The Composite Two Higgs Doublet Model

Andrea Wulzer
ETHZ

Introduction

The main question for the **LHC:**

What is the **Nature** of **EWSB ?**

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What is the **Nature** of **EWSB ?**

The answers from **LEP:**

- If strong-sector, $\widehat{S}$ must be **tuned**
- Higgs model is **fine** for a **light** Higgs
- Not light enough though, **SUSY** in trouble
  (need for more complicated/tuned versions)

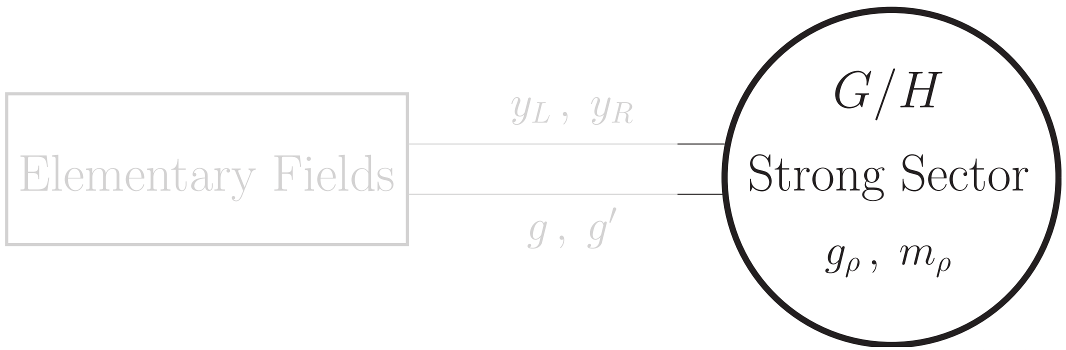
Introduction

One possible interpretation:

EWPT **Hierarchy Problem**

The **Higgs exists**, but it is **Composite**

The PNGB Higgs



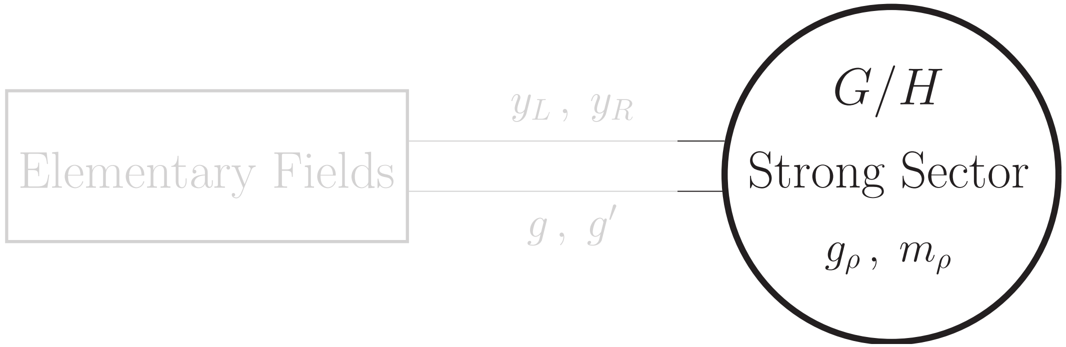
$H \supset SO(4)$

Constraints (from $\rho = 1$) on G/H:

$G/H \supset \mathbf{4}$

	G	H	N_G	NGB's rep.$[H]$ = rep.$[SU(2) \times SU(2)]$
MCHM	SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
	SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
CTHDM	SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \mathbf{\bar{4}_{-2}} = 2 \times (\mathbf{2}, \mathbf{2})$
	SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
	SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
	SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
	SO(7)	$[SO(3)]^3$	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \times (\mathbf{2}, \mathbf{2})$
CTHDM	Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4}, \mathbf{2}) = 2 \times (\mathbf{2}, \mathbf{2}), (\mathbf{2}, \mathbf{2}) + 2 \times (\mathbf{2}, \mathbf{1})$
CTHDM	SU(5)	SU(4) × U(1)	8	$\mathbf{4_{-5}} + \mathbf{\bar{4}_{+5}} = 2 \times (\mathbf{2}, \mathbf{2})$
Georgi-Kaplan	SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$

The PNGB Higgs



Adopt the simplest description of the Strong Sector:

