A Fat Top for the Fat Higgs

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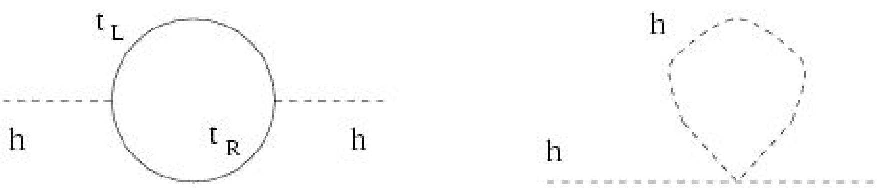
Outline

- Introduction: the SUSY little hierarchy problem
- The Fat Higgs
- A Fat Top too?
- Phenomenology & Signatures
- Conclusions

Minimal Supersymmetric Standard Model

Hierarchy Problem

The Higgs mass is quadratically sensitive to heavy physics:

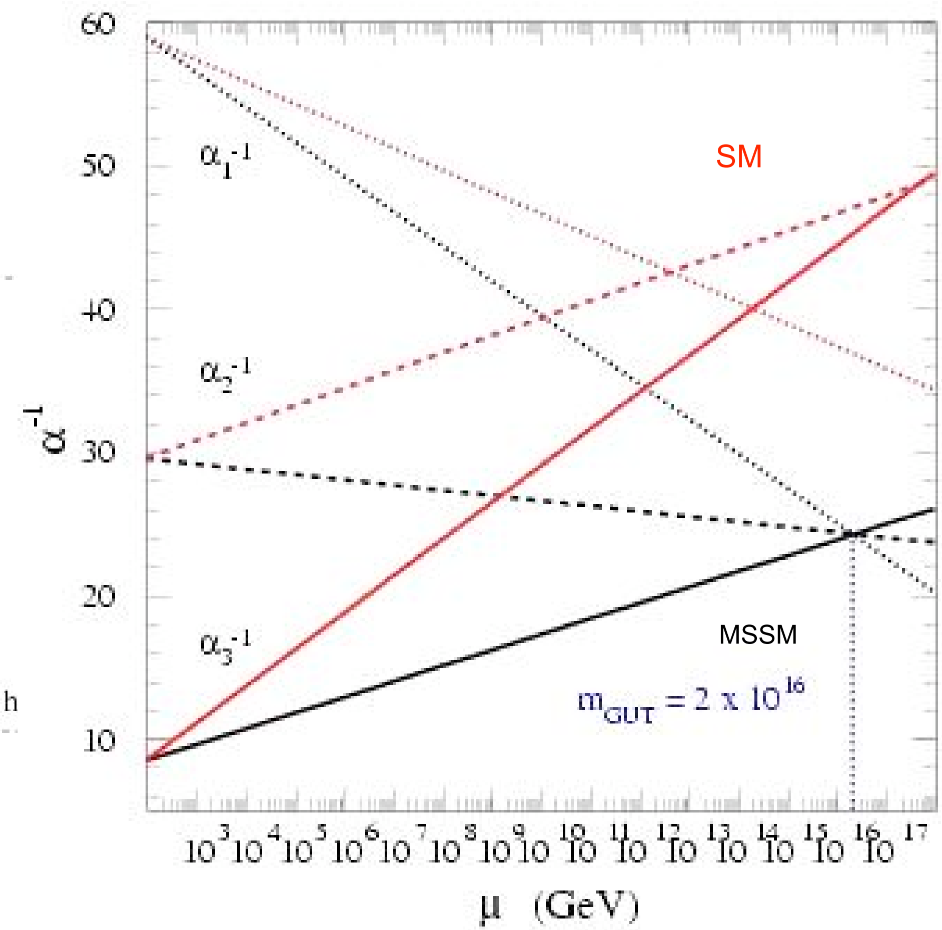


$$\delta m^2 = \frac{g^2}{16\pi^2}\Lambda^2 + \ldots$$

SUSY stabilizes the hierarchy:

$$\delta m_\Phi^2 = \frac{g^2}{16\pi^2} M^2 \log\left[\frac{\Lambda}{M}\right] + \ldots$$

