Hierarchies in $SU(2)_L \times SU(2)_R \times U(1)_X$ effective potential models

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1. Introduction

- **Motivation**: no new particles have been observed yet at current accelerators energy scale ⇒ to introduce new scalar particles, we need to have a **mass hierarchy**

  Is it possible to obtain hierarchy in a *natural* way? (i.e. general model/models & wide range of parameters)

- **Problem**: we need to produce new particles while recovering the SM at low energies (masses, couplings, θ_W, ...)

- **Proposal**: start from a massless lagrangian and make use of the Coleman & Weinberg mechanism to obtain spontaneous symmetry; effective potential formalism (1-loop)

  This does not work for the SM alone, but we can introduce a **new symmetry and scalar field**

2. The model

$SU(2)_L \times SU(2)_R \times U(1)_X$ + 2 scalars

$$\mathcal{L} = \frac{1}{2}(\mathrm{D}^\mu_L\phi_L)^\dagger(\mathrm{D}_{L\mu}\phi_L) + \frac{1}{2}(\mathrm{D}^\mu_R\phi_R)^\dagger(\mathrm{D}_{R\mu}\phi_R) - V(\phi_L,\phi_R)$$

$$\mathrm{D}^\mu_{L,R} = \partial^\mu - \frac{i}{2}g_{L,R}\sigma_a W^{a\mu}_{L,R} - \frac{i}{2}g_X Q_{L,R}X^\mu$$

$$V(\phi_L,\phi_R) = \frac{1}{4!}\lambda_L\phi_L^4 + \frac{1}{4!}\lambda_R\phi_R^4 + \frac{1}{4!}\lambda_{LR}\phi_L^2\phi_R^2$$

Classical fields: $\phi_L \to (0,\varphi) \sim$ SM, $\phi_R \to (0,\eta)$

Mass matrix → eigenvalues and eigenvectors

$$\frac{1}{4}\begin{pmatrix} g_L^2\varphi^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & g_L^2\varphi^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & g_L^2\varphi^2 & 0 & 0 & 0 & g_L g_X Q_L\varphi^2 \\ 0 & 0 & 0 & g_R^2\eta^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & g_R^2\eta^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & g_R^2\eta^2 & g_R g_X Q_R\eta^2 \\ 0 & 0 & g_L g_X Q_L\varphi^2 & 0 & 0 & g_R g_X Q_R\eta^2 & g_X^2(Q_L^2\varphi^2 + Q_R^2\eta^2) \end{pmatrix}$$

$$\Rightarrow \tau_L = \frac{1}{4}g_L^2\varphi^2 \to W_L^\pm,\ \tau_R = \frac{1}{4}g_R^2\eta^2 \to W_R^\pm,\ \tau_0 = 0 \to\sim \gamma,\ \tau_\pm \to\sim Z_{L,R}$$

Effective potential (1-loop + Coleman & Weinberg hypothesis)

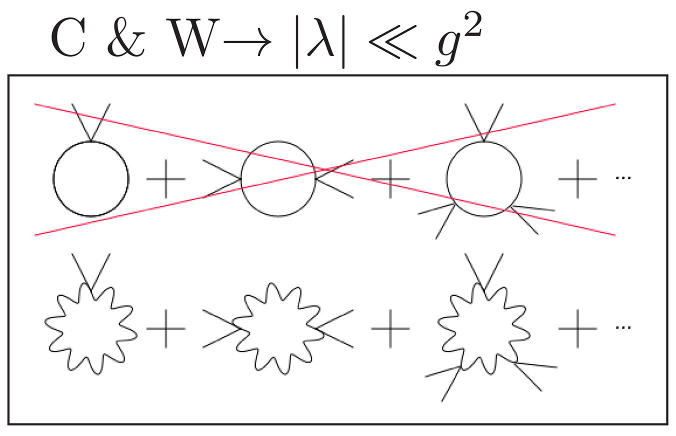
$$V(\varphi,\eta) = \frac{1}{4!}\lambda_L\varphi^4 + \frac{1}{4!}\lambda_R\eta^4 + \frac{1}{4!}\lambda_{LR}\varphi^2\eta^2 + \\ + \frac{3}{64\pi^2}\left\{2\left\{\tau_L^2(\varphi)\left[\ln\left(\frac{\tau_L(\varphi)}{\mu^2}\right) - \frac{25}{6}\right] + \tau_R^2(\eta)\left[\ln\left(\frac{\tau_R(\eta)}{\mu^2}\right) - \frac{25}{6}\right]\right\} + \\ + \tau_+^2(\varphi,\eta)\left[\ln\left(\frac{\tau_+(\varphi,\eta)}{\mu^2}\right) - \frac{25}{6}\right] + \tau_-^2(\varphi,\eta)\left[\ln\left(\frac{\tau_-(\varphi,\eta)}{\mu^2}\right) - \frac{25}{6}\right]\right\}$$