One Coupling: g_ρ

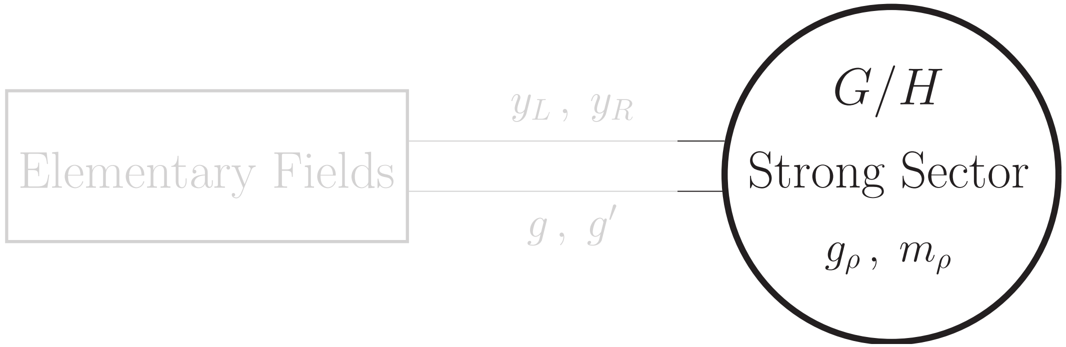
One Mass: m_ρ

$\sim$

Large-N: $g_\rho \sim 4\pi/\sqrt{N}$

Explicit Realization: $5d$

The PNGB Higgs



Adopt the simplest description of the Strong Sector:

One Coupling: g_ρ

One Mass: m_ρ

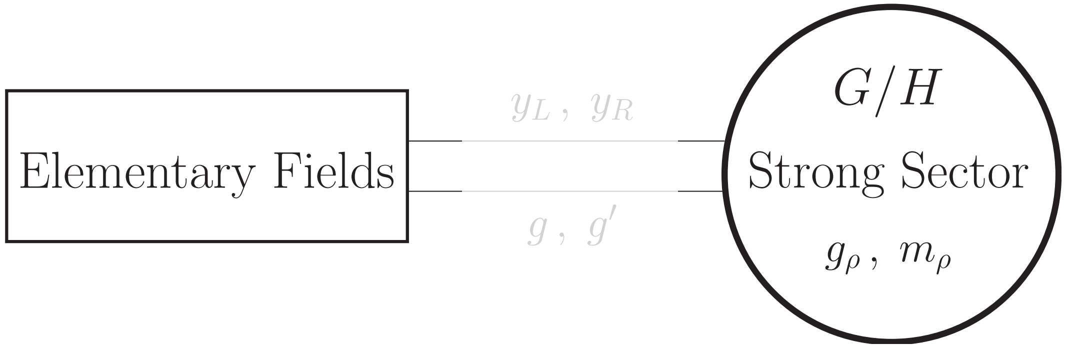
$\Longrightarrow$

$$f = \frac{m_\rho}{g_\rho}$$

Tuning: $\xi = \dfrac{v^2}{f^2} < 1$

$$m_\rho = \frac{g_\rho}{\sqrt{\xi}} v$$

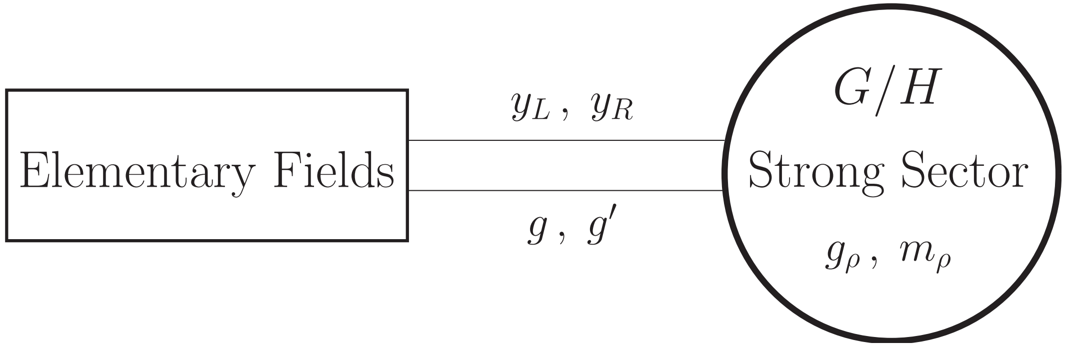
The PNGB Higgs



SM fermions and gauge fields are elementary d.o.f.

