Supersymmetric extensions of the Standard Model

(Lecture 3 of 4)

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Outline

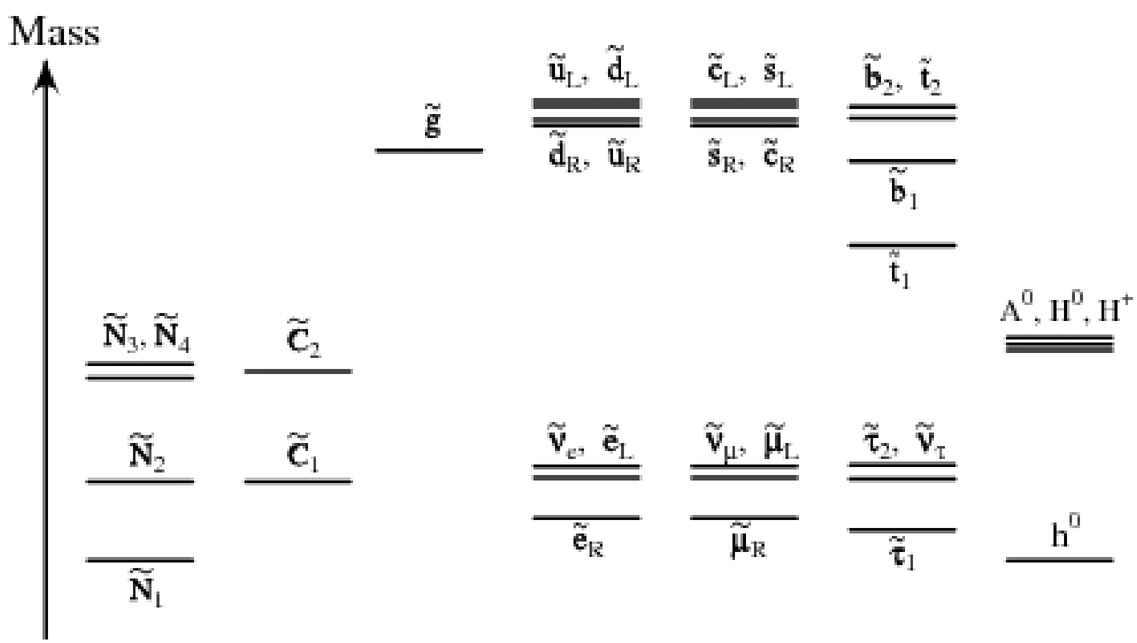
Lecture 1: Introducing SUSY

Lecture 2: SUSY Higgs sectors

Lecture 3: Superpartner spectra and detection

Lecture 4: Measuring spins, couplings, and masses

In my first lecture I showed a schematic sample SUSY spectrum (which may or may not have anything to do with reality):



from Martin, hep-ph/9709356

Some features:

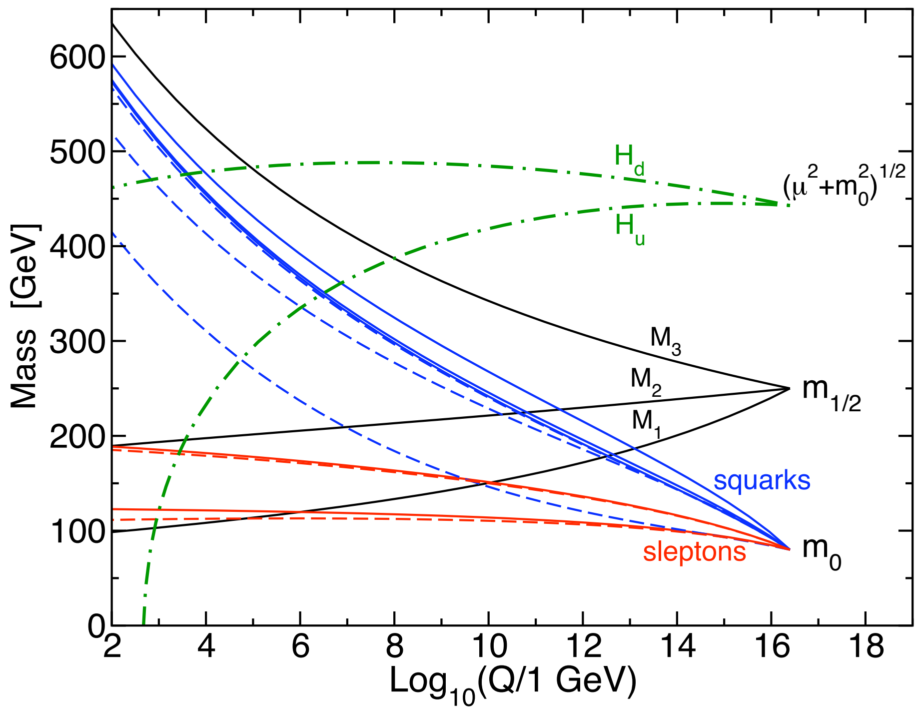
- $\widetilde{N}_1$ is the LSP
- $\tilde{t}_1$ and $\tilde{b}_1$ are the lightest squarks
- $\tilde{\tau}_1$ is the lightest charged slepton
- Colored particles are heavier than uncolored particles

Where do these features come from?

SUSY particle masses are (presumably) set at a high scale by some SUSY-breaking mechanism.

Masses run down by renormalization group equations.

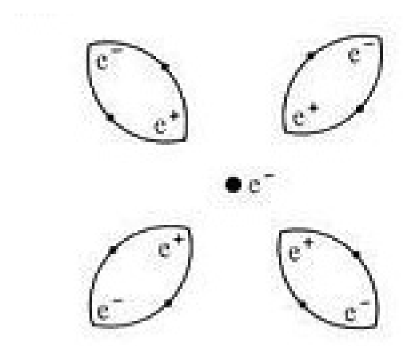
E.g., "Constrained MSSM" (CMSSM, a.k.a. mSUGRA):



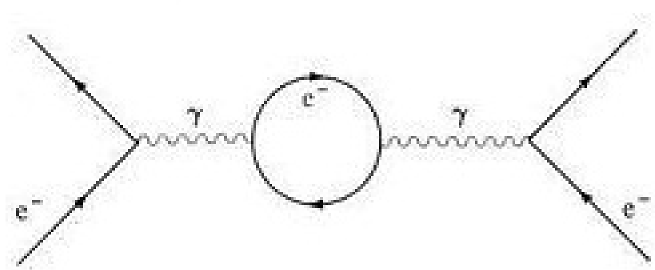
from Martin, hep-ph/9709356

To do phenomenology, we need to know what the SUSY breaking terms are at the electroweak scale.

These are different from the high-scale SUSY breaking terms because of vacuum polarization.



Charge measured at large distance (low energy) is different from charge measured at short distance (high energy) due to screening by virtual particles.



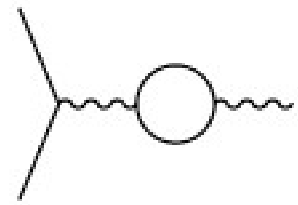
[figure stolen from universe-review.ca]

Same idea applicable to other couplings, masses, etc.

Coupling dependence on scale is encoded in renormalization group equations.

Gauge couplings: Running is given by the beta functions b_a.

$$\frac{d}{dt}\alpha_a^{-1} = -\frac{b_a}{2\pi} \qquad (a = 1,2,3)$$



- the energy scale dependence is encoded by $t \equiv \ln(Q/Q_0)$

Q is the "current" scale; Q_0 is the starting scale

- $a = 1,2,3$ refers to $\mathrm{U}(1)_Y$, $\mathrm{SU}(2)_L$, and $\mathrm{SU}(3)_c$ gauge couplings

