Constraints on the Scalar Sector of the Minnimal Left-Right Symmetric Model

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Based On
1308.1291, 1311.5666
1508.04960, 1604.06987

Outline

- The Model : Left Right Symmetry
- Scalar Potential : MLRSM
- Tree Unitarity
- Plots

Left Right Symmetry

$$\mathrm{L} \leftrightarrow \mathrm{R}$$

Discrete symmetry that connects left and right sector.

$$G_{LR} = SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

Quarks and leptons are in doublets

$$L_{iL} = \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix}_L : (2, 1, -1) \quad ; \quad L_{iR} = \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix}_R : (1, 2, -1)$$

$$Q_{iL} = \begin{pmatrix} u_i \\ d_i \end{pmatrix}_L : (2, 1, \frac{1}{3}) \quad ; \quad Q_{iR} = \begin{pmatrix} u_i \\ d_i \end{pmatrix}_R : (1, 2, \frac{1}{3})$$

LR Model Symmetry Breaking Pattern

$$SU(2)_L \otimes \underbrace{SU(2)_R \otimes U(1)_{B-L}}$$

$$\downarrow$$

$$\underbrace{SU(2)_L \otimes U(1)_Y}$$

$$\downarrow$$

$$U(1)_Q$$

LR Model Symmetry Breaking Pattern

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$$\downarrow$$

$$\underbrace{SU(2)_L \otimes U(1)_Y}$$

$$\downarrow$$

$$U(1)_Q$$

- Triplet Scalars

$$\Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^+_{L,R} & -\delta^0_{L,R}/\sqrt{2} \end{pmatrix}$$

$(3,1,2)$ & $(1,3,2)$

- Doublet Scalars

$$H_{L,R} = \begin{pmatrix} h^0_{L,R} \\ h^+_{L,R} \end{pmatrix} : (2,1,1) \& (1,2,1)$$

- Higgs bi-doublet

$$\Phi = \begin{pmatrix} \phi^0_1 & \phi^+_1 \\ \phi^-_2 & \phi^0_2 \end{pmatrix} : \qquad (2,2,0)$$