Grand Unification



SUSY Light Higgs Mass

- In the SM, the Higgs quartic λ is a free parameter. The physical Higgs mass is $m_h^2 = \lambda\, v^2$.
- Remarkably, in the MSSM λ is not a free parameter:

$$\lambda^2 = g_W^2 + g_Y^2$$

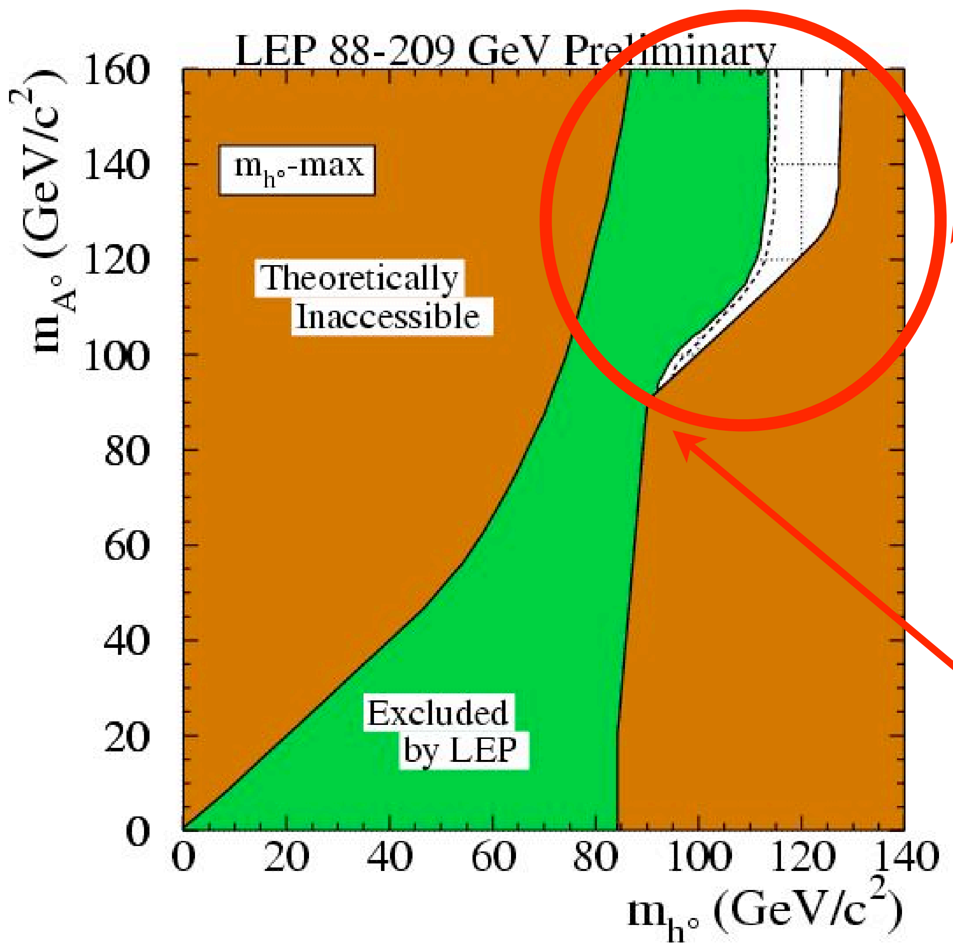
- This results in a tree-level prediction for m_h:

$$m_h^2 = \lambda v^2 \cos^2 2\beta \leq M_Z^2$$

- This is corrected at one-loop by top/stop:

$$\delta m_h^2 = \frac{3 m_t^4}{8\pi^2 v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \text{stop mixing}\right]$$

LEP II



- LEP II rules out

  $m_h^{(SM)} \leq$ 115 GeV

- The boundary on the right is the MSSM upper limit, assuming M~1 TeV and maximal stop mixing.
- The dashed curves are hypothetical exclusions assuming only SM backgrounds.
- The MSSM lives in the white sliver.

SUSY Little Hierarchy Problem

- This is the "SUSY Little Hierarchy Problem".
- mh is consistent with LEP-II only if stops are heavy:

$$\delta m_h^2 = \frac{3m_t^4}{8\pi^2 v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \text{stop mixing}\right]$$

- But this contributes to the soft mass, destabilizing the weak scale:

$$\delta m_\Phi^2 = \frac{-12 y_t^2}{16\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda^2}{m_{\tilde{t}}^2}$$

- To arrange for v, one fine-tunes μ to the % level:

$$\frac{1}{2}m_Z^2 = -\mu^2 - \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{\tan^2\beta - 1}$$

- Unlike the usual MSSM problems (i.e. flavor), this has nothing to do with SUSY breaking. It is an aspect of the MSSM itself.

