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Supersymmetry: Motivation, Algebra, Models and Signatures (Lecture 4)

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Supersymmetry:
Motivation, Algebra, Models and Signatures

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Outline

- Lecture 1:
  Motivation
  Introduction to Supersymmetry
- Lecture 2 :
  Supersymmetric Interactions
  The Minimal Supersymmetric extension of the Standard Model
- Lecture 3 :
  Soft Supersymmetry Breaking
  Higgs and Super-particle masses
- Lecture 4 :
  Gauge Coupling Unification
  Models of Supersymmetry Breakdown
  MSSM Higgs searches at Colliders
- Appendix

Lecture 4:

Guage Couplings Unification

Models of Supersymmetry Breakdown

SUSY Higgs signals at Colliders

Last lecture:

We discussed the conditions for Soft Supersymmetry Breaking
and
presented a general parametrization of the SUSY breaking Lagrangian

We discussed the MSSM Higgs sector

We derived the mass eigenstates and mass formulae
for Charginos, Neutralinos, Squarks and Sleptons

The Soft SUSY-breaking Lagrangian for the MSSM

$$\mathcal{L}_{soft} = -\frac{1}{2}(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B})$$
$$-m_Q^2\tilde{Q}^\dagger\tilde{Q} - m_U^2\tilde{U}^\dagger\tilde{U} - m_D^2\tilde{D}^\dagger\tilde{D} - m_L^2\tilde{L}^\dagger\tilde{L} - m_E^2\tilde{E}^\dagger\tilde{E}$$
$$-m_{H_1}^2 H_1^* H_1 - m_{H_2}^2 H_2^* H_2 - (\mu B H_1 H_2 + cc.)$$
$$-(A_u h_u \tilde{U}\tilde{Q}H_2 + A_d h_d \tilde{D}\tilde{Q}H_1 + A_l h_l \tilde{E}\tilde{L}H_1) + c.c.$$

Trilinear terms are proportional to the Yukawa couplings

⟶ induce L-R mixing on the squark sector once the Higgs acquire v.e.v.
mixing proportional to fermion masses: relevant for 3rd generation

B ⟶ soft SUSY breaking paramete determined from condition of proper EWSB

MSSM Higgs Sector

→ 2 CP-even h, H with mixing angle α
1 CP-odd A and a charged pair $\mathrm{H}^{\pm}$

$$m_A^2 = m_1^2 + m_2^2 = m_{H_1}^2 + m_{H_2}^2 + 2\mu^2$$

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

$$m_H^2 \simeq m_A^2$$

$$m_h^2 \simeq M_Z^2 cos^2 2\beta + \frac{3m_t^4}{4\pi^2 \mathrm{v}^2}\left[log\left(\frac{M_{SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right)\right]$$

Dependence on SUSY breaking parameters

through the stop sector:

$M_{SUSY} \rightarrow$ averaged stop mass and stop mixing $: X_t = A_t - \mu/\tan\beta$

and $m_{H_i}^2$

The chargino eigenstates are two Dirac, charged fermions with masses:

$$m^2_{\tilde{\chi}^{\pm}_{1,2}} = \frac{1}{2}\left[|M_2|^2 + |\mu|^2 + 2m_W^2 \mp \sqrt{(|M_2|^2 + |\mu|^2 + 2m_W^2)^2 - 4|\mu M_2 - m_W^2 \sin 2\beta|^2} \right].$$

The neutralino eigenstates are four Majorana fermions with masses that depend on M_1 M_2 μ $\tan\beta$

The gluino masses are given by the Soft SUSY breaking parameter M_3

The squark and lepton masses are determined by the soft SUSY breaking parameters:

m_{Q_i} m_{U_i} m_{D_i} m_{L_i} m_{E_i}

with i= family indices 1-3

Stop Mass Matrix

- The stop, and other squarks, acquire masses that are controlled by the supersymmetry breaking parameters.
- Once the Higgs acquires a v.e.v., the mass matrix is

$$M_{\tilde{t}}^2 \simeq \begin{bmatrix} m_Q^2 + m_t^2 & m_t(A_t - \mu^* / \tan\beta) \\ m_t(A_t^* - \mu / \tan\beta) & m_U^2 + m_t^2 \end{bmatrix}$$

- In general, the existence of A_t and μ denote couplings of the stops to the Higgs bosons, that induce finite corrections to the quartic couplings.

Only for the 3rd generation the Left-Right mixing effects are relevant since they are proportional to the quark masses

The SUSY Particles of the MSSM

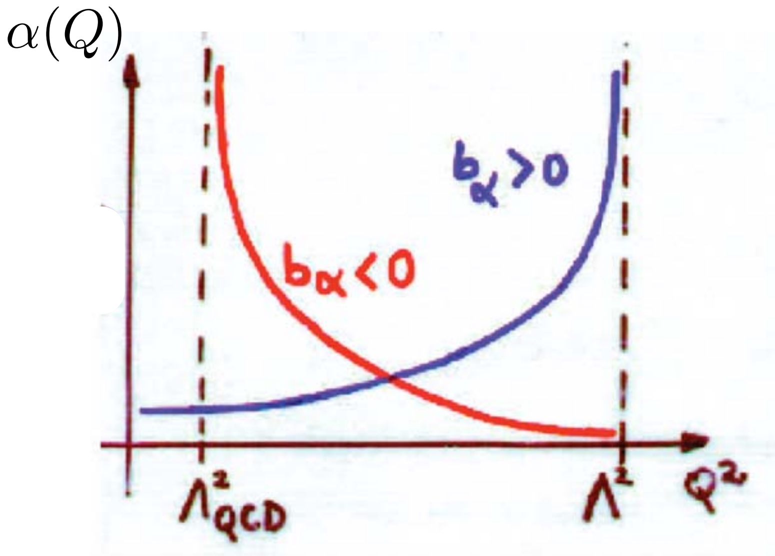
Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	$+1$	h H A $H^{\pm}$	H_u^0 H_d^0 H_u^+ H_d^-
squarks	0	-1	u_L u_R d_L d_R s_L s_R c_L c_R t_1 t_2 b_1 b_2	" " " " t_L t_R b_L b_R
sleptons	0	-1	e_L e_R e μ_L μ_R μ 1 2	" " " " L R
neutralinos	1/2	-1	$\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$	B^0 W^0 H_u^0 H_d^0
charginos	1/2	-1	$\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_2^{\pm}$	$W^{\pm}$ H_u^+ H_d^-
gluino	1/2	-1	g	" "

Unification of Gauge Couplings

Renormalization group evolution ⟶ allows to study the scaling of the gauge couplings with energy

$$\frac{d\alpha_i}{d\ln Q^2} = b_i \frac{\alpha_i^2}{4\pi}$$

$\alpha_i = g_i^2/4\pi$
$b_i = \beta$ function coefficient



Abelian theories: $b_\alpha > 0$
Are only consistent as an effective theory up to a cutoff scale

Non-Abelian theories: (May have $b_\alpha < 0$)
May be asymptotically free at large energies, but strongly interacting at small ones.
==> at $\Lambda_{QCD} \simeq 300\text{MeV}$ color is confined!

$$b_{QCD} = -\frac{11}{3}N_C + \frac{1}{3}N_f = -7 \qquad N_f = \underbrace{3}_{gen,} \times \underbrace{4}_{u_R, u_L, d_R, d_L}$$

In the SM, U(1) coupling is non-asymptotically free but it blows up above M_{Pl}
All couplings seem to converge but quantitatively it does not work!

