Constraints on DLRSM from Higgs Data

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Parity Violation

- Weak interactions are not symmetric under Parity.
- Standard Model (SM) "explains this" by assumting that, under weak isospin, left-chiral fermions form doublets whereas right-chiral fermions are singlets.
- That is, the Lagrangian of the model is not invariant under Parity.
- In the Left-Right Symmetric Model (LRSM), the Lagrangian is symmetric under Parity.
- Parity violation is introduced by Spontaneous Symmetry Breaking (SSB).
- Can also account for CP violation in Kaon system with just two generations of fermions.

Left-Right Symmetric Model

- In this model, an additional $SU(2)$ symmetry is introduced so that left and right-chiral fermions can be treated on par.
- The gauge group of LRSM is $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{(B-L)}$.
- The left-chiral fermions are doublets under $SU(2)_L$ and singlets under $SU(2)_R$.
- The right-chiral fermions are singlets under $SU(2)_L$ and doublets under $SU(2)_R$.
- Left-right symmetry requires that the gauge coupling constants of $SU(2)_L$ and $SU(2)_R$ should be the same.

Additional $U(1)$ Symmetry

- The extra $U(1)$ symmetry is needed so that the electromagnetic interactions are parity invariant.
- Its gauge coupling constant g_{BL} is different.
- We assign $U(1)_{(B-L)}$ quantum numbers, $Y_{(B-L)}$, in such a way that the electric charge is given by

$$Q = T_{3L} + T_{3R} + Y_{(B-L)}/2.$$

- This symmetry also brings in the Baryon number B and the Lepton number L into the model.

Field Content of the Model

- The fermions of the model are

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (3, 2, 1, 1/3), \qquad Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \sim (3, 1, 2, 1/3),$$

$$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1, 2, 1, -1), \qquad L_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \sim (1, 1, 2, -1).$$

- The scalar multiplets of the model are

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (1, 2, 2, 0), \;\; \chi_L = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix} \sim (1, 2, 1, 1),$$

$$\chi_R = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix} \sim (1, 1, 2, 1).$$

- The gauge quantum numbers are given in parantheses.

Spontaneous Symmetry Breaking in the Model

- The neutral components acquire vacuum expectation values (*vevs*)

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_2 \end{pmatrix}, \quad \langle \chi_L \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_L \end{pmatrix}, \quad \langle \chi_R \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_R \end{pmatrix}.$$

- The spontaneous breaking of $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ is driven by the *vev* v_R of the doublet χ_R whereas the electro-weak symmetry breaking (EWSB, $SU(2)_L \times U(1)_Y \to U(1)_{EM}$) is triggered by the three *vevs* κ_1, κ_2, and v_L.

Parity Violation in the Model

- The last three *vevs* are constrained by $\kappa_1^2 + \kappa_2^2 + v_L^2 = v^2$, where $v = 246\,\text{GeV}$. For later use, it is convenient to introduce the ratios $r = \kappa_2/\kappa_1$ and $w = v_L/\kappa_1$.
- The *vevs* of the scalars must have the hierarchy $v_R \gg v$, which ensures that the gauge bosons of $SU(2)_R$ are much heavier than the weak gauge bosons.
- The Yukawa couplings of the bidoublet with left-chiral and right-chiral fermions lead to fermion masses and mixings.

Our Aim in this Work

- Most of the work in LRSM assumes that the ratios $r = \kappa_2/\kappa_1$ and $w = v_L/\kappa_1$.
- That is EWSB is essentially due to κ_1.
- This is convenient from the model building point of view.
- The question we asked is:
  what does the Higgs data from LHC say about these ratios?
- Do κ_2 and especially v_L have any role in EWSB? What does the data say?

Our Strategy

- The LHC experiments, ATLAS and CMS, have measured the mass of the Higgs boson and its couplings to the gauge bosons and the heavy fermions.
- The measurements of the couplings are parametrized in terms of κ factors, defined as measured coupling/SM coupling.
- We compute $\kappa_W, \kappa_Z, \kappa_t$ and κ_b in DLRSM and compare them to the measured values.
- In addition, we also impose the theoretical constraints from perturbativity and unitarity and the experimental constraints on Higgs boson mass and the lower limit on the mass of heavier Higgs bosons.