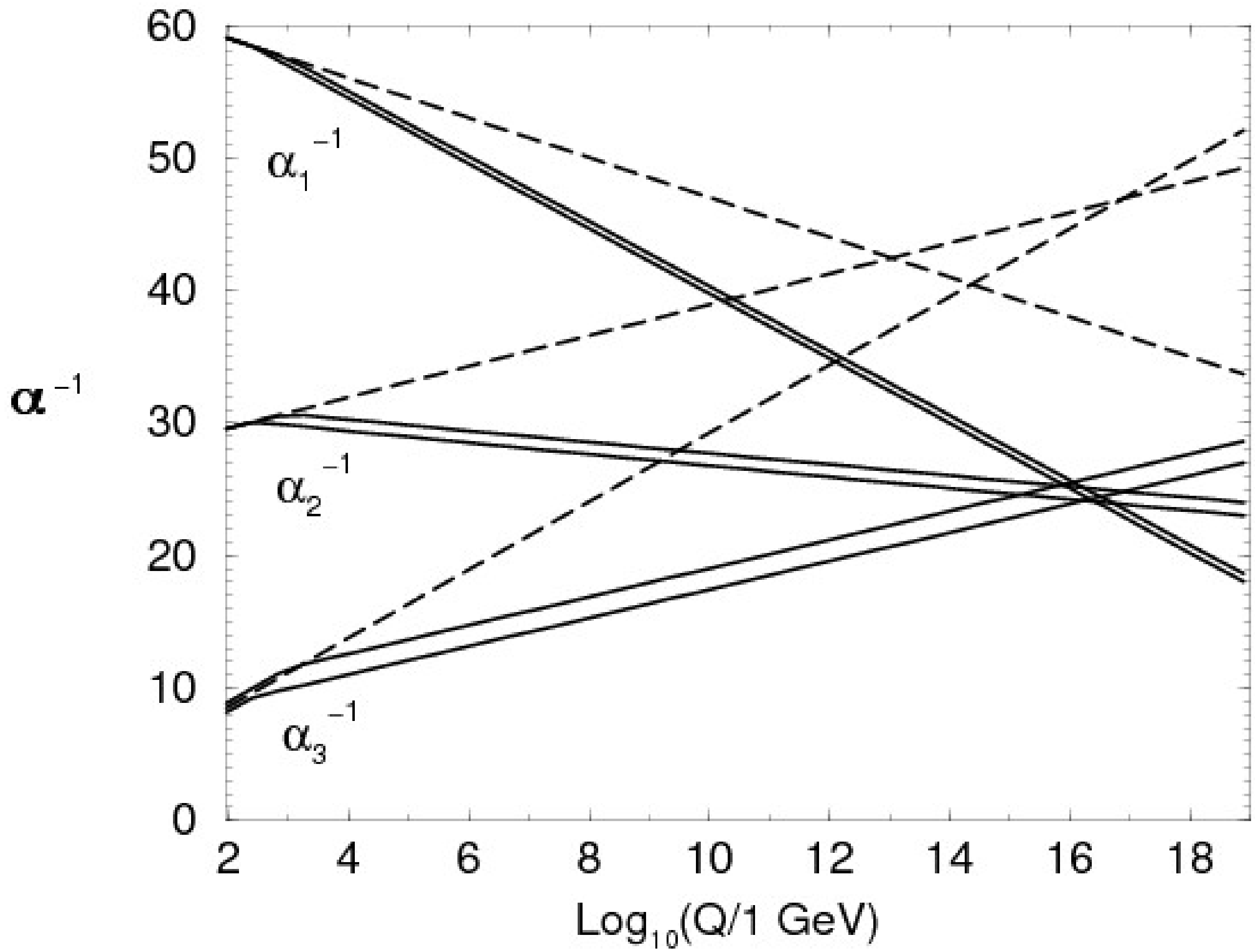
- The beta functions b_a are what you get when you calculate all the loop diagrams:

$$b_a^{\mathrm{SM}} = \left(\frac{41}{10}, -\frac{19}{6}, -7\right) \qquad b_a^{\mathrm{MSSM}} = \left(\frac{33}{5}, 1, -3\right)$$

These depend on the number of particles and their gauge charges.

Gauge couplings:

figure from Martin, hep-ph/9709356



Dashed lines: SM Solid lines: MSSM

(Bands are the uncertainties in the low-energy values.)

Here's another glory of SUSY: gauge coupling unification!

Gaugino mass parameters:

Running determined by same b_a as gauge couplings:

$$\frac{d}{dt}M_a = \frac{1}{8\pi^2} b_a \, g_a^2 M_a \qquad\qquad b_a^{\mathrm{MSSM}} = \left(\frac{33}{5}, 1, -3\right)$$

Ratios M_a/g_a^2 are scale independent up to small 2-loop effects.

In mSUGRA (Constrained MSSM), the gaugino masses unify:

$$M_1(M_{\mathrm{Pl}}) = M_2(M_{\mathrm{Pl}}) = M_3(M_{\mathrm{Pl}}) \equiv m_{1/2}$$

Gauge couplings also unify nearby, at $M_{\mathrm{GUT}} \simeq 0.01 M_{\mathrm{Pl}}$, so

$$g_1^2(M_{\mathrm{Pl}}) \approx g_2^2(M_{\mathrm{Pl}}) \approx g_3^2(M_{\mathrm{Pl}}) \approx g_{\mathrm{GUT}}^2$$ [$g_1 = \sqrt{5/3}g'$: GUT norm'n]

Therefore in the CMSSM (and any model with gaugino mass unification near M_{Pl}),

$$\frac{M_1}{g_1^2} \simeq \frac{M_2}{g_2^2} \simeq \frac{M_3}{g_3^2} \simeq \frac{m_{1/2}}{g_{\mathrm{GUT}}^2}$$

Low-scale gaugino mass parameters satisfy unification relations:

$$M_1 = \frac{g_1^2}{g_2^2} M_2 \simeq 0.5 M_2 \qquad\qquad M_3 = \frac{g_3^2}{g_2^2} M_2 \simeq 3.5 M_2$$

M_1: bino mass parameter, controls mass of lightest neutralino in mSUGRA.

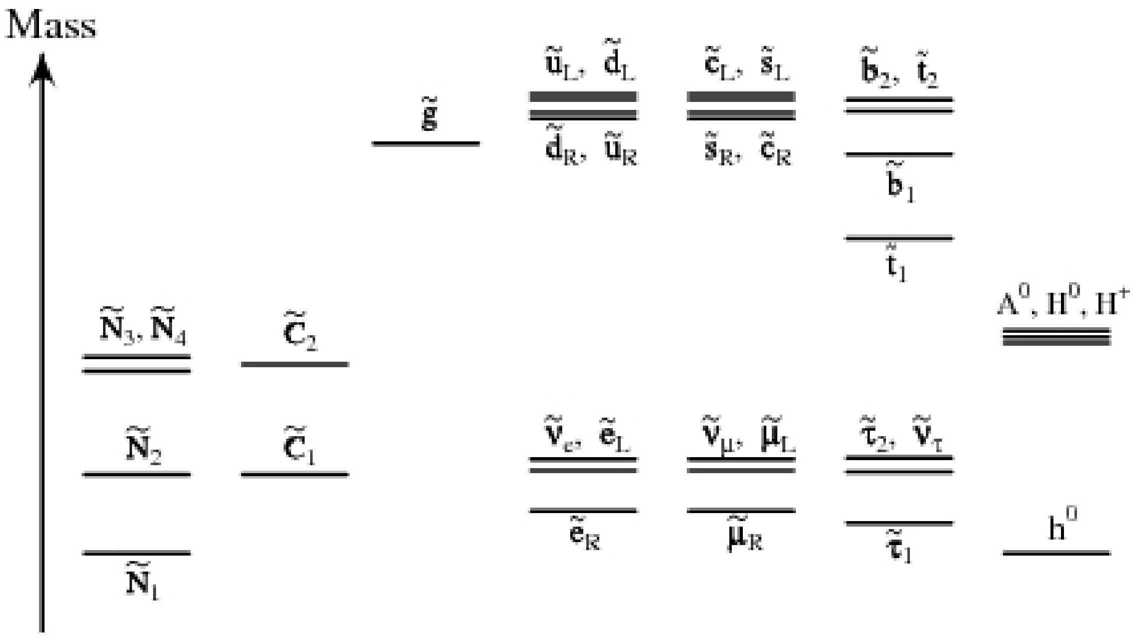
M_2: wino mass parameter, controls mass of one chargino and one neutralino.

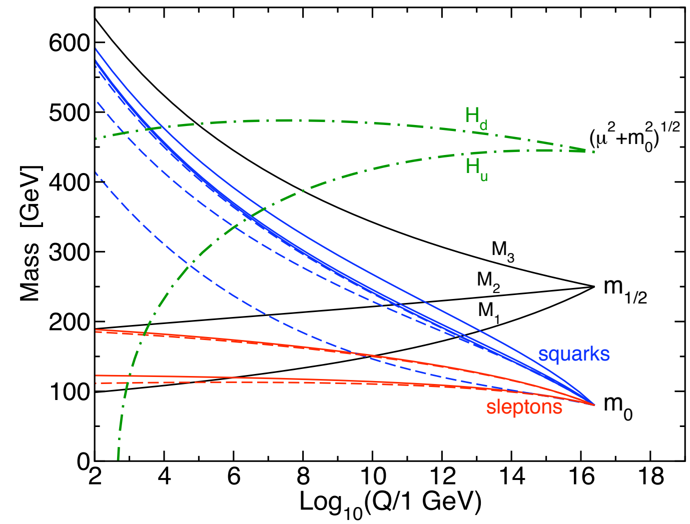
(Other chargino and two neutralinos controlled by Higgsino mass parameter μ)

M_3: gluino mass parameter: this is the mass of the gluino.

