The lowest limits on the doubly charged Higgs boson masses in the minimal left-right symmetric model

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The doubly charged Higgs bosons would undoubtedly be clear messengers of the new physics. We discuss their mass spectrum and show how experimental data and relations between scalar masses put limits on it. In particular, both the mass level $M_{PCNC}$ of the particles that play a crucial role in FCNC effects and the masses of the additional gauge bosons are notably important. For instance, if $M_{PCNC} \simeq 15$ TeV and $M_{H^\pm} \simeq 3.76$ TeV then the lowest mass of $H_{2}^{\pm\pm}$ is 465 GeV. In contrast, due to the freedom in the parameter space of the full scalar potential, there is no lowest limit on the mass of $H_{2}^{\pm\pm}$. It is shown to which signals at hadron colliders such relatively light doubly charged scalars might correspond. LHC working at $\sqrt{s} = 14$ TeV will enter into the region where existence of such particles with minimal masses can be thoroughly explored for a much wider MLRSM parameter space. Taking into account our considerations and present ATLAS and CMS exclusion limits on $M_{H^{\pm\pm}}$, there exist already first partial bounds on some of the MLRSM scalar potential parameters.

As argued among others in [1], the Higgs boson discovery at the LHC [2][3] was a “Big Deal”. It established the Standard Model (SM) of gauge interactions and proved that the intuition was correct, as far as the mechanism of mass generation is concerned.

Now further investigations are needed as we would like to know the details of the scalar sector. The underlying gauge theory need not to be necessarily the SM which is based on the $SU(2) \times U(1)$ symmetry. In fact, there are many arguments that the SM is an effective theory working at relatively low energies [4]. Then, going beyond the SM, one or two open and crucial questions are: what is the representation for the scalar multiplets and what is the shape of the scalar potential of the fundamental theory in particle physics? Are the fundamental forces unified, and if yes, then in which way? So far we do not have any particular answer to these queries. For instance, there are suggestions that the measured values of $m_{H}$ and $m_{t}$ make the electroweak vacuum metastable, and a new physics should be below $\sim 10^{10} - 10^{12}$ GeV [5]. However, there are also arguments for the Standard Model being a valid theory up to the Planck scale [6].

SM scalar sector consists of a doublet of complex scalar fields. There are four real scalar fields, three of them are responsible for giving masses to the three gauge bosons $W^{\pm}, Z^{0}$ through the Higgs mechanism. The remaining scalar is associated with the neutral Higgs boson which has been discovered at the LHC. However, if we go beyond the SM, we may need to deal with more complex scalar systems, for instance $SU(2)$ triplet which contains charged (singly and/or doubly) scalar particles. These particles are naturally embedded in the left-right symmetric models where a new characteristic energy scale exists and the symmetry between left and right $SU(2)$ gauge sectors is broken spontaneously [7][8]. Here we focus on the so-called minimal and manifest version of the model (MLRSM), see e.g. [7][10].

There is presently large activity in searching for the scalar particles of any sort (neutral, charged) at the LHC. In particular, knowledge of the existence of doubly charged scalar bosons would be crucial for further directions in exploration of particle physics phenomena, for instance, their presence would strongly disfavour the minimal version of the supersymmetric Standard Model. There are two basic ways in which doubly charged particles can be searched for. The first is indirect: looking for rare lepton flavour and number violating processes and precision measurements (deviations from the SM expectations). The second opportunity is provided by the accelerators where new particles can be produced directly at high energies, as in the LHC. There are already many analysis undertaken by the CMS and ATLAS collaborations regarding these kind of searches, and the present limits for doubly charged scalars are:

$$M_{H^{\pm\pm}} \geq 445 \text{ GeV} \quad (409 \text{ GeV}) \quad \text{for CMS (ATLAS)}, \quad (1)$$

in the 100% leptonic branching fraction scenarios [11][12]. We assume the same framework here. Other scenarios are also possible within MLRSM [13] or in another models, e.g. Higgs Triplet Model [14][15].

