What do the Higgs data tell about the Doublet Left-Right Symmetric Model?

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(based on arXiv: 2211.08445 with Jai More, Akhila K. Pradhan, S. Uma Sankar)

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Road beyond the standard model...11 years after finding Higgs

- The usual traits of BSM theory are driven by the symmetry argument. Popular examples: Supersymmetry, Composite Higges, Left-Right symmetric models, etc.
- **IF** (or not) such new physics exist, perhaps we can accommodate neutrino mass, matter-antimatter asymmetry, dark matter.
- With null results at the new physics searches at the colliders, dark matter experiments we are compelled to relook at our favourite models and verify our perceptions.

Gist of our work

- Investigate the scalar sector of the simplest doublet left-right symmetric model in light of the Higgs data.
- What pattern of EW symmetry breaking is favoured?
- We find: doublet-dominated EW symmetry breaking is still viable.
- Can be eventually disfavoured by more precise measurement of trilinear Higgs coupling.

The Doublet Left-Right Symmetric Model (DLRSM): Notations

All the fields are charged under an extended gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

The fermion multiplets, with an additional RH neutrino

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (3,2,1,1/3),\ Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \sim (3,1,2,1/3),\ L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1,2,1,-1),\ L_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \sim (1,1,2,-1)$$

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

Vacuum expectation value (VEV) structure: $\langle\Phi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_2 \end{pmatrix}, \quad \langle\chi_L\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_L \end{pmatrix}, \quad \langle\chi_R\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_R \end{pmatrix}$

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$$\kappa_1^2 + \kappa_2^2 + v_L^2 = v^2$$
$$v = 246\,\text{GeV}$$

$$SU(2)_R \times U(1)_{B-L} \to U(1)_Y$$
$$v_R \gg v$$

Senjanovic 1979;
Babu, Mathur 1988;
Perez, Murgui 2016, 2017;
Majumdar, Senapati, Yajnik 2018-
Babu, Thapa 2020;
Bernard, Descotes-Genon 2020;

Gauge bosons and their mixing

W and its partner :

$$\mathcal{L}_{mass} \supset \begin{pmatrix} W_L^+ & W_R^+ \end{pmatrix} \begin{pmatrix} \frac{g_L^2}{4}(v_L^2 + \kappa_1^2 + \kappa_2^2) & -\frac{1}{2} g_L g_R \kappa_1 \kappa_2 \\ -\frac{1}{2} g_L g_R \kappa_1 \kappa_2 & \frac{g_R^2}{4}(v_R^2 + \kappa_1^2 + \kappa_2^2) \end{pmatrix} \begin{pmatrix} W_L^- \\ W_R^- \end{pmatrix}$$

$$\begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\xi & -\sin\xi \\ \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} W_1^\pm \\ W_2^\pm \end{pmatrix}$$

Small mixing, $\xi \simeq -2\kappa_1\kappa_2/v_R^2$

Z and its partner :

$$\mathcal{L}_{mass} \supset \frac{1}{8} \begin{pmatrix} W_{L\mu}^3 & W_{R\mu}^3 & B_\mu \end{pmatrix} \begin{pmatrix} g_L^2 v^2 & -g_L g_R \kappa_+^2 & -g_L g_{BL} v_L^2 \\ & g_R^2 V^2 & -g_R g_{BL} v_R^2 \\ & & g_{BL}^2 (v_L^2 + v_R^2) \end{pmatrix} \begin{pmatrix} W_{L\mu}^3 \\ W_{R\mu}^3 \\ B_\mu \end{pmatrix}$$

$$\begin{pmatrix} A_\mu \\ Z_{1\mu} \\ Z_{2\mu} \end{pmatrix} = \begin{pmatrix} s_W & c_W s_Y & c_W c_Y \\ -c_W & s_W s_Y & s_W c_Y \\ 0 & c_Y & s_Y \end{pmatrix} \begin{pmatrix} W_{L\mu}^3 \\ W_{R\mu}^3 \\ B_\mu \end{pmatrix}$$

$$s_W \equiv \sin\theta_W = \frac{g_{BL}}{\sqrt{g^2 + 2g_{BL}^2}}, \quad c_W \equiv \cos\theta_W = \sqrt{\frac{g^2 + g_{BL}^2}{g^2 + 2g_{BL}^2}},$$

$$s_Y \equiv \sin\theta_Y = \frac{g_{BL}}{\sqrt{g^2 + g_{BL}^2}}, \quad c_Y \equiv \cos\theta_Y = \frac{g}{\sqrt{g^2 + g_{BL}^2}}.$$

Scalar potential: Minimization and free parameters

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

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

$$\begin{aligned}
\mu_1^2 &= \frac{1}{2(r^2-1)}\Bigg(\kappa_1^2\Big(w^2((r^2-1)\alpha_1 + r^2\alpha_3 - \alpha_4) + 2(r^2-1)((r^2+1)\lambda_1 + 2r\lambda_4)\Big) \\
&\quad + 2\sqrt{2} r v_R w \mu_4 + v_R^2\Big((r^2-1)\alpha_1 + r^2\alpha_3 - \alpha_4 + 2w^2\rho_{12}\Big)\Bigg), \\
\mu_2^2 &= \frac{1}{4(r^2-1)}\Bigg(\kappa_1^2\Big(w^2(r^2-1)\alpha_2 - w^2 r\alpha_{34} + 2(r^2-1)(2r\lambda_{23} + (r^2+1)\lambda_4)\Big) \\
&\quad - \sqrt{2}(r^2+1) v_R w \mu_4 + v_R^2\Big((r^2-1)\alpha_2 - r\alpha_{34} - 2w^2\rho_{12}\Big)\Bigg), \\
\mu_3^2 &= \frac{1}{2}\kappa_1^2((r^2+1)\alpha_1 + 2r\alpha_2 + r^2\alpha_3 + \alpha_4 + 2w^2\rho_1) + v_R^2\rho_1, \\
\mu_5 &= -r\mu_4 - \sqrt{2} v_R w \rho_{12}.
\end{aligned}$$

$\rho_{12} = \rho_2/2 - \rho_1$, $\alpha_{34} = \alpha_3 - \alpha_4$, and $\lambda_{23} = 2\lambda_2 + \lambda_3$

Unknown parameters in the generic basis of DLRSM $\{\lambda_{1,2,3,4}, \alpha_{1,2,3,4}, \rho_{1,2}, \mu_4, r, w, v_R\}$

Where, $r = \kappa_2/\kappa_1$, $w = v_L/\kappa_1$

Higgs mass

Full CP-even scalar mass matrix $\frac{M^2}{v_R^2} = \left(M^{2\,(0)} + \frac{1}{v_R} M^{2\,(1)} + \frac{1}{v_R^2} M^{2\,(2)} \right)$

Leading order correction $\frac{M^{2\,(0)}}{v_R^2} = \begin{pmatrix} \frac{r^2\alpha_{34}+2w^2\rho_{12}}{2(1-r^2)} & \frac{r(\alpha_{34}+2w^2\rho_{12})}{2(1-r^2)} & -w\rho_{12} & 0 \\ & \frac{\alpha_{34}+2w^2\rho_{12}}{2(1-r^2)} & 0 & 0 \\ & & \rho_{12} & 0 \\ & & & 2\rho_1 \end{pmatrix}$

Positivity criteria leads to

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

Orthogonal Transformation takes $M^{2\,(2)}$ to block diagonal form $O_I = \begin{pmatrix} \frac{1}{k} & \frac{r}{k} & \frac{w}{k} & 0 \\ -\frac{r}{\sqrt{1+r^2}} & -\frac{1}{\sqrt{1+r^2}} & 0 & 0 \\ -\frac{w}{k\sqrt{1+r^2}} & -\frac{rw}{k\sqrt{1+r^2}} & -\frac{\sqrt{1+r^2}}{k} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$

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

Babu Thapa 2020; Bernard 2020; SK, More, Pradhan, Uma Sankar 2022

Higgs couplings : gauge bosons

Numerical diagonalization becomes necessary due to the pitfalls of non-degenerate perturbation theory.

