The Twin Composite Higgs Scenario

Andrea Wulzer

UNIVERSITÀ DEGLI STUDI DI PADOVA

Introduction

"Leaving no stone unturned in the hunt for Naturalness"

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"Is m_H Unnatural? $" \equiv "$ Is m_H Unpredictable? "

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$$
(m_H^2)_{Phys.} = \int_0^\infty F_{true}(E; g_{true})
$$

=
$$
\int_0^\infty \frac{\Lambda_{\rm SM}}{(\ldots)} + \int_{\lesssim \Lambda_{\rm SM}}^\infty (\ldots)
$$

"Is m_H Unnatural? $" \equiv "$ Is m_H Unpredictable? "

Measures how much Unpredictable m_H is.

The usual argument:

$$
\Delta \ge \left(\frac{\Lambda_{\rm SM}}{500 \,\text{GeV}}\right)^2 \implies \Lambda_{\rm SM} \le 500 \,\text{GeV} \cdot \sqrt{\Delta}
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The usual **interpretation**:

$$
\Lambda_{\rm SM} = M_{\rm Partners} =
$$

"Scale where m_H finds its physical origin "

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The usual **interpretation**:

 $\Lambda_\text{SM} = M_\text{Partners} =$

Partners are SM charged:
CH: Top Partners, EW partners...

"Scale where m_H finds its physical origin " m_H

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\Delta \ge \left(\frac{\Lambda_{\rm SM}}{500 \,\text{GeV}}\right)^2 \implies \Lambda_{\rm SM} \le 500 \,\text{GeV} \cdot \sqrt{\Delta}
$$

The usual **interpretation**:

 $\xi=$ v^2 Minimal source of tuning: $\xi\!=\!\frac{\varepsilon}{f^2}\!\ll\!1\;$ (from EWPT&Higgs)

Potential from Elementary loops (Top dominates) dimension (see Eq. (3.1.3) or \overline{C} *C* is the coupling dimension of \overline{C} is the coupling dimension of \overline{C} and \overline{C} is the coupling dimension of \overline{C} and \overline{C} is the coupling dimension of \overline{C} a

Potential from Elementary loops (Top dominates)

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*m*EW

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Plus resonances at m_{*} , like in ordinary CH, but heavier

Gauge contribution to the potential, from a model

$$
V_{g_2^2} = \frac{9g_*^2 f^4}{512\pi^2} \left(g_2^2 \sin^2 \frac{H}{f} + \tilde{g}_2^2 \cos^2 \frac{H}{f} \right)
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Twin Higgs miracle: $g_2 = \tilde{g}_2 \Rightarrow V_{g_2^2} = \text{const.}$

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Guessing the cancellation: quadratic divergence

$$
E_{\text{SO(8)/SO(7)}} \qquad \vec{\Sigma} = \begin{bmatrix} \vec{\pi} \\ \vec{\pi} \end{bmatrix} = U[H/f] \cdot \begin{bmatrix} \vec{0} \\ \vec{0} \\ \vec{0} \end{bmatrix} = \begin{bmatrix} \vec{0} \\ s_H f \\ \vec{0} \\ c_H f \end{bmatrix}
$$
\nsigma-model\n
$$
V^{\Lambda^2} = \frac{\Lambda^2}{16\pi^2} [g_2^2 |\vec{\pi}|^2 + \tilde{g}_2^2 |\vec{\pi}|^2] = \frac{\Lambda^2 f^2}{16\pi^2} [g_2^2 s_H^2 + \tilde{g}_2^2 c_H^2]
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\n
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$$
\nBut, in reality:
\n
$$
V = \int_0^\infty dE(\ldots) = \int_0^{<\Lambda} dE(\ldots) + \int_{<\Lambda}^\infty dE(\ldots)
$$
\nwhat about this one?

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Twin Higgs miracle: $g_2 \!=\! \widetilde{g}_2 \Rightarrow V_{g_2^2}$ 2 =const.

Proving the cancellation: Spurion classification

$$
\mathcal{L}_{\text{int}} = W^{\alpha}_{\mu} G^A_{\alpha} J^{\mu}_A + \widetilde{W}^{\alpha}_{\mu} \widetilde{G}^A_{\alpha} J^{\mu}_A \qquad G, \widetilde{G} \in 28 = 21 \oplus 7
$$

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of invariant operators = (# of H invariants) - (# of G invariants) = **2 - 1** $\mathcal{L}_{\mathrm{int}}\!=\!W_{\mu}^{\alpha}G_{\alpha}^{A}J_{A}^{\mu}\!+\!\widetilde{W}_{\mu}$ $\widetilde{G}_{\mu}^{\alpha}\widetilde{G}_{\alpha}^{A}J_{A}^{\mu}$ $G,\widetilde{G}\in \mathbf{28}= \mathbf{21}\oplus \mathbf{7}$

