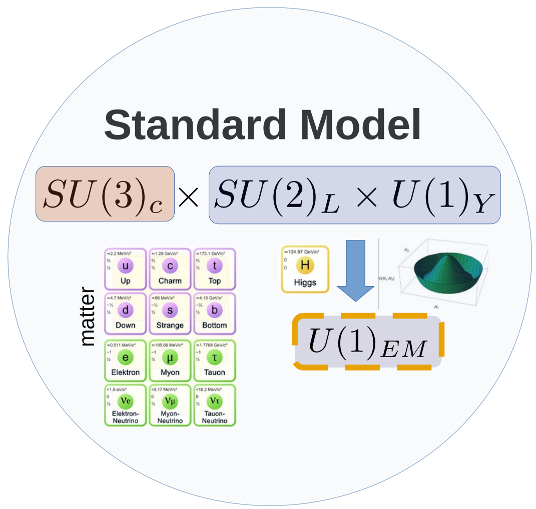
The goofy-symmetric Standard Model and the Hierarchy Problem

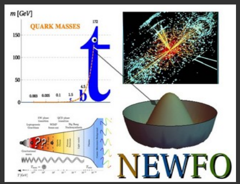


HIDDeN Webinar

17.9.2025

Florian Goertz

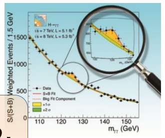
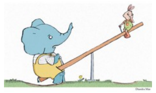
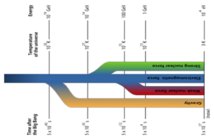
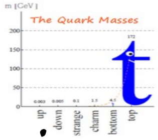
de Boer, FG, Incrocci
2507.22111



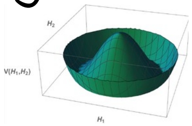
MPIK
Max-Planck-Institut für Kernphysik Heidelberg

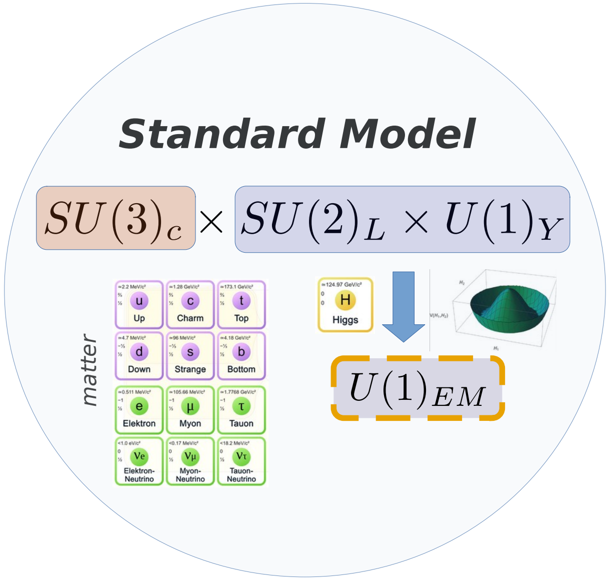
The SM is an EFT

SM does not explain everything!

- Gravity $\not\subset$ SM

- Hierarchy Problem: $m_h << M_{PL}$
- Tiny Neutrino Masses

- Grand Unification of Forces?

- Hierarchical Flavor Structure


- Baryogenesis → Existence of Universe
- Dark Matter $\not\in$ SM

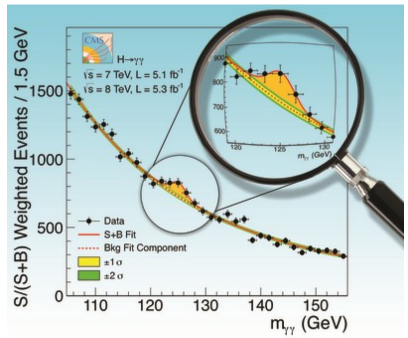
- Trigger for Symmetry-Breaking?

- Strong CP Problem ...



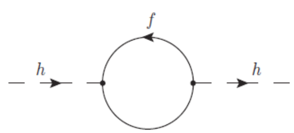
The Hierarchy Problem

$$\mathcal{L} \supset \boxed{m_H^2} \, |H|^2$$

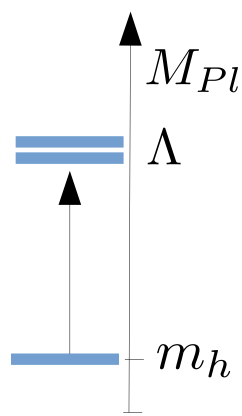
$$\sim (100\,\mathrm{GeV})^2$$



expect $\boxed{m_H \sim M_{\mathrm{Pl,GUT}} \gg 100\,\mathrm{GeV}}$



$$\to \Delta m_H^2 \sim \Lambda^2$$



$\Lambda^2 \sim M_{Pl}^2 \to$ *Fine tuning 1 in 10^{34}*

The Hierarchy Problem

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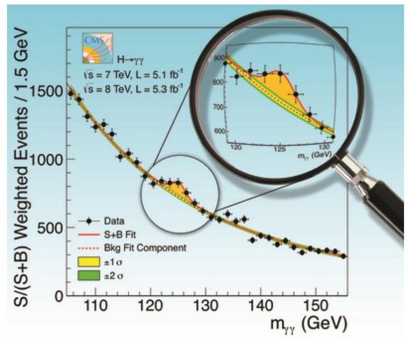

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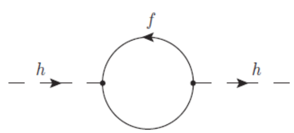

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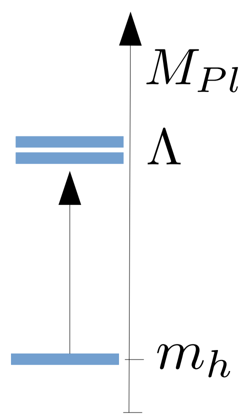


$\Lambda^2 \sim M_{Pl}^2 \to$ *Fine tuning 1 in 10^{34}*

gauge boson and fermion masses protected by gauge symmetry and chiral symmetry, respectively

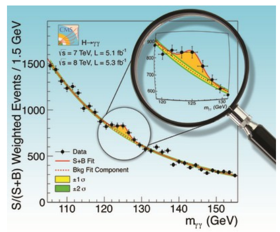
$$\psi_{L,R} \to e^{i\theta_{L,R}} \psi_{L,R}$$

$$\Delta m_V, \Delta m_f \sim v$$

The Hierarchy Problem

$$\mathcal{L} \supset \boxed{m_H^2} \, |H|^2$$

$\sim (100\,\mathrm{GeV})^2$



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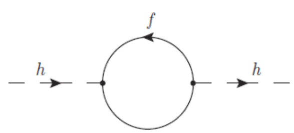
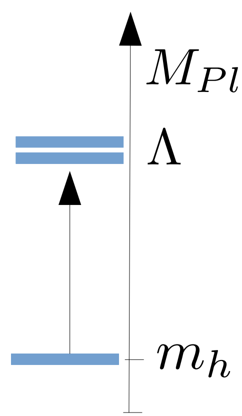


