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Exploring Constraints on the Doublet Left-Right Symmetric Model Using Higgs Data

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In this work, we examine the constraints imposed on the doublet left-right symmetric model (DLRSM) by analyzing Higgs data from LHC. Specifically, we investigate the key parameters of the model, denoted as the ratios $r = \kappa_2/\kappa_1$ and $w = v_L/\kappa_1$. While previous research assumed these ratios to be very small, we find that there is no lower bound on either r or w and the upper bound is set by the perturbative requirement of Yukawa couplings . Notably, the Yukawa coupling of the bottom quark to the lightest CP-even scalar not only discourages the selection of small r values but also implies a preference for w values approximately around $O(1)$. These values are also favored by the indirect constraint on the mass of heavy CP-even scalars.

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1. Introduction

Left-right symmetric models, based on the symmetry group $SU(2)_L \times SU(2)_R \times U(1)_{\mathrm{B-L}}$ [1, 2], are promising for physics beyond the standard model (SM). This model's scalar sector necessitates at least three distinct Higgs multiplets. Fermion mass generation relies on a scalar bidoublet Φ, which is a doublet under both $SU(2)_L$ and $SU(2)_R$. The other two scalars can be either $SU(2)$ triplets or doublets. In doublet left-right symmetric models (DLRSM), these two scalars are referred to as χ_L (doublet under $SU(2)_L$ and singlet under $SU(2)_R$) and χ_R (singlet under $SU(2)_L$ and doublet under $SU(2)_R$). The *vev* (vacuum expectation value) v_R of χ_R breaks the symmetry to $SU(2)_L \times U(1)_Y$ and the *vev*s κ_1 and κ_2 of Φ and v_L of χ_L lead to electroweak symmetry breaking (EWSB). The EWSB *vev*s obey the constraint $\sqrt{\kappa_1^2 + \kappa_2^2 + v_L^2} = v_{\mathrm{EW}} = 246$ GeV. For later convenience, we define the two ratios $r = \kappa_2/\kappa_1$ and $w = v_L/\kappa_1$.

Most models based on left-right symmetry assume that EWSB occurs primarily through κ_1, implying $r, w \ll 1$. In this Proceeding, we investigate the constraints imposed on r and w by the precision Higgs data from LHC.

2. Scalar potential

All the particle content and other notations of the model can be found in ref. [3]. The most general, renormalizable Higgs potential involving Φ, χ_L and χ_R fields is given by

$$
\begin{aligned}
V &= V_2 + V_3 + V_4, \\
V_2 &= -\mu_1^2 \mathrm{Tr}(\Phi^\dagger\Phi) - \mu_2^2\, [\mathrm{Tr}(\tilde{\Phi}\Phi^\dagger) + \mathrm{Tr}(\tilde{\Phi}^\dagger\Phi)] - \mu_3^2\, [\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R]\ , \\
V_3 &= \mu_4\, [\chi_L^\dagger\Phi\chi_R + \chi_R^\dagger\Phi^\dagger\chi_L] + \mu_5\, [\chi_L^\dagger\tilde{\Phi}\chi_R + \chi_R^\dagger\tilde{\Phi}^\dagger\chi_L]\ , \\
V_4 &= \lambda_1 \mathrm{Tr}(\Phi^\dagger\Phi)^2 + \lambda_2\, [\mathrm{Tr}(\tilde{\Phi}\Phi^\dagger)^2 + \mathrm{Tr}(\tilde{\Phi}^\dagger\Phi)^2] + \lambda_3 \mathrm{Tr}(\tilde{\Phi}\Phi^\dagger)\,\mathrm{Tr}(\tilde{\Phi}^\dagger\Phi) \\
&\quad +\lambda_4 \mathrm{Tr}(\Phi^\dagger\Phi)\, [\mathrm{Tr}(\tilde{\Phi}\Phi^\dagger) + \mathrm{Tr}(\tilde{\Phi}^\dagger\Phi)] + \rho_1\, [(\chi_L^\dagger\chi_L)^2 + (\chi_R^\dagger\chi_R)^2] + \rho_2\, \chi_L^\dagger\chi_L\chi_R^\dagger\chi_R \\
&\quad +\alpha_1 \mathrm{Tr}(\Phi^\dagger\Phi)[\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R] + \left\{\alpha_2\, [\chi_L^\dagger\chi_L \mathrm{Tr}(\tilde{\Phi}\Phi^\dagger) + \chi_R^\dagger\chi_R \mathrm{Tr}(\tilde{\Phi}^\dagger\Phi)] + \mathrm{h.c.}\right\} \\
&\quad +\alpha_3\, [\chi_L^\dagger\, \Phi\Phi^\dagger\chi_L + \chi_R^\dagger\Phi^\dagger\Phi\chi_R] + \alpha_4\, [\chi_L^\dagger\, \tilde{\Phi}\tilde{\Phi}^\dagger\chi_L + \chi_R^\dagger\tilde{\Phi}^\dagger\tilde{\Phi}\chi_R]\ .
\end{aligned}
$$