Renormalization Group Equations (1)

$$\frac{\partial g^2}{\partial x} = \hat\beta g^4 \longrightarrow g^2(x) = \frac{g_0^2}{1-\hat\beta g_0^2 x}$$

$$\frac{\partial \lambda}{\partial x} = \hat\delta g^4 \longrightarrow \lambda(x) = \lambda_0 + \frac{\hat\delta}{\hat\beta}\left[g^2(x) - g_0^2\right]$$

C & W→ $|\lambda| \ll g^2$



$x = \ln(\mu^2)$, μ: renormalization scale

4. Conclusions and future work

- model with $SU(2)_L \times SU(2)_R \times U(1)_X$ symmetry → 2 sectors of particles with **possible hierarchy** between them
- hierarchy: depends on the **couplings** $g_L, g_R, \lambda_L, \lambda_R, g_X Q_{L,R}, \lambda_{LR}$
- **promising results**: wide region of parameter space giving place to hierarchy

⋆ we are studying a hierarchy∼ LHC scale ⇒ $\mathfrak{R} \sim 10^2$; but: **other hierarchies?**: ∼ gravity/inflation scale ⇒ $\mathfrak{R} \sim 10^{32}$; neutrino mass scale ⇒ $\mathfrak{R} \sim 10^{-12}$

⋆ include **fermions** in the model and study their effects; specifically: introduce $y_t \neq 0$

⋆ thorough study of the **compatibility** of the model with SM!

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3. Phenomenolgy

Mass hierarchy? → possible cases

$$\mathfrak{R} = \frac{m^2_{W_R}}{m^2_{W_L}} = \frac{g_R^2\langle\eta\rangle^2}{g_L^2\langle\varphi\rangle^2}$$

1. $g_X = 0,\ \lambda_{LR} = 0$

$$\mathfrak{R} = e^{\frac{128\pi^2}{27}\left(\frac{\lambda_L}{g_L^4} - \frac{\lambda_R}{g_R^4}\right)}$$

- analytical expressions
- $g_L \neq g_R, \lambda_L \neq \lambda_R$ needed for $\mathfrak{R} \neq 1$

2. $g_X \neq 0,\ \lambda_{LR} = 0$

$$\mathfrak{R} = e^{\frac{99g_R^4 + 57g_R^2 g_X^2 Q_R^2 - 128\pi^2\lambda_R}{54g_R^4 + 36g_R^2 g_X^2 Q_R^2} - (R\to L)}$$

- $g_X \ll 1$ ⇒ analytical expressions
- $\mathfrak{R} \neq 1$ for $g_L = g_R, \lambda_L = \lambda_R$ with $Q_L \neq Q_R$