$\rightarrow \Delta m_H^2 \sim \Lambda^2$



$\Lambda^2 \sim M_{Pl}^2 \rightarrow$ *Fine tuning 1 in 10^{34}*

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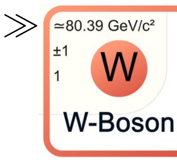
$M_{\mathrm{Pl}} \gg$



$\Leftrightarrow g_{\mathrm{grav}} \ll g_{\mathrm{weak}}$

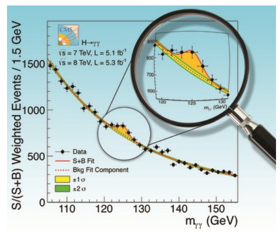
Protection of weak scale?!

Allowed from laws of nature…
… though puzzling

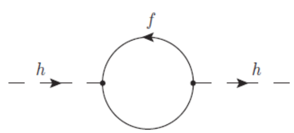
The Hierarchy Problem

$$\mathcal{L} \supset \boxed{m_H^2} |H|^2$$

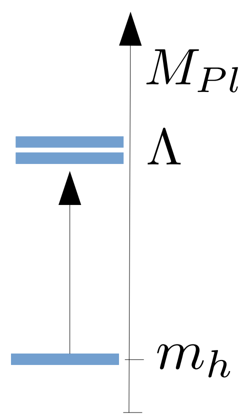
$$\sim (100\,\mathrm{GeV})^2$$



expect $\boxed{m_H \sim M_{\mathrm{Pl,GUT}} \gg 100\,\mathrm{GeV}}$



$$\to \Delta m_H^2 \sim \Lambda^2$$



$\Lambda^2 \sim M_{Pl}^2 \to$ *Fine tuning 1 in 10^{34}*

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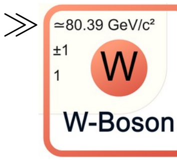
$M_{\mathrm{Pl}} \gg$



$\Leftrightarrow g_{\mathrm{grav}} \ll g_{\mathrm{weak}}$

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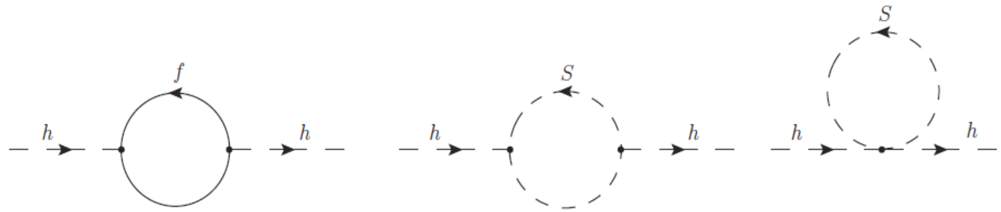
Solving the Hierarchy Problem

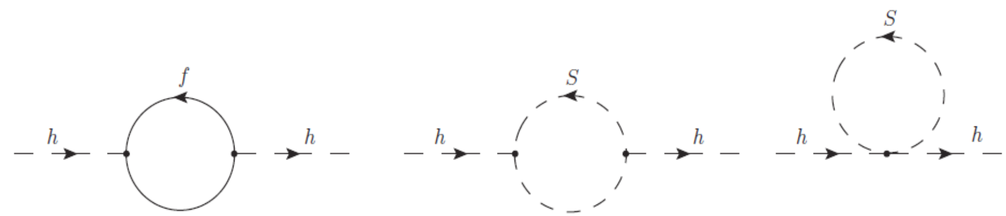
$$\Delta m_h^2 \sim \Lambda^2$$



Protecting the mass term $m_H^2 |H|^2$

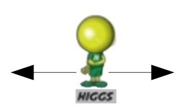
Solving the Hierarchy Problem

$$\Delta m_h^2 \sim \Lambda^2$$

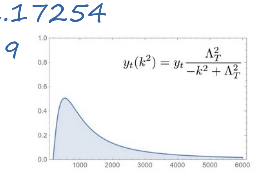


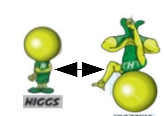
Protecting the mass term $m_H^2|H|^2$

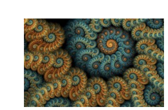
Symmetry



Bally, Chung, FG [PRD] 2211.17254
Chung, FG [PRD] 2311.17169



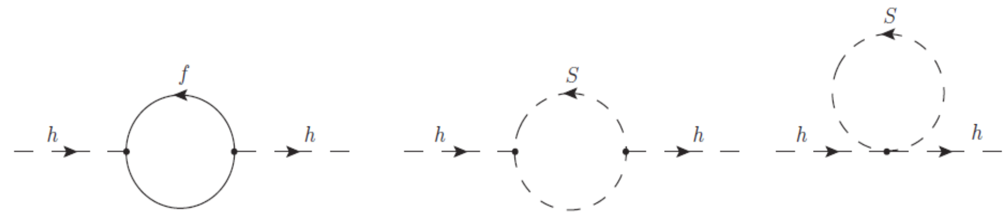
- Shift-Symmetry $H \to H + \delta$ $\quad -y_t \bar{Q}_L \tilde{H} t_R$?!
- Supersymmetry (spacetime): boson $\leftrightarrow$ fermion 

- Conformal Symmetry (Scale invariance?) $\to$ just D=4 $\cancel{|H|^2}$ 

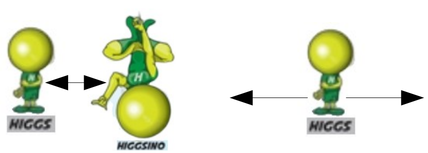
[broken at quantum level]