Not the t_R, it might be **totally composite**

The PNGB Higgs

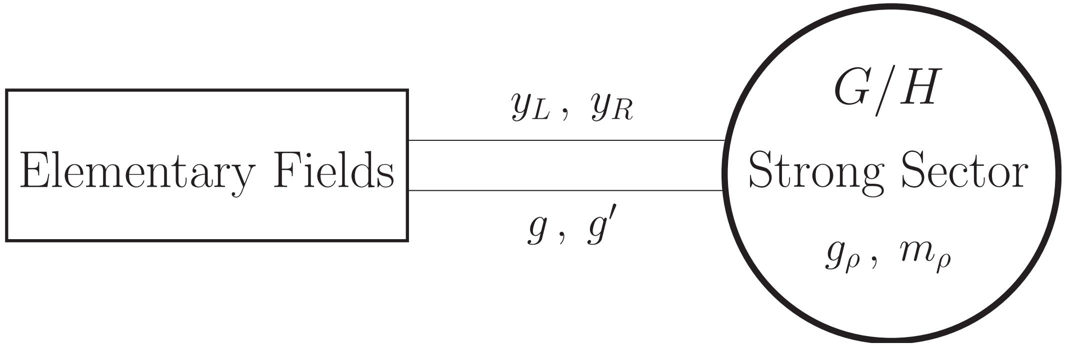


Elementary-Composite Couplings:

$$g_{SM}\cdot\Psi_{SM}\cdot\mathcal{O}=\begin{cases} gA_\mu J^\mu \\ y_{L,R}f_{L,R}\mathcal{O}_{L,R}\end{cases}$$

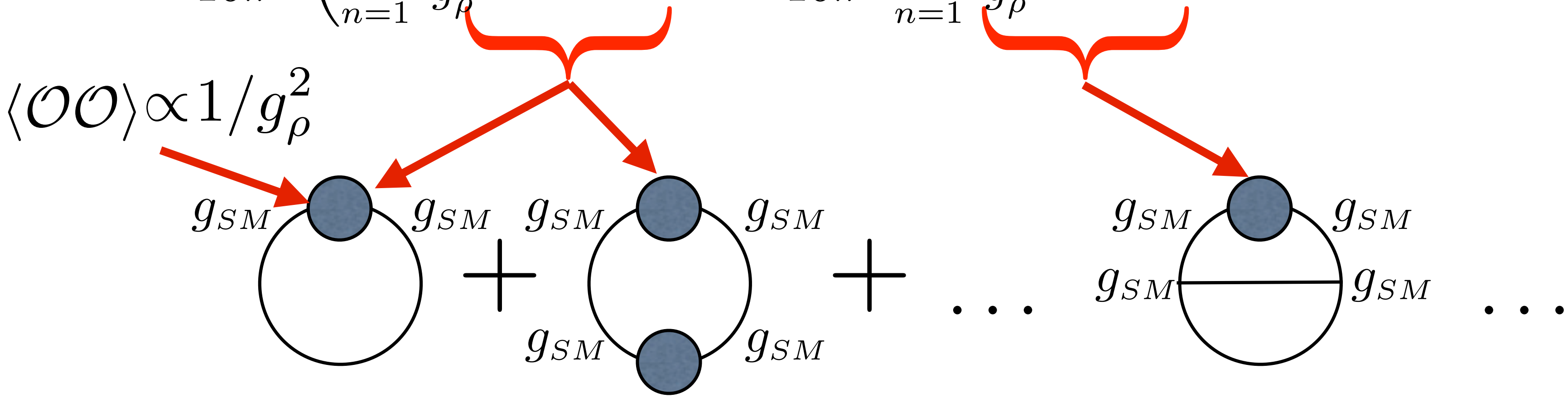
We adopt **partial compositeness** for fermions

The PNGB Higgs

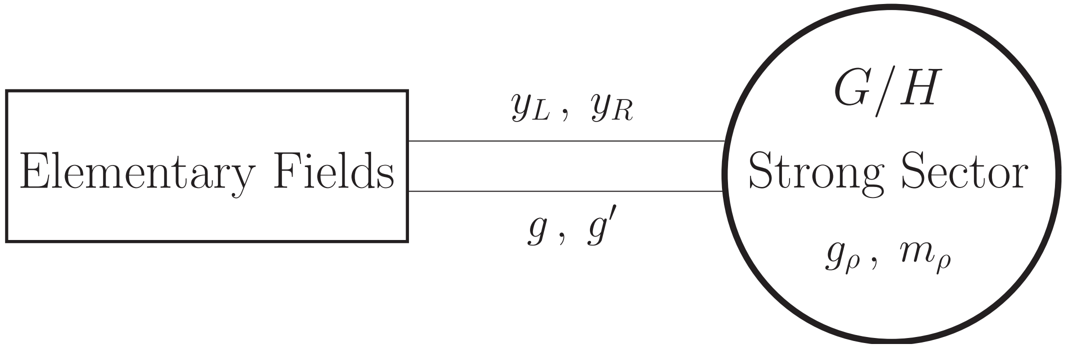


We also assume g_{SM} is the only $\not{G}$ source

$$V(\Pi) = \frac{m_\rho^4}{16\pi^2}\left(\sum_{n=1}^{\infty}\frac{g_{\rm SM}^{2n}}{g_\rho^{2n}}F_{1n}(\Pi/f) + \frac{g_\rho^2}{16\pi^2}\sum_{n=1}^{\infty}\frac{g_{\rm SM}^{2n}}{g_\rho^{2n}}F_{2n}(\Pi/f) + \text{higher loops}\right)$$



