Physics beyond the Standard Model

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- Motivations for BSM physics
- Supersymmetry: MSSM
- Extra-dimensions: ADD, Randall-Sundrum, UED

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Motivations for physics beyond the Standard Model

The Standard Model is extremely successful:

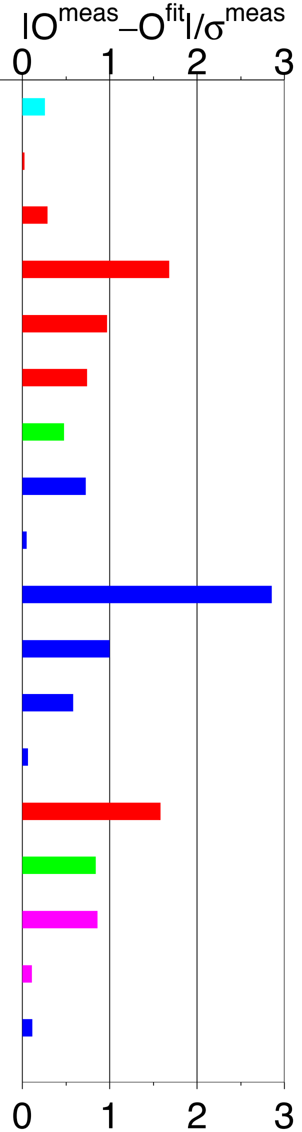
- it as been tested with a very high precision (1‰) in the electroweak sector
- no clear sign of deviation from the SM in the experimental data accumulated over years [some debated discrepancies in B physics (see Prof. Hou's lecture) and in the muon (g-2)]

So why look for physics beyond the Standard Model ?

In fact, there are good reasons (both observational and theoretical) to believe that the SM is an incomplete theory

Standard Model fit using data from LEP, SLC and Tevatron

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.377
Γ_W [GeV]	2.097 ± 0.048	2.092
m_t [GeV]	172.6 ± 1.4	172.8



March 2008

Theoretical reasons

1) the SM contains many arbitrary parameters:

- gauge sector: $g_S,\ g,\ g' \quad (\theta_{QCD})$
- Higgs sector: $\lambda,\ m_H$
- Yukawa sector: $m_u,\, m_c,\, m_t \quad m_d,\, m_s,\, m_b \quad V_{us},\, V_{ub},\, V_{cb},\, \delta$
  $m_e,\, m_\mu,\, m_\tau \quad (+\ \nu$ masses and mixing$)$

2) it does not unify the fundamental interactions

3) it suffers from the gauge hierarchy problem (instability of the Higgs mass / weak scale under radiative corrections)

These diagrams give $\Delta m_H^2 \sim \Lambda_{UV}^2/16\pi^2$, where Λ_{UV} is some physical ultraviolet cutoff (e.g. the GUT or Planck scale)

$\Rightarrow$ need to fine-tune $m_H^2 + \Delta m_H^2$ to 10^{-30} or so to maintain the weak scale / Planck scale hierarchy, and this must be repeated at any order in perturbation theory

Ways out: (i) the quadratically divergent diagrams are regulated by new physics at the TeV scale ($\Lambda_{UV} \sim 1\,\mathrm{TeV}$)

(ii) there is no fundamental Higgs boson (technicolor; higgsless models) – this possibility is not discussed here

Observational reasons

Some observational facts are not explained by the SM:

1) neutrino masses: a priori, can be accounted for by adding a RH neutrino to the SM

$$- y_\nu \, \overline{L} \, i\sigma^2 H^* \nu_R + \text{h.c.} \quad \Rightarrow \quad m_\nu = h_\nu v$$

but ν_R is a gauge singlet and can have an arbitrarily large Majorana mass M (unless lepton number is imposed) ⇒ new physics at M

$$-\frac{1}{2} M \, \nu_R^T C \nu_R + \text{h.c.} \quad \Rightarrow \quad m_\nu = (h_\nu v)^2 / M \ll v^2$$

(seesaw mechanism)

Alternatives to introducing ν_R also require new physics

2) <u>dark matter</u>: observations (galactic rotation curves, CMB anisotropies...) indicate that there must be a non-baryonic cold dark matter (CDM) component

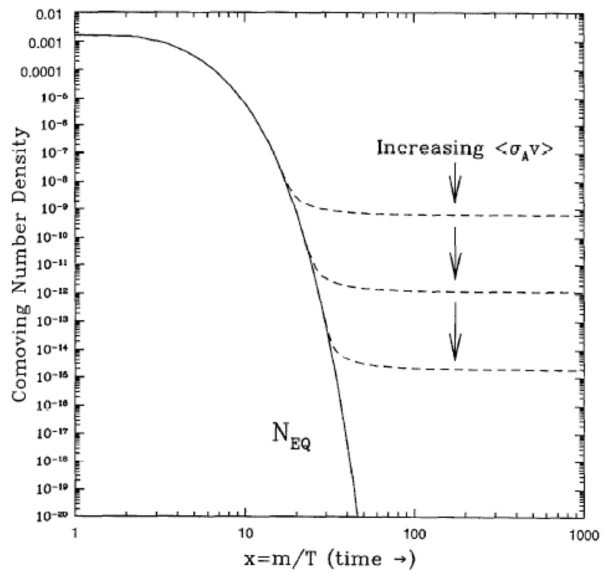
<u>no candidate within the SM</u>

The most popular DM candidate is a WIMP (weakly interacting massive particle)

Its relic density is determined by its thermally averaged annihiliation rate: $\Omega_\chi \propto 1/\langle \sigma_A v \rangle$

$$\sigma_A \sim \frac{\alpha_w^2}{m_\chi^2} \implies {}_\chi \sim 0.1 \quad [\text{obs.: } 0.23]$$

for $m_\chi \sim (0.1 - 1)\,\text{TeV}$, precisely at the scale suggested by the hierarchy problem!



[Kolb, Turner]

3) baryon asymmetry: the observed baryon asymmetry of the universe

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10} \qquad (WMAP)$$

must be explained by some dynamical mechanism (the alternative possibility of fine-tuning the initial conditions by $\mathcal{O}(10^{-9})$ is problematic with inflation)

This requires [Sakharov's conditions] (i) B violation; (ii) C and CP violation; (iii) departure from thermal equilibrium. These are satisfied in the SM, but not at the required level: standard electroweak baryogenesis fails

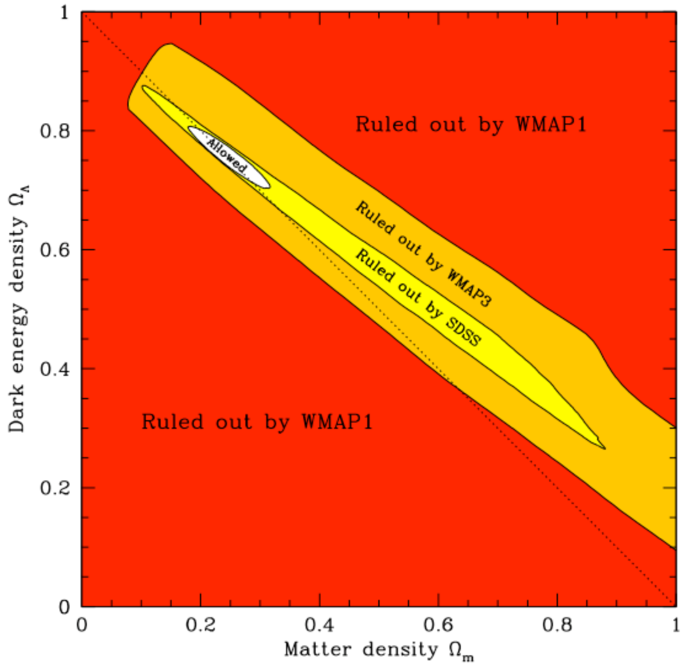
4) inflation: observations (flatness, homogeneity and isotropy of the universe; CMB anisotropies, large scale structures...) are consistent with a period of exponential expansion in the early universe

Inflationary models involve one or several scalar fields with different properties from the SM Higgs boson

5) <u>dark energy</u>: observations (type Ia supernovae, CMB anisotropies...) indicate that our universe is dominated by dark energy: $\Omega_\Lambda \approx 0.73$

The old cosmological constant problem has been replaced by the problem of explaining why the vacuum energy should be so small (it corresponds to an energy scale in the meV range, well below the scales we encounter in high energy physics)

M.Tegmark et al., astro-ph/0608632



Most observational reasons for going beyond the SM come from astrophysics and cosmology

Among them, dark matter strongly suggests* new physics around the TeV scale, in agreement with theoretical arguments based on the hierarchy problem ⇒ strong case for BSM physics at the LHC

* but does not require: DM could be made of e.g. very light axions

Finaly, one should keep in mind that the SM has not been fully tested: the electroweak symmetry breaking (EWSB) sector has not been observed yet, and it might reserve some surprises (although the precision electroweak data put strong constraints on alternatives to a fundamental Higgs boson)

Which physics beyond the Standard Model?