Solving the Hierarchy Problem

$$\Delta m_h^2 \sim \Lambda^2$$



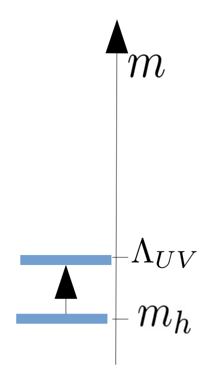
Protecting the mass term $m_H^2 |H|^2$



Symmetry

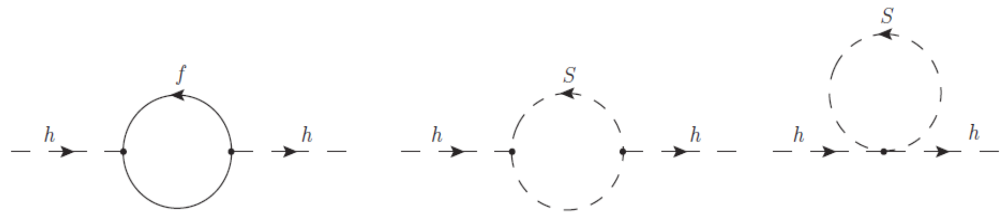
Low Cutoff

$$\Lambda_{UV} \ll M_{Pl}$$

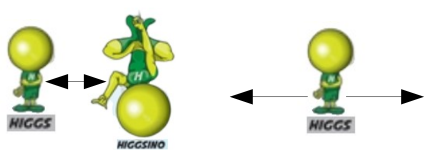


Solving the Hierarchy Problem

$$\Delta m_h^2 \sim \Lambda^2$$



Protecting the mass term $m_H^2|H|^2$



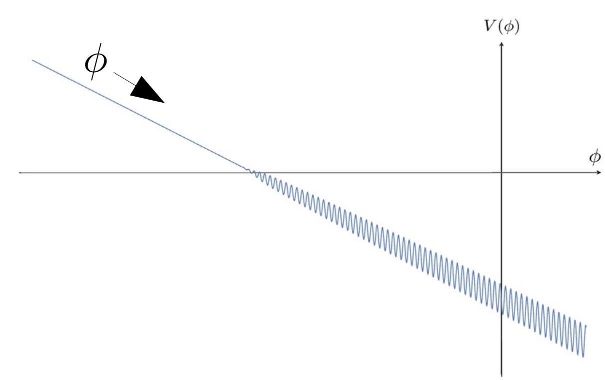
Symmetry

$$\Lambda_{UV} \ll M_{Pl}$$

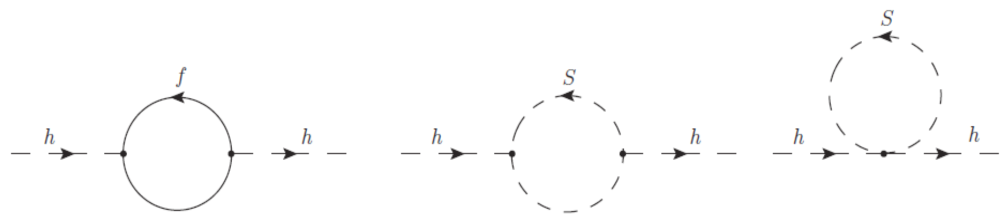
Low Cutoff

$$m_h \ll \Lambda_{UV}$$

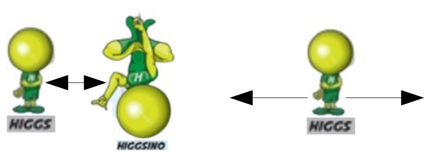
Vacuum selection



Solving the Hierarchy Problem

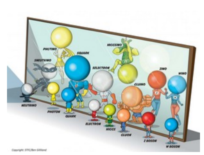
$\Delta m_h^2 \sim \Lambda^2$ 

Protecting the mass term $m_H^2 |H|^2$

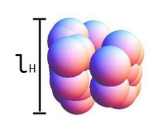


Symmetry	Low Cutoff	Vacuum selection
	$\Lambda_{UV} \ll M_{Pl}$	$m_h \ll \Lambda_{UV}$

Symmetry

- SUSY 
- Goldstone Higgs: Little Higgs
- Conformal Sym. ?

Low Cutoff ($\Lambda_{UV} \ll M_{Pl}$)

- Extra Dimensions
- Composite Higgs 
- Technicolor

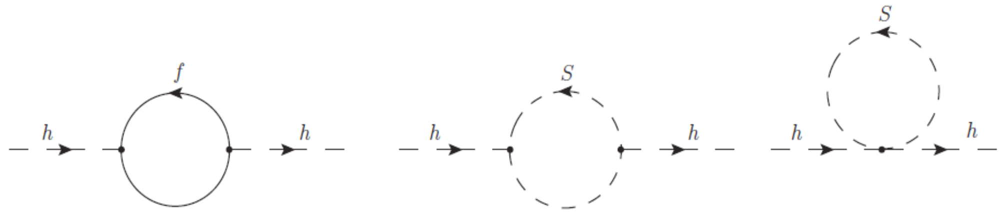
Vacuum selection ($m_h \ll \Lambda_{UV}$)

- Relaxation
- NNaturalness, …

+ Reduced Top-Yukawa, Agravity, WGC, …

Solving the Hierarchy Problem

$$\Delta m_h^2 \sim \Lambda^2$$



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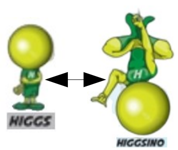
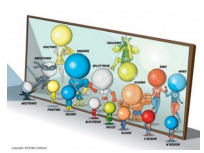


$m_h \ll \Lambda_{UV}$

Symmetry

- SUSY 
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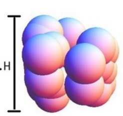
- Technicolor

ns

s l_H 

Vacuum selection

- Relaxation
- NNaturalness, ...

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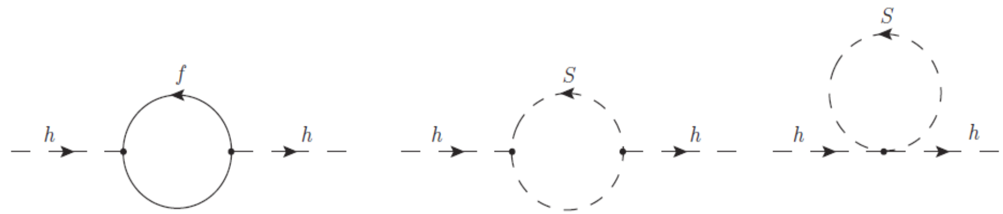
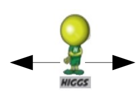
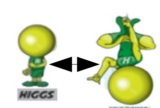
Solving the Hierarchy Problem

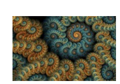
$$\Delta m_h^2 \sim \Lambda^2$$ 

<u>Protecting the mass term</u> $m_H^2 |H|^2$

New Symmetry ?

- Shift-Symmetry $H \to H + \delta$ 

- Supersymmetry (spacetime): boson ↔ fermion 

- Conformal Symmetry → just D=4 $\cancel{|H|}^2$ 
- Goofy Symmetry  ??

