A Spin-1 Top Partner

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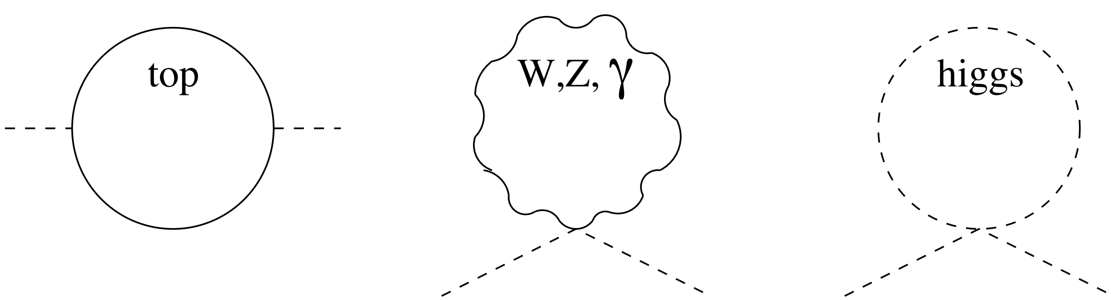
Introduction

- 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.



top loop	$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$
$SU(2)$ gauge boson loops	$\frac{9}{64\pi^2}g^2\Lambda^2$
Higgs loop	$\frac{1}{16\pi^2}\lambda^2\Lambda^2$

Introduction

- These contributions need to be cut off at scales not much higher than the EW symmetry breaking scale so the the EW scale is stable.
- For no more than ~10% fine-tuning, it requires that

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

- 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

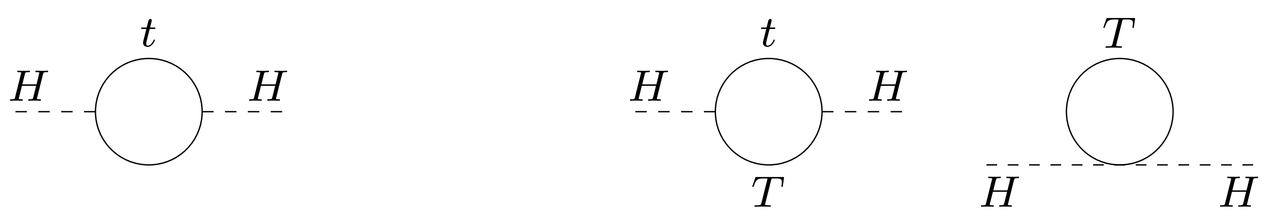
- Supersymmetry: SUSY is still the most popular candidate for new physics at the TeV scale.
  - In MSSM, there is a superpartner for each SM particle with opposite spin-statistics.
  - The quadratic radiative corrections are cancelled between fermions and bosons.
  - The superpartners of the top are scalar particles in MSSM, and they are required to be around ~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 Z_2 symmetry.

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

  - Mirror (twin) model: SM_A x SM_B x Z_2

    Top sector: $\mathcal{L} = y_t H_A q_L^A t_R^A + y_t H_B q_L^B t_R^B + \mathrm{h.c}$

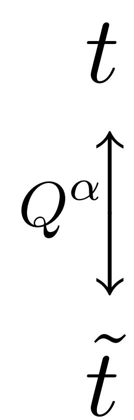
    Top loop is canceled by the mirror top charged under the mirror gauge group => difficult to find at LHC.

  - Left-right model: $SU(2)_L$ x $SU(2)_R$ x $U(1)_{B-L}$

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



  - UV theory requires SUSY breaking by 5D orbifold.
  - Exotic (string) phenomenology associated with the new particle.

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$$
\begin{array}{ccc}
t & \overset{Z_2}{\longleftrightarrow} & t' \\
Q^\alpha \big\updownarrow & & \big\updownarrow Q^\alpha \\
\tilde{t} & \underset{Z_2}{\longleftrightarrow} & \tilde{t}'
\end{array}
$$

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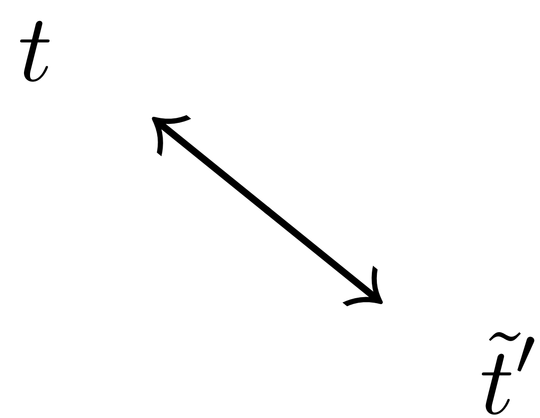

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Other possibilities?

