MULTI-HIGGS DOUBLET MODELS & SOFTLY-BROKEN SYMMETRIES

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MOTIVATION

The Standard Model (SM) has proven remarkably successful, but some questions remain unanswered.

Mass Hierarchy Problem **Neutrino Masses** **Dark matter & Dark energy**

Gravity **Matter-Antimatter Asymmetry** **...**

Multi-Higgs Doublet Models (NHDMs)

Due to their complexity, it is usual to impose symmetries.

Renormalization Group Equations (RGEs)

RENORMALIZATION GROUP EVOLUTION

For a general parameter relation,

$$X = 0 \Rightarrow \beta_X \neq 0$$

Non RG stable

For a condition imposed by a symmetry at tree-level,

$$X = 0 \Rightarrow \beta_X = 0$$

At orders of perturbation theory

RG stable

BETA FUNCTIONS

For a general field theory with a lagrangian given by,

$$\mathcal{L} = \partial^\mu \varphi_i \partial_\mu \varphi_i - \frac{1}{2} m_{ij}^2 \varphi_i \varphi_j - \frac{1}{4!} \lambda_{ijkl} \varphi_i \varphi_j \varphi_k \varphi_l$$

where all the fields are real, the one- and two-loop β functions are given by,

$$\beta^I_{m^2_{ij}} = m^2_{mn} \lambda_{ijmn}$$

$$\beta^I_{\lambda_{ijk\ell}} = \frac{1}{8} \sum_{perm} \lambda_{ijmn} \lambda_{mnk\ell} = \lambda_{ijmn} \lambda_{mnk\ell} + \lambda_{ikmn} \lambda_{mnj\ell} + \lambda_{i\ell mn} \lambda_{mnjk}$$

$$\beta^{II}_{m^2_{ij}} = \frac{1}{12} \left(\lambda_{ik\ell m} \lambda_{nk\ell m} m^2_{nj} + \lambda_{jk\ell m} \lambda_{nk\ell m} m^2_{ni} \right) - 2 m^2_{k\ell} \lambda_{ikmn} \lambda_{j\ell mn}$$

$$\beta^{II}_{\lambda_{ijk\ell}} = \frac{1}{72} \sum_{\text{perm}} \lambda_{inpq} \lambda_{mnpq} \lambda_{mjk\ell} - \frac{1}{4} \sum_{\text{perm}} \lambda_{ijmn} \lambda_{kmpq} \lambda_{\ell npq}$$

Here, the sum is over the permutations of uncontracted indices and there is an implicit sum over repeated indices.

GOOFY SYMMETRIES

GOOFy symmetries were introduced in 2023 by Ferreira, Grzadkowski, Ogreid and Osland. They consist of the transformation $r_0 \to -r_0$. In the 2HDM, this translates to the symmetries summarised in the table below.

Symmetry	m_{11}^2	m_{22}^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
r_0		$-m_{11}^2$			λ_1					$-\lambda_6$
$0CP1$		$-m_{11}^2$	Real		λ_1			Real	Real	$-\lambda_6$
$0Z_2$		$-m_{11}^2$	0		λ_1				0	0
$0U(1)$		$-m_{11}^2$	0		λ_1			0	0	0
$0CP2$	0	0	0		λ_1					$-\lambda_6$
$0CP3$	0	0	0		λ_1			$\lambda_1 - \lambda_3 - \lambda_4$	0	0
$0SO(3)$	0	0	0		λ_1		$\lambda_1 - \lambda_3$	0	0	0

GOOFY SYMMETRIES

First, the beta functions of the most general 3HDM were calculated. Then, the idea was to extend these symmetries to the 3HDM. Three attempts were done.

$$r_0 \to -r_0$$

Does not meet the required criteria: the beta function of M_0 is not 0 when this parameter is set to 0.

$$r_0 \to -r_0,\ \vec{r} \to -\vec{r}$$

Meets the required criteria, but the model would be massless. Not very interesting from the physical point of view.

$$\begin{aligned} \phi_1 &\to \phi_2^*, & \phi_1 &\to -\phi_2^\dagger \\ \phi_2 &\to \phi_3^*, & \phi_2 &\to -\phi_3^\dagger \\ \phi_3 &\to \phi_1^*, & \phi_3 &\to -\phi_1^\dagger \end{aligned}$$

Meets the required criteria. **Viable model!**

The beta functions for this model were also calculated.

