Studying the Left-Right Symmetric Model through charged Higgs production at the LHC

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We investigate the single production of doubly and singly charged Higgs bosons in the Minimal Left Right Symmetric Model (MLRSM), in association with gauge bosons and neutral scalars. In order to accommodate the present experimental constraints, the $SU(2)_R$ breaking scale is considered to be about 8 TeV and the vacuum expectation value of one of the Higgs doublets is set close to zero, while that of the other doublet is kept as the same as EW symmetry breaking scale. We have found that the cross-section for two particle productions involving doubly charged scalars is not significant enough at 14 TeV LHC. On the other hand, three particle productions like $H_L^{++}W^-H_3^0$ / $H_L^{++}W^-W^-$ / $H_L^{++}W^-A_2^0$ / $H_L^{++}W^-H_1^-$ are found to be significant with cross-section in the 1-10 pb range. Right handed doubly charged scalar (H_R^{++}) does not have enough production cross-section even in the three body production modes. We analyze the above processes considering the subsequent decays into SM final state particles. We also carry out the background analysis and establish the significant parameter space regions that could be probed at the LHC.

1. Introduction

The Standard Model (SM) successfully explains almost all the experimental results so far, including the measurements related to the recently discovered Higgs boson at LHC. Yet, there are many unanswered questions related to the hierarchy problem, dark matter, the number of families in the quark and lepton sector, neutrino mass problem, etc., requiring to go beyond the SM to find explanations. The Left-Right Symmetric Model (LRSM) is one of the simplest models beyond the SM, which has the potential to offer answers to some of the above issues. The gauge group of the LRSM is a very simple extension of the SM, with an additional $SU(2)_R$ symmetry under which the right-handed fermions transform as doublets, while the left-handed ones are invariant. This leads to three heavy gauge bosons $W_R^\pm$ and Z_R along with SM gauge bosons in EW scale.The presence of additional right-handed neutrinos give rise to Majorana Masses, resulting in naturally small neutrino masses through. This minimal version of the model, MLRSM incorporates a Higgs bi-doublet and two Higgs triplets. The Left -Right Symmetric gauge theory keep the fermionic content of the SM intact, also incorporate the full quark-lepton symmetry of the weak interactions and give rise the U(1) generator of the electroweak symmetry group a definite meaning in terms of the $B - L$ quantum number. The triplet representations of the Higgs fields are chosen such that they can couple to lepton-lepton channels, thereby leading to the generartion of Seesaw Mechanism.

The MLRSM is elaborately explained in [1, 2, 3, 4], to which we refer the reader for the details, while the next section introuduces the model in a concise manner, especially focusing on what is relevant to this report. Following this, in section 3, we discuss the process being considered, and the results obtained. In section 4 we summarise the study and present the conclusions.

2. The Model

The full Lagrangian of the MLRSM, with the gauge symmetry of $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ is discussed in Ref. [1]. In order to be brief, we shall present the scalar potential of the model, which is relevant to the phenomenology of the Higgs sector at the LHC. The bi-doublet (ϕ), and the left- and right-triplet scalar fields transform under the $SU(3)_c$, $SU(2)_L$, $SU(2)_R$ and $U(1)_{B-L}$ gauge groups as denoted in the brackets along side the fields below:

$$\phi(1, 2, 2, 0),\ \Delta_L(1, 3, 1, 2),\ \Delta_R(1, 1, 3, 2). \tag{1}$$

The $B-L$ quantum number in Δ_R field has been chosen to realise the seesaw mechanism to explain small neutrino masses. A convenient representation of the field is given by the 2×2 matrices:

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

The most general scalar field potential of the model can be written as [5]

