Loop suppressed EWSB
and naturally heavy superpartners

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CERN, Charting the Unknown, August 11, 2016
Motivation
Elegant EWSB in SUSY

Radiatively driven EWSB (by stops or gluino):

\[
\beta \tilde{m}_{H_u}^2 = \frac{3y_t^2}{8\pi^2} \left( \tilde{m}_{H_u}^2 + \tilde{m}_{t_L}^2 + \tilde{m}_{t_R}^2 \right) + \ldots
\]

\[
\tilde{m}_{H_u}^2 \simeq -m_{t_{1,2}}^2
\]

preference for EW symmetry to be broken
Situation in generic SUSY models

Assuming no significant new contributions to Higgs quartic coupling at $Q = m_{\tilde{t}_1, 2}$ (this also ignores possible contributions from mixing in the stop sector):

![Diagram showing the relationship between $y_t$, $\lambda_{h,SM}$, $\lambda_{h,SUSY-tree}$, and $\lambda_{h,SUSY-tree}$ with $Q$ in units of $\log_{10} Q [\text{GeV}]$. The diagram indicates that the stop masses should be $\sim 10 \text{ TeV}$.)
Higgs mass in MSSM

Higgs requires 7 - 18 TeV stops (assuming no mixing) depending on the $\mu$ term and gaugino masses


G. F. Giudice and A. Strumia, arXiv:1108.6077
M. Binger, hep-ph/0408240
Elegant EWSB in SUSY

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\[ \tilde{m}^2_{H_u} \simeq -m^2_{t_{1,2}} \]

but EW scale seems to be highly tuned

\sim 0.01\% for a high scale mediation

\sim 0.1\% from 1st decade of RG running
What do the limits on gluino indicate?

Gluino drives stops up which in turn drive $\tilde{m}^2_{H_u}$ down

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Limits may be depressing, but:

~2 TeV gluino does not result in more than 10% tuning in EWSB as far as the mediation scale is below ~1000 TeV
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$\sim 2$ TeV gluino does not result in more than 10% tuning in EWSB as far as the mediation scale is below $\sim 1000$ TeV

On a positive note:

The heavier the gluino is, the more preferred low mediation scale is and sooner we will be building a collider to search for messengers :)
No-go?

While gluino just prefers lower mediation scale, it seems impossible to have simultaneously:

- 10 TeV stops
- At least 1 decade of RG running from the mediation scale
- Not contributing way too much to $\tilde{m}^2_{H_u}$
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- models/par. space with as light stops as possible and additional sources of the Higgs mass, for example:
  - models with large A-terms - to maximize the Higgs mass
  - singlet extensions $\lambda S H_u H_d$
  - ...
  
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- natural in a different way - crazy$^N$ ideas

$^N$“crazy” is a necessary ingredient of any good idea
Loophole

Stops are mixtures of states that couple to the Higgs but don’t have large soft masses and states with large soft masses that don’t couple to the Higgs

\( H_U \)

\( q, \bar{u} \)

\( Q, \bar{Q}, U, \bar{U} \)

\( t, \tilde{t}_{1,2} \)

\( \sim 10 \text{ TeV} \)

stops get large soft masses without ever contributing in RG evolution
“Instant” stop masses
Top sector of the model

Superpotential related to top quark:

\[ W \supset \lambda q\bar{u}H_u + m_qq\bar{Q} + m_uU\bar{u} + M_QQ\bar{Q} + M_UU\bar{U} \]

- \( f \supset \{q, \bar{u}\} \) up-type quark doublets and singlets
- \( \bar{F} \supset \{Q, U\} \) conjugate quantum numbers to \( f \)
- \( F \supset \{Q, \bar{U}\} \) another copy of up-type quark doublets and singlets
Top sector of the model

Superpotential related to top quark:

\[ W \supset \lambda q\bar{u}H_u + m_q q\bar{Q} + m_u U\bar{u} + M_Q Q\bar{Q} + M_U U\bar{U} \]