Most General Scalar Potential

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

Minimization of Scalar Potential

- The conditions for the minimization of the potential are

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

- We use the above four conditions to express μ_1^2, μ_2^2, μ_3^2 and μ_5 in terms of the *vevs*, μ_4 and the quartic couplings.
- We can rewrite the potential in terms of the electroweak symmetry breaking *vev* $v = 246$ GeV and the following fourteen undetermined parameters

$$\{\lambda_{1,2,3,4}, \alpha_{1,2,3,4}, \rho_{1,2}, \mu_4, r, w, v_R\} \ .$$

- Among these, the dimensionful parameters are μ_4 and v_R. For most of the following discussions, we will either set $\mu_4 = 0$ or restrict it to $\mu_4 \lesssim v_R$.

CP-even Neutral Scalar Mass Matrix

- The CP-even neutral scalar mass matrix can be written as a power series in v_R

$$M^2 = \left(M^{2\,(0)} v_R^2 + M^{2\,(1)} v_R + M^{2\,(2)} \right),$$

where each $M^{2(a)}$ $(a = 0, 1, 2)$ is a symmetric 4×4 matrix.

- There is an orthogonal matrix O which diagonalizes $M^{2(0)}$. By applying a similarity transformation using this matrix, we get

$$O^\dagger M^2 O = \tilde{M}^2 = \left(\tilde{M}^{2\,(0)} v_R^2 + \tilde{M}^{2\,(1)} v_R + \tilde{M}^{2\,(2)} \right),$$

where $\tilde{M}^{2\,(0)}$ is diagonal, with one zero eigenvalue.

- The positivity of its non-zero eigenvalues leads to the constraints

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

Mass of the lightest CP-even Scalar

- The lightest CP-even scalar mass must be of the order of v. This imposes the constraint $(\tilde{M^{2}}^{(1)})_{11} = 0$, which also follows from our construction.
- Using non-degenerate perturbation theory, the smallest eigenvalue of M^2 is found to be

$$
\begin{aligned}
m_h^2 &= (\tilde{M}^{2\,(2)})_{11} - \frac{[(\tilde{M}^{2\,(1)})_{14}]^2}{2\rho_1} \\
&= \frac{\kappa_1^2}{2(1+r^2+w^2)}\Bigg(4\Big(\lambda_1(r^2+1)^2 + 4r(\lambda_4(r^2+1)+r\lambda_{23}) \\
&\quad +w^2(\alpha_{124}+r^2(\alpha_1+\alpha_3)+\alpha_2 r)+\rho_1 w^4\Big) \\
&\quad -\frac{1}{\rho_1}(\alpha_{124}+r^2(\alpha_1+\alpha_3)+\alpha_2 r+2\rho_1 w^2)^2\Bigg),
\end{aligned}
$$

where $\lambda_{23} = 2\lambda_2 + \lambda_3$ and $\alpha_{124} = \alpha_1 + r\alpha_2 + \alpha_4$.

Constraints on Third Generation Yukawa Couplings

- Because of the large mass of the top quark, we expect that one of the Yukawa couplings of the third generation should be large.
- However, it should not so large that the perturbation theory breaks down.
- The third generation Yukawa couplings are given by

$$y_{33} = \frac{\sqrt{2}(1+r^2+w^2)^{1/2}}{v(1-r^2)}\left(m_t - r\, m_b\right) \ ,$$
$$\tilde{y}_{33} = \frac{\sqrt{2}(1+r^2+w^2)^{1/2}}{v(1-r^2)}\left(m_b - r\, m_t\right) \ .$$

- The perturbativity requirement of $y_{33} < (4\pi)^{1/2}$ leads to strong upper limits $r \lesssim 0.8$, and $w \lesssim 3.5$.

Theoretical Constraints in $r - w$ plane

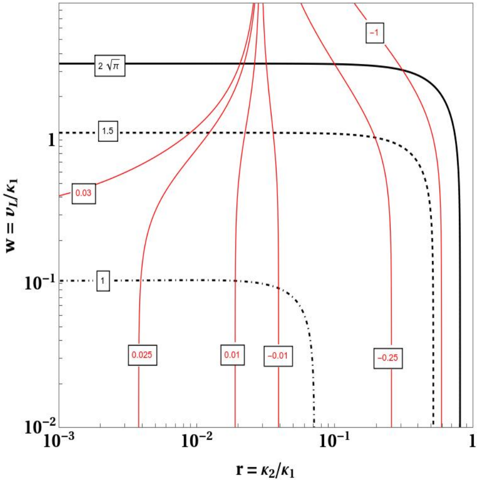

Figure: The black and red contours represent the values of y_{33} and $\tilde{y}_{33}$ respectively.