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

Gauge basis: $X = (\phi^0_{1r}, \phi^0_{2r}, \chi^0_{Lr}, \chi^0_{Rr})$

Physical basis: $X_{\rm ph} = (h, H_1, H_2, H_3)$

Example 1 : hWW coupling

$$\mathcal{L} \supset \frac{1}{2} g^2 \left((\kappa_1 - 2c_\xi s_\xi \kappa_2)\phi^0_{1r} + (\kappa_2 - 2c_\xi s_\xi \kappa_1)\phi^0_{2r} + v_L c_\xi^2 \chi^0_{Lr} + v_R s_\xi^2 \chi^0_{Rr} \right) W^+_{1\mu} W_1^{-\mu}$$

hWW coupling multiplier $\kappa_W = \frac{c_{hW_1W_1}}{c^{\rm SM}_{hWW}} = \frac{1}{k}\Big((1 - 2c_\xi s_\xi r) U_{11} + (r - 2c_\xi s_\xi) U_{21} + w c_\xi^2 U_{31} + \frac{v_R}{\kappa_1} s_\xi^2 U_{41} \Big)$

Example 2 : hZZ coupling

$$\mathcal{L} \supset \frac{g^2}{4} (c_W + s_W s_Y)^2 (\kappa_1 \phi^0_{1r} + \kappa_2 \phi^0_{2r} + v_L \chi^0_{Lr})\, Z_{1\mu} Z_1^\mu$$

hZZ coupling multiplier $\kappa_Z = \frac{g^2(g^2 + 2g^2_{BL})}{(g^2 + g'^2)(g^2 + g^2_{BL})} \frac{1}{k} (U_{11} + rU_{21} + wU_{31})$

We work in the limit $g_{BL} = gg'/(g^2 - g'^2)^{1/2}$

Higgs couplings : fermions

Mohapatra, Zhang 2007

$$\mathcal{L}_{Yuk} \supset -\bar{Q}_{Li}(y_{ij}\Phi + \tilde{y}_{ij}\tilde{\Phi})Q_{Rj} + h.c.$$

In terms of the gauge eigenstates, $U' \equiv (u', c', t')$, $D' \equiv (d', s', b')$

The quark mass matrix, $\mathcal{L}_m \supset -\bar{U}'_{Li}(M_U)_{ij}U'_{Rj} - \bar{D}'_{Li}(M_D)_{ij}D'_{Rj} + h.c.$

$$M_U = \frac{1}{\sqrt{2}}(\kappa_1 y + \kappa_2 \tilde{y}) \text{ , } M_D = \frac{1}{\sqrt{2}}(\kappa_2 y + \kappa_1 \tilde{y})$$

$$\mathcal{L}_N \supset \frac{\kappa_1}{\sqrt{2}\,\kappa_-^2}\,\bar{u}_{Li}\left((\phi_1^0 - r\phi_2^{0*})\hat{M}_u + (-r\phi_1^0 + \phi_2^{0*})V_L^{\rm CKM}\,\hat{M}_d\,V_R^{\rm CKM\dagger}\right)u_{Rj}$$
$$+\frac{\kappa_1}{\sqrt{2}\,\kappa_-^2}\,\bar{d}_{Li}\left((\phi_1^{0*} - r\phi_2^0)\hat{M}_d + (-r\phi_1^{0*} + \phi_2^0)V_L^{\rm CKM\dagger}\,\hat{M}_u\,V_R^{\rm CKM}\right)d_{Rj} + h.c.$$

$$c_{htt\,(hbb)} = \frac{\kappa_1}{\sqrt{2}\,\kappa_-^2}\left((U_{11} - rU_{21})m_{t(b)} + (U_{21} - rU_{11})(V_L^{\rm CKM}\,\hat{M}_{d(u)}\,V_R^{\rm CKM\dagger})_{33}\right)$$

$\kappa_-^2 = \kappa_1^2 - \kappa_2^2 = (1-r^2)\kappa_1^2$

$\hat{M}_{u(d)}$ are physical masses

Manifest LR Symmetry

$V_R^{\rm CKM} = V_L^{\rm CKM}$

Perturbativity of third-generation Yukawa couplings

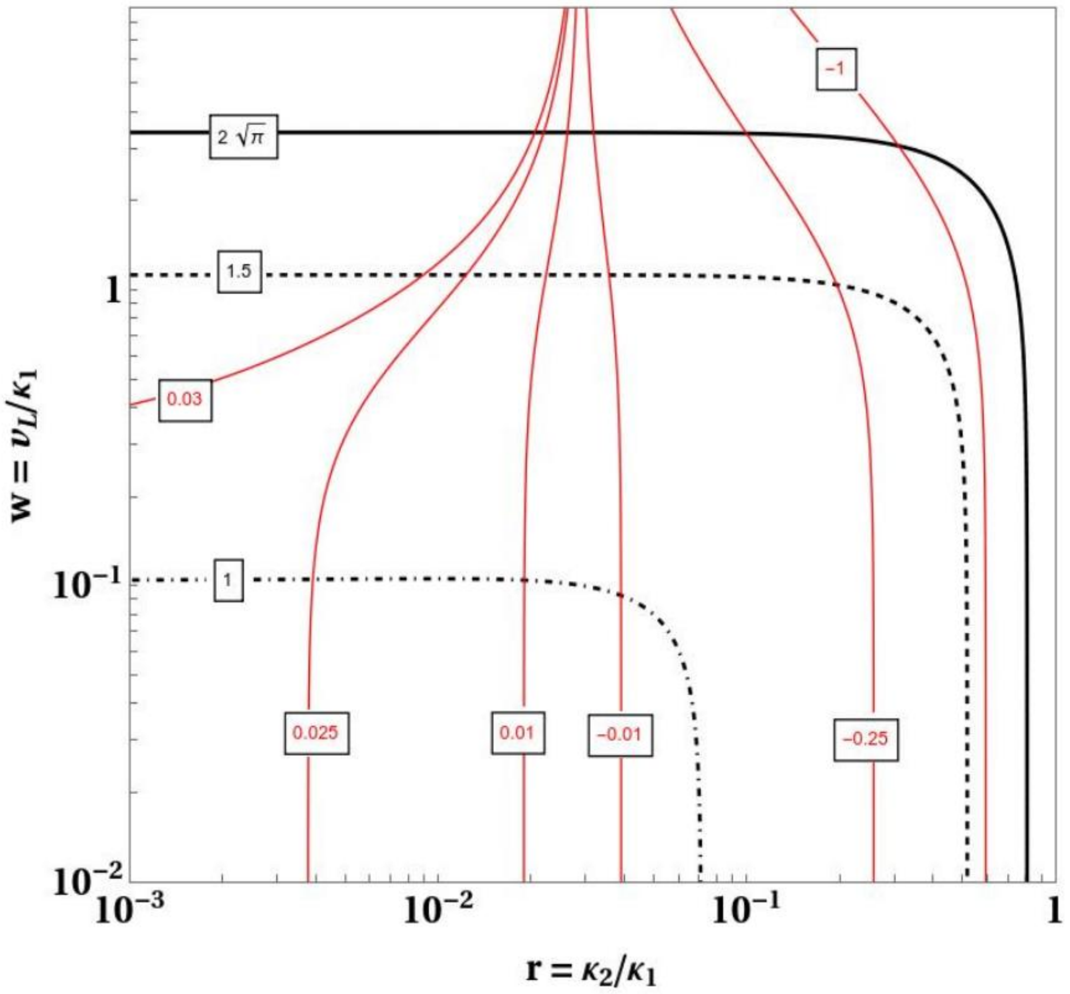
$$M_U = \frac{1}{\sqrt{2}}(\kappa_1 y + \kappa_2 \tilde{y}) \qquad M_D = \frac{1}{\sqrt{2}}(\kappa_2 y + \kappa_1 \tilde{y})$$

$$r = \kappa_2/\kappa_1$$
$$w = v_L/\kappa_1$$

$$\left(V_{L,R}^{\mathrm{CKM}}\right)_{33} \sim 1$$

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

Perturbativity of third-generation Yukawa couplings



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SK, More, Pradhan, Uma Sankar, 2211.08445

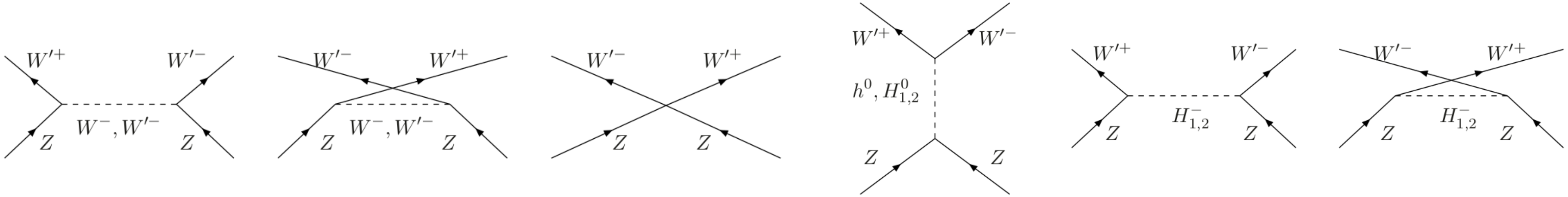
Unitarity

Upper bound to masses from unitarity of gauge boson scattering

$$Z'Z' \to WW \qquad Z'Z \to Z'Z \qquad W'W' \to WW$$

Example:

$ZZ \to W'W'$



$$0 < \rho_1 < \frac{8\pi}{3}\,, \;\; \text{or}, \; \frac{m^2_{H_3}}{v_R^2} \;<\; \frac{16\pi}{3}$$

$$\frac{(c_{H_3})^2}{k^4}\,\frac{m^2_{H_3}}{v_R^2} \;<\; \frac{16\pi}{3}$$

$$2\frac{w^2}{k^2}\sum_{i=1,2} F_i^2\,\frac{m^2_{H_i^\pm}}{v_R^2} + \frac{c_{H_3}}{k^2}\,\frac{m^2_{H_3}}{v_R^2} \;<\; 16\pi$$

$$2\frac{w^2}{k^2}\sum_{i=1,2} S_i^2\,\frac{m^2_{H_i^\pm}}{v_R^2} + \frac{c_{H_3}}{k^2}\,\frac{m^2_{H_3}}{v_R^2} \;<\; 16\pi$$

Bernard et. al. (2001.00886)

Boundedness from below

Chauhan (1907.07153)
Frank, Majumdar, Senapati, Yajnik (2111.08582)

$$\left\{\begin{array}{ll}\lambda_1 & \\ \left(\lambda_1 - \frac{\lambda_4^2}{2\lambda_2+\lambda_3}\right) & \Longleftarrow \; 2\lambda_2 + \lambda_3 > |\lambda_4| \\ (\lambda_1 + \lambda_3 + 2(\lambda_2 - |\lambda_4|)) & \\ \left(\lambda_1 + \lambda_3 - 2\lambda_2 - \frac{\lambda_4^2}{4\lambda_2}\right) & \Longleftarrow \; |4\lambda_2| > |\lambda_4| \end{array}\right\} > 0$$

$$\{\rho_1 > 0, \quad 2\rho_1 + \rho_2 > 0\}$$

$$\alpha_1 + \alpha_3 + \sqrt{\lambda_1(2\rho_1 + \rho_2)} > 0$$
$$\alpha_1 + \alpha_4 + \sqrt{\lambda_1(2\rho_1 + \rho_2)} > 0$$
$$\alpha_1 + \alpha_3 + 2\sqrt{\lambda_1\rho_1} > 0$$
$$\alpha_1 + \alpha_4 + 2\sqrt{\lambda_1\rho_1} > 0 \;\; .$$

$$\alpha_1 - 2|\alpha_2| + \frac{\alpha_3}{2} + \frac{\alpha_4}{2} + \sqrt{\left(\lambda_1 + \lambda_3 - 2\lambda_2 - \frac{\lambda_4^2}{4\lambda_2}\right)(2\rho_1 + \rho_2)} > 0$$
$$\alpha_1 - 2|\alpha_2| + \frac{\alpha_3}{2} + \frac{\alpha_4}{2} + 2\sqrt{\left(\lambda_1 + \lambda_3 - 2\lambda_2 - \frac{\lambda_4^2}{4\lambda_2}\right)\rho_1} > 0 \;\; .$$

$$\alpha_1 - 2|\alpha_2|\frac{|\lambda_4|}{2\lambda_2 + \lambda_3} + \frac{\alpha_3}{2}\left(1 \pm \sqrt{1 - \frac{\lambda_4^2}{(2\lambda_2+\lambda_3)^2}}\right) + \frac{\alpha_4}{2}\left(1 \mp \sqrt{1 - \frac{\lambda_4^2}{(2\lambda_2+\lambda_3)^2}}\right)$$
$$+\sqrt{\left(\lambda_1 - \frac{\lambda_4^2}{2\lambda_2 + \lambda_3}\right)(2\rho_1 + \rho_2)} > 0 \;\; ,$$
$$\alpha_1 - 2|\alpha_2|\frac{|\lambda_4|}{2\lambda_2 + \lambda_3} + \frac{\alpha_3}{2}\left(1 \pm \sqrt{1 - \frac{\lambda_4^2}{(2\lambda_2+\lambda_3)^2}}\right) + \frac{\alpha_4}{2}\left(1 \mp \sqrt{1 - \frac{\lambda_4^2}{(2\lambda_2+\lambda_3)^2}}\right)$$
$$+\sqrt{\left(\lambda_1 - \frac{\lambda_4^2}{2\lambda_2 + \lambda_3}\right)\rho_1} > 0 \;\; .$$

$$\alpha_1 - 2|\alpha_2| + \frac{\alpha_3}{2} + \frac{\alpha_4}{2} + \sqrt{(\lambda_1 + \lambda_3 + 2(\lambda_2 - |\lambda_4|))(2\rho_1 + \rho_2)} > 0$$
$$\alpha_1 - 2|\alpha_2| + \frac{\alpha_3}{2} + \frac{\alpha_4}{2} + 2\sqrt{(\lambda_1 + \lambda_3 + 2(\lambda_2 - |\lambda_4|))\rho_1} > 0 \;\; .$$

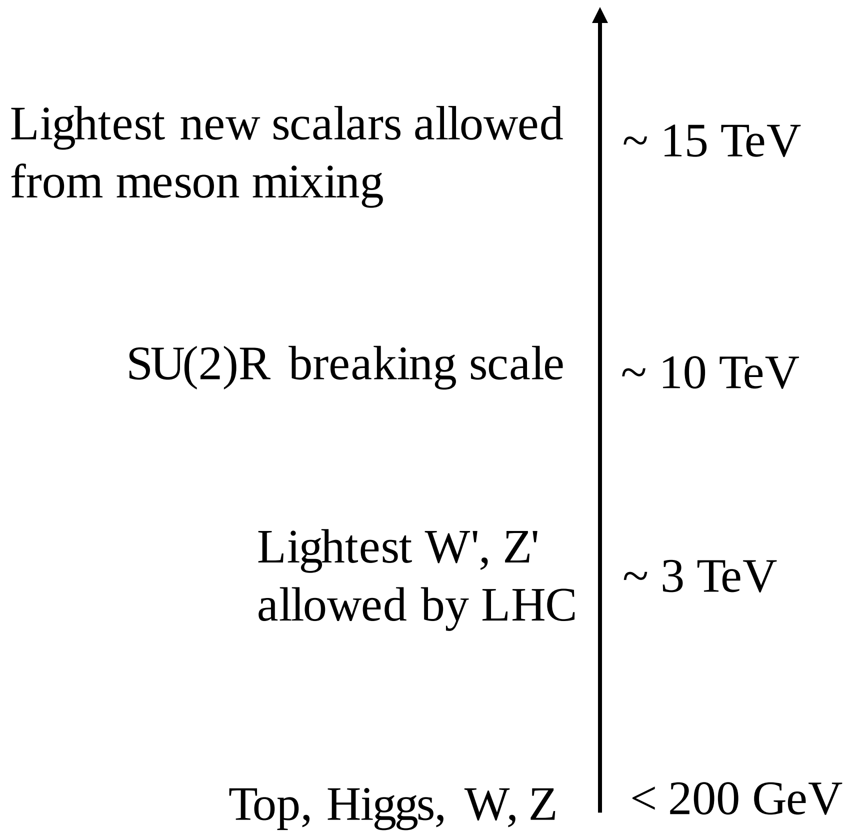
Taking stock of what we have till now...

- Theoretical constraints such as (1) perturbativity, (2) unitarity and (3) boundedness from below leads to a few restrictions on the quartic couplings.

- Direct searches of new scalars rule out masses up to ~ 1.5 TeV.

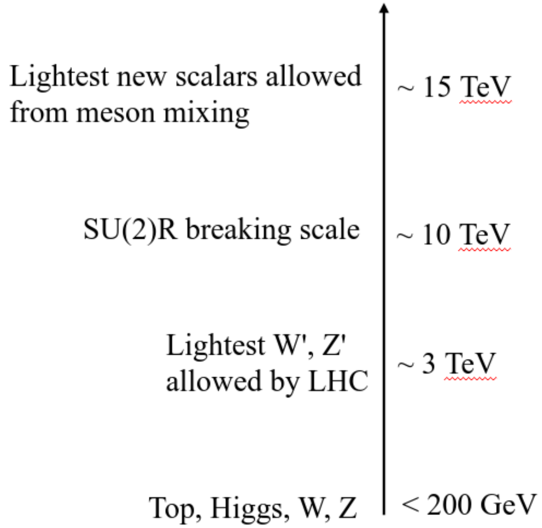
- Direct searches of W' and Z' bosons rule out up to ~ 3.2 TeV and ~ 1.2 TeV respectively.

