Vacuum Stability in Left-Right Symmetric Model

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- It features heavy right-handed Majorana neutrinos, and thus explains small masses of left-handed neutrinos via see-saw mechanism.
- Hypercharge generator arises in a more natural sense from (B-L)

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

Particle Content of LRSM

	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
$Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	2	1	$\frac{1}{3}$
$Q_R \equiv \begin{pmatrix} u_R \\ d_R \end{pmatrix}$	1	2	$\frac{1}{3}$
$\psi_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	2	1	-1
$\psi_R \equiv \begin{pmatrix} N \\ e_R \end{pmatrix}$	1	2	-1
$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$	2	2	0
$\Delta_L = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_L^+ & \Delta_L^{++} \\ \Delta_L^0 & -\frac{1}{\sqrt{2}}\Delta_L^+ \end{pmatrix}$	3	1	2
$\Delta_R = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix}$	1	3	2

Scalar Potential

$$
\begin{aligned}
V \;=\; & -\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(\mathrm{Tr}[\Delta_L\Delta_L^\dagger] + \mathrm{Tr}[\Delta_R\Delta_R^\dagger]\right) + \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] + \lambda_4 \mathrm{Tr}[\phi^\dagger\phi]\left(\mathrm{Tr}[\tilde{\phi}\phi^\dagger] + \mathrm{Tr}[\tilde{\phi}^\dagger\phi]\right) \\
& +\rho_1\left(\mathrm{Tr}[\Delta_L\Delta_L^\dagger]^2 + \mathrm{Tr}[\Delta_R\Delta_R^\dagger]^2\right) + \rho_2\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) \\
& +\rho_3 \mathrm{Tr}[\Delta_L\Delta_L^\dagger]\mathrm{Tr}[\Delta_R\Delta_R^\dagger] + \rho_4\left(\mathrm{Tr}[\Delta_L\Delta_L]\mathrm{Tr}[\Delta_R^\dagger\Delta_R^\dagger] + \mathrm{Tr}[\Delta_L^\dagger\Delta_L^\dagger]\mathrm{Tr}[\Delta_R\Delta_R]\right) \\
& +\alpha_1 \mathrm{Tr}[\phi^\dagger\phi]\left(\mathrm{Tr}[\Delta_L\Delta_L^\dagger] + \mathrm{Tr}[\Delta_R\Delta_R^\dagger]\right) + \alpha_3(\mathrm{Tr}[\phi\phi^\dagger\Delta_L\Delta_L^\dagger] + \mathrm{Tr}[\phi^\dagger\phi\Delta_R\Delta_R^\dagger]\big) \\
& +\alpha_2\left(\mathrm{Tr}[\Delta_L\Delta_L^\dagger]\mathrm{Tr}[\tilde{\phi}\phi^\dagger] + \mathrm{Tr}[\Delta_R\Delta_R^\dagger]\mathrm{Tr}[\tilde{\phi}^\dagger\phi] + \mathrm{H.c.}\right) \\
& +\beta_1\left(\mathrm{Tr}[\phi\Delta_R\phi^\dagger\Delta_L^\dagger] + \mathrm{Tr}[\phi^\dagger\Delta_L\phi\Delta_R^\dagger]\right) + \beta_2\left(\mathrm{Tr}[\tilde{\phi}\Delta_R\phi^\dagger\Delta_L^\dagger] + \mathrm{Tr}[\tilde{\phi}^\dagger\Delta_L\phi\Delta_R^\dagger]\right) \\
& +\beta_3\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}
$$

Deshpande, Gunion, Kayser, Olness (PRD ’91)

Maiezza, Senjanovic, Vasquez (PRD ’17)

Vacuum Stability

- For viability of the model to be extension for SM, the potential for the theory should be stable.

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- For viability of the model to be extension for SM, the potential for the theory should be stable.
- Given a random set of quartic couplings, it does not ensure the stability of the vacuum.
- Using the concepts of boundedness, copositivity and gauge orbit spaces, conditions for stability of the potential can be derived.

