The Goofy-symmetric Standard Model and the Hierarchy Problem

Andrea Incrocci

Based on [de Boer, Goertz, AI 2507.22111]



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Brief introduction to the Hierachy problem

Symmetries and naturalness

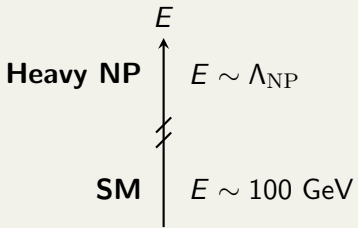
The 2HDM and its goofy symmetries

The goofy-symmetric Standard Model and beyond

The Hierarchy Problem

The SM as an EFT

$$\mathcal{L} \supset m_H^2 |H|^2, \quad m_H^2 \sim (100\,GeV)^2$$

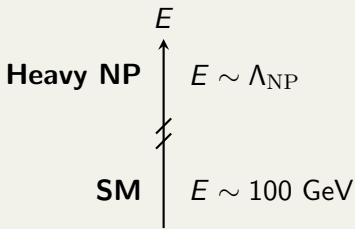


$$\Delta m_H^2 \sim \Lambda_{NP}^2$$

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Gauge bosons $\iff$ gauge symmetry

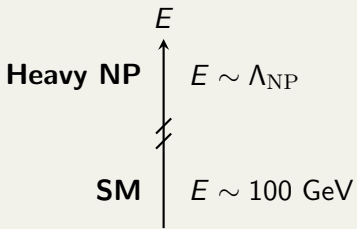
Fermion masses $\iff$ chiral symmetry

Higgs mass $\iff$???

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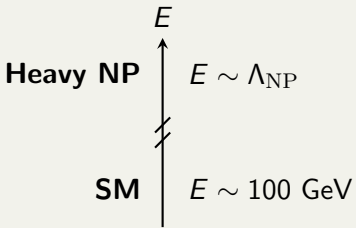
Common solutions

Composite Higgs models
Supersymmetry
Extradimensions
Classical scale invariance
Dimensional transmutation

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Symmetries and Naturalness

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At an energy scale μ, a physical parameter or set of physical parameters $\alpha_i(\mu)$ is allowed to be very small only if the replacement $\alpha_i(\mu) = 0$ would increase the symmetry of the system. In what follows this is what we mean by naturalness.

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$$\beta_g \equiv \mu \frac{\mathrm{d}g}{\mathrm{d}\mu} \propto g \qquad \xleftrightarrow{g \to 0} \qquad \text{symmetry}$$

Every RG-stable parameter relation correspond to a symmetry...

[Trautner (JHEP) 2505.00099], [de Boer, Trautner 2603.12318]

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Or does it?

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The 2HDM and its symmetries

$$
\begin{aligned}
V(\Phi_1,\Phi_2) =& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
& - \left\{ m_{12}^2 (\Phi_1^\dagger \Phi_2) + \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2) \right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\}
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Ivanov [PLB] hep-ph/0507132, [PRD] hep-ph/0609018, [PRD] 0710.3490,
Battye, Brawn, Pilaftsis [JHEP] 1106.3482, Pilaftsis [PLB] 1109.3787

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

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New RG stable parameter relations

$$m_{11}^2 + m_{22}^2 = 0 \qquad \lambda_1 = \lambda_2 \qquad \lambda_6 = -\lambda_7$$

stable to *all* orders

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Can we find a symmetry that enforces this parameter relation?



Goofy symmetries

The relations are obtained if we require $V(\Phi_1, \Phi_2)$ to be invariant under

$$\begin{cases} \Phi_1 \to -\Phi_2^* \\ \Phi_1^* \to \Phi_2 \end{cases} \quad \text{and} \quad \begin{cases} \Phi_2 \to \Phi_1^* \\ \Phi_2^* \to -\Phi_1 \end{cases}$$

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GOOFy literature

- [Ferreira, Grzadkowski, Ogreid, Osland (EPJC) 2306.02410]
- [Haber and Ferreira (EPJC) 2502.11011]
- [Trautner (JHEP) 2505.00099, (PLB)2508.02646]
- [de Boer, Trautner 2603.12318]
- [Ferreira, Grzadkowski, Ogreid (PRD)2506.21145]
- [De Boer, Goertz, Al 2507.22111]
- [Kuncinas, Osland, Rebelo (PRD) 2512.07657]
- [de Medeiros Varzielas, Kuncinas 2608.05304]
- [Grzadkowski, Ogreid (JHEP) 2602.20849]
- [Ferreira (JHEP) 2604.07458]
- [Pilaftsis (JHEP) 2605.18341]

[de Boer, Goertz, AI, 2507.22111]

The goofy symmetric Standard Model

Higgs sector

$$H \rightarrow iH, \quad H^\dagger \rightarrow iH^\dagger$$

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Fermion sector

$$\mathcal{L} \supset y_d \bar{Q}_L H d_R + y_u \bar{Q}_L \tilde{H} u_R + \text{h.c.}$$

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Space-time coordinates

$$\mathcal{L}_{kin} = (D_\mu H)^\dagger (D^\mu H) + i\bar{\Psi} \not{D} \Psi \text{ invariant} \iff \partial_\mu \to i\partial_\mu \text{ and } A^a_\mu \to -iA^a_\mu$$

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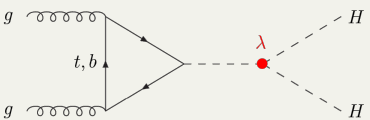
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$$k_{3h} \sim 3, \quad k_{4h} \sim 17$$



$$-0.4 < k_3 < 6.3, -230 < k_4 < 240$$

ATLAS [PLB] 2211.01216, [PRD] 2411.02040

Electroweak symmetry breaking II: complex scalar singlet

We introduce a complex scalar singlet $S = \frac{1}{\sqrt{2}}(S_R + iS_I)$ and its goofy transformation

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Assuming $\lambda_p \ll 1, m_1^2 > 0$

$$\left\langle S_I^2 \right\rangle \equiv v_s^2 = \frac{m_1^2}{2\,\mathrm{Re}\{\lambda_1\} + \lambda_S}$$

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Goofy is *spontaneously broken*

If $\lambda_1 \in \mathbb{R}$, S_R is a Dark Matter candidate being stable due to an unbroken Z_2 symmetry

Vector-like fermions

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$$\mathcal{L} \supset y_s S \bar{T}_L T_R + y_S^* S^* \bar{T}_R T_L$$

$$\Rightarrow m_T \sim \frac{|y_s|}{\sqrt{2}} v_s \sim \mathcal{O}(\text{TeV})$$

Mass scale set by spontanous goofy breaking. Fermionic loop corrections do not introduce large corrections to m_H!

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Weinberg operator

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$\Rightarrow$**Link between Higgs mass and neutrino masses**

Goofy inverse seesaw

$$\mathcal{L} = -\bar{L}_L y_\nu \tilde{H} N_R - \bar{N}_L \lambda_N S N_R - \frac{1}{2}\bar{N}_L \lambda_L S^* N_L^c - \frac{1}{2}\bar{N}_R \lambda_R S N_R^c + \text{h.c.}$$

$\lambda_{L,R}$ break lepton number
$\Rightarrow$ **naturally small**

$$\begin{cases} m_N \sim \mathcal{O}(\text{TeV}) \\ m_D \sim \mathcal{O}(\text{GeV}) \\ m_{L,R} \sim \mathcal{O}(\text{keV}) \end{cases} \Rightarrow m_\nu^{\text{light}} \sim \frac{m_D^2 m_L}{m_N^2}$$

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Thanks for the attention!