What do we do?

1. Accept that the MSSM is tuned at the % level.

2. Give up and build Little Higgs theories instead.

3. Try to reduce the fine-tuning by mixing SUSY with Little Higgs, RS, technicolor...

4. **Extend the MSSM Higgs sector to increase the Higgs mass at tree level.**

NMSSM

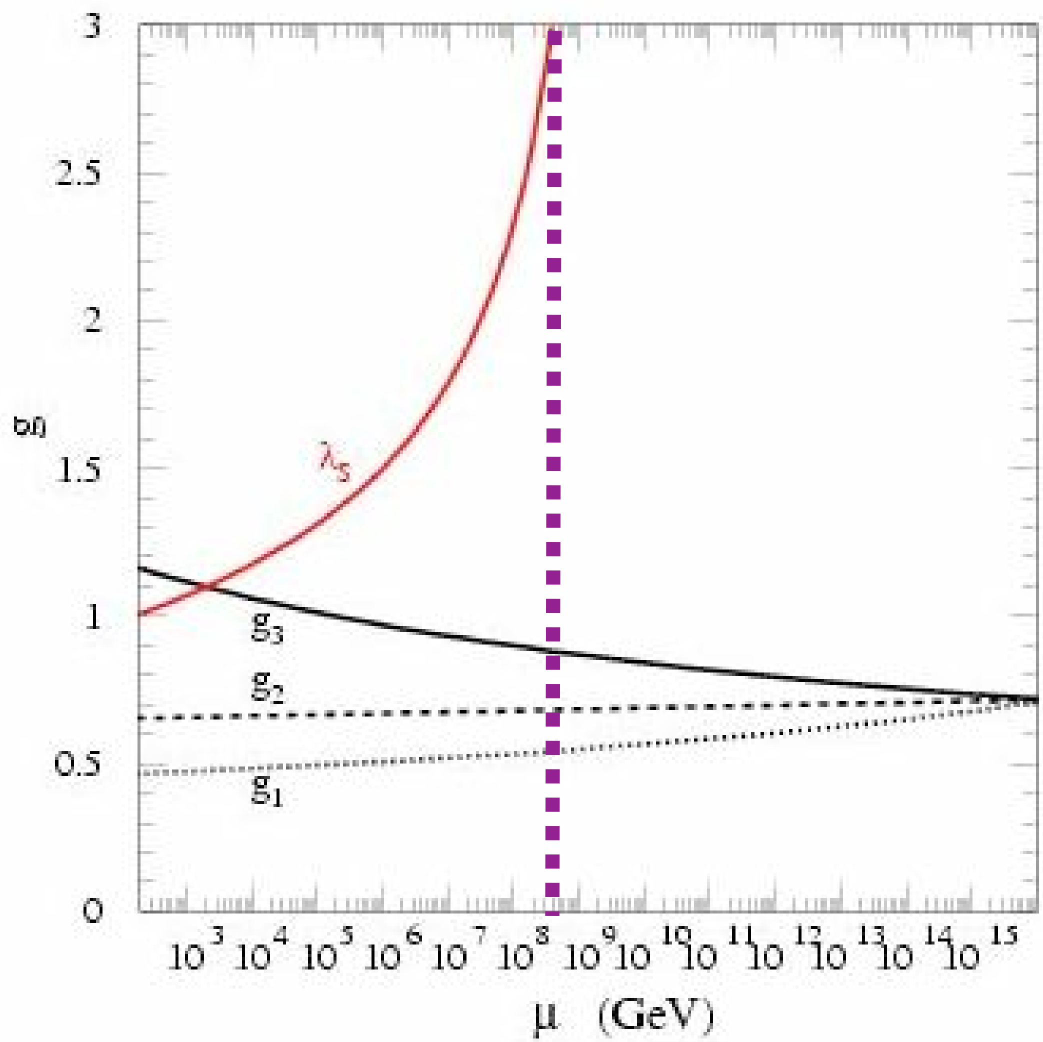
- One way to increase the Higgs mass is to consider the Next to Minimal Supersymmetric Standard Model.
- We add a singlet S with super-potential:

$$W = \lambda_S S H_u H_d + \ldots$$

- λ is now a free parameter.
- The effective quartic is:

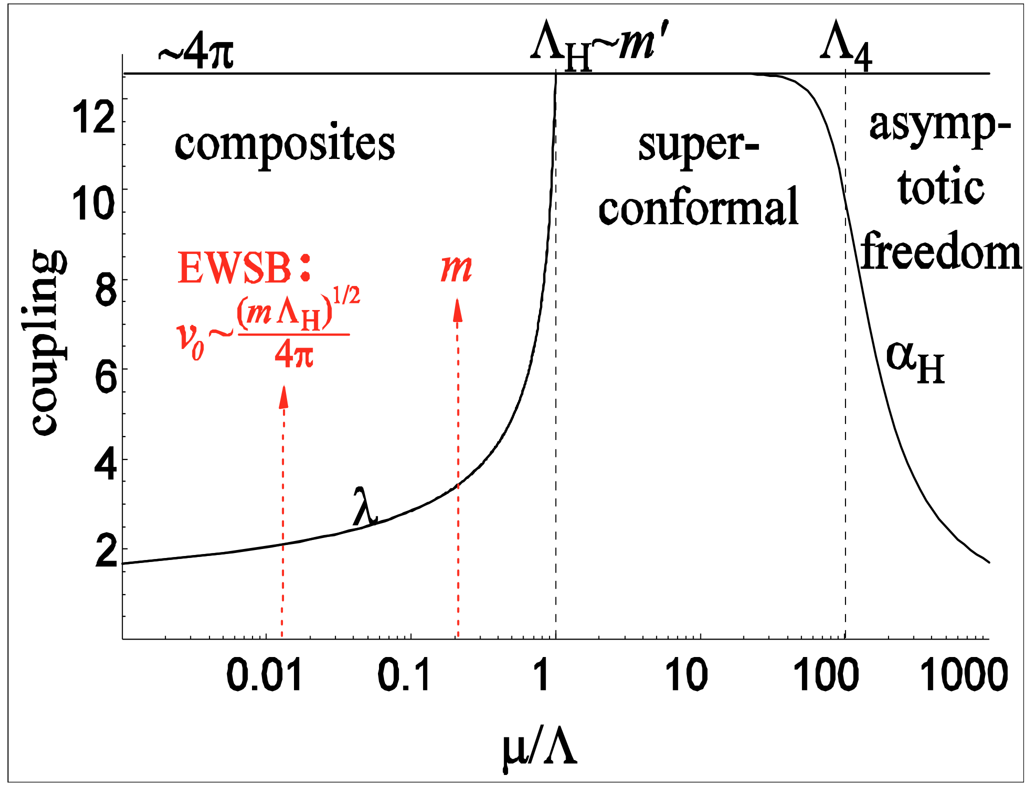
$$\lambda^2 = g_W^2 + g_Y^2 + \lambda_S^2 \tan^2 2\beta$$

- Howevers, λ blows up in the UV, and perturbativity to the GUT scale implies that mh is less than about 150 GeV.
- Or, m_h can be larger provided there is new physics at some intermediate scale.



Fat Higgs

- The Fat Higgs interprets the Landau pole as a compositeness scale.
- The theory is NMSSM-like below the compositeness scale, with the Higgses a set of composite fields resulting from a confining SUSY SU(2) gauge theory.
- The Higgs quartic is part of the dynamical super-potential generated by the SU(2) confining dynamics. It is analogous to the pion-nucleon interaction of ordinary QCD.
- The electroweak symmetry is broken even in the supersymmetric limit because the singlet field has a tadpole:

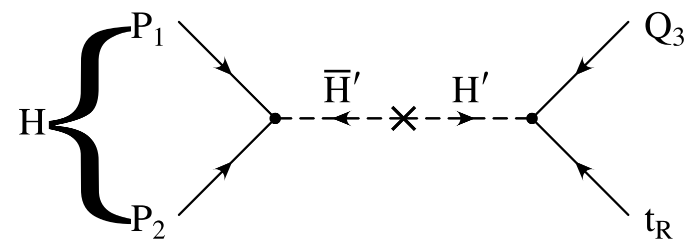


Harnik, Kribs, Larson, Murayama, hep-ph/0311349

$$W = \lambda N \left(H_u H_d - v_0^2 \right)$$

Top Yukawa

- The large top Yukawa is a challenge for the Fat Higgs.
- The top (and all of the fermions) is a fundamental object, and it must couple to the Higgs through higher dimensional operators, because the Higgs is composite.
- The original Fat Higgs induces such a coupling by integrating out a vector-like pair of "spectator Higgses".
- For a light fermion mass, this works fine. Small effective Yukawa interactions are naturally explained for weak couplings and large masses of the spectator Higgses.
- For the top quark, this is problematic. The couplings y and y' must be very strong in order to reproduce the observed top mass. Such strong couplings at best require strange tunings of in principle unrelated quantities. At worst, they could disturb the solution of the strong SU(2) confinement, and cast doubts on the analysis of the spectrum and dynamically induced couplings.



$$y_{eff} \sim \frac{yy'}{4\pi}\frac{\Lambda}{M_H}$$

A variation has fundamental H's, but a fat N field. There is no problem with the top Yukawa coupling, but the NMSSM-like term must be induced through a higher-dimensional operator, just as yt was in the original model.

Chang, Kilic, Mahbubani PRD71:015003,2005 [hep-ph/0405267]

A Fat Top!

- An obvious solution would be to have the top result from the same confining dynamics that produced the Higgs.

- The top Yukawa would then be part of the dynamical super-potential, and we would expect it to be large at the confinement scale.

- (Of course, it will be driven toward the quasi-IR fixed point at lower energies).

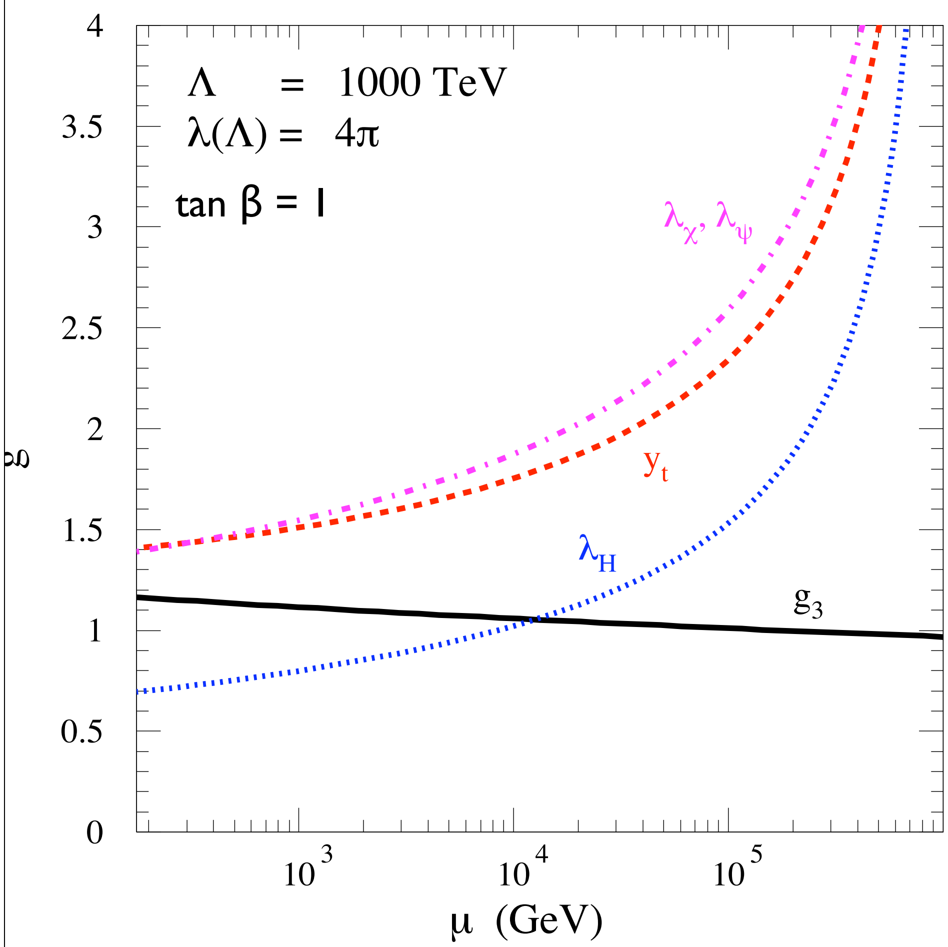
- We expand the confining gauge group to SU(3), and charge the *preons* under the MSSM gauge groups such that the Higgses, singlet, and left- and right-handed top quark are among the composite spectrum.