The PNGB Higgs



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Spurion power-counting will **fix** the F's:

Higgs potential **strongly constrained**

EW Precision Observables

Tree-Level contribution to $\widehat{S}$:

$$\widehat{S} \sim \frac{m_W^2}{m_\rho^2} \sim \frac{g^2}{g_\rho^2}\frac{v^2}{f^2} \quad \Rightarrow \quad \xi \equiv \frac{v^2}{f^2} \lesssim 0.01\, g_\rho^2$$

Best case: $\mathcal{O}_L = (\mathbf{2},\mathbf{2})_{\mathbf{2/3}},\ \mathcal{O}_R = (\mathbf{1},\mathbf{1})_{\mathbf{2/3}}$

$$\frac{\delta g_b}{g_b} \sim \frac{y_L^2}{g_\rho^2}\xi \qquad \widehat{T} \sim \frac{N_c y_L^4}{16\pi^2 g_\rho^2}\xi$$

Extra pressure from δg_b:

$$Y_t \simeq y_L y_R / g_\rho \qquad \begin{cases} y_L \sim Y_t \\ y_R \sim g_\rho \end{cases}$$

EW Precision Observables

Avoided by P_{LR} symmetry: $\begin{array}{c} L \leftrightarrow R \\ b_L \to b_L \end{array}$

$$\bar{b}_L i \not{D} b_L + \bar{b}_L \left[\delta_L \not{L} + \delta_R \not{R} + \delta_X \not{X}\right] b_L$$

P_{LR} plus unbroken sym. ➡ $\delta_L = \delta_R = \delta_X = 0$

Do we really need **another** symmetry ?

EW Precision Observables

NO, P_{LR} is **accidental !**

Use the $\mathrm{SO}(4)/\mathrm{SO}(3)$ symmetry:

$$(y_L)_A\, q_L\, \mathcal{O}_L^A \equiv Q_A\, \mathcal{O}_L^A$$

$$\psi_i = Q_A U^*_{Ai} \qquad\qquad \eta = Q_A U^*_{A4}$$

$$\mathcal{O}_1 = \bar{\psi}\bar{\sigma}^\mu(\partial_\mu + \mathcal{E}_\mu)\psi \qquad\qquad \mathcal{O}_2 = \bar{\eta}\bar{\sigma}^\mu\partial_\mu\eta$$

$$\mathcal{O}_3 = \bar{\psi}_i\bar{\sigma}^\mu\eta\mathcal{D}_{i\mu} \qquad\qquad \boxed{\mathcal{O}_4 = \bar{\psi}_i\bar{\sigma}^\mu\psi_j\mathcal{D}_{k\,\mu}\epsilon_{ijk}}$$

Can this term emerge with the full symmetry ?

EW Precision Observables

NO, P_{LR} is **accidental** !

Use now the full $SO(5)/SO(4)$

With $\mathcal{O}_L = \mathbf{5}_{2/3}$:

$$\psi_i = Q_A U^*_{Ai} \qquad \eta = Q_A U^*_{A5}$$

cannot use the ϵ tensor !

Reduction of $\delta g_b/g_b$ allows larger $y_L \sim \sqrt{Y_t g_\rho}$.

Two Composite Higgses

Two **guidelines** for model-building:

- Custodial $\mathrm{SO}(3)_c$ can be broken by the VEVs
- Second Higgs is a possible new source of FCNC

Two Composite Higgses

$\text{S}\not{\text{O}}(3)_c:$

$$\Phi^{\hat{\mathbf{1}}} = (0,0,0,v_4^{\hat{\mathbf{1}}}) \qquad H^{\hat{\mathbf{1}}} = \begin{pmatrix} 0 \\ v_4^{\hat{\mathbf{1}}} \end{pmatrix}$$

$$\Phi^{\hat{\mathbf{2}}} = (0,0,v_3^{\hat{\mathbf{2}}},v_4^{\hat{\mathbf{2}}}) \qquad H^{\hat{\mathbf{2}}} = \begin{pmatrix} 0 \\ v_4^{\hat{\mathbf{2}}} - i v_3^{\hat{\mathbf{2}}} \end{pmatrix}$$

$$\frac{c_T}{f^2}\left(\Phi^{\hat{\mathbf{1}}} \cdot \overleftrightarrow{D}_\mu \Phi^{\hat{\mathbf{2}}}\right)^2 \Rightarrow \widehat{T} = 2c_T \frac{(v_4^{\hat{\mathbf{1}}})^2 (v_3^{\hat{\mathbf{2}}})^2}{f^2[(v_4^{\hat{\mathbf{1}}})^2 + (v_4^{\hat{\mathbf{2}}})^2 + (v_3^{\hat{\mathbf{2}}})^2]} \sim \frac{c_T}{2}\frac{v^2}{f^2}$$

