Recent developments in the phenomenology of supersymmetric models

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Outline:

- Motivations for SUSY
- The classic model frameworks (mSUGRA, GMSB, AMSB)
- Challenges
    - SUSY little hierarchy problem
    - SUSY flavor problem
- Recent model-building advances, and consequences for phenomenology

There are several reasons why supersymmetry (SUSY) is regarded as likely:

- The lightest supersymmetric particle (LSP) is stable, could be dark matter
- SUSY predicts a light Higgs boson, in agreement with precision electroweak constraints
- Minimal SUSY predicts unification of gauge couplings
- Mathematical beauty (perhaps a matter of taste!)

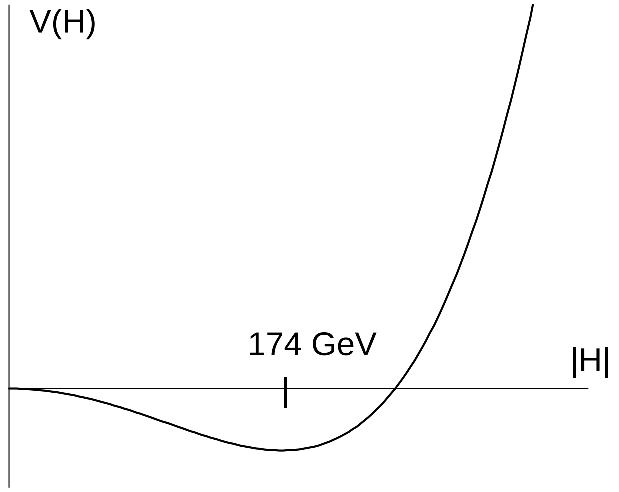
However, the single best reason to suspect that SUSY is real:

- **The Hierarchy Problem**

The Hierarchy Problem

Consider the potential for H, the complex scalar field that is the electrically neutral part of the Standard Model Higgs field:

$$V(H) = m^2|H|^2 + \frac{\lambda}{2}|H|^4$$



For electroweak symmetry breaking to agree with the experimental m_Z, we need:

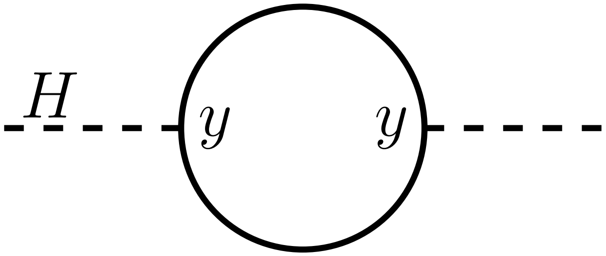
$$\langle H \rangle = \sqrt{-m^2/\lambda} \approx 175 \text{ GeV}$$

The requirement of unitarity in the scattering of Higgs bosons and longitudinal W bosons tells us that λ is not much larger than 1. Therefore,

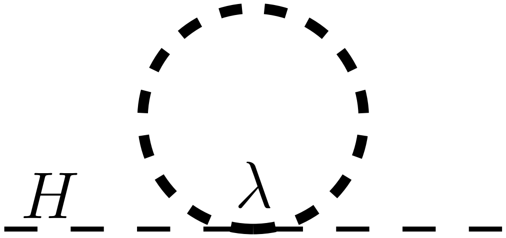
$$-(\text{few hundred GeV})^2 \lesssim m^2 < 0.$$

However, this appears fine-tuned (in other words, incredibly and mysteriously lucky!) when we consider the likely size of quantum corrections to m^2.

Contributions to m_H^2 from a fermion loop:



Contributions to m_H^2 from a scalar loop:



$$\Delta m_H^2 \quad = \quad \frac{1}{8\pi^2}(\lambda - y^2) M_{\rm UV}^2 + \ldots$$

One would expect that $M_{\rm UV}$ is of order the Planck mass, or the string scale, or whatever is the ultimate high cutoff energy. However, then $m_H^2/M_{\rm UV}^2 \sim 10^{-32}$ seems to require extreme fine-tuning.

Supersymmetry asserts that each fermion comes with a boson partner, and automatically predicts $\lambda = y^2$.

Supersymmetry (SUSY) is a symmetry between fundamental fermion and boson degrees of freedom. It predicts **at least** the following new particles:

Names	Spin	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	$h^0 \; H^0 \; A^0 \; H^\pm$	$H_u^0 \; H_d^0 \; H_u^+ \; H_d^-$
squarks	0	$\tilde{u}_L \; \tilde{u}_R \; \tilde{d}_L \; \tilde{d}_R$	“ ”
		$\tilde{s}_L \; \tilde{s}_R \; \tilde{c}_L \; \tilde{c}_R$	“ ”
		$\tilde{t}_1 \; \tilde{t}_2 \; \tilde{b}_1 \; \tilde{b}_2$	$\tilde{t}_L \; \tilde{t}_R \; \tilde{b}_L \; \tilde{b}_R$
sleptons	0	$\tilde{e}_L \; \tilde{e}_R \; \tilde{\nu}_e$	“ ”
		$\tilde{\mu}_L \; \tilde{\mu}_R \; \tilde{\nu}_\mu$	“ ”
		$\tilde{\tau}_1 \; \tilde{\tau}_2 \; \tilde{\nu}_\tau$	$\tilde{\tau}_L \; \tilde{\tau}_R \; \tilde{\nu}_\tau$
neutralinos	$1/2$	$\tilde{N}_1 \; \tilde{N}_2 \; \tilde{N}_3 \; \tilde{N}_4$	$\tilde{B}^0 \; \tilde{W}^0 \; \tilde{H}_u^0 \; \tilde{H}_d^0$
charginos	$1/2$	$\tilde{C}_1^\pm \; \tilde{C}_2^\pm$	$\tilde{W}^\pm \; \tilde{H}_u^+ \; \tilde{H}_d^-$
gluino	$1/2$	$\tilde{g}$	“ ”

Beyond that, almost everything else is negotiable!