Several approaches have been followed by theorists:

• extend gauge symmetries ⇒ Grand Unified Theories [SU(5), SO(10), ...]
naturally small neutrino masses / baryogenesis via leptogenesis /
main signal: proton decay / hierarchy problem unless supersymmetric

• extend space-time symmetries ⇒ SUSY ($D = 4$) or X-Dims ($D > 4$)
address the hierarchy problem / new physics at the TeV scale /
DM candidate / (electroweak) baryogenesis may work

• alternative to the Higgs mechanism ⇒ strong dynamics (technicolor or X-dim version = higgsless model) or pseudo-Goldstone Higgs boson (little Higgs or X-dim version = gauge-Higgs unification)

• more radical: replace point part. by extended objects ⇒ String Theory
unifies all interactions including (quantum) gravity / lives in $D = 10$

These lectures: SUSY (MSSM) + popular X-dim models (ADD, RS, UED)

Supersymmetric extension of the Standard Model

Supersymmetry = extension of the Poincare group by "fermionic" operators transforming a boson into a fermion (and vice versa)

$\Rightarrow$ each boson (fermion) has a fermion (boson) partner with identical mass (in the exact SUSY limit)

$\Rightarrow$ doubles the spectrum of the SM

- fermion (S = $1/2$) $\leftrightarrow$ sfermion (S = 0) [chiral supermultiplet]

  squarks ($\tilde{q}$), sleptons ($\tilde{l}$), higgsinos ($\tilde{H}_u, \tilde{H}_d$)

- gauge boson (S = 1) $\leftrightarrow$ gaugino (S = $1/2$) [vector supermultiplet]

  gluinos ($\tilde{g}^a$), winos ($\tilde{W}^{\pm}, \tilde{W}^0$), bino ($\tilde{B}$)

Note: 2 Higgs supermultiplets are necessary to give masses to both up-type dans down-types fermions, and to cancel anomalies

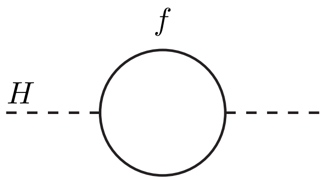
Field Content of the MSSM					
Super-Multiplets	Boson Fields	Fermionic Partners	SU(3)	SU(2)	U(1)
gluon/gluino	g	$\widetilde{g}$	8	0	0
gauge/	$W^{\pm}, W^0$	$\widetilde{W}^{\pm}, \widetilde{W}^0$	1	3	0
gaugino	B	$\widetilde{B}$	1	1	0
slepton/	$(\widetilde{\nu}, \widetilde{e}^-)_L$	$(\nu, e^-)_L$	1	2	-1
lepton	$\tilde{e}_R^-$	e_R^-	1	1	-2
squark/	$(\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$	3	2	1/3
quark	$\widetilde{u}_R$	u_R	3	1	4/3
	$\widetilde{d}_R$	d_R	3	1	$-2/3$
Higgs/	(H_d^0, H_d^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$	1	2	-1
higgsino	(H_u^+, H_u^0)	$(\widetilde{H}_u^+, \widetilde{H}_u^0)$	1	2	1

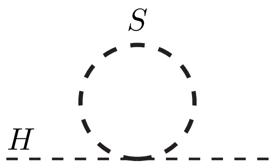
The electroweak gauginos mix with the higgsinos $\Rightarrow$ mass eigenstates:

2 charginos $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$ and 4 neutralinos $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

Motivations for supersymmetry

1) solves the hierarchy problem:





$$\Delta m_H^2 = \frac{\Lambda_{UV}^2}{16\pi^2}\left(-2|\lambda_f|^2 + n_S\lambda_S\right)$$

quadratic diverges cancel out if $\lambda_S = |\lambda_f|^2$ and $n_S = 2$ (equal number of fermionic and bosonic dofs, e.g. $t = (t_L, t_R) \leftrightarrow \tilde{t}_L, \tilde{t}_R$)

If $m_S = m_f$, logarithmic divergences further cancel

<u>automatically ensured by supersymmetry</u>

2) allows gauge couplings to unify at high energy

3) provides a candidate for dark matter, the lightest neutralino

4) successful electroweak baryogenesis is possible

5) necessary ingredient of viable string theories $\Rightarrow$ Superstrings

Supersymmetric interactions

All non-gauge masses and interactions are determined by a superpotential
= holomorphic function of the chiral superfields which contain matter fields

$$W_{MSSM} \;=\; Y_u Q\bar{u}H_u - Y_d Q\bar{d}H_d - Y_e L\bar{e}H_d + \mu H_u H_d$$

H_u (H_d) gives mass to up quarks (down quarks and charged leptons) as well as to their scalar partners

μ is a supersymmetric Higgs mass

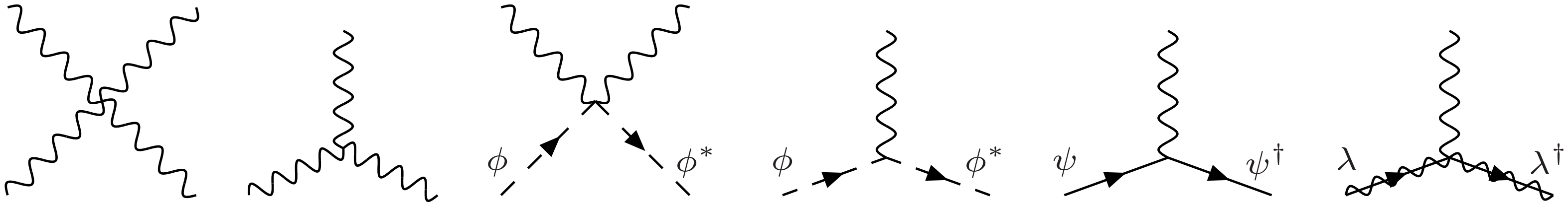
The trilinear term give Yukawa couplings (fermion-fermion-sfermion) and quartic scalar couplings satisfying $\lambda_S = |y_f|^2$

Triscalar couplings of the form $\mu^* Y_u H_d^\dagger \tilde{Q}\tilde{\bar{u}} + \mathrm{h.c.}$ are also generated

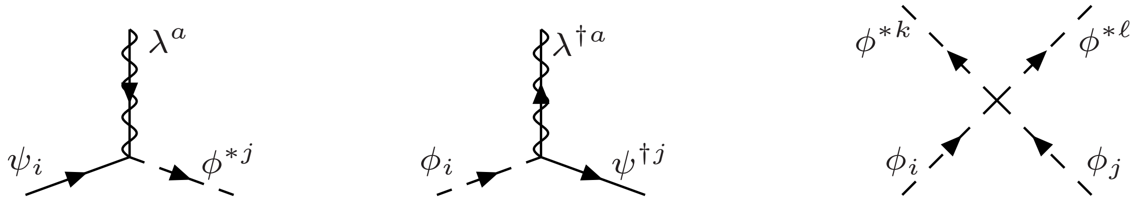
(these interactions are actually not the most important at colliders)

Supersymmetric gauge interactions

The following interactions are dictated by ordinary gauge invariance alone:



SUSY also predicts interactions that have gauge coupling strength, but are not gauge interactions in the usual sense:



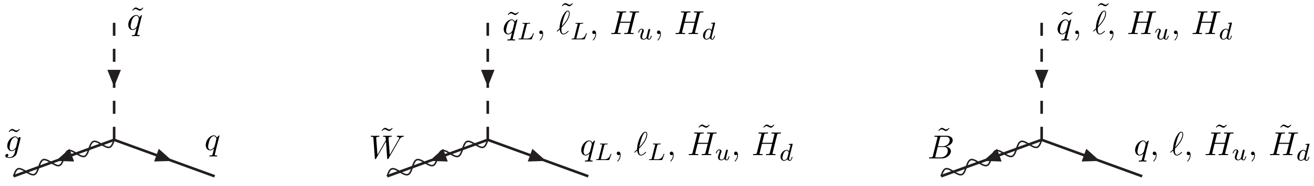
$-i\sqrt{2}g_a(T^a)_i{}^j$ $\quad$ $-i\sqrt{2}g_a(T^a)_i{}^j$ $\quad$ $-ig_a^2(T_i^{ak}T_j^{a\ell}+T_i^{a\ell}T_j^{ak})$

These interactions are entirely determined by supersymmetry and the gauge group. Experimental measurements of the magnitudes of these couplings will provide an important test that we really have SUSY.

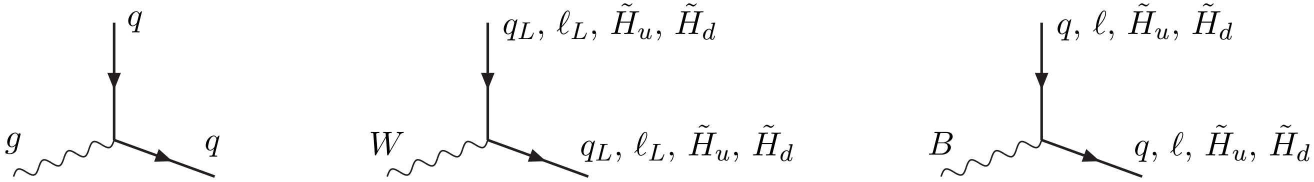
(slide borrowed from S. P. Martin)

Let us have a closer look at the genuine supersymmetric gauge interactions

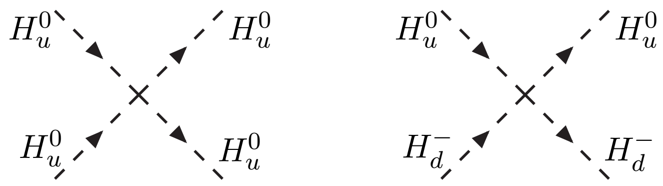
The sfermion-fermion-gaugino interactions:



are related by supersymmetry to the standard fermion gauge interactions:



The MSSM quartic Higgs couplings are scalar "gauge" interactions, such as



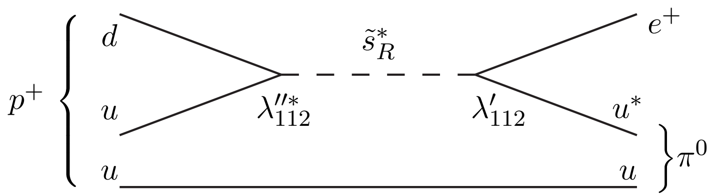
⇒ more predictive Higgs sector as in the SM ($\lambda \rightarrow$ function of g and g')

R-parity

The most general MSSM superpotential actually includes baryon and lepton number violating interactions:

$$W_{RPV} \; = \; \lambda \, L L \bar{e} \, + \, \lambda' L Q \bar{d} \, + \, \lambda'' \bar{u} \bar{d} \bar{d} \, + \, \mu' H_u L$$

This is different from the SM, in which B and L are accidental symmetries. These interactions induce proton decay at an unacceptable rate, unless λ' and λ'' are extremelly small ($|\lambda' \lambda''| \lesssim 10^{-25}$ for $m_{\tilde{d}_R} = 1 \, \mathrm{TeV}$)



To avoid this problem, one introduces a discrete symmetry defined as:

$$R_P \; = \; (-1)^{3B+L+2S} \; = \; \begin{cases} -1 & \text{for SM particles} \\ +1 & \text{for superpartners} \end{cases}$$

Consequences of R-parity:

• all interactions with an odd number of superpartners, like the B- and L-violating interactions induced by W_{RPV}, are forbidden

• the proton is stable

• superpartners are produced in pairs

• the lightest supersymmetric particle (LSP) is stable, hence:

- any superpartner produced at colliders will eventually decay into a state containing a LSP, leaving a missing energy signal
- the LSP is a good DM candidate (if it is the lightest neutralino): massive, stable, weakly interacting

R-parity violation:

The proton stability can be ensured by alternative symmetries, such as a baryon parity (which forbids λ''). If λ and λ' are large enough, this leads to a rich phenomenology at colliders (LSP decay and displaced vertices, RPV sparticle decays, single sparticle production...)

