Asymptotically Free Supersymmetric Twin Higgs

Marcin Badziak

University of Warsaw

Based on:
MB, Keisuke Harigaya
JHEP 1706 (2017) 065 [1703.02122]
JHEP 1710 (2017) 109 [1707.09071]
PRL 120 (2018) 211803 [1711.11040]
Motivation

• LHC set strong constraints on colored top partners (e.g. stops in Supersymmetry)
• Neutral Naturalness (uncolored top partners) becomes a new paradigm to solve the hierarchy problem
• Twin Higgs idea is a nice implementation of Neutral Naturalness but still requires UV completion to solve the big hierarchy problem of the SM
• All known UV completions involve some non-perturbative dynamics not far above the EW scale
• In this talk: Supersymmetric Twin Higgs model perturbative up to around the Planck scale
**Twin Higgs model in a nutshell**

*Chacko, Goh, Harnik ’05*

- The Higgs is a pNGB of a global SU(4) symmetry
- SU(4) enforced by $Z_2$ symmetry exchanging two copies of the SM

$$V = \lambda (|H'|^2 + |H|^2)^2 - m^2 (|H'|^2 + |H|^2) + \Delta \lambda (|H'|^4 + |H|^4) + \Delta m^2 |H|^2$$

SU(4) spontaneously broken to SU(3) → 7 NGB: 6 eaten + massless Higgs

Scale of SU(4) breaking: $f^2 \equiv v^2 + v'^2$ \hspace{1cm} $\langle H \rangle \equiv v$ \hspace{1cm} $\langle H' \rangle \equiv v'$

SU(4) symmetric

SU(4) breaking

$SU(4) \& Z_2$ breaking

the Higgs is pNGB maximal mixture of $H$ and $H'$

the Higgs with SM-like couplings
Fine-tuning in Twin Higgs models

• Maximal gain in fine-tuning depends on the size of $\lambda$:

\[
\frac{2\lambda}{\lambda_{SM}} \quad \lambda_{SM} \approx 0.13
\]

• Large $\lambda$ preferred which suggests non-perturbative UV completions of Twin Higgs model:

  Composite Twin Higgs or SUSY with low Landau pole scale

  Batra, Chacko ’08  Geller, Telem ’14  Falkowski, Pokorski, Schmaltz ’06  Chang, Hall, Weiner ’06

How to make UV completed Twin Higgs perturbative up to high scales?

  Supersymmetry with new gauge symmetry
SU(4) invariant quartic term generated by a D-term potential of a new gauge symmetry

\[ V_{U(1)_X} = \frac{g_X^2}{8} (|H_u|^2 - |H_d|^2 + |H'_u|^2 - |H'_d|^2)^2 (1 - \epsilon^2) \]

must be large

\[ \lambda = g_X^2 \frac{\cos^2 (2\beta)}{8} (1 - \epsilon^2) \equiv \lambda_D \]

New U(1) works well for low mediation scale of SUSY breaking – better than 10% tuning but Landau Pole at O(100) TeV

Keeping new gauge coupling in the perturbative regime prefers:
• Non-abelian gauge interaction preferred
• number of fields charged under the new interaction as small as possible
Particle Content of the Minimal Model

\[ \mathcal{H} = (H_u, H_2)^T \]