LR Model with Triplet Scalars

Most general Scalar Potential

$$
\begin{aligned}
V(\Phi, \Delta_L, \Delta_R) = \; & - \mu_1^2 \left\{ \mathrm{Tr}[\Phi^\dagger \Phi] \right\} - \mu_2^2 \left\{ \mathrm{Tr}[\tilde{\Phi}\Phi^\dagger] + \mathrm{Tr}[\tilde{\Phi}^\dagger \Phi] \right\} - \mu_3^2 \left\{ \mathrm{Tr}[\Delta_L^\dagger \Delta_L] + \mathrm{Tr}[\Delta_R^\dagger \Delta_R] \right\} \\
& + \lambda_1 \left\{ \left(\mathrm{Tr}[\Phi^\dagger \Phi]\right)^2 \right\} + \lambda_2 \left\{ \left(\mathrm{Tr}[\tilde{\Phi}\Phi^\dagger]\right)^2 + \left(\mathrm{Tr}[\tilde{\Phi}^\dagger \Phi]\right)^2 \right\} + \lambda_3 \left\{ \mathrm{Tr}[\tilde{\Phi}\Phi^\dagger]\mathrm{Tr}[\tilde{\Phi}^\dagger \Phi] \right\} \\
& + \lambda_4 \left\{ \mathrm{Tr}[\Phi^\dagger \Phi] \left(\mathrm{Tr}[\tilde{\Phi}\Phi^\dagger] + \mathrm{Tr}[\tilde{\Phi}^\dagger \Phi] \right) \right\} \\
& + \lambda_5 \left\{ \left(\mathrm{Tr}[\Delta_L \Delta_L^\dagger] \right)^2 + \left(\Delta_R \Delta_R^\dagger \right)^2 \right\} \\
& + \lambda_6 \left\{ \mathrm{Tr}[\Delta_L \Delta_L] \; \mathrm{Tr}[\Delta_L^\dagger \Delta_L^\dagger] + \mathrm{Tr}[\Delta_R \Delta_R] \; \mathrm{Tr}[\Delta_R^\dagger \Delta_R^\dagger] \right\} + \lambda_7 \left\{ \mathrm{Tr}[\Delta_L \Delta_L^\dagger] \; \mathrm{Tr}[\Delta_R \Delta_R^\dagger] \right\} \\
& + \lambda_8 [\Delta_L \Delta_L^\dagger] \left\{ \mathrm{Tr}[\Delta_L \Delta_L^\dagger] \; \mathrm{Tr}[\Delta_R \Delta_R^\dagger] \right\} \\
& + \lambda_9 \left\{ \mathrm{Tr}[\Phi^\dagger \Phi] \left(\mathrm{Tr}[\Delta_L \Delta_L^\dagger] + \mathrm{Tr}[\Delta_R \Delta_R^\dagger] \right) \right\} \\
& + (\lambda_{10} + i\,\lambda_{11}) \left\{ \mathrm{Tr}[\Phi \tilde{\Phi}^\dagger] \mathrm{Tr}[\Delta_R \Delta_R^\dagger] + \mathrm{Tr}[\Phi^\dagger \tilde{\Phi}] \mathrm{Tr}[\Delta_L \Delta_L^\dagger] \right\} \\
& + (\lambda_{10} - i\,\lambda_{11}) \left\{ \mathrm{Tr}[\Phi^\dagger \tilde{\Phi}] \mathrm{Tr}[\Delta_R \Delta_R^\dagger] + \mathrm{Tr}[\tilde{\Phi}^\dagger \Phi] \mathrm{Tr}[\Delta_L \Delta_L^\dagger] \right\} \\
& + \lambda_{12} \left\{ \mathrm{Tr}[\Phi \Phi^\dagger \Delta_L \Delta_L^\dagger] + \mathrm{Tr}[\Phi^\dagger \Phi \Delta_R \Delta_R^\dagger] \right\} + \lambda_{13} \left\{ \mathrm{Tr}[\Phi \Delta_R \Phi^\dagger \Delta_L^\dagger] + \mathrm{Tr}[\Phi^\dagger \Delta_L \Phi \Delta_R^\dagger] \right\} \\
& + \lambda_{14} \left\{ \mathrm{Tr}[\tilde{\Phi} \Delta_R \Phi^\dagger \Delta_L^\dagger] + \mathrm{Tr}[\tilde{\Phi}^\dagger \Delta_L \Phi \Delta_R^\dagger] \right\} + \lambda_{15} \left\{ \mathrm{Tr}[\Phi \Delta_R \tilde{\Phi}^\dagger \Delta_L^\dagger] + \mathrm{Tr}[\Phi^\dagger \Delta_L \tilde{\Phi} \Delta_R^\dagger] \right\},
\end{aligned}
$$

P.Duka, J. Gluza, and M. Zralek. arXiv:hep-ph/9910279

LR Model with Triplet Scalars

Neutral component of scalar field will get *vev*

$$\langle\Phi\rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 \end{pmatrix}_{(2,2,0)}, \langle\Delta_L\rangle = \begin{pmatrix} 0 & 0 \\ v_L & 0 \end{pmatrix}_{(3,1,2)}, \langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}_{(1,3,2)}$$

Step 1 : v_R breaks the $SU(2)_R \otimes U(1)_{B-L}$ symmetry to $U(1)_Y$,

$$\frac{Y}{2} = T_{3R} + \frac{B-L}{2}$$

Step 2 : $\langle\Phi\rangle, \langle\Delta_L\rangle$ breaks the $SU(2)_L \otimes U(1)_Y$symmetry to $U(1)_{em}$

Higgs Sector after Symmetry Breaking

20 real fields (8 from bi-doublet and 6 from each triplet)

- 6 Goldstone Bosons (Z_1, Z_2, $W_L^{\pm}$, $W_R^{\pm}$)
- 4 CP-even neutral Higgs (H_0^0, H_1^0, H_2^0, H_3^0)
- 2 CP-odd neutral pseudo scalars (A_1^0, A_2^0)
- 2 Singly charged scalars ($H_{1/2}^{\pm}$) and
- 2 Doubly charged scalars ($H_{L/R}^{\pm\pm}$) .