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Twin Higgs miracle: $g_2 \!=\! \widetilde{g}_2 \Rightarrow V_{g_2^2}$ 2 =const. win Higgs miracle: g_2 = **IWIII FIIGGS IIIII acie:** $y_2 - y_2 \rightarrow v_{g_2^2} - \text{const.}$

Proving the cancellation: Spurion classification *p*urion classificatio **n** ... Proving the cancellation: Spurion classification one invariant exists, given by

out the various spurious spurious spurious spurious \sim $\mathcal{L}_{int} = W_{\mu}^{\alpha} G_{\alpha}^{\gamma} J_{A}^{\gamma} + W_{\mu}^{\alpha} G_{\alpha}^{\gamma} J_{A}^{\gamma}$ $G, G \in 28$ # of invariant operators = $($ # of H invariants $)$ - $($ # of G invariants $)$ = $2 - 1$ 21's and one in the product of two 7's, but one full *SO*(8) singlet arises from two 28's, only ↵*,a*ˆ $\alpha \circ A$ $\cdots \mu \circ \alpha \circ A$ \cdots \cdots μ ^{*u*} α *A*
- *(*# of H inva # of invariant operators = (# of H invariants) - (# of G invariants) = **2 - 1** $\mathcal{L}_{\mathrm{int}}\!=\!W_{\mu}^{\alpha}G_{\alpha}^{A}J_{A}^{\mu}\!+\!\widetilde{W}_{\mu}$ $\widetilde{G}_{\mu}^{\alpha}\widetilde{G}_{\alpha}^{A}J_{A}^{\mu}$ $G,\widetilde{G}\in \mathbf{28}= \mathbf{21}\oplus \mathbf{7}$

$$
I = \sum_{\alpha, \hat{a}} \left\{ \text{Tr} [T_7^{\hat{a}} U^t G_\alpha U] \right\}^2 = \begin{cases} I = \frac{3}{4} g_2^2 \sin^2 \frac{H}{f} & \text{with same coefficient:} \\ \widetilde{I} = \frac{3}{4} \widetilde{g}_2^2 \cos^2 \frac{H}{f} & \text{from CS viewpoint} \end{cases}
$$

with sam 51
:
-² cos² *^H* $\frac{1}{f}$ *Trom* CS viewpoint with same coefficient: Spurions are identical from CS viewpoint

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Having one invariant only, Λ^2 cancellation is sufficient

$$
\mathbf{IF} \quad V^{\Lambda^2} \propto [I + \widetilde{I}] \propto [g_2^2 s_H^2 + \widetilde{g}_2^2 c_H^2]
$$
\n
$$
\mathbf{THEN} \quad V \propto [I + \widetilde{I}] \propto [g_2^2 s_H^2 + \widetilde{g}_2^2 c_H^2]
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Disproving the cancellation: SU(4)/SU(3) coset

$$
G, \tilde{G} \in \mathbf{15} = \mathbf{8} \oplus \mathbf{3} \oplus \mathbf{1}
$$

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$$
I_1 = g_2^2 s_H^2 \qquad \qquad \widetilde{I}_1 = \widetilde{g}_2^2 c_H^2 I_2 = g_2^2 s_H^4 \qquad \qquad \widetilde{I}_2 = \widetilde{g}_2^2 c_H^4
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Twin Composite Higgs to really realize the cancellation via the condition *^g*² ⁼ *^g*e². This can be enforced by Twin

Gauge contribution to the potential, from a model Parity, which is defined as the operation

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Enforcing the cancellation: Twin Parity f which interchanges the *SO*(4)*^L* and *SO* ma the cancellation[.] Twin Parity

$$
\mathcal{P}_{\text{Twin}} = \left[\begin{array}{cc} 0 & \mathbb{1}_4 \\ \mathbb{1}_4 & 0 \end{array} \right] \in \text{SO}(8) \quad \begin{array}{ll} \text{automatically a} \\ \text{symmetry of the CS} \end{array}
$$

 $\mathcal{L} \mathcal{L} = W_\mu \leftrightarrow W_\mu \text{,}$

 $\epsilon \in SO(8)$ duturnationally a
example of the CS $\epsilon \in SO(8)$ automatically a
symmetry of the CS

 W_μ *i* imposed on the ES
requires $q_2 = \widetilde{q}_2$ times $W_\mu \leftrightarrow \widetilde{W}_\mu$ if imposed on the ES requires $g_2 = \widetilde{g}_2$