- Meson mixing puts a strong constraint on the masses of new scalars of LR models > 15 TeV. (Mohapatra, Zhang 2007)



Taking stock of what we know till now...

- In LR models, if the new VEVs are large, first constraints will come from EW precision tests. W, Z boson self-energies will modify, additional vertex and box diagrams will show up. (Bernard et. al.)
- Sensitivity to precision tests are suppressed by, say mW^2/mW'^2
- Large number of parameters – electroweak fit may be inadequate

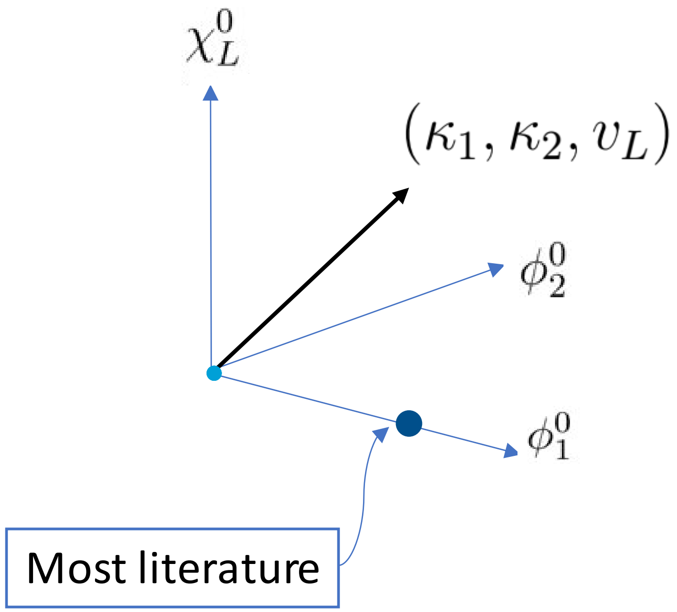


Combining unitarity, electroweak precision observables and the radiative corrections to the muon Δr parameter within a frequentist (CKMfitter) approach, we see that the model is only mildly constrained: the fit bounds DLRM corrections to remain small, pushing the LR scale to be of the order of a few TeV, thus limiting the sensitivity to the new fundamental parameters. Nonetheless, a new qualitative feature, favoured by the data, emerges from our analysis of DLRM, which is the possibility of having spontaneous EW symmetry breaking triggered also by a doublet under $SU(2)_L$, as opposed to the case mostly studied in which EWSB is triggered only by the bi-doublet under $SU(2)_L \times SU(2)_R$. This possibility has not received much attention in the literature as it is not allowed in the triplet scenario, in which a triplet under $SU(2)_L$ is considered.

Bernard et. al. (2001.00886)

Questions:

- Does the bidoublet predominantly drive EW symmetry breaking in this model, as it is assumed in most of the literature?
- How large a contribution from the SU(2)L doublet is still allowed from Higgs data? We show the constraints on the r – w plane, where $r = \kappa_2/\kappa_1$ and $w = v_L/\kappa_1$
- If allowed, what will it take to rule out large values of w?
- Unlike in two-Higgs-doublet model, a blind fit will fail due to the hierarchy of scale protecting the model from most of the observations. How can we reduce the parameter space?



A *simple* basis

$$\lambda_1 = \lambda_3 = \lambda_4 = \lambda_0$$

Boundedness from below : $x = \frac{\lambda_2}{\lambda_4}$

$$\alpha_1 = \alpha_2 = \alpha_4 = \alpha_0$$

Positivity of mass-sq matrix : $p = \frac{\alpha_3}{\alpha_4} - 1$

$$\rho_1$$

Positivity of mass-sq matrix : $q = \frac{\rho_2}{2\rho_1} - 1$

A minimal set of parameters with all the essence of DLRSM $\{\lambda_0, \alpha_0, \rho_1, x, p, q, \mu_4, r, w, v_R\}$

A *simple* basis

$$\lambda_1 = \lambda_3 = \lambda_4 = \lambda_0$$

Boundedness from below : $x = \frac{\lambda_2}{\lambda_4}$

$$\alpha_1 = \alpha_2 = \alpha_4 = \alpha_0$$

Positivity of mass-sq matrix : $p = \frac{\alpha_3}{\alpha_4} - 1$

$$\rho_1$$

Positivity of mass-sq matrix : $q = \frac{\rho_2}{2\rho_1} - 1$

A minimal set of parameters with all the essence of DLRSM $\{\lambda_0, \alpha_0, \rho_1, x, p, q, \mu_4, r, w, v_R\}$

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

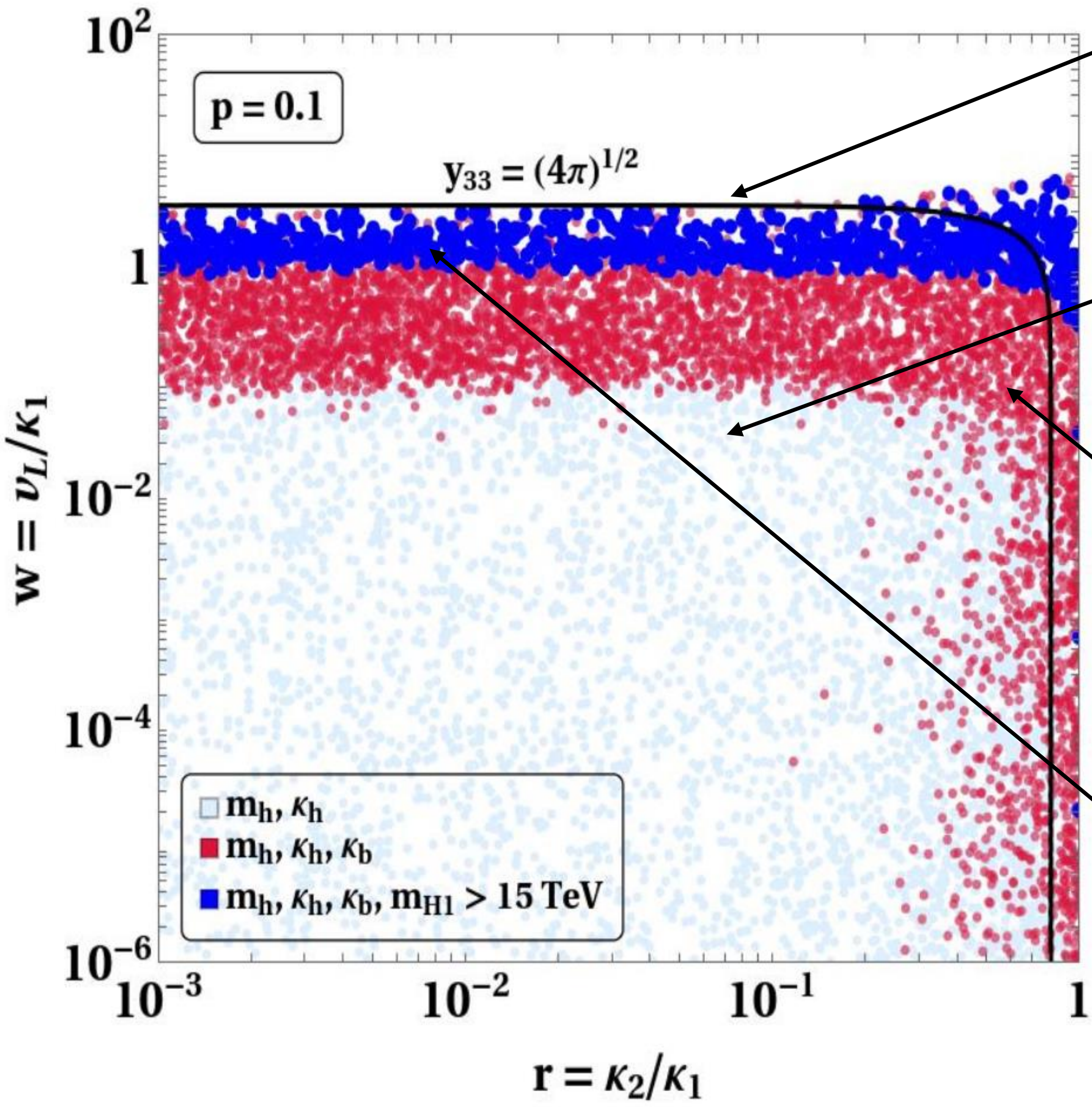
$$\lambda_0 = (1 + y)\,\Lambda_0 \text{ with } y \in [-0.1, 0.1] \qquad \Lambda_0 = \lambda_0(m_h^{analytical} = 125.38) \qquad x \equiv \lambda_2/\lambda_0 \in [0.25, 0.85]$$