Supersymmetry breaking

In principle, the MSSM is more predictive than the SM: it has more particles but less parameters (more constrained Higgs potential)

However, this is only true if SUSY is exact, and we know that it must be broken (no scalar particle with 511 keV mass has been observed)

Since we do not know how SUSY is broken, we parametrize its breaking by soft terms, i.e. terms that do not reintroduce quadratic divergences (as expected if SUSY is spontaneously broken):

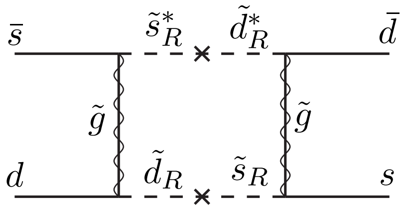
$$
\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} \;=\; & -\frac{1}{2}\Big(M_3\,\tilde{g}\tilde{g} + M_2\,\tilde{W}\tilde{W} + M_1\,\tilde{B}\tilde{B} + \text{h.c.}\Big) \\
& -\Big(A_u\,\tilde{Q}\tilde{\bar{u}}H_u - A_d\,\tilde{Q}\tilde{\bar{d}}H_d - A_e\,\tilde{L}\tilde{\bar{e}}H_d + \text{h.c.}\Big) \\
& -\tilde{Q}^\dagger m_Q^2\,\tilde{Q} - \tilde{L}^\dagger m_L^2\,\tilde{L} - \tilde{\bar{u}}^\dagger m_{\bar{u}}^2\,\tilde{\bar{u}} - \tilde{\bar{d}}^\dagger m_{\bar{d}}^2\,\tilde{\bar{d}} - \tilde{\bar{e}}^\dagger m_{\bar{e}}^2\,\tilde{\bar{e}} \\
& - m_{H_u}^2 H_u^\dagger H_u - m_{H_d}^2 H_d^\dagger H_d - (B\mu\, H_u H_d + \text{h.c.})
\end{aligned}
$$

- gaugino masses ($M_a\, \lambda_a \lambda_a$): M_3, M_2, M_1
- scalar masses ($m^2_{ij}\, \phi_i^\dagger \phi_j$): $m^2_Q, m^2_{\bar{u}}, m^2_{\bar{d}}, m^2_L, m^2_{\bar{e}}, m^2_{H_u}, m^2_{H_d}$
- A-terms ($A_{ijk}\, \phi_i \phi_j \phi_k$): A_u, A_d, A_e
- B-term ($B_{ij}\, \phi_i \phi_j$): $B\mu$

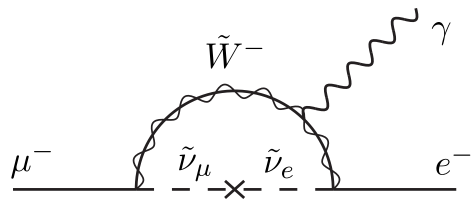
≈ 100 parameters (taking into account the flavour structure and phases),
all expected to be in the few 100 GeV - few TeV range (hierarchy problem).

The flavour structure of the soft terms is strongly constrained by flavour changing neutral current (FCNC) processes [see Prof. Hou's lecture]:

$K^0 - \overline{K}^0$ mixing



$\mu \to e\gamma$



[analogy with charged current in the SM: bases of fermion and sfermion mass eigenstates do not match $\Rightarrow$ flavour-violating gaugino couplings]

Suggests close-to-flavour-universal soft terms: $(m^2_Q)_{ij} \approx m^2 \delta_{ij}$, etc

Neutralino and chargino masses

Electroweak gauginos and higgsinos mix due to EWSB
$\Rightarrow$ neutral (neutralinos) and charged (charginos) mass eigenstates

Neutralino mass matrix in the basis $(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$:

$$M_N = \begin{pmatrix} M_1 & 0 & -g' v_d/\sqrt{2} & g' v_u/\sqrt{2} \\ 0 & M_2 & g v_d/\sqrt{2} & -g v_u/\sqrt{2} \\ -g' v_d/\sqrt{2} & g v_d/\sqrt{2} & 0 & -\mu \\ g' v_u/\sqrt{2} & -g v_u/\sqrt{2} & -\mu & 0 \end{pmatrix}$$

where $v_u \equiv \langle H_u^0 \rangle, \;\; v_d \equiv \langle H_d^0 \rangle$

The mass eigenstates are 4 Majorana fermions $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$. In many SUSY scenarios (e.g. mSUGRA), one has $M_1 \approx 0.5\, M_2 < \mu$ and $M_Z \ll \mu$, which implies:

$$\tilde{\chi}_1^0 \approx \tilde{B}, \qquad \tilde{\chi}_2^0 \approx \tilde{W}^0, \qquad \tilde{\chi}_3^0, \tilde{\chi}_4^0 \approx (\tilde{H}_u^0 \pm \tilde{H}_d^0)/\sqrt{2}$$

$\tilde{\chi}_1^0$ is a good dark matter candidate

Chargino mass matrix in the basis $(\tilde{W}^-, \tilde{H}_d^-) \times (\tilde{W}^+, \tilde{H}_u^+)$:

$$M_C = \begin{pmatrix} M_2 & gv_u \\ gv_d & \mu \end{pmatrix}$$

The mass eigenstates are 2 charged Dirac fermions $\tilde{\chi}_1^\pm \quad \tilde{\chi}_2^\pm$. In many SUSY scenarios, one has $M_2 \ll \mu$, which implies:

$$\tilde{\chi}_1^\pm \approx \text{wino}, \qquad \tilde{\chi}_2^\pm \approx \text{higgsino}$$

Sfermion masses

Dirac fermion f → 2 complex scalars $\tilde{f}_L,\ \tilde{f}_R$ → 2 soft mass parameters.
In addition, $\tilde{f}_L - \tilde{f}_R$ mixing mass terms from (e.g. for $f = t$):

superpotential → $\mu^* Y_u H_d^\dagger \tilde{Q}\tilde{\bar{u}}$ → $\mu^* \cot\beta\, m\ \ \tilde{t}\ \ \tilde{t}^*$

A-terms → $-A_u\, \tilde{Q}\tilde{\bar{u}} H_u$ → $-a_t m_t\, \tilde{t}_L \tilde{t}_R^*$ $\qquad (A_t = a_t y_t)$

⇒ 2x2 mass matrix in $(\tilde{t}_L, \tilde{t}_R)$ basis:

$$\begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_{\tilde{u}_L} & m_t(a_t^* - \mu\cot\beta) \\ m_t(a_t - \mu^*\cot\beta) & m_{\bar{u}_3}^2 + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix}$$

The mass eigenstates are called $(\tilde{t}_1, \tilde{t}_2)$. One defines a stop mixing angle:

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{t}} & -\sin\theta_{\tilde{t}} \\ \sin\theta_{\tilde{t}} & \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$ (real case)

Since the $\tilde{f}_L - \tilde{f}_R$ mixing is proportional to m_f, it is sizeable only for the third generation sfermions ⇒ $(\tilde{t}_1, \tilde{t}_2),\ (\tilde{b}_1, \tilde{b}_2),\ (\tilde{\tau}_1, \tilde{\tau}_2)$

For the other sfermions, one has $\tilde{f}_1 \simeq \tilde{f}_R$ and $\tilde{f}_2 \simeq \tilde{f}_L$

Electroweak symmetry breaking and Higgs sector

Tree-level Higgs potential:

$$V = (|\mu|^2 + m^2_{H_u})\, H_u^\dagger H_u + (|\mu|^2 + m^2_{H_d})\, H_d^\dagger H_d + (B\mu\, H_u H_d + \text{h.c.})$$
$$+ \frac{g^2}{2} \left| H_u^\dagger H_d \right|^2 + \frac{g^2 + g'^2}{8} \left(H_u^\dagger H_u - H_d^\dagger H_d \right)^2$$

Electroweak symmetry is broken when the neutral components of the Higgs doublets $H_u = \left(H_u^+, H_u^0\right)^T, \; H_d = \left(H_d^0, H_d^-\right)^T$ acquire a vev:

$$\langle H_u^0 \rangle = v_u, \; \langle H_d^0 \rangle = v_d \quad \text{with} \quad v_u^2 + v_d^2 = v^2 = (174\,\text{GeV})^2$$

Using the minimization conditions and the fact that v is known, the Higgs sector only depends on 2 parameters at tree level, m_A and $\tan\beta \equiv v_u / v_d$

Perturbativity restricts $1.5 \lesssim \tan\beta \equiv \frac{v_u}{v_d} \lesssim 55$

$$\frac{m_t}{m_b} = \frac{y_t}{y_b} \tan\beta \quad \Longrightarrow \quad \begin{cases} \text{small tan}\beta: & y_b(y_\tau) \ll y_t \text{ as in the SM} \\ \text{large tan}\beta: & y_b(y_\tau) \sim y_t \end{cases}$$

