A Spin-1 Top Partner

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Introduction

- The electroweak hierarchy problem has been the major motivation for new physics at the TeV scale.
- In Standard Model (SM), the Higgs mass-squared receives quadratically divergent corrections from interactions with other SM fields. The largest contributions come from the top quark loop, the EW gauge loop, and the Higgs self-coupling.

\[
\begin{align*}
\text{top} & \quad \text{top loop} \\
\text{W,Z, } \gamma & \quad SU(2) \text{ gauge boson loops} \\
\text{higgs} & \quad \text{Higgs loop}
\end{align*}
\]
Introduction

• These contributions need to be cut off at scales not much higher than the EW symmetry breaking scale so that the EW scale is stable.

• For no more than $\sim 10\%$ fine-tuning, it requires that

$$\Lambda_{\text{top}} \lesssim 2 \text{ TeV} \quad \Lambda_{\text{gauge}} \lesssim 5 \text{ TeV} \quad \Lambda_{\text{Higgs}} \lesssim 10 \text{ TeV}.$$ 

• New physics at the TeV scale will be explored at the LHC in coming years.
Introduction

- For a long time, there were only 2 solutions to the hierarchy problem: Supersymmetry (SUSY) and Technicolor, and SUSY is heavily favored.

- In recent years, there are many new ways to address the hierarchy problem, with the contributions to the Higgs mass-squared cancelled by different particles and diagrams, including little Higgs models, twin Higgs models, folded SUSY, and so on.
Possible ways to cancel the top loop

• Supersymmetry: SUSY is still the most popular candidate for new physics at the TeV scale.
  - In MSSM, there is a superpartner for each SM particle with opposite spin-statistics.
  - The quadratic radiative corrections are cancelled between fermions and bosons.
  - The superpartners of the top are scalar particles in MSSM, and they are required to be around \(~\text{TeV}\) to avoid excessive fine-tuning. They can be copious produced at the LHC as they are colored.
Possible ways to cancel the top loop

- Little Higgs models: Higgs field(s) are pseudo-Nambu-Goldstone bosons (PNGBs) of G/H.
  - G is explicitly broken by 2 sets of interactions. The Higgs is an exact NGB when either set of the couplings is absent.

\[ \mathcal{L} = \mathcal{L}_0 + \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2 \]

- The quadratic divergences are canceled by the same-spin partners of the SM top quark, gauge bosons and Higgs.
Possible ways to cancel the top loop

• Twin Higgs: Higgs is also a PNGB, but the accidental global symmetry is due to a discrete symmetry. The quadratic term is accidentally SU(4) invariant due to a $\mathbb{Z}_2$ symmetry.

Chacko, Goh, and Harnik, hep-ph/0506256, 0512088

• Mirror (twin) model: $\text{SM}_A \times \text{SM}_B \times \mathbb{Z}_2$

Top sector: $\mathcal{L} = y_t H_A q^A_L t^A_R + y_t H_B q^B_L t^B_R + h.c$

Top loop is canceled by the mirror top charged under the mirror gauge group => difficult to find at LHC.

• Left-right model: $\text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_{B-L}$
Possible ways to cancel the top loop

- Folded SUSY: quadratic correction of the top loop is cancelled by scalar particles that are not charged under color, but another SU(3) gauge symmetry.  
  Burdman, Chacko, Goh, and Harnik, hep-ph/0609152

\[
\begin{align*}
  t & \quad t \\
  Q^\alpha & \quad \tilde{t} \\
\end{align*}
\]

- UV theory requires SUSY breaking by 5D orbifold.
- Exotic (string) phenomenology associated with the new particle.
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Burdman, Chacko, Goh, and Harnik, hep-ph/0609152

\[
\begin{align*}
  t & \xleftarrow{\mathbb{Z}_2} t' \\
  Q^\alpha & \downarrow \quad Q^\alpha \\
  \tilde{t} & \xleftarrow{\mathbb{Z}_2} \tilde{t}'
\end{align*}
\]

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Other possibilities?

- SUSY relates particles with spins that differ by $1/2$. Can a spin-1 particle cancel the top loop?
- We need to assign the top to a vector supermultiplet which transform as an adjoint representation of some gauge group.
- If we consider an enlarged gauge group such as SU(5), the off-diagonal $(X/Y)$ gauge bosons transform as $(3,2)$. They can be the superpartner of the left-handed top quark if the left-handed top quark is identified as the gaugino.
A spin-1 top partner

- To get the top Yukawa coupling from the gaugino coupling, the right-handed top and the Higgs should be unified into a chiral supermultiplet transforming under the SU(5) gauge group.