Dev, Mohapatra, Rodejohann, Xu (JHEP '19)
Kim (JMP '84)

Kannike (EPJC '12)

Scalar Potential: λ terms

$$\begin{aligned} V \quad \supset \quad & -\mu_1^2 \mathrm{Tr}[\phi^\dagger \phi] - \mu_2^2 \left(\mathrm{Tr}[\tilde{\phi}\phi^\dagger] + \mathrm{Tr}[\tilde{\phi}^\dagger \phi] \right) \\ & + \lambda_1 \mathrm{Tr}[\phi^\dagger \phi]^2 + \lambda_2 \left(\mathrm{Tr}[\tilde{\phi}\phi^\dagger]^2 + \mathrm{Tr}[\tilde{\phi}^\dagger \phi]^2 \right) + \lambda_3 \mathrm{Tr}[\tilde{\phi}\phi^\dagger] \mathrm{Tr}[\tilde{\phi}^\dagger \phi] \\ & + \lambda_4 \mathrm{Tr}[\phi^\dagger \phi] \left(\mathrm{Tr}[\tilde{\phi}\phi^\dagger] + \mathrm{Tr}[\tilde{\phi}^\dagger \phi] \right) \end{aligned}$$

Stability : λ terms

- By analyzing the boundedness of λ sector of the potential,

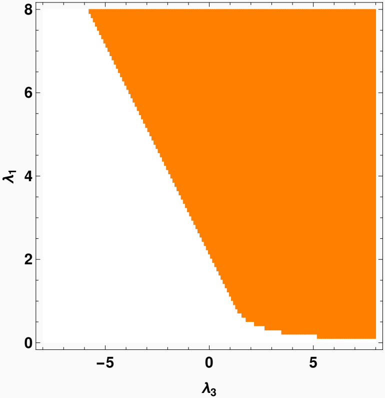
$$\lambda_1 > 0 \tag{1}$$

$$\lambda_1 - \frac{\lambda_4^2}{2\lambda_2 + \lambda_3} > 0 \tag{2}$$

$$\lambda_1 + \lambda_3 - 2\lambda_2 - \frac{\lambda_4^2}{4\lambda_2} > 0 \tag{3}$$

$$\lambda_1 + \lambda_3 + 2(\lambda_2 - |\lambda_4|) > 0 \tag{4}$$

Numerical case 1: λ's

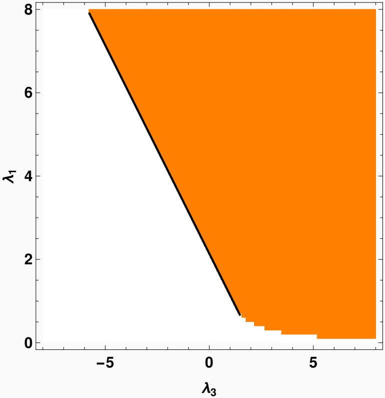


Values of set λ's are:

$$\lambda_2 = 0$$

$$\lambda_4 = 1$$

Numerical case 1: λ's



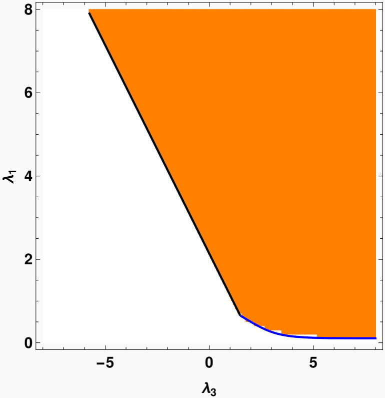
Values of set λ's are:

$$\lambda_2 = 0$$
$$\lambda_4 = 1$$

$$\lambda_1 > 0$$
$$\lambda_1 - \frac{1}{\lambda_3} > 0$$

$$\lambda_1 + \lambda_3 > 2$$

Numerical case 1: λ's



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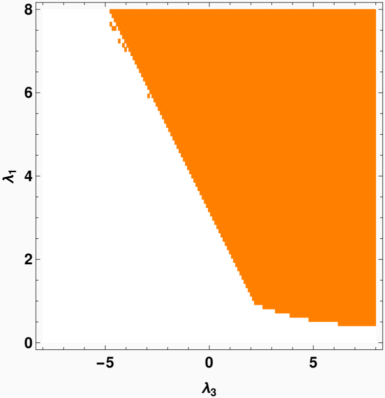
Numerical case 2: λ's



Values of set λ's are:

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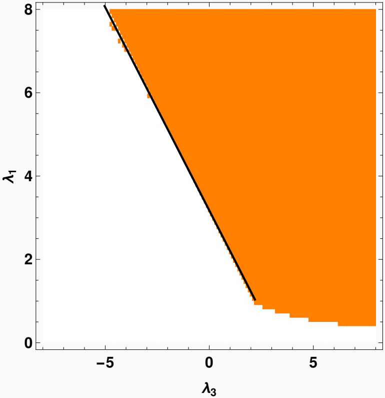
Numerical case 2: λ's