$\text{SO}(4) \rightarrow SO(2)_c$ **triggered by:** $v_4^{\hat{\mathbf{1}}} v_3^{\hat{\mathbf{2}}} \propto \text{Im}\,(H^{\hat{\mathbf{1}}\dagger} H^{\hat{\mathbf{2}}})$

Two Composite Higgses

Three ways to control $\widehat{T}$:

$C_1 \in SO(4)$: $(\phi_1,\, \phi_2,\, \phi_3,\, \phi_4) \to (-\phi_1,\, \phi_2,\, -\phi_3,\, \phi_4)$

(or, $H \to H^*$)

Two Composite Higgses

Three ways to control $\widehat{T}$:

$C_1 \in SO(4)$: $(\phi_1,\, \phi_2,\, \phi_3,\, \phi_4) \to (-\phi_1,\, \phi_2,\, -\phi_3,\, \phi_4)$

(or, $H \to H^*$)

Acts like C, also on the EW bosons

C is broken by fermions, **we impose** $C_1 P \equiv CP$

Two Composite Higgses

Three ways to control $\widehat{T}$:

$$C_2 : \quad \begin{array}{c} \Phi^{\hat{\mathbf{1}}} \to \Phi^{\hat{\mathbf{1}}} \\ \Phi^{\hat{\mathbf{2}}} \to -\Phi^{\hat{\mathbf{2}}} \end{array}$$

$C_2 = P_6$ in $SO(6)/SO(4) \times SO(2)$

Accidental C_2 in 2-der. σ-model

If unbroken, C_2 leads to **Inert Higgs**

Two Composite Higgses

Three ways to control $\widehat{T}$:

Extended Custodial:

$$\Phi_{\hat{\mathbf{1}}} \rightarrow L\Phi_{\hat{\mathbf{1}}}R_1^\dagger$$

$$\Phi_{\hat{\mathbf{2}}} \rightarrow L\Phi_{\hat{\mathbf{2}}}R_2^\dagger$$

$\mathrm{SO}(3)_c$ **is preserved** by the VEV

Mechanism at work in the ren. THDM

Realized in $\mathrm{Sp}(6)/\mathrm{SU}(2) \times \mathrm{Sp}(4)$

Two Composite Higgses

Higgs-Mediated **FCNC:**

Renormalizable effects:

$$\bar{q}_L\big(Y_1^u\tilde{H}_1+Y_2^u\tilde{H}_2\big)u_R+\bar{q}_L\big(Y_1^dH_1+Y_2^dH_2\big)d_R$$

Solution is restore MFV by:

i) Symmetry: C_2 →

type	u_R	d_R	e_R
I	$+$	$+$	$+$
II	$+$	$-$	$-$
X	$+$	$+$	$-$
Y	$+$	$-$	$+$

ii) Ansatz: (uv-motivated) $Y_1^u\propto Y_2^u,\ Y_1^d\propto Y_2^d$

(type-III)

Two Composite Higgses

Higgs-Mediated **FCNC:**

Effects of **compositeness:** (for 1 or 2 Higgses)

$$\bar{q}_L \big(Y_1^u \tilde{H} + Y_3^u \tilde{H} H^\dagger H / f^2 + \ldots \big) u_R$$

Solution is again MFV: **(Agashe-Contino)**

$$\bar{q}_L \big(Y_1^u \tilde{H} F_u (H^\dagger H / f^2) \big) u_R$$

Enforced by G **selection rules**

Two Composite Higgses

Higgs-Mediated **FCNC:**

$$\mathcal{L}_{\rm mix} = (\bar{f}_L)_{\overline{\alpha}}(y_L{}^{\overline{\alpha}})^{I_{f_L}}\mathcal{O}_{I_{f_L}} + (\bar{f}_R)(y_R)^{I_{f_R}}\mathcal{O}_{I_{f_R}}$$

$$\Psi_L{}^{I_{f_L}} = (f_L)_{\overline{\alpha}}(y_L^{*\overline{\alpha}})^{I_{f_L}}/g_\rho \qquad \Psi_R{}^{I_{f_R}} = (f_R)(y_R^{*})^{I_{f_R}}/g_\rho$$

$U^\dagger\Psi$ transforms as in H.