Experimental Constraints

Observable	Observed value
m_h	(125.38 ± 0.14) GeV
κ_W	1.05 ± 0.06
κ_Z	0.96 ± 0.07
κ_h	$[-2.3, 10.3]$ at 95% CL
κ_t	1.01 ± 0.11
κ_b	$0.98^{+0.14}_{-0.13}$

Table: Experimental values of the Higgs mass and coupling multipliers used in our calculations.

- We first do our analysis using only the observables in the table.
- Then, we impose the additional constraint that the next to lightest neutral scalar mass to be greater than 15 TeV, coming from flavour sector.

Simple Parametrization of Quartic Couplings

- The masses of scalar bosons and their Yukawa couplings to fermions depend on fourteen undetermined parameters in the Scalar potential.
- In order to get a better handle on the problem, we consider the following simpler set of ten parameters.
- The three parameters, v_R, $r = \kappa_2/\kappa_1$ and $w = v_L/\kappa_1$, are related to the *vevs*. One is the μ_4. The other six, defined below are related to the quartic couplings

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

Analysis Strategy

- We fix $v_R = 20$ TeV. This satisfies the LHC constraints on the searches for heavy W and heavy Z.
- We fix the ratio $q = 1$ and consider four different values of the ratio p.
- We are interested in obtaining the bounds on the *vev* ratios r and w, which satisfy all theoretical and experimental constraints.
- To make sure that we satisfy the bound of Higgs boson mass, the fix the value of λ_0 in terms of m_h^2 and the other five quartic couplingss.
- We randomly choose a point in the parameter space by varying the undetermined parameters of the model in the following ranges

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

- For each such point, we check if all the experimental constraints on κ factors are satisfied.

Allowed points in $r - w$ plane for $p = 0.02$ (simple basis)

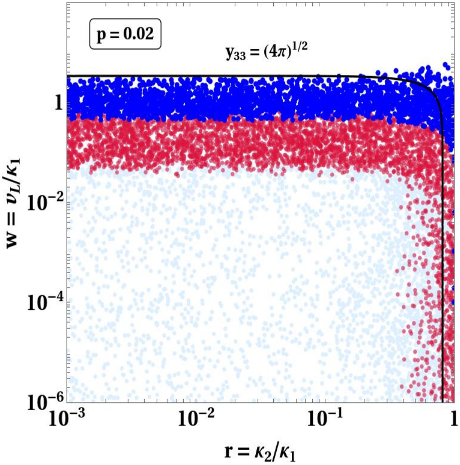

Figure: Light blue points satisfy m_h, κ_W, κ_Z and κ_t constraints and theoretical bounds. Red points satisfy κ_b constraint also and dark blue points satisfy the additional constraint heavy Higgs mass > 15 TeV.

Allowed points in $r - w$ plane for $p = 0.1$ (simple basis)

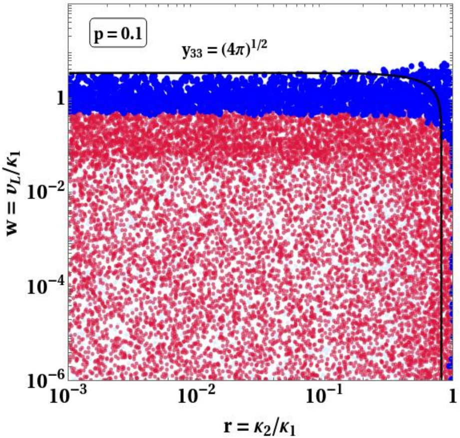

Figure: Light blue points satisfy m_h, κ_W, κ_Z and κ_t constraints and theoretical bounds. Red points satisfy κ_b constraint also and dark blue points satisfy the additional constraint heavy Higgs mass > 15 TeV.