Unification Conditions

Given the 3 RG equations for α_i and assuming they unify at a common value α_{GUT} at a scale M_{GUT}

$$\frac{1}{\alpha_{GUT}} = \frac{1}{\alpha_i(M_{GUT})} = \frac{1}{\alpha_i(M_Z)} - \frac{b_i}{4\pi} \ln\left(\frac{M_{GUT}^2}{M_Z^2}\right)$$

$$M_{GUT} = exp\left[\left(\frac{1}{\alpha_1(M_z)} - \frac{1}{\alpha_2(M_z)}\right)\frac{2\pi}{b_1 - b_2}\right] M_Z$$

$$\frac{1}{\alpha_3(M_Z)} = \left(1 + \frac{b_3 - b_2}{b_2 - b_1}\right)\frac{1}{\alpha_2(M_Z)} - \frac{b_3 - b_2}{b_2 - b_1}\frac{1}{\alpha_1(M_Z)}$$

Depending on the specific model that defines the values of the b_i coefficients, the unification condition gives a specific relation between

$$\alpha_3(M_Z) \text{ and } \quad \sin^2\theta_W(M_Z) = \alpha_1^{SM} / \left(\alpha_1^{SM} + \alpha_2^{SM}\right).$$

Rules to compute the beta function coefficients

The one loop coefficients for the U(1) and the SU(N) gauge couplings are given by (recall $Q = T_3 + Y$)

$$\frac{5}{3} b_1 = \frac{2}{3} \sum_f Y_f^2 + \frac{1}{3} \sum_s Y_s^2$$

$$b_N = -\frac{11N}{3} + \frac{n_f}{3} + \frac{n_S}{6} + \frac{2N}{3} n_A$$

$Y_{f,s}$ are the hypercharges of the chiral fermions and scalars fields
$n_{f,s}$ are the number of fermions and scalars in the fundamental representation of SU(N), and n_A is the number of fermions in the adjoint

The factor 5/3 is for normalization so that over one generation:

$$Tr[T^3 T^3] = \frac{3}{5} Tr[Y_F^2]$$

One can compute the coefficients both in the SM and in the MSSM and obtain

$$b_1^{SM} = \frac{41}{10} \qquad b_2^{SM} = -\frac{19}{6} \qquad b_3^{SM} = -7$$

$$b_1^{MSSM} = \frac{33}{5} \qquad b_2^{MSSM} = 1 \qquad b_3^{MSSM} = -3$$

$$\left(\frac{b_3 - b_2}{b_2 - b_1}\right)^{SM} = \frac{1}{2} + \frac{3}{109} \simeq \frac{1}{2} \quad \to \frac{1}{\alpha_3(M_Z)} \approx 15!!$$

$$\left.\frac{1}{\alpha_3(M_Z)}\right|_{exp} \simeq 8.5$$

Although qualitatively possible, unification of couplings in the SM is ruled out !

Instead, in the MSSM

$$\left(\frac{b_3 - b_2}{b_2 - b_1}\right)^{MSSM} = \frac{5}{7} \quad \to \frac{1}{\alpha_3(M_Z)} \approx 8.5!!$$

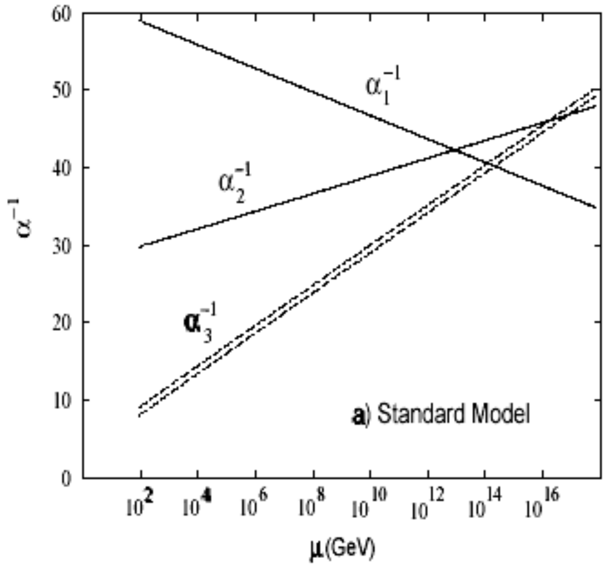
All done at one loop:
two-loop corrections give
slight modifications

$$M_{GUT} \simeq 2 \times 10^{16} \mathrm{GeV}$$

SUSY particles around the TeV scale allow Unification of Couplings

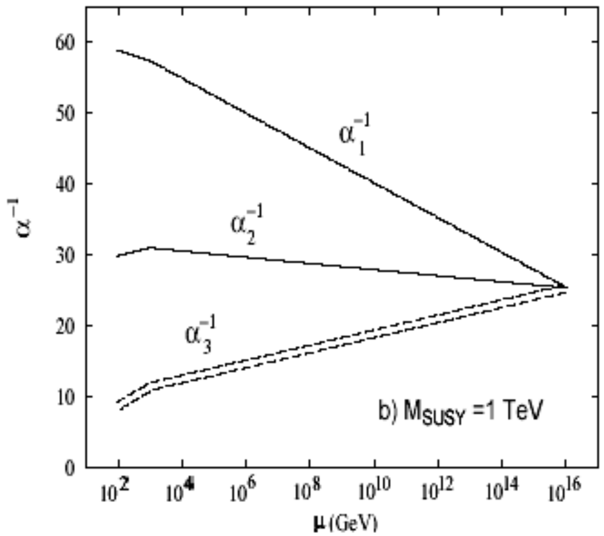
SM:

Couplings tend to converge at high energies, but unification is quantitatively ruled out.



MSSM:

Unification at $\alpha_{GUT} \simeq 0.04$ and $M_{GUT} \simeq 10^{16}$ GeV.



Experimentally, $\alpha_3(M_Z) \simeq 0.118 \pm 0.004$ Bardeen, M.C., Pokorski & Wagner

in the MSSM: $\alpha_3(M_Z) = 0.127 - 4(\sin^2\theta_W - 0.2315) \pm 0.008$

Remarkable agreement between Theory and Experiment!!

Understanding the origins of SUSY Breaking

To gain deeper understanding, let us consider how SUSY could be spontaneously broken. This means that the Lagrangian is invariant under SUSY transformations, but the ground state is not:

$$Q\,|0\rangle \neq 0, \qquad Q^{\dagger}\,|0\rangle \neq 0.$$

The SUSY algebra tells us that the Hamiltonian is related to the SUSY charges by:

$$H = P^0 = \tfrac{1}{4}\left(Q_1 Q_1^{\dagger} + Q_1^{\dagger} Q_1 + Q_2 Q_2^{\dagger} + Q_2^{\dagger} Q_2\right).$$

Therefore, if SUSY is unbroken in the ground state, then $H\,|0\rangle = 0$, so the ground state energy is 0. Conversely, if SUSY is spontaneously broken, then the ground state must have positive energy. $\langle 0|H|0\rangle > 0$

Recall the potential energy : $V = \sum_i F^{*i} F_i + \frac{1}{2} \sum_a D^a D^a$

So, for Spontaneous SUSY breaking, one must arrange that **no** state has **all F_i =0 and all D^a=0**

Spontaneous Breaking of SUSY requires us to extend the MSSM

- $D^a =$ 0 are called “Fayet-Iliopoulis models” or “D-term breaking models”

U(1) gauge symmetry, with a scalar chiral multiplet carrying its charges, one can add a term:

$$L = - \ D$$

with D the auxiliary field for the U(1) gauge multiplet

PROBLEM: **no D-term breaking for any U(1) does the job for the MSSM**

- $F_i =$ 0 are called “O’Raifeartaigh models” or “F-term Breaking models”

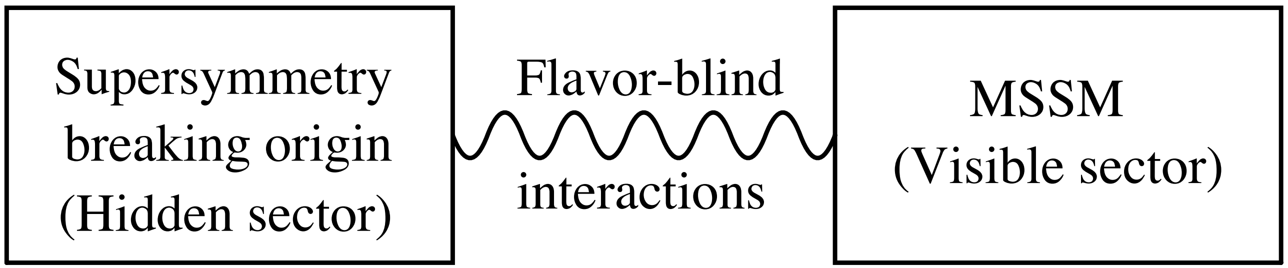
Add a gauge singlet chiral supermultiplet, such that the superpotential

$$W = L^i \ _i + \frac{1}{2} M^{ij} \ _i \ _j + \frac{1}{6} y^{ijk} \ _i \ _j \ _k \longrightarrow F^i = - L^i - M^{ij} \ _j - \frac{1}{2} y^{ijk} \ _j \ _k$$

PROBLEM: **no gauge singlet in the MSSM that could get <F> ≠ 0**

Proposal: MSSM Soft SUSY breaking terms arise indirectly,

not through treel level, renormalizable couplings to the SUSY breaking sector



Spontaneous SUSY breaking occurs in a Hidden sector of particles,
with none or tiny direct couplings to the MSSM particles,
when some components of the hidden sector acquire a vev $< F > \neq 0$.

