SUSY Breaking and Phenomenology

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Outline

1. Soft Breaking of SUSY

2. The MSSM

3. mSUGRA

4. Gauge Mediation

5. Anomaly Mediation
This is a huge field! I’ll present a very sparse overview. Some useful references:


John Terning, *Modern Supersymmetry*, early 2006?
Soft Breaking of SUSY
Breaking SUSY

- SUSY is clearly not exact in nature

- We must break it, but we want to do so without reintroducing quadratic divergences.

- This is called "soft SUSY breaking"

- Terms: $m\lambda\lambda$, $m^2_{ij}\phi^i\phi^j$, $A_{ijk}\phi^i\phi^j\phi^k$, $B_{ij}\phi^i\phi^j$, $C_i\phi^i$. 
A useful tool in the theoretical study of SUSY is to treat couplings as superfields. If the lowest component of a supermultiplet has a vev, it doesn’t break SUSY, i.e. $Q_\alpha \langle \Phi \rangle = 0$. On the other hand, a nonzero vev for a higher component of the multiplet will break SUSY. For instance, in a Lagrangian $\mathcal{L} = \int d^4 \theta Z \Phi^\dagger \Phi$, $Z$ can be treated as a real superfield with only its lowest component nonzero. (You can think of this as an explanation of why the superpotential is holomorphic in couplings, not just fields.)

(One also tends to treat the couplings as spurions transforming under symmetries.)
Brief theoretical aside, part 2.

But suppose higher components of the superfield are nonzero. $Z = 1 + (\theta^2 B + h.c.) + \theta^2 \bar{\theta}^2 C$. Then $\phi$ gets a mass $m^2 = -C + |B|^2$. You get SUSY breaking terms in this way, with their renormalization controlled by renormalization in the SUSY limit.

As another example, the gauge coupling turns into a superfield

$$\tau = \frac{1}{g^2} - \frac{i\theta_{vac}}{16\pi^2} - \theta^2 \frac{m_{\lambda}}{g^2}.$$ 

The vev of its higher (SUSY-breaking) component corresponds to a gaugino mass.

In general (modulo a subtlety or two) soft SUSY breaking terms come from higher components of superfield couplings in the Lagrangian.
The MSSM
The MSSM

The MSSM is the minimal SUSY extension of the Standard Model. The known matter and gauge fields are promoted to superfields. We have squarks and sleptons (separate partners for left- and right-handed fermions!), and gauginos.

The only subtlety is in the Higgs sector. The SM Higgs sector has one SU(2) doublet $h$. In the MSSM, we need two Higgs doublets, $H_u$ and $H_d$, coupling to up- and down-type fermions. This is because in the SM the up-type couplings involve an $h^*$, but in SUSY holomorphy of the superpotential forbids this coupling. Anomaly cancellation requires that the two Higgs doublets have opposite hypercharge.
Details of the MSSM

• The superpotential: \( W = y_U^{ij} Q_i u_j^c H_u + y_d^{ij} Q_i d_j^c H_d + y_l^{ij} L_i e_j^c H_d + \mu H_u H_d \). Yukawas + \( \mu \) term (more on that later.)

• SUSY breaking: gaugino masses \( M_1 \tilde{B}^2 + M_2 (\tilde{W}^a)^2 + M_3 (\tilde{g})^2 \)

• Scalar masses \( m_{Qij}^2, m_{uij}^2, m_{dij}^2, m_{Lij}^2, m_{eij}^2, m_{Hu}^2, m_{Hd}^2 \)

• “A” terms \( A_u^{ij} \tilde{Q}_i \tilde{u}_j^c H_u \), etc.

• “B” term \(-B\mu H_u H_d + h.c.\)
Phenomenological issues in the MSSM

- We impose **R-parity** to forbid proton decays and other problems. Lightest SUSY particle (**LSP**) is a dark matter candidate. Get a “missing energy” ($E_T$) signature at colliders.

- The $\mu$ problem: there is a relevant interaction $\Delta \mathcal{L} = \int d^2 \theta \mu H_u H_d$ not forbidden by any symmetry. But $\mu$ must not be large for EWSB to work properly. This can become a tricky model-building issue; might use e.g. a $U(1)$ Peccei-Quinn symmetry.