In this paper, we show that theoretical considerations are also important, and we find that in the MLRSM some of the scalar masses are constrained from below. In particular, the lowest limit for the doubly charged scalar $H_{2}^{\pm\pm}$ mass is not much beyond the present limit given in Eq. (1) for many different model parameters.
Recently, it has been shown in [13] that charged scalars with masses at the level of a few hundred GeV can be realized in the MLRSM by allowing a percent-level tuning of the scalar potential parameters, compatible with both the large parity breaking scale $v_R$ and severe bounds on neutral scalar masses ($M_{FCNC}$) derived from flavour changing neutral currents (FCNC). This is non-trivial as both $v_R$ and $M_{FCNC}$ are at the level of a few TeV and all scalars apart form $H_0^\pm$ are naturally heavy, their leading mass terms are proportional to $v_R$. In this paper, we look into further details and show that in fact lowest bounds can be obtained for some of the scalar masses. The MLRSM scalar potential and its minimization followed by the diagonalization have been investigated in [10] and explicit relations between physical and unphysical scalar fields are given in [17]. For our purposes, we repeat here only a subset of formulas which we need for further discussion, they are valid as long as $\kappa_1 \ll v_R$, which is true as $\kappa_1$ and $v_R$ are connected directly with masses of light and heavy charged gauge bosons, and $M_{W_1} \ll M_{W_2}$ [13, 18].

$$M^2_{H_0^\pm} \simeq 2\kappa^2_2 \lambda_1,$$

$$M^2_{H_0^\mp} \simeq \frac{1}{2} \alpha_3 v^2_R,$$  

$$M^2_{A_1} \simeq \frac{1}{2} \alpha_3 v^2_R - 2\kappa^2_2 (2\lambda_2 - \lambda_3),$$

$$M^2_{A_1} \simeq \frac{1}{2} v^2_R (\rho_3 - 2\rho_1),$$

$$M^2_{H_2^\pm} \simeq \frac{1}{2} \left[ v^2_R (\rho_3 - 2\rho_1) + \alpha_3 \kappa^2_1 \right],$$

$$M^2_{H_2^\mp} \simeq 2\rho_2 v^2_R + \frac{1}{2} \alpha_3 \kappa^2_1.$$  

As we can see, SM-like Higgs boson $H_0^\pm$ has a mass proportional to the vacuum expectation value $\kappa_1$ (≈ electromagnetic breaking scale, $M_{W_1} \sim \kappa_1$ [9]). Here, among the neutral scalars only $A_1^0$ and $H_0^\mp$ contribute to the FCNC interactions. To our knowledge, their effects have been discussed for the first time in the context of left-right models in [19], see also [20, 24] and the Appendix in [13]. In general their masses need to be at least of the order of 10 TeV, though some alternatives have been also considered in [25]. Also, the parity breaking scale $v_R$ is already strongly constrained by a “golden” decay chain process $W_R \to l_1 N_1 \to l_1 z j j$ [26, 27], $M_{W_2} \geq 2.8$ TeV. This limit (at 95% C.L.) is for a genuine left-right symmetric model which we consider here (MLRSM). There are also other model independent limits on the masses of gauge bosons $\sim 4$ TeV and we stay conservative while choosing this value that implies $v_R$ is already bigger than 8 TeV. For more details and other possible scenarios see [13] and recent [28, 29].

Now, taking into account the above facts, for example with $M_{H_1^\pm, A_1^0} \geq 10$ TeV and $v_R \geq 8$ TeV, the scalar potential parameter $\alpha_3$ can be determined, see Eq. [8]. This parameter also enters into the relations of the masses of doubly charged scalars, Eqs. [6] and [7]. Thus the only free parameter that constrains $M_{H_1^\pm}$ is $\delta \rho \equiv \rho_3 - 2\rho_1$.