- 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

	$SU(3)$	$SU(2)$	$U(1)_H$	$U(1)_V$	$SU(5)$	$H+V+aT_{24}$
Q_i	$\Box$	$\Box$	$\frac{1}{6}$	0	$\mathbf{1}$	$\frac{1}{6}$
$\overline{u}_i$	$\overline{\Box}$	$\mathbf{1}$	$-\frac{2}{3}$	0	$\mathbf{1}$	$-\frac{2}{3}$
$\overline{d}_i$	$\overline{\Box}$	$\mathbf{1}$	$\frac{1}{3}$	0	$\mathbf{1}$	$\frac{1}{3}$
L_i	$\mathbf{1}$	$\Box$	$-\frac{1}{2}$	0	$\mathbf{1}$	$-\frac{1}{2}$
$\overline{e}_i$	$\mathbf{1}$	$\mathbf{1}$	1	0	$\mathbf{1}$	1
H	$\mathbf{1}$	$\mathbf{1}$	$\frac{1}{2}$	$\frac{1}{10}$	$\Box$	$(\frac{2}{3}, \frac{1}{2})$
$\overline{H}$	$\mathbf{1}$	$\mathbf{1}$	$-\frac{1}{2}$	$-\frac{1}{10}$	$\overline{\Box}$	$(-\frac{2}{3}, -\frac{1}{2})$
Φ_3	$\overline{\Box}$	$\mathbf{1}$	$-\frac{1}{6}$	$\frac{1}{10}$	$\Box$	$(0, -\frac{1}{6})$
Φ_2	$\mathbf{1}$	$\overline{\Box}$	0	$\frac{1}{10}$	$\Box$	$(\frac{1}{6}, 0)$
$\overline{\Phi}_3$	$\Box$	$\mathbf{1}$	$\frac{1}{6}$	$-\frac{1}{10}$	$\overline{\Box}$	$(0, \frac{1}{6})$
$\overline{\Phi}_2$	$\mathbf{1}$	$\Box$	0	$-\frac{1}{10}$	$\overline{\Box}$	$(-\frac{1}{6}, 0)$

$$H+V+aT_{24} = Y, \quad a = 1/\sqrt{15}$$

$$H = (\overline{T}^c, H_2).$$

$$\overline{H} = (\overline{T}, H_1),$$

The superpotential is given by

$$\begin{aligned} W &= y_1 Q_3 \Phi_3 \overline{\Phi}_2 + \mu_3 \Phi_3 \overline{\Phi}_3 + \mu_2 \Phi_2 \overline{\Phi}_2 \\ &+ y_2 \overline{u}_3 H \overline{\Phi}_3 + \mu_H H \overline{H} + Y_{Uij}\, Q_i\, \overline{u}_j\, \overline{\Phi}_2 H \\ &+ Y_{Dij}\, Q_i\, \overline{d}_j \Phi_2 \overline{H} + Y_{Eij}\, L_i\, \overline{e}_j \Phi_2 \overline{H}. \end{aligned}$$

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 Φ_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

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

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

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

$\overline{\Phi}_3$, Φ_2 contain fields with same quantum numbers as the left-handed top-bottom doublet.

The masses of the heavy gauge bosons are

$$
\begin{aligned}
m_{G'}^2 &= (\hat{g}_3^2 + \hat{g}_5^2)(f_3^2 + \bar{f}_3^2), \\
m_{W'}^2 &= (\hat{g}_2^2 + \hat{g}_5^2)(f_2^2 + \bar{f}_2^2), \\
m_{\vec{Q}}^2 &= \frac{1}{2}\hat{g}_5^2(f_3^2 + \bar{f}_3^2 + f_2^2 + \bar{f}_2^2).
\end{aligned}
$$

Spin-1 top partner

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

$$
\begin{aligned}
\mathcal{L} \supset \quad & \frac{1}{2}\Big\{6(f_3^2 + \bar{f}_3^2)(\frac{\hat{g}_{1H}}{6}B_{1H} - \frac{\hat{g}_{1V}}{10}B_{1V} - \frac{\hat{g}_5}{\sqrt{15}}B_{24})^2 \\
& +4(f_2^2 + \bar{f}_2^2)(\frac{\hat{g}_{1V}}{10}B_{1V} - \frac{\sqrt{15}}{10}\hat{g}_5 B_{24})^2\Big\}. \qquad (6)
\end{aligned}
$$