$$\begin{aligned}
V(\phi,\Delta_L,\Delta_R) &= -\mu_1^2(Tr[\phi^\dagger\phi]) - \mu_2^2(Tr[\tilde{\phi}\phi^\dagger] + (Tr[\tilde{\phi}^\dagger\phi])) - \mu_3^2(Tr[\Delta_L\Delta_L^\dagger] + Tr[\Delta_R\Delta_R^\dagger]) \\
&+\lambda_1((Tr[\phi\phi^\dagger])^2) + \lambda_2(Tr[\tilde{\phi}\phi^\dagger]^2 + Tr[(\tilde{\phi}^\dagger\phi])]^2) + \lambda_3(Tr[\tilde{\phi}\phi^\dagger]Tr[\tilde{\phi}^\dagger\phi]) \\
&+\lambda_4(Tr[\phi\phi^\dagger](Tr[\tilde{\phi\phi}] + Tr[\tilde{\phi}^\dagger\phi])) + \rho_1((Tr[\Delta_L\Delta_L^\dagger])^2 + (Tr[\Delta_R\Delta_R^\dagger])^2) \\
&+\rho_2(Tr[\Delta_L\Delta_L]Tr[\Delta_L^\dagger\Delta_L^\dagger] + Tr[\Delta_R\Delta_R]Tr[\Delta_R^\dagger\Delta_R^\dagger]) + \rho_3(Tr[\Delta_L\Delta_L^\dagger]Tr[\Delta_R\Delta_R^\dagger]) + \\
&+\rho_4(Tr[\Delta_L\Delta_L]Tr[\Delta_R^\dagger\Delta_R^\dagger]) + \alpha_1(Tr[\phi\phi^\dagger](Tr[\Delta_L\Delta_L^\dagger] + Tr[\Delta_R\Delta_R^\dagger])) + \alpha_2(Tr[\phi\tilde{\phi}^\dagger]Tr[\Delta_R\Delta_R^\dagger] \\
&+Tr[\phi^\dagger\tilde{\phi}]Tr[\Delta_L\Delta_L^\dagger]) + \alpha_2^\star(Tr[\phi\tilde{\phi}^\dagger]Tr[\Delta_R\Delta_R^\dagger] + Tr[\phi^\dagger\tilde{\phi}]Tr[\Delta_L\Delta_L^\dagger]) \\
&+\alpha_3(Tr[\phi\phi^\dagger\Delta_L\Delta_L^\dagger] + Tr[\phi^\dagger\phi\Delta_R\Delta_R^\dagger]) + \beta_1(Tr[\phi\Delta_R\phi^\dagger\Delta_L^\dagger] + Tr[\phi\Delta_L\phi\Delta_R^\dagger]) + \\
&\beta_2(Tr[\tilde{\phi}\Delta_R\phi^\dagger\Delta_L^\dagger] + Tr[\tilde{\phi}^\dagger\Delta_L\phi\Delta_R^\dagger]) + \beta_3(Tr[\phi\Delta_R\tilde{\phi}^\dagger\Delta_L^\dagger] + Tr[\phi^\dagger\Delta_L\phi\Delta_R^\dagger]).
\end{aligned} \tag{3}$$

Because of the non-zero quantum number $B-L$ of the Δ_R and Δ_L triplets, these always appear in quadratic combinations. Here, $\tilde{\phi} \equiv \tau_2\phi^\star\tau_2$, and the LR symmetry implies that the Lagrangian is symmetric under

$$\Delta_R \leftrightarrow \Delta_L, \phi \leftrightarrow \phi^\dagger. \tag{4}$$

The $SU(2)_R$ symmetry is broken spontaneously with the neutral Higgs fields δ_R^0 acquiring VEV of υ_R, leading to massive W_R and Z_R, and also generating masses to the right-handed neutrinos. The VEV's of the higgs bidoublet field κ_1 and κ_2 with the relation of SM VEV $v = \sqrt{k_1^2 \pm k_2^2}$ have double action of breaking the remaining symmetry $SU(2)_L \times U(1)_{B-L}$ down to the usual $U(1)_{EM}$ and setting the mass scale for the W_L and Z boson along with quark and lepton Dirac masses. The VEV of the left-triplet, $< \delta_L^0 > = \upsilon_L$, if present, will affect the precision electroweak observable, ρ parameter, and therefore requires to be very small (less than 3.5 GeV) [6]. The VEV υ_R must be larger than κ_1 and κ_2 such that the mass of W_R and Z_R are significantly heavier than W_L and Z. After the symmetry breaking of the potential, we will have three extra heavy gauge bosons $W_R^\pm$ and Z_R; four neutral Higgs scalars H_0^0, H_1^0, H_2^0 and H_3^0; two neutral pseudo scalars A_1^0, A_2^0 and four charged Higgs scalars $H_1^\pm, H_2^\pm, H_L^{\pm\pm}, H_R^{\pm\pm}$. The parameters and mass relations of scalars and gauge bosons of MLRSM can be found in Ref. [7].