GOOFy Symmetry

Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410

- new renormalization-group (RG) stable parameter relations in 2HDMs, that do not correspond to any known symmetry

GOOFy Symmetry

Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410

- new renormalization-group (RG) stable parameter relations in 2HDMs, that do not correspond to any known symmetry

- known 2HDM symmetries and corresponding preserved param. relations

Symmetry	m_{11}^2	m_{22}^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	N
CP1			real					real	real	real	9
Z_2			0						0	0	7
U(1)			0					0	0	0	6
CP2		m_{11}^2	0		λ_1					$-\lambda_6$	5
CP3		m_{11}^2	0		λ_1			$\lambda_1 - \lambda_3 - \lambda_4$	0	0	4
$SO(3)$		m_{11}^2	0		λ_1		$\lambda_1 - \lambda_3$	0	0	0	3

$H_1 \to H_1,\ H_2 \to -H_2$
FCNC protection

$H_1 \to H_2^*,\ H_2 \to -H_1^*$

Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410

Ivanov [PLB] hep-ph/0507132, [PRD] hep-ph/0609018, [PRD] 0710.3490, Battye, Brawn, Pilaftsis [JHEP] 1106.3482, Pilaftsis [PLB] 1109.3787

$$V = m_{11}^2 |H_1|^2 + m_{22}^2 |H_2|^2 - \left[m_{12}^2 H_1^\dagger H_2 + \text{h.c.} \right] + \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4$$
$$+ \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left| H_1^\dagger H_2 \right|^2 + \left[\frac{\lambda_5}{2} \left(H_1^\dagger H_2 \right)^2 + [\lambda_6 |H_1|^2 + \lambda_7 |H_2|^2] H_1^\dagger H_2 + \text{h.c.} \right]$$

GOOFy Symmetry

Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410

- ***new*** renormalization-group (RG) stable parameter relations in 2HDMs, that do not correspond to any known symmetry:

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

$$\begin{aligned}
\beta_{m_{11}^2+m_{22}^2} &= 3(\lambda_1 m_{11}^2 + \lambda_2 m_{22}^2) + (2\lambda_3+\lambda_4)\,(m_{11}^2+m_{22}^2) - 3\ \left[(\lambda_6^* + \lambda_7^*) m_{12}^2 + \text{h.c.}\right] \\
&\quad - \frac{1}{4}\,(9g^2 + 3g'^2)(m_{11}^2 + m_{22}^2)\,, \\
\beta_{\lambda_1-\lambda_2} &= 6\left(\lambda_1^2 - \lambda_2^2\right) + 12\left(|\lambda_6|^2 - |\lambda_7|^2\right) - \frac{3}{2}(\lambda_1 - \lambda_2)\,(3g^2 + g'^2), \\
\beta_{\lambda_6+\lambda_7} &= 6\,(\lambda_1\lambda_6 + \lambda_2\lambda_7) + (3\lambda_3 + 2\lambda_4)\,(\lambda_6+\lambda_7) + 6\lambda_5\,(\lambda_6^* + \lambda_7^*) \\
&\quad - \frac{3}{2}(\lambda_6 + \lambda_7)\,(3g^2 + g'^2)\,,
\end{aligned}$$

- basis invariant
- preserved to all orders in scalar & gauge-ints

Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410

$$\begin{aligned}
V = {}& m_{11}^2\,|H_1|^2 + m_{22}^2\,|H_2|^2 - \left[m_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}\,|H_1|^4 + \frac{\lambda_2}{2}\,|H_2|^4 \\
&+ \lambda_3\,|H_1|^2|H_2|^2 + \lambda_4\left|H_1^\dagger H_2\right|^2 + \left[\frac{\lambda_5}{2}\left(H_1^\dagger H_2\right)^2 + \left[\lambda_6\,|H_1|^2 + \lambda_7\,|H_2|^2\right] H_1^\dagger H_2 + \text{h.c.}\right]
\end{aligned}$$

GOOFy Symmetry

Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410

- new renormalization-group (RG) stable parameter relations in 2HDMs, that do not correspond to any known symmetry:

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

'Goofy' Symmetry transformation:

Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410

$$H_1 \to -H_2^*, \ \ H_1^\dagger \to H_2^T, \\ H_2 \to H_1^*, \quad H_2^\dagger \to -H_1^T$$

peculiar transformation on the doublets....

$$r_0 \equiv \frac{1}{2}(|H_1|^2 + |H_2|^2) \to -r_0$$

$$V = m_{11}^2\,|H_1|^2 + m_{22}^2\,|H_2|^2 - \left[m_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}\,|H_1|^4 + \frac{\lambda_2}{2}\,|H_2|^4 \\ + \lambda_3\,|H_1|^2|H_2|^2 + \lambda_4\left|H_1^\dagger H_2\right|^2 + \left[\frac{\lambda_5}{2}\left(H_1^\dagger H_2\right)^2 + \left[\lambda_6\,|H_1|^2 + \lambda_7\,|H_2|^2\right] H_1^\dagger H_2 + \text{h.c.}\right]$$

kin. terms not invariant...

GOOFy Symmetry

- **new** renormalization-group (RG) stable parameter relations in 2HDMs, that do not correspond to any known symmetry:

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

'Goofy' Symmetry transformation:

Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410

$$H_1 = \begin{pmatrix} h_1 + ih_2 \\ h_3 + ih_4 \end{pmatrix}, \ H_2 = \begin{pmatrix} h_5 + ih_6 \\ h_7 + ih_8 \end{pmatrix}$$

$$\underset{\text{real dof}}{\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ h_5 \\ h_6 \\ h_7 \\ h_8 \end{pmatrix}} \to \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & i & 0 & 0 \\ 0 & 0 & 0 & 0 & i & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & i \\ 0 & 0 & 0 & 0 & 0 & 0 & i & 0 \\ 0 & -i & 0 & 0 & 0 & 0 & 0 & 0 \\ -i & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -i & 0 & 0 & 0 & 0 \\ 0 & 0 & -i & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ h_5 \\ h_6 \\ h_7 \\ h_8 \end{pmatrix}$$

$$V = m_{11}^2 |H_1|^2 + m_{22}^2 |H_2|^2 - \left[m_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4$$
$$+ \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \left[\frac{\lambda_5}{2} \left(H_1^\dagger H_2\right)^2 + \left[\lambda_6 |H_1|^2 + \lambda_7 |H_2|^2\right] H_1^\dagger H_2 + \text{h.c.}\right]$$

GOOFy Symmetry

- **new** renormalization-group (RG) stable parameter relations in 2HDMs, that do not correspond to any known symmetry:

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

r_0 + regular

Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410

$$V = m_{11}^2 |H_1|^2 + m_{22}^2 |H_2|^2 - \left[m_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4$$
$$+ \lambda_3 |H_1|^2|H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \left[\frac{\lambda_5}{2}\left(H_1^\dagger H_2\right)^2 + \left[\lambda_6 |H_1|^2 + \lambda_7 |H_2|^2\right] H_1^\dagger H_2 + \text{h.c.}\right]$$