Here the potential is made CP-conserving by ensuring that all the couplings are real through suitable field redefinitions.

The conditions which minimize the potential are

$$
\frac{\partial V}{\partial \kappa_1} = \frac{\partial V}{\partial \kappa_2} = \frac{\partial V}{\partial v_L} = \frac{\partial V}{\partial v_R} = 0\ . \tag{1}
$$

We employ these conditions to replace the four mass parameters $\mu_1^2, \mu_2^2, \mu_3^2$, and μ_5 in terms of the vacuum expectation values (*vev*) and quartic couplings. Thus the parameters characterizing the scalar sector of the DLRSM are as follows: $\{\lambda_{1,2,3,4}, \alpha_{1,2,3,4}, \rho_{1,2}, \mu_4, r, w, v_R\}$.

3. CP-even neutral scalars

The gauge and physical bases for the CP-even neutral scalars are $X = (\phi_{1r}^0, \phi_{2r}^0, \chi_{Lr}^0, \chi_{Rr}^0)$ and $X_{\mathrm{ph}} = (h, H_1, H_2, H_3)$ respectively and they are related by

$$
X_{\mathrm{ph}} = U^T X, \qquad U^T M^2 U = M^{2\ \mathrm{diag}}\ . \tag{2}
$$

Here h is the lightest CP-even scalar, with mass of the order of $v_{\rm EW}$, whose properties will be very similar to those of SM Higgs boson and H_i $(i = 1, 2, 3)$ are heavier scalars with masses of the order of v_R. We construct the mass matrix M^2 for scalars using the above potential in the gauge basis. Utilizing non-degenerate perturbation theory, we determine the smallest eigenvalue of the matrix M^2, denoted as the Higgs boson mass m_h^2, as follows:

$$\begin{aligned} m_h^2 &= \frac{\kappa_1^2}{2(1+r^2+w^2)} \times \\ &\quad \Bigg(4\Big(\lambda_1(r^2+1)^2 + 4r(\lambda_4(r^2+1) + r\lambda_{23}) + w^2(\alpha_{124} + r^2(\alpha_1+\alpha_3) + \alpha_2 r) + \rho_1 w^4\Big) \\ &\quad -\frac{1}{\rho_1}(\alpha_{124} + r^2(\alpha_1+\alpha_3) + \alpha_2 r + 2\rho_1 w^2)^2\Bigg), \end{aligned} \tag{3}$$

where $\alpha_{124} = \alpha_1 + r\alpha_2 + \alpha_4$. The positivity of the non-zero eigenvalues of mass matrix leads to the following constraints on the quartic couplings

$$2\rho_{12} = \rho_2 - 2\rho_1 > 0 \ \text{ and } \ \alpha_{34} = \alpha_3 - \alpha_4 > 0 \ .$$