One can think of Messengers mediating some interactions that transmit
SUSY breaking effects indirectly from the hidden sector to the MSSM

If the mediating interactions are flavor blind, so will the soft SUSY breaking terms of the MSSM (favored experimentally)

Flavor blind interactions: gravitational and ordinary gauge interactions

Gravity mediated SUSY breaking

The idea: SUSY breaking is transmitted from a hidden sector to the MSSM by the new interactions, including gravity, that enter near the Planck mass scale M_P.

Moduli/dilaton fields interact with MSSM fields with gravity type interactions

Effective field theory non-renormalizable Lagrangian couples their F component to MSSM scalar/gaugino fields

$$L_{GMSB} = -\frac{f^a}{2M_P} F \quad a \quad a + c.c. - \frac{k_i^j}{M_P^2} F F \quad _i \quad ^j$$

$$- \frac{ijk}{6M_P} F \quad i \; j \; k + \frac{ij}{2M_P} F \quad i \; j + c.c.$$

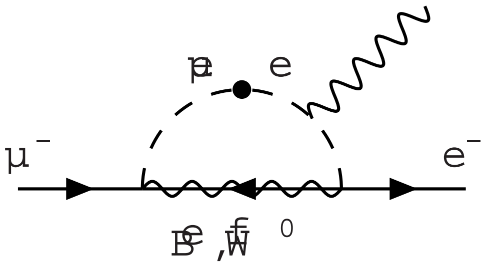
When F acquires a non-zero vev, the above yields the soft SUSY breaking terms we proposed before, however, in principle, they are not flavor blind!!

Observe, if $\frac{<F>}{M_P} \simeq$ a few hundred GeV, and $M_P \simeq 2.4 \times 10^{18}$ GeV

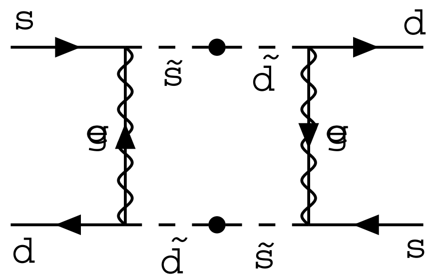
$$\Rightarrow \sqrt{< F >} \simeq 10^{11} - 10^{12} \text{ GeV}$$

SUSY Breaking and Flavour Changing Neutral Currents

- Two particularly constraining examples of flavor changing neutral currents induced by off-diagonal soft supersymmetry breaking parameters
- Contribution to the mixing in the Kaon sector, as well as to the rate of decay of a muon into an electron and a photon.
- While the second is in good agreement with the SM predictions, the first one has never been observed.
- Rate of these processes suppressed as a power of supersymmetric particle masses and they become negligible if relevant masses are heavier than 10 TeV



$\mu^- \quad e^-$



$K^0 \quad \overline{K^0}$

Solution to the Flavor Problem

- There are two possible solutions to the flavor problem
- The first one is to push the masses of the scalars, in particular to the first and second generation scalars, to very large values, larger than a few TeV.
- Some people have taken the extreme attitude of pushing them to values of order of the GUT scale. This is fine, but supersymmetry is then broken in a hard way and the solution to the hierarchy problem is lost.
- A second possibility is to demand that the scalar mass parameters are approximately flavor diagonal in the basis in which the fermions mass matrices are diagonal. All flavor violation is induced by either CKM mixing angles, or by very small off-diagonal mass terms.
- This latter possibility is a most attractive one because it allows to keep SUSY particles with masses of the order of the weak scale.

Minimal Supergravity models (MSUGRA)

Assuming a huge simplification of the underlying theory

- A common gaugino mass: $M_{1/2} = f \frac{F}{M_P}$
- A common scalar squared mass: $m_0^2 = k \frac{|F|^2}{M_P^2}$
- A scalar[3] coupling prefactor: $A_0 = \frac{F}{M_P}$
- A scalar mass[2] prefactor $B_0 = \frac{F}{M_P}$

In terms of the four parameters $M_{1/2}$, m_0^2, A_0, and B_0:

$$M_3 = M_2 = M_1 = M_{1/2}$$

$$m_Q^2 = m_U^2 = m_D^2 = m_L^2 = m_E^2 = m_0^2$$

$$m_{H_1}^2 = m_{H_2}^2 = m_0^2$$

$$A_u = A_d = A_l = A_0 \qquad B = B_0$$

These values of soft parameters are taken at the renormalization scale $Q_0 = M_{GUT}$, and then run down to the electroweak scale.

Renormalization Group Evolution

- One interesting thing is that the gaugino masses evolve in the same way as the gauge couplings:

  $d(M_i/\alpha_i)/dt = 0, \qquad \frac{dM_i}{dt} = -b_i \alpha_i M_i/4\pi, \qquad d\alpha_i/dt = -b_i \alpha_i^2/4\pi$

  $t \equiv \ln(M_{GUT}^2/Q^2)$

- The scalar fields masses evolve in a more complicated way.

  $4\pi dm_i^2/dt = +C_a^i 4M_a^2 \alpha_a - |Y_{ijk}|^2[(m_i^2 + m_j^2 + m_k^2 + A_{ijk}^2)]/4\pi$

- There is a positive contribution coming from the gaugino masses and a negative contribution proportional to the Yukawa couplings.

- Colored particles are affected by positive, strongly coupled corrections and tend to be the heaviest ones.

- Weakly interacting particles tend to be lighter, particular those affected by large Yukawas.

- There scalar field H_2 is both weakly interacting and couples with the top quark Yukawa. Its mass naturally becomes negative.

Low energy masses and EWSB in MSUGRA

Squark Masses: $m^2_{\tilde{Q}} \simeq m_0^2 + 6\ M^2_{1/2}$

Left-Slepton Masses $m^2_{\tilde{L}} \simeq m_0^2 + 0.5\ M^2_{1/2}$

Right-Slepton Masses $m^2_{\tilde{E}} \simeq m_0^2 + 0.15\ M^2_{1/2}$

Wino Mass $M_2 = 0.8\ M_{1/2}$.

Gluino Mass $M_3 = \frac{\alpha_3}{\alpha_2} M_2$

Bino Mass $M_1 = \frac{\alpha_1}{\alpha_2} M_2$

- The above relations apply to most squarks and leptons, but not to the Higgs particles and the third generation squarks.
- The renormalization group equations of these mass parameters include negative corrections proportional to the square of the large top Yukawa coupling.
- In particlular, the H_2 Higgs mass parameter m_2^2, is driven to negative values due to the influence of the top quark Yukawa coupling.
- Electroweak symmetry breaking is induced by the large top mass !
- Also the superpartners of the top quark tend to be lighter than the other squarks. This effect is more pronounced if $M_{1/2}$ is small.