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- **new** renormalization-group (RG) stable parameter relations in 2HDMs, that do not correspond to any known symmetry:

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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

r_0 + regular

Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410

$$V = m_{11}^2 |H_1|^2 + m_{22}^2 |H_2|^2 - \left[m_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4$$
$$+ \lambda_3 |H_1|^2|H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \left[\frac{\lambda_5}{2}\left(H_1^\dagger H_2\right)^2 + \left[\lambda_6 |H_1|^2 + \lambda_7 |H_2|^2\right] H_1^\dagger H_2 + \text{h.c.}\right]$$

GOOFy Symmetry

- **new** renormalization-group (RG) stable parameter relations in 2HDMs, that do not correspond to any known symmetry:
  - Explored further systematically and extended in Trautner, 2505.00099
    [new goofy symmetries (change of kin. terms), arguments for all-order stability)

Goofy trafo.	m_{11}^2	m_{22}^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	accidental regular sym.	leading vanishing co-/in-variants
	parameter relations											
$\mathcal{P}_G$	0	0	0								–	$Y=0$
$\mathbb{Z}_{2,G}\equiv\Sigma_3$	0	0							0	0	–	$YT=0$, $QYT=0$
$\mathrm{CP1}_G$	0	0	$-m_{12}^{2\,*}$					λ_5^*	λ_6^*	λ_7^*	–	$YT=0$, $QYT=0$
$\mathrm{CP2}_G\equiv\mathcal{G}$		$-m_{11}^2$			λ_1					$-\lambda_6$	–	$T=0$
$\mathrm{U(1)}_G$	0	0	0					0	0	0	U(1)	$Y=0$
$\mathrm{CP3}_G$	0	0	0		λ_1			$\lambda_1-\lambda_3-\lambda_4$	0	0	CP2	$Y=T=0$
$\mathrm{SU(2)}_G$	0	0	0		λ_1		$\lambda_1-\lambda_3$	0	0	0	SU(2)	$Q=Y=T=0$
$\mathrm{CP2}_G^{\mathrm{soft}}$					λ_1					$-\lambda_6$	–	$T=0$
$\mathbb{Z}_{2,G}^-$		$0^{\dagger 2}$	0			$0^{\dagger 1}$	$0^{\dagger 1}$		0	0	$\mathbb{Z}_2$	–
$\mathrm{CP4}_G$		$0^{\dagger 2}$	0			$0^{\dagger 1}$	$0^{\dagger 1}$	λ_5^*	0	0	$\mathbb{Z}_2$	–
$\mathbb{Z}_{4,G}^-$		$0^{\dagger 2,g}$	0			$0^{\dagger 1,g}$	$0^{\dagger 1,g}$	0	0	0	U(1)	–

goofy sym. can forbid bare mass terms → hierarchy problem?!

Trautner, 2505.00099

GOOFy Symmetry

'Goofy' Symmetry transformation:

Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410

$$H_1 \to -H_2^*, \; H_1^\dagger \to H_2^T,$$
$$H_2 \to H_1^*, \quad H_2^\dagger \to -H_1^T$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ h_5 \\ h_6 \\ h_7 \\ h_8 \end{pmatrix} \to \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & i & 0 & 0 \\ 0 & 0 & 0 & 0 & i & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & i \\ 0 & 0 & 0 & 0 & 0 & 0 & i & 0 \\ 0 & -i & 0 & 0 & 0 & 0 & 0 & 0 \\ -i & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -i & 0 & 0 & 0 & 0 \\ 0 & 0 & -i & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ h_5 \\ h_6 \\ h_7 \\ h_8 \end{pmatrix}$$

- Can become regular sym. after complexifying the real dof (doubling of dof!)
  Haber, Ferreira, [EPJC] 2502.11011

- Trautner, 2505.00099
  Kinetic terms also receive signs: don't harm relations / can be made invariant via

  Ferreira, Grzadkowski, Ogreid, Osland [EPJC] 2306.02410, $\partial_\mu \to -i\partial_\mu, \; B_\mu \to iB_\mu, \; W_{1\mu} \to iW_{1\mu}, \quad W_{2\mu} \to -iW_{2\mu}, \quad W_{3\mu} \to iW_{3\mu}$

  $\Updownarrow$

  Ferreira, Grzadkowski, Ogreid, 2506.21145 $x_\mu \to ix_\mu$

- 1-loop eff. potential of 2HDM (including scalar corrections) under goofy sym.

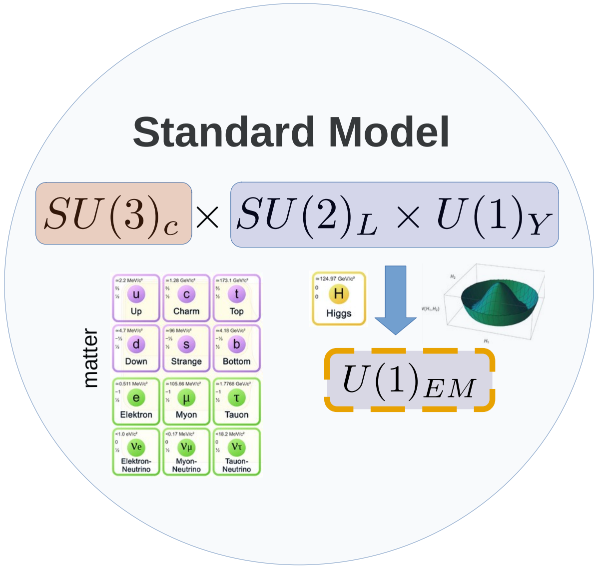
(+ see Pilaftsis [PLB] 2408.04511)

The Goofy-Symmetric SM

de Boer, FG, Incrocci, 2507.22111

… and beyond…

- SM Higgs sector + extension to fermions



The Goofy-Symmetric SM

de Boer, FG, Incrocci, 2507.22111

... and beyond...

- **SM** Higgs sector

- Define goofy transformation of scalars as $\boxed{h_i \to i\, U_h^{ij} h_j}$

rotations of real scalar dofs
in the complex plane by 90°

U_h^{ij} : orthogonal matrix

see also Trautner, 2508.02646

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de Boer, FG, Incrocci, 2507.22111

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rotations of real scalar dofs in the complex plane by 90°

U_h^{ij} : orthogonal matrix

- SM Higgs ($U_h = \mathbf{1}$): $\boxed{H \to iH, \quad H^\dagger \to iH^\dagger}$

  on doublets $H = \begin{pmatrix} h_1 + ih_2 \\ h_3 + ih_4 \end{pmatrix}$

see also Trautner, 2508.02646

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de Boer, FG, Incrocci, 2507.22111

... and beyond...