This unification assumption underlies usually-quoted mass limits on lightest neutralino: really the limit is on M_2 from chargino searches at LEP and Tevatron.

These relations can be avoided in models in which the gaugino masses do not unify at the GUT scale; e.g. gauge mediated models.





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Gaugino mass unification:

$$M_1 = \frac{g_1^2}{g_2^2} M_2 \simeq 0.5 M_2 \qquad\qquad M_3 = \frac{g_3^2}{g_2^2} M_2 \simeq 3.5 M_2$$

$$M_{\widetilde{N}_1} \simeq 0.5\ M_{\widetilde{N}_2,\widetilde{C}_1} \qquad\qquad M_{\widetilde{g}} \simeq 3.5\ M_{\widetilde{N}_2,\widetilde{C}_1}$$

These relations can be avoided in models in which the gaugino masses do not unify at the GUT scale; e.g. gauge mediated models.

Higgs sector mass parameters

recall $V_{\text{breaking}} \supset m^2_{H_1} H_1^\dagger H_1 + m^2_{H_2} H_2^\dagger H_2$

$$16\pi^2 \frac{d}{dt} m^2_{H_1} = 3X_b + X_\tau - 6g_2^2|M_2|^2 - \frac{6}{5}g_1^2|M_1|^2$$
$$16\pi^2 \frac{d}{dt} m^2_{H_2} = 3X_t - 6g_2^2|M_2|^2 - \frac{6}{5}g_1^2|M_1|^2$$

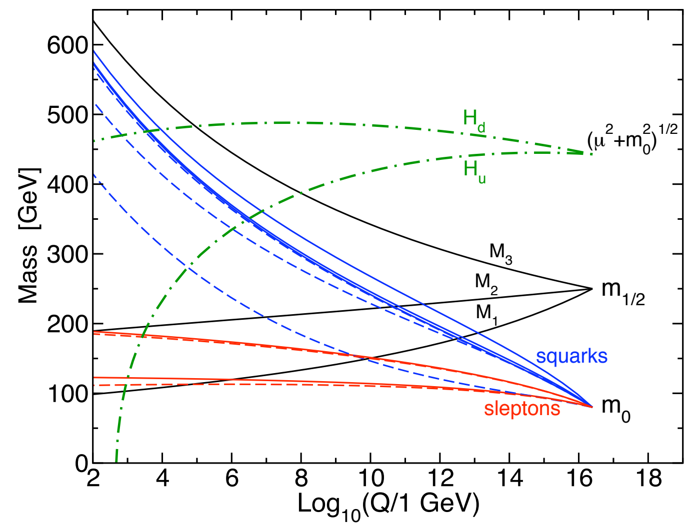
X_t, X_b, X_τ are some convenient positive-definite parameter combinations,

$$X_t = 2|y_t|^2(m^2_{H_u} + m^2_{Q_3} + m^2_{\bar{u}_3}) + 2|a_t|^2$$
$$X_b = 2|y_b|^2(m^2_{H_d} + m^2_{Q_3} + m^2_{\bar{d}_3}) + 2|a_b|^2$$
$$X_\tau = 2|y_\tau|^2(m^2_{H_d} + m^2_{L_3} + m^2_{\bar{e}_3}) + 2|a_\tau|^2$$

$X_{t,b,\tau}$ decrease the Higgs masses as you evolve down from the GUT scale.

Can start with positive m_{H_u} and m_{H_d} at the GUT scale and have them run negative by the EW scale.

This is radiative electroweak symmetry breaking – usually caused by X_t because y_t is large.



from Martin, hep-ph/9709356

Squark and slepton mass parameters:

The RGEs for the 3rd generation are:

$$16\pi^2 \frac{d}{dt} m^2_{Q_3} = X_t + X_b - \frac{32}{3} g_3^2 |M_3|^2 - 6 g_2^2 |M_2|^2 - \frac{2}{15} g_1^2 |M_1|^2$$

$$16\pi^2 \frac{d}{dt} m^2_{\bar{u}_3} = 2X_t - \frac{32}{3} g_3^2 |M_3|^2 - \frac{32}{15} g_1^2 |M_1|^2$$

$$16\pi^2 \frac{d}{dt} m^2_{\bar{d}_3} = 2X_b - \frac{32}{3} g_3^2 |M_3|^2 - \frac{8}{15} g_1^2 |M_1|^2$$

$$16\pi^2 \frac{d}{dt} m^2_{L_3} = X_\tau - 6 g_2^2 |M_2|^2 - \frac{3}{5} g_1^2 |M_1|^2$$

$$16\pi^2 \frac{d}{dt} m^2_{\bar{e}_3} = 2X_\tau - \frac{24}{5} g_1^2 |M_1|^2$$

RGEs for 1st and 2nd generations are the same but without the $X_{t,b,\tau}$ Yukawa contributions.

Large g_3^2 contribution runs squarks heavier than sleptons.

$X_{t,b,\tau}$ contributions run 3rd gen lighter than 1st & 2nd. [dashed lines]

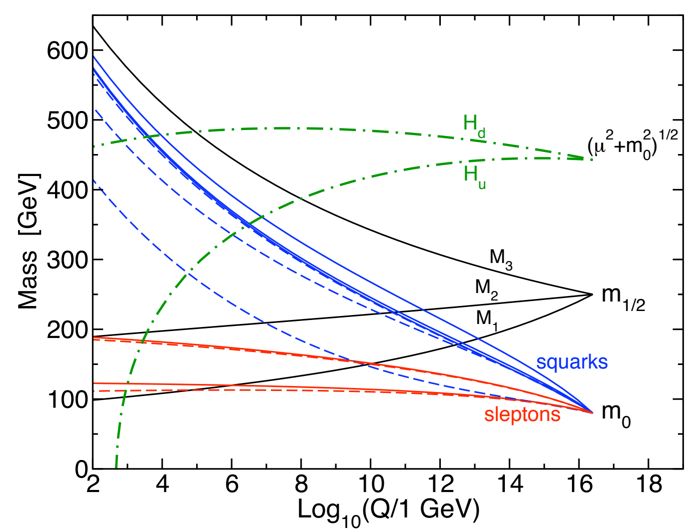


figure from Martin, hep-ph/9709356

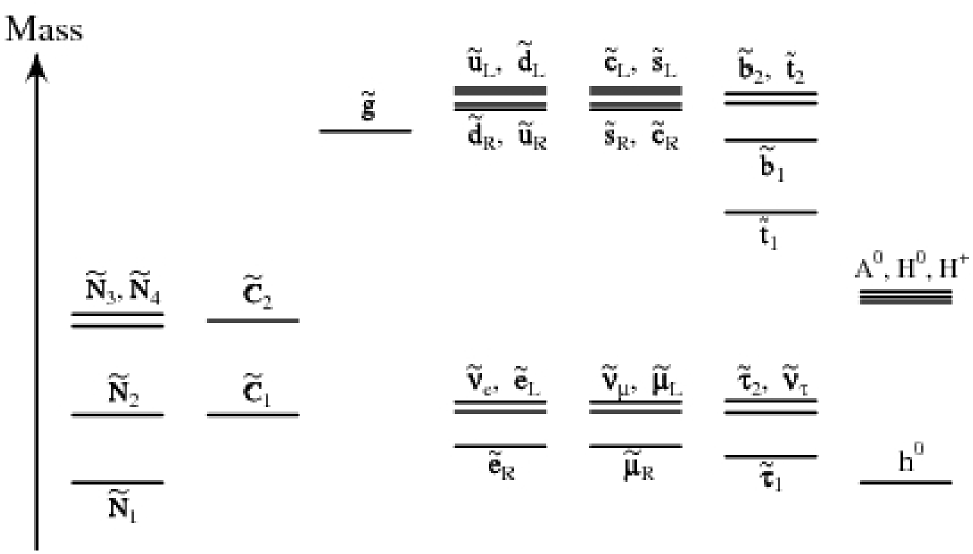
What have we learned from the RGEs?