Electroweak Symmetry Breaking radiatively generated

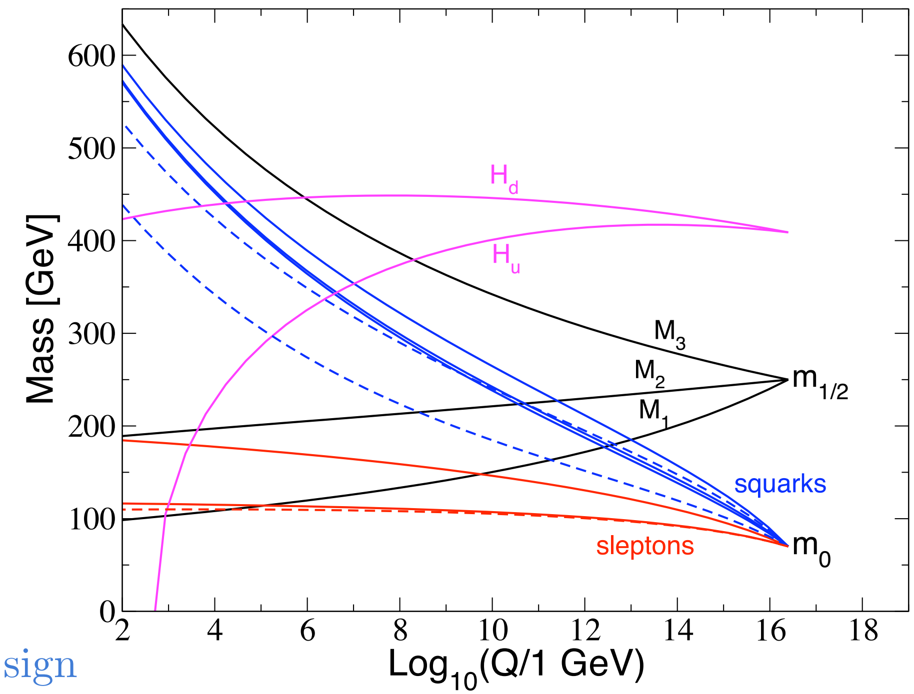
Renormalization Group Running for mSUGRA with $m_{1/2} = 250$ GeV, $m_0 = 70$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, and sign(μ) = +1

Gaugino masses M_1, M_2, M_3

Slepton masses (dashed=stau)

Squark masses (dashed=stop)

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

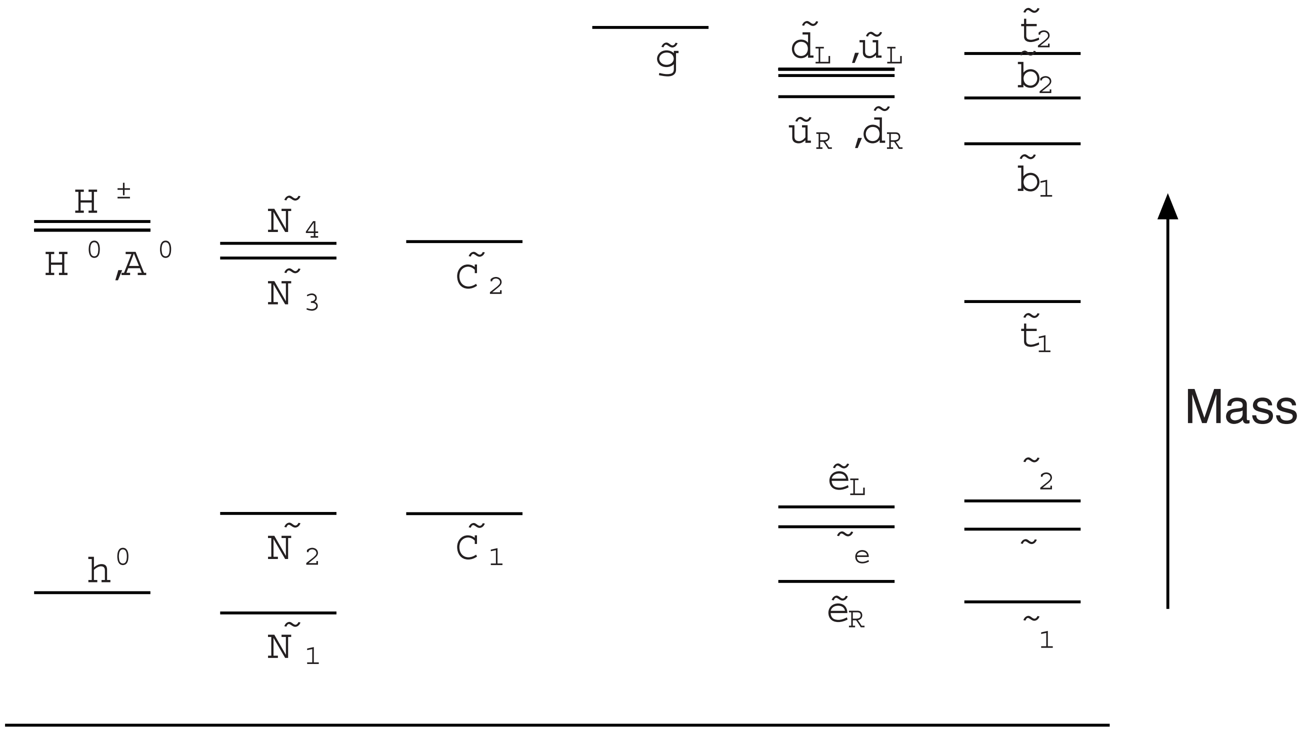


μ determined by EWSB but for its sign

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.

Resulting MSSM Spectrum:

Typical for MSUGRA models with $M_{\frac{1}{2}} > m_0$.



Higgs Sector in the decoupling limit.

Neutralino is the LSP.

The lightest squark is the stop.

The Gluino is the heaviest sparticle

The lightest slepton is the stau.

Gauge mediated SUSY breaking

The idea: SUSY breaking is transmitted from a hidden sector by the ordinary $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge interactions.

This makes them automatically flavor blind !

* Hidden sector singlet superfield S, analogous to moduli fields in SUGRA, has an F-term with non-zero v.e.v. ==> induces SUSY breakdown

New, heavy chiral multiplets - **MESSENGER superfields -** which couple to $\langle F \rangle$, and to the MSSM particles through ordinary gauge interactions

If the typical messenger particle masses are M_{mess}, the MSSM soft terms are:

$$m_{soft} \quad \frac{a}{4} \frac{F}{M_{mess}}$$

$a/4$ one loop factor for diagrams with gauge interactions

$$\text{If } m_{soft} \simeq 100 \text{ GeV} \Rightarrow \frac{\langle F \rangle}{M_{mess}} \simeq 100 \text{ TeV}$$

$\sqrt{\langle F \rangle}$ as low as 10^4 GeV if M_{mess} comparable

A Minimal Gauge mediated SUSY Breaking Model

For a minimal model, take a set of new chiral supermultiplets $q, \bar{q}, \ell, \bar{\ell}$ that transform under $SU(3)_C \times SU(2)_L \times U(1)_Y$ as

$$q \sim (3, 1, -\frac{1}{3}); \quad \bar{q} \sim (\bar{3}, 1, \frac{1}{3}); \quad \ell \sim (1, 2, \frac{1}{2}); \quad \bar{\ell} \sim (1, 2, -\frac{1}{2}).$$

These supermultiplets contain messenger quarks $\psi_q, \psi_{\bar{q}}$ and scalar quarks $A_q, A_{\bar{q}}$ and messenger leptons $\psi_\ell, \psi_{\bar{\ell}}$ and scalar leptons $A_l, A_{\bar{l}}$

The messengers acquire heavy masses by coupling to the gauge- singlet chiral multiplet S, whose auxiliary and scalar components acquire v.e.v's

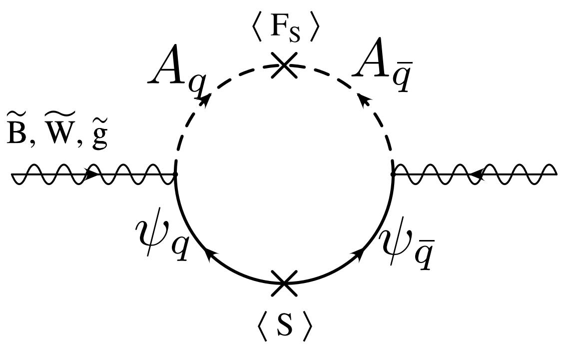
$$W_{mess} = y_2 S \ell \bar{\ell} + y_3 S q \bar{q}.$$

The effect of SUSY breaking is to split the messenger masses:

$$\ell, \bar{\ell}: \quad m^2_{\text{fermions}} = |y_2 \langle S \rangle|^2, \quad m^2_{\text{scalars}} = |y_2 \langle S \rangle|^2 \pm |y_2 \langle F_S \rangle|$$

$$q, \bar{q}: \quad m^2_{\text{fermions}} = |y_3 \langle S \rangle|^2, \quad m^2_{\text{scalars}} = |y_3 \langle S \rangle|^2 \pm |y_3 \langle F_S \rangle|$$