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- $\mathcal{L}_{\rm kin} = (D_\mu H)^\dagger (D^\mu H) \to (D_\mu H)^\dagger (D^\mu H)$ if $\boxed{\partial_\mu \to -i\,\partial_\mu\,, \quad A_\mu^a \to -iA_\mu^a \quad (x_\mu \to i x_\mu)}$

see also Trautner, 2508.02646

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de Boer, FG, Incrocci, 2507.22111

… and beyond…

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$$V = m_H^2 |H|^2 + \lambda |H|^4 \to -m_H^2 |H|^2 + \lambda |H|^4 \Rightarrow \boxed{m_H = 0}$$ ✓

Small m_H 't Hooft natural, if symmetry respected by full SM (+NP)

see also Trautner, 2508.02646

The Goofy-Symmetric SM

de Boer, FG, Incrocci, 2507.22111

... and beyond...

- SM Higgs sector + fermions

$$\mathcal{L} \supset -y_d \bar{Q}_L H d_R - y_u \bar{Q}_L \tilde{H} u_R - y_d^* \bar{d}_R H^\dagger Q_L - y_u^* \bar{u}_R \tilde{H}^\dagger Q_L$$

$$\Psi = \psi_1^r + i\,\psi_2^r$$

$$\boxed{\psi_k^r \to \sqrt{i}\, U_f^{kl} \psi_l^r}$$

rotations of real dofs
in the complex plane by 45°

U_f^{kl}: orthogonal matrix

$$\bar{Q}_L \to \sqrt{i}\,\bar{Q}_L\,, \quad Q_L \to \sqrt{i}\,Q_L\,,$$
$$d_R \to -\sqrt{i}\,d_R\,, \quad \bar{d}_R \to -\sqrt{i}\,\bar{d}_R\,, \quad U_f = \pm\mathbf{1}$$
$$u_R \to -\sqrt{i}\,u_R\,, \quad \bar{u}_R \to -\sqrt{i}\,\bar{u}_R$$

→ invariant ✓

see also Trautner, 2508.02646

The Goofy-Symmetric SM

de Boer, FG, Incrocci, 2507.22111

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→ invariant ✓

$$\mathcal{L}_{\rm kin}^{\rm ferm} = i\bar{Q}_L \not{D} Q_L + i\bar{d}_R \not{D} d_R + i\bar{u}_R \not{D} u_R$$

$$\boxed{\partial_\mu \to -i\,\partial_\mu\,, \;\; A_\mu^a \to -i A_\mu^a}$$

invariant ✓

→ solution to the HP

The Goofy-Symmetric SM

de Boer, FG, Incrocci, 2507.22111

... and beyond...

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invariant ✓

→ solution to the HP

SM invariant ✓

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→ invariant ✓

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invariant ✓

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SM invariant ✓

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de Boer, FG, Incrocci, 2507.22111

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→ invariant

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invariant → solution to the HP

Electroweak Symmetry Breaking

$$V = \cancel{m_H^2}|H|^2 + \lambda|H|^4$$

Electroweak Symmetry Breaking

$$V = \cancel{m_H^2}|H|^2 + \underbrace{\lambda}_{<0}|H|^4 + \frac{c_6}{\Lambda^2}|H|^6 + \frac{c_8}{\Lambda^4}|H|^8 + \dots$$

PHYSICAL REVIEW D **94**, 015013 (2016)

Electroweak symmetry breaking without the μ^2 term

Florian Goertz*
Theory Division, CERN, 1211 Geneva 23, Switzerland

Electroweak Symmetry Breaking

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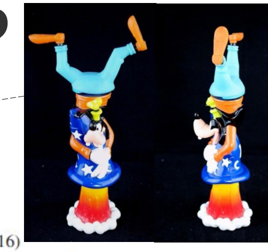
Electroweak Symmetry Breaking



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Electroweak symmetry breaking without the μ^2 term

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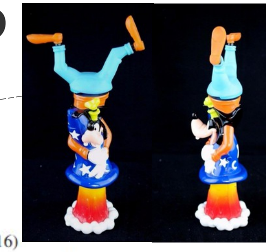
$$\lambda = -0.065\,,\; c_8 = 4\pi\left(\frac{\Lambda}{773\,\mathrm{GeV}}\right)^4 \;\Rightarrow\; \boxed{m_h = 125\,\mathrm{GeV}\,,\;\; v = 246\mathrm{GeV}}$$

de Boer, FG, Incrocci, 2507.22111

Electroweak Symmetry Breaking



$$V = \cancel{m_H^2}|H|^2 + \underset{<0}{\lambda}|H|^4 + \frac{\cancel{c_6}}{\Lambda^2}|H|^6 + \frac{c_8}{\Lambda^4}|H|^8 + \dots$$

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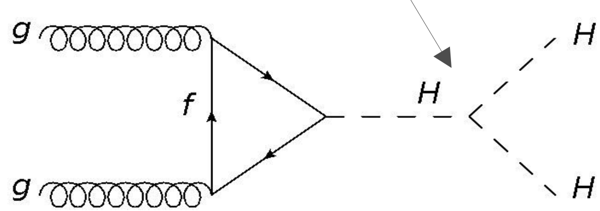
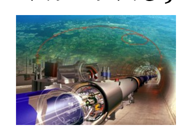
➡ $\kappa_{hhh}/\kappa_{hhh}^{\mathrm{SM}} = 3,\;\; \lambda_{hhhh}/\lambda_{hhhh}^{\mathrm{SM}} = 17$

still ok with limits:

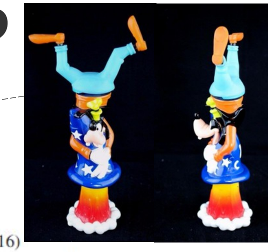
e.g.: ATLAS [PLB] 2211.01216, [PRD] 2411.02040

→ HL-LHC, FCC, ...