John F. Gunion et al. The Higgs Hunter's Guide. Front. Phys. 80 (2000)

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Constraint from ρ parameter

EW symmetry is broken by v_1 , v_2 , v_L.

$$\rho = \frac{\sum_{T,Y}[4T(T+1) - Y^2]|V_{T,Y}|^2}{\sum_{T,Y} 2Y^2|V_{T,Y}|^2}$$

ρ parameter tells v_L should be < 2 GeV.

John F. Gunion et al. The Higgs Hunter's Guide. Front.Phys. 80 (2000)

Higgs Sector after Symmetry Breaking

If $v_R >> v_1$ then masses can be written as

$$
\begin{aligned}
M^2_{H^0_0} &\simeq 2\,\lambda_1\, v_1^2 \\
M^2_{H^0_1} &\simeq \frac{1}{2}\lambda_5\, v_R^2 \\
M^2_{H^0_2} \simeq M^2_{A^0_1} \simeq M^2_{H^\pm_2} &\simeq 2\,\lambda_{12}\, v_R^2 \\
M^2_{H^0_3} \simeq M^2_{A^0_2} \simeq M^2_{H^\pm_1} \simeq M^2_{H^{\pm\pm}_L} &\simeq \frac{1}{2}(\lambda_7 - 2\lambda_5)\, v_R^2 \\
M^2_{H^{\pm\pm}_R} &\simeq 2\,\lambda_6\, v_R^2
\end{aligned}
$$

Unitarity

Using partial wave decomposition we have

$$\mathcal{M} = 16\pi \sum_{J=0}^{\infty} (2J+1) P_J(\cos\theta) a_J(\theta)$$

And the the cross-section

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} |\mathcal{M}|^2 \quad \Longrightarrow \quad \sigma = \frac{16\pi}{s} \sum_{J=0}^{\infty} (2J+1) |a_J|^2 .$$

According to optical theorem:

$$\Im |\mathcal{M}(\theta = 0)| = 2 E_{cm} p_{cm} \ \sigma \quad \Longrightarrow \quad \sigma = \frac{1}{s} \Im |\mathcal{M}(\theta = 0)|$$

We get
$|a_J|^2 = \Im(a_J) \Longrightarrow \Re(a_J)^2 + \Im(a_J)^2 = \Im(a_J) \Longrightarrow |\Re(a_J)| \leq \frac{1}{2}$

$$|\mathcal{M}| \leq 8\pi$$

Computation of Unitarity constraints : Method I

Rewrite scalar potential in terms of field components

$\downarrow$

Find all possible 0, 1, $\cdots$, q charged 2-particle states

$\downarrow$

Taking 2-particle states as rows and columns construct the matrix

$\downarrow$

This matrix contains scattering amplitude of $2 \to 2$ processes

$\downarrow$

Find the eigenvalues. Eigenvalues $\leq 8\pi$

$\downarrow$

Satisfy above constraint along with VS and perturbativity.

Computation of Unitarity constraints : Method I

Number of all possible q-charged 2-particle states constructed from n neutral, s singly charged and d doubly charged fields.

Charge(q)	0	1	2	3	4
Number of states (general)	$\frac{n(n+1)}{2} + s^2 + d^2$	$s(n+d)$	$nd + \frac{s(s+1)}{2}$	sd	$\frac{d(d+1)}{2}$
Number of states (LRT Model)	56	40	26	8	3
Independent constraints	29	14	16	3	2