Integrating the messenger sector gives mass to gauginos at one-loop

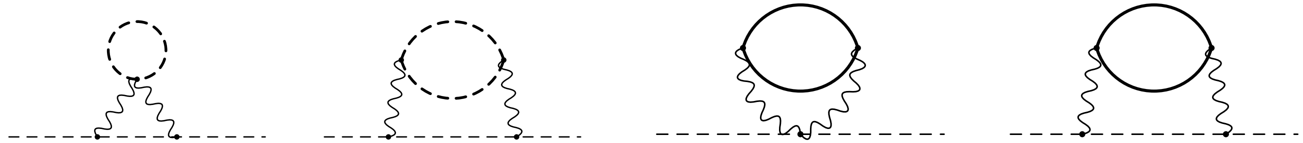


$$M_a = \frac{a}{4} ,$$ where $$\frac{F_S}{S}$$

Gauge bosons do not get contributions since they are protected by gauge invariance ==> successful SUSY breakdown

Scalar superpartner masses are generated at two-loops

$$m^2_{A_i} = 2\,^2 \left[\left(\frac{_3}{4}\right)^2 C_3^{A_i} + \left(\frac{_2}{4}\right)^2 C_2^{A_i} + \left(\frac{_1}{4}\right)^2 C_1^{A_i} \right]$$



Minimal GMSB model can be generalized by putting N copies of the messenger sector. All expressions above multiplied by N

GMSB mass parameters

Gaugino masses arise at one-loop and scalar squared masses at two-loops, hence they are comparable

$$M_i \simeq m_{A_i} \simeq \frac{\alpha}{4\pi}\Lambda$$

However, different scaling with N, number of messenger!

A_i trilinear SUSY breaking mass parameter arise at two-loop and are suppressed by an extra loop factor with respect to gaugino masses

Assumed to be zero at the SUSY breaking scale, but get renormalized at low energies

Mass hierarchies related to the strength of their gauge interactions

$$\frac{M_i}{M_j} = \frac{\alpha_i}{\alpha_j} \qquad \frac{m_{\tilde{q}}}{m_{\tilde{l}}} = \frac{\alpha_3}{\alpha_{1,2}}$$

Lightest SM-SUSY partner tends to be a Bino or Higgsino, unless N >1

The Gravitino

- When standard symmetries are broken spontaneously, a massless **Goldstone** boson appears for every broken generator.
- If the symmetry is local, this bosons are absorbed into the longitudinal components of the gauge bosons, which become massive.
- The same is true in supersymmetry. But now, a massless fermion appears, called the Goldstino.
- In the case of local supersymmetry, this Goldstino is absorbed into the Gravitino, which acquires mass $m_{\tilde{G}} = F/M_{Pl}$, with F the order parameter of SUSY breaking.
- The coupling of the Goldstino (gravitino) to matter is proportional to $1/\sqrt{F} = 1/\sqrt{m_{\tilde{G}} M_{Pl}}$, and couples particles with their superpartners.

The gravitino is the LSP !

$$m_{3/2} \quad \frac{F}{M_P} \qquad\qquad m_{soft} \quad \frac{a}{4} \frac{F}{M_{mess}}$$

$m_{3/2}$ can be as low as 0.1 eV

Gauge-Mediated, Low-energy SUSY Breaking Scenarios

- Special feature $\longrightarrow$ LSP: light (gravitino) Goldstino:

$$m_{\tilde{G}} \sim \frac{F}{M_{Pl}} \simeq 10^{-6} - 10^{-9}\text{GeV}$$

If R-parity conserved, heavy particles cascade to lighter ones and

NLSP $\longrightarrow$ SM partner + $\tilde{G}$

- Signatures: The NLSP (Standard SUSY particle) decays

decay length $$L \sim 10^{-2}\text{cm} \left(\frac{m_{\tilde{G}}}{10^{-9}\text{GeV}}\right)^2 \times \left(\frac{100\text{GeV}}{M_{\text{NLSP}}}\right)^5$$

⋆ NLSP can have prompt decays:

Signature of SUSY pair: 2 hard photons, (H's, Z's) + $\not{E}_T$ from $\tilde{G}$

⋆ macroscopic decay length but within the detector:

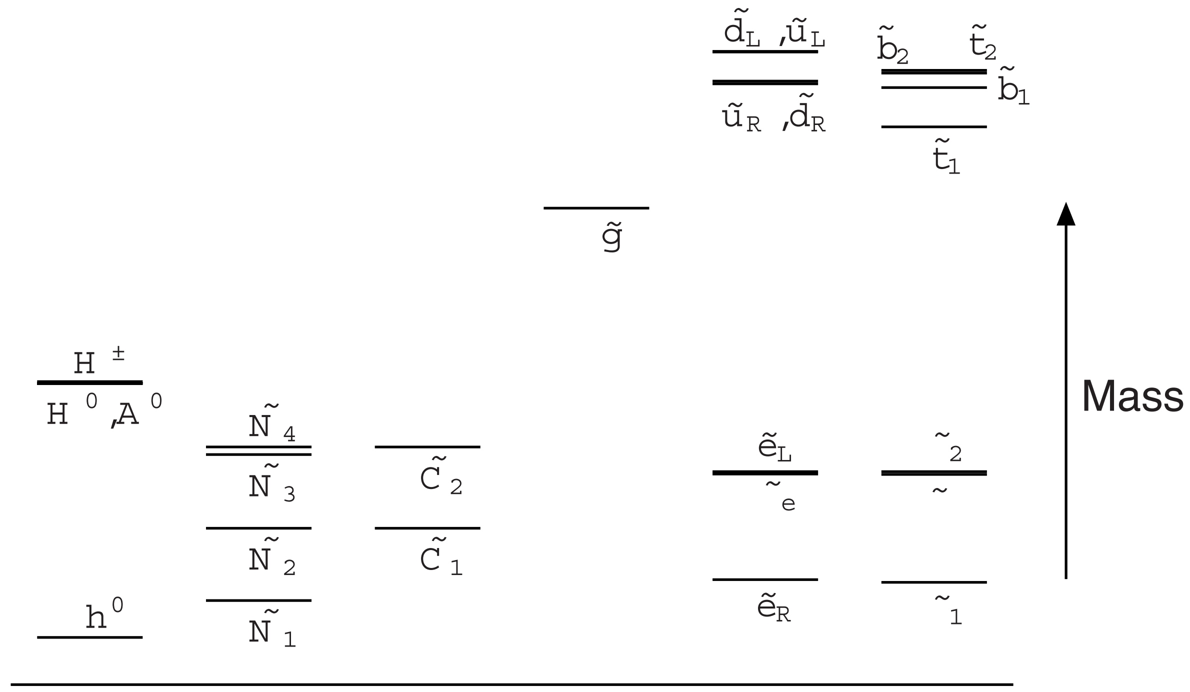
displaced photons; high ionizing track with a kink to a minimum ionizing track

(smoking gun of low energy SUSY)

⋆ decay well outside the detector: $\not{E}_T$ like SUGRA

A sample sparticle mass spectrum for Minimal GMSB

with $N = 1$, $= 150$ TeV, $M_{mess} = 300$ TeV, $\tan = 15$, $\text{sign}(\mu) = +1$



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

Interesting: The NLSP does not need to be neutral, can be the stau/slepton

Outlook

The SM Higgs mechanism solves the Mystery of Mass of all the fundamental particles

==> The Tevatron and ultimately the LHC will have the final word on the SM Higgs

Cosmology shows the universe is mostly made of Dark Matter and Dark Energy

All evidence comes from gravitational interactions:

how well do we really understand gravity?

The SM must be superceded by a more fundamental theory at the TeV scale

Many EWSB theories predict the existence of Dark Matter at the weak scale !

