Folded Supersymmetry as a Neutral Natural solution to the Hierarchy Problem of the Standard Model

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Outline

1. The Hierarchy Problem
2. Supersymmetric Solution
3. Folded Supersymmetry
4. Conclusions

The hierarchy problem

The Standard Model Higgs potential is given by:

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \tag{1}$$

Minimizing this potential we find:

$$\text{Electroweak VEV} \;\Rightarrow\; v^2 = \frac{m^2}{2\lambda} \approx 246\,\text{GeV} \tag{2}$$

$$\text{Higgs boson mass} \;\Rightarrow m^2 = 2\mu^2 \approx 125\,\text{GeV} \tag{3}$$

The physical value m^2_{phys} is given by

$$m^2_{phys} = m^2 + \delta m^2 \tag{4}$$

$$\text{Fine tuning: } \frac{m^2_{phys}}{\delta m^2} \times 100\% \tag{5}$$

The hierarchy problem

Assume the Standard Model is valid up to a energy Λ (cutoff).

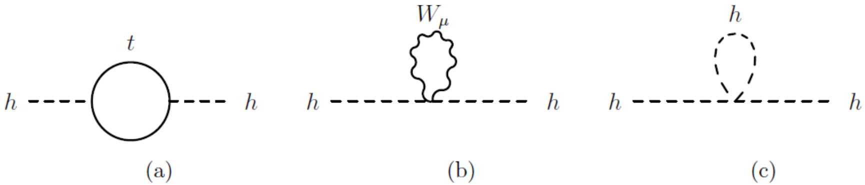


Figure 1: One loop contributions to the Higgs mass parameter due to (a) top quark, (b) gauge boson and (c) Higgs self-interactions.

$$(a)\ -\frac{3}{8\pi^2}y_t^2\Lambda^2 \sim -(2000\text{GeV})^2, \qquad (b)\ \frac{1}{16\pi^2}g_2\Lambda^2 \sim (700\text{GeV})^2$$

$$(c)\ \frac{1}{16\pi^2}\lambda\Lambda^2 \sim (500\text{GeV})^2$$

for $\Lambda = 10$ TeV.

$$m_{\text{phy}}^2 \approx m_{\text{bare}}^2 - (100 - 10 - 5)(200\,GeV)^2 \tag{6}$$

Fine tuning of 1%.

The Minimal Supersymmetric Standard Model (MSSM)

Names		Spin-0	Spin-1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
sleptons, leptons	L_I	$\tilde{l}_I = \begin{pmatrix} \tilde{\nu}_{IL} \\ \tilde{l}_{IL} \end{pmatrix}$	$l_I = \begin{pmatrix} \nu_{IL} \\ l_{IL} \end{pmatrix}$	**1**, **2**, -1/2
	E_I	$\tilde{e}_I$	$e_I \equiv (e_{IR})^c$	**1**, **1**, 1
squarks, quarks	Q_I	$\tilde{q}_I = \begin{pmatrix} \tilde{u}_{IL} \\ \tilde{d}_{IL} \end{pmatrix}$	$q_I = \begin{pmatrix} u_{IL} \\ d_{IL} \end{pmatrix}$	**3**, **2**, 1/6
	U_I	$\tilde{u}_I$	$u_I \equiv (u_{IR})^c$	$\bar{\mathbf{3}}$, **1**, -2/3
	D_I	$\tilde{d}_I$	$d_I \equiv (d_{IR})^c$	$\bar{\mathbf{3}}$, **1**, 1/3
Higgs, higgsinos	H_U	$h_U = \begin{pmatrix} h_U^+ \\ h_U^0 \end{pmatrix}$	$\tilde{h}_U = \begin{pmatrix} \tilde{h}_U^+ \\ \tilde{h}_U^0 \end{pmatrix}$	**1**, **2**, 1/2
	H_D	$h_D = \begin{pmatrix} h_D^0 \\ h_D^- \end{pmatrix}$	$\tilde{h}_D = \begin{pmatrix} \tilde{h}_D^0 \\ \tilde{h}_D^- \end{pmatrix}$	**1**, **2**, -1/2

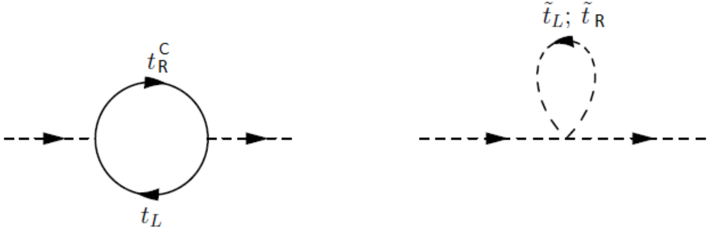
Figure 2: Chiral supermultiplet fields in the MSSM with corresponding transformations under the gauge group. The index I runs from 1 to 3 and denotes each of the three families of particles.

