Supersymmetry and Little Higgs

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Outline

1. What's Wrong With the MSSM
2. Supersymmetric Alternatives to the MSSM
3. Introducing Little Susy
4. Twin Susy version of Little Susy

Motivations for Physics Beyond SM

Why New Physics at TeV?

- Naturalness: Faith that the electroweak scale $m_Z = 91 GeV$ is calculable in a fundamental theory and its small value (compared to e.g. M_{GUT}) is not a result of accidental cancellations

Why Supersymmetry?

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(Historical) Motivations for MSSM

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Most importantly: obeys the naturalness principle by linking electroweak scale to Susy breaking scale $M_{\rm susy}$ via radiative electroweak breaking

Moreover:

- Simplest consistent supersymmetric extension of SM
- Easily passes electroweak precision tests (low energy gauge group not modified)
- Predicts a light Higgs boson $m_{\rm Higgs} \gtrsim M_Z$
- Predicts gauge coupling unification at $M_{GUT} \sim 10^{16}\,{\rm GeV}$
- Posseses a dark matter candidate (the lightest neutralino)

Problems: flavour problem, CP problem, μ problem, proton decay problem, doublet-triplet splitting problem .....and after LEP2 electroweak little fine-tuning problem and dark matter fine-tuning problem

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Higgs mass parameter at one loop in MSSM
(Simple setup: large tan β, no A-terms, degenerate stops)

$$m_H^2 \approx m_{H_u}^2 + |\mu|^2 - \frac{3}{8\pi^2} y_t^2 \tilde{m}_t^2 \log \frac{\Lambda_{UV}^2}{\tilde{m}_t^2}$$

For $\Lambda_{UV} \sim M_{\rm GUT}$ large log cancels loop factor and we expect:

$$|m_H^2| \sim \mathrm{Max}\{m_{H_u}^2, |\mu|^2, \tilde{m}_t^2\}$$

...unless cancellations occur....
Higgs mass parameter related to Higgs boson mass

$$m_H^2 = -2\lambda \langle H \rangle^2 = -m_{\rm Higgs}^2/2$$

For $m_{\rm Higgs}^2 \sim 115\,\mathrm{GeV}$, l.h.s. of order

$$|m_H^2| \sim 0.01\,\mathrm{TeV}^2$$

Higgs boson mass puts a lower bound on the stop mass $\tilde{m}_t$

$$m_{\rm Higgs}^2 \approx m_Z^2 + \frac{3m_t^2}{4\pi^2} y_t^2 \log(\tilde{m}_t/m_t) \quad \longrightarrow \quad \tilde{m}_t \gtrsim 1\,\mathrm{TeV}$$

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Solving electroweak little fine-tuning problem

The Troublemaker: $m_H^2 \approx m_{H_u}^2 + |\mu|^2 - \frac{3}{8\pi^2} y_t^2 M_{\rm susy}^2 \log \frac{\Lambda_{UV}^2}{M_{\rm susy}^2}$

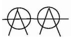
Solutions

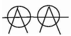
1. Finding justification for the cancellation between tree-level and one-loop contributions. Recent example: Mirage Mediation.
2. Engineering additional contributions to the Higgs quartic term or hiding the less-than-100-GeV-Higgs boson, while keeping superpartner masses close to 100 GeV. Well-known example: NMSSM
3. Cut off the large logarithm at lower scale $\Lambda_{UV} \sim 1 - 100\,\mathrm{TeV}$, so that $m_H^2 \sim M_{\rm susy}^2/4\pi$
   - Low scale susy breaking mediation. Well-known example: Gauge Mediation
   - New symmetries emerging close to TeV scale. Recent example: Little Susy

Introducing Little Susy

- MSSM is extended so as to incorporate an approximate global symmetry of the Higgs sector
- Higgs is a pseudo-Goldstone boson after spontaneous breaking of this global symmetry at the scale $f \sim 1\,\mathrm{TeV}$, similarly as in Little Higgs

Birkedal, Chacko, Gaillard (*April* 2004)

Berezhiani, Chankowski, , Pokorski (*September* 2005)
Roy, Schmaltz (*September* 2005)
Csaki, Marandella, Shirman, Strumia (*September* 2005)

, Pokorski, Schmaltz (*April* 2006)
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Introducing Little Susy

Minimal ingredients to exorcise the superymmetric little fine-tuning problem by Little Susy:

1. Global symmetry unifying the Higgs doublet and new electroweak singlets into larger multiplets
2. Spontaneous breaking of this global symmetry at the TeV scale along the electroweak singlet direction
3. Extended top sector softly breaking this global symmetry: global symmetry broken explicitly only by a *supersymmetric mass parameter* $M_{\rm global}$

Outcome

- Higgs potential at one loop is finite
- Higgs vev and Higgs mass fully determined by low energy observable parameters
- $m_Z \sim m_{\rm Higgs} \sim M_{\rm susy}/4\pi$ naturally