![FIG. 1: Dependence of the $H_1^{\pm\pm}$ mass on $\delta \rho \equiv \rho_3 - 2\rho_1$ for $v_R = 8$ TeV and various masses of flavour changing neutral Higgs scalars $H_1^\pm$ and $A_1^0$. Points marked on the vertical dotted line by square, circle and triangle show minimal $M_{H_1^{\pm\pm}}$ corresponding to $M_{H_1^0, A_1^0} = 10, 15$ and 20 TeV, respectively (see Tab. [1]). In the region left to the vertical dotted line, $M_{H_1^0}$ (dashed line) is smaller than 55.4 GeV (dash-dotted horizontal line). The horizontal grey strip represents the latest CMS exclusion limit on doubly charged Higgs boson mass. The mass spectrum represented by the filled square is obviously ruled out by the LHC. Hence, for $v_R = 8$ TeV and $M_{H_1^0, A_1^0} = 10$ TeV the minimal allowed value of $M_{H_1^{\pm\pm}}$ is 445 GeV (empty square) and one gets the following lower bound $\delta \rho \gtrsim 3 \cdot 10^{-3}$.](image-url)
It is worthwhile to note that taking into account experimental limits one can obtain the following bound on $M_{H_1^{±±}}$:

$$\sqrt{\min(M_{R_1}^2) + M_{H_1^{±±}}^2 v_R^2} \approx 2.41 \text{ TeV}^2 \quad \frac{v_R}{(8)}$$

The dashed line in Fig. 1 is for $M_{H_1^{±±}}$. At $\delta \rho \approx 10^{-4}$, it crosses the horizontal line which corresponds to the lowest bound on mass of $H_1^{±±}$. Hence, the region left to the vertical, dotted line is excluded due to the above mentioned LEP constraints and minimal mass of $H_1^{±±}$ can be determined from the points at which solid lines intersect vertical, dotted line. Some precise values of $H_1^{±±}$ masses corresponding to such points are presented in the Tab. 1.

| $v_R = 8$ TeV ($M_{W_2} = 3.76$ TeV) | $M_{A_1^±, H_1^0}$ [TeV] | $\alpha_3$ | $\min(M_{H_1^{±±}}^±)$ [GeV] |
|--------------------------------|----------------------|---------|--------------------------------|
| 10                             | 3.13                 | 312     | (■)                            |
| 15                             | 7.03                 | 465     | (●)                            |
| 20                             | 12.5                 | 617     | (▲)                            |

| $v_R = 10$ TeV ($M_{W_2} = 4.7$ TeV) | $M_{A_1^±, H_1^0}$ [TeV] | $\alpha_3$ | $\min(M_{H_1^{±±}}^±)$ [GeV] |
|--------------------------------|----------------------|---------|--------------------------------|
| 10                             | 2.0                  | 252     |                                |
| 15                             | 4.5                  | 373     |                                |
| 20                             | 8.0                  | 495     |                                |

| $v_R = 12$ TeV ($M_{W_2} = 5.64$ TeV) | $M_{A_1^±, H_1^0}$ [TeV] | $\alpha_3$ | $\min(M_{H_1^{±±}}^±)$ [GeV] |
|--------------------------------|----------------------|---------|--------------------------------|
| 10                             | 1.39                 | 212     |                                |
| 15                             | 3.13                 | 312     |                                |
| 20                             | 5.56                 | 413     |                                |

TABLE I: Minimal masses of a doubly charged Higgs boson $H_1^{±±}$ as a function of the parity breaking scale $v_R$ of the right sector of the model and the mass of neutral Higgs bosons $\{A_1^0, H_1^0\}$ which contribute to the FCNC effects. Corresponding masses of $H_1^{±±}$ are fixed by taking in addition $\rho_2 = \delta \rho/4$, what yields $M_{H_1^{±±}} = M_{H_1^{±±}}$. No LHC direct limits from Eq. 4 applied. Square, circle and triangle correspond to points marked on Fig. 1.