Cancellation of the top loop contribution in the MSSM

- Superpotential:

$$W_{MSSM} = y_u^{IJ} U_I Q_J \cdot H_U - y_d^{IJ} D_I Q_J \cdot H_D - y_e^{IJ} E_I L_J \cdot H_D + \mu H_U \cdot H_D. \quad (7)$$

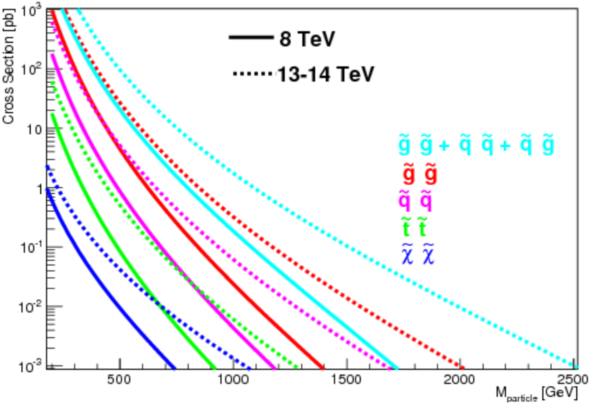
$$\Rightarrow \mathcal{L}_{MSSM} \supset -y_t \left[t_R^C t_L h_U^0 + h.c. \right] - y_t^2 \left| \tilde{t}_L h_U^0 \right|^2 - y_t^2 \left| \tilde{t}_R h_U^0 \right|^2 \quad (8)$$



- Stops have the same quantum numbers as the top particle.
- Coupling parameters are related by supersymmetry.

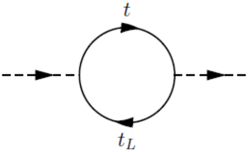
Neutral Naturalness

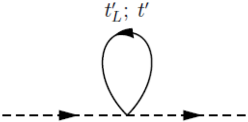
- Colored top partners are easier to produce at the LHC. However, none of them were detected, so far.
- In theories with "Neutral Naturalness", the top partners are uncolored and their cross sections are suppressed.



Andrea Ventura, Int. J. Mod. Phys. Conf. Ser., 46, 1860006 (2018)

Cancellation of quadratic divergences in Little Higgs and twin Higgs models





- Little Higgs: Top partners are fermions with the same quantum numbers as the top quark. Interactions parameters are related by a global symmetry.

  N. Arkani-Hamed, A. G. Cohen and H. Georgi, Phys. Lett. B 513, 232 (2001) [arXiv:hep-ph/ 0105239].

- Twin Higgs: Top partners are also fermions but they do not have necessarily the same quantum numbers. Interaction parameters are related by a discrete symmetry.

  Z. Chacko, H. S. Goh and R. Harnik, JHEP 0601, 108 (2006) [hep-ph/0512088].

Question:
Is it possible to construct theories where the quadratic divergence from the top loop is canceled by diagrams similar to the supersymmetric case where the top partners are neutral under *SM* color?

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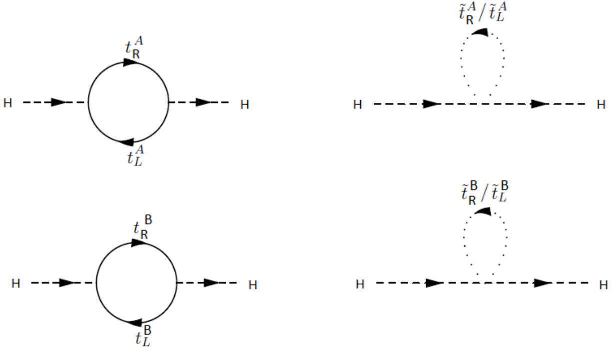
G. Burdman, Z. Chacko, H-S Goh and R. Harnik in 2006. *Folded Supersymmetry and the LEP paradox*. JHEP 0702 (2007) 009. arXiv:hep-ph/0609152.

Toy Model

1. Supersymmetrize.
2. Enlarge the symmetry in order for the theory to enjoy bifold protection.
3. Project out the states odd under the combined $Z_{2\Gamma} \times Z_{2R}$ discrete symmetry.