Supersymmetry is the leading candidate

It can also explain the Mystery of the Baryon asymmetry with EW scale physics

We are about to enter an exciting era in which findings both in particle physics and cosmology will further revolutionize our understanding of nature

Appendix on Higgs at Colliders

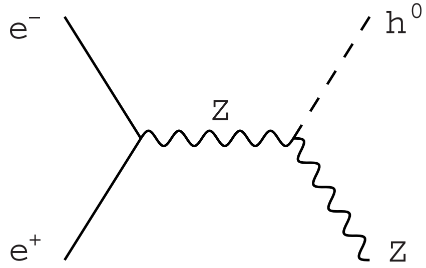
MSSM Higgs Boson Searches at colliders

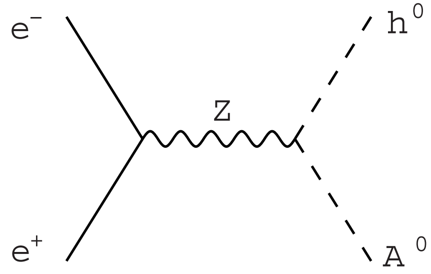
1) Search for a SM-like Higgs responsible for EWSB
must have SM-like couplings to W-Z gauge bosons
and most probably SM-like couplings to the top-quark

2) Search for the non-SM-like neutral Higgs bosons A and H
they have $\tan\beta$ enhanced couplings to the bottom quarks

The past: Higgs Searches at LEP

The most important constraints on SUSY parameter space come from searches for the MSSM Higgs bosons at LEP2. The relevant processes include:





$\sin^2(\quad - \quad)$ $\qquad\qquad$ $\cos^2(\quad - \quad)$

The first diagram is the same as for the Standard Model Higgs search in the decoupling limit, where $\sin^2(\quad - \quad) \quad 1$. Many SUSY models fall into this category, and the LEP2 bound (nearly) applies:

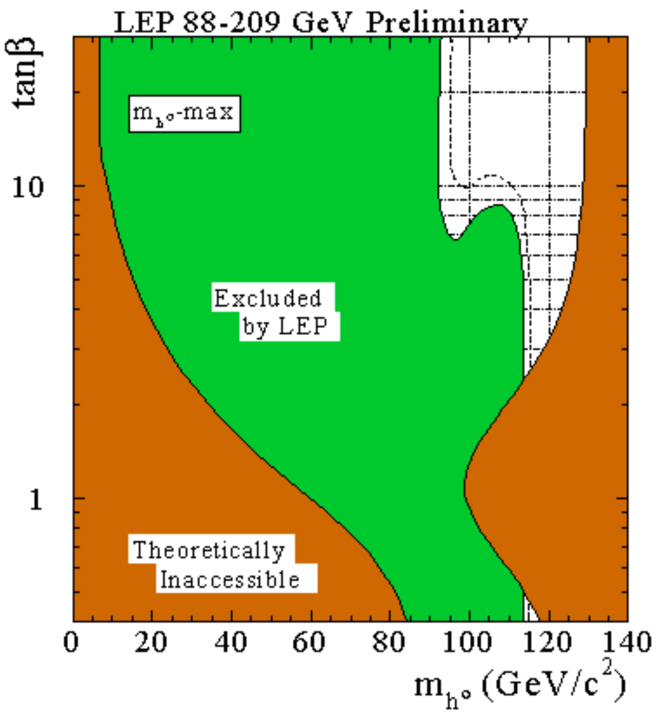
$$m_{h^0} > 114.4\,\mathrm{GeV} \qquad (95\%\ \mathrm{CL})$$

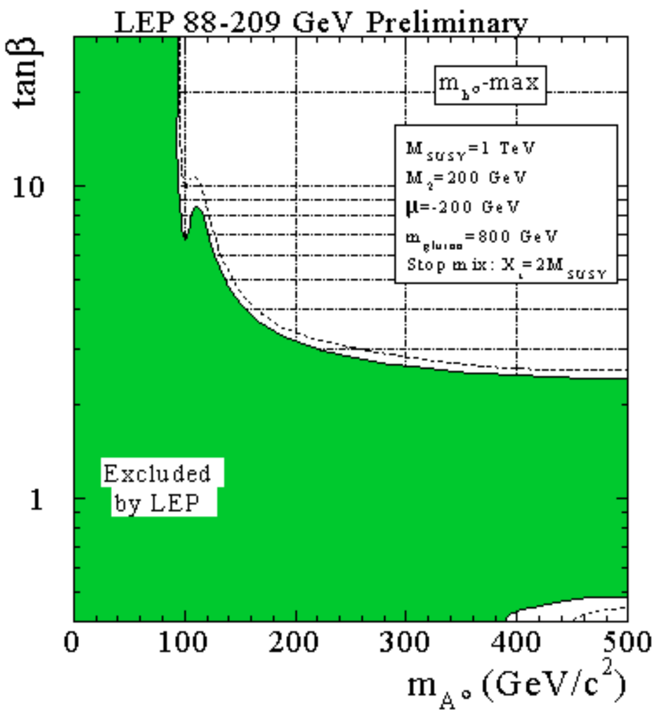
General bounds in SUSY are much weaker, but “most” of parameter space in the MSSM yields a Standard-Model-like lightest Higgs boson.

Present Status of MSSM Higgs searches

95%C.L. limits

$e^+e^- \xrightarrow{Z^*} hZ, HZ, Ah, AH$ main decay mode $h \to b\bar{b}$

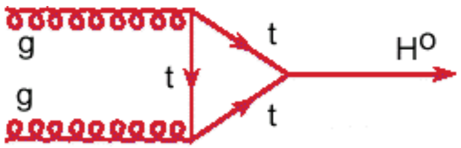




LEP MSSM HIGGS limits: → $m_{H^\pm} > 78.6\text{GeV}$

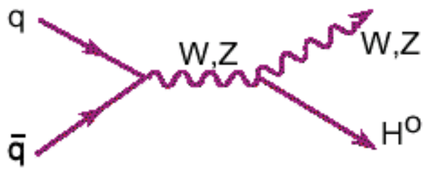
$m_h > 91.0$ GeV; $m_{A,H} > 91.9$ GeV; $m_h^{\text{SM-like}} > 114.6\text{GeV}$

Direct Higgs searches at the Tevatron



g g fusion

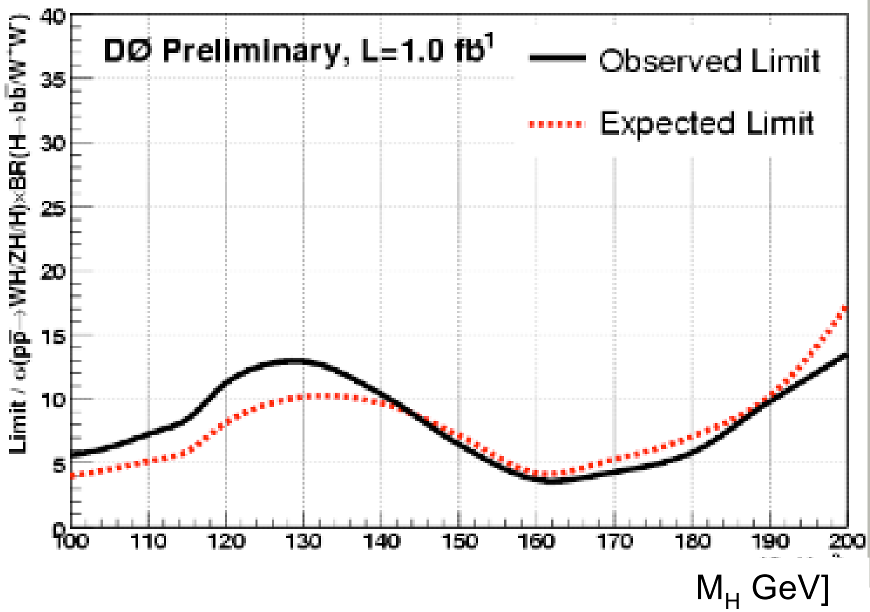
with $H \to WW$



W, Z bremsstrahlung

with $H \to b\bar{b}$, WW

- Tevatron can search for a Higgs in most of the mass range preferred by precision data