- Flavor constraints: scalar masses roughly flavor independent, $A$ terms roughly proportional to Yukawas.
SUSY breaking and the MSSM

- Radiative EWSB happens only as a consequence of SUSY breaking: hierarchy protected

- Hierarchy origin: $v \ll M_{Pl}$ if $m_{SUSY} \ll M_{Pl}$

- **Dynamical SUSY breaking** (Witten): $m_{SUSY}$ from dimensional transmutation.

- Dynamical SUSY breaking investigated by e.g. Affleck, Dine, Seiberg.
The “hidden sector” paradigm

It is difficult to directly couple a dynamical SUSY breaking sector to the Standard Model. Thus the usual paradigm is:

- **A hidden sector** at scale $\Lambda = M_{Pl} e^{-8\pi^2/g_0^2 b_0}$ breaks SUSY dynamically.

- **Supergravity** couples to all fields, both hidden and visible.

- The SM feels SUSY-breaking at a scale $m_{SUSY} = \Lambda^2/M_{Pl}$. Then $\Lambda$ is at the **intermediate scale** of about $10^{11}$ GeV.

- Often $\Lambda^2 = \langle F_X \rangle$, couplings $X^\dagger X Q^\dagger Q$, $X H_u H_d$, etc.
From high-scale to low-scale

Most SUSY-breaking models determine all the soft terms of the MSSM in terms of a small number of parameters at some high scale. This might be, for instance, the GUT scale.

One can then determine the low-energy MSSM spectrum (with all mixings and couplings) by RG running from the high scale down to the low scale.

There are some software packages that automate this process, e.g. IsaSUSY and Suspect, and output MSSM parameters in Les Houches accords format. This can then be fed into Pythia. It’s easy to simulate arbitrary SUSY models in this way.
mSUGRA: the usual unmotivated ansatz
**mSUGRA: “Minimal Supergravity”**
(Hall, Lykken, Weinberg; Barbieri, Ferrara, Savoy)

Something of a misnomer: mSUGRA is a specific, but not well-motivated (or radiatively stable!), assumption about gravity mediation. Features:

- \( m_0, m_{1/2}, A_0 \): universal scalar mass, gaugino mass, trilinear coupling at high scale
- \( \tan \beta \): ratio of Higgs vevs
- \( \text{sign } \mu \): rest is determined by requiring EWSB
“Snowmass Points and Slopes” Point 1a (hep-ph/0202233)
General mSUGRA Features

- Under RGE, gauge interactions raise scalar masses, Yukawa interactions decrease them.

- Squarks are heavier than sleptons, gluinos heavier than winos

- Left-handed scalars are heavier than right-handed scalars.

- Large left-right mixing in sbottom, stop, stau: stop is usually lightest squark. Stau is usually lightest slepton.
General mSUGRA Features

- SUSY production dominated by $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$ at LHC (not necessarily at Tevatron!)

- $H_u$ mass-squared most easily goes negative (from Yukawas): so EWSB works.

- Need some sort of flavor symmetry for this ansatz to really make sense.
Generic mSUGRA Points at Colliders

One “golden” discovery mode (especially for the Tevatron) with low background is the trilepton signature from $\chi_1^+ \chi_2^0 \rightarrow \ell^+ \ell^+ \ell^- + 2\chi_1^0$.

At the LHC one is more frequently making the heavier but more strongly interacting squarks and gluinos. A discovery can be made simply by looking for high-$p_T$ leptons and jets in events above a certain “sphericity” threshold to reduce dijet backgrounds from QCD, and $E_T > 100$ GeV or more. One can quickly establish an excess over the SM, and then an “effective mass” $(E_T + \sum_{i=1}^{4} p_{T_i})$ gives a rough idea of the mass scale.
Focus Point mSUGRA

The focus point region of mSUGRA space offers different phenomenology (people talk about some other different regions, e.g. coannihilation region; we won’t get into that). In the focus point region, $m_0$ is large and the LSP is Higgsino-like. The gluino is lighter than the squarks.

In this region (also called “hyperbolic branch”) large radiative corrections result in a small $\mu$, not so much fine-tuning needed for $Z$ mass. This region might not exist if the top mass is at the low end of its allowed range.
“Snowmass Points and Slopes” Point 2: Focus Point (hep-ph/0202233)
Gauge mediation
Gauge mediation (GMSB)
(Dine, Fischler, Srednicki; Dimopoulos, Raby; Dine, Nelson; others?)