Electroweak Symmetry Breaking



$$V = \cancel{m_H^2}|H|^2 + \underset{<0}{\lambda}|H|^4 + \frac{\cancel{c_6}}{\Lambda^2}|H|^6 + \frac{c_8}{\Lambda^4}|H|^8 + \dots$$

PHYSICAL REVIEW D **94**, 015013 (2016)

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de Boer, FG, Incrocci, 2507.22111

$\Rightarrow \kappa_{hhh}/\kappa_{hhh}^{\mathrm{SM}} = 3,\;\; \lambda_{hhhh}/\lambda_{hhhh}^{\mathrm{SM}} = 17$

still ok with limits:

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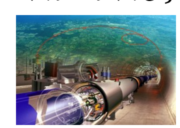

- *breaks conformal symmetry*
- *breaks shift symmetry*
- *respects goofy symmetry*

  H^2 will not be generated at loop level

  see, e.g., Helset, Jenkins, Manoha [JHEP] 2212.03253

Electroweak Symmetry Breaking II: extended scalar sector

$$S = \frac{1}{\sqrt{2}}(S_R + iS_I) \qquad \boxed{S \to -S\,,\;\; S^* \to S^*} \qquad (U_S = -i\sigma_2)$$

allowed!

$$\Rightarrow\; V = \boxed{\lambda_H |H|^4 + \lambda_p |S|^2 |H|^2} + \frac{m_1^2}{2}\left[S^2 + (S^*)^2\right] + \lambda_S |S|^4 + \left[\lambda_1 S^4 + \lambda_1^* (S^*)^4\right]$$

→ structure preserved along RG flow (checked with PyR@TE)!

de Boer, FG, Incrocci, 2507.22111

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$$\Rightarrow\; V = \underbrace{\frac{\lambda_p}{2}}_{\ll 1}(S_R^2 + S_I^2)|H|^2 + \underbrace{\frac{m_1^2}{2}}_{>0}\left[S_R^2 - S_I^2\right] + \ldots$$

$$\Downarrow$$

$$\langle S_I^2 \rangle \equiv v_S^2 = \frac{m_1^2}{2\mathrm{Re}(\lambda_1) + \lambda_S}$$

de Boer, FG, Incrocci, 2507.22111

spontaneous goofy symmetry breaking

(SGSB)

Electroweak Symmetry Breaking II: extended scalar sector

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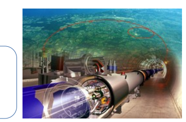
$\boxed{\text{TeV scale}}$



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$$\boxed{m_H^2 = \lambda_p v_S^2/2}$$

spontaneous goofy symmetry breaking

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de Boer, FG, Incrocci, 2507.22111

$$\boxed{m_H^2 = \lambda_p v_S^2/2}$$

$$\ll M_{\mathrm{Pl}}^2$$

spontaneous goofy symmetry breaking

(SGSB)

dimensional transmutation: condensation in IR, ...

$$\mathcal{L} \supset -\lambda_p\,\mathcal{O}\cdot|H|^2\,, \quad \mathcal{O} = \phi^\dagger\phi,\; \bar\psi\psi\bar\psi\psi$$

Electroweak Symmetry Breaking II: extended scalar sector

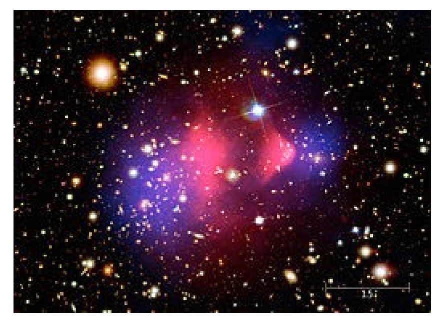
$$S = \frac{1}{\sqrt{2}}\left(S_R + i S_I\right) \qquad \boxed{S \to -S\,,\;\; S^* \to S^*} \qquad (U_S = -i\sigma_2)$$

$$\Rightarrow \quad V = \underset{\ll 1}{\frac{\lambda_p}{2}}(S_R^2 + S_I^2)|H|^2 + \underset{>0}{\frac{m_1^2}{2}}\left[S_R^2 - S_I^2\right] + \ldots$$

$$\langle S_R^2 \rangle = 0$$

DM candidate

(Z_2 for real λ_1)



The Goofy-Symmetric SM

de Boer, FG, Incrocci, 2507.22111

... and beyond...

- Scalar Singlets ✓

The Goofy-Symmetric SM

de Boer, FG, Incrocci, 2507.22111

... and beyond...

- Scalar Singlets ✓
- Vector-like Fermions

vector-like quark T, singlet of $SU(2)_L$ with $Y = \frac{2}{3}$

$$\mathcal{L} \supset \; m_{\mathcal{T}} \bar{T}_L T_R + m_{\mathcal{T}}^* \bar{T}_R T_L + m \bar{T}_L u_R + m^* \bar{u}_R T_L + y \bar{Q}_L \tilde{H} T_R + y^* \bar{T}_R \tilde{H}^\dagger Q_L$$

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de Boer, FG, Incrocci, 2507.22111

... and beyond...

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$$\mathcal{L} \supset \underbrace{m_T \bar{T}_L T_R + m_T^* \bar{T}_R T_L + m \bar{T}_L u_R + m^* \bar{u}_R T_L}_{} + \underbrace{y \bar{Q}_L \tilde{H} T_R + y^* \bar{T}_R \tilde{H}^\dagger Q_L}_{}$$

no way to respect goofy invariance ✗

$\rightarrow \boxed{m_T = m = 0}$

$T_R \to -\sqrt{i}\, T_R\,, \;\; \bar{T}_R \to -\sqrt{i}\, \bar{T}_R$

→ invariant ✓

The Goofy-Symmetric SM

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$\rightarrow \boxed{m_T = m = 0}$

→ invariant ✓

- mass from SGSB: $\mathcal{L} \supset y_S S \bar{T}_L T_R + y_S^* S^* \bar{T}_R T_L$

✓ $\bar{T}_L \to -i\sqrt{i}\, \bar{T}_L\,,\ T_L \to i\sqrt{i}\, T_L$

$$\rightarrow m_T \simeq \frac{|y_S|}{\sqrt{2}} v_S$$

The Goofy-Symmetric SM

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$$\to m_T \simeq \frac{|y_S|}{\sqrt{2}} v_S$$

$$\mathcal{L}_{\text{kin}} = i\bar{T}_L \not{D} T_L + i\bar{T}_R \not{D} T_R$$

→ invariant ✓

The Goofy-Symmetric SM

de Boer, FG, Incrocci, 2507.22111

... and beyond...

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- Vector-like Fermions ✓

vector-like quark T, singlet of $SU(2)_L$ with $Y = \frac{2}{3}$

$$\mathcal{L} \supset \underbrace{m_T \bar{T}_L T_R + m_T^* \bar{T}_R T_L + m \bar{T}_L u_R + m^* \bar{u}_R T_L}_{\text{no way to respect goofy invariance } \times} + \underbrace{y \bar{Q}_L \tilde{H} T_R + y^* \bar{T}_R \tilde{H}^\dagger Q_L}_{T_R \to -\sqrt{i}\, T_R\,,\ \bar{T}_R \to -\sqrt{i}\, \bar{T}_R}$$

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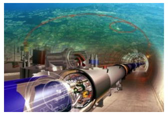
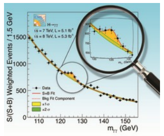
$$\to m_T \simeq \frac{|y_S|}{\sqrt{2}} v_S$$

$$\to \boxed{m_T \sim v_S \sim \mathcal{O}(\mathrm{TeV})}$$ ✓



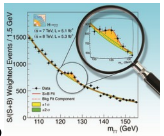


$$\mathcal{L}_{\mathrm{kin}} = i \bar{T}_L \not{D} T_L + i \bar{T}_R \not{D} T_R$$

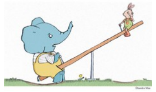
→ invariant ✓

The SM is an EFT

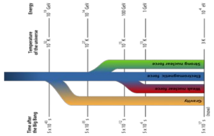
SM does not explain everything!