Let us remark that there is, in principle, no restriction from the scalar potential parameters on $M_{H_1^{±±}}$, as the parameter $\rho_2$ does not play any role to determine the masses of other remaining scalars, $H_2^0, A_2^0, H_2^{±±}, H_2^{±±}$. Thus this parameter is not constrained within perturbative limit. Here, for example we have set $\rho_2 = \delta \rho/4$ in Tab. 1. Moreover, note that $\min(M_{H_1^{±±}})$ decreases with $v_R$, see Eq. 8.

It is clear that some of $M_{H_1^{±±}}$ in Tab. 1 are already excluded by the LHC limits, Eq. 1. It means that the first constraints on scalar potential parameters can be derived from those experimental bounds, as already seen in Fig. 1 (point marked by empty square). To this end, it is worthwhile to examine the influence of $\alpha_3$ on masses of $H_1^{±±}$. Let us focus on $v_R = 8$ TeV case. When $\delta \rho$ is smaller than about $10^{-4}$ then mass of doubly charged scalar is dominated by the term $\sqrt{\alpha_3 v_1}/\sqrt{2}$. On the other hand, if $\delta \rho$ is bigger than $10^{-2}$ then its mass is mainly driven by $v_R \sqrt{\delta \rho/2}$. On Fig. 2 it is shown how those masses depend on $\delta \rho$ and $\alpha_3$ in the region of the parameter space where both contributions to masses are important. On that plot, we have shaded the regions of the parameter space which are excluded either by FCNC (i.e. $M_{H_1^0, A_1^0} \geq 10$ TeV) or LHC. Note that there is also excluded region related to the lower bound on $H_3^0$ mass (left of the vertical dashed line). It is straightforward to do similar analysis for dependence of $H_2^{±±}$ mass on $\alpha_3$ and $\rho_2$.

As an example, we present benchmark set of scalar masses which satisfy both FCNC and LHC constraints with light and degenerate masses of doubly charged scalars, assuming $v_R = 8$ TeV (all masses are given in GeV):

$$M_{H_1^0} = 125,$$
$$M_{H_2^0} = 16492, \quad M_{H_2^0} = 11314, \quad M_{H_1^0} = 253,$$ (9)
$$M_{A_1^0} = 16496, \quad M_{A_1^0} = 253,$$ (11)
$$M_{H_1^{±±}} = 439, \quad M_{H_2^{±±}} = 16496,$$ (12)
$$M_{H_1^{±±}} = 567, \quad M_{H_2^{±±}} = 567.$$ (13)

These masses are outcome of the following parameters of
the scalar potential:
\[
\rho_1 = 1.0, \quad \rho_2 = 5 \cdot 10^{-4}, \quad \rho_3 - 2 \rho_1 = 2 \cdot 10^{-3},
\]
\[
\lambda_1 = 0.13, \quad \lambda_2 = 0, \quad \lambda_3 = 1,
\]
\[
\alpha_3 = 8.5.
\]

This scenario realizes mass spectrum with maximal number (three) of light charged scalars [13]. Of course, yet another setups are also possible. For example, in-number (three) of light charged scalars [13]. Of course, increasing parity breaking scale to 20 TeV, setting
\[
\delta \rho \sim 10^{-3}
\]
and tuning \(\alpha_3 \sim 0.5\), \(\rho_1 \sim \rho_2 \gtrsim \alpha_3 / 4\) and tuning \(\delta \rho \sim 10^{-3}\) give \(H_{3}^{0}, H_{2}^{\pm}\) and \(H_{1}^{\pm}\) masses \(\sim v_R \sqrt{\alpha_3 / 2} \sim 450\) GeV, while the remaining scalars (beside \(H_{0}^{0}\)) have masses larger than \(v_R \sqrt{\alpha_3 / 2} \sim 10\) TeV. The other option is to keep \(v_R \sim 10\) TeV but also choose \(\rho_2 \sim 10^{-3}\) and set \(\delta \rho \sim \alpha_3 \sim 2\). As a result, only \(H_{2}^{\pm}\) is light, with mass \(\sim 500\) GeV, while other scalars are heavier than 10 TeV.