- Gauge interactions couple hidden and visible sectors.

- Simplest: $N_5$ vector-like $5 + \bar{5}$ of $SU(5)$ to preserve grand unification.

- Universal messenger mass $M_{mess}$.

- Messenger sector chiral superfields have SUSY-breaking mass $F$, so masses are at $\Lambda = F/M_{mess}$. 
More on GMSB

• SUSY breaking scale is relatively low: $F < 10^{10}$ GeV (if it’s higher, you get larger SUGRA contributions to gaugino masses)

• Gaugino masses at one loop (since new fields have gauge charge): $\tilde{M}_\tilde{g} \approx \alpha_s N_5 \Lambda$

• Squark and slepton masses at two loops (couple to gauge fields, gauge fields couple to messengers): $\tilde{M}_{\tilde{e}} \approx \alpha \sqrt{N_5} \Lambda$ (no flavor problem!)

• Six parameters: $\Lambda, M, N_5, \tan \beta, \text{sign} \mu, C_{\text{grav}}$
Gauge mediation spectrum

- The LSP is the gravitino $\tilde{G}$, $m_{3/2} = F_0/(\sqrt{3}M_{Pl}) \ll 100$ GeV.

- Distinguishing signatures depend on the NLSP.

- A neutralino NLSP ($N_5 = 1$) gives $\tilde{\gamma} \rightarrow \gamma \tilde{G}$: lots of photons!

- A slepton NLSP ($N_5 \gg 1$: often stau) gives an abundance of leptons plus $E_T$. 
SPS Point 7: $\tilde{\tau}$ NLSP GMSB (hep-ph/0202233)
Note squark/slepton mass ratio is significantly bigger, $\sqrt{3}\alpha_s/\alpha$.

Heavy stop: fine-tuning is a concern!
Delayed decays in GMSB

It is possible in GMSB for the NLSP to be quasi-stable. Its lifetime goes as $F^2/m_{NLSP}^5$. This can lead to striking collider signatures, and also means that a determination of the mass and lifetime of the NLSP lead to a determination of the fundamental SUSY breaking scale.

Suppose the NSLP is a neutralino. Then one has decays $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$ that can happen at macroscopic distances in the detector from the interaction point. If one has enough granularity in the EM calorimeter, one can see that the photons are non-pointing, i.e. they did not come from the interaction point directly!
Anomaly Mediation (AMSB)
The AMSB Model
(Randall, Sundrum; Giudice, Luty, Murayama, Rattazzi. 1998)

In some sense AMSB is the true “minimal” gravity mediation model. The SUGRA Lagrangian can be written in terms of the superconformal supergravity multiplet together with a “superconformal compensator” supermultiplet $\phi = (\eta, \chi, F_\phi)$. (This might look weird, but there’s a similar treatment of normal non-SUSY GR! In some gauge this reduces to normal SUGRA.)

Why would we do this? We can write appropriate powers of $\phi$ to make terms superconformal invariant. Think of it as a bookkeeping device. Then a SUSY breaking VEV $\langle F_\phi \rangle \neq 0$ can be introduced. At tree-level the only term in the MSSM that isn’t scale invariant is the $\mu$ term, but at loop level $F_\phi$ can contribute. Let’s see what this means....
Consequences of AMSB

We are assuming SUSY is broken only by $\langle F_\phi \rangle$ in the conformal compensator. We know this only affects us at loop level (aside from the $\mu$ term). But all of the $\phi$ dependence in our loop corrections is determined by conformal invariance. In the end, this amounts to saying all our soft terms are set by the conformal anomaly, i.e. by $\beta$ functions!

We get gaugino masses $m_\lambda = \frac{\beta(g)}{2g} F_\phi$, and scalar masses at two loops, $m^2 = -(1/4)|F_\phi|^2 d\gamma/d(\log \mu)$. (This means we still have the fine-tuning worry of GMSB!)