- Squarks run heavier than sleptons due to g_3^2 contribution.
- Gluino runs heavier than weak gauginos due to strong g_3.

Expect colored sparticles to be heavier than uncolored sparticles.
[if their high-scale masses are not too different]

- Third generation runs lighter due to Yukawa contributions.

Combined with $\widetilde{f}_L$–$\widetilde{f}_R$ mixing in 3rd gen, expect lightest squark, slepton to be 3rd-gen.



Collider complementarity

LHC: Produce heavy colored particles via QCD; lighter uncolored particles harder to see (lower rates).

ILC: Produce lighter uncolored particles via EW interactions; heavy colored particles beyond kinematic reach.

SUSY particles and collider phenomenology

The general features of SUSY phenomenology are controlled by:

R-parity conservation [introduced to avoid fast proton decay]

- Lightest R-odd particle (LSP) is stable
- Decay chains of R-odd (SUSY) particles must end in LSP
- LSP as dark matter: requires LSP to be neutral and uncolored
  $\rightarrow$ escapes from detector $\rightarrow$ missing energy

Mass spectrum [controlled by SUSY breaking and RGEs]

- Heavier particles decay through a cascade of lighter particles
  $\rightarrow$ High multiplicity of objects in SUSY events – multijets, multileptons
- NLSP affects event content:
  - light stau $\rightarrow$ events with taus
  - light sbottom $\rightarrow$ events with b-jets

Couplings

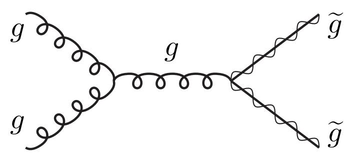
- In general, couplings are just the supersymmetrized version of SM couplings. Necessary to preserve solution to the hierarchy problem!

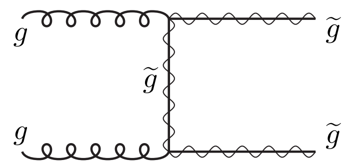
Superparticle production at hadron colliders

SUSY particles are produced in pairs (because of R-parity).

Production via QCD generally dominates, even though squarks and gluinos are typically heavy:

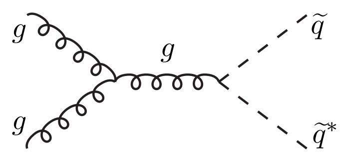
Gluino pairs

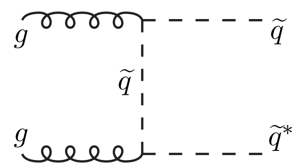


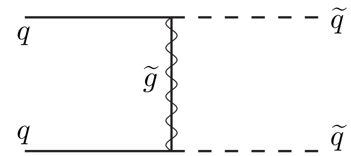


etc.

Squark pairs

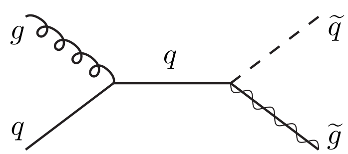


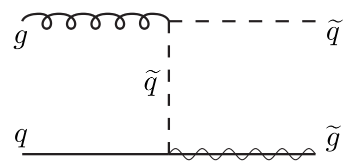




etc.

Squark + gluino





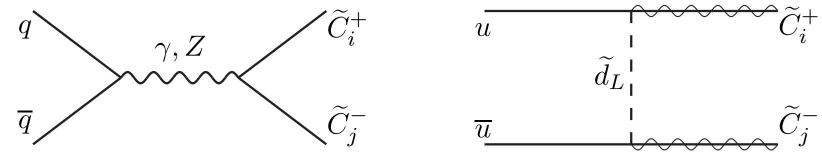
etc.

LHC reach depends on mass spectrum.
Reach for gluinos & squarks is typically out to about 2 TeV.

Superparticle production at hadron colliders

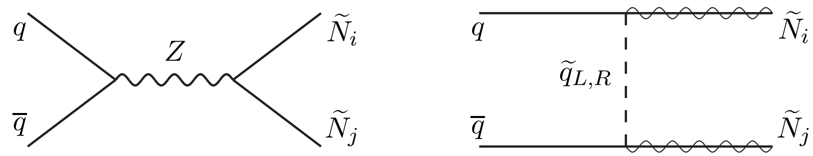
Production via electroweak interactions is also possible.

Chargino pairs

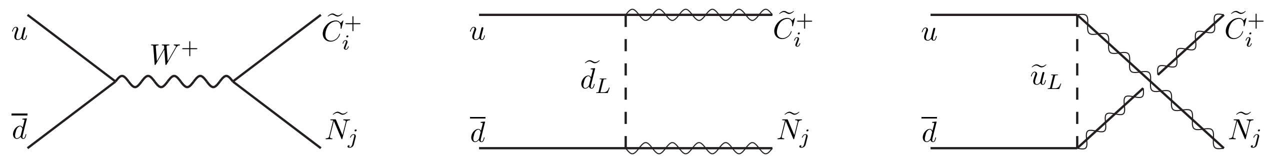


etc.

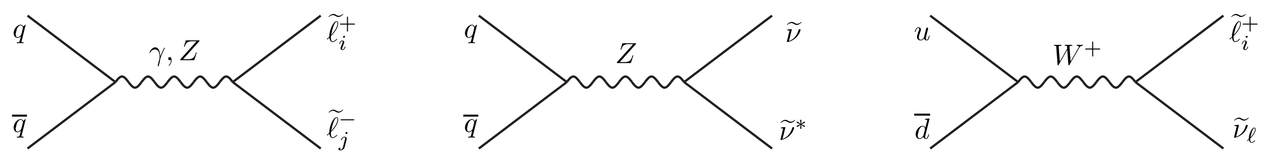
Neutralino pairs



Chargino + neutralino



Slepton pairs



Rates are smaller than for colored particles because production cross sections involve EW couplings.

Superparticle decays

Gluino decays: always to $q\,\tilde{q}$.

If $M_{\widetilde{g}} < M_{\widetilde{q}}$, then gluino will decay via an off-shell squark:
3-body decays, $\widetilde{g} \to q\widetilde{q}^* \to q\bar{q}\widetilde{N}_i$ or $q\bar{q}'\widetilde{C}_i$

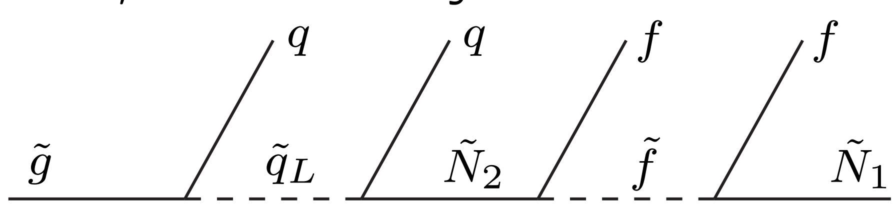
Squark decays:
To $q\,\tilde{g}$ (strong coupling) if kinematically allowed.
Otherwise $q\,\widetilde{N}$ or $q\,\widetilde{C}$ or (for 3rd gen.) $q\,\widetilde{H}$.
Decay branching fractions controlled by squark and -ino compositions.

Slepton decays: to $\ell\,\widetilde{N}$ or $\ell\,\widetilde{C}$ $\quad$ ($\ell = \ell^{\pm}$ or ν as appropriate)

Neutralino and chargino decays: to $\ell\,\tilde{\ell}$ or $q\,\tilde{q}$,
or to gauge or Higgs boson + lighter neutral-/charg-ino

Typically get decay chains, which always end with the LSP.