To understand SUSY breaking is to understand SUSY phenomenology.

The minimal SUSY Standard Model (MSSM) with R-parity conserved in general has 105 new parameters, almost all associated with SUSY breaking. They consist of gaugino fermion masses, scalar squared masses, and scalar^3 couplings.

However, this 105-dimensional parameter space is not relevant, since existing flavor physics constraints ($\mu \to e\gamma$, K^0–$\overline{K^0}$ mixing) rule out most of it.

The “mSUGRA” parameter space

In terms of four input parameters $m_{1/2},\ m_0^2,\ A_0$:

Gaugino masses: $M_3 = M_2 = M_1 = m_{1/2}$

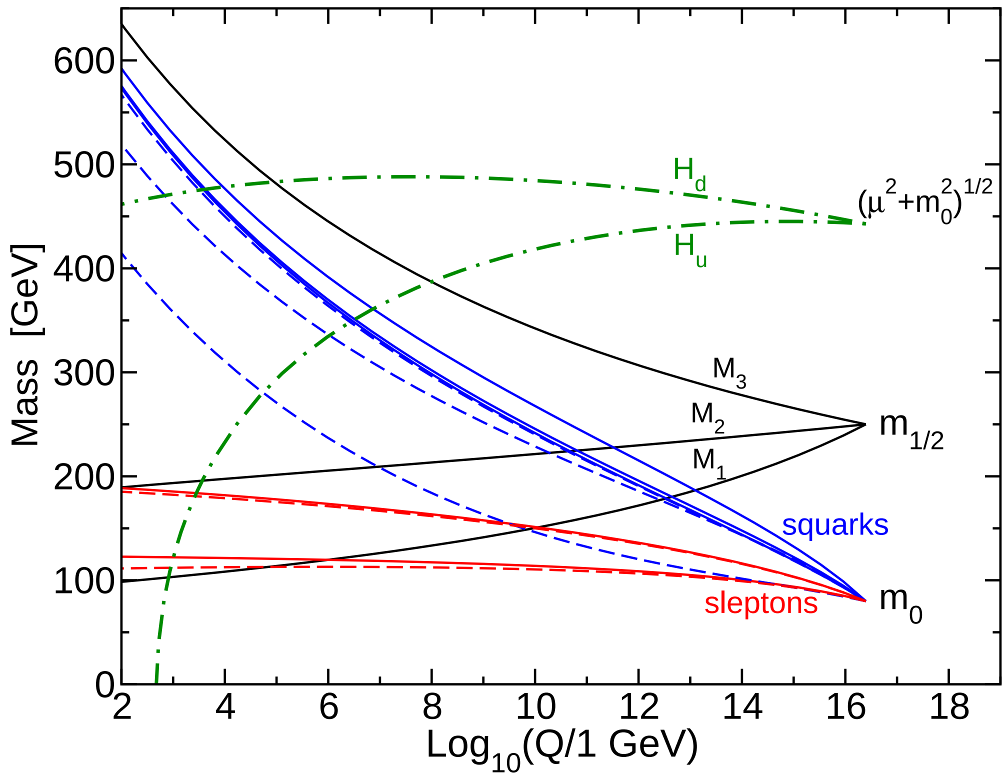
Scalar masses: $\mathbf{m^2_{\tilde{Q}}} = \mathbf{m^2_{\tilde{\bar{u}}}} = \mathbf{m^2_{\tilde{\bar{d}}}} = \mathbf{m^2_{\tilde{L}}} = \mathbf{m^2_{\tilde{\bar{e}}}} = m^2_{H_u} = m^2_{H_d} = m_0^2$

Scalar^3 terms: $\mathbf{a_u} = A_0\mathbf{y_u}, \qquad \mathbf{a_d} = A_0\mathbf{y_d}, \qquad \mathbf{a_e} = A_0\mathbf{y_e}$

These parameters are usually taken as inputs at the GUT scale.

Also, define $\tan\beta \equiv \langle H_u\rangle/\langle H_d\rangle$, and the sign (or phase) of the Higgs mass parameter μ.

Typical mSUGRA model (actually an infamous benchmark point, SPS1a$'$):