We set $v_R = 20$ TeV in our numerical work in order to satisfy the experimental lower bound on heavy gauge bosons mass (m_{Z_2} and m_{W_2}), which also ensures that $\kappa_1^2, \kappa_2^2, v_L^2 \ll v_R^2$. We now calculate the coupling of lightest scalar h to gauge bosons and to third generation quarks of this model and express it in terms of coupling multipliers.

$$\begin{aligned} \kappa_W &= \frac{c_{hW_1W_1}}{c_{hWW}^{\rm SM}} = \frac{1}{k}\Big((1-2c_\xi s_\xi r)U_{11} + (r - 2c_\xi s_\xi)U_{21} + w c_\xi^2 U_{31} + \frac{v_R}{\kappa_1} s_\xi^2 U_{41}\Big), \\ \kappa_Z &= \frac{c_{hZ_1Z_1}}{c_{hZZ}^{\rm SM}} = \frac{g^2(g^2+2g_{BL}^2)}{(g^2+g'^2)(g^2+g_{BL}^2)}\,\frac{1}{k}\,(U_{11} + rU_{21} + wU_{31}) \ . \\ \kappa_{t(b)} &= \frac{c_{htt(hbb)}}{c_{htt(hbb)}^{\rm SM}} = \frac{k}{m_{t(b)}(1-r^2)}\Big((U_{11} - rU_{21})m_{t(b)} + (U_{21} - rU_{11})(V_L^{\rm CKM}\,\hat{M}_{d(u)}\,V_R^{\rm CKM\dagger})_{33}\Big). \end{aligned}$$

Here $k = \sqrt{1+r^2+w^2}$ and ξ is the mixing angle between $W_{L,R}$. g' and g_{BL} are the gauge coupling of $U(1)_Y$ and $U(1)_{B-L}$ respectively. In this work we assume manifest LR symmetry in the gauge sector which means the gauge couplings associated with $SU(2)_{L(R)}$ are equal i.e. $g_L = g_R = g$. In this model, it is also possible to compute the triple Higgs (h^3) vertex and represent it using the coupling parameter κ_h.

4. Theoretical constraints

All the theoretical constraints on DLRSM including requirements for perturbativity in quartic and Yukawa couplings, maintenance of perturbative unitarity in gauge boson scattering, and criteria for boundedness of the scalar potential from below can be found here[3, 4]. The requirement of perturbativity of the Yukawa couplings of quarks to Higgs bidoublet leads to strong upper bounds $r \lesssim 0.8$, and $w \lesssim 3.5$. The ratio $x = \lambda_2/\lambda_4$ is constrained by the boundedness of the scalar potential, leading to the inequality: $8x(1-x) > 0$. This inequality implies that for positive values of x, the range is restricted to $0.25 \leq x \leq 0.85$.

5. Constraints from Higgs data

We want to examine how the Higgs data restrict the possible values of the parameters r and w. We have ten quartic couplings that can vary independently, as long as they satisfy the above mentioned inequalities. However, to better understand how the data influences the values of r and w, we fix the ten quartic couplings using the following relations

$$\{\lambda_1 = \lambda_3 = \lambda_4 = \lambda_0, \;\; x = \frac{\lambda_2}{\lambda_4}, \;\; \alpha_1 = \alpha_2 = \alpha_4 = \alpha_0, \;\; p = \frac{\alpha_3}{\alpha_4} - 1, \;\; q = \frac{\rho_2}{2\rho_1} - 1\}.$$