For example:



Generic signatures of SUSY at hadron colliders:

Missing transverse energy
- From two escaping LSPs

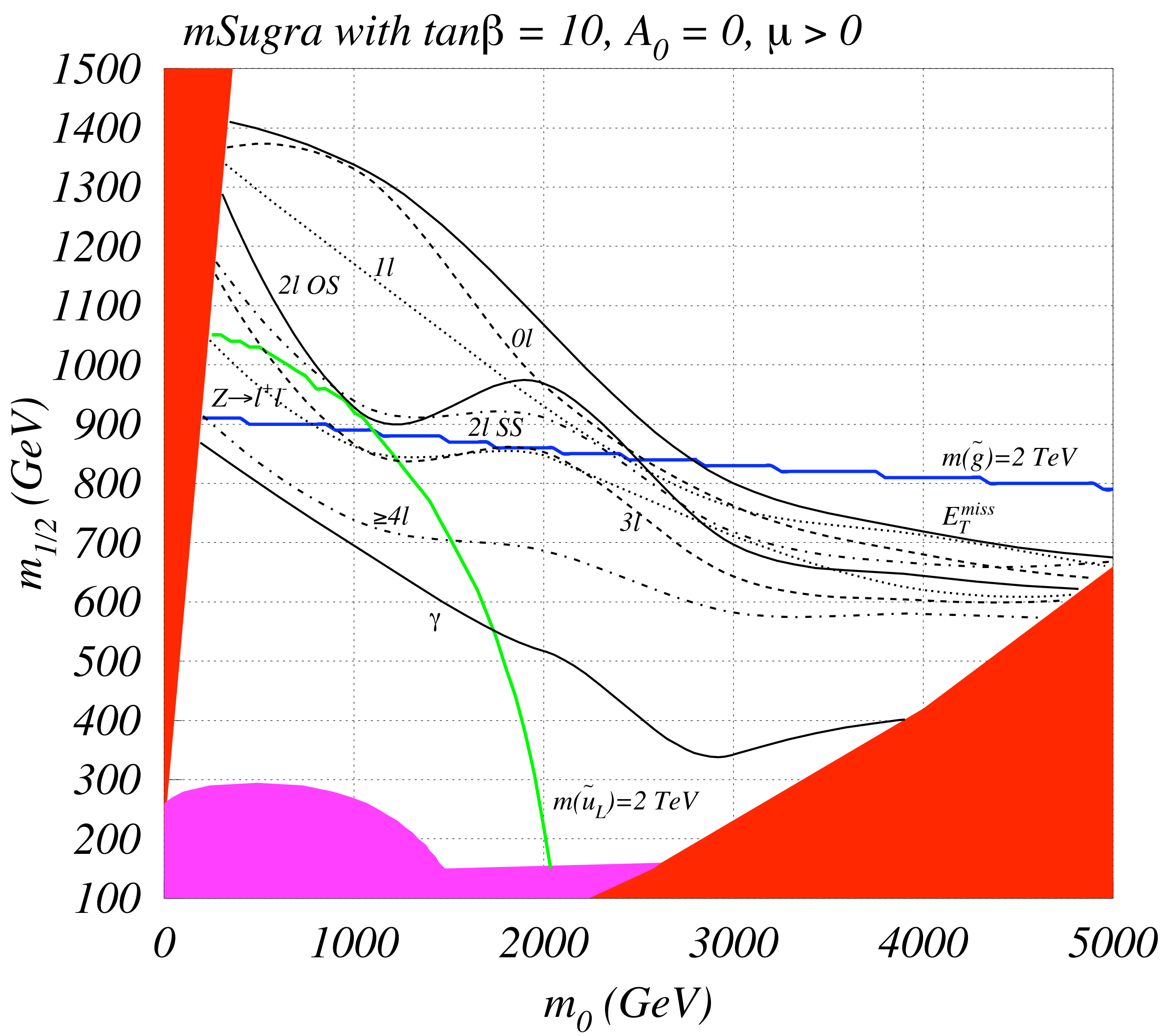
Large jet multiplicity
- Produce heavier SUSY particles via QCD; long decay chains

Large $\sum E_T$ in event
- Decay of heavy particles produces energetic jets, leptons
- Relatively spherical distribution in detector

Like-sign leptons or b-jets
- Gluino is Majorana—decays equally likely to $q\,\tilde{q}^*$ or $\bar{q}\,\tilde{q}$
- Decay chain gives leptons—like-sign if $qq\tilde{q}^*\tilde{q}^*$ or $\bar{q}\bar{q}\tilde{q}\tilde{q}$

Many more specific signatures have been studied in detail.
Signatures depend strongly on mass spectrum.

LHC reach for discovering SUSY [an example in mSUGRA]



from Baer, Balázs, Belyaev, Krupovnickas, & Tata, hep-ph/0304303

SUSY breaking and phenomenological problems

The flavor sector has features that happen “by accident” in the Standard Model that must be engineered in the MSSM.

Small flavor-changing neutral currents

- SM: GIM mechanism
- MSSM: generic set of SUSY-breaking squark and slepton mass terms cause large mixing: disastrously huge contributions to flavor-changing observables.

CP violation appears to come only from phase of the CKM matrix

- SM: CKM matrix is the only possible source of CP violation (aside from $\theta_{\rm QCD}$...)
- MSSM: generic set of SUSY-breaking couplings can have lots of new CP-violating phases: disastrously huge contributions to CP-violating observables (electric dipole moments, etc.)

Solutions to these problems drive the form of the SUSY-breaking mediation mechanisms.

SUSY-breaking models try to keep SUSY breaking "flavor-blind", so that the only flavor dependence comes from the CKM matrix.
- Prevents large flavor-changing effects that would come from different mixing among squarks than among quarks
- Prevents large CP-violation by avoiding new phases in squark sector

Make the 3 generations of each squark type degenerate at the high scale:
$\to$ characteristic mass patterns in low-energy spectrum due to RGE running
$\to$ squark flavors correspond to quark flavors

SUSY-breaking mediation mechanisms

"Minimal supergravity" (mSUGRA), also called the Constrained MSSM (CMSSM)

- Non-universal scalar mass model (for dark matter)

Gauge-mediated SUSY breaking (GMSB)

Anomaly-mediated SUSY breaking (AMSB)

“Minimal supergravity” (mSUGRA)

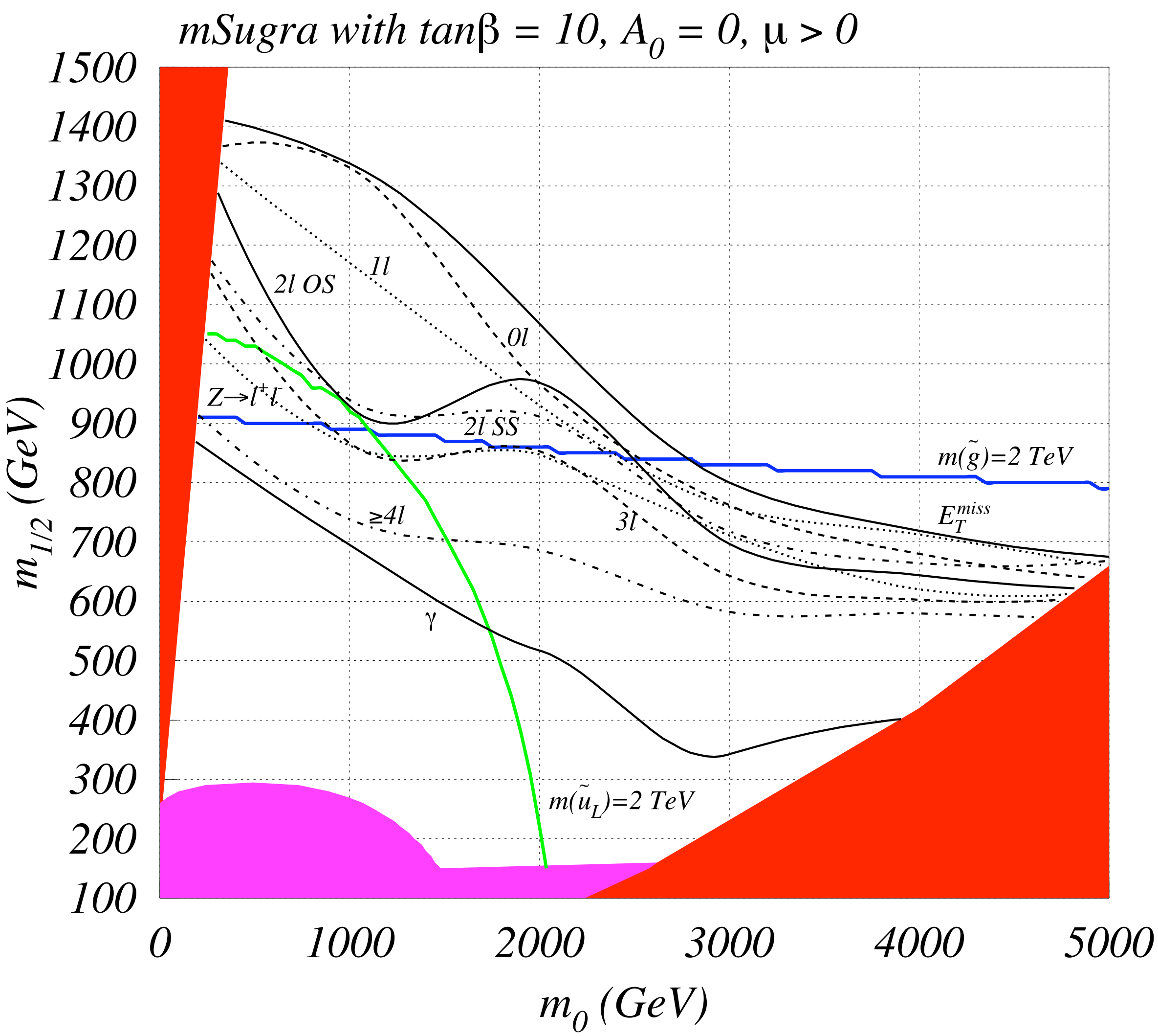
Rationale:

- Any SUSY-breaking hidden sector is bound to interact with visible sector via gravity.
- Gravity doesn’t care about any particle properties (other than mass), except maybe spin.