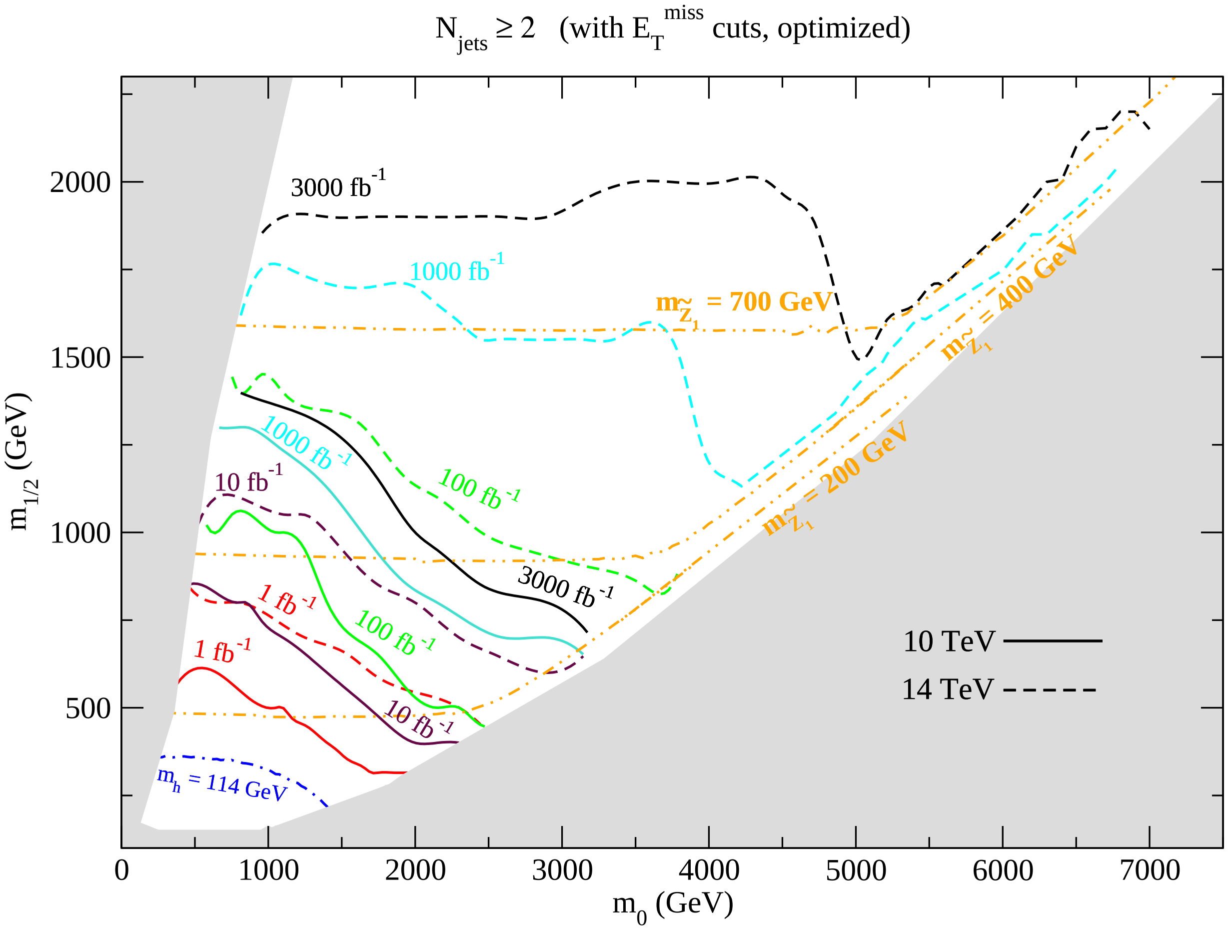


$$\begin{aligned} m_{1/2} &= 250\text{ GeV} \\ m_0 &= 70\text{ GeV} \\ A_0 &= -300\text{ GeV} \\ \tan\beta &= 10 \\ \mu &> 0 \end{aligned}$$

The mSUGRA parameter space is predictive and convenient for practical studies, but is almost certainly **wrong**!

The LHC will not turn on at 14 TeV, and may not reach it for a long time.

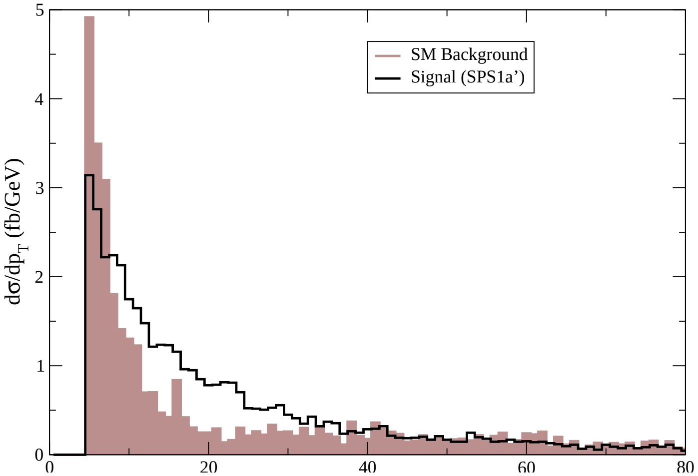
Study of reach of 10 TeV vs. 14 TeV LHC, for mSUGRA (fully understood detectors):

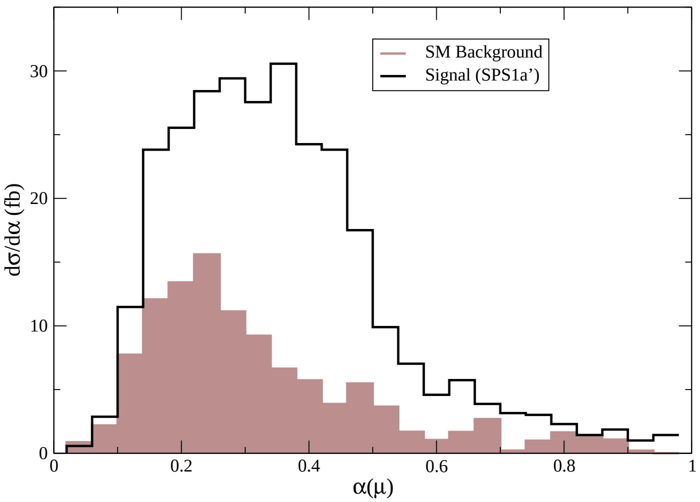


Baer, Barger,
Lessa, Tata
0907.1922

Reach in mass decreases by 25% to 60%.

$\not\!\!E_T$ is difficult at LHC. Maybe not the way to early SUSY discovery?