- The composites include all of the desired fields, as well as some new exotic states not present in the MSSM. Some get masses only through EWSB and should be light (~200 GeV).

	$SU(3)_s$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Z_2
P_3	$\square$	$\square$	$\mathbf{1}$	0	$+$
P_1	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-2/3$	$-$
$\overline{P}_2$	$\overline{\square}$	$\mathbf{1}$	$\square$	$+1/6$	$-$
$\overline{P}_1$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$+2/3$	$+$
$\overline{P}_{\tilde{1}}$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	$-$
P'	$\square$	$\mathbf{1}$	$\mathbf{1}$	$+1/3$	$-$
$\overline{P}'$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	$-$

		$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Z_2
$B_1 \leftrightarrow t_R$	$P_3P_3P_1$	$\overline{\square}$	$\mathbf{1}$	$-2/3$	$-$
$B_2 \leftrightarrow S$	$P_3P_3P_3$	$\mathbf{1}$	$\mathbf{1}$	0	$+$
$\overline{B}_1 \leftrightarrow H$	$\overline{P}_2\overline{P}_1\overline{P}_{\tilde{1}}$	$\mathbf{1}$	$\square$	$+1/2$	$+$
$\overline{B}_2 \leftrightarrow \psi$	$\overline{P}_2\overline{P}_2\overline{P}_1$	$\mathbf{1}$	$\mathbf{1}$	$+1$	$+$
$\overline{B}_3 \leftrightarrow \chi$	$\overline{P}_2\overline{P}_2\overline{P}_{\tilde{1}}$	$\mathbf{1}$	$\mathbf{1}$	0	$-$
$M_1 \leftrightarrow Q_3$	$P_3\overline{P}_2$	$\square$	$\square$	$+1/6$	$-$
$M_2 \leftrightarrow q_1$	$P_3\overline{P}_1$	$\square$	$\mathbf{1}$	$+2/3$	$+$
$M_3 \leftrightarrow q_2$	$P_3\overline{P}_{\tilde{1}}$	$\square$	$\mathbf{1}$	$-1/3$	$-$
$M_4 \leftrightarrow \overline{H}$	$P_1\overline{P}_2$	$\mathbf{1}$	$\square$	$-1/2$	$+$
$M_5 \leftrightarrow \overline{\chi}$	$P_1\overline{P}_1$	$\mathbf{1}$	$\mathbf{1}$	0	$-$
$M_6 \leftrightarrow \overline{\psi}$	$P_1\overline{P}_{\tilde{1}}$	$\mathbf{1}$	$\mathbf{1}$	-1	$+$

RGEs



EW exotics get masses from EWSB of order v ~ 200 GeV!

- Our theory is SUSY QCD with N+1 flavors.
- It s-confines and a dynamical super-potential is induced (at Λ):

$$W_{dyn} = \frac{1}{\Lambda^5}\left\{\overline{B}MB - \det\, M\right\}$$

$$\rightarrow \lambda\left\{HQ_3t_R + H\overline{H}S + \psi q_2 t_R + \psi\overline{\psi}S + \chi\overline{\chi}S - \right.$$