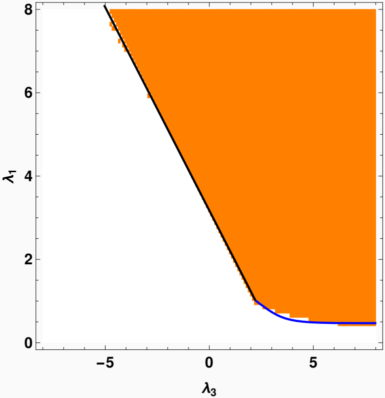


Values of set λ's are:

$$\lambda_2 = 1$$
$$\lambda_4 = -2$$

$$\lambda_1 > 0$$
$$\lambda_1 - \frac{4}{2+\lambda_3} > 0$$
$$\lambda_1 + \lambda_3 > 3$$
$$\lambda_1 + \lambda_3 > 2$$

Numerical case 2: λ's



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Scalar Potential : ρ terms

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\begin{aligned}
V \quad \supset \quad & -\mu_3^2 \left(\mathrm{Tr}[\Delta_L \Delta_L^\dagger] + \mathrm{Tr}[\Delta_R \Delta_R^\dagger] \right) \\
& + \rho_1 \left(\mathrm{Tr}[\Delta_L \Delta_L^\dagger]^2 + \mathrm{Tr}[\Delta_R \Delta_R^\dagger]^2 \right) \\
& + \rho_2 \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) \\
& + \rho_3 \, \mathrm{Tr}[\Delta_L \Delta_L^\dagger] \mathrm{Tr}[\Delta_R \Delta_R^\dagger] \\
& + \rho_4 \left(\mathrm{Tr}[\Delta_L \Delta_L] \mathrm{Tr}[\Delta_R^\dagger \Delta_R^\dagger] + \mathrm{Tr}[\Delta_L^\dagger \Delta_L^\dagger] \mathrm{Tr}[\Delta_R \Delta_R] \right)
\end{aligned}
$$

Stability : ρ terms

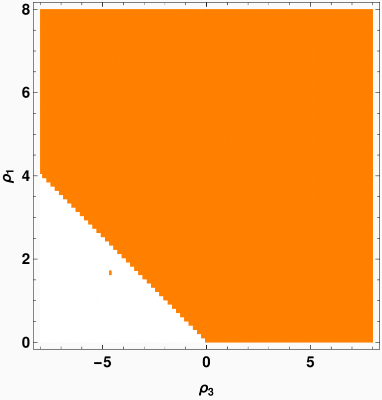
- For boundedness of ρ sector of the potential,

$$\rho_1 > 0 \tag{5}$$

$$\rho_1 + \rho_2 > 0 \tag{6}$$

$$\rho_3 - 2|\rho_4| + 2(\rho_1 + \rho_2) > 0 \tag{7}$$

Numerical case 1: ρ's

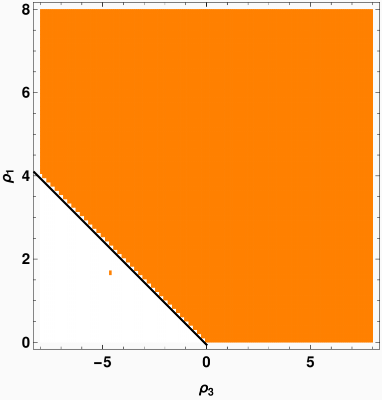


Values of set ρ's are:

$$\rho_2 = 1$$

$$\rho_4 = -1$$

Numerical case 1: ρ's



Values of set ρ's are:

$$\rho_2 = 1$$

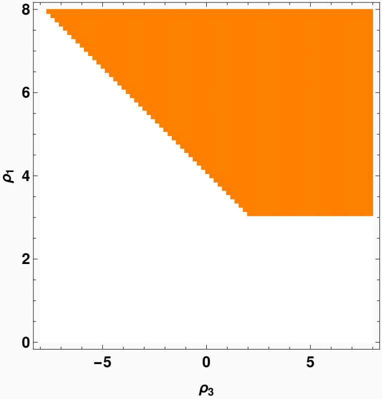
$$\rho_4 = -1$$

$$\rho_1 > 0$$

$$\rho_1 + 1 > 0$$

$$\rho_3 + 2\rho_2 > 0$$

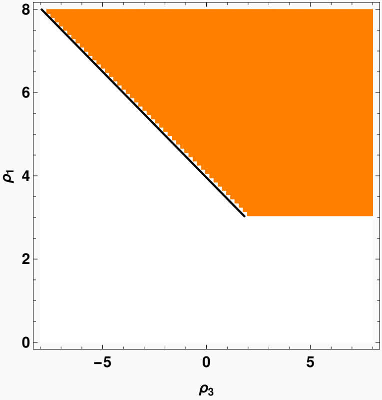
Numerical case 2: ρ's



Values of set ρ's are:

$$\rho_2 = -3$$
$$\rho_4 = -1$$

Numerical case 2: ρ's



Values of set ρ's are:

$$\rho_2 = -3$$
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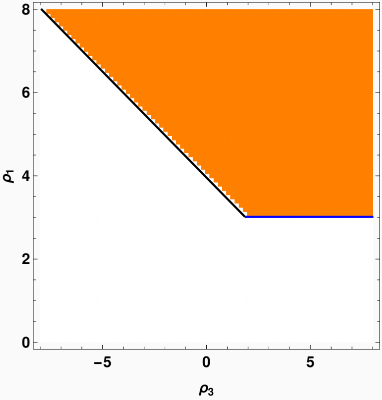
$$\rho_1 > 0$$
$$\rho_1 - 3 > 0$$
$$\rho_3 + 2\rho_2 - 8 > 0$$

Numerical case 2: ρ's



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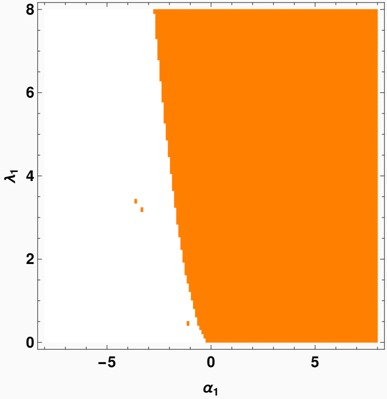
$$\rho_3 + 2\rho_2 - 8 > 0$$

Dreaded case: $\alpha_1 \neq 0$

- For boundedness of the potential,

$$\alpha_1 + 2\sqrt{\left(\lambda_1 - \frac{\lambda_4^2}{2\lambda_2+\lambda_3}\right)(\rho_1+\rho_2)} > 0$$
$$\alpha_1 + \sqrt{\left(\lambda_1 - \frac{\lambda_4^2}{2\lambda_2+\lambda_3}\right)(\rho_3 - 2|\rho_4| + 2(\rho_1+\rho_2))} > 0$$
$$\alpha_1 + 2\sqrt{\left(\lambda_1 + \lambda_3 - 2\lambda_2 - \frac{\lambda_4^2}{4\lambda_2}\right)(\rho_1+\rho_2)} > 0$$
$$\alpha_1 + \sqrt{\left(\lambda_1 + \lambda_3 - 2\lambda_2 - \frac{\lambda_4^2}{4\lambda_2}\right)(\rho_3 - 2|\rho_4| + 2(\rho_1+\rho_2))} > 0$$
$$\alpha_1 + 2\sqrt{(\lambda_1 + \lambda_3 + 2(\lambda_2 - |\lambda_4|))(\rho_1+\rho_2)} > 0$$
$$\alpha_1 + \sqrt{\lambda_1 + \lambda_3 + 2(\lambda_2 - |\lambda_4|))(\rho_3 - 2|\rho_4| + 2(\rho_1+\rho_2))} > 0$$

Numerical case 1: $\alpha_1 \neq 0$



- Values of couplings are:

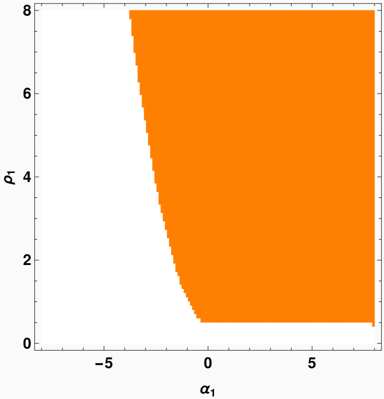
$$\lambda_2 = \lambda_4 = \rho_2 = 0$$

$$\lambda_3 = \rho_1 = \rho_3 = 1$$

$$\rho_4 = -1$$

- Condition 2: $\alpha_1 + \sqrt{\lambda_1} > 0$

Numerical case 2: $\alpha_1 \neq 0$



- Values of quartic couplings are:

$$\lambda_1 = \lambda_3 = \rho_3 = 1$$

$$\lambda_2 = \lambda_4 = \rho_2 = 0$$

$$\rho_4 = -1$$

- Condition 2: $\alpha_1 + \sqrt{2\rho_1 - 1} > 0$

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- We obtained necessary and sufficient conditions for the stability of the potential.
- Renormalization group analysis of the potential requires these conditions and can put important constraints on breaking scale. GC, Dev, Mohapatra, Zhang (JHEP '19)
- For correct symmetry breaking, conditions for λ presented here are required.
- Work presented here can be generalized. Conditions on quartic couplings of a higgs potential for a theory can be obtained completely.

Thank you !!