Baer Prosper Summy 0801.3799

Baer Lessa Summy 0809.4719.

An example: $\tilde{g}\tilde{g} \to \mu^+\mu^+$ + 4 jets,

at $\sqrt{s} = 10$ TeV.

$\alpha \equiv p_T(\mu_2)/m(\mu^+\mu^+)$,

similar to variable in

Randall-Tucker-Smith 0806.1049

Discovery without $\not\!\!E_T$ possible with only

0.1 fb^{-1} at $\sqrt{s} = 10$ TeV.

Gauge Mediated SUSY Breaking (GMSB):

$$M_a = \frac{\alpha_a}{4\pi} N \Lambda, \qquad \text{(gauginos)}$$

$$m_\phi^2 = 2N\Lambda^2 \Big[\Big(\frac{\alpha_3}{4\pi}\Big)^2 C_3^\phi + \Big(\frac{\alpha_2}{4\pi}\Big)^2 C_2^\phi + \Big(\frac{\alpha_1}{4\pi}\Big)^2 C_1^\phi \Big], \qquad \text{(scalars)}$$

$$A_0 = 0. \qquad \text{(scalar}^3 \text{ couplings)}$$

The parameters of this model framework are just:

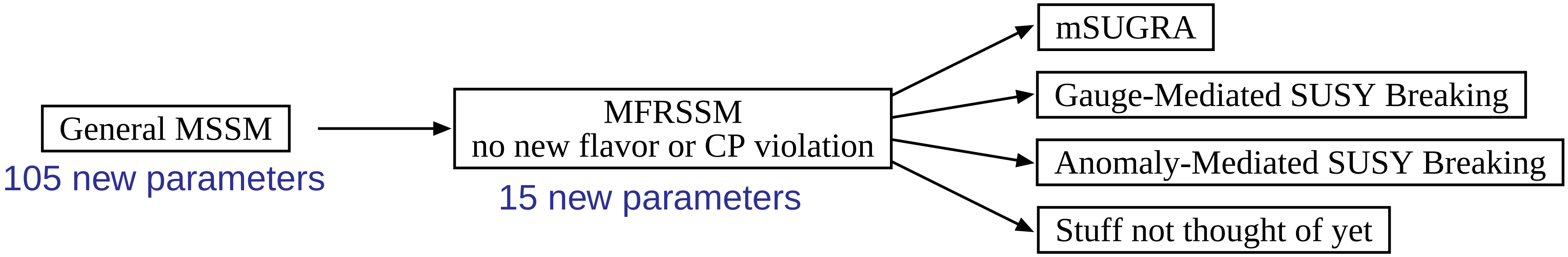
- $N =$ number of messengers,
- $\Lambda =$ effective SUSY-breaking order parameter,
- $M_{\rm mess} =$ messenger mass scale, where above running masses are input.
- $\tan\beta$ and sign(μ)

The minimal model is $N = 1$. Recently, even more general GMSB models have been constructed (Meade Seiberg Shih 0801.3278).

The MSSM has 105 new parameters. Too general!

GMSB and mSUGRA each have only few parameters. Not general enough?

A reasonable working hypothesis is the **Minimal Flavor-Respecting Supersymmetric Standard Model**. It is neither too painfully general, nor too naively specific:



MFRSSM parameter count:

3 gaugino masses	$M_1,\ M_2,\ M_3$
5 sfermion $(\text{mass})^2$	$m^2_{\tilde{Q}},\ m^2_{\tilde{u}},\ m^2_{\tilde{d}},\ m^2_{\tilde{L}},\ m^2_{\tilde{e}}$
3 $(\text{scalar})^3$ couplings	$A_{u0},\ A_{d0},\ A_{e0}$
3 Higgs mass parameters	$\tan\beta,\ \mu,\ m^2_{H_u},\ m^2_{H_d}$ (but M_Z known)
1 input RG scale	Q_0

Fully exploring the phenomenology of this parameter space is challenging!

Recent work by Cotta, C. Berger, Gainer, Hewett, Rizzo 0812.0890, 0903.4409 did random scans, $\sim 50k$ models with realistic simulations

Many features qualitatively different from typical mSUGRA. Among them:

- Quasi-stable charginos (because nearly degenerate with LSP neutralino. DZERO constraint on quasi-stable charged particles is crucial.
- Higgs can hide from LEP: ZZh coupling reduced, or $h \to \tilde{N}_1 \tilde{N}_1$ invisible.
- Gluino or squarks can be light, ~ 200 GeV, and still hide from Tevatron. Squarks still accesible to a $\sqrt{s} = 500$ GeV ILC.

Physics thrives on crisis.

Fortunately, supersymmetry has arguably been in crisis since about 2001.

The reason: LEP2 did not discover a Higgs boson or any other direct sign of SUSY.

If SUSY is the solution to the hierarchy problem, shouldn't the lightest Higgs have been discovered at LEP?

At one-loop order in the MSSM,

$$m_h^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} y_t^2 m_t^2 \sin^2(\beta) \ln(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2) + \ldots$$

To avoid $m_h < 115$ GeV as suggested by LEP2, need $\sin\beta \approx 1$ and (naively):

$$\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} > 700 \text{ GeV}.$$

so that the logarithm is $\gtrsim 3$.

This appears to be fine-tuned once one realizes that m_Z^2 and $m_{\tilde{t}}^2$ are connected to each other by soft SUSY-breaking. . .

Meanwhile, the condition for Electroweak Symmetry Breaking is:

$$-\frac{m_Z^2}{2} \;=\; m_{H_u}^2 + |\mu|^2 + \text{small loop corrections} \;+\; \mathcal{O}(1/\tan^2\beta).$$

Here $|\mu|^2$ is a SUSY-preserving Higgs squared mass,
$m_{H_u}^2$ is a SUSY-violating Higgs scalar squared mass.