Bounds on Higgs mass and couplings

Observable	Observed value	
m_h	$(125.38 \pm 0.14)\,\mathrm{GeV}$	(CMS 2002.06398)
κ_W	1.05 ± 0.06	(ATLAS-CONF-2020-027)
κ_Z	0.96 ± 0.07	(CMS-PAS-HIG-19-005)
κ_h	$[-2.3, 10.3]$ at 95% CL	(ATLAS-CONF-2019-049)
κ_t	1.01 ± 0.11	(CMS-PAS-HIG-19-005)
κ_b	$0.98^{+0.14}_{-0.13}$	(ATLAS-CONF-2020-027)

Bounds from Higgs data

Perturbativity of top-like Yukawa coupling rule out points with large w and r.



- Satisfy theoretical constraints, Higgs mass
- Automatically satisfy hWW, hZZ, htt
- Satisfy hhh

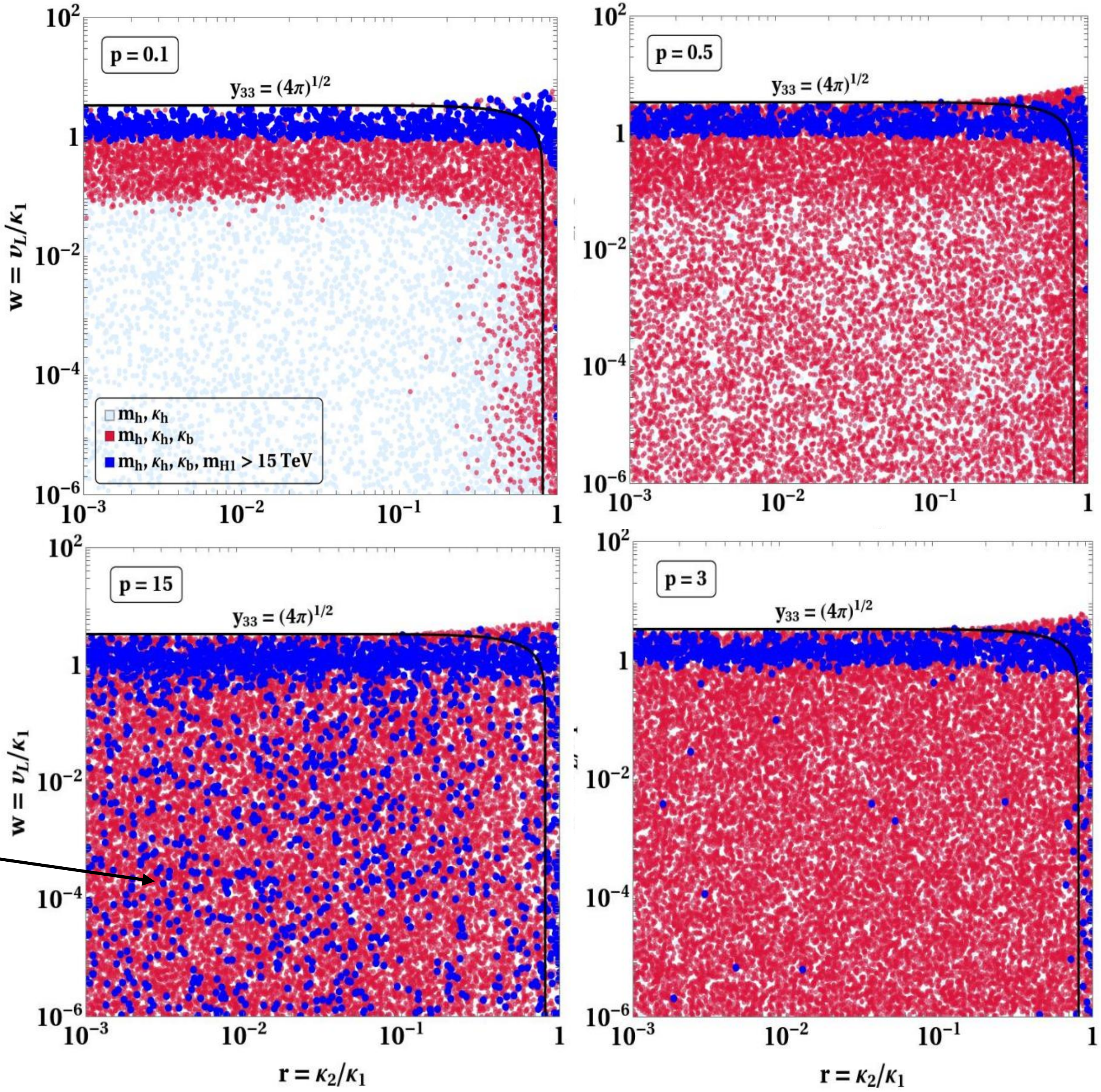
- Also satisfies hbb coupling

- Also satisfies mH1 > 15 TeV

Varying $p = \frac{\alpha_3}{\alpha_4} - 1$

More points become allowed by mH1 > 15 TeV once the value of p increases

3% of the points populate the low-r, low-w region, Large ρ_1



The role of bottom Yukawa

$$c_{hbb} = \frac{(1+r^2+w^2)^{1/2}}{\sqrt{2}\,v(1-r^2)}\Big((U_{11}-rU_{21})m_b + (U_{21}-rU_{11})m_t\Big)$$

If U_{21} becomes too large, the term multiplying m_t blows up.

If $M_{22}^{2(0)}$ is too small, next-to-lightest Higgs will have large mixing with the lightest Higgs, U_{21} will be large.

$$\frac{M^{2\,(0)}}{v_R^2} = \begin{pmatrix} \frac{r^2\alpha_{34}+2w^2\rho_{12}}{2(1-r^2)} & \frac{r(\alpha_{34}+2w^2\rho_{12})}{2(1-r^2)} & -w\rho_{12} & 0 \\ & \frac{\alpha_{34}+2w^2\rho_{12}}{2(1-r^2)} & 0 & 0 \\ & & \rho_{12} & 0 \\ & & & 2\rho_1 \end{pmatrix}$$

$$M_{22}^{2(0)} = \frac{p\alpha_4 + 2w^2 q\rho_1}{2(1-r^2)} \times v_R^2$$

To satisfy bottom Yukawa, either (1) Large p, or (2) Large w, (3) r ~ 1, (4) Large ρ_1 – Or any combination of these.

A strong upper limit on w from Higgs mass

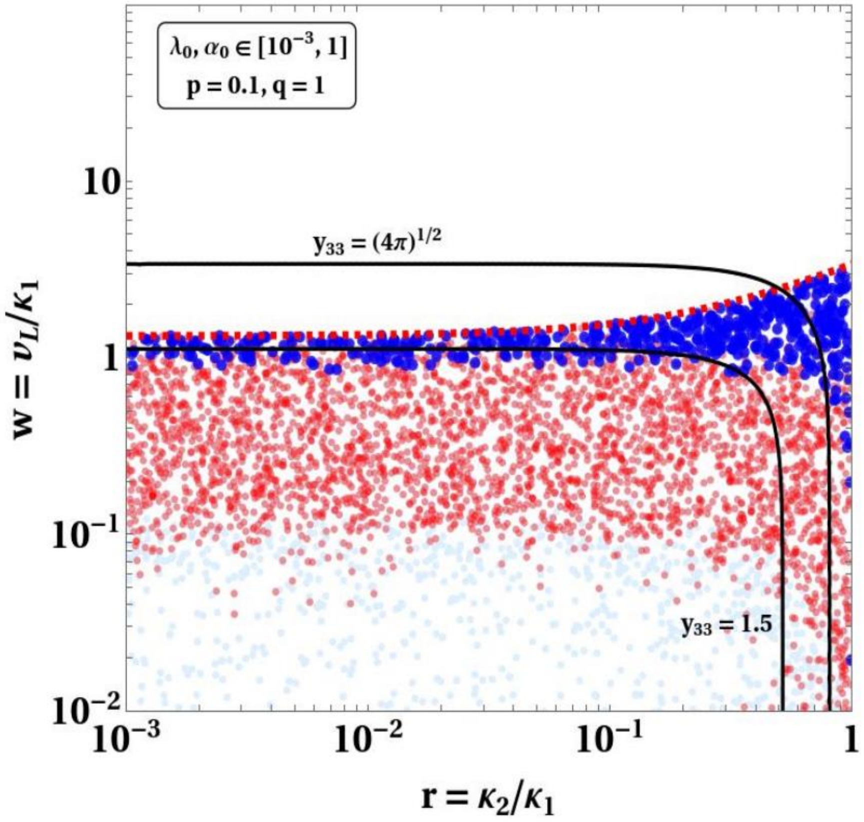
- In the simple basis, the Higgs mass is given by

$$m_h^2 = \frac{v^2}{(1+r^2+w^2)^2}\left[2\left(8\lambda_2 r^2 + \lambda_0(1+r^2)^4\right) - \frac{\alpha_0^2(2+r(2+(2+p)r))^2}{2\rho_1}\right]$$