GOOFY POTENTIAL

The potential resulting from the imposition of this new symmetry is given by

$$\mathcal{L}_{\text{GOOFy}} = \Lambda_0 \left(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3\right)^2 + \Lambda_1 \Big[(\phi_1^\dagger\phi_1)^2 + (\phi_2^\dagger\phi_2)^2 + (\phi_3^\dagger\phi_3)^2 - (\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) -$$

$$- (\phi_1^\dagger\phi_1)(\phi_3^\dagger\phi_3) - (\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3)\Big] + \Lambda_2 \left[\mathrm{Re}(\phi_1^\dagger\phi_2)^2 + \mathrm{Re}(\phi_2^\dagger\phi_3)^2 + \mathrm{Re}(\phi_3^\dagger\phi_1)^2\right] +$$

$$+ \Lambda_3 \left[\mathrm{Im}(\phi_1^\dagger\phi_2)^2 + \mathrm{Im}(\phi_2^\dagger\phi_3)^2 + \mathrm{Im}(\phi_3^\dagger\phi_1)^2\right] + \Lambda_4 \Big[\mathrm{Re}(\phi_1^\dagger\phi_2)\,\mathrm{Re}(\phi_2^\dagger\phi_3) +$$

$$+ \mathrm{Re}(\phi_1^\dagger\phi_2)\,\mathrm{Re}(\phi_3^\dagger\phi_1) + \mathrm{Re}(\phi_2^\dagger\phi_3)\,\mathrm{Re}(\phi_3^\dagger\phi_1)\Big] + \Lambda_5 \Big[\mathrm{Im}(\phi_1^\dagger\phi_2)\,\mathrm{Im}(\phi_2^\dagger\phi_3) +$$

$$+ \mathrm{Im}(\phi_1^\dagger\phi_2)\,\mathrm{Im}(\phi_3^\dagger\phi_1) + \mathrm{Im}(\phi_2^\dagger\phi_3)\,\mathrm{Im}(\phi_3^\dagger\phi_1)\Big] +$$

$$+ \Lambda_6 \left(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3\right) \left[\mathrm{Re}(\phi_1^\dagger\phi_2) + \mathrm{Re}(\phi_2^\dagger\phi_3) + \mathrm{Re}(\phi_3^\dagger\phi_1)\right] +$$

$$+ \Lambda_7 \Big[\mathrm{Re}(\phi_1^\dagger\phi_2)(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 - 2\phi_3^\dagger\phi_3) + \mathrm{Re}(\phi_2^\dagger\phi_3)(-2\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3) +$$

$$+ \mathrm{Re}(\phi_3^\dagger\phi_1)(\phi_1^\dagger\phi_1 - 2\phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3)\Big] + \Lambda_8 \Big[\mathrm{Re}(\phi_1^\dagger\phi_2)(\phi_1^\dagger\phi_1 - \phi_2^\dagger\phi_2) +$$

$$+ \mathrm{Re}(\phi_3^\dagger\phi_1)(\phi_3^\dagger\phi_3 - \phi_1^\dagger\phi_1) + \mathrm{Re}(\phi_2^\dagger\phi_3)(\phi_2^\dagger\phi_2 - \phi_3^\dagger\phi_3)\Big]$$

CONCLUSION

- The RGE study of these symmetries allows for a better understanding of the models under study.

- The study of GOOFy symmetries in the context of 2HDM allowed for the intuition necessary to obtain a new GOOFy symmetry in the context of the 3HDM.

- Future work includes:
  - the study of this new model
  - the RGE analysis of models with softly-broken symmetries.
  - the extension of the ScannerS program to other BSM models, like the 3HDM and the inclusion of the bounded from below conditions for the most general 2HDM with $\lambda_6, \lambda_7 \neq 0$.

THANK YOU