The problem: if $m_{\tilde{t}_1} m_{\tilde{t}_2} \;\gtrsim\; (700\,\mathrm{GeV})^2$ as found above, and $m_{H_u}^2$ is comparable as suggested by mSUGRA, then the required cancellation here is of order 1%.

This is the “SUSY little hierarchy problem”.

Maybe things aren't so bad? Include effects of a stop mixing angle with (cosine, sine) $= c_{\tilde{t}},\ s_{\tilde{t}}$:

$$M_h^2 = m_Z^2 + \frac{3y_t^2}{4\pi^2} m_t^2 \left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{c_{\tilde{t}}^2 s_{\tilde{t}}^2}{m_t^2}(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln\left(\frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2}\right) + \frac{c_{\tilde{t}}^4 s_{\tilde{t}}^4}{m_t^4}\left\{(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2}(m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4) \ln\left(\frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2}\right)\right\}\right].$$

The Blue term is positive definite, the Red term negative definite.

Maximizing with respect to the stop mixing angle, one can show:

$$M_h^2 \lesssim m_Z^2 + \frac{3y_t^2}{4\pi^2} m_t^2 \left[\ln\left(m_{\tilde{t}_2}^2/m_t^2\right) + 3 \right]$$

This is the "maximal mixing" scenario.

However, mSUGRA and GMSB do not naturally achieve this large stop mixing. Another reason to look beyond these frameworks.

Another way things may not be so bad: fine tuning of the electroweak scale is reduced if the pernicious influence of the gluino is suppressed. (G. Kane and S. King, `hep-ph/9810374`)

$$\begin{aligned} -m_{H_u}^2 &= 1.92\hat{M}_3^2 + 0.16\hat{M}_2\hat{M}_3 - 0.21\hat{M}_2^2 \\ &\quad -0.63\hat{m}_{H_u}^2 + 0.36\hat{m}_{t_L}^2 + 0.28\hat{m}_{t_R}^2 \\ &\quad + \text{many terms with tiny coefficients} \end{aligned}$$

The parameters on the right are at the GUT scale, result on left is at the TeV scale.

If one takes a smaller gluino mass at the GUT scale, say $\hat{M}_3/\hat{M}_2 \sim 0.3$, then $-m_{H_u}^2$ will be much smaller.

Fine-tuning is substantially reduced if gluino is relatively lighter than in mSUGRA or GMSB.

A classic way to get non-universal gaugino masses from theory:

(Ellis Enqvist Kounnas Nanopoulos 1984, Anderson et al hep-ph/9609457)

The F-term that breaks SUSY may not be a singlet, as assumed in mSUGRA. Instead, it may transform under $SU(5)$ as:

$$(\mathbf{24}\times\mathbf{24})_{\rm symm} = \mathbf{1}+\mathbf{24}+\mathbf{75}+\mathbf{200}$$

Predictions for gaugino masses are affected by Clebsch-type coefficients:

$$\begin{aligned} M_1 &= m_{1/2}(1 + c_{24} - 5c_{75} + 10c_{200}) \\ M_2 &= m_{1/2}(1 + 3c_{24} + 3c_{75} + 2c_{200}) \\ M_3 &= m_{1/2}(1 - 2c_{24} + c_{75} + c_{200}) \end{aligned}$$

Note that the number of free parameters $(m_{1/2}, c_{24}, c_{75}, c_{200})$ exceeds the number of predictions (M_1, M_2, M_3).

So even in a GUT model, the gaugino masses can be anything you want. Many recent papers have explored the resulting parameter space.

Another recent proposal is “Mirage Unification” of gaugino masses:

$$M_1 : M_2 : M_3 \quad = \quad (1 + 0.66\alpha) : (1.93 + 0.19\alpha) : (5.87 - 1.76\alpha)$$

at the TeV scale. This follows from certain string-motivated models.

Choi et al, hep-th/0411066, hep-th/0503216, hep-ph/0702146

For $\alpha = 0$, recover the mSUGRA prediction.

For $\alpha \neq 0$, the gaugino masses appear to unify at a scale:

$$M_{\rm mirage} = \left(\frac{m_W}{M_{\rm Planck}}\right)^{\alpha/2} M_{\rm GUT}.$$

The Anomaly Mediated SUSY Breaking (AMSB) pattern is:

$$M_1 : M_2 : M_3 \quad = \quad 3.3 : 1 : -9$$

at the TeV scale. This corresponds to Mirage Unification with $\alpha \to \infty$.

The Lesson: gaugino mass unification need not be the default assumption.

Personal opinion: the pattern of gaugino masses is the most prominent feature of SUSY breaking that we can hope to uncover at the LHC.

What is the overall scale of SUSY breaking?
What is $M_1 : M_2 : M_3$?

Another attempt to solve the SUSY little hierarchy problem: additional vector-like matter supermultiplets with large Yukawa couplings.

Actually an old idea: Moroi+Okada 1991 and 1992;
Babu Gogoladze Kolda hep-ph/0410085;
Babu Gogoladze Rehman Shafi 0807.3055

The simplest model of this type is. . .

Extra new chiral superfields = $Q, \overline{Q}, U, \overline{U}, E, \overline{E}$

Transform under $SU(3)_c \times SU(2)_L \times U(1)_Y$ as

$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ + $(\overline{\mathbf{3}}, \mathbf{2}, -\frac{1}{6})$ + $(\mathbf{3}, \mathbf{1}, \frac{2}{3})$ + $(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$ + $(\mathbf{1}, \mathbf{1}, -1)$ + $(\mathbf{1}, \mathbf{1}, 1)$.