- In the limit $\alpha_0 \to 0$, $r \to 1$, with the perturbativity bounds, $\lambda_0, \lambda_2 < 4\pi$, the upper bound from mh = 125 GeV is $w < 6.81$

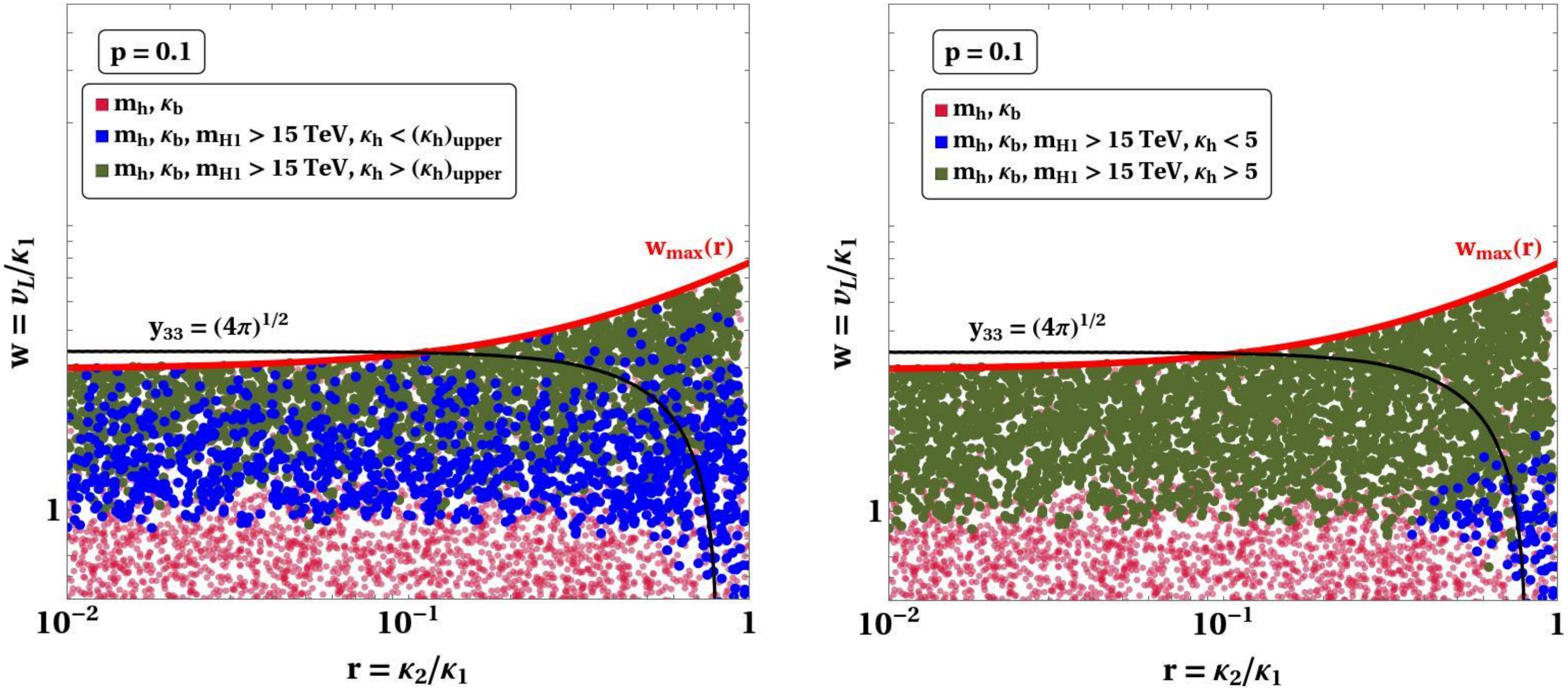
- The upper bound is slightly improved with boundedness from below criteria $\lambda_2 < 0.85\,\lambda_0$ to $w < 6.71$

- The maximum allowed value of w can be expressed as a function of r, $w_{\max}(r) \simeq a + br + cr^2$



The role of Higgs trilinear self-coupling

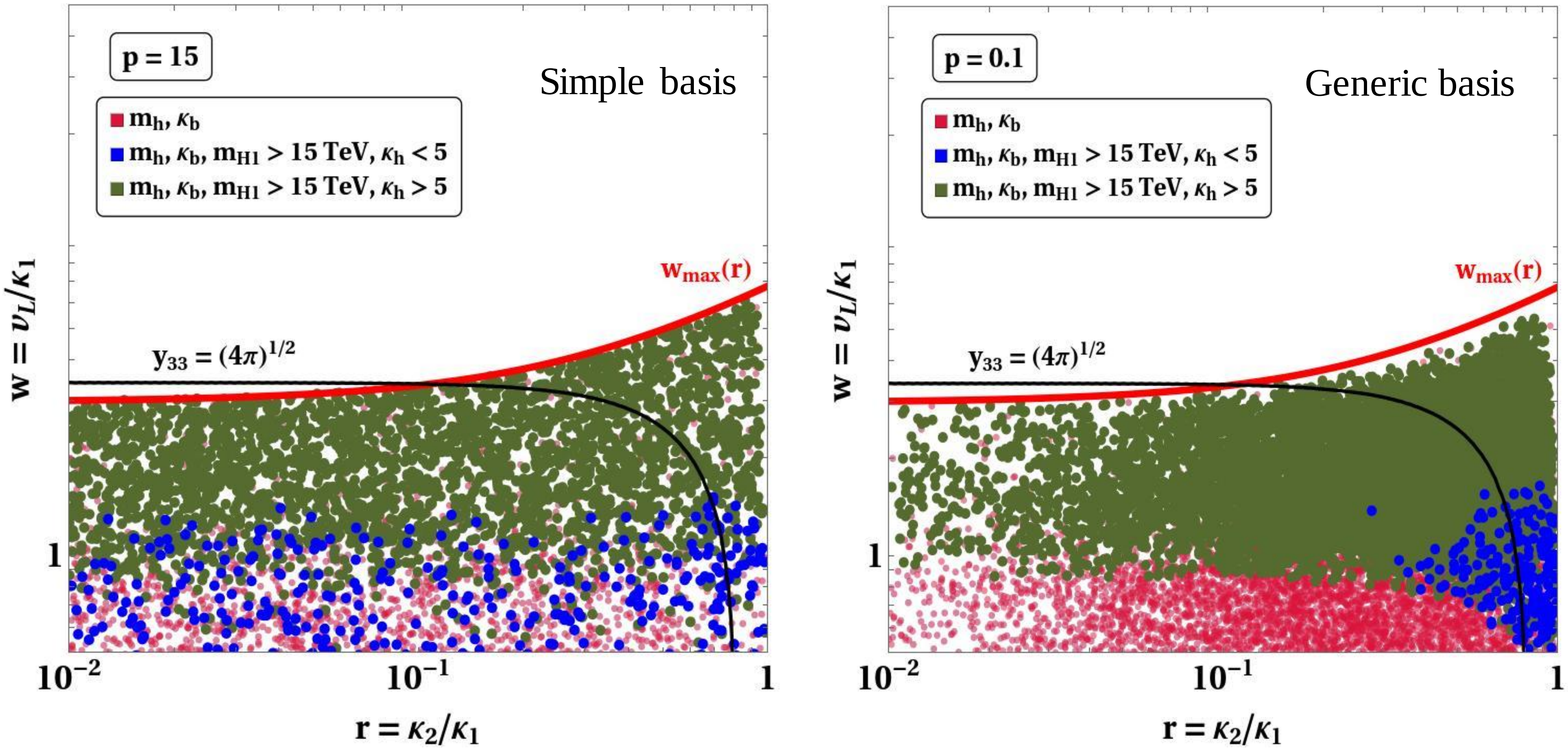
$-2.3 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 10.3$ At 95% CL, ATLAS (80 fb^-1)