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Explicit mass terms are general allowed by SM symmetries, Yukawa couplings are not; other Yukawa couplings can be small and thus neglected or not allowed by a simple U(1) if explicit masses originate from vevs of SM singlets:

\[ m_{q,u} = \lambda_{q,u} \langle S_m \rangle \quad M_{Q,U} = \lambda_{Q,U} \langle S_M \rangle \]

The same charges can be extended to whole families

\[ Q_F = +1 \]
\[ Q_{\bar{F}} = -1 \]
\[ Q_{S_m} = +1 \]
Top quark and fermion partners

Superpotential related to top quark:

\[
W \supset \lambda q\bar{u}H_u + m_q q\bar{Q} + m_u U\bar{u} + M_Q Q\bar{Q} + M_U U\bar{U}
\]

Fermion mass matrix:

\[
(q \hspace{0.5cm} Q \hspace{0.5cm} U) M_F \begin{pmatrix}
\bar{u} \\
\bar{Q} \\
\bar{U}
\end{pmatrix} = (q \hspace{0.5cm} Q \hspace{0.5cm} U) \begin{pmatrix}
\lambda v_u & m_q & 0 \\
0 & M_Q & 0 \\
m_u & 0 & M_U
\end{pmatrix} \begin{pmatrix}
\bar{u} \\
\bar{Q} \\
\bar{U}
\end{pmatrix}
\]

Mass eigenvalues:

\[
m_{top} \simeq \lambda v_u M^2 / (m^2 + M^2)
\]

\[
m_{t_{2,3}} \simeq (M^2 + m^2)^{1/2}
\]

Simplification:

\[
m_q = m_u \equiv m \\
M_Q = M_U \equiv M
\]
Top quark and top partners

Top quark mass fixes $m/M$:

\[ W \supset \lambda q \bar{u} H_u + m_q Q + m_u U \bar{u} + M_Q Q Q + M_U U U \]

for $\lambda = 1 \pm 0.1$ at $Q = (M^2 + m^2)^{1/2}$

\[ m_{top} \simeq \lambda v_u M^2 / (m^2 + M^2) \quad \Rightarrow \quad y_t = \lambda M^2 / (m^2 + M^2) \]
Stops and stop partners

Scalar mass-squared matrix in the basis \((q, Q, U, \bar{u}^*, \bar{Q}^*, \bar{U}^*)\):

\[
M^2_S = \begin{pmatrix}
M_F M_F^\dagger & 0 \\
0 & M_F^\dagger M_F
\end{pmatrix} + \text{diag} \left( \tilde{m}_q^2, \tilde{m}_Q^2, \tilde{m}_U^2, \tilde{m}_{\bar{u}}^2, \tilde{m}_{\bar{Q}}^2, \tilde{m}_{\bar{U}}^2 \right)
\]

Eigenvalues (neglecting \(\lambda \nu_u\)):

\[
m^2_{l_{1,2}} = \frac{1}{2} \tilde{M}^2 - \frac{1}{2} \sqrt{\tilde{M}^4 - 4 \left( M^2 \tilde{m}_f^2 + m^2 \tilde{m}_F^2 + \tilde{m}_f^2 \tilde{m}_F^2 \right)}
\]

\[
m^2_{l_{3,4}} = \frac{1}{2} \tilde{M}^2 + \frac{1}{2} \sqrt{\tilde{M}^4 - 4 \left( M^2 \tilde{m}_f^2 + m^2 \tilde{m}_F^2 + \tilde{m}_f^2 \tilde{m}_F^2 \right)}
\]

\[
m^2_{l_{5,6}} = M^2 + m^2 + \tilde{m}_F^2
\]

