^\pm)^T$ are related by the orthogonal transformation $\mathbf{W}_g = U_W \mathbf{W}_m$, where

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

The mixing angle ξ 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

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

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

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

The gauge eigenstates $\mathbf{Z}_g = (W_L^3, W_R^3, B)^T$ are related to the mass eigenstates $\mathbf{Z}_m = (Z_1, Z_2, A)^T$ by the orthogonal transformation $\mathbf{Z}_g = U_Z \mathbf{Z}_m$. The mixing matrix has the following form:

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

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 ϕ is defined by the following relation:

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

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

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