“Four and a half” free parameters:

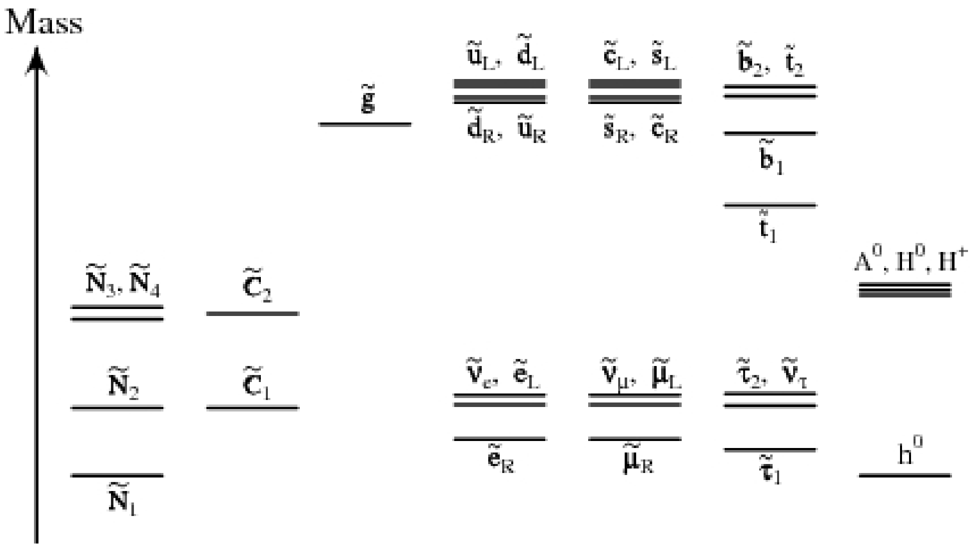
- Common scalar mass m_0
- Common gaugino mass $m_{1/2}$
- $\tan\beta$ (trade for, e.g., b after minimizing the Higgs potential)
- A squark/slepton trilinear coupling called A_0
- The sign of μ (SUSY-preserving parameter)—magnitude of μ is fixed by getting the right W mass from EWSB

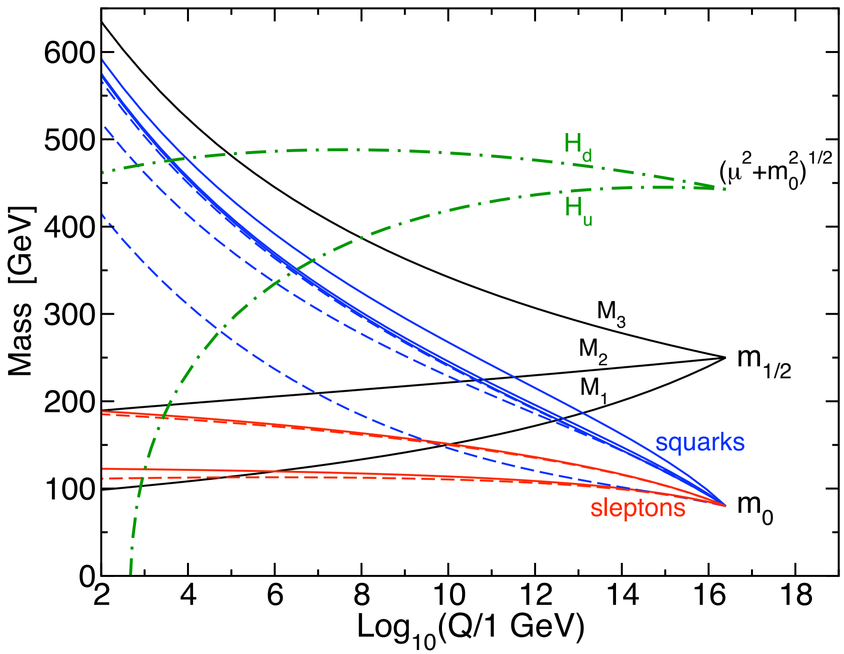
Can plot things in a nice low-dimensional parameter space in terms of the high-scale parameters:



from Baer, Balázs, Belyaev, Krupovnickas, & Tata, hep-ph/0304303

Complicated-looking spectrum, but mostly controlled by RGEs.

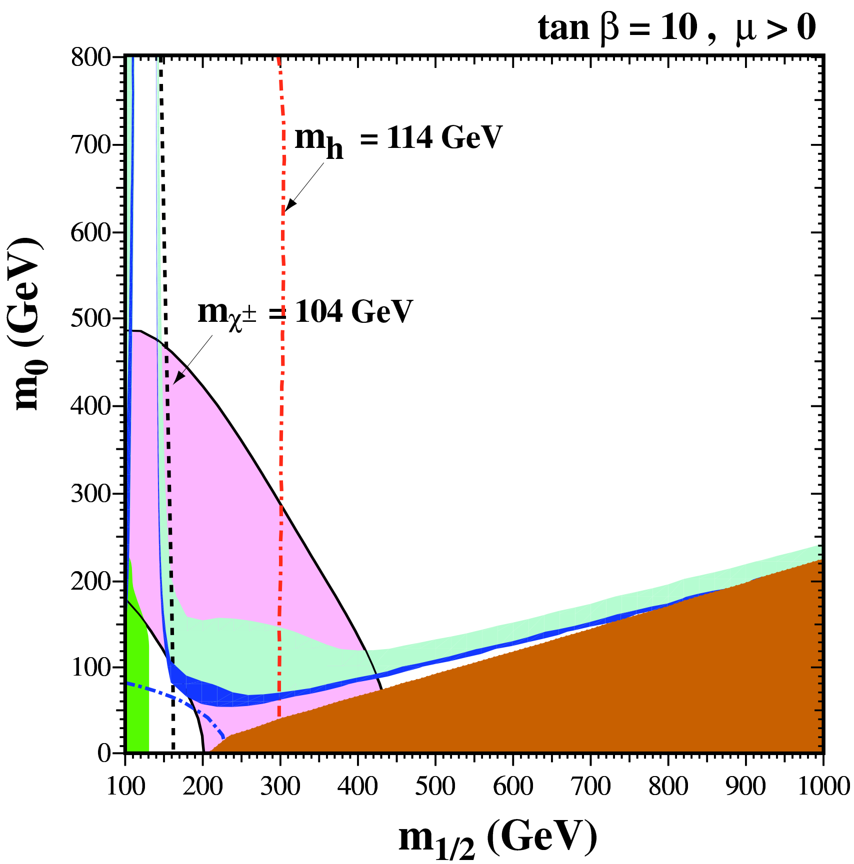




from Martin, hep-ph/9709356

mSUGRA with non-universal scalar masses (NUHM)

In mSUGRA, regions with acceptable dark matter density look very fine-tuned. (Hard to get enough annihilation)



"Bulk region":
- $\widetilde{N}_1$ mostly bino
- Light superparticles: mostly ruled out

"Stau coannihilation":
- Large $m_{1/2}$
- $\tilde{\tau}_1$ only slightly heavier than $\widetilde{N}_1$

"Focus point":
- Large m_0; μ becomes small
- $\widetilde{N}_1$ is mixed bino-Higgsino

Can relax fine-tuning if m_0 for the Higgses is different from m_0 for the squarks/sleptons.

Motivated by SO(10) SUSY GUT:
- Higgs multiplets live in one SO(10) representation while SM fermions all live in a different one.
- "Natural" to have a different m_0 parameter for the different SO(10) multiplets.
- Gauge groups are unified $\rightarrow$ should have common gaugino mass at high scale.