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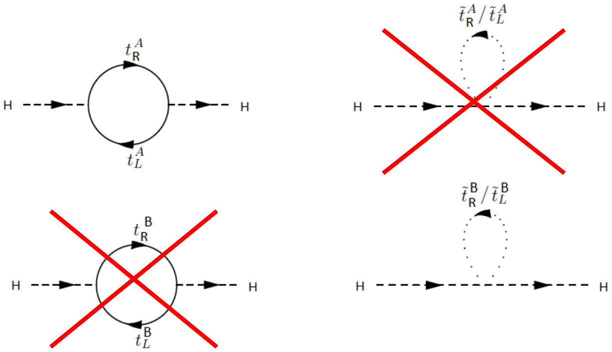

Application to the Standard Model Yukawa term

- In the SM, the top Yukawa terms are:

$$\mathcal{L}_{SM} \supset -y_t \left(\bar{q}_3 \tilde{H} u_3 + \bar{u}_3 \tilde{H}^\dagger q_3 \right). \tag{9}$$

- Supersymmetrization implies

$$W_{MSSM} \supset y_t Q_3^\alpha \cdot H_U U_3^\alpha, \tag{10}$$

where fields transform as

$$Q_3(\mathbf{3},\mathbf{2}), \qquad H_U(\mathbf{1},\mathbf{2}), \qquad U_3(\bar{\mathbf{3}},\mathbf{1}). \tag{11}$$

under the $SU(3)_C \times SU(2)_L$ local group.

- The supersymmetric Lagrangian contains

$$\begin{aligned} \mathcal{L} \supset & - y_t \left[\tilde{u}_3^\alpha q_3^\alpha \cdot \tilde{h}_u + \tilde{q}_3^\alpha \cdot \tilde{h}_u u_3^\alpha + h_u \cdot q_3^\alpha u_3^\alpha + \text{h.c.} \right] \\ & - y_t^2 \left[|\tilde{q}_3 \cdot h_u|^2 + |h_u|^2 |\tilde{u}_3|^2 + |\tilde{q}_3|^2 |\tilde{u}_3|^2 \right]. \end{aligned} \tag{12}$$

- We will enlarge the symmetry from $SU(3) \times SU(2)$ to $SU(6) \times SU(2)$. The superpotential will contain

$$W_{MSSM} \supset y_t Q_3^\alpha \cdot H_U U_3^\alpha, \tag{13}$$

but now the fields transform as

$$Q_3(\mathbf{6}, \mathbf{2}), \quad H_U(\mathbf{1}, \mathbf{2}), \quad U_3(\bar{\mathbf{6}}, \mathbf{1}). \tag{14}$$

under the $SU(6) \times SU(2)$ local group.

  - Q_3 contains, in addition to the three color states of the SM, three new states charged under $SU(2)_L$ and $U(1)_Y$ but not under $SU(3)_C$ of the SM.
  - U_3 contains, in addition to the 3 color states of the SM, three exotic states charged under $U(1)_Y$ but not under SM color.

These new fields are called *Folded partners* (or *F-partners*, for short) of the corresponding MSSM fields.

- Under the combined symmetry $Z_{2\Gamma} \times Z_{2R}$, fields transform as

$$\tilde{q}_3 = \begin{pmatrix} \tilde{q}_A(-) \\ \tilde{q}_B(+) \end{pmatrix}, \qquad q_3 = \begin{pmatrix} q_A(+) \\ q_B(-) \end{pmatrix}, \tag{15}$$

$$\tilde{u}_3 = \begin{pmatrix} \tilde{u}_A(-) \\ \tilde{u}_B(+) \end{pmatrix}, \qquad u_3 = \begin{pmatrix} u_A(+) \\ u_B(-) \end{pmatrix}, \tag{16}$$

$$h_u(+), \qquad \tilde{h}_u(-), \tag{17}$$

- Orbifolding out the odd states:

$$\mathcal{L} \supset -y_t \left[h_u \cdot q_A^\alpha u_A^\alpha + \text{h.c.}\right] - y_t^2 \left[|\tilde{q}_B \cdot h_u|^2 + |h_u|^2 |\tilde{u}_B|^2 + |\tilde{q}_B|^2 |\tilde{u}_B|^2\right] \tag{18}$$

Conclusions

- One loop divergent contributions to the mass of h_u cancel out. Furthermore, we note that the fermionic loop with fields charged under $SU(3)$ SM color is canceling out with bosonic loops not charged under $SU(3)$ SM color but under another $SU(3)$ hidden color group.
- Since the fields $\tilde{q}_B$ and $\tilde{u}_B$ do not couple to fermionic fields, quadratically divergent contribution to their masses will not cancel. Then, radiative stability of the mass of h_u is not guaranteed to orders higher than one.
- A UV completion is needed in order to set the values of the parameters at high scale. This can be done by embedding the fields in a 5 dimensional space-time and applying suitable boundary conditions.