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$$

Broken by not gauging the Twin Hypercharge: a Twin partner of the Hypercharge gauge boson, which however we have not introduced. Broken by not gauging the Twin Hypercharge:

$$
V_{g_1^2} = \frac{3g_*^2 f^4}{512\pi^2} g_1^2 \sin^2 \frac{H}{f}
$$
 not cancelled (not danger
quadratic contribution

 $V_2 = \frac{3g_*^2 J^4}{g_*^2} a^2 \sin^2 \frac{H}{\phi}$ and canceled (not dangerous) not canceled (not dangerous) quadratic contribution

of the CS

Twin Composite Higgs Ω erent estimates for the size of the associated couplings Ω Composite Higgs **have to below to be weakly composite** to be weak, much below **given** left–handed counterparts. However we can also interpret *t^R* and e*t^R* as completely composite

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Plus resonances at $\,m_{\ast},$ like in ordinary CH, but heavier for both completely composite and partially elementary right–handed fields. Aside from the

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Twin Composite Higgs Potential

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V_{y^4} \simeq \frac{N_c f^4}{16\pi^2} y_L^4 \sin^2 \frac{H}{f}
$$

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 $\overline{}$

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\n3) From **Detuning** $V_{y^2} = \frac{N_c f^2 m_*^2}{32\pi^2} [y_L^2 s_H^2 + \tilde{y}_L^2 c_H^2]$

Twin Composite Higgs $\overline{}$ ⇢ *y*2 *L* $\overline{}$ 0 **osite** *M*² Higgs *M*² *^S* + *f* ²*y*²

Twin Composite Higgs Potential +*y*e2 *L* f2 $\overline{\Omega}$ *M* f2 *n f* ial

 $\overline{}$ potential in the previous section, we see the Twin Higgs cancellation, we see the Twin Higgs cancella

 $m_{\widetilde{t}}(H)^2$

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\n4) From **IR running** $V_{IR}(H) = \frac{N_c}{16\pi^2} \left[m_i(H)^4 \log \frac{m_*^2}{m_i(H)^2} + m_{\tilde{t}}(H)^4 \log \frac{m_*^2}{m_{\tilde{t}}(H)^2} \right]$

 $16\pi^2$

Twin Composite Higgs where g = $\frac{1}{\sqrt{2}}$ is the e $\frac{1}{\sqrt{2}}$ is the e $\frac{1}{\sqrt{2}}$ is the overall size of the fermion which is also expected to be around $\mathbf{A} = \mathbf{A} \mathbf{A} \mathbf{A}$ and $\mathbf{A} = \mathbf{A} \mathbf{A} \mathbf{A}$ and $\mathbf{A} = \mathbf{A} \mathbf{A} \mathbf{A}$ and $\mathbf{A} = \mathbf{A} \mathbf{A} \mathbf{A} \mathbf{A}$ and $\mathbf{A} = \mathbf{A} \mathbf{A} \mathbf{A} \mathbf{A} \mathbf{A}$ and $\mathbf{A} =$

Twin Composite Higgs Potential

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\frac{V(H)}{f^4} = \alpha s^2 + \beta \left(s^4 \log \frac{a}{s^2} + c^4 \log \frac{a}{c^2} \right)
$$

$$
\alpha = \frac{3g_1^2 g_*^2}{512\pi^2} A + \frac{3\Delta y^2 g_*^2}{32\pi^2} B \qquad \beta = \frac{3y_t^4}{64\pi^2} \qquad \log a = \log \frac{2m_*^2}{y_t^2 f^2} + \frac{y_L^4}{y_t^4} F_1
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Twin Composite Higgs Potential p·(1 m)
(1 m)
(1 m) $\overline{}$ *.* (3.9)

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$$

\nNaturally light Higgs:
\n
$$
\log a \simeq 6 + \log \sqrt{\xi} \qquad \text{OK for } \begin{cases} g_* = 4\pi \Rightarrow m_* = 4\pi f \sim 9 \text{TeV} \sqrt{10\xi} \\ y_L = y_t \text{: composite } t_R \\ \text{Elementary } t_R \text{ is disfavoured} \end{cases}
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$$

Minimal VEV tuning (1/ξ) if:

\n
$$
\log \frac{\Lambda_{\text{UV}}}{m_*} = \frac{80\pi^2}{bBg_1^2} \frac{y_t^2}{g_*^2} \ge \frac{50}{bB}
$$
\nlarge scale separation

• Twin Higgs protects m_H from partner scale m_* But only under certain conditions (1 invariant in the potential)

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- •Phenomenology: (more in backup)
	- 1.**Future** Top Partner bounds avoided (currently not an issue) 2. Order ξ modified Higgs couplings are still there (and EWPT?) 3.Resonances might be at 10 TeV, FCC-hh is needed 4."Portal—like" phenomenology. Is it robust?

