The SUSY Twin Higgs

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based on work in progress
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Why a SUSY Twin Higgs?

SUSY needs some help with 3 issues:

- **LITTLE FINE-TUNING PROBLEM**
- **HIGGS MASS**
- **WHERE IS EVERYBODY?**

\[ \Lambda \]

\[ \Delta_{SUSY} = \frac{3y_t^2 M_s^2}{2\pi^2 m_h^2} \log \frac{\Lambda}{M_s} \sim 100 \]

extra non-decoupled quartic is needed to get \( m_h = 125 \text{ GeV} \)

ex. NMSSM \( m_h^2 = m_z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 \)

\[ M_s \] controls the scale of colored states
Twin Higgs needs a UV completion:

**what happens if**
\[ \Lambda_{\text{Twin}} = M_s \]
?

(mild) **Gain in Fine-Tuning**

**Higgs Mass**

**Neutral Naturalness**

\[ \Delta_{\text{Twin-SUSY}} \sim \frac{1}{\lambda} \Delta_{\text{SUSY}} \]

\( \lambda \) controls the accidental symmetry making the Higgs a PGB

It is typically heavier than in the MSSM

The Twin sector dynamics at \( \sqrt{\lambda} f \) is Neutral under the SM
Twin SUSY

“Twin Higgs”
Higgs is PGB of accidental global symmetry from explicit $Z_2$ symmetry

top partners uncolored

Supersymmetry
calculability,
gauge coupling unification

ameliorates fine-tuning

provides calculable UVC

Only few existing models (tuning 1-2 %)

Explore general structure and identify new promising directions (tuning 10 - 20 % !?)

0604076 Chang, Hall & Weiner
0604066 Falkowski, Pokorski & Schmaltz
1312.1341 Craig & Howe
2) SUSY implementations

1) A fresh look to the Twin Higgs

2) SUSY implementations

3) sketching the phenomenology of the extended Higgs sector

Understanding Twin SUSY from the bottom up…

Higgs couplings vs direct searches of extra Higgses
A fresh look to the Twin Higgs
Twin Higgs: Setup

Double SM gauge fields, Higgs and tops

\[ G_{\text{SM}} \rightarrow G^A_{\text{SM}} \times G^B_{\text{SM}} \]
\[ H, Q_3, U_3 \rightarrow H_A, Q_{3A}, U_{3A} + H_B, Q_{3B}, U_{3B} \]

visible sector

“dark” sector: neutral under SM!

Natural \( Z_2 \) exchange symmetry:

\[ H_A \longleftrightarrow H_B \ldots \]

the role of \( Z_2 \)

- \( Z_2 \) involves the full SM
- Minimal (“fraternal”) Twin Higgs; double only fields most relevant for naturalness + add what is needed for anomaly cancellation

Affect a lot of phenomenology but we leave it unspecified in our discussion...
Linear sigma model

\[ V_H(H_A, H_B) = V_H^{U_4} + V_H^{\Psi_4, Z_2} + V_H^{\Psi_4, \mathbb{Z}_2} \]

\( \mathcal{H} = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \) respects only gauge symmetry

depends only on \( H_A \leftrightarrow H_B \)

\( U_4 \) part dominant, negative mass term

\[ V_H^{U_4} = \lambda (|H_A|^2 + |H_B|^2 - f^2)^2 \]

Dark Higgs gets large \( U_4 \) breaking vev

\[ |H_B|^2 = f^2 - |H_A|^2 \]

7 GB - 6 eaten visible/dark gauge bosons = SM Higgs \( \approx H_A \)
Twin Higgs: radiative corrections

Radiative corrections mainly from top sector

\[ V_{Yuk} = y_{tA} Q_A U_A H_A + y_{tB} Q_B U_B H_B \]

\[ \Delta V_{top} = -\frac{3}{16\pi^2} \left[ y_{tA}^2 |H_A|^2 \Lambda_t^2 + y_{tB}^2 |H_B|^2 \Lambda_t^2 - y_{tA}^4 |H_A|^4 \log \frac{\Lambda_t^2}{m_{tA}^2} - y_{tB}^4 |H_B|^4 \log \frac{\Lambda_t^2}{m_{tB}^2} \right] \]
Twin Higgs: radiative corrections

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Impose Z\(_2\) invariance
\[ y_{tA} = y_{tB} = y_t \]

\[ y_t^2 \left[ |H_A|^2 + |H_B|^2 \right] \Lambda_t^2 \]
\[ y_t^4 \left[ |H_A|^4 + |H_B|^4 \right] \log \Lambda_t^2 \]
Twin Higgs: radiative corrections