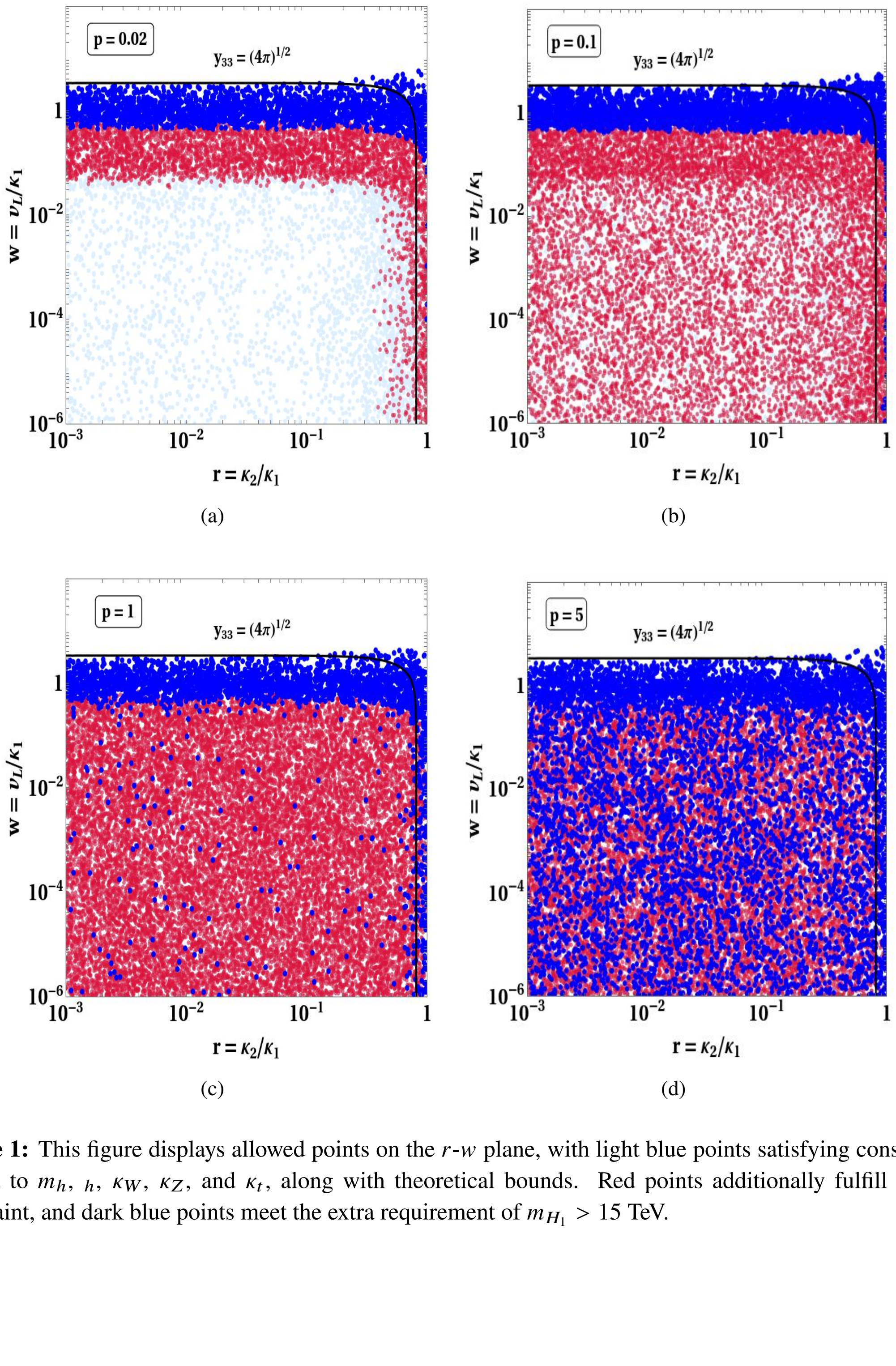
We refer to this set of parameters $\{\lambda_0, \alpha_0, \rho_1, x, p, q, r, w, v_R\}$ as the '*simple*' basis as opposed to the '*generic*' basis where all the λs and all the αs are taken to be independent. In our calculations, we set v_R to a constant value of 20 TeV. For specific values of α_0, ρ_1, x, p, and q, we solve equation (3) to determine a solution for λ_0, denoted as Λ_0. To maximize the number of solutions that satisfy the m_h constraint, we randomly select values for λ_0 within the restricted range: $\lambda_0 = (1 + y)\Lambda_0$ where y ranges from -0.1 to 0.1. Random values for x and y are selected on a linear scale within their respective ranges, while random values for the other parameters are chosen on a logarithmic scale, in the ranges specified below:

$$\alpha_{1,2,4} \equiv \alpha_0 \in [10^{-3}, 4\pi], \;\; \rho_1 \in [0.1, 8\pi/3], \;\; \mu_4 \in [10^{-2}, 1] \times v_R. \tag{4}$$