Higgs boson spectrum:

SM: 1 Higgs doublet $\Rightarrow$ 1 physical Higgs boson

2 x 2 (complex) - 3 (Goldstones eaten by W, Z) = 1

MSSM: 2 Higgs doublets $\Rightarrow$ 5 physical Higgs bosons

2 x 2 x 2 (complex) - 3 (Goldstones eaten by W, Z) = 5

neutral: CP-even h, H / CP-odd A – charged: H±

Tree-level mass relations:

$$m_h^2 \;\leq\; m_Z^2 \cos^2 2\beta \;\leq\; m_Z^2$$

upper limit on the lightest Higgs mass!

$$m_h^2 + m_H^2 \;=\; m_A^2 + m_W^2$$

$$m_{H^\pm}^2 \;=\; m_A^2 + m_W^2$$

At the one-loop level, m_h receives large corrections, due to an incomplete cancellation between top and stop loops:

$$m_h^2 \;\leq\; m_Z^2 \cos^2 2\beta + \frac{3 g^2 m_t^4 \sin^2\beta}{8\pi^2 m_W^2} \left[\ln \frac{m_S^2}{m_t^2} + \frac{X_t}{m_S^2} \left(1 - \frac{X_t^2}{12 m_s^2} \right) \right]$$

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$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4 \sin^2\beta}{8\pi^2 m_W^2} \ln \frac{m_S^2}{m_t^2} + \frac{X_t}{m_S^2} \quad 1 - \frac{X_t^2}{12 m_s^2}$$

where $m_S^2 \equiv \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{2}\,, \quad X_t \equiv a_t - \mu \cot\beta$

The bound is saturated for large m_A and large tanβ , and strongly depends on the stop mixing. For $m_S \lesssim 2\,\mathrm{TeV}$:

$$m_h \lesssim \begin{cases} 122\,\mathrm{GeV} & X_t = 0 & \text{(no mixing)} \\ 135\,\mathrm{GeV} & X_t = \sqrt{6}\, m_S & \text{(maximal mixing)} \end{cases}$$

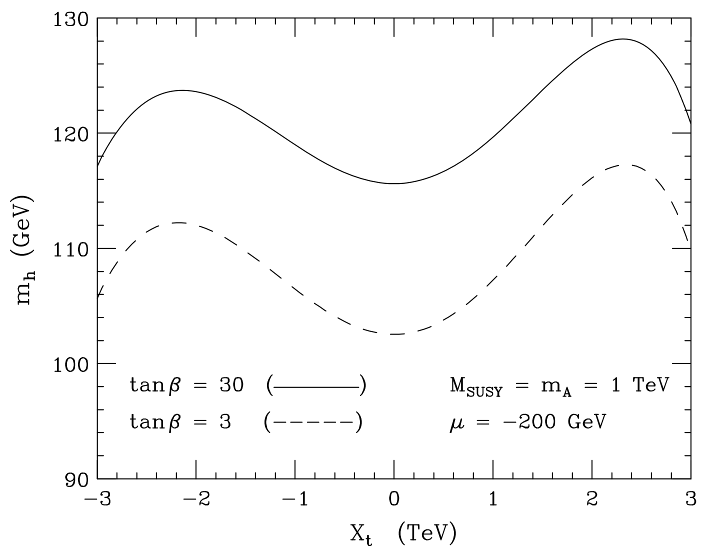
<u>light Higgs boson = prediction of low-energy supersymmetry</u>

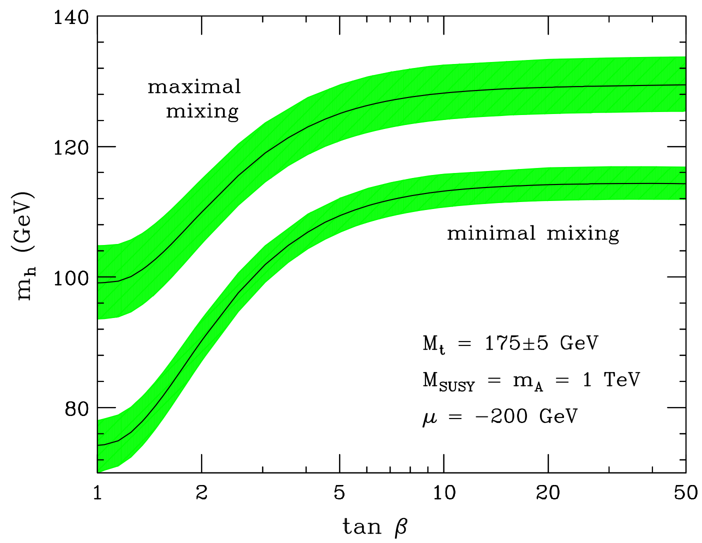
<u>LHC</u>: gluon fusion (gg → h) generally dominates, but other competitive production processes (EW boson fusion, associated production with tt/bb...)

Decay: $h \to b\bar{b}$ dominates but very difficult (QCD background)

$h \to \gamma\gamma$ clean but small BR $(10^{-4} - 10^{-3})$

The state-of-the-art computation includes the full one-loop result, all the significant two-loop contributions, and renormalization-group improvements. The final conclusion is that $m_h \lesssim 130$ GeV [assuming that the top-squark mass is no heavier than about 2 TeV].





Maximal mixing corresponds to choosing the MSSM Higgs parameters in such a way that m_h is maximized (for a fixed $\tan\beta$). This occurs for $X_t/M_S \sim 2$. As $\tan\beta$ varies, m_h reaches is maximal value, $(m_h)_{\max} \simeq 130$ GeV, for $\tan\beta \gg 1$ and $m_A \gg m_Z$.

(slide borrowed from H. Haber)

Higgs boson couplings:

The couplings of h and H can be very different from the SM Higgs. They depend on $(\beta-\alpha)$, where α is the mixing angle of the CP-even Higgs bosons:

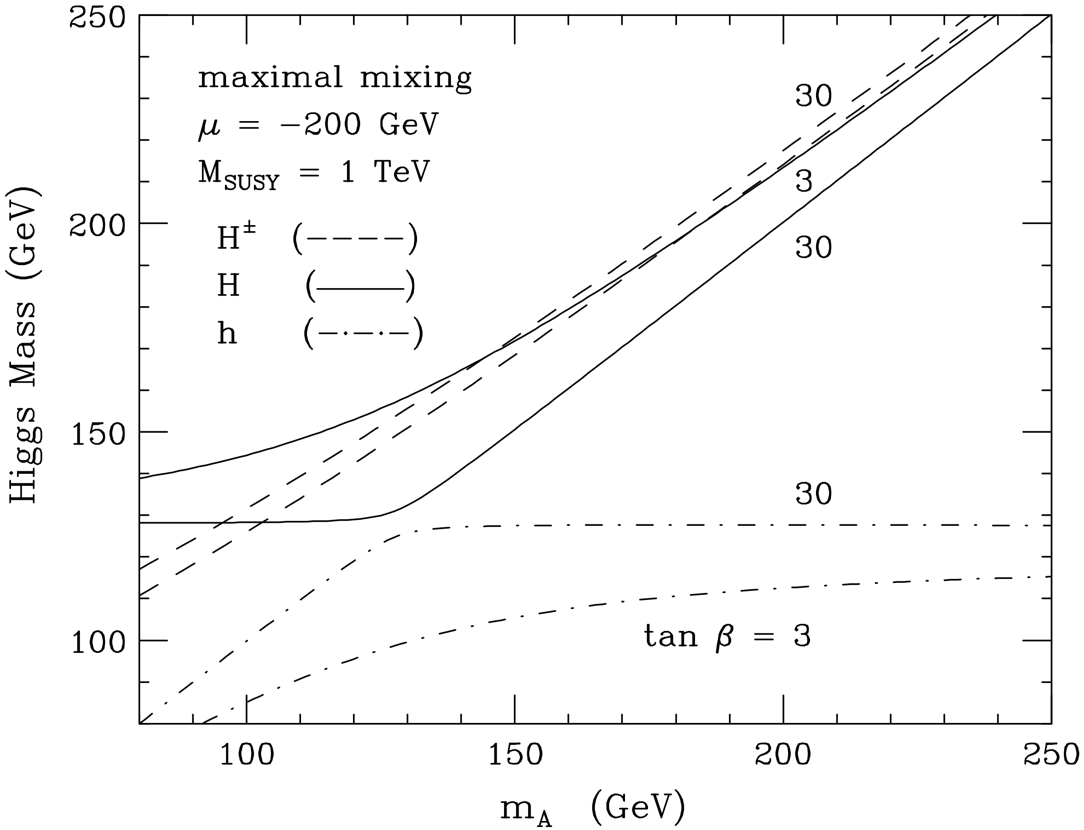
$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \sqrt{2}\,\mathrm{Re}H_d^0 \\ \sqrt{2}\,\mathrm{Re}H_u^0 \end{pmatrix}$$

Φ	h	H	A	SM Higgs
$\Phi WW, \Phi ZZ$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0	1
$Z\Phi A$	$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$	0	NA
$\Phi t\bar{t}$	$\sin(\beta-\alpha)+\cot\beta\cos(\beta-\alpha)$	$\cos(\beta-\alpha)-\cot\beta\sin(\beta-\alpha)$	$\gamma^5\cot\beta$	1
$\Phi b\bar{b}, \Phi\tau\bar{\tau}$	$\sin(\beta-\alpha)-\tan\beta\cos(\beta-\alpha)$	$\cos(\beta-\alpha)+\tan\beta\sin(\beta-\alpha)$	$\gamma^5\tan\beta$	1