$\mathrm{SO}(5)/\mathrm{SO}(4),\ \{\mathbf{5},\mathbf{5}\}$ → $2-1=1$

$\mathrm{SO}(6)/\mathrm{SO}(4)\times\mathrm{SO}(2),\ \{\mathbf{20},\mathbf{1}\}$ → 1

$\mathrm{SO}(6)/\mathrm{SO}(4)\times\mathrm{SO}(2),\ \{\mathbf{6},\mathbf{6}\}$ → $3-1=$ ~~2~~ $\xrightarrow{C_2}$ 1

Explicit Models

$$\mathrm{SO}(6)/\mathrm{SO}(4)\times\mathrm{SO}(2)$$

Two doublets: $\Phi^{\alpha}=\{\Phi^{\hat{\mathbf{1}}},\Phi^{\hat{\mathbf{2}}}\}$

$$\left(U^{\mathbf{6}}\right)^{I}{}_{\bar{I}}=\left(e^{\imath\frac{\Pi}{f}}\right)^{I}{}_{\bar{I}},\quad \Pi=T^{i}_{\alpha}\Phi^{\alpha}_{i}=\frac{i}{\sqrt{2}}\left(\begin{array}{c|c} 0_{4\times4} & \Phi^{\hat{\mathbf{1}}}\ \ \Phi^{\hat{\mathbf{2}}} \\ \hline \begin{array}{c}-\Phi^{\hat{\mathbf{1}}}\\ -\Phi^{\hat{\mathbf{2}}}\end{array} & 0_{2\times2}\end{array}\right)$$

$$U^{\mathbf{6}}\to\mathcal{C}^{\mathbf{6}}_{1,2}\cdot U^{\mathbf{6}}\cdot\mathcal{C}^{\mathbf{6}}_{1,2}\quad\text{with}\quad\mathcal{C}^{\mathbf{6}}_{1}=\mathrm{diag}(-1,1,-1,1\ ,\ 1,1)\,,\quad\mathcal{C}^{\mathbf{6}}_{2}=\left(\begin{array}{c|c} 1_{4\times4} & 0\ \ 0 \\ \hline \begin{array}{c}0\\ 0\end{array} & \sigma_3\end{array}\right)$$

Explicit Models

$$L_{\rm mix} = (\bar{q}_L)_{\overline{\alpha}} (y_L{}^{\overline{\alpha}})^{I_Q} Q_{I_Q} + (\bar{t}_R)(y_R)^{I_T} T_{I_T} + \text{h.c.}$$

$$\begin{aligned} (\Upsilon_L)^{I_Q J_Q} &= (y^*_{L\ \overline{\alpha}})^{I_Q} (y^{\overline{\alpha}}_L)^{J_Q} \,, \\ (\Upsilon_R)^{I_T J_T} &= (y^*_R)^{I_T} (y_R)^{J_T} \,. \end{aligned}$$

$\Rightarrow$

$$\begin{aligned} (\overline{\Upsilon}_L)^{\overline{I}\,\overline{J}} &\equiv \left(U^{\mathbf{r}_Q \dagger}\right)^{\overline{I}}{}_{I} \left(U^{\mathbf{r}_Q \dagger}\right)^{\overline{J}}{}_{J} (\Upsilon_L)^{IJ} \\ (\overline{\Upsilon}_R)^{\overline{I}\,\overline{J}} &\equiv \left(U^{\mathbf{r}_T \dagger}\right)^{\overline{I}}{}_{I} \left(U^{\mathbf{r}_T \dagger}\right)^{\overline{J}}{}_{J} (\Upsilon_R)^{IJ} \end{aligned}$$

$$V = \frac{m_\rho^4}{16\pi^2} \sum_{n_L, n_R} \frac{1}{(g_\rho^2)^{n_L + n_R}} \sum_\delta c_\delta^{n_L, n_R} \, \mathcal{I}^\delta_{n_L, n_R}$$

The potential terms are H-invariants made of $\overline{\Upsilon}$.

Explicit Models

Model **A** : $\{\mathbf{r}_Q,\, \mathbf{r}_T\} = \{\mathbf{20}',\, \mathbf{1}\}$

$$\mathbf{20}' \;=\; (\mathbf{9},\mathbf{1}) \oplus (\mathbf{4},\mathbf{2}) \oplus (\mathbf{1},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})$$

- we impose $C_1 P$ to align the VEVs
- **unique** generalized Yukawa
- **multiple** q_L embedding (pick one)

Explicit Models

Model **A** : $\{\mathbf{r}_Q,\ \mathbf{r}_T\} = \{\mathbf{20}',\ \mathbf{1}\}$

$$\mathbf{20}' = (\mathbf{9},\mathbf{1}) \oplus (\mathbf{4},\mathbf{2}) \oplus (\mathbf{1},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})$$

accidental symmetries !