Computation of Unitarity constraints : Method I

$$\Phi = \begin{pmatrix} \frac{\phi_1^{0r} + \ i\ \phi_1^{0i}}{\sqrt{2}} & \phi_1^+ \\ \phi_2^- & \frac{\phi_1^{0r} + \ i\ \phi_1^{0i}}{\sqrt{2}} \end{pmatrix}$$

$$\Delta_R = \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ \frac{i\delta_R^{0i}+\delta_R^{0r}}{\sqrt{2}} & -\frac{\delta_R^+}{\sqrt{2}} \end{pmatrix}, \Delta_L = \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ \frac{i\delta_L^{0i}+\delta_L^{0r}}{\sqrt{2}} & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix}$$

Computation of Unitarity constraints : Method I

$$\Phi = \begin{pmatrix} \frac{\phi_1^{0r} + i\,\phi_1^{0i}}{\sqrt{2}} & \phi_1^{+} \\ \phi_2^{-} & \frac{\phi_1^{0r} + i\,\phi_1^{0i}}{\sqrt{2}} \end{pmatrix}$$

$$\Delta_R = \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ \frac{i\delta_R^{0i}+\delta_R^{0r}}{\sqrt{2}} & -\frac{\delta_R^+}{\sqrt{2}} \end{pmatrix}, \Delta_L = \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ \frac{i\delta_L^{0i}+\delta_L^{0r}}{\sqrt{2}} & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix}$$

Doubly charged basis(26-d)

$$\begin{pmatrix} {\phi_1^+}^2 \\ \phi_1^+\phi_2^+ \\ \delta_R^+\phi_1^+ \\ \delta_L^+\phi_1^+ \\ {\phi_2^+}^2 \\ \delta_R^+\phi_2^+ \\ \delta_L^+\phi_2^+ \\ {\delta_R^+}^2 \\ \delta_L^+\delta_R^+ \\ {\delta_L^+}^2 \\ \delta_R^{++}\phi_1^{0r} \\ \vdots \end{pmatrix}$$

Computation of Unitarity constraints : Method I

$$\Phi = \begin{pmatrix} \frac{\phi_1^{0r} + \ i\ \phi_1^{0i}}{\sqrt{2}} & \phi_1^+ \\ \phi_2^- & \frac{\phi_1^{0r} + \ i\ \phi_1^{0i}}{\sqrt{2}} \end{pmatrix}$$

$$\Delta_R = \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ \frac{i\delta_R^{0i}+\delta_R^{0r}}{\sqrt{2}} & -\frac{\delta_R^+}{\sqrt{2}} \end{pmatrix}, \Delta_L = \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ \frac{i\delta_L^{0i}+\delta_L^{0r}}{\sqrt{2}} & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix}$$

We have constructed all 0, 1, 2, 3 and 4-charged two-particle scattering matrix and find their eigenvalues.

Doubly charged basis(26-d)

$$\begin{pmatrix} {\phi_1^+}^2 \\ \phi_1^+\phi_2^+ \\ \delta_R^+\phi_1^+ \\ \delta_L^+\phi_1^+ \\ {\phi_2^+}^2 \\ \delta_R^+\phi_2^+ \\ \delta_L^+\phi_2^+ \\ {\delta_R^+}^2 \\ \delta_L^+\delta_R^+ \\ {\delta_L^+}^2 \\ \delta_R^{++}\phi_1^{0r} \\ \vdots \end{pmatrix}$$

Constraints on physical scalar masses

$$\begin{aligned}
M^2_{H^0_0} &\simeq 2\,\lambda_1\, v_1^2 = (125\ \mathrm{GeV})^2 \\
M^2_{H^0_1} &\simeq \frac{1}{2}\lambda_5\, v_R^2 \\
M^2_{H^0_2} \simeq M^2_{A^0_1} \simeq M^2_{H^\pm_2} &\simeq 2\,\lambda_{12}\, v_R^2 \\
M^2_{H^0_3} \simeq M^2_{A^0_2} \simeq M^2_{H^\pm_1} \simeq M^2_{H^{\pm\pm}_L} &\simeq \frac{1}{2}(\lambda_7 - 2\lambda_5)\, v_R^2 \\
M^2_{H^{\pm\pm}_R} &\simeq 2\,\lambda_6\, v_R^2
\end{aligned}$$