3. $g_X = 0,\ \lambda_{LR} \neq 0$

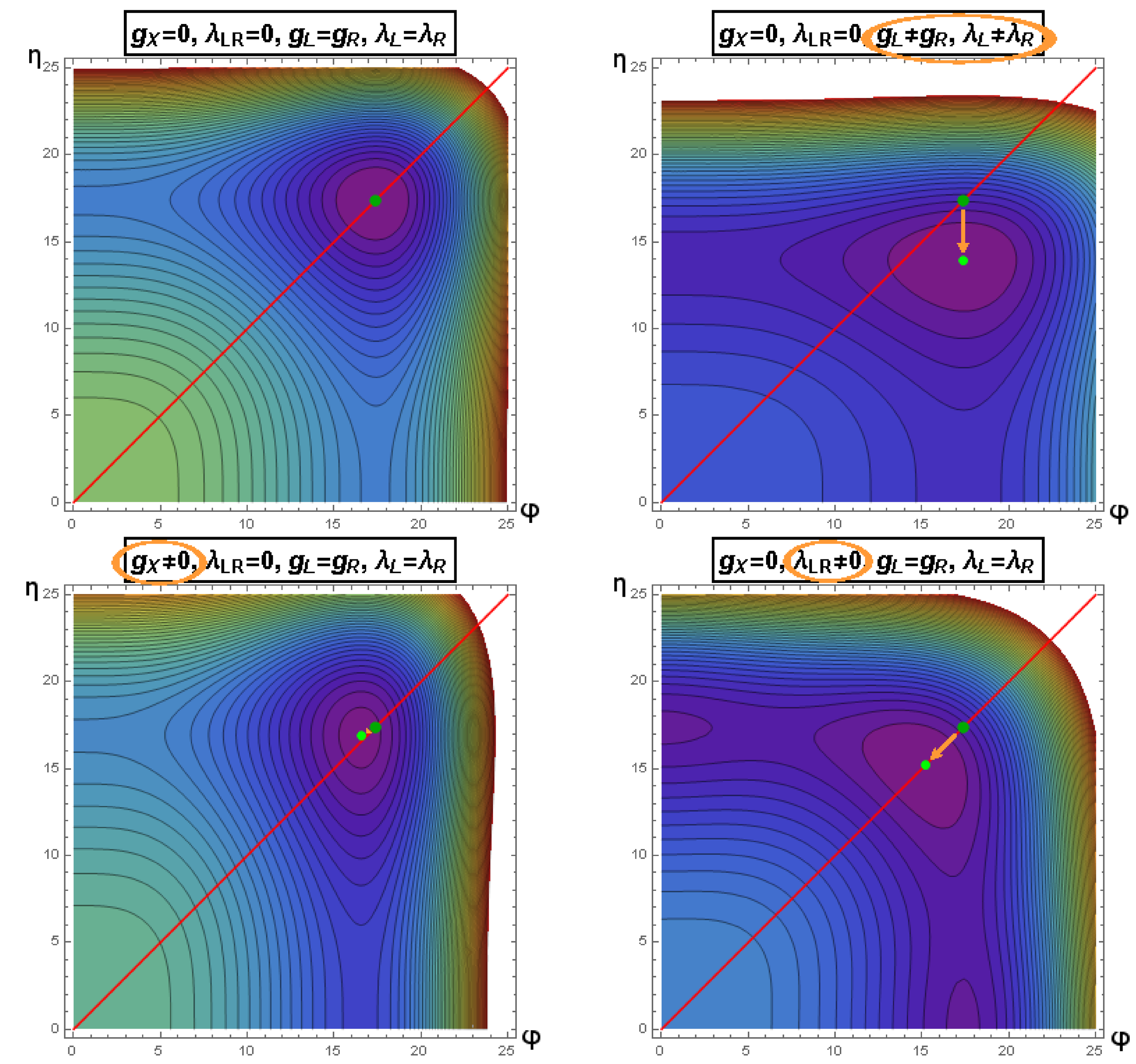
$\mathfrak{R} = ?$

- $g_L \neq g_R, \lambda_L \neq \lambda_R$ needed for $\mathfrak{R} \neq 1$
- but: no analytical expressions
- problems with the behaviour of the potential: critical points on $\varphi = 0, \eta = 0$