- $\tan\beta$−enhancement of the couplings to down-type fermions

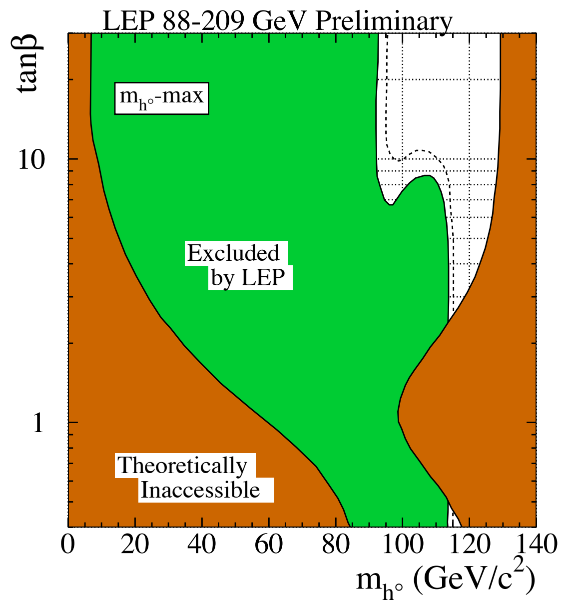
- in the limit $\sin(\beta-\alpha)\to 1$, h behaves as the SM Higgs boson, while H has very different couplings. The LEP limit of 114.4 GeV applies to h. This is the case in the decoupling regime $m_A \to \infty$ (in practice $m_A \gtrsim 200\,\mathrm{GeV}$), in which $m_h \approx m_h^{max}$ and $m_H \approx m_A \approx m_{H^\pm}$

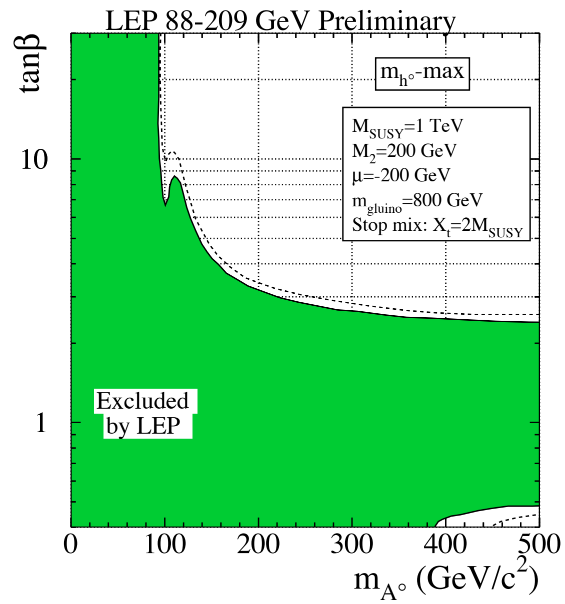
- in the limit $\sin(\beta-\alpha)\to 0$, H behaves as the SM Higgs boson, while h has very different couplings. The 114.4 GeV limit does not apply. This is the case in the antidecoupling regime $m_A \sim m_Z,\ \tan\beta \gg 1$, in which $m_h \approx m_A < m_H$



[Carena, Haber]

Summary of the LEP MSSM Higgs Search [95% CL limits]





- Charged Higgs boson: $m_{H^\pm} > 79.3$ GeV
- MSSM Higgs: $m_h > 92.9$ GeV; $m_A > 93.4$ GeV [max-mix scenario]

WARNING: Allowing for possible CP-violating effects that can enter via radiative corrections, large holes open up in the Higgs mass exclusion plots.

(slide borrowed from H. Haber)

Supersymmetry breaking scenarios

FCNC constraints suggest close-to-flavour-universal sfermion masses

$\longrightarrow$ flavour-blind supersymmetry breaking:

$$M^2_Q = m^2_Q\,\mathbf{I}_3\,, \qquad M^2_{\bar{u}} = m^2_{\bar{u}}\,\mathbf{I}_3\,, \qquad M^2_{\bar{d}} = m^2_{\bar{d}}\,\mathbf{I}_3$$
$$A_u = a^{(0)}_u Y_u\,, \qquad A_d = a^{(0)}_d Y_d$$

and similarly for sleptons. Since there is also a CP problem in SUSY (neutron and electron EDMs), assume $M_{1,2,3},\ a^{(}_{u,d,e}$ real $\longrightarrow$ 15 parameters

$\longrightarrow$ more radical assumption: universal scalar and gaugino masses at a high scale (usually the GUT scale):

$$M^2_Q = M^2_{\bar{u}} = M^2_{\bar{d}} = M^2_L = M^2_{\bar{e}} = m^2_0\,\mathbf{I}_3\,, \quad m^2_{H_u} = m^2_{H_d} = m^2_0$$
$$A_{u,d,e} = a_0 Y_{u,d,e}\,, \qquad M_1 = M_2 = M_3 = M_{1/2}$$

Assuming proper EWSB (which allows to trade $|\mu|$ and $B\mu$ for v and $\tan\beta$), one ends up with a 5-parameter model (constrained MSSM = CMSSM):

$$m_0\,,\ \ M_{1/2}\,,\ \ A_0\,,\ \ \tan\beta\,,\ \ \mathrm{sign}(\mu)$$

SUSY cannot be spontaneously in the observable (MSSM) sector. It must be broken in a hidden sector, and subsequently transmitted to the MSSM by mediating interactions

1) (super)gravity-mediated supersymmetry breaking

Gravity is universal $\rightarrow$ assume universal SUSY breaking: mSUGRA (= CMSSM with input scale = Planck scale, or more usually GUT scale)

This is really an assumption: gravity mediation can lead to arbitrary soft terms in the observable sector

Renormalization group effects are important: colored sparticles heavier, third generation sfermion lighter (Yukawas), gaugino masses in the ratios $M_1 : M_2 : M_3 = \Box_1 : \Box_2 : \Box_3$, radiative EWSB ($m^2_{H_u}$ driven negative)

2) gauge-mediated supersymmetry breaking (GMSB)

In this case, the soft terms are automatically flavour-blind (but not universal as in mSUGRA) at the messenger scale - main signature: gravitino LSP

gaugino masses (1-loop): $M_a = (g_a^2/16\pi^2)\,\Lambda$

scalar masses (2-loop): $m_\Phi^2 = \sum_a 2C_a (g_a^2/16\pi^2)^2 \Lambda$

$\Box \sim 100\,\mathrm{TeV}$ typically

Renormalization Group Running for an mSUGRA model (SPS1A′) with

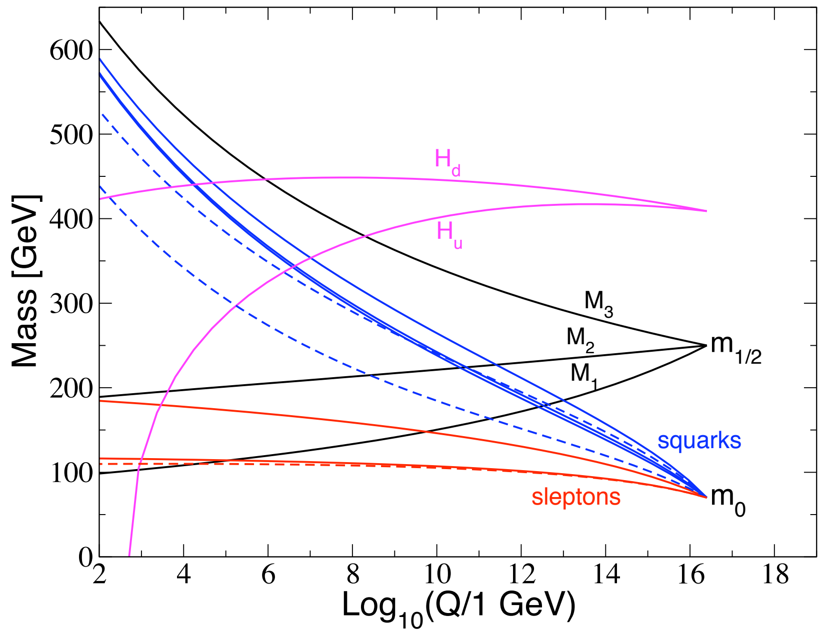
$m_{1/2} = 250$ GeV, $m_0 = 70$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, and sign(μ) = +1

Gaugino masses M_1, M_2, M_3

Slepton masses (dashed=stau)

Squark masses (dashed=stop)

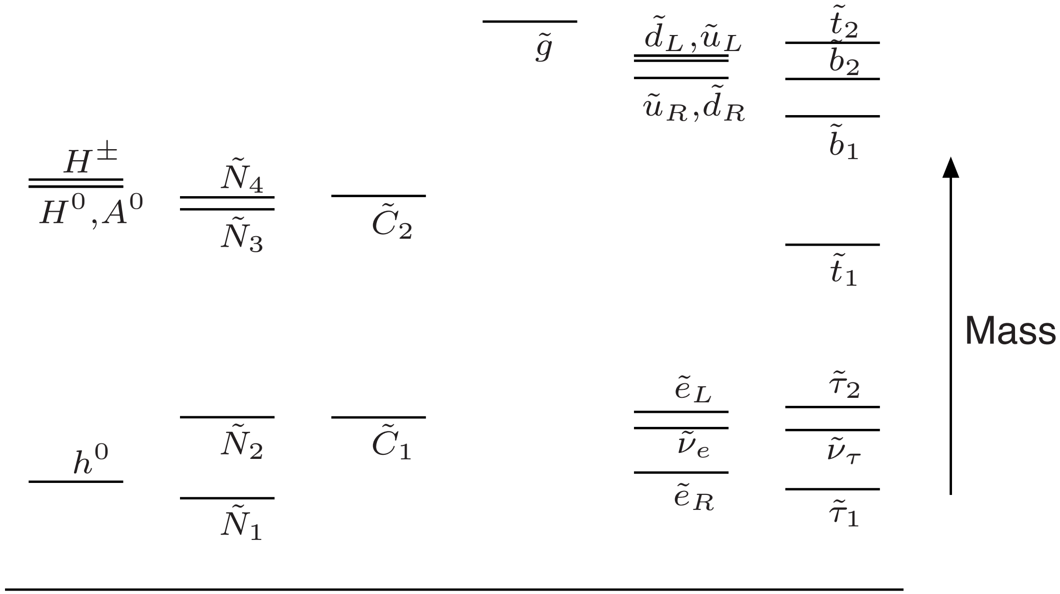
Higgs: $(m^2_{H_u} + \mu^2)^{1/2}$,
$(m^2_{H_d} + \mu^2)^{1/2}$



Electroweak symmetry breaking occurs because $m^2_{H_u} + \mu^2$ runs negative near the electroweak scale. This is due directly to the large top quark Yukawa coupling.