		Intrinsic Parity C_2	Intrinsic Parity C_1P	Residual $SO(4)$
y_L^2	$\mathcal{I}_1^1 = \delta_{ij}\delta_{kl}(\overline{\Upsilon}_L^{\mathbf{20}'})^{ijkl}$	$+$	$+$	✓
	$\mathcal{I}_1^2 = \delta_{ik}\delta_{jl}(\overline{\Upsilon}_L^{\mathbf{20}'})^{ijkl}$	$+$	$+$	✓
	$\mathcal{I}_1^3 = \delta_{\alpha\gamma}\delta_{\beta\delta}(\overline{\Upsilon}_L^{\mathbf{20}'})^{\alpha\beta\gamma\delta}$	$+$	$+$	✓
	$\mathcal{I}_1^4 = \epsilon_{\alpha\gamma}\delta_{\beta\delta}(\overline{\Upsilon}_L^{\mathbf{20}'})^{\alpha\beta\gamma\delta}$	$-$	$-$	×
	$\mathcal{I}_1^5 = \epsilon_{\alpha\gamma}\delta_{ij}(\overline{\Upsilon}_L^{\mathbf{20}'})^{i\alpha j\beta}$	$-$	$-$	×

Explicit Models

Model **A** : $\{\mathbf{r}_Q, \mathbf{r}_T\} = \{\mathbf{20}', \mathbf{1}\}$

- accidental C_2 and $SO(4)$ in the potential
- accidental C_2 in the top Yukawa
- **broken** C_2 in the other Yukawas

Almost Inert Higgs

Explicit Models

Model **A** : $\{\mathbf{r}_Q,\, \mathbf{r}_T\} = \{\mathbf{20'},\, \mathbf{1}\}$

Operator	$\mathcal{I}_1^1$	$\mathcal{I}_1^2$	$\mathcal{I}_1^3$
$\frac{1}{16\pi^2}\times$	y_L^2	$-\frac{5}{2}y_L^2$	y_L^2
m_{11}^2/f^2	1	1	1
m_{22}^2/f^2	0	0	$\frac{1}{2}$
λ_1	$-\frac{2}{3}$	$-\frac{11}{30}$	$-\frac{2}{3}$
λ_2	0	0	$-\frac{1}{12}$
λ_3	0	$-\frac{1}{10}$	$-\frac{1}{4}$
λ_4	$-\frac{2}{3}$	$-\frac{4}{15}$	$-\frac{1}{2}$
$\tilde{\lambda}_4$	0	0	0

From the "**explicit**" potential:

- check that it is **tunable** $(\frac{v}{f} < 1)$
- derive constraints on the spectrum

$$m_h^2 \sim \frac{N_c}{16\pi^2} y_L^2 g_\rho^2\, v^2 \sim (100\ \text{GeV})^2 \left(\frac{y_L}{1}\right)^2 \left(\frac{3}{N}\right)$$

$$m_{H_2}^2 \sim \frac{N_c}{16\pi^2} y_L^2 g_\rho^2\, f^2 \sim (200\ \text{GeV})^2 \left(\frac{y_L}{1}\right)^2 \left(\frac{3}{N}\right) \left(\frac{0.25}{\xi}\right)$$

Explicit Models

Model **A** : $\{\mathbf{r}_Q,\, \mathbf{r}_T\} = \{\mathbf{20'},\, \mathbf{1}\}$

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$\frac{1}{16\pi^2}\times$	y_L^2	$-\frac{5}{2}y_L^2$	y_L^2
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$\tilde{\lambda}_4$	0	0	0

From the "**explicit**" potential:

- check that it is **tunable** $(\frac{v}{f} < 1)$
- derive constraints on the spectrum

$$\frac{m_H^2 - m_{H^a}^2}{m_H^2} \simeq \frac{m_h^2}{3m_H^2} + \frac{2}{3}\xi \sim \xi$$

$$\left|\frac{m_{H^\pm} - m_A}{m_T}\right|_{\text{gauge}} \sim \left(\frac{v}{f}\right)^2 \left(\frac{g'}{y_L}\right)^2 \simeq 0.03 \left(\frac{1}{y_L}\right)^2 \left(\frac{\xi}{0.25}\right)$$

Explicit Models

Model **B** : $\{\mathbf{r}_Q,\, \mathbf{r}_T\} = \{\mathbf{6}, \mathbf{6}\}$

$$\mathbf{6} = (\mathbf{4}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{2})$$

- we impose C_2
- **unique** Yukawa because of C_2
- **unique** embedding (again, C_2)
- gives the **Composite Inert Higgs**