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Higgs potential from top loops: $V = \delta m_H^2 |H|^2 + \ldots$

$$\delta m_H^2 = -\frac{N_c}{4\pi^2} y_t^2 \Lambda_{UV}^2 + \ldots$$

Global symmetry and supersymmetry united forbid quadratic AND logarithmic divergences. Double protection structure:

$$\delta m_H^2 \approx -\frac{3y_t^2}{8\pi^2}\left[(M_{\rm susy}^2 + M_{\rm global}^2)\log(M_{\rm susy}^2 + M_{\rm global}^2) - M_{\rm susy}^2 \log M_{\rm susy}^2 - M_{\rm global}^2 \log M_{\rm global}^2\right]$$

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Why not end of story?

Because such global symmetry is unstable against radiative corrections and does not survive in the presence of scales much larger than TeV.
In particular, gauge interactions break this global symmetry, therefore in realistic models gauge symmetry must be extended as well.
Note that in supersymmetry we try to be more ambitious.
In non-susy little Higgs high scales “do not exist” and so the problem of radiative stability of the global symmetry “does not exist” either.

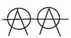
Twin Susy = discrete symmetry inducing approximate global symmetry

Twin Higgs (non-susy) idea Chacko, Goh, Harnik (*June* 2005)

- Mirror partner for the SM Higgs doublet: $H \longleftrightarrow \tilde{H}$
- Exact discrete Z_2 symmetry $H \longleftrightarrow \tilde{H}$ of the action
- Quadratic terms $M^2(|H|^2 + |\tilde{H}|^2)$ by Z_2 have accidental $SU(4)$ global symmetry
- When $\tilde{H}$ acquires vev spontaneous breaking of this symmetry results in appearance of Goldstone bosons

Application in supersymmetry

- Twin Susy in a left-right symmetric model

  $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$, , Pokorski, Schmaltz (*April* 2006)
- Twin Susy in a mirror world $[SU(3)_C \times SU(2)_L \times U(1)_Y]^2$, Chang, Hall, Weiner (*April* 2006)

- Left-Right symmetric gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$
- Z_2 interchanging left and right gauge bosons, $A^L_\mu \longleftrightarrow A^R_\mu$
- MSSM left doublets related by Z_2 to weak singlets, e.g. $Q = (t, b) \leftrightarrow \tilde{Q} = (t^c, b^c)$
- Twin partners of the MSSM Higgs doublets $(H_u)_{1/2} \leftrightarrow (\tilde{H}_u)_{-1/2}$, $(H_d)_{-1/2} \leftrightarrow (\tilde{H}_d)_{1/2}$
- Singlet superfield N to produce Z_2 (and $SU(4)$) invariant interactions between twin Higgs sectors; tadpole superpotential to induce vevs of the $\tilde{H}_u$ $\tilde{H}_d$ pair

$$W = \lambda N(H_u H_d + \tilde{H}_u \tilde{H}_d - F^2)$$

Result: Approximate global symmetry of the Higgs potential spontaneously broken, with $\langle \tilde{H}_u \rangle \sim \langle \tilde{H}_d \rangle \sim F$

7 Goldstone bosons, 3 eaten by breaking $SU(2)_R \times U(1)_X \to U(1)$. Four uneaten Goldstone bosons collected into H transform as a doublet under $SU(2)_L$ $\to$ can be identified with the SM Higgs doublet. Non-linear parametrization:

$$H_u \to f \sin\beta \sin(|H|/f) \qquad H_d \to f \cos\beta \sin(|H|/F)$$

$$\tilde{H}_u \to f \sin\beta \cos(|H|/f) \qquad \tilde{H}_d \to f \cos\beta \cos(|H|/F)$$

Top sector

- Weak doublet $Q = (t, b)$ and its twin $\tilde{Q} = (\tilde{t}, \tilde{b})$
- New vectorlike pair of tops T, T^c of top quarks needed for renormalizable Yukawas

$$W = yH_uQT^c + y\tilde{H}_u\tilde{Q}\tilde{T} + M\tilde{T}T^c$$

Top interactions break global $SU(4)$ and generate Higgs potential at loop level. Log divergent term in one-loop potential

$$V_{CW} \sim y^2 M^2_{\rm susy}(|H_u|^2 + |\tilde{H}_u|^2)\log\Lambda_{UV} \to y^2 M^2_{\rm susy} f^2 \sin^2\beta \log\Lambda_{UV}$$

does not contribute to mass parameter of pseudo-Goldstone H

Summary

- The MSSM suffers from the supersymmetric little hierarchy problem,
- Little SUSY = SUSY + Little Higgs leads to double protection of electroweak breaking, which removes the large logarithm and cures the fine-tuning problem
- Several realistic (though complicated) realizations so far.
- `LHC signal:` heavy (TeV scale) superparticles AND fermionic partners of the top quark