- Randomly vary the quartic couplings $\lambda_5, \lambda_6, (\lambda_7 - 2\lambda_5)$ and λ_{12} in their allowed range $[0, 4\pi]$.
- These quartic couplings run according to their respective RGEs.
- Ensure that the quartic couplings obey all the conditions coming from vacuum stability, unitarity & perturbativity.
- The input quartic couplings which obey these conditions, till M_{Pl}, are interpreted as the accepted mass scale of physical scalars

Computation of Unitarity constraints : Method II

Rewrite the scalar potential in terms of physical fields

$$\downarrow$$

$$V\left(H^0_{0,1,2,3}, A^0_{1,2}, H^{\pm}_{1,2}, H^{\pm\pm}_{1,2}\right) = \sum_m \ \Lambda_m H_i H_j H_k H_\ell$$

$$\downarrow$$

Find all possible $H_i H_j \longrightarrow H_k H_\ell$ processes

$$\downarrow$$

Gauge boson mediated terms diverges logarithmicaly. Neglect.

$$\downarrow$$

Conditions: $\Lambda_m \leq 8\pi$

$$\downarrow$$

Satisfy above constraint along with VS and perturbativity.

Computation of Unitarity constraints : Method II

$$\lambda_1 < 4\pi/3,\ (\lambda_1 + 4\lambda_2 + 2\lambda_3) < 4\pi,$$
$$(\lambda_1 - 4\lambda_2 + 2\lambda_3) < 4\pi,$$
$$\lambda_4 < 4\pi/3,$$
$$\alpha_1 < 8\pi,\ \alpha_2 < 4\pi,\ (\alpha_1 + \alpha_3) < 8\pi,$$
$$\rho_1 < 4\pi/3,\ (\rho_1 + \rho_2) < 2\pi,\ \rho_2 < 2\sqrt{2}\pi,$$
$$\rho_3 < 8\pi,\ \rho_4 < 2\sqrt{2}\pi.$$

Constraints coming from FCNC

$$\frac{\sqrt{2}}{\kappa_-^2}\overline{\mathbf{U}}^L \left[\phi_-^0 \frac{\kappa_-^2}{\kappa_+}\mathbf{M}^{\mathbf{U}} + \phi_+^0 \left(\frac{-2\kappa_1^*\kappa_2}{\kappa_+}\mathbf{M}^{\mathbf{U}} + \kappa_+ \mathbf{V}_L^{\mathrm{CKM}}\mathbf{M}^{\mathbf{D}}\mathbf{V}_R^{\mathrm{CKM}\,\dagger}\right)\right]\mathbf{U}^R$$

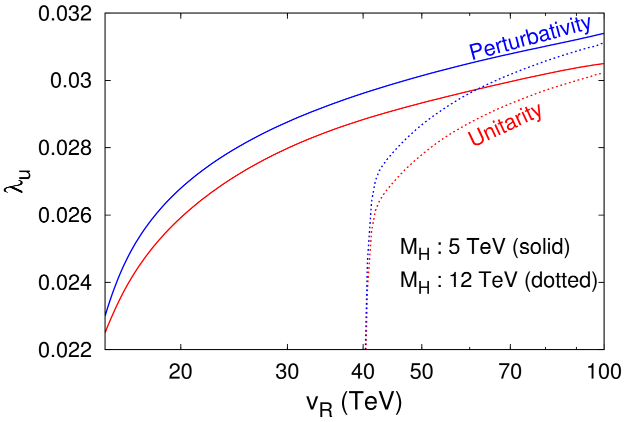
$$\frac{\sqrt{2}}{\kappa_-^2}\overline{\mathbf{D}}^L \left[\phi_-^{0*} \frac{\kappa_-^2}{\kappa_+}\mathbf{M}^{\mathbf{D}} + \phi_+^{0*} \left(\frac{-2\kappa_1\kappa_2^*}{\kappa_+}\mathbf{M}^{\mathbf{D}} + \kappa_+ \mathbf{V}_L^{\mathrm{CKM}\,\dagger}\mathbf{M}^{\mathbf{U}}\mathbf{V}_R^{\mathrm{CKM}}\right)\right]\mathbf{D}^R$$