Allowed points in $r - w$ plane for $p = 1$ (simple basis)

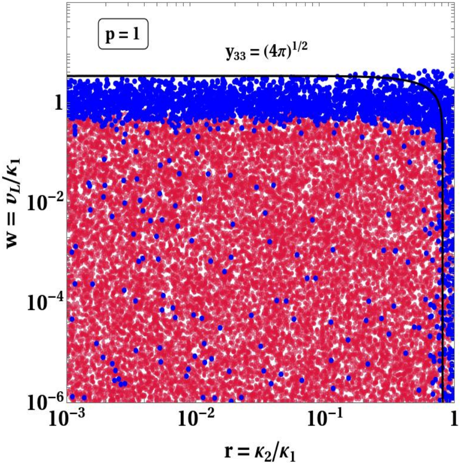

Figure: Light blue points satisfy m_h, κ_W, κ_Z and κ_t constraints and theoretical bounds. Red points satisfy κ_b constraint also and dark blue points satisfy the additional constraint heavy Higgs mass > 15 TeV.

Allowed points in $r - w$ plane for $p = 5$ (simple basis)

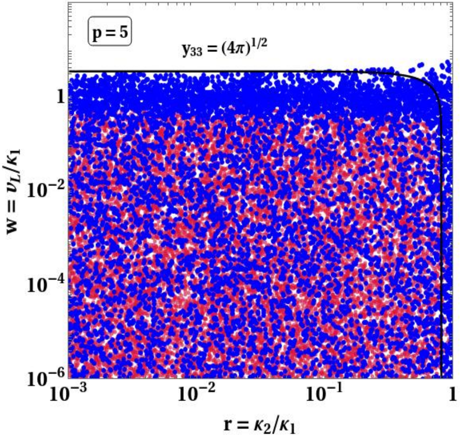

Figure: Light blue points satisfy m_h, κ_W, κ_Z and κ_t constraints and theoretical bounds. Red points satisfy κ_b constraint also and dark blue points satisfy the additional constraint heavy Higgs mass > 15 TeV.

Allowed points in $r - w$ plane for $p = 0.02$ (generic basis)

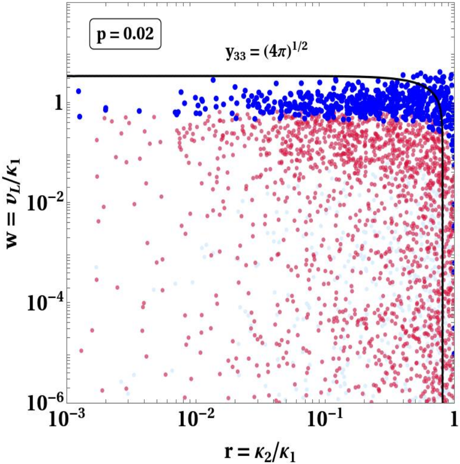

Figure: Light blue points satisfy m_h, κ_W, κ_Z and κ_t constraints and theoretical bounds. Red points satisfy κ_b constraint also and dark blue points satisfy the additional constraint heavy Higgs mass > 15 TeV.

Allowed points in $r - w$ plane for $p = 0.1$ (generic basis)

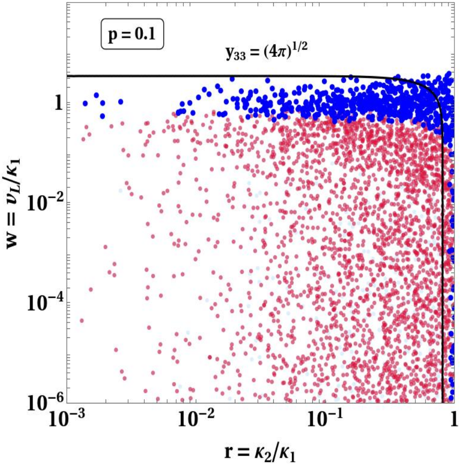

Figure: Light blue points satisfy m_h, κ_W, κ_Z and κ_t constraints and theoretical bounds. Red points satisfy κ_b constraint also and dark blue points satisfy the additional constraint heavy Higgs mass > 15 TeV.