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- Two directions to work on:

PH/EXP TH/PH

Could the Twin W, t (or b) be directly testable at the LHC?
directly testable at the LHC?

Non—Twin implementations of Twin cancellation?

Top Partners

MCHM Models, simplified model approach:

Top Partners denote the excluded regions for α = 0, which the change in the change in the bounds for α = 1*//* dashed lines. The darker green region shows the exclusions on the charge-2*/*3 states if only pair production

MCHM Models, simplified model approach:

Top Partners lines denote the excluded regions for *c* = 0, while the change in the bounds for *c* = 1*/* ^p2 is shown by the dashed lines. The darker green region shows the exclusions on the charge-2*/*3 states if only pair production

MCHM Models, simplified model approach:

Higgs Couplings

A rough comparison with data:

Vector Resonances

[Pappadopulo, Torre, Thamm, AW, 2014]

Vector Resonances

[Torre, Thamm, AW, for FCC W.G.]

Direct versus Indirect @ LHC

Vector Resonances

[Torre, Thamm, AW, for FCC W.G.]

Direct versus Indirect @ FCC

EWPT

Strict EWPT have a dramatic impact!

and ∆S ≈ 0.04 from (2.14). In principle, this is consistent (at the 20 ellipse) for mholder of the 20 ellipse)
In principle, this is consistent (at the 20 ellipse) for mholder of the 20 ellipse) for mholder of the 20 elli close to the direct lower bound. However, the finetuning price of f = 1 TeV from (2.8) is ∼ 3%, which is starting to get uncomfortably large for this we would like to get uncomfortably large for this we would like to get uncomfortably large $\mathcal{L}_\mathcal{S}$ the support of the SWPT contributions can unavoid an unavoidable model dependence, so that include UV contributions can unavoid an unavoidable model dependence, so that include Γ substantially relax these constraints [20]. We believe that presenting the corresponding exclu-

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 $\frac{1}{2}$ and $\frac{1}{2}$ the distribution of $\frac{1}{2}$

stick to f \sim 500 GeV, and pursue another strategy to improve the EWPT consistency. Namely, \sim

 $\Delta \hat{S}=% {\displaystyle\sum\nolimits_{n,\sigma}} g_{n}g_{n}^{\dag }=\displaystyle\sum_{n,\sigma}} g_{n}g_{n}^{\dag }=\displaystyle\sum_{n,\sigma}} g_{n}g_{n}^{\dag }=0\text{.} \label{deltaS}$ $\frac{g^2}{96\pi^2}\xi\log\left(\frac{8\pi m_W}{gm_h\sqrt{\xi}}\right)$ ◆ $\frac{1}{2}$ $\Delta\hat{T} = -\frac{3g^{\prime\,2}}{32\pi^2}\xi\log\left(\frac{8\pi m_W}{g m_h\sqrt{\xi}}\right)$ ◆

Modified Higgs couplings go in bad direction.

sion contours in the previous plots with p into account any possible U contribution \mathcal{L}

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$$
\Delta \hat{S} = \frac{g^2}{96\pi^2} \xi \log \left(\frac{8\pi m_W}{gm_h \sqrt{\xi}} \right) + \frac{m_W^2}{m_\rho^2}
$$

$$
\Delta \hat{T} = -\frac{3g^{\prime 2}}{32\pi^2} \xi \log \left(\frac{8\pi m_W}{gm_h \sqrt{\xi}} \right)
$$

 γ second term in South in *S*
South and the last term in the last terms in the last terms in γ and the last terms in the last Modified Higgs couplings go in bad direction. Resonance exchange as well

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$$
\begin{split} \Delta \hat{S} &= \frac{g^2}{96\pi^2} \xi \log\left(\frac{8\pi m_W}{gm_h\sqrt{\xi}}\right) + \frac{m_W^2}{m_\rho^2} + \alpha \frac{g^2}{16\pi^2} \xi \,, \\ \Delta \hat{T} &= -\frac{3g^{\prime\,2}}{32\pi^2} \xi \log\left(\frac{8\pi m_W}{gm_h\sqrt{\xi}}\right) + \beta \frac{3y_t}{16\pi^2} \xi \,, \end{split}
$$

sion contours in the previous plots with p into account any possible U contribution \mathcal{L}

 γ second term in *S*^s comes from the second terms from the last terms of vector resonances and th $\frac{1}{2}$ $\frac{1}{2}$ and $\frac{2}{5}$ and $\frac{1}{2}$ are of order one and contract $\frac{1}{2}$ and $\frac{1}{2}$ **Example 2018** Light Top Partners come to rescue. Modified Higgs couplings go in bad direction. Resonance exchange as well

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EWPT

[Torre, Thamm, AW, for FCC W.G.]

Allowing for a 1/5 cancellation