Superpotential:

$$W = M_Q Q\overline{Q} + M_U U\overline{U} + M_E E\overline{E} + \kappa_u H_u Q\overline{U} + \kappa_d H_d \overline{Q}U.$$

This just consists of a $\mathbf{10} + \overline{\mathbf{10}}$ of $SU(5)$.

New particle content (beyond the MSSM):

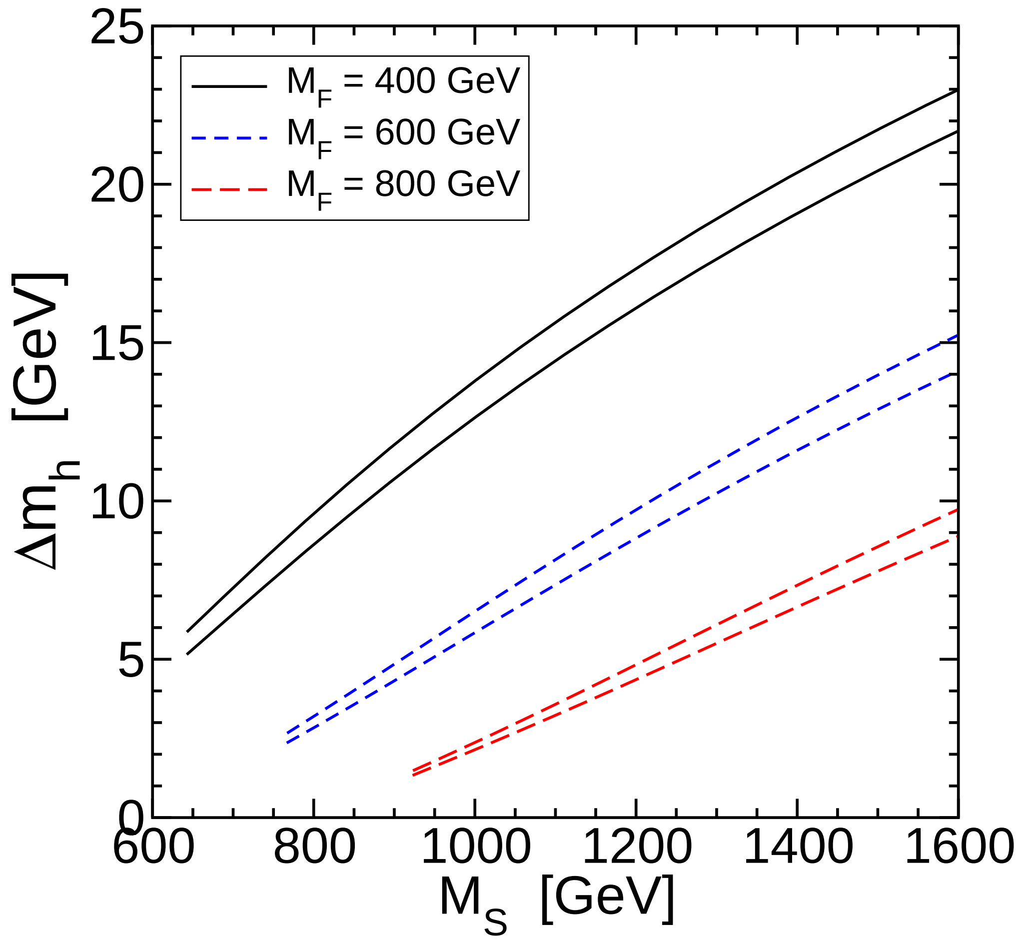
Fermions: $t', \quad t'', \quad b', \quad \tau'$.

Scalars: $\tilde{t}'_{1,2,3,4}, \quad \tilde{b}'_{1,2}, \quad \tilde{\tau}'_{1,2}$.

Corrections to precision EW observables decouple for large masses.

Corrections to m_h do **not** decouple.

Corrections to m_h, for fixed-point Yukawa coupling of vector-like t':