For $f_2^2 + \bar{f}_2^2 \gg f_3^3 + \bar{f}_3^2$,

$$
\begin{aligned}
m_{B'}^2 &\approx \frac{15\hat{g}_5^2\hat{g}_{1V}^2}{6(\hat{g}_{1V}^2 + 15\hat{g}_5^2)}(f_3^2 + \bar{f}_3^2), \\
m_{B''}^2 &\approx \frac{\hat{g}_{1V}^2 + 15\hat{g}_5^2}{25}(f_2^2 + \hat{f}_2^2).
\end{aligned}
$$

The Yukawa couplings for the light SM fermions arise from the last 3 terms of the superpotential:

$$Y_{Uij}Q_i\overline{u}_j\overline{\Phi}_2 H + Y_{Dij}Q_i\overline{d}_j\Phi_2\overline{H} + Y_{Eij}L_i\overline{e}_j\Phi_2\overline{H}$$

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

The fact that they come from nonrenormalizable interactions can explain why they are small.

For the top quark, Q_3 and $\overline{u}_3$ mix with other states of the same quantum numbers under SM gauge group

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

	λ	Φ_{2t}	$\overline{\Phi}_{3t}$	Q_3
$\bar{\lambda}$	M_5	$\hat{g}_5 f_2$	$\hat{g}_5 \bar{f}_3$	0
Φ_{3t}	$\hat{g}_5 f_3$	0	μ_3	$y_1 \bar{f}_2$
$\overline{\Phi}_{2t}$	$\hat{g}_5 \bar{f}_2$	μ_2	0	$y_1 f_3$

,

For $\bar{M}_5 \ll \hat{g}_5 f_2,\ \hat{g}_5 f_3 \ll \mu_3\,(\hat{g}_5 \bar{f}_2)$, 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 $\bar{f}_2 = 1.5\,\mathrm{TeV}$ $f_2 = 1.7\,\mathrm{TeV}, \bar{f}_3 = 0.6\,\mathrm{TeV}, f_3 = 0.4\,\mathrm{TeV}, M_5 = 0.7\,\mathrm{TeV},$ $\mu_2 = 5\,\mathrm{TeV}, \mu_3 = 2\,\mathrm{TeV}, \hat{g}_5 = 1.2, y_1 = 1.5,$ then

$$Q \equiv (t,\, b)_L \approx 0.93\lambda - 0.31\Phi_{2t} - 0.02\overline{\Phi}_{3t} - 0.18Q_3.$$

For the right-handed top quark,

	$\overline{T}$	$\overline{u}_3$
$\overline{T}^c$	μ_H	$y_2 \bar{f}_3.$

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

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

The top Yukawa coupling predominantly comes from the gaugino interaction,

$$\hat{g}_5 H_1^\dagger \lambda \overline{T}$$

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.

- There can be a large tree-level correction, $\propto \hat{g}_5^2$, to the Higgs quartic coupling after integrating out heavy states. For $\bar{f}_{2,3}/f_{2,3} \sim \mathcal{O}(1)$ and large $B\mu_{2,3}$ terms, the Higgs can be significantly heavier.
- 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) 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 $f_2^2 + \bar{f}_2^2$.

$$\begin{aligned} f_2^2 + \bar{f}_2^2 &\gtrsim (3\,\mathrm{TeV})^2 \text{ for a light Higgs} \\ &\gtrsim (2\,\mathrm{TeV})^2 \text{ for a heavier Higgs} \end{aligned}$$

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

- It still possible to have $m_{\vec{Q}} \lesssim 2\,\mathrm{TeV}$.