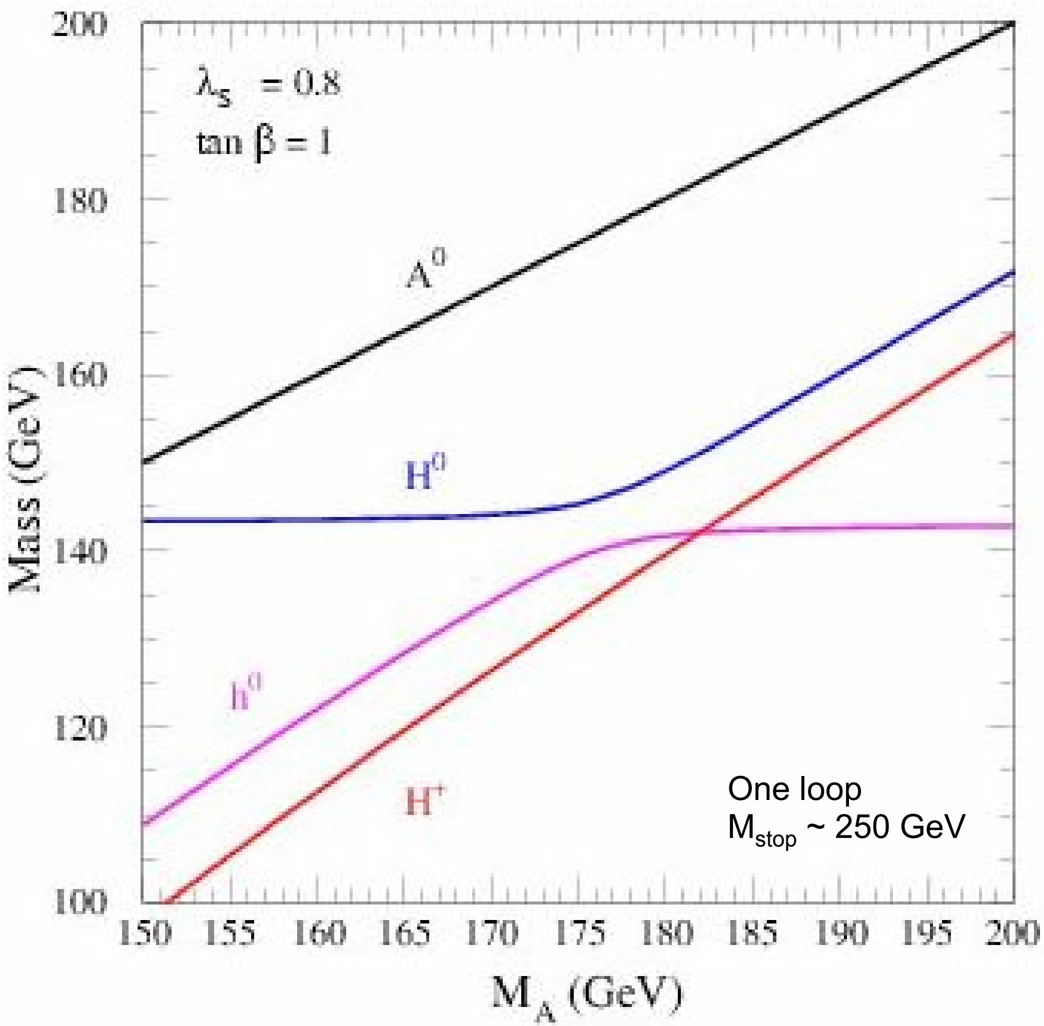
$$\left. + \chi q_1 t_R - \frac{\lambda}{\Lambda}\det M\right\}$$

- This includes both the fat Higgs term, and also yt!
- The couplings evolve apart at low energies, as described by the RGEs.
- A singlet tadpole arises from a fundamental preon interaction:

$$W_S = -y_S\epsilon_{\alpha\beta\gamma}P_3^\alpha P_3^\beta P_3^\gamma$$
$$\rightarrow -\left(\frac{y_S}{4\pi}\Lambda^2\right)S\ ,$$

- $W_H = \lambda_H S\left(H\overline{H} - v_0^2\right) + \lambda_\psi S\psi\overline{\psi} + \lambda_\chi S\chi\overline{\chi}$

Sample Higgs Spectrum



- Higgs Masses:
  - CP even Higgses from diagonalizing a 3 x 3 matrix including the singlet, but for simplicity we take it heavy so it decouples, leaving a modified MSSM-like spectrum.
  - We include one loop corrections from top/stop, though we choose smallish stop masses (~ 250 GeV) so these are not important.
  - Charged Higgs Mass:

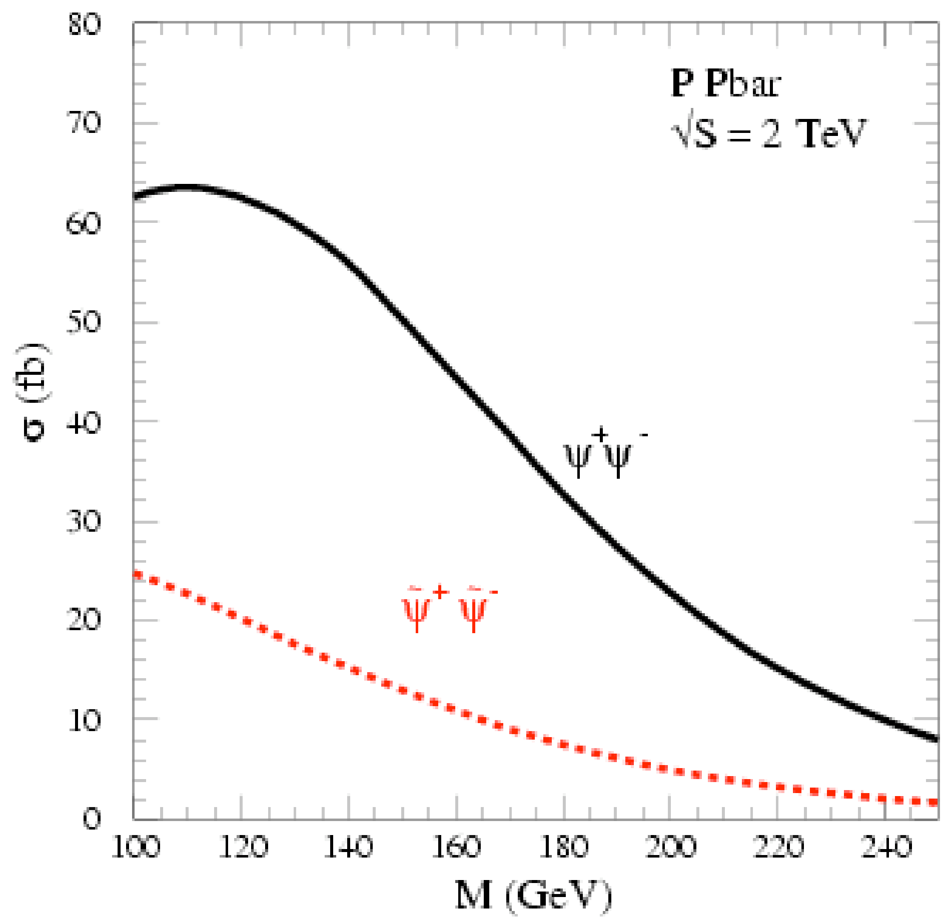
$$M_{H^\pm}^2 = M_A^2 + M_W^2 - \lambda_S^2 v^2$$

- The result is an interesting Higgs spectrum with H^+ often as the lightest Higgs – impossible for allowed NMSSM parameters.

- For lower M_A, the heavier CP even Higgs is the SM-like one, mostly responsible for EWSB.

Collider Signatures

- The exotic quasi-stable objects are an interesting signature of this model.
- They get masses from EWSB, and thus are of order v.
- One set has charge Q=±1, resulting in charged tracks which escape from the detector before decaying outside of it.
- They can be discovered at the Tevatron and LHC for a wide range of masses.
- Run II (with 2 fb^{-1}) expects to see charged quasi-stable particles provided their production cross sections are greater than about 10 fb.



Conclusions

- The Fat Higgs is a solution to the SUSY Little Hierarchy problem which proposes the MSSM Higgses are composites.
- It has some distinctive phenomenology, but has difficulty realizing the large top quark mass.
- A new version of the model described here has the top part of the composite sector as well, motivating the large top mass.
- The result is interesting and distinctive departures from MSSM Higgs phenomenology.
- New exotic quasi-stable states carrying electric charge are predicted and may be discovered at the Tevatron or LHC.

Fundamental Fields

	$SU(3)_s$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Z_2
L_i	$\mathbf{1}$	$\mathbf{1}$	$\square$	$-1/2$	$-$
e_i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$+1$	$-$
$Q_{1,2}$	$\mathbf{1}$	$\square$	$\square$	$+1/6$	$-$
d_i	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$+1/3$	$-$
$u_{1,2}$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$-2/3$	$-$
$\overline{q}_1$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$-2/3$	$+$
$\overline{q}_2$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$+1/3$	$-$
H'	$\mathbf{1}$	$\mathbf{1}$	$\square$	$+1/2$	$+$
$\overline{H}'$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$-1/2$	$+$

Colored Exotics!

We include the first and second generations (and right-handed bottom and 3rd family leptons) as fundamental fields. In addition, a pair of quark-like objects cancels anomalies (but will get masses of order the confinement scale), and a pair of Higgs-like objects helps us generate all needed Yukawa interactions.