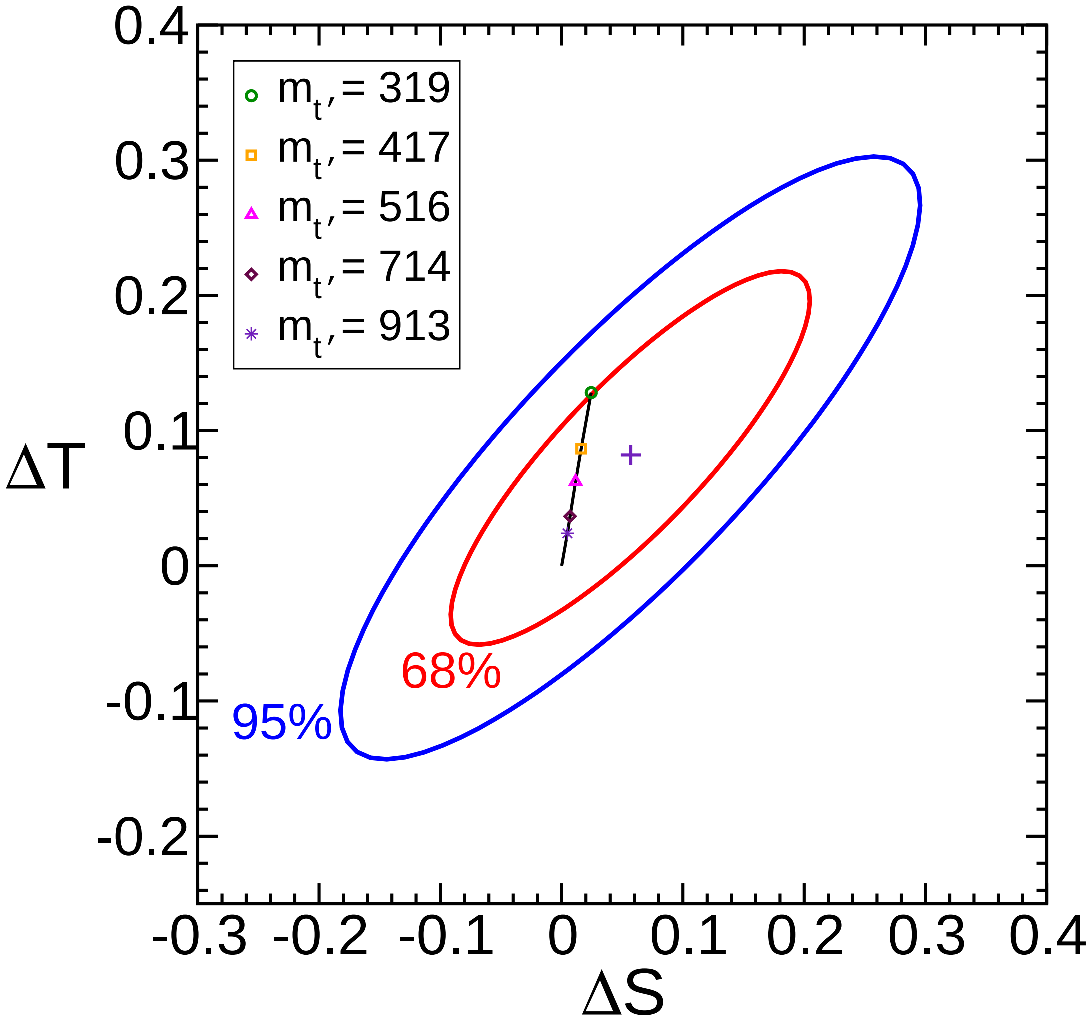


$$M_F = (m_{t'} m_{t''})^{1/2}$$

$$M_S = (m_{\tilde{t}'_1} m_{\tilde{t}'_2} m_{\tilde{t}'_3} m_{\tilde{t}'_4})^{1/4}$$

The pairs of lines are for maximal and minimal mixing suggested by RG fixed points for scalar^3 couplings.

Corrections to precision electroweak Peskin-Takeuchi S,T parameters



(SPM, to appear)

Does not include other MSSM contributions, which are typically smaller.

The lightest new (non-MSSM) particle is the t'.

The t' is pair produced at hadron colliders, decays by mixing with Standard Model quarks:

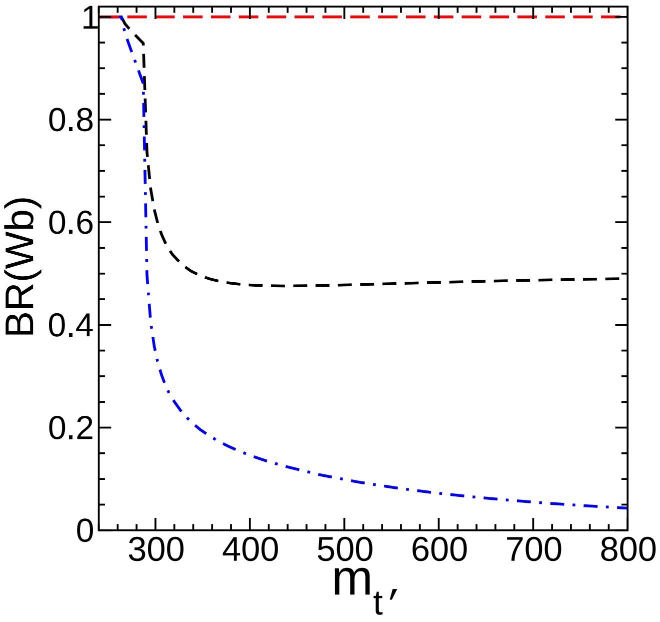
$$\begin{aligned} t' &\rightarrow Wb \\ t' &\rightarrow Zt \\ t' &\rightarrow h^0 t \end{aligned}$$

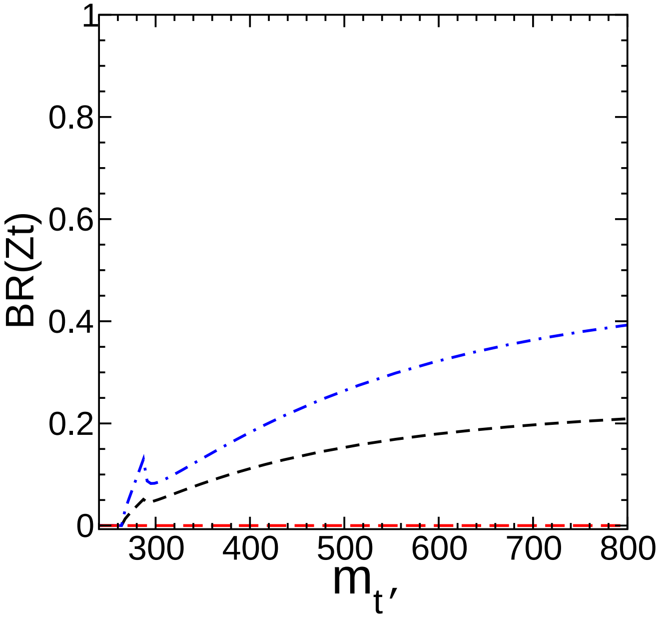
Tevatron bound is $m_{t'} > 311$ GeV, **if** $t' \rightarrow Wq$ is 100%
(CDF Note 9446, based on 2.8 fb^{-1}).