(slide borrowed from S. P. Martin)

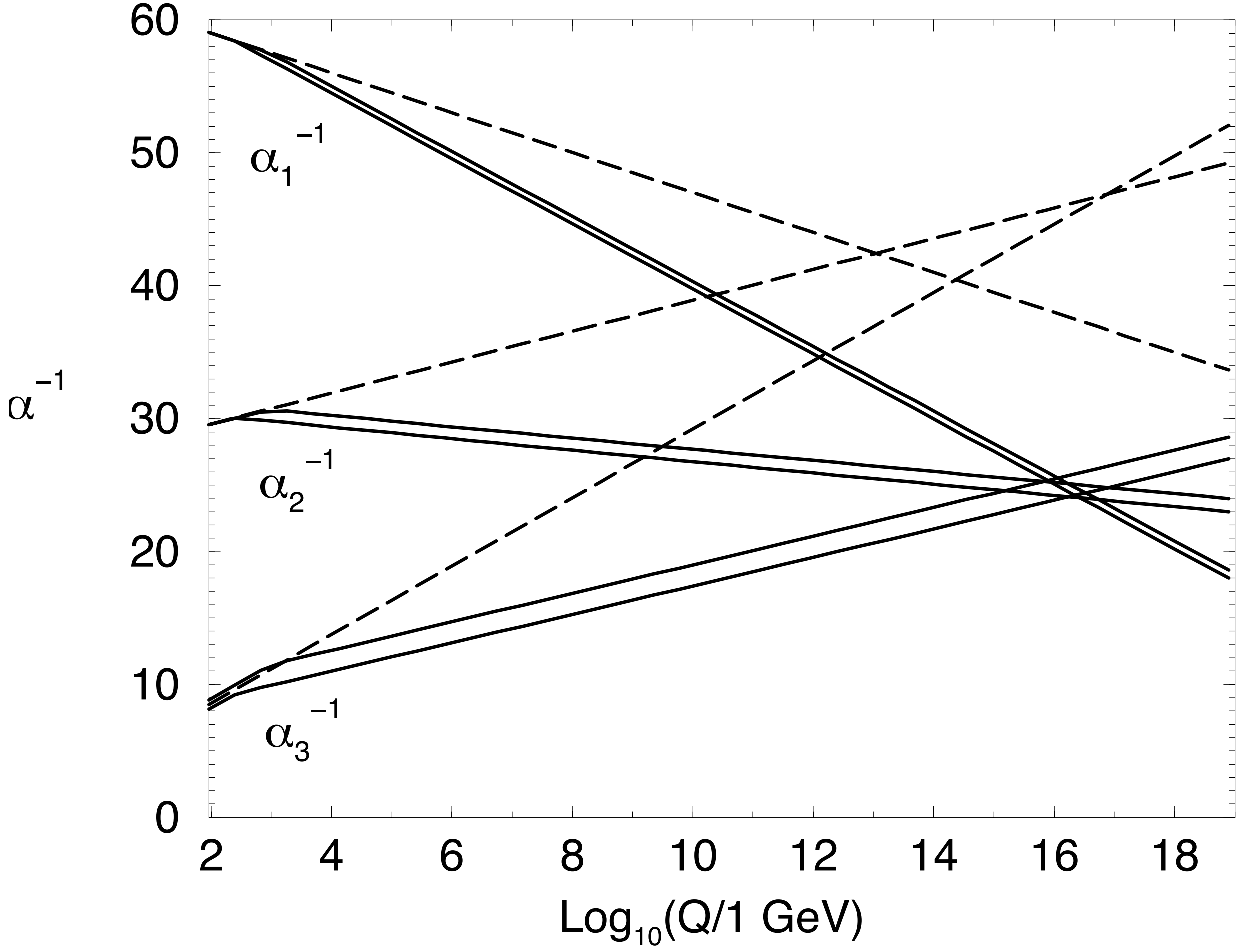
Here is the resulting sparticle mass spectrum:



This is typical, qualitatively, of mSUGRA models with relatively large $m_{1/2}$.

Notes: The Higgs sector is in the decoupling limit, with h^0 near the LEP2 limit. A neutralino is the LSP. The gluino is the heaviest sparticle. The lightest squark is the top squark. The lightest slepton is the tau slepton.

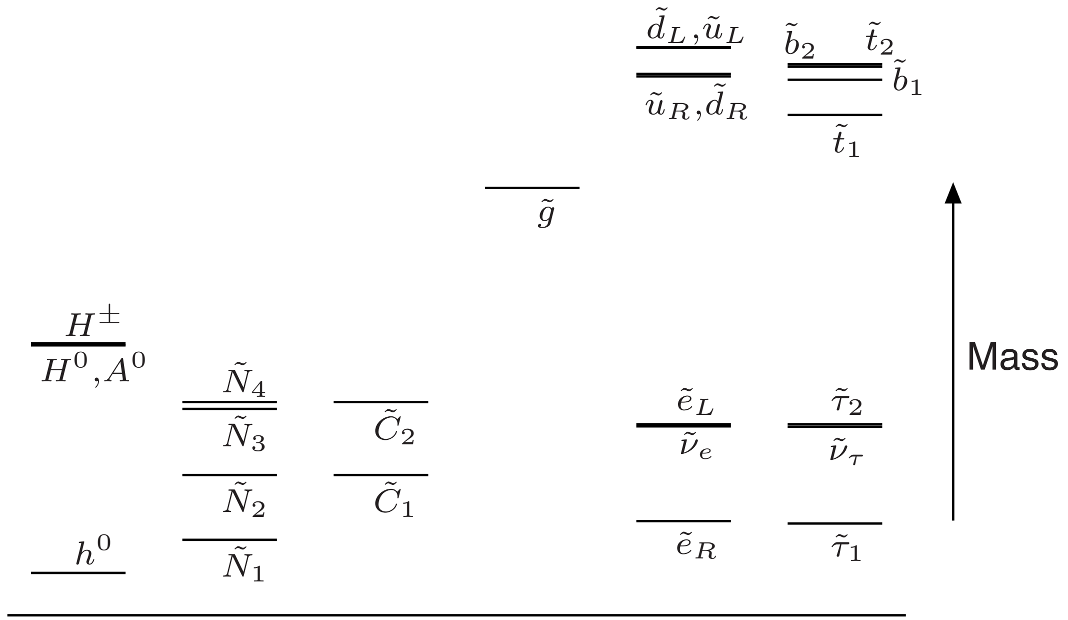
(slide borrowed from S. P. Martin)



60
50
40
30
20
10
0
α^{-1}
α_1^{-1}
α_2^{-1}
α_3^{-1}
2
4
6
8
10
12
14
16
18
$\mathrm{Log}_{10}(Q/1\ \mathrm{GeV})$

A sample sparticle mass spectrum for Minimal GMSB

with $N = 1$, $\Lambda = 150$ TeV, $M_{\rm mess} = 300$ TeV, $\tan\beta = 15$, sign(μ) = +1



The NLSP is a neutralino, which can decay to the nearly massless Goldstino/gravitino by: $\tilde{N}_1 \to \gamma\tilde{G}$. This decay can be prompt, or with a macroscopic decay length.

(slide borrowed from S. P. Martin)

SUSY signatures at colliders

I will concentrate mostly on models with conserved R-parity and a neutralino LSP dark matter candidate $(\tilde{N}_1)$. Recall:

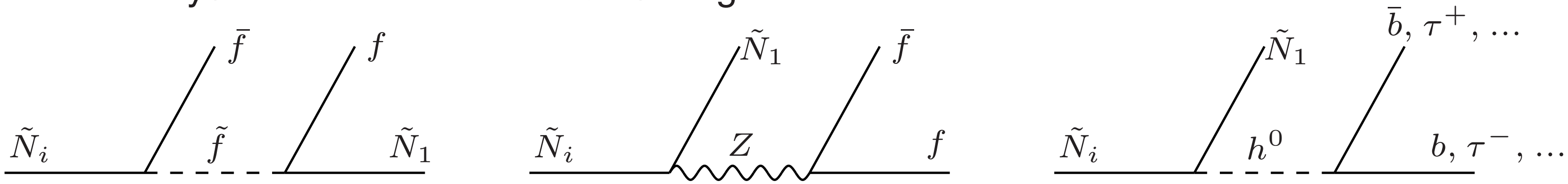
- The most important interactions for producing sparticles are gauge interactions, and interactions related to gauge interactions by SUSY. Their strength is known, up to mixing of sparticles.
- Two sparticles produced in each event, with opposite momenta.
- The LSPs are neutral and extremely weakly interacting, so they carry away energy and momentum.
  - At e^+e^- colliders, the total energy can be accounted for, so one sees missing energy, $\not{E}$.
  - At hadron colliders, the component of the momentum along the beam is unknown on an event-by-event basis, so only the energy component in particles transverse to the beam is observable. So one sees "missing transverse energy", $\not{E}_T$.

(slide borrowed from S. P. Martin)

Sparticle Decays

1) Neutralino Decays

If R-parity is conserved and $\tilde{N}_1$ is the LSP, then it cannot decay. For the others, the decays are of weak-interaction strength:



In each case, the intermediate boson (squark or slepton $\tilde{f}$, Z boson, or Higgs boson h^0) might be on-shell, if that two-body decay is kinematically allowed.