Is AMSB reasonable? Planck-suppressed contributions $\frac{1}{M^2_{Pl}} X^\dagger X Q^\dagger Q$ generally give bigger scalar masses. Why would they be absent? Randall and Sundrum proposed that $X$ and $Q$ live on different branes.
The AMSB Gaugino Spectrum

The gaugino mass ratios are $M_1 : M_2 : M_3 = 3 : 1 : 8$, approximately. The LSP then is a set of nearly degenerate winos, and the gluinos are almost an order of magnitude heavier.

(A sign that I was thinking too much about SUSY while writing this talk: I was surprised to Google “degenerate winos” and find hits totally unrelated to physics.)

We’ll look closely at degenerate winos shortly, because it’s a nice example of an unusual signal of the sort one doesn’t often think about.
The Tachyonic Slepton Problem

The RG running for AMSB with nothing added gives tachyonic slepton masses! (Since they do not couple to $SU(3)$ and the electroweak running goes the wrong way.)

The minimal, but ad hoc, way to fix this is to add universal scalar masses $m_0$. There are other more sophisticated approaches; in the original Randall-Sundrum AMSB paper they had contributions from bulk fields.

The main thing to keep in mind is that degenerate winos are a feature of any AMSB-dominated scenario, but the scalar sector can be highly model-dependent.
Degenerate Winos

Depending on the splitting $\Delta M = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$, one can get very different behavior. The decay is $\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0$ if accessible, otherwise $\tilde{\chi}_1^\pm \rightarrow e^\pm \tilde{\chi}_1^0$.

Other models with wino LSPs often have a near-degeneracy as well. For the Tevatron this was studied in detail by Feng, Moroi, Randall, Strassler, and Su (hep-ph/9904250). They argued:

I. For long-lived enough winos, one can look for $q\bar{q} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0, \tilde{\chi}_1^+ \tilde{\chi}_1^-$ just by searching for heavy particles triggering in the muon chamber, with low velocity and high ionization.

II. For shorter lifetimes, one can look for pair-production of charginos or a chargino and neutralino in association with a jet. One can trigger on jet plus $E_T$.
More on Degenerate Winos

Feng et. al. make a further argument: if the winos decay before reaching the muon chamber, they will make a stiff track but will not leave localized energy in the calorimeter. This is strange! They proposed a Tevatron trigger on events with a stiff track but little hadronic energy (or more conservatively, on events with two balanced stiff tracks). If the decay product is hard enough, one might hope to see a track with a kink in it, but generally this wouldn’t happen.

That’s a nice analysis at the Tevatron; what happens at the LHC? Ian Hinchliffe at least says that ATLAS triggers are good enough to pick up any model anyone has come up with. There’s a study by Allanach, Barr, Lester, Parker, and Richardson (hep-ph/0208214) of AMSB at ATLAS. Let’s see what they found.
AMS B at the LHC (Allanach et al.)

General idea: can look for cascade decays of squarks; these will often have a lepton. Multi-lepton + $E_T$ searches are straightforward. How do we pin down the wino LSP?

Case 1: $\Delta M < m_\pi$. With the pion decay mode unavailable, the $\tilde{\chi}_1^+$ is long-lived and leaves a track in the muon chamber. With $dE/dx$ and time-of-flight measurements, it can be discriminated from muons and the mass can be estimated. If the lifetime is short enough that some still decay in the inner detector, the fraction decaying gives additional mass information.
AMS B at the LHC (Allanach et al.)

Case 2: $m_\pi < \Delta M < 200$ MeV: chargino tracks often decay in the detector. Look for kinks or for disappearing tracks. Thus the major backgrounds are detector backgrounds. Must understand tracking very well.

Case 3: 200 MeV < $\Delta M$ < few GeV. (Unlikely in AMSB.) Chargino can decay before leaving a track; need to find the tracks of the electron or pion it decays to. This is probably the most difficult case; have heavy quark backgrounds. Use isolation cuts, impact parameter.
Conclusions?

- Most studies look at a few mSUGRA points – but other models can have drastically different spectra!

- Many others we didn’t consider – gaugino mediation, intersecting brane models, stringy models with various moduli stabilization schemes, split SUSY (long-lived gluinos)...

- The map from models to collider signatures is probably many-to-one, so it’s not clear how much one learns about high-scale physics.

- Interesting things to think about are cases with near degeneracy (as in first LHC Olympics dataset?), long-lived particles, and other things that look strange in the detector.