- Our model is based on the gauge group
  $$SU(3) \times SU(2) \times U(1)_H \times SU(5) \times U(1)_V$$

  It is broken down to the diagonal SM gauge group at the TeV scale by VEVs of fields transforming under both $$SU(3) \times SU(2) \times U(1)_H$$ and $$SU(5) \times U(1)_V$$
## Field Content

<table>
<thead>
<tr>
<th>$SU(3)$</th>
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<th>$U(1)_H$</th>
<th>$U(1)_V$</th>
<th>$SU(5)$</th>
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$H = (\bar{T}^c, H_2)$.  
$\bar{H} = (\bar{T}, H_1)$,
The superpotential is given by

\[ W = y_1 Q_3 \Phi_3 \Phi_2 + \mu_3 \Phi_3 \Phi_3 + \mu_2 \Phi_2 \Phi_2 + y_2 u_3 H \Phi_3 + \mu H H H + Y_{Uij} Q_i \overline{u}_j \Phi_2 H + Y_{Dij} Q_i \overline{d}_j \Phi_2 \Phi + Y_{Eij} L_i \overline{e}_j \Phi_2 \Phi. \]

There are the usual soft-SUSY-breaking terms, including the gaugino masses, scalar masses, \(A\)-terms and \(B\)-terms. We assume that the potential for \( \Phi_j, \overline{\Phi}_j \) is unstable at the origin so they get the following VEVs, breaking the gauge group down to the diagonal SM gauge group.

\[
\langle \Phi_3 \rangle = \begin{pmatrix}
  f_3 & 0 & 0 & 0 & 0 \\
  0 & f_3 & 0 & 0 & 0 \\
  0 & 0 & f_3 & 0 & 0
\end{pmatrix},
\langle \overline{\Phi}_3 \rangle^T = \begin{pmatrix}
  \overline{f}_3 & 0 & 0 & 0 & 0 \\
  0 & \overline{f}_3 & 0 & 0 & 0 \\
  0 & 0 & \overline{f}_3 & 0 & 0
\end{pmatrix}
\]
\[
\langle \Phi_2 \rangle = \begin{pmatrix}
  0 & 0 & 0 & f_2 & 0 \\
  0 & 0 & 0 & 0 & f_2
\end{pmatrix},
\langle \overline{\Phi}_2 \rangle^T = \begin{pmatrix}
  0 & 0 & 0 & \overline{f}_2 & 0 \\
  0 & 0 & 0 & 0 & \overline{f}_2
\end{pmatrix}.
\]
The gauge couplings for the SM $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group are given by

$$\frac{1}{g_{2,3}^2} = \frac{1}{\hat{g}_{2,3}^2} + \frac{1}{\hat{g}_3^2}, \quad \frac{1}{g_1^2} = \frac{1}{\hat{g}_{1H}^2} + \frac{1}{\hat{g}_{1V}^2} + \frac{1}{15\hat{g}_5^2},$$

$\Phi$ fields split into the following representations under $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\Phi_3 \rightarrow (1, 1, 0) + (8, 1, 0) + (\bar{3}, 2, -1/6)$$
$$\overline{\Phi}_3 \rightarrow (1, 1, 0) + (8, 1, 0) + (3, 2, 1/6)$$
$$\Phi_2 \rightarrow (3, 2, 1/6) + (1, 1, 0) + (1, 3, 0)$$
$$\overline{\Phi}_2 \rightarrow (\bar{3}, 2, -1/6) + (1, 1, 0) + (1, 3, 0)$$

$\overline{\Phi}_3, \Phi_2$ contain fields with same quantum numbers as the left-handed top-bottom doublet.
The masses of the heavy gauge bosons are

\[
m_{G'}^2 = (\hat{g}_3^2 + \hat{g}_5^2)(f_3^2 + \bar{f}_3^2),
\]

\[
m_{W'}^2 = (\hat{g}_2^2 + \hat{g}_5^2)(f_2^2 + \bar{f}_2^2),
\]

\[
m_{\tilde{Q}}^2 = \frac{1}{2}\hat{g}_5^2(f_3^2 + \bar{f}_3^2 + f_2^2 + \bar{f}_2^2). \tag{Spin-1 top partner}
\]