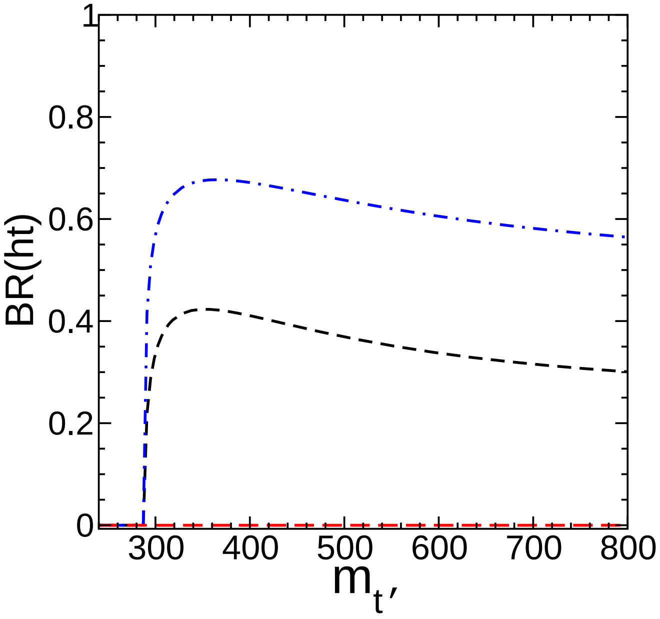
However, the other decays can be important or even dominant…

Branching ratios for $t' \to Wb$, Zt, and ht, from different kinds of mixing with Standard Model third family quarks.

Note that existing Tevatron search looks for $t' \to Wb$; plausible but hardly inevitable.







Maybe the Higgs in SUSY is lighter than 114 GeV, but hid from LEP2?

Adding another singlet Higgs scalar a to the MSSM, can hide from LEP if $2m_\tau < m_a < 2m_B$, or 3.6 GeV $<m_a<$ 10.5 GeV. Dermisek Gunion hep-ph/0502105, 0510322, 0611142.

Then

$$h \to aa \to \tau^+\tau^-\tau^+\tau^-$$

does not have a LEP bound for 86 GeV $\lesssim m_h \lesssim$ 100 GeV.

BaBar (2008) discovered the η_b, with $M_{\eta_b} \approx 9.39$ GeV. However, $M_{\Upsilon(1s)} - M_{\eta_b} = 71.4 \pm 4.1$ MeV, compared to two independent QCD calculations 44 ± 11 and 39 ± 14 MeV.

Perhaps the discrepancy is due to η_b mixing with a, with 9.4 GeV $< m_a < 10.5$ GeV? Domingo et al 0810.4736; Domingo Ellwanger Sanchis-Lozano 0907.0348

The stakes are high, so need to take this challenging scenario seriously.

How to discover the Higgs bosons h and a at LHC?

- $h^0 \rightarrow aa \rightarrow \tau\tau\tau\tau \rightarrow \mu\mu jj + \not{E}_T$ in Higgsstrahlung and/or Vector Boson Fusion

(Belyaev et al, 0805.3505)

- $pp \rightarrow pph^0 \rightarrow pp + \tau^+\tau^-\tau^+\tau^-$ using proposed forward detectors for the protons.

(Forshaw et al, 0712.3510)

- $h^0 \rightarrow \mu\mu\tau\tau$ using the rare dimuon decay mode.

(Lisanti Wacker 0903.1377)

The flavor problem is another challenge for SUSY. General flavor mixing in soft terms would mediate flavor changing processes:

To avoid this, an interesting proposal is the R-symmetric MSSM (RMSSM) of Kribs Poppitz Weiner 0712.2039.

Note: this is a continuous $U(1)$ R-**symmetry**; has nothing to do with discrete Z_2 R-**parity**!

Everything you knew about SUSY breaking in the MSSM is wrong!

- Gaugino masses are Dirac, not Majorana
- Left-right mixing for squarks and sleptons is absent
- Squarks and sleptons can be light, with anarchic flavor mixing
- Can't talk about "stops" or "selectrons"; they mix with charm, up squarks and tau, mu sleptons respectively!

LHC phenomenology of the R-symmetric MSSM is largely unexplored, and difficult. Some general features:

- The gauginos are heavy, so the LSP is not bino-like, but can be Higgsino-like or singlino instead.
- No Majorana masses for gauginos, so no same-charge dilepton signals
- Besides looking for e^+e^- and $\mu^+\mu^-$ mass edges, should also look for $e\mu$ mass edges.
- "First-family" squark production can decay to single tops, bottoms, since $\tilde{q} \rightarrow t\tilde{N}_1$ is not flavor-suppressed.

Similar features present in other flavor schemes for the MSSM (Feng et al 0712.0674; Nomura Papucci Stolarski 0712.2074) and other models with Dirac gauginos (Fox Nelson Weiner hep-ph/0206096)

Outlook: some opinions

- Supersymmetry remains the best solution to the hierarchy problem
- The “little” hierarchy problem is a strong suggestion that the simplest frameworks (mSUGRA, GMSB) are too simple
- Gaugino mass non-unification (especially a lighter gluino) is attractive
- The Minimal Flavor-Respecting SSM (15 to 19 new parameters, depending on who is counting) is a sensible framework to discuss collider phenomenology
- Even Flavor-Respect may well be too strong
- It is time for LHC collisions!