In general, the visible decays are either:

$$\tilde{N}_i \to q\bar{q}\tilde{N}_1 \qquad \text{(seen in detector as } jj + \not{E}\text{)}$$

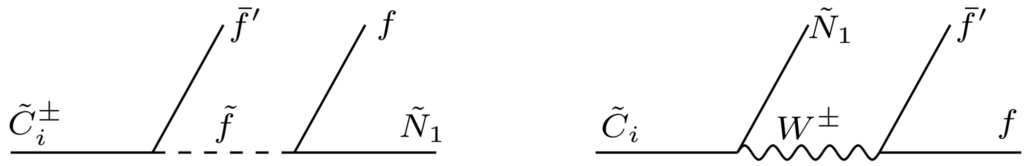
$$\tilde{N}_i \to \ell^+\ell^-\tilde{N}_1 \qquad \text{(seen in detector as } \ell^+\ell^- + \not{E}\text{)}$$

Some SUSY signals rely on leptons in the final state. This is more likely if sleptons are relatively light. If $\tilde{N}_i \to \tilde{N}_1 h^0$ is kinematically open, then it often dominates. This is called a "spoiler" mode, because leptonic final states are rare.

(slide borrowed from S. P. Martin)

2) Chargino Decays

Charginos $\tilde{C}_i$ have decays of weak-interaction strength:



In each case, the intermediate boson (squark or slepton $\tilde{f}$, or W boson) might be on-shell, if that two-body decay is kinematically allowed.

In general, the decays are either:

$$\tilde{C}_i^{\pm} \rightarrow q\bar{q}'\tilde{N}_1 \qquad \text{(seen in detector as } jj + \not{E}\text{)}$$

$$\tilde{C}_i^{\pm} \rightarrow \ell^{\pm}\nu\tilde{N}_1 \qquad \text{(seen in detector as } \ell^{\pm} + \not{E}\text{)}$$

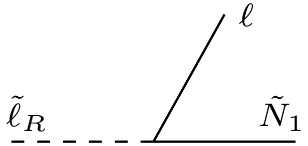
Again, leptons in final state are more likely if sleptons are relatively light.

For both neutralinos and charginos, a relatively light, mixed $\tilde{\tau}_1$ can lead to enhanced τ's in the final state. This is increasingly important for larger $\tan\beta$. Tau identification may be a crucial limiting factor for experimental SUSY.

(slide borrowed from S. P. Martin)

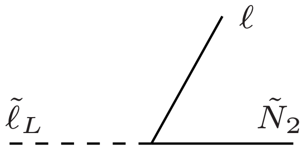
3) Slepton Decays

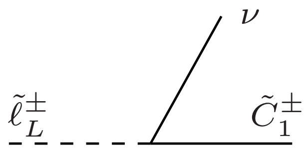
When $\tilde{N}_1$ is the LSP and has a large bino content, the sleptons $\tilde{e}_R$, $\tilde{\mu}_R$ (and often $\tilde{\tau}_1$ and $\tilde{\tau}_2$) prefer the direct two-body decays with strength proportional to g'^2:

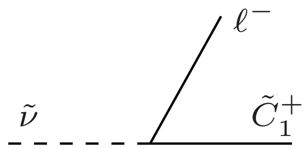


(seen in detector as $\ell^{\pm} + \not{E}$)

However, the left-handed sleptons $\tilde{e}_L$, $\tilde{\mu}_L$, $\tilde{\nu}$ have no coupling to the bino component of $\tilde{N}_1$, so they often decay preferentially through $\tilde{N}_2$ or $\tilde{C}_1$, which have a large wino content, with strength proportional to g^2:





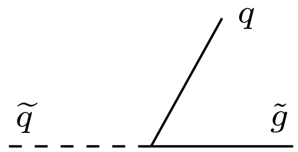


with $\tilde{N}_2$ and $\tilde{C}_1$ decaying as before.

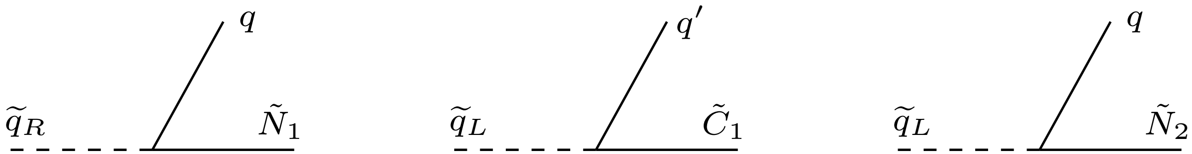
(slide borrowed from S. P. Martin)

4) Squark Decays

If the decay $\tilde{q} \longrightarrow q\tilde{g}$ is kinematically allowed, it will always dominate, because the squark-quark-gluino vertex has QCD strength:



Otherwise, right-handed squarks prefer to decay directly to a bino-like LSP, while left-handed squarks prefer to decay to a wino-like $\tilde{C}_1$ or $\tilde{N}_2$:



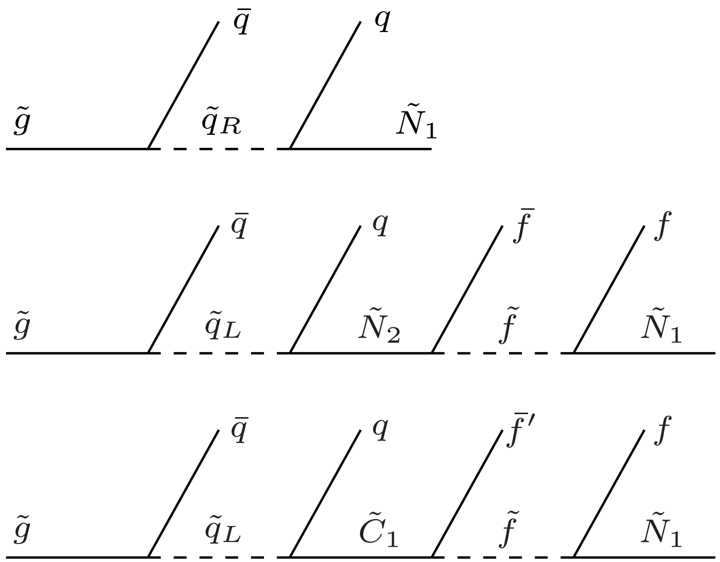
If a top squark is light, then the decays $\tilde{t}_1 \longrightarrow t\tilde{g}$ and $\tilde{t}_1 \longrightarrow t\tilde{N}_1$ may not be kinematically allowed, and it may decay only into charginos: $\tilde{t}_1 \longrightarrow b\tilde{C}_1$. If those decays are also closed, it has $\tilde{t}_1 \longrightarrow bW\tilde{N}_1$. If even that is closed, it has only a suppressed flavor-changing decay $\tilde{t}_1 \longrightarrow c\tilde{N}_1$ or 4-body decay $\tilde{t}_1 \longrightarrow bf\bar{f}'\tilde{N}_1$.

(slide borrowed from S. P. Martin)

5) Gluino Decays

The gluino can only decay through squarks, either on-shell (if allowed) or virtual.

For example:



$jj + \not{E}$ or $t\bar{t} + \not{E}$

$jjjj + \not{E}$ or $t\bar{t}jj + \not{E}$ or $jj\ell^+\ell^- + \not{E}$

$jjjj + \not{E}$ or $t\bar{t}jj + \not{E}$ or $jj\ell^\pm + \not{E}$

Because $m_{\tilde{t}_1} \ll$ other squark masses, top quarks can appear in these decays.

The possible signatures of gluinos and squarks are typically numerous and complicated because of these and other **cascade decays**.

(slide borrowed from S. P. Martin)

An important feature of gluino decays with one lepton:

In these decays, $\tilde{g} \to jj\ell^{\pm} + \not{E}$, the lepton has either charge with equal probability. (The gluino does not "know" about electric charge.)

So, events with two gluinos, and exactly one charged lepton in the final state from each, will have probability 0.5 to have **same-charge leptons**, and probability 0.5 to have opposite-charge leptons.

This is important at hadron colliders, where the backgrounds with same-charge leptons are much smaller.

$$pp \to \tilde{g}\tilde{g} \to \ell^{+}\ell'^{+} + \text{jets} + \not{E}_T$$

(slide borrowed from S. P. Martin)

Trilepton + $\not\!\!E_T$ Signal at the Tevatron

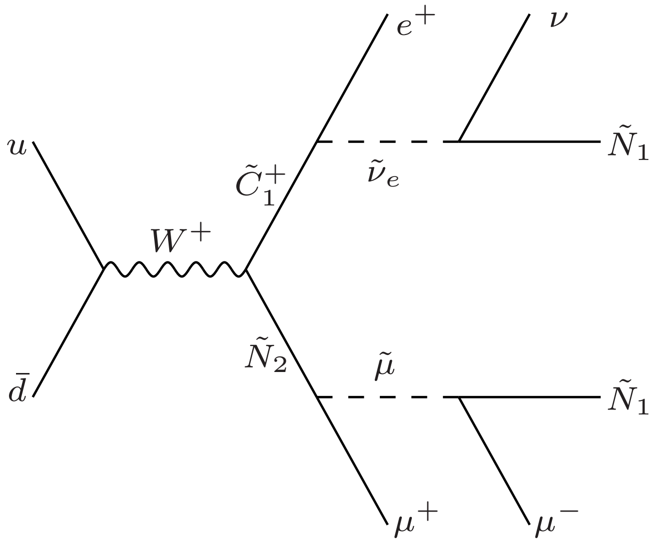
This signal arises if one can produce a pair of wino-like sparticles

$$p\overline{p} \longrightarrow \tilde{C}_1^{\pm}\tilde{N}_2,$$

which then each decay leptonically with a significant branching fraction,

$$\tilde{N}_2 \longrightarrow \ell^+\ell^-\tilde{N}_1, \qquad \tilde{C}_1^{\pm} \longrightarrow \ell^{\pm}\nu\tilde{N}_1$$