There are 2 massive broken U(1) gauge bosons:

\[
\mathcal{L} \supset \frac{1}{2} \left\{ 6(f_3^2 + \bar{f}_3^2)(\frac{\hat{g}_{1H}}{6}B_{1H} - \frac{\hat{g}_{1V}}{10}B_{1V} - \frac{\hat{g}_5}{\sqrt{15}}B_{24})^2
\right.
\]

\[
+ 4(f_2^2 + \bar{f}_2^2)(\frac{\hat{g}_{1V}}{10}B_{1V} - \frac{\sqrt{15}}{10}\hat{g}_5B_{24})^2 \right\}. \tag{6}
\]

For \[f_2^2 + \bar{f}_2^2 \gg f_3^2 + \bar{f}_3^2,\]

\[
m_{B'}^2 \approx \frac{15\hat{g}_5^2\hat{g}_{1V}^2}{6(\hat{g}_{1V}^2 + 15\hat{g}_5^2)}(f_3^2 + \bar{f}_3^2),
\]

\[
m_{B''}^2 \approx \frac{\hat{g}_{1V}^2 + 15\hat{g}_5^2}{25}(f_2^2 + \bar{f}_2^2).
\]
The Yukawa couplings for the light SM fermions arise from the last 3 terms of the superpotential:

\[ Y_{U_{ij}} Q_i \bar{u}_j \Phi_2 H + Y_{D_{ij}} Q_i \bar{d}_j \Phi_2 \bar{H} + Y_{E_{ij}} L_i \bar{e}_j \Phi_2 \bar{H} \]

They become the usual Yukawa terms after substituting in the VEVs of $\Phi_2$, $\bar{\Phi}_2$.

The fact that they come from nonrenormalizable interactions can explain why they are small.
For the top quark, $Q_3$ and $\bar{u}_3$ mix with other states of the same quantum numbers under SM gauge group

For the (3,2,1/6) sector:

<table>
<thead>
<tr>
<th></th>
<th>$\lambda$</th>
<th>$\Phi_{2t}$</th>
<th>$\bar{\Phi}_{3t}$</th>
<th>$Q_3$</th>
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<td>$\bar{\lambda}$</td>
<td>$M_5$</td>
<td>$\hat{g}_5 f_2$</td>
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<td>$\mu_3$</td>
<td>$y_1 \bar{f}_2$</td>
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<td>$\bar{\Phi}_{2t}$</td>
<td>$\hat{g}_5 \bar{f}_2$</td>
<td>$\mu_2$</td>
<td>0</td>
<td>$y_1 f_3$</td>
</tr>
</tbody>
</table>

For $M_5 \ll \hat{g}_5 f_2$, $\hat{g}_5 f_3 \ll \mu_3 \left(\hat{g}_5 \bar{f}_2\right)$, and $\hat{g}_5 \bar{f}_2 \ll \mu_2$, the left-handed top-bottom state is mostly made of the gaugino. For example, if we take $\bar{f}_2 = 1.5$ TeV, $f_2 = 1.7$ TeV, $\bar{f}_3 = 0.6$ TeV, $f_3 = 0.4$ TeV, $M_5 = 0.7$ TeV, $\mu_2 = 5$ TeV, $\mu_3 = 2$ TeV, $\hat{g}_5 = 1.2$, $y_1 = 1.5$, then

$$Q \equiv (t, b)_L \approx 0.93 \lambda - 0.31 \Phi_{2t} - 0.02 \bar{\Phi}_{3t} - 0.18 Q_3.$$
For the right-handed top quark,

\[
\begin{array}{c|cc}
\bar{T} & \mu_H & y_2 \bar{f}_3 \\
\hline
T & \bar{u}_3 & \\
\end{array}
\]

For \( y_2 \bar{f}_3 \gg \mu_H \), the massless combination is mostly \( \bar{T} \).

For example, if we take \( \mu_H = 0.3 \text{ TeV}, \bar{f}_3 = 0.6 \text{ TeV}, y_2 = 1.5 \), then \( \bar{t}_R = 0.95 \bar{T} - 0.32 \bar{u}_3 \).

The top Yukawa coupling predominantly comes from the gaugino interaction,

\[
\hat{g}_5 H_1^\dagger \lambda \bar{T}
\]

which can explain why it’s order 1.