The recent LHC analysis limits the W_R mass to be above 2.8 TeV [8, 9]. For the left-right symmetry of the model, we considered $g_L = g_R$. Z_R is related to the W_R mass, $M_{Z_2} \simeq 1.7 M_{W_2}$. The heavy gauge boson masses restrict the $SU(2)_R$ breaking scale to be $\upsilon_R >$ 5 TeV, which dictates the mixing between the left and right sectors to be negligibly small, due to the relation, $\tan 2\xi = -\frac{2k_1k_2}{\upsilon_R^2}$. Experimental limits on $W_L - W_R$ mixing constrains $\xi \leq 0.05$ [6]. We have also taken in to account the bounds on neutral Higgs bosons obtained from FCNC constraints assuming $M_{A_1^0}, M_{H_1^0} >$ 15 TeV by requiring $\alpha_3 = 7.1$. Assuming a 100% same-sign di-lepton decay, the LHC direct searches limit the doubly charged Higgs boson mass to be $M_{H^{++}} \geq 445$ GeV (409 GeV) for CMS (ATLAS) [10, 11].

3. Results

We consider the production of one doubly charged Higgs boson in association with other Higgses, as well as the gauge bosons at the 13 TeV LHC. Compatible with the constrained described above, we consider the following Benchmark Points (BP).

Input parameters:

υ_R = 8 TeV, υ_L = 0, υ = 246 GeV, k_1 = 246 GeV, k_2 = 0

ρ_1 = 0.239764, ρ_2 = 2.36 $\times 10^{-4}$, ρ_3 = 0.48, α_3 = 4.69, λ = 0.13

Derived masses (in GeV):

$W_R^{\pm}$ = 3676.9 , Z_R = 6150.7, H_0^0 = 125, H_1^0 = 15073, H_2^0 = 5539.84, H_3^0 = 122.9

H_1^+ = 350, H_2^+ = 15076.7, A_1^0 = 15073, A_2^0 = 122.9, H_L^{++} = 479.5, H_R^{++} = 495

We have calculated the production cross-section of different channels containing $H_{L/R}^{++}$ in association with scalars and gauge bosons with BP mentioned above at 13 TeV LHC as shown in Table 1. It is seen that the cross-section for production of $H_L^{++}H_1^-$ is sizable at 13 TeV LHC.

Table 1. List of production cross-section of $H_{L/R}^{\pm}$ in association with gauge boson and scalars with the BP at 13 TeV LHC.

Production of H_R^{++} at LHC	σ in fb	Production of H_L^{++} at LHC	σ in fb
$H_R^{++}W^-$	0	$H_L^{++}W^-$	0
$A_2^0H_3^0$	0.4	$H_L^{++}H_1^-$	4.2
$H_R^{++}W_2^-$	0.02	$H_L^{++}W^-H_3^0$	2.0
$H_R^{++}W^-H_1^-$	0	$H_L^{++}W^-A_2^0$	2.0
$H_R^{++}ZH_1^-$	0	$H_L^{++}W^-H_1^-$	1.8
$H_R^{++}W^-A_2^0/H_3^0$	0	$H_L^{++}ZH_1^-$	0.02
$H_R^{++}H_1^-H_1^-$	0.007	$H_L^{++}W^-W^-$	0
$H_R^{++}W_2^-W_2^-$	$6.39.10^{-9}$	$H_L^{++}W^-\gamma$	0

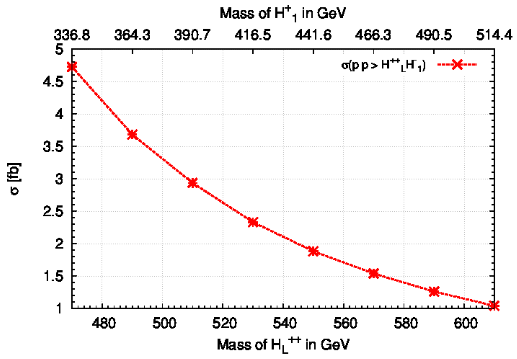

Figure 1. Variation of production cross-section of $H_L^{++}H_1^-$ with different mass of H_L^{++} at 13 TeV LHC.