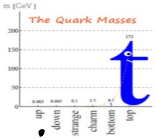
- Gravity $\not\subset$ SM
- Hierarchy Problem: $m_h \ll M_{PL}$



- Tiny Neutrino Masses

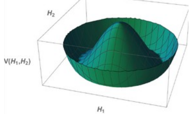


- Grand Unification of Forces?

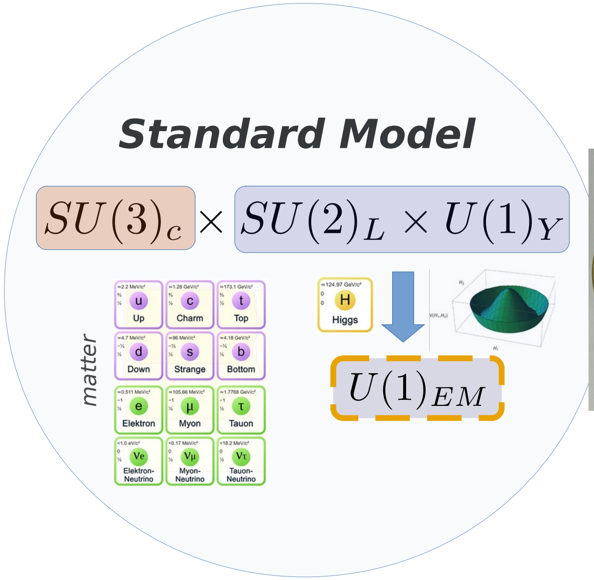


- Hierarchical Flavor Structure
- Baryogenesis → Existence of Universe

- Dark Matter $\not\in$ SM
- Trigger for Symmetry-Breaking?



- Strong CP Problem ...



Outlook

SM does not explain everything!

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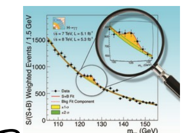
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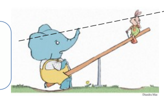

Seesaw: Majorana mass forbidden

$$\bar{N}_R \cancel{m_R} N_R^c$$

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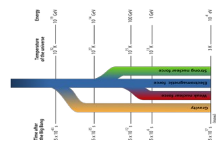
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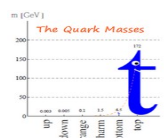

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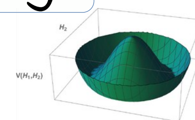
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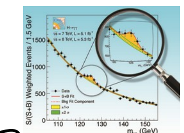
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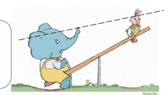
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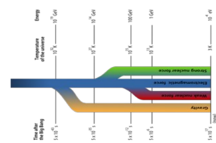
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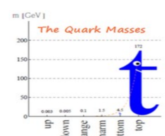

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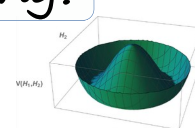
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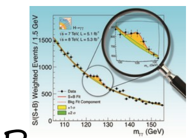

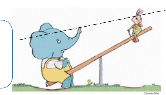

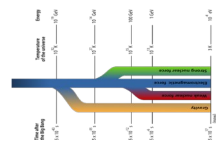

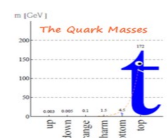

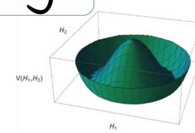

Seesaw: Majorana mass forbidden

$$\bar{N}_R \cancel{m_R} N_R^c$$

$$\langle S_I \rangle \lesssim \mathcal{O}(\text{TeV})$$

-> inverse seesaw: natural link with TeV scale

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

Outlook

SM does not explain everything!

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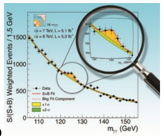

- Hierarchy Problem: $m_h << M_{PL}$
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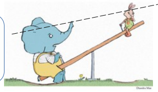

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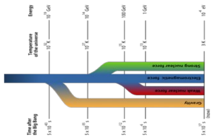

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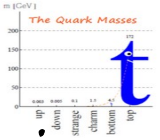

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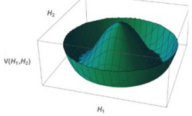
$$m_\nu \simeq \frac{m_D^2 m_L}{m_N^2}$$

- Strong CP Problem ...



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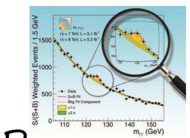
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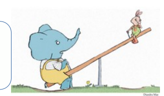
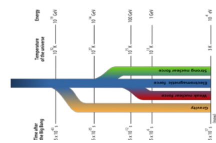
- Tiny Neutrino Masses 

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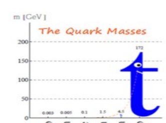

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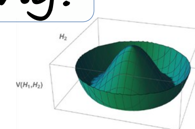
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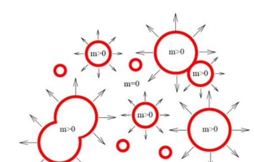

EWPhT in presence of S

Espinosa, Quiros [PLB] hep-ph/9301285, ...

Outlook

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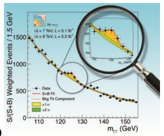
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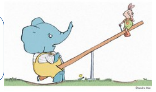
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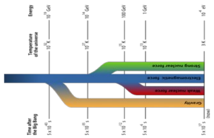
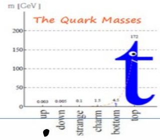
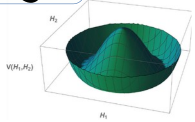

- Hierarchical Flavor Structure


- Baryogenesis → Existence of Universe
- Dark Matter $\notin$ SM

- Trigger for Symmetry-Breaking?

- Strong CP Problem ...

space-time symmetries

$$\text{goofy} \cong \sqrt{PT}\ ??$$

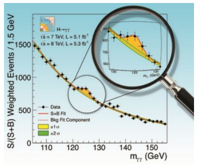
$$\mathrm{SU}(2)_L?$$

Conclusions

- Goofy Symmetry as a new means to protect parameters / relations

- Fermion transformations can be included in a consistent way

- Applied to the SM, it offers a handle to explain the lightness of the Higgs boson



- Extensions of the SM are considerably constrained, interesting directions regarding DM, baryogenesis, neutrino masses, ...

- Typically new signatures around the TeV scale → HL-LHC, FCC, ...