Allowed points in $r - w$ plane for $p = 1$ (generic basis)

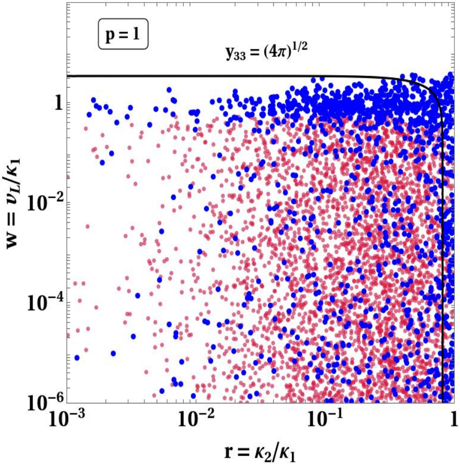

Figure: Light blue points satisfy m_h, κ_W, κ_Z and κ_t constraints and theoretical bounds. Red points satisfy κ_b constraint also and dark blue points satisfy the additional constraint heavy Higgs mass > 15 TeV.

Allowed points in $r - w$ plane for $p = 5$ (generic basis)

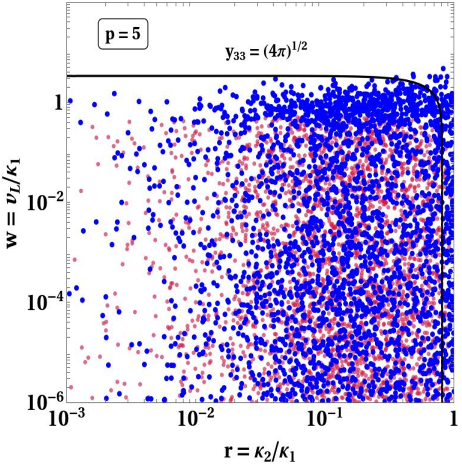

Figure: Light blue points satisfy m_h, κ_W, κ_Z and κ_t constraints and theoretical bounds. Red points satisfy κ_b constraint also and dark blue points satisfy the additional constraint heavy Higgs mass > 15 TeV.

Allowed points in $\kappa_b - \kappa_t$ plane (simple basis)

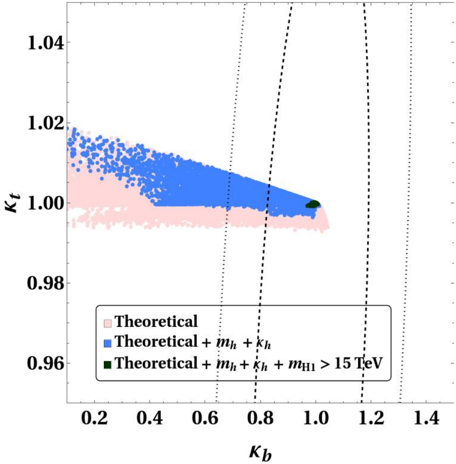

Figure: Pink points satisfy theoretical constraints. Bluepoints satisfy m_h constraint also and dark green points satisfy heavy Higgs mass > 15 TeV. In addition to varying quartic couplings, we varied in p and q in the range $(0.1, 10)$.

Allowed points in $\kappa_b - \kappa_t$ plane for (generic basis)

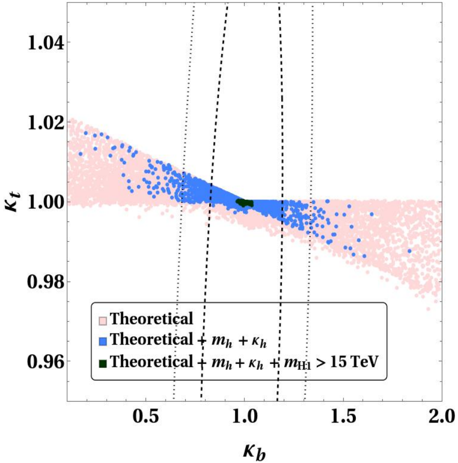

Figure: Pink points satisfy theoretical constraints. Bluepoints satisfy m_h constraint also and dark green points satisfy heavy Higgs mass > 15 TeV. In addition to varying quartic couplings, we varied in p and q in the range $(0.1, 10)$.

Conclusions

- In DLRSM studies, it is usually assumed that v_L, the *vev* of the $SU(2)_L$ doublet, is negligibly small.
- We studied, if the measurements of the Higgs couplings to gauge bosons and fermions, by ATLAS and CMS experiments, can justify this assumption.
- For a large volume of the parameter space, we found that v_L is required to be substantial, by the measurement of κ_b and the limit on heavy Higgs mass.
- A negligible value for v_L is possible, but only if $\alpha_3 > 5\alpha_4$.