right-handed top

SU(2)_x breaking fields

Required by U(1)_Y-SU(2)_x^2 anomaly cancellation

<table>
<thead>
<tr>
<th>( SU(2)_x )</th>
<th>( SU(2)_L )</th>
<th>( SU(2)'_L )</th>
<th>( U(1)_Y )</th>
<th>( U(1)'_Y )</th>
<th>( SU(3)_c )</th>
<th>( SU(3)'_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H )</td>
<td>2</td>
<td>2</td>
<td>1/2</td>
<td>( H' )</td>
<td>1/2</td>
<td>( \bar{3} )</td>
</tr>
<tr>
<td>( Q_R )</td>
<td>2</td>
<td>2</td>
<td>-2/3</td>
<td>( Q'_R )</td>
<td>-2/3</td>
<td>( \bar{3} )</td>
</tr>
<tr>
<td>( \tilde{H}_R )</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>( H' )</td>
<td>1</td>
<td>( 3 )</td>
</tr>
<tr>
<td>( E )</td>
<td>2</td>
<td>2</td>
<td>2/3</td>
<td>( E' )</td>
<td>2/3</td>
<td>( 3 )</td>
</tr>
<tr>
<td>( U )</td>
<td>2</td>
<td>2</td>
<td>-1</td>
<td>( U' )</td>
<td>-1</td>
<td>( 3 )</td>
</tr>
<tr>
<td>( E_{1,2} )</td>
<td>2</td>
<td>2</td>
<td>1/2</td>
<td>( E'_{1,2} )</td>
<td>1/2</td>
<td>( \bar{3} )</td>
</tr>
<tr>
<td>( \phi_u )</td>
<td>2</td>
<td>2</td>
<td>-1/2</td>
<td>( \phi'_{e_u} )</td>
<td>-1/2</td>
<td>( 3 )</td>
</tr>
<tr>
<td>( \phi_{d_{1,2,3}} )</td>
<td>2</td>
<td>2</td>
<td>1/6</td>
<td>( \phi_{d_{1,2,3}}' )</td>
<td>1/6</td>
<td>( \bar{3} )</td>
</tr>
<tr>
<td>( Q_{1,2,3} )</td>
<td>2</td>
<td>2</td>
<td>-2/3</td>
<td>( Q'_{1,2,3} )</td>
<td>-2/3</td>
<td>( 3 )</td>
</tr>
<tr>
<td>( u_{1,2} )</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>( u'_{1,2} )</td>
<td>1</td>
<td>( \bar{3} )</td>
</tr>
<tr>
<td>( d_{1,2,3} )</td>
<td>2</td>
<td>2</td>
<td>1/3</td>
<td>( d'_{1,2,3} )</td>
<td>1/3</td>
<td>( \bar{3} )</td>
</tr>
<tr>
<td>( L_{1,2,3} )</td>
<td>2</td>
<td>2</td>
<td>-1/2</td>
<td>( L'_{1,2,3} )</td>
<td>-1/2</td>
<td>( 3 )</td>
</tr>
</tbody>
</table>

M. Badziak (Warsaw)
Breakdown of the $SU(2)_X$ symmetry

$$W = \kappa Z (S \bar{S} - M^2) \quad V_{\text{soft}} = m_S^2 (|S|^2 + |ar{S}|^2)$$

$$\langle S \rangle = \begin{pmatrix} 0 \\ \nu_S \end{pmatrix}, \quad \langle \bar{S} \rangle = \begin{pmatrix} \nu_S \\ 0 \end{pmatrix}, \quad \nu_S = \sqrt{M^2 - m_S^2 / \kappa^2}$$

- $SU(4)$ invariant term from D-term potential:

$$\frac{g_X^2}{8} \sin^4 \beta (1 - \epsilon^2) (|H|^2 + |H'|^2)^2$$

$$\epsilon^2 = \frac{m_X^2}{2m_S^2 + m_X^2}$$
The Landau pole for the SU(2)$_X$ interaction is much higher than in the U(1) model.

- Tuning better than 5% can be obtained for mediation scale as high as $10^7$ GeV.
- For gravity mediated SUSY breaking 1% tuning.
Asymptotically Free SUSY Twin Higgs

The non-abelian model can be extended to make the new interaction asymptotically free!

$$SU(2)_X \times SU(2)_{X}'$$

$$W = Y \left( \Sigma^2 - v_\Sigma^2 \right)$$

$$W = \kappa \Xi (S \bar{S} - M^2) + \kappa \Xi' (S' \bar{S}' - M'^2)$$

$$V_{\text{soft}} = m_S^2 ( |S|^2 + |\bar{S}|^2 + |S'|^2 + |\bar{S}'|^2 )$$

<table>
<thead>
<tr>
<th></th>
<th>$SU(2)_X$</th>
<th>$SU(2)'_X$</th>
<th>$3-2-1$</th>
<th>$3'-2'-1'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$</td>
<td>2</td>
<td>2</td>
<td>(1, 2, 1/2)</td>
<td>(1, 2, 1/2)</td>
</tr>
<tr>
<td>$H'$</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{S}$</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S'$</td>
<td>2</td>
<td>2</td>
<td>(3, 1, -2/3)</td>
<td>(3, 1, -2/3)</td>
</tr>
<tr>
<td>$\bar{S}'$</td>
<td>2</td>
<td>2</td>
<td>(1, 1, 1)</td>
<td>(1, 1, 1)</td>
</tr>
<tr>
<td>$Q_R$</td>
<td>2</td>
<td>2</td>
<td>(1, 1, -1)</td>
<td>(1, 1, -1)</td>
</tr>
<tr>
<td>$Q'_R$</td>
<td>2</td>
<td>2</td>
<td>(1, 2, 1/2)</td>
<td>(1, 2, 1/2)</td>
</tr>
<tr>
<td>$E$</td>
<td>2</td>
<td>2</td>
<td>(1, 2, -1/2)</td>
<td>(1, 2, -1/2)</td>
</tr>
<tr>
<td>$E'$</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{1,2}$</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E'_{1,2}$</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\phi_u$</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\phi'_{u}$</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_d, \phi_{d,1,2}$</td>
<td>2</td>
<td>2</td>
<td>(1, 2, -1/2)</td>
<td>(1, 2, -1/2)</td>
</tr>
<tr>
<td>$H'<em>d, \phi'</em>{d,1,2}$</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Twin states charged under different $SU(2)$s at high scales