- ϕ_+^0 gives tree level FCNC.
- Mass of this scalar is constrained severely ($\geq$ 10 TeV).
- $\sqrt{\alpha_3(\lambda_{12})}\, v_R > 10$ TeV

Deshpande, Gunion, Kayser, Olness PRD, 1991

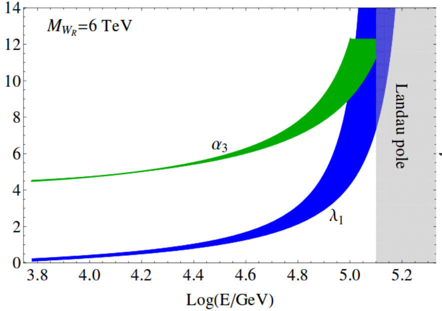
Constraints on LRSM parameter space from unitarity

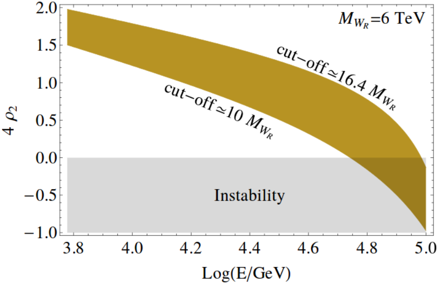
Constraints on "universal" quartic couplings



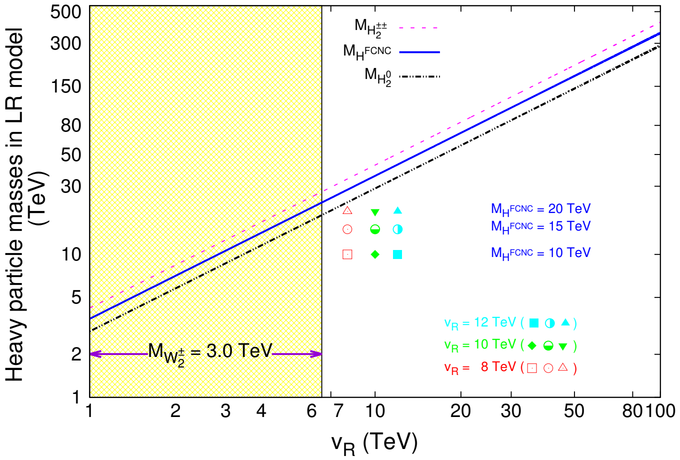
LHC scale W_R

$$W_R = 6\ TeV \implies v_R \simeq 13\ TeV$$





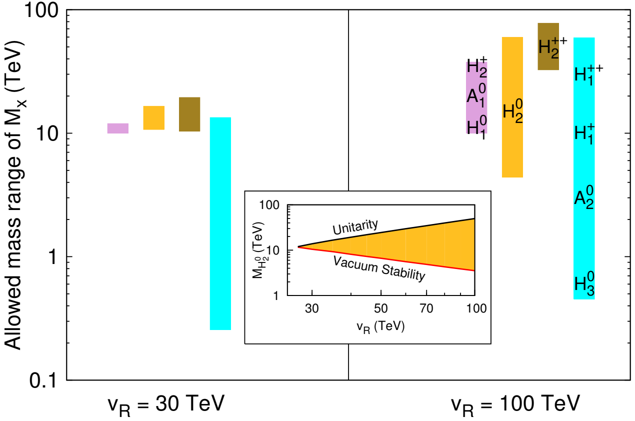
Constraints on physical scalars



J. Chakrabortty, J. Gluza, T. Jelinski, T. Srivastava arXiv: 1604.06987

Constraints on physical scalar masses

$$M_{H_1^0} \geq 10 \text{ TeV and } \lambda_u = 0.01.$$



Color codes

Purple : $M_{H_1^0}, M_{A_1^0} \geq 10$ TeV $\Rightarrow$ Bound on λ_{12} from below. Maximum allowed value is restricted by perturbativity. Large v_R relaxes maximum bound on λ_{12}.