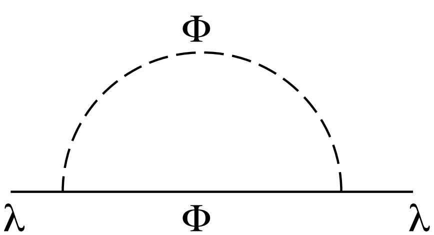
Make Higgsinos lighter; get mixed bino-Higgsino LSP without as much fine-tuning.

Gauge-mediated SUSY breaking (GMSB)

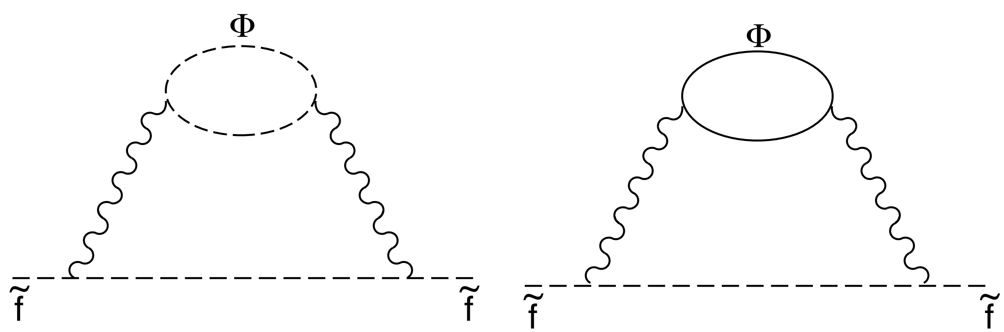
Mechanism:

- SUSY breaking happens in a field in the “hidden sector”
- That field couples to some chiral supermultiplets (the “messengers”), giving them mass M_{mess} and splitting the scalar/fermion masses by the SUSY breaking scale-squared F_{SUSY}
- The messengers are charged under SM gauge group(s)—SUSY breaking is induced in the visible sector by loops involving gauge interactions.

Gaugino masses:



Sfermion masses:



Figures from Giudice & Rattazzi, Phys. Rept. 322, 419 (1999), GMSB review article

Nice features of GMSB:

- Very predictive: only 2 SUSY-breaking parameters $F_{\rm SUSY}$ and $M_{\rm mess}$; otherwise depends only on number of messengers and their gauge charges.
- Gauge couplings are flavor-blind: avoid FCNC problems!
- Less ad-hoc than mSUGRA; does not involve nonrenormalizable supergravity.
- Mass scale of SUSY-breaking physics can be much lower.

$M_{\rm SUSY} \sim {\rm TeV} \simeq C_{\rm mess} \frac{F_{\rm SUSY}}{M_{\rm mess}}$ ($C_{\rm mess}$: coefficient from messenger couplings)

Interesting new phenomenology:

- Fermionic part of the field that causes SUSY-breaking ("goldstino") gets eaten by gravitino, giving it mass.
- Gravitino mass is $M_{\widetilde{G}} \sim \frac{F_{\rm SUSY}}{M_{\rm Pl}} \sim \frac{1}{C_{\rm mess}} \frac{{\rm TeV} \times M_{\rm mess}}{M_{\rm Pl}}$
- For low $M_{\rm mess}$, $F_{\rm SUSY}$ can be small: gravitino can be the LSP!

Next-lightest SUSY particle (NLSP) decays into gravitino, plus another particle depending on NLSP's identity.

Gravitino (really goldstino) couplings can be very weak: NLSP can have macroscopic decay length.

Photino NLSP: $\widetilde{N}_1 \to \tilde{G}\gamma$
SUSY events all contain two hard photons.
Macroscopic decay length means displaced vertices, non-pointing photons.

Slepton NLSP: metastable heavy charged particle.
Slow minimum-ionizing tracks, displaced charged-lepton vertices.
Decays in the cavern wall if lifetime long enough.

Gravitino dark matter:
Terrible implications for direct or indirect detection because DM particle is super-weakly interacting.

Anomaly-mediated SUSY breaking (AMSB)

Special case of gravity mediation:
- No tree-level coupling to communicate SUSY breaking to visible sector.
- SUSY-breaking mediated by loop effects (also present in mSUGRA, but much smaller than tree-level).
- Flavor-blind. [Simplest models have negative slepton mass-squared: have to introduce scalar mass parameter m_0^2 to fix it up.]

Gaugino masses generated at one-loop by the "superconformal anomaly" from the gravitino mass:

$$M_a = b_a^{\text{MSSM}} \left(\frac{\alpha_a}{4\pi} \right) m_{3/2}$$

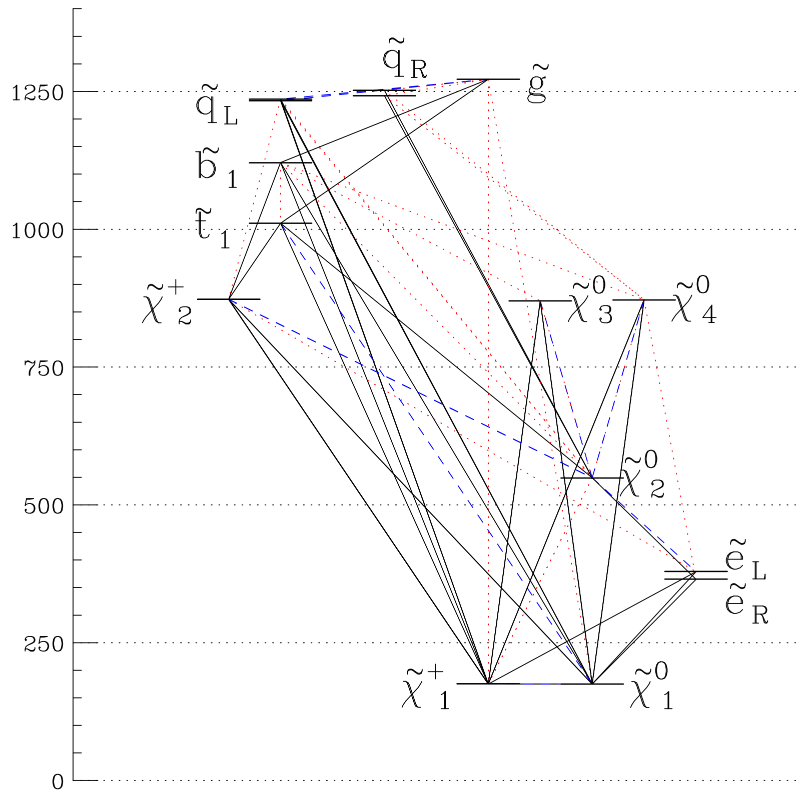
$b_a^{\text{MSSM}} = \left(\frac{33}{5}, 1, -3 \right)$ are the gauge beta functions

Minus signs in fermion masses can be eliminated by field redefinition—not physical.

After RGE running, $M_1 : M_2 : M_3 = 2.8 : 1 : 8.3$.
Wino is lightest!

Dramatic impact on phenomenology:

- $\widetilde{N}_1$ and $\widetilde{C}_1^{\pm}$ are nearly degenerate: typically $\Delta M \lesssim$ GeV.
- $\widetilde{C}_1^{\pm}$ decays almost exclusively into $\widetilde{N}_1$ plus a soft $\pi^{\pm}$.
- $\widetilde{C}_1^{\pm}$ can have detectably-long decay length.



Barr et al, JHEP 0303, 045 (2003)

Benchmark point SPS9

Can have other patterns for sfermion mass scale.

Key feature is the nearly-degenerate lightest neutralino & chargino.

Still see missing E_T.

Maybe it's something else entirely?