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Impose \( Z_2 \) invariance
\[ y_{tA} = y_{tB} = y_t \]

\[ y_t^2 \left[ |H_A|^2 + |H_B|^2 \right] \Lambda_t^2 \]

\( U_4 \) invariant! \( \delta f \sim \Lambda_t/4\pi \)

SM quartic+mass term
\[ \delta m_h \sim f/4\pi \]

UV cutoff enlarged by loop factor
\[ \delta m_h \sim f/4\pi \sim \Lambda_t/(4\pi)^2 \]

The B-states are neutral under SM

0506256
Chacko, Goh and Harnik
Twin Higgs: EWSB

\[ V_H(H_A, H_B) = V_H^U + V_H^{U', Z_2} + V_H^{U', Z_2} \]

\[ \lambda (|H_A|^2 + |H_B|^2 - f^2) \quad \kappa [|H_A|^4 + |H_B|^4] \quad \rho |H_A|^4 + \sigma f^2 |H_A|^2 \]

\[ \rightarrow |H_B|^2 = f^2 - |H_A|^2 \]

Match to SM Higgs potential

\[ V_{eff} \sim -f^2 \left( k + \frac{\sigma}{2} \right) H^2 + \frac{1}{6} \left( 4k + \frac{\sigma + \rho}{2} \right) H^4 \]

need explicit Z2 breaking

**SOFT:** tune \( \sigma \sim -2k \)

**HARD:** \( \sigma \sim \rho \frac{\Lambda^2}{4\pi^2 f^2} \)

quartic > mass \( \Lambda_\rho < 2\pi f \)

this is what was mostly studied so far
## Twin Higgs: EWSB

\[ V_{\text{eff}} \sim -f^2 \left( \frac{\kappa}{(4\pi)^2} + \sigma \right) H^2 + \left( \frac{\kappa}{(4\pi)^2} + \sigma + \rho \right) H^4 \]

<table>
<thead>
<tr>
<th></th>
<th>soft Z2 breaking</th>
<th>hard Z2 breaking</th>
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<tbody>
<tr>
<td><strong>EW scale</strong></td>
<td></td>
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<tr>
<td>( \frac{v^2}{f^2} )</td>
<td>( \frac{1}{2} \left( 1 - \frac{\sigma}{2\kappa} \right) )</td>
<td>( \frac{1}{2} \left( \frac{k - \rho\Lambda_{\rho}^2}{8\pi^2 f^2} \right) )</td>
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<tr>
<td><strong>Tuning</strong></td>
<td>( \Delta^\text{soft} \approx \frac{f^2}{2v^2} )</td>
<td>( \Delta</td>
</tr>
<tr>
<td><strong>Higgs Mass</strong></td>
<td>( m_h^2</td>
<td>_{\text{soft}} = 2\sqrt{2\kappa}v )</td>
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Hard breaking model is sensibly less fine tuned if \( \Lambda_{\rho} < 2\pi f \quad \text{who is} \quad \Lambda_{\rho} \) ?

The Higgs mass increases by the same amount \( \rightarrow \text{small} \ \kappa \) ?
**in summary**

\[ \lambda = 1, \Lambda_t = \Lambda, m_h = 125 \text{ GeV} \]

\[ \Lambda_\rho \sim \Lambda_t \] overshoots the Higgs

WAYS OUT:

- small \( f \) and low \( \Lambda_t \)
- \( k_0 < 0 \) challenged by Higgs coupling & direct searches

\[ \Lambda_\rho \neq \Lambda_t \]

the cut-off of the Higgs loop can correspond to uncoloured states?

see later…

Gain in fine-tuning up to a factor of 5-10
Twin SUSY
matching the SUSY potential to the Twin Higgs linear sigma model

\[
\begin{align*}
    h_u^A &= H_A s_A & h_u^A &= H_A^\dagger c_A \\
    h_u^B &= H_B s_B & h_d^B &= H_B^\dagger c_B
\end{align*}
\]