Explicit Models

Model **B** : $\{\mathbf{r}_Q,\, \mathbf{r}_T\} = \{\mathbf{6}, \mathbf{6}\}$

Peculiarities of the potential:

- **not tunable** at the **LO**
- accidental $C_1 P$ at **NLO**
- accidental $SO(4)$ at **LO**

Explicit Models

Model **B** : $\{\mathbf{r}_Q,\, \mathbf{r}_T\} = \{\mathbf{6}, \mathbf{6}\}$

Spectrum:

$$m_h^2 = \; Y_t^2 \frac{g_\rho^2}{16\pi^2} v^2 \sim (100\ \text{GeV})^2 \left(\frac{3}{N}\right)$$

$$m_{H_2}^2 \sim N_c \frac{g_\rho Y_t}{16\pi^2} m_\rho^2 \simeq (500\ \text{GeV})^2 \sqrt{\frac{3}{N}} \left(\frac{m_\rho}{2\ \text{TeV}}\right)^2$$

$$m_H^2 \simeq \left(1 - \frac{\xi}{6}\right) m_{H^a}^2$$

Explicit Models

Model **B** : $\{\mathbf{r}_Q,\, \mathbf{r}_T\} = \{\mathbf{6}, \mathbf{6}\}$

Spectrum:

$$\left|\frac{m_{H^\pm} - m_A}{m_{H^\pm}}\right|_{\rm NLO} \sim \left(\frac{v}{f}\right)^2 \frac{Y_t}{g_\rho} \simeq 0.03\sqrt{\frac{N}{3}}\left(\frac{\xi}{0.25}\right)$$

Conclusions

Realistic composite THDM are easily constructed

Our examples have **peculiar** phenomenology, because of the many **accidental symmetries**

Some progresses on the **general understanding** of the scenario, **better use** of symmetries

Two Composite Higgses

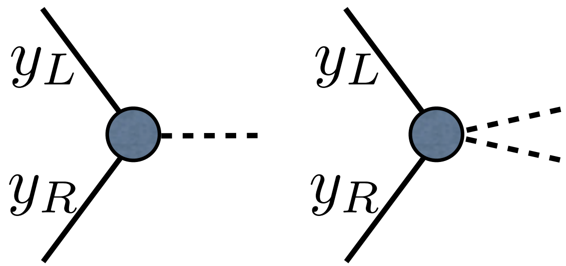
Higgs-Mediated **FCNC:**

Effects of **compositeness:** (for 1 or 2 Higgses)

$$\bar{q}_L\big(Y_1^u \tilde{H} + Y_3^u \tilde{H} H^\dagger H/f^2 + \dots\big)u_R$$

These operators are generated by

$$\mathcal{L}_{\rm mix} = (\bar{f}_L)_{\overline{\alpha}}(y_L{}^{\overline{\alpha}})^{I_{f_L}}\mathcal{O}_{I_{f_L}} + (\bar{f}_R)(y_R)^{I_{f_R}}\mathcal{O}_{I_{f_R}}$$



$$Y_{1,3}^{ij} = \frac{y_L^i y_R^j}{g_\rho} \times a_{1,3}^{ij} = g_\rho \frac{y_L^i}{g_\rho}\frac{y_R^j}{g_\rho} \times a_{1,3}^{ij}$$

Two Composite Higgses

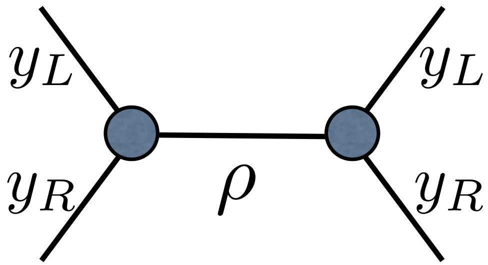
Higgs-Mediated **FCNC:**

Effects of **compositeness:** (for 1 or 2 Higgses)

$$\bar{q}_L\left(Y_1^u\tilde{H} + Y_3^u\tilde{H}H^\dagger H/f^2 + \ldots\right)u_R$$

$\Delta S = 2$ transitions: $$\epsilon_L^i\epsilon_R^j\epsilon_L^k\epsilon_R^\ell\frac{g_\rho^2}{m_h^2}\frac{v^4}{f^4}\left(\bar{f}_L^i f_R^j \bar{f}_L^k f_R^\ell\right)$$

v.s. resonance effects:



$$\epsilon_L^i\epsilon_R^j\epsilon_L^k\epsilon_R^\ell\frac{g_\rho^2}{m_\rho^2}\left(\bar{f}_L^i f_R^j \bar{f}_L^k f_R^\ell\right)$$