Most of the w > 1 region will be ruled out if Higgs self-coupling is measured even with 400% accuracy

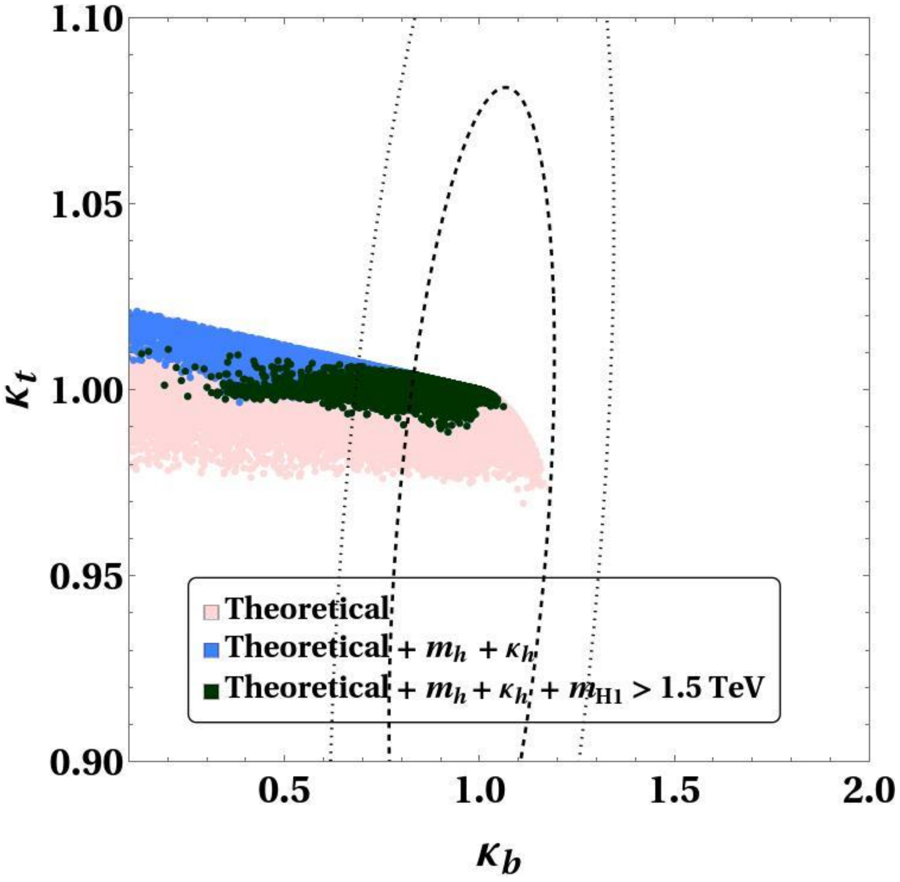
The role of Higgs trilinear self-coupling

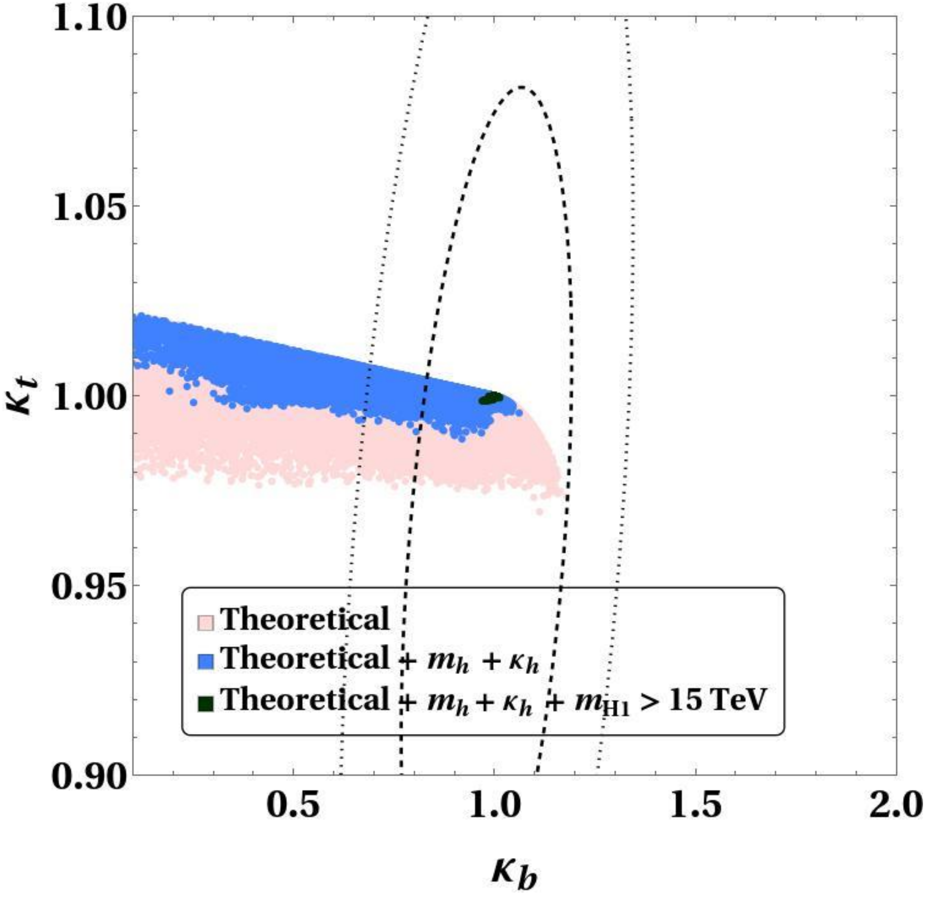
The impact of Higgs trilinear coupling measurement will be robust: Same fate for large values of p, q, and also in the generic basis.



Alignment through decoupling

The flavour bound on next-to-lightest CP-even scalar ensures that the fermion couplings of the SM-like Higgs are aligned with the observation.