M. Badziak (Warsaw)
Asymptotically Free SUSY Twin Higgs: RG running of couplings

• $g_x$ asymptotically free!
• New interaction drives the top Yukawa coupling to small values at high scales – suppressed tuning from stops and gluino
Asymptotically Free SUSY Twin Higgs

- Twin Higgs mechanism works perturbatively even for mediation around the Planck scale
- Tuning better than 5% (for 2 TeV stops and gluino) even for gravity mediation of SUSY breaking

\[
M_3=2 \text{ TeV}, \quad m_{\text{stop}}=2 \text{ TeV}, \quad \tan \beta = 3, \quad f=3v, \quad \epsilon^2 = 1/3
\]
Asymptotically Free SUSY Twin Higgs: flavor-violating top decays

The model has non-trivial flavor structure

The top Yukawa coupling is generated via $W \sim H Q_R Q_3$

The interaction includes $\mathcal{L} = y_t H_2 \bar{u}_R Q_3$ which generates top decay to the Higgs and the up quark

$$\text{BR}(t \rightarrow h u) \sim \left(\frac{\theta_{H_2}}{0.1}\right)^2 10^{-3}$$

Sizable $\text{BR}(t \rightarrow h u)$ even for not large $H_2 - h$ mixing

Current LHC limit on $\text{BR}(t \rightarrow h u) \sim 10^{-3}$ may be improved to $10^{-4}$ at HL-LHC
Conclusions

• Twin Higgs mechanism is the leading idea of Neutral Naturalness that used to be thought to require some non-perturbative dynamics
• I presented natural SUSY UV completion of Twin Higgs in which D-term of a new gauge symmetry provides approximate SU(4) symmetry for the Higgs sector
• Fine-tuning may be relaxed by a factor of 10 as compared to SUSY models without Twin Higgs mechanism
• EW scale is obtained naturally for stop and gluino masses that easily satisfy current constraint and may even escape detection at HL-LHC
• The model with new non-abelian interactions is perturbative and does not require any further UV completion below the energy scale of gravity
• Perturbativity up to the Planck scale enforces non-trivial flavor structure leading e.g. to $t \rightarrow h u$ decay which may be discovered at the LHC
BACKUP
The Higgs mass in SUSY Twin Higgs

- In SUSY Twin Higgs SU(4) is broken by the EW gauge interaction

\[ V_D = \frac{g^2 + g'^2}{8} \left[ (|H_u|^2 - |H_d|^2)^2 + (|H_u'|^2 - |H_d'|^2)^2 \right] \rightarrow \frac{g^2 + g'^2}{8} \cos^2 (2\beta) \equiv \Delta \lambda_{\text{SUSY}} \approx 0.07 \cos^2 (2\beta) \]

- The tree-level Higgs mass is given by

\[ (m_h^2)_{\text{tree}} \approx 2M_Z^2 \cos^2 (2\beta) \left( 1 - \frac{v^2}{f^2} \right) + \mathcal{O}(\Delta \lambda/\lambda) \]

- The Higgs mass enhanced by a factor of \( \sqrt{2} \) (after \( Z_2 \) breaking which is needed anyway) as compared to MSSM.

- \( m_h \approx 125 \text{ GeV} \) obtained at tree level in the limit of large \( \tan \beta \)!

- But:

- In explicit models corrections \( \mathcal{O}(\Delta \lambda/\lambda) \) are non-negligible
Asymptotically Free SUSY Twin Higgs: spectrum for simple UV boundary conditions

• Universal scalar masses
• $M_3$ fixed at the EW scale
Low mediation scale of SUSY breaking

- For $\Lambda=100m_{\text{stop}}$ much larger $g_X$ consistent with perturbativity than in the U(1) model
- For very large $g_X$ tuning dominated by the threshold correction:

$$\left(\delta m^2_{H_u}\right)_X = \frac{3}{64\pi^2} \frac{g_X^2}{m_X^2} \ln (\epsilon^{-2})$$

- 10% tuning can be obtained for 2 TeV stops and gluino (similarly to the U(1) model)
Moriond stop search results

\[ \bar{\tau}_1 - b f f' \rightarrow t \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - t \rightarrow \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - b f f' \rightarrow t \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - t \rightarrow \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - b f f' \rightarrow t \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - t \rightarrow \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - b f f' \rightarrow t \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - t \rightarrow \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - b f f' \rightarrow t \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - t \rightarrow \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - b f f' \rightarrow t \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - t \rightarrow \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - b f f' \rightarrow t \bar{t} \chi_1 \]

\[ \bar{\tau}_1 - t \rightarrow \bar{t} \chi_1 \]