With ongoing improvement in sensitivity + two detectors

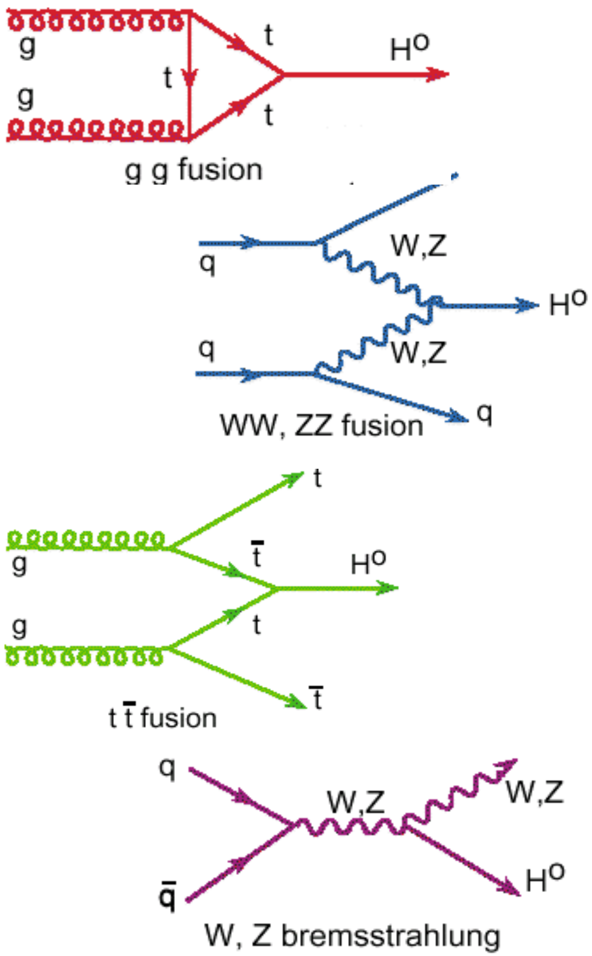
Probe of a Higgs with mass = 115 GeV ➜ 2.5 fb^{-1}

160 GeV ➜ ~3 fb^{-1}

Ultimate Tevatron Luminosity: 4-8 fb^{-1} ⟶ Quite challenging!

Evidence of a signal will mean that the Higgs has SM-like couplings to the W and Z

The search for the Standard Model Higgs at the LHC

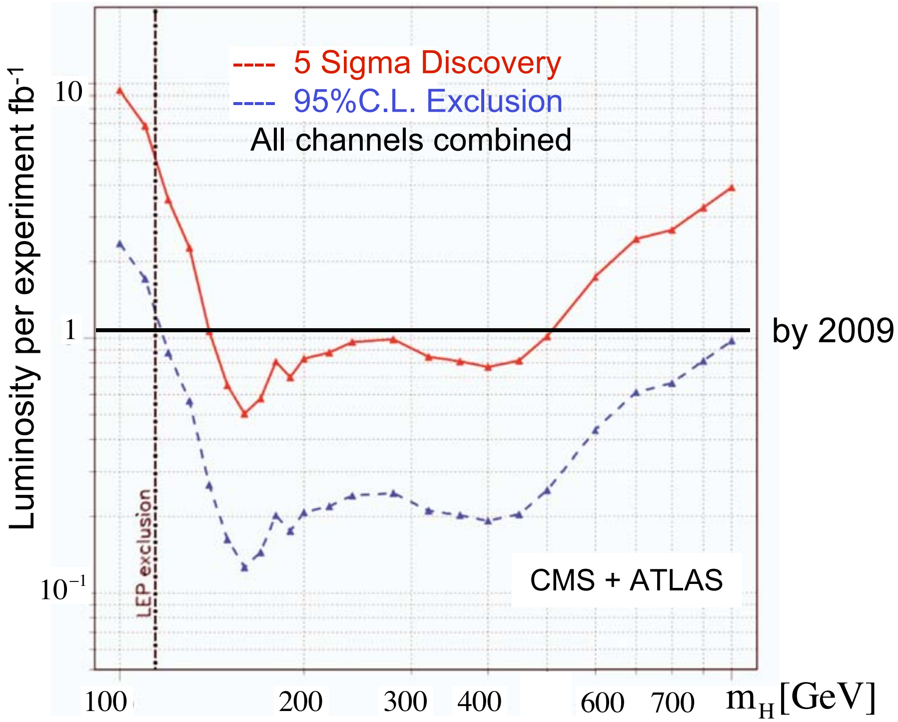


- **Low mass range** $m_{H_{SM}} < 200$ GeV

$$H \rightarrow \gamma\gamma, \tau\tau, bb, WW, ZZ$$

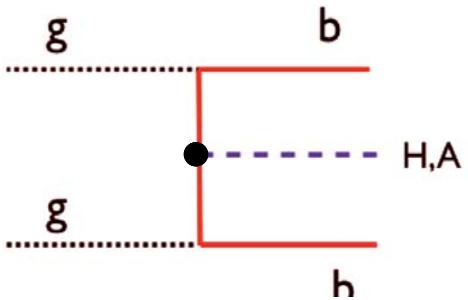
- **High mass range** $m_{H_{SM}} > 200$ GeV

$$H \rightarrow WW,\ ZZ$$

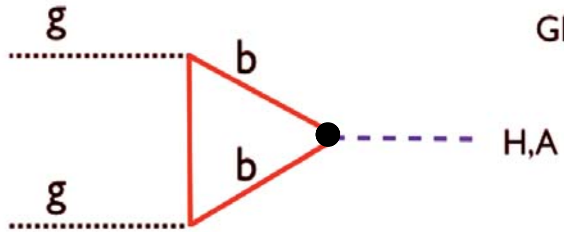


A Standard Model Higgs cannot escape detection at the LHC !

Non-Standard Higgs Production at the Tevatron and LHC



Associated Production



Gluon Fusion

$$\bullet \equiv g_{bbA/H} \approx \frac{m_b \tan\beta}{(1+\Delta_b)\,\mathrm{v}}$$

$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \cong \sigma(b\bar{b}, gg \to A)_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2 + 9}$$

Δ_b depends on SUSY parameters

Mild dependence in the H/A $\to \tau\tau$ channel

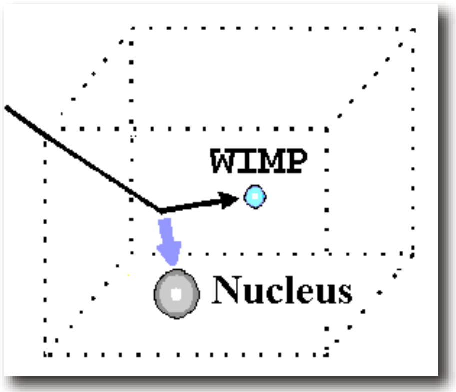
Direct Detection Dark Matter Experiments

• **Collider experiments can find evidence of DM through $\not{E}_T$ signature but no conclusive proof of the stability of a WIMP**

- Direct Detection Experiments can establish the existence of Dark Matter particles

✸ WIMPs elastically scatter off nuclei in targets, producing nuclear recoils

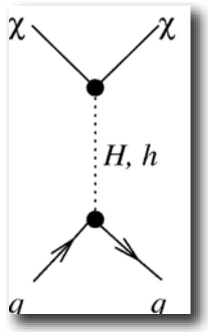
$$R = \sum_i N_i \ \eta_\chi \langle \sigma_{i\chi} \rangle$$

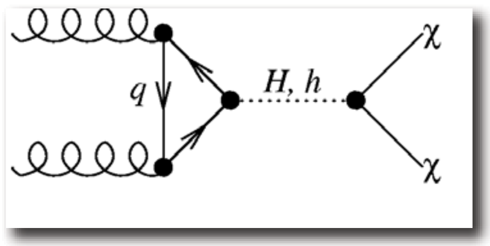


Direct DM experiments: CDMS, ZEPLIN, EDELWEISS, CRESST,WARP,…
sensitive mainly to spin-independent elastic scattering cross section ($\sigma_{SI} \leq 10^{-8} pb$)