The variation of cross-section for $H_L^{++}H_1^-$ produced at LHC with different mass of H_L^{++}/H_1^+ is depicted in Fig. 1, which decreases with increasing mass of H_L^{++}/H_1^+. The channel we considered for our preliminary study at LHC is $H_L^{++}W^-H_3^0/A_2^0$, which constitutes most of $H_L^{++}H_1^-$, with subsequent decay of $H_1^- \to W^-H_3^0/A_2^0$. Below we list out all possible tri-linear and quartic couplings, which contribute to the above process:

$H_1^-W^-H_L^{++}$: i $\cos\xi\; g_W$, $\qquad W^+H^-H_3^0(W^+H^-A_2^0)$: i $\cos\xi\; g_W/\sqrt{2}\;(\cos\xi g_W/\sqrt{2})$

$W^-H_3^0W^-H_L^{++}$: -i $\cos\xi^2\; g_w^2\sqrt{2}$, $\qquad H_R^{++}H_3^0H_L^{++}$: -2i $\rho_4\upsilon_R$

$H_2^-H_1^-H_L^{++}$: $\frac{i\alpha_3k_1k_2}{\upsilon\sqrt{1+0.5(k_1^2-k_2^2)^2/\upsilon^2\upsilon_R^2}}$, $\qquad H_1^-H_3^0H_2^-$: $\frac{-i\alpha_3k_1k_2}{\upsilon\sqrt{2}\sqrt{1+0.5(k_1^2-k_2^2)^2/\upsilon^2\upsilon_R^2}}$

In Table 2 we present the cross sections, at two different chosen values of $\upsilon_R = 8$, and 10 TeV at 13 TeV LHC. The BR of $H_L^{++} \to W^+H_1^+$ is 99% and corresponding BR of $H_1^+ \to W^+H_3^0$ is 50 %. The cross-section of the major SM background is also listed in Table 2. The Transverse Momentum (PT) of W boson and the Missing Transverse Energy (MET) for the intermediate state $W^+W^-W^+\nu_\ell\nu_\ell\nu_\ell\nu_\ell$ for signal with two different υ_R value of 8 TeV and 10 TeV are showed in red and blue respectively and in green, PT of W boson and MET for SM

Table 2. Final state cross-section with different υ_R value along with SM background at LHC.

Signal	cross-section in fb
$pp \to H_L^{++} W^- H_3^0 \to W^+ W^- W^+ \nu_\ell \nu_\ell \nu_\ell \nu_\ell$	σ_{13TeV} = 0.94 fb (υ_R = 8 TeV) σ_{13TeV} = 2.6 fb (υ_R = 10 TeV)
SM background $pp \to W^+ W^- W^+ \nu_\ell \tilde{\nu}_\ell$	σ_{13TeV} = 0.08 fb

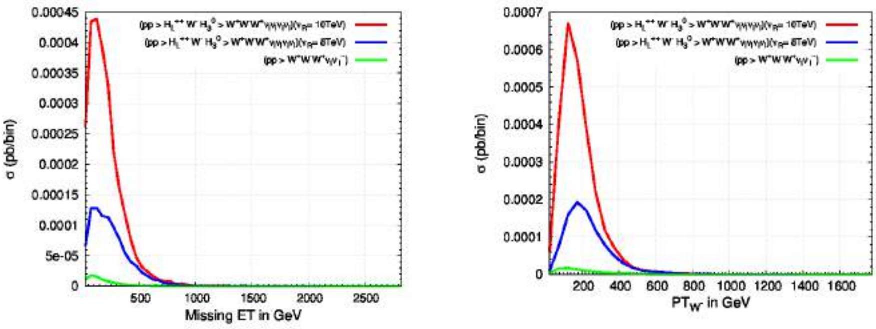

Figure 2. Kinematic distribution of W boson for the final state $W^+ W^- W^+ \upsilon_\ell \upsilon_\ell \upsilon_\ell \upsilon_\ell$ of the process $pp \to H_L^{++} W^- H_3^0$ with different υ_R at 13 TeV LHC.

background are shown in Fig. 2. In this preliminary study, we have found that MLRSM signal with a chosen BP can be found over SM background at 13 TeV LHC.

4. Summary and outlook

The Minimal Left Right Symmetric Model (MLRSM) has the potential to address the issues of dark matter as well as the neutrino mass problems. The Higgs sector of this model is much richer and non-standard with triplet and bidoublet scalar fields present, leading to doubly charged Higgs boson in the physical spectrum, apart from singly charged and more than one neutral Higgs bosons. In the project being discussed, we consider the signatures of the doubly charged Higgs bosons at the LHC. In the preliminary analysis, we have found that distinct scenarios (with different Benchmark Points in the parameter space) where cross section for single production of H_L^{++} along with H_1^- is significant . Detailed of the study will be carried out with the analyses of detector level final states, to establish methods to identify the signature of the doubly charged Higgs bosons for the selected Benchmark Points.

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