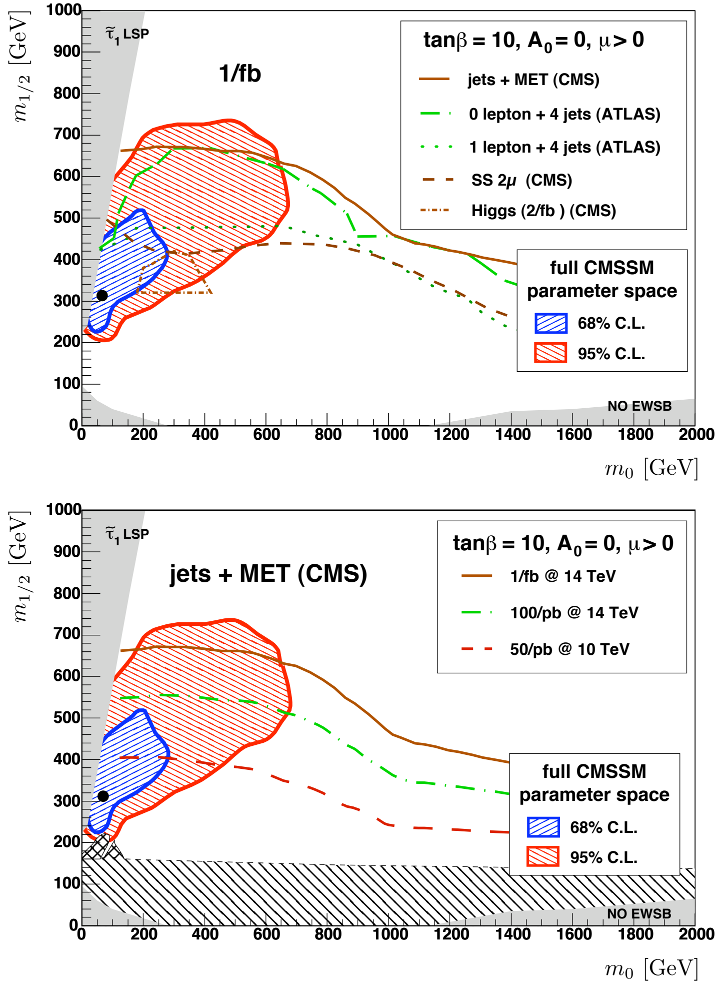
With no hard jets in the event, and three identified leptons, the Standard Model backgrounds are small. Here is a typical Feynman diagram for the whole event:



$$p\bar{p} \longrightarrow \ell^+\ell^-\ell'^{\pm} + \not\!\!E_T$$

Decays of $\tilde{C}_1^{\pm}$ and $\tilde{N}_2$ through virtual squarks and/or virtual h^0 kill the signal. Decays through Z, W hurt the signal. Decays through sleptons, as shown, help the signal.

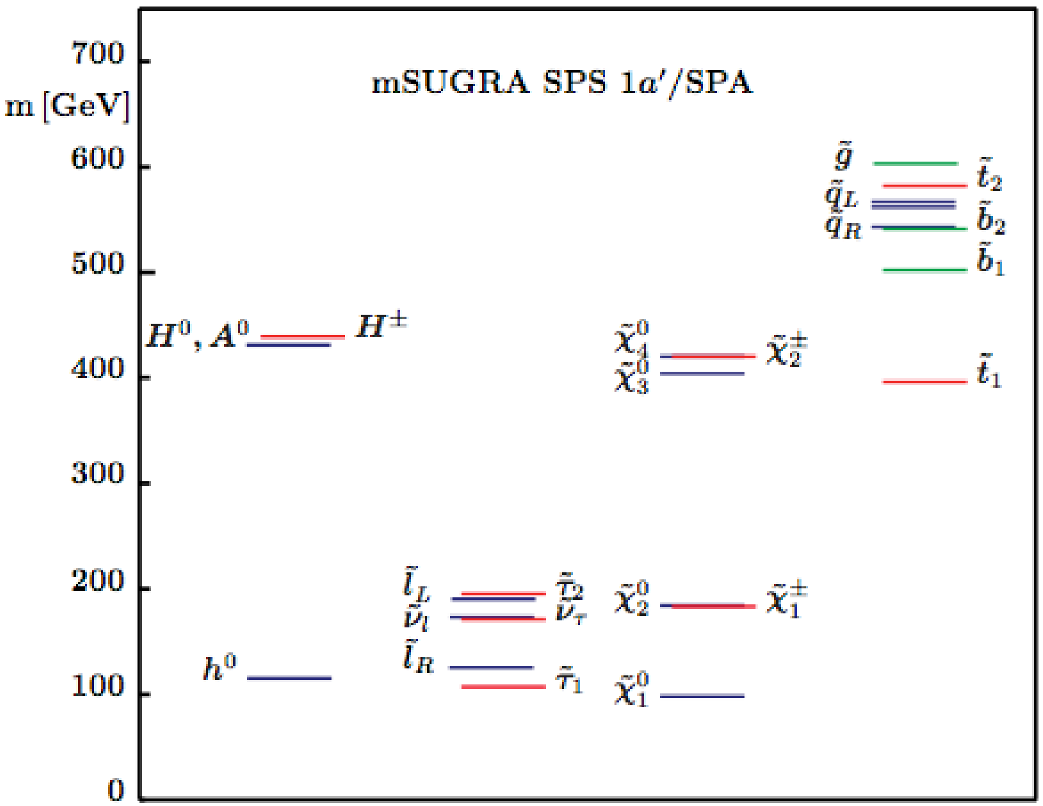
(slide borrowed from S. P. Martin)



O. Buchmueller et al. (2008)

Figure 1. The $(m_0, m_{1/2})$ plane in the CMSSM for $\tan\beta = 10$ and $A_0 = 0$. The dark shaded area at low m_0 and high $m_{1/2}$ is excluded due to a scalar tau LSP, the light shaded areas at low $m_{1/2}$ do not exhibit electroweak symmetry breaking. The nearly horizontal line at $m_{1/2} \approx 160$ GeV in the lower panel has $m_{\tilde{\chi}_1^\pm} = 103$ GeV, and the area below is excluded by LEP searches. Just above this contour at low m_0 in the lower panel is the region that is excluded by trilepton searches at the Tevatron. Shown in both plots are the best-fit point, indicated by a filled circle, and the 68 (95)% C.L. contours from our fit as dark grey/blue (light grey/red) overlays, scanned over all $\tan\beta$ and A_0 values. Upper plot: Some $5\,\sigma$ discovery contours at ATLAS and CMS with 1 fb^{-1} at 14 TeV, and the contour for the $5\,\sigma$ discovery of the Higgs boson in sparticle decays with 2 fb^{-1} at 14 TeV in CMS. Lower plot: The $5\,\sigma$ discovery contours for jet + missing E_T events at CMS with 1 fb^{-1} at 14 TeV, 100 pb^{-1} at 14 TeV and 50 pb^{-1} at 10 TeV centre-of-mass energy.

Back-up slides



mSUGRA SPS 1a′/SPA
m [GeV]
700
600
500
400
300
200
100
0
H^0, A^0
$H^\pm$
h^0
$\tilde{l}_L$
$\tilde{\nu}_l$
$\tilde{l}_R$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
$\tilde{\tau}_1$
$\tilde{\chi}^0_4$
$\tilde{\chi}^0_3$
$\tilde{\chi}^\pm_2$
$\tilde{\chi}^0_2$
$\tilde{\chi}^\pm_1$
$\tilde{\chi}^0_1$
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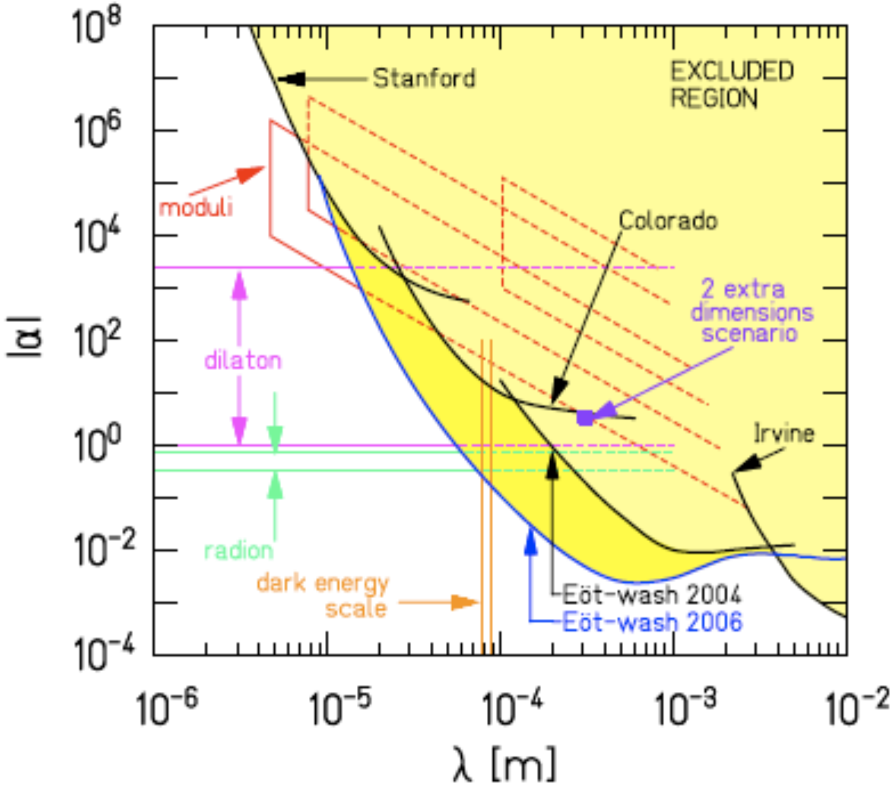
$\tilde{b}_2$
$\tilde{b}_1$
$\tilde{t}_1$



Stanford
EXCLUDED REGION
moduli
Colorado
2 extra dimensions scenario
dilaton
Irvine
radion
dark energy scale
Eöt-wash 2004
Eöt-wash 2006
|α|
λ [m]
10^8
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-6
10^-5
10^-4
10^-3
10^-2