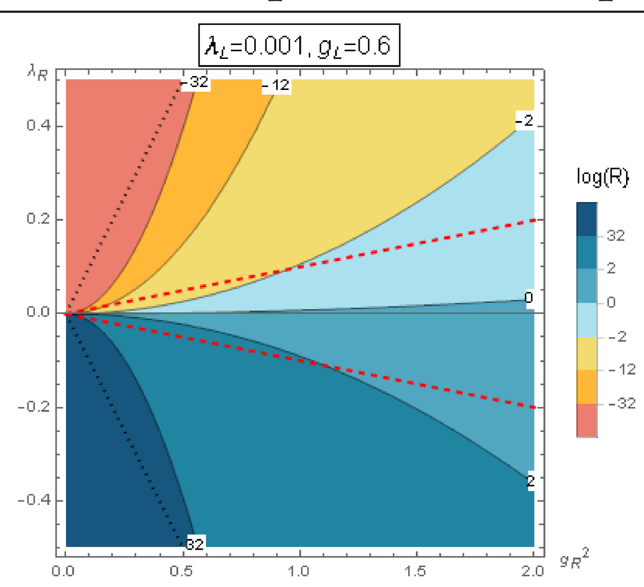
4. $g_X \neq 0,\ \lambda_{LR} \neq 0$

$\mathfrak{R} = ?$

- difficult numerical analysis



Parameter space for simplest case (1) + C & W hypothesis

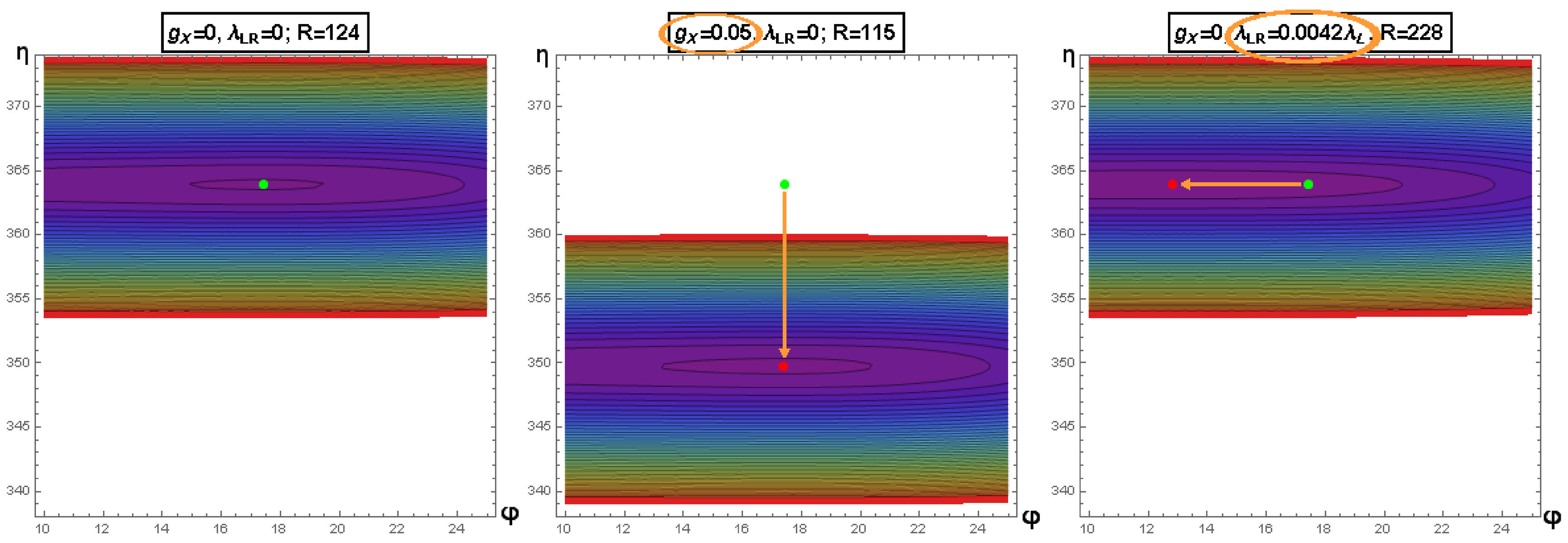


$$\mathfrak{R} = e^{\frac{128\pi^2}{27}\left(\frac{\lambda_L}{g_L^4} - \frac{\lambda_R}{g_R^4}\right)} \downarrow$$

$$\lambda_R = \overbrace{\left(\frac{\lambda_L}{g_L^4} - \frac{27}{128\pi^2}\ln\mathfrak{R}\right)}^{\mathcal{P}(\mathfrak{R})} g_R^4$$

$$\Rightarrow \lambda_R = \mathcal{P}(\mathfrak{R})g_R^4,\ |\lambda_R| = \varepsilon g_R^2$$

More complicated models (2, 3)



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