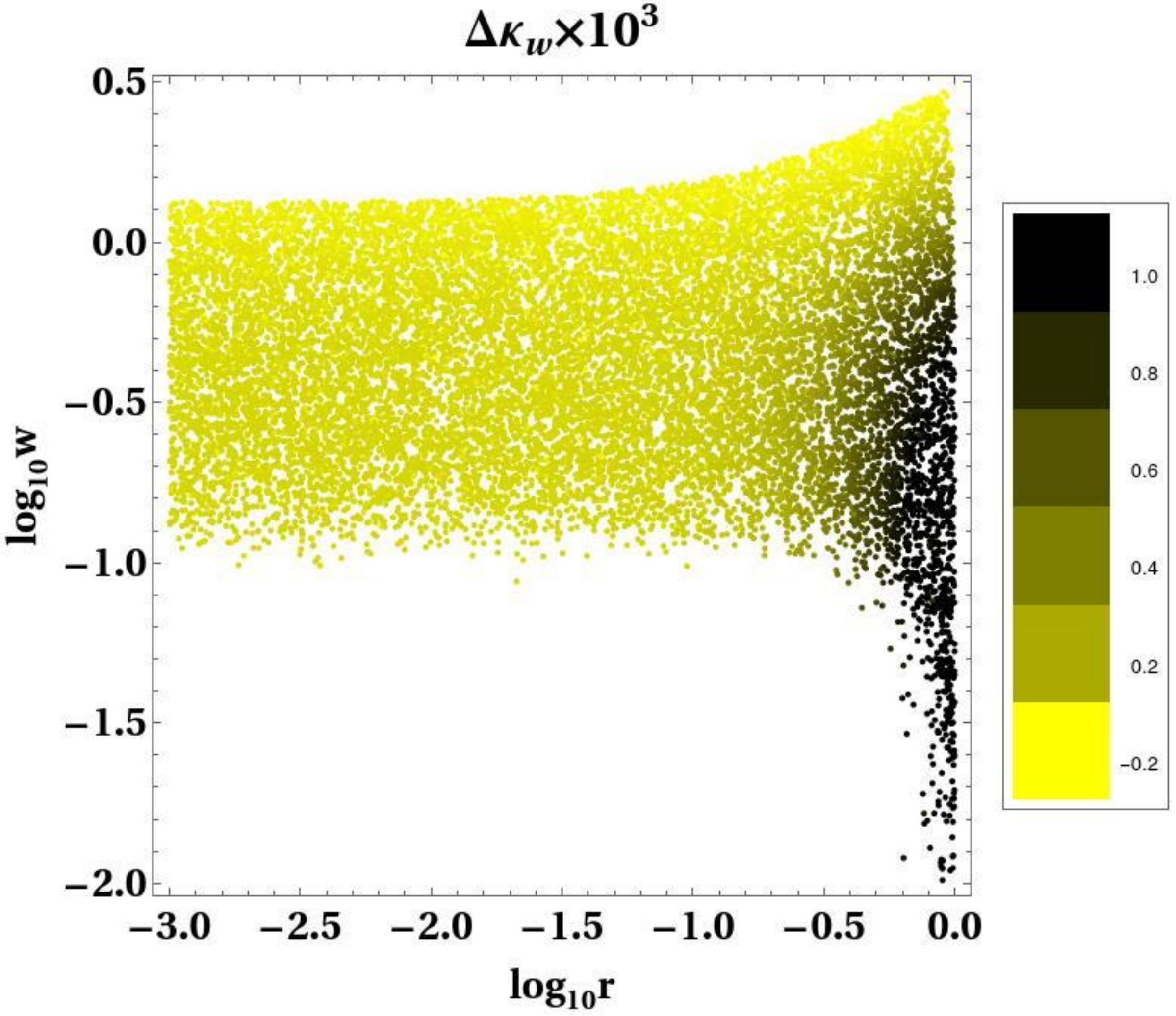
Summary

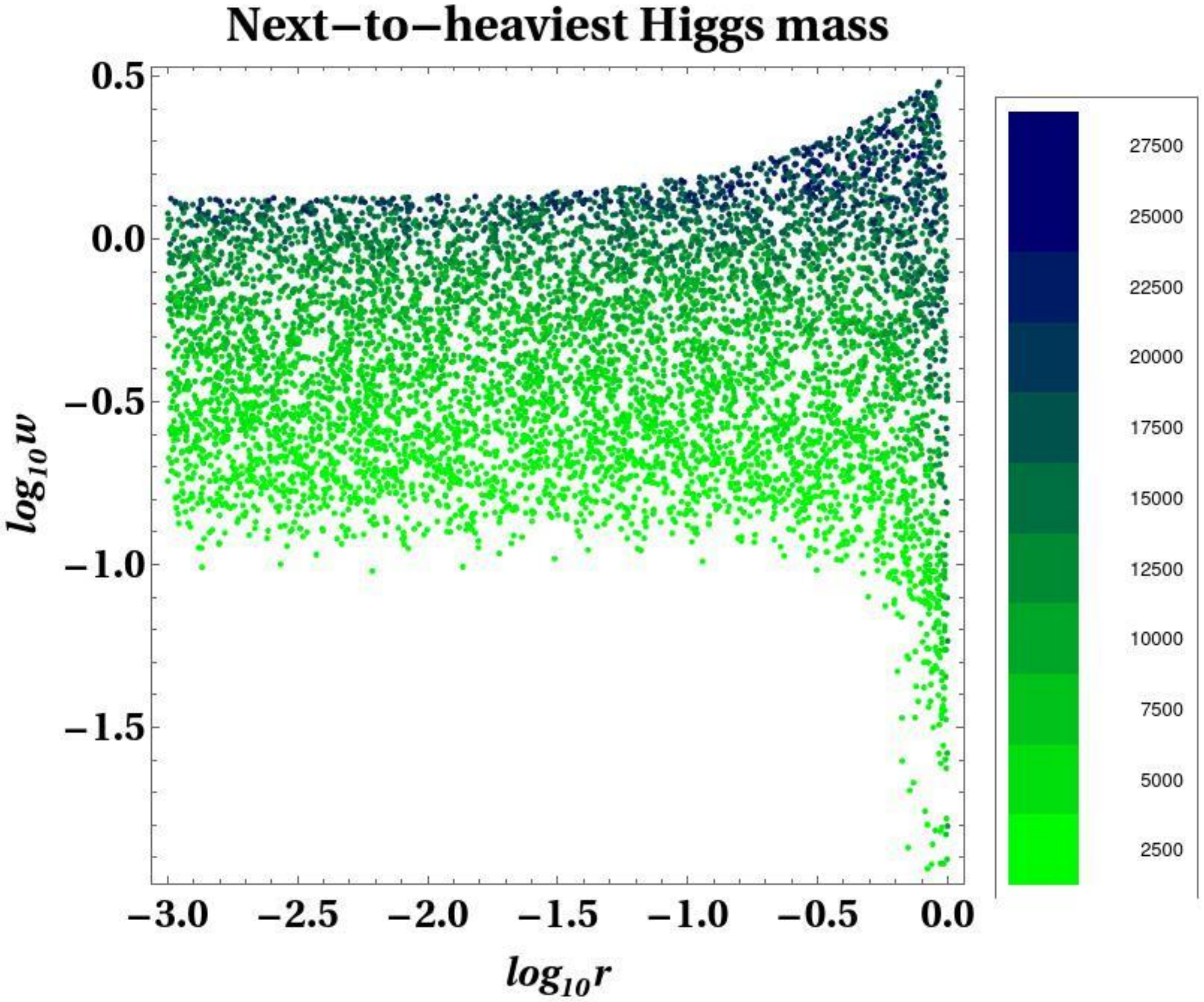
- We investigate the doublet LR symmetric model in light of the Higgs mass and coupling measurements.
- EW symmetry breaking can predominantly happen through the VEV of SU(2)L doublet, a possibility rarely explored in the literature.
- The key constraints came from Higgs mass, bottom Yukawa, flavour bounds on the next-to-lightest Higgs, and Higgs trilinear coupling.
- More precise measurement of Higgs trilinear coupling can rule out the benchmark points where the most dominant source of EWSB is the doublet.
- Complementary tests – future LHC? Gravitational waves?

Comments? Suggestions? Questions?

Effect of q

We now briefly discuss what happens when the ratio q is allowed to deviate from 1. From eq. (2.17), we see that leading contribution to the mass of one of the heavier Higgses is $\rho_{12}v_R^2 = \rho_1 q v_R^2$. Hence, very small values of q will not satisfy $m_{H_1} > 15$ TeV constraint whereas larger values of q will violate unitarity bounds. These two constraints together restrict q to the range $0.1 \leq q \leq 4$. The constraints from m_h, κ_h, κ_W, κ_Z, κ_t and κ_b are unaffected by changes in the value of q. As a result, the points satisfying all the constraints (dark blue points of fig. (2)) are depleted overall if q deviates from 1. For the extreme allowed values of q, *i.e.*, $q \sim 0.1$ and $q \sim 4$, $m_{H_1} > 15$ TeV is only satisfied for $w \gtrsim 1$. As mentioned above, these extreme values will be ruled out if κ_h is measured to be less than 1.5.


$\Delta\kappa_w \times 10^3$
0.5
0.0
−0.5
−1.0
−1.5
−2.0
$\log_{10}w$
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
$\log_{10}r$
1.0
0.8
0.6
0.4
0.2
−0.2


Next−to−heaviest Higgs mass
0.5
0.0
−0.5
−1.0
−1.5
$\log_{10}w$
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
$\log_{10}r$
27500
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500

Triple Higgs (h^3) vertex in this model is given by

$$c_{h^3} = \frac{\kappa_1}{2}\Big(2(\lambda_1 + r\lambda_4)U_{11}^3 + 2(r\lambda_1 + \lambda_4)U_{21}^3 + 2w\rho_1 U_{31}^3 + 2(r(\lambda_1 + 4\lambda_2 + 2\lambda_3) + 3\lambda_4)U_{11}^2 U_{21}$$
$$+2(\lambda_1 + 4\lambda_2 + 2\lambda_3 + 3\lambda_4 r)U_{11}U_{21}^2 + w(\alpha_1 + \alpha_4)U_{11}^2 U_{31} + (\alpha_1 + r\alpha_2 + \alpha_4)U_{11}U_{31}^2$$
$$+w(\alpha_1 + \alpha_3)U_{21}^2 U_{31} + (\alpha_2 + r(\alpha_1 + \alpha_3))U_{21}U_{31}^2\Big) \ ,$$

with the corresponding coupling multiplier being $\kappa_h = c_{h^3}/c_{h^3}^{\rm SM}$ where $c_{h^3}^{\rm SM} = m_h^2/2v$.