Get large U_4 preserving quartic from non-decoupling F-term of singlet

\[
V_{H}^{U_4} = \lambda \left( |H_A|^2 + |H_B|^2 - f^2 \right)^2
\]

\[
W = \lambda S H_u H_d
\]

\[
V_{\mu}^{U_4} = m_u^2 |H_u|^2 + m_d^2 |H_d|^2 b (H_u H_d + c.c) + \lambda S |H_u H_d|^2
\]

\[
\lambda = \frac{\lambda_S^2}{4} s_{2A} s_{2B} \approx \frac{\lambda_S^2}{4} s_{2\beta}^2
\]

\[
f^2 \approx -\frac{2}{\lambda_S^2 s_{2\beta}^2} (m_u^2 s_{\beta}^2 + m_d^2 c_{\beta}^2 - b s_{2\beta})
\]

In the full 4 Higgs doublet model there are two more EWSB conditions fixing

\[
\begin{align*}
    t_\beta \\
    \delta t_\beta = t_A - t_B
\end{align*}
\]
we can reliably compute the fine-tuning with respect to the UV cut-off

We want to stay agnostic with respect to the origin of $Z_2$-breaking $\Lambda = 100 M_s$

Two sources of tuning

$$\frac{f}{M_S}$$

U$_4$, similar NMSSM tuning $v \to f$

$$\Delta_f \sim \frac{\delta m_{H_u}^2}{2\lambda^2 f^2 c_\beta^2}$$

$$\frac{v}{f}$$

U$_4$ breaking, model-dependent

$$\frac{f^2/2v^2}{(\Lambda_\rho/4\pi v)^2}$$

origin of explicit $Z_2$ breaking:

- **soft** via gauge mediation
- **hard** via non-decoupled F-term

$$W = \tilde{\lambda} \tilde{S} H_u^A H_d^A \quad m_{\tilde{S}} \gg M_{\tilde{S}}$$

$$\Lambda_\rho \approx M_{\tilde{S}}$$
we can reliably compute the Higgs mass at 1-loop

\[ m_h = 125 \pm 5 \text{ GeV} \]

(large theory uncertainty to be fixed including gluino contributions @ 2-loops)

\[ \kappa \approx \frac{g^2 + g'^2}{8} c_{2\beta}^2 + \frac{3 y_t^4 s_{\beta}^4}{16\pi^2} \log \frac{M_s^2}{y_t^2 s_\beta^2 f^2} - \delta t_{\beta} \frac{\lambda_s^2}{4} s_{4\beta} c_{\beta}^2 \]

D-terms \hspace{1cm} \text{stop-top loops} \hspace{1cm} \text{F-terms}

strong upper bound on \( t_{\beta} \) and \( \delta t_{\beta} \)

the bounds get even stronger if we have hard-breaking…

\[ m_h^2 \approx 8v^2 \left( \kappa + \frac{\rho}{2} \right) \]
negative quartic in SUSY?

ugly example...

\[ W = \lambda_d \Phi_d^{AB} H_u^A H_u^B \]

\[ m_{\Phi_d} \gg M_{AB} \]

\[ \kappa \rightarrow \kappa - \lambda_d s_\beta^4 \]

colored states decoupled from LHC

1312.1341 Craig & Howe

colored states within the reach of LHC because of the Higgs mass constraint

hard-breaking+AB bi-doublet
Extra Higgsses
We have a full 4 Higgs doublet model

The structure of the spectrum

\[ m_A \ f \]

2 mass parameters + angles

Higgs coupling constraints work like in the usual Twin Higgs

\[ f > 2.2 \nu \]

CAN WE OBSERVE THE EXTRA HIGGSES?

\[ \begin{align*}
A_2^0 & \quad H_2^0 & \quad H_2^\pm & \sim m_A \\
A_1^0 & \quad H_1^0 & \quad H_1^\pm & \sim \sqrt{m_A^2 - \lambda f^2} \\
h_2^0 & \quad h & \sim \sqrt{\lambda f}
\end{align*} \]
Colored states are decoupled
extra Higgses become smoking guns of these construction

Searches for singlet Higgses
&
charged/CP-odd Higgses

Twin Higgs

The invisible BR is highly model dependent

\[ t_\beta < 2 - 3 \] makes life harder
what we learned...

- Twin Higgs models can stabilize weak scale up to few TeV
- SUSY provides UV completion with calculable observables: “Twin SUSY”
- Systematic understanding by matching to the Twin Higgs
- Hard Z2 breaking models allow for natural v/f hierarchies & they have SUSY realizations

what is left...

- Can one relate Z2-breaking with SUSY-breaking?
- Hunting for the least fine-tuned perturbative model?
- New fraternal phenomenology? Cosmology?