Note that the top gets its mass mostly from \( H_1 \), which is the same Higgs giving down type quark and lepton masses.
• Even though we unify the right-handed top with Higgs, one can still define a new conserved R-parity which involves a twist $P=(-1,-1,-1,1,1,1)$ in the SU(5) sector.

• Similarly, there is a new baryon number which is a linear combination of the original baryon number and a gauge transformation which stays unbroken.
Electroweak constraints

• The couplings of $W'$, $B'$, and $B''$ to the light SM fermions are suppressed, the $Z'$ constraint is mild, about 800 GeV.

• **The strongest constraint comes from the $T$ parameter** (if $\hat{g}_{1V}$ is large enough to suppress $S$). It depends only on $f_2^2 + \bar{f}_2^2$.
  
  $f_2^2 + \bar{f}_2^2 \gtrsim (3 \text{ TeV})^2$ for a light Higgs
  
  $\gtrsim (2 \text{ TeV})^2$ for a heavier Higgs

• The correction to $Zb_L\bar{b}_L$ coupling requires
  
  $m_{W'} \gtrsim 1.6 \text{ TeV}$.

• It’s still possible to have $m_{\tilde{g}} \lesssim 2 \text{ TeV}$. 
A sample spectrum

For the parameters chosen earlier,

\[ \bar{f}_2 = 1.5 \text{ TeV}, f_2 = 1.7 \text{ TeV}, \bar{f}_3 = 0.6 \text{ TeV}, f_3 = 0.4 \text{ TeV}, \]
\[ M_5 = 0.7 \text{ TeV}, \mu_2 = 5 \text{ TeV}, \mu_3 = 2 \text{ TeV}, \mu_H = 0.3 \text{ TeV}, \]
\[ \hat{g}_5 = 1.2, y_1 = 1.5, y_2 = 1.5, \hat{g}_{1V} = 3.5, \]
and \( \hat{g}_3 = 2.0, \hat{g}_2 = 0.75, \hat{g}_{1H} = 0.36 \) at \( \sim 2 \text{ TeV} \)

<table>
<thead>
<tr>
<th>( G' )</th>
<th>( W' )</th>
<th>( B' )</th>
<th>( B'' )</th>
<th>( \tilde{Q} )</th>
<th>( Q' )</th>
<th>( Q'' )</th>
<th>( Q''' )</th>
<th>( \bar{T}' )</th>
</tr>
</thead>
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<tr>
<td>( M/\text{TeV} )</td>
<td>1.7</td>
<td>3.2</td>
<td>0.83</td>
<td>2.6</td>
<td>2.0</td>
<td>0.65</td>
<td>3.0</td>
<td>5.8</td>
</tr>
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</table>
Superpartner spectrum

- Phenomenology will depend on the spectrum of other superpartners.
- The superpartners of the light fermions can have multi-TeV masses without affecting the naturalness.
- The soft-SUSY-breaking masses of $\Phi_{2,3}$, $\bar{\Phi}_{2,3}$ are likely to be in multi-TeV range too.
- The Soft masses of $H$ and $\bar{H}$ and gaugino masses are relevant for stabilizing the EW scale. They should be at $\sim 1$ TeV or below.
Phenomenology

• We assume that all soft-SUSY-breaking scalar masses except those of $H$ and $\bar{H}$ are large, then the corresponding superpartners are beyond the reach of the LHC.

• With this assumption, the superpartners of the SM particles that are accessible at the LHC are the spin-1 partner of the left-handed top-bottom doublet, the scalar partner of the right-handed top, gauginos of the SM gauge group, and Higgsinos.

• We may also see some of the new heavy gauge bosons, $t'$, $b'$ and their superpartners
Phenomenology

- For the spin-1 top partner, the main production mechanism is $GG \rightarrow Q\bar{Q}^*$. The processes with $q\bar{q}$ initial states are suppressed by destructive interference between $G$ and $G'$ exchanges.

The spin-1 top partner has a much larger cross-section than that of the usual scalar top partner.
Conclusion

• We have shown the possibility that the top partner can have spin-1.
  - It requires an extended gauge symmetry.
  - The top Yukawa coupling comes from the gaugino coupling and it can explains why one quark is much heavier than the others.

• The spin-1 top partner has a much larger production cross section for the same mass compared with the stop. However, a direct measurement of spin is not easy at LHC.