Let us note that all these spectra are also in agreement with low-energy constraints, here muon \(\Delta \tau\) parameter plays a crucial role [24, 31, 32]. It is interesting to note that scalar and fermionic loop contributions come up with opposite signs to \(\Delta \tau\) and heavy neutrinos can compensate possible large scalar effects [24, 31, 32].

We have focused here on doubly charged Higgs bosons, aiming at their small masses, but we can see that they are entangled by the scalar potential parameters, and in this way also some singly charged and neutral scalars are relatively light. Their effects at hadron colliders will be studied in details elsewhere.

Fig. 3 gives estimation of cross sections for the pair production of doubly charged Higgs bosons at LHC for the center of mass energies at present (8 TeV), forthcoming run (13 – 14 TeV) and in the further perspective (100 TeV). For the simplicity, we assume that masses of \(H_{1}^{\pm\pm}\) and \(H_{2}^{\pm\pm}\) are degenerate i.e. \(\delta \rho = 4 \rho_2\). Limits on the doubly charged Higgs boson \(H_{2}^{\pm\pm}\) masses from recent LHC data have been taken into account, and exclusion limits are explicitly given in Fig. 3.

Here, the cross section for the process \(pp \rightarrow (H_{1}^{\pm\pm} + H_{1}^{\mp\mp} + H_{2}^{\pm\pm} + H_{2}^{\mp\mp}) \rightarrow 4\ell\) for different centre of mass energies \(\sqrt{s} = 8, 14\) and 100 TeV at the LHC with only basic cut (lepton \(p_T > 10\) GeV) is shown in Fig. 3 for different set of doubly charged scalar masses. We have also implemented the detailed event selection criteria, as given in [13] to compute the SM background for this final state coming from \(t\bar{t}(Z/\gamma^*)\), \((Z/\gamma^*) Z/\gamma^*)\). Using the same set of cuts the signal event cross section is estimated for doubly charged scalar masses [450-900] GeV. We have pointed out four benchmark points for the following masses of doubly charged scalars: 450, 600, 700, and 900 GeV. The corresponding significances [34] of the signal for integrated luminosity 300 fb\(^{-1}\) are 13.8, 5.7, 3.3, 1.0 respectively. Thus at the LHC with \(\sqrt{s} = 14\) TeV centre of mass energy and 300 fb\(^{-1}\) luminosity up to 600 GeV mass of the doubly charged scalars can be probed with significance \(\geq 5\). Finally, it is worthwhile to note that due to kinematics for \(\sqrt{s} = 100\) TeV discussed cross-section does not change significantly when mass of doubly charged scalars increases.

In summary, though BSM models (to which MLRSM belongs) usually include mass spectrum at large energy scales, relatively light scalar masses (below TeV level) might be allowed. In this brief report we have analysed correlations between the scalar masses and the scalar potential parameters within MLRSM framework. We have noted that it is still possible to find some of the scalar fields as light as few hundred GeV even when the new scale is around \(\sim 10\) TeV, and these spectra are in good agreement with sharp conditions forced by experimental data. Though there are many free parameters in the Higgs sector, present experimental limits on masses of doubly charged Higgs bosons put already first partial constraints on some of these parameters. Moreover, our analysis shows that the lowest limit on doubly charged scalar mass \(M_{H_{2}^{\pm\pm}}\) can be obtained. The other doubly charged scalar \(H_{2}^{\pm\pm}\) is theoretically not constrained from below in the discussed model and it can be tuned to any desirable value, in agreement with experimental data. The lowest limit on \(M_{H_{1}^{\pm\pm}}\) is important, as we know that production of \(H_{1}^{\pm\pm}\) is much bigger than that of \(H_{2}^{\pm\pm}\) [39].

Cross sections for the pair productions of doubly charged scalars followed by their leptonic decays have been discussed toghether with estimation of the SM background
at 14 TeV centre of mass energy.  
Using an example of the MLRSM model we have shown that we are slowly approaching era at the LHC physics where details of the elusive Higgs sector of the tested theory can be analysed.

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