We fix the ratio q at $q = 1$ and examine four distinct values of p, ranging from 0.02 to 5. At each random point, we compute the numerical values of the lightest Higgs mass m_h and the coupling parameters κ_W, κ_Z, κ_h, κ_t, and κ_b. These values are required to align with the corresponding experimentally measured values listed in reference [4]. The results of our calculation are displayed in fig. 1. As the value of p increases, there is a preference for larger values of w as long as $p \leq 0.1$, though a few points with low r and low w are allowed. Only for $p \geq 1$, the distribution of allowed points becomes uniform over the entire range of r and w. Consequently, to maintain the standard assumption that v_L and κ_2 are significantly smaller than κ_1, α_3 must be at least twice as large as the other α values.

Flavor-changing neutral interactions impose a significant lower limit of 15 TeV on the mass of heavy CP-even scalars (m_{H_1})[5]. Dark blue dots in fig. 1 represent points adhering to this requirement. This bound strongly prefers that *vev* of χ_L has a significant influence on the breaking of $SU(2)_L$. For significantly large values of p (with $p \geq 5$), a substantial number of blue dots appear in the region characterized by low r and low w. These points correspond to larger values of ρ_1 (typically $\rho_1 \gtrsim 1$), which, in turn, drive ρ_2 to exceed 4, rendering it relatively large. Therefore, the conventional assumption that v_L and κ_2 are much smaller than κ_1 remains valid only when quartic couplings ρ_1 and ρ_2 take moderately large values. Additionally, it is worth noting that very small values of q do not satisfy the $m_{H_1} > 15$ TeV constraint, while larger values of q lead to violations of unitarity bounds. These two constraints together constrain the range of q to be between 0.01 and 4. We apply the same approach in generic basis and discover that the patterns of permissible points as a function of w, as shown in fig. 1, reappear in this basis as well.

We systematically vary model parameters, calculate κ_b and κ_t for each combination. When we require the heavy Higgs mass m_{H_1} to be above 15 TeV, we find that only a very small number of the test points satisfy all the experimental constraints. These points tend to concentrate around the coordinates $\kappa_b = 1$ and $\kappa_t = 1$, resembling the 'alignment by decoupling' scenario observed in the two-Higgs-doublet model (2HDM).



(a) (b) (c) (d)

Figure 1: This figure displays allowed points on the r-w plane, with light blue points satisfying constraints related to m_h, $_h$, κ_W, κ_Z, and κ_t, along with theoretical bounds. Red points additionally fulfill the κ_b constraint, and dark blue points meet the extra requirement of $m_{H_1} > 15$ TeV.

6. Conclusions

From the above analysis, it can be concluded that the typical assumption of $v_L, \kappa_2 \ll \kappa_1$ only holds true for only a fine-tuned set of parameters, especially when quartic couplings ρ_1 and ρ_2 have somewhat large values, even when the value of q deviates from 1. We performed calculations with the full, *generic* set of quartic couplings and found that the scarcity of allowed points for small values of r and w remains, and it is even more pronounced. Therefore, our main finding is as follows: While most DLRSM studies assume that $\kappa_1 \approx v_{\rm EW}$ with other $SU(2)_L$ breaking *vev*s being negligible, we have demonstrated that significant values of r and w are consistent with Higgs data and are favored by the indirect constraint on m_{H_1}. Additionally, all points satisfying the constraint $m_{H_1} > 15$ TeV also exhibit $\kappa_{t,,b} \sim 1$ with high precision. This provides confirmation that the lightest scalar in the DLRSM achieves alignment with the SM-like Higgs through the process of decoupling from the heavier scalar states.

7. Acknowledgements

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