"SUSY without prejudice": Berger et al, JHEP 0902, 023 (2009)

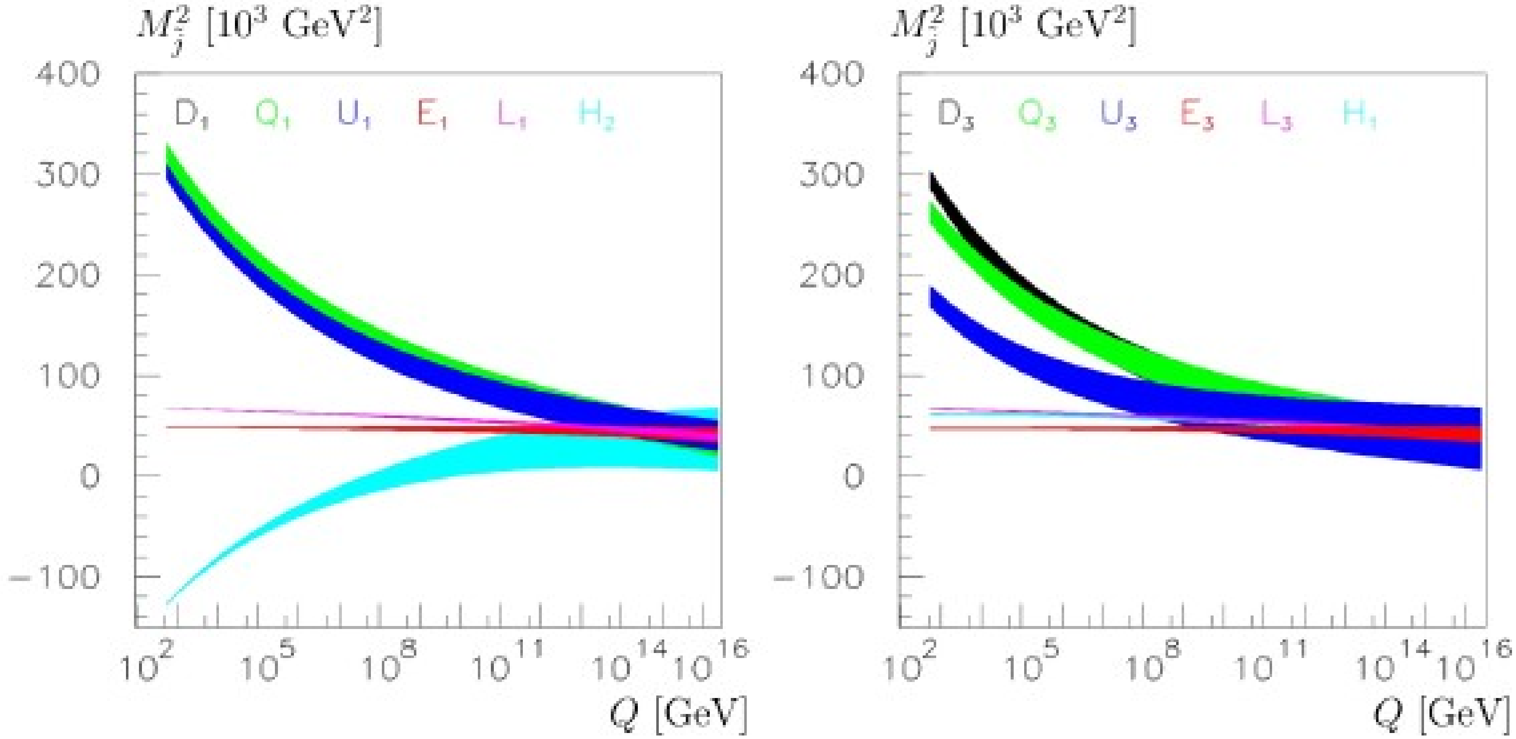
- Randomly sample a general CP-conserving MSSM with minimal flavor violation
- Impose all expt constraints and DM requirement (upper bound)
- Generate signal MC and survey characteristic signatures

Much broader set of predictions for SUSY properties, expt observables than in standard benchmarks.

Reconstructing the high-scale theory

The RGEs will let us extrapolate the high-scale physics based on measurements of the EW scale parameters.

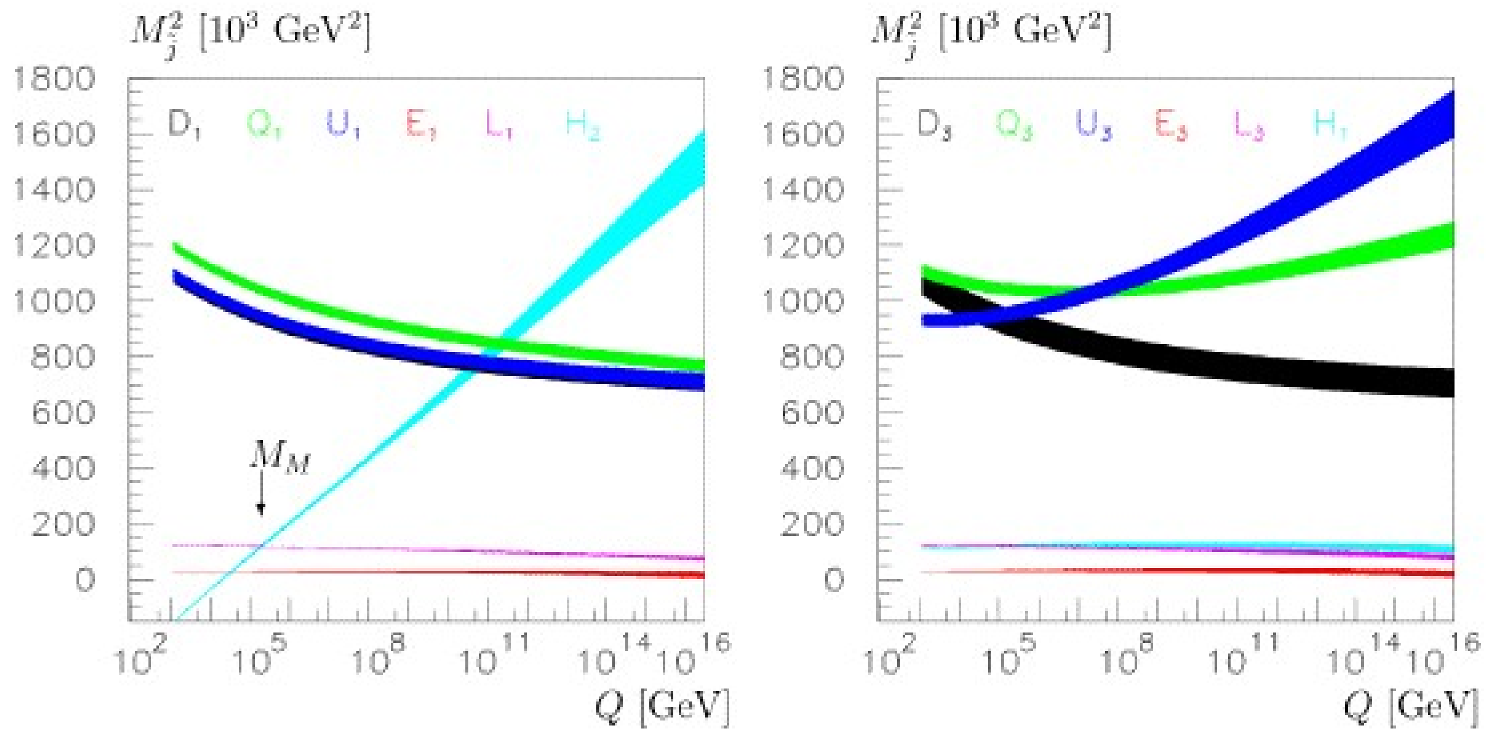
Sample mSUGRA spectrum:



from Blair, Porod & Zerwas, hep-ph/0210058

Run soft-SUSY-breaking parameters up, see if they unify: insight into physics at the highest energy scale!

Contrast gauge-mediated SUSY breaking spectrum:



from Blair, Porod & Zerwas, hep-ph/0210058

Soft-SUSY-breaking parameters do not unify in GMSB:
they are related to beta-functions at the messenger scale M_{mess}.

This is the real motivation for measuring SUSY masses and couplings. Need high precision as much as possible.

Measure SUSY masses and couplings

A new challenge:
- Each SUSY event contains *two* invisible massive particles.
- Can't reconstruct invariant mass bumps.
- Can't even measure transverse mass like for $W \to \ell\nu$.

Need to use more sophisticated techniques:
Take advantage of decay chains.
  - Kinematic endpoints
  - Four-momentum conservation relations
  - Other kinematic tricks

(More on this in Lecture 4.)

Summary

SUSY discovery prospects generically good at LHC
- Lots of jets, missing p_T

SUSY phenomenology is mostly controlled by the mass spectrum.
- SUSY-breaking mediation mechanism
- Renormalization-group running

Potential insight into the highest energy scales through the pattern of SUSY-breaking masses

Near-term challenge:
- Discover new physics!
- See whether it's SUSY by measuring couplings, spins
- Measure masses, other coups and reconstruct high-scale theory