A sample spectrum

For the parameters chosen earlier,

$$\bar{f}_2 = 1.5\,\mathrm{TeV}, f_2 = 1.7\,\mathrm{TeV}, \bar{f}_3 = 0.6\,\mathrm{TeV}, f_3 = 0.4\,\mathrm{TeV},$$

$$M_5 = 0.7\,\mathrm{TeV}, \mu_2 = 5\,\mathrm{TeV}, \mu_3 = 2\,\mathrm{TeV}, \mu_H = 0.3\,\mathrm{TeV},$$

$$\hat{g}_5 = 1.2, y_1 = 1.5, y_2 = 1.5, \hat{g}_{1V} = 3.5,$$

$$\text{and } \hat{g}_3 = 2.0, \hat{g}_2 = 0.75, \hat{g}_{1H} = 0.36 \text{ at } \sim 2\,\mathrm{TeV}$$

	G'	W'	B'	B''	$\vec{Q}$	Q'	Q''	Q'''	$\overline{T}'$
M/TeV	1.7	3.2	0.83	2.6	2.0	0.65	3.0	5.8	0.95

Superpartner spectrum

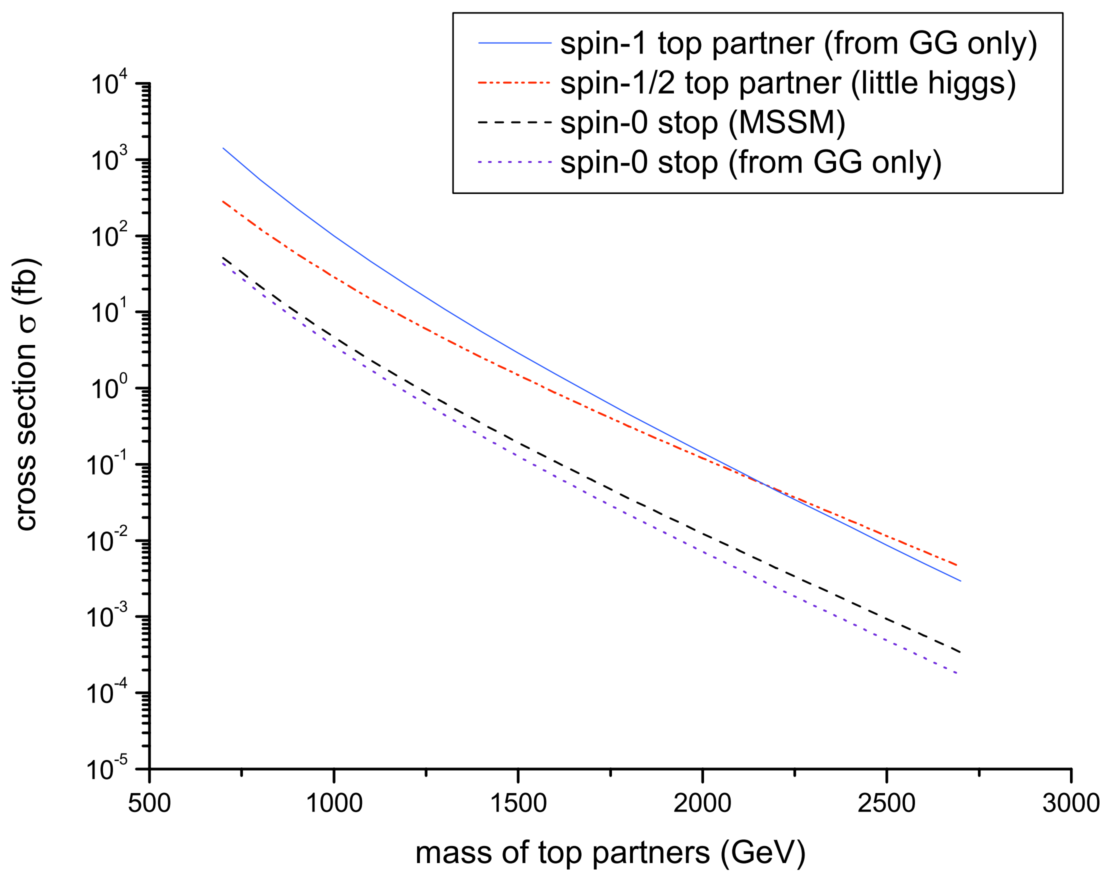
- Phenomenology will depends on the spectrum of other superpartners.
- The superpartners of the light fermions can have multi-TeV masses without affecting the naturalness.
- The soft-SUSY-breaking masses of $\Phi_{2,3},\ \overline{\Phi}_{2,3}$ are likely to be in multi-TeV range too.
- The Soft masses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

Phenomenology

- We assume that all soft-SUSY-breaking scalar masses except those of H and $\overline{H}$ 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 $GG \to \vec{Q}\vec{Q}^*$. 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.
- A large Higgs quartic coupling and hence a much heavier Higgs is possible in this model.
- 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.