Yellow : Explained in Inset. λ_5 and λ_{12} are coupled through vacuum stability. Maximum allowed value of λ_5 is restricted from unitarity. Minimum depends on λ_{12}. Higher $v_R \Rightarrow$ lower $\lambda_{12} \Rightarrow$ low λ_5.

Brown : With low initial value, λ_6 decreases with energy and eventually becomes negative leading to tachyonic states. To get rid of this λ_6 should be high enough $\Rightarrow$ higher mass states.

Cyan : $(\lambda_7 - 2\lambda_5)$ is not constrained from vacuum stability and can be very low. $\mathcal{O}(100)$ GeV physical scalar masses are possible.

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v_R (TeV)	$M_{H_1^0}, M_{A_1^0}, M_{H_2^\pm}$ (TeV)	$M_{H_2^0}$ (TeV)	$M_{H_2^{\pm\pm}}$ (TeV)	$M_{H_3^0}, M_{A_2^0}, M_{H_1^\pm}, M_{H_1^{\pm\pm}}$ (TeV)
30	$10 - 12$	$10.5 - 16.5$	$10.5 - 20$	$\mathcal{O}(0.1) - 13.5$
100	$10 - 37.5$	$4.4 - 60$	$33 - 78$	$\mathcal{O}(0.1) - 59$

Conclusion

- BSM scalar sector is constrained by VS, unitarity and perturbativity.
- LRSM symmetry breaking vev is related to Unitarity via scalar masses.
- LHC scale W_R is valid upto $\sim$ 100 TeV.
- Scalars which take part in FCNC are very heavy.
- In turn most of the scalars become heavy for low v_R.
- For heavy W_R some of the scalars can be light.

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Thank You

Back up

Constraints on physical scalars

$$\lambda_1 = 0.13,\ \lambda_2 = 0,\ \lambda_3 = 0,\ \lambda_4 = 0,$$
$$\alpha_1 = 0,\ \alpha_2 = 0,\ \alpha_3 = 1.39,$$
$$\rho_1 = 1.0,\ \rho_2 = 7.5 \times 10^{-4},\ \rho_3 = 2.003.$$

All masses are given in GeV:

$$M_{H_0^0} = 125,$$
$$M_{H_1^0} = 10000,\ M_{H_2^0} = 16971,\ M_{H_3^0} = 465,$$
$$M_{A_1^0} = 10000,\ M_{A_2^0} = 465,$$
$$M_{H_1^\pm} = 487,\quad M_{H_2^\pm} = 10001,$$
$$M_{H_1^{\pm\pm}} = 508,\quad M_{H_2^{\pm\pm}} = 508.$$

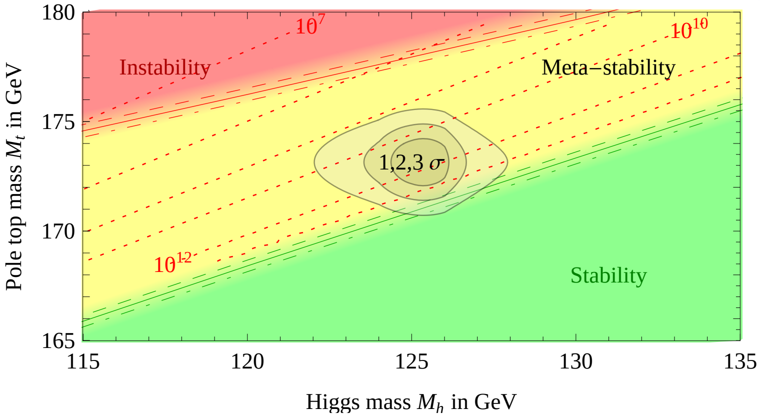

Figure: Dead or Alive ??

- SM in metastable region with 98% C.L.

Strumia et al. arXiv: 1205.6497