Simplification:

\[
\tilde{m}_q^2 = \tilde{m}_{\bar{u}}^2 \equiv \tilde{m}_f^2
\]

\[
\tilde{m}_Q^2 = \tilde{m}_{\bar{Q}}^2 \equiv \tilde{m}_F^2
\]

\[
\tilde{m}_U^2 = \tilde{m}_{\bar{U}}^2 \equiv \tilde{m}_F^2
\]
Stops and stop partners

for $\tilde{m}_f^2 = 0$:

$$m_{i_{1,2}} / M$$

$$m_{i_{3,4}} / M$$

Eigenvalues:

$$m_{i_{1,2}}^2 = \frac{1}{2} \tilde{M}^2 - \frac{1}{2} \sqrt{\tilde{M}^4 - 4(M^2 \tilde{m}_f^2 + m^2 \tilde{m}_F^2 + \tilde{m}_f^2 \tilde{m}_F^2)}$$

$$m_{i_{3,4}}^2 = \frac{1}{2} \tilde{M}^2 + \frac{1}{2} \sqrt{\tilde{M}^4 - 4(M^2 \tilde{m}_f^2 + m^2 \tilde{m}_F^2 + \tilde{m}_f^2 \tilde{m}_F^2)}$$

$$\tilde{M}^2 \equiv M^2 + m^2 + \tilde{m}_f^2 + \tilde{m}_F^2$$

Simplification:

$$\tilde{m}_q^2 = \tilde{m}_u^2 \equiv \tilde{m}_f^2$$

$$\tilde{m}_Q^2 = \tilde{m}_U^2 \equiv \tilde{m}_F^2$$

All scalars acquire masses even if $\tilde{m}_f^2 = 0$!
RG evolution to O(10 TeV) scale

In the RG evolution from an arbitrary scale,

\[ \beta \tilde{m}^2_{H_u} = \frac{3\lambda^2}{8\pi^2} \left( \tilde{m}^2_{H_u} + \tilde{m}^2_q + \tilde{m}^2_{\bar{u}} \right) + \cdots \simeq 0 \]

no contribution to \( \tilde{m}^2_{H_u} \) is generated from scalar masses

(the same combination of soft masses appears in beta functions of \( \tilde{m}^2_q \) and \( \tilde{m}^2_{\bar{u}} \))

At O(10 TeV):

- stop masses are generated from mixing with VQ
- all heavy particles are integrated out
Integrating out heavy particles

At $O(10 \text{ TeV})$:

- Stop masses are generated from mixing with VQ
- All heavy particles are integrated out
- Threshold corrections to $\tilde{m}^2_{H_u}$ and $\lambda_h$ are calculated
- The model is matched to SM + inos
Threshold corrections to $\tilde{m}_{H_u}^2$ and $\lambda_h$

$M = 23$ TeV:

- the matching scale to SM + inos is chosen to be $Q = m_{\tilde{t}_{1,2}}$
- threshold corrections to $\tilde{m}_{H_u}^2$ do not depend on $Q$
  (besides the dependence through couplings)
Threshold corrections to $\tilde{m}_{H_u}^2$

- (for comparable parameters) within 1 TeV
- can be small, + or -, EWSB not preferred by scalar sector
- depend on the origin of soft masses (complete models)
Universal heavy scalar masses

Just two parameters:

~20% range of soft mass squared results in < 300 GeV correction
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explicit masses may originate from vevs of SM singlets:

\[ M_{Q,U} = \lambda_{Q,U} \langle S_M \rangle \]

which are related to soft masses by Yukawa couplings
(< 300 GeV correction obtained in ~10% range of Yukawa couplings)
Summary

Assumptions about the heavy sector - VQ:

- does not couple to the Higgs
- mixes with “stops”
- feels SUSY breaking stronger than MSSM sector

Results:

- contribution from scalars to $\tilde{m}^2_{H_u}$ from RG running completely eliminated; reduced to threshold corrections
- stop masses (Higgs mass) determined by masses of VQ
- no preference for EWSB (from scalars), it is still driven by gluino
- simple mechanism that can be combined with any model
Conclusions

10 TeV scale might be super-exciting

\( H_u \), \( q, \bar{u} \), \( t, \bar{t}_{1,2} \), \( Q, \bar{Q}, U, \bar{U} \), SUSY