==> dominated by virtual exchange of H and h

- $\tan\beta$ enhanced couplings of H to strange, and to gluons via bottom loops

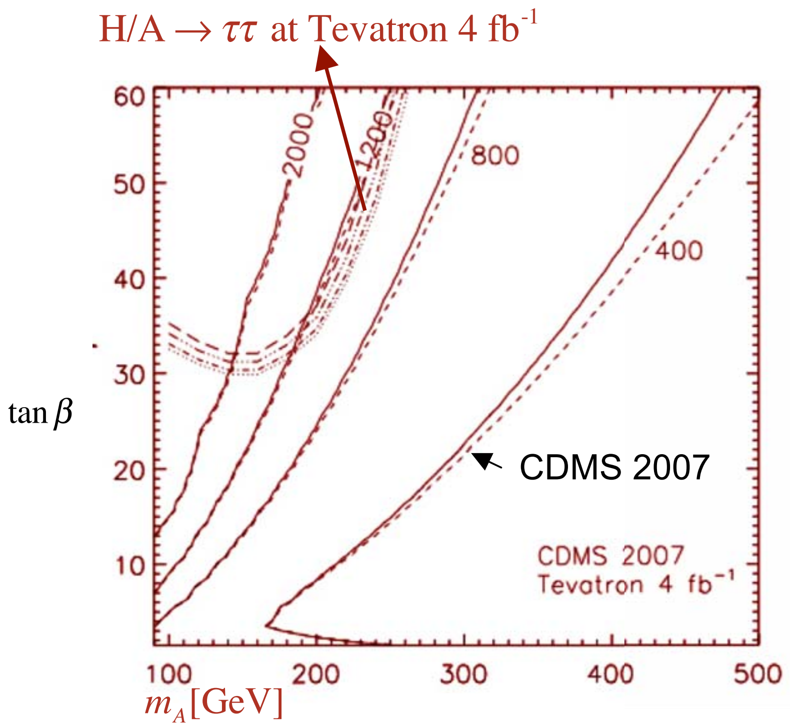


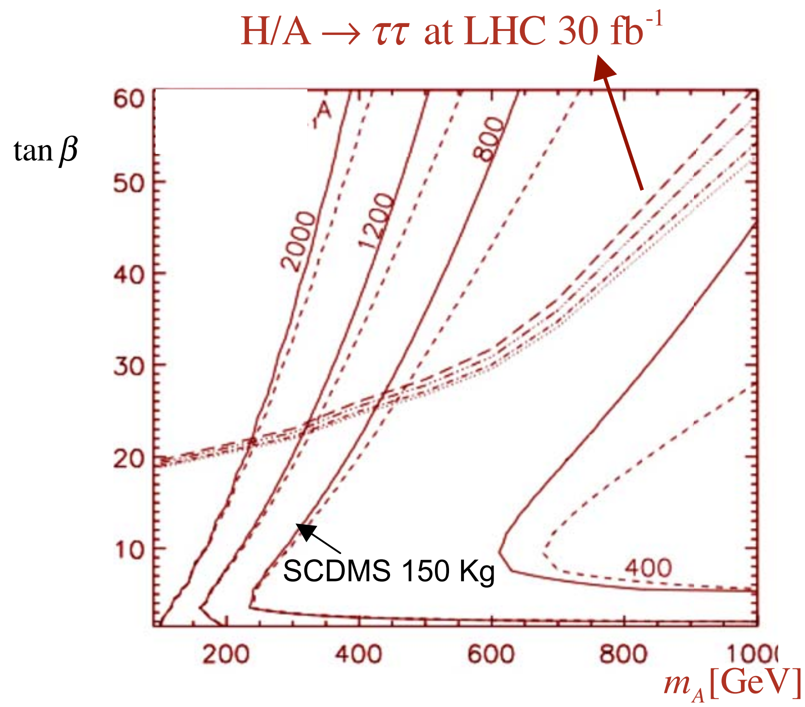


Indirect Non-SM-like MSSM Higgs searches via Direct Detection DM experiments

-- the interplay with direct Higgs searches at Colliders --

H/A Higgs searches at the Tevatron and LHC and neutralino direct DM searches,
both depend on m_A and $\tan\beta$





For $\mu = 400, 800, 1200, 2000$ GeV

M.C., Hooper, Skands 06

Smaller μ values imply larger Higgsino component of the LSP ==> larger σ_{SI}

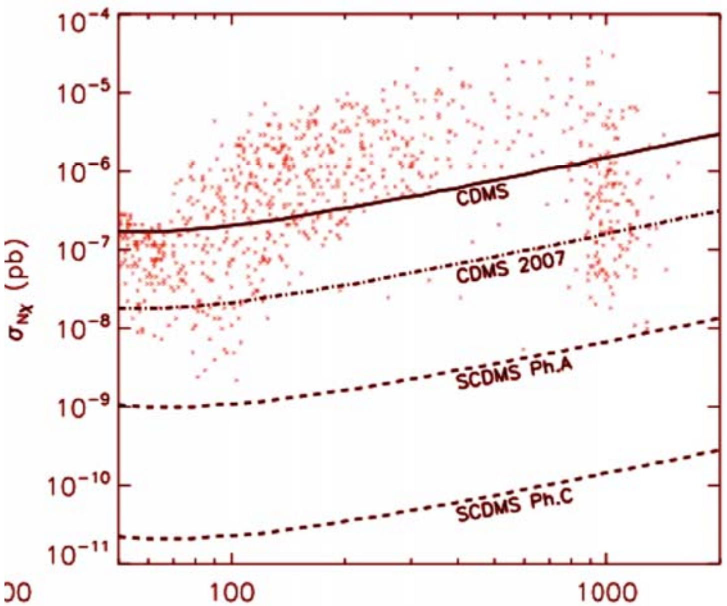
Direct detection of DM ⟷ detection of A/H at the Tevatron and LHC

CDMS DM searches Vs the Tevatron and LHC H/A searches

==> Evidence for H/A at the Tevatron (LHC) implies neutralino cross sections typically within the reach of present (future) direct DM detection experiments.

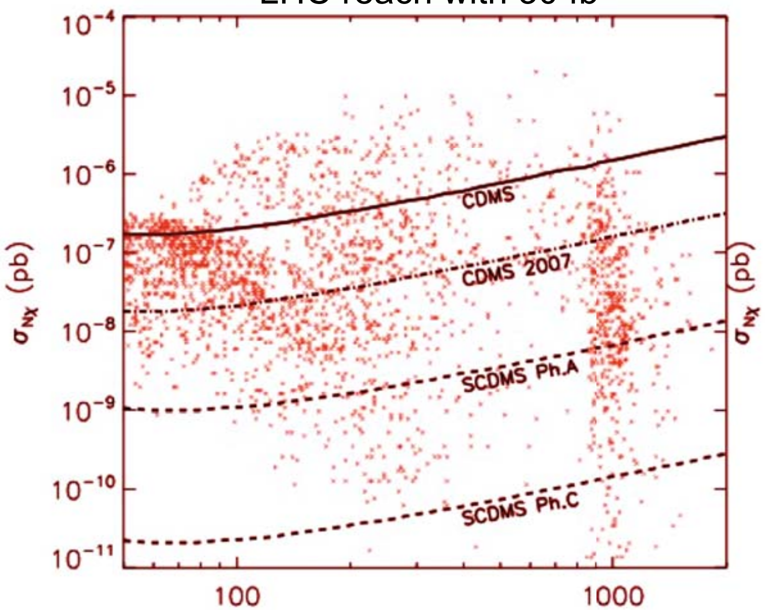
(strong μ dependence)

Tevatron reach with 4 fb^{-1}



m_{WIMP}[GeV]

LHC reach with 30 fb^{-1}



m_{WIMP}[GeV]

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Appendices on SUSY breaking mechanisms

Appendix A:

D-Term Breaking: Iliopoulis Model

Suppose a $U(1)$ gauge symmetry is present, with some scalar supermultiplets carrying its charges. There is a supersymmetric and gauge-invariant term:

$$\mathcal{L} = - \; D$$

where is called the Fayet-Iliopoulis constant, and D is the auxiliary field for the $U(1)$ gauge supermultiplet. The part of the potential involving D is:

$$V = \; D - \tfrac{1}{2}D^2 - gD \sum_i q_i | \;_i|^2 .$$

The q_i are the $U(1)$ charges of scalar fields $\;_i$. The equation of motion for D is:

$$D = \; - g \sum_i q_i | \;_i|^2 .$$

Now suppose the $\;_i$ have superpotential masses M_i. (Gauge invariance requires that they come in pairs with opposite charges.) Then the potential will be:

$$V = \sum_i |M_i|^2 | \;_i|^2 + \tfrac{1}{2}(\; - g \sum_i q_i | \;_i|^2)^2 .$$

Note that $V = 0$ is not possible for any $\;_i$. So SUSY must break. . .

D-term (continued)

$$V = \sum_i |M_i|^2 |\ _i|^2 + \tfrac{1}{2}(\ - g \sum_i q_i |\ _i|^2)^2 .$$

If the superpotential masses are large enough ($M_i^2 > gq_i$ for each i), then the minimum of the potential is at:

$$\ _i = 0, \qquad D = \ , \qquad V = \tfrac{1}{2}\ ^2$$

The scalar and fermion masses are not degenerate:

$$m^2_{\ i} = M_i^2 - gq_i$$
$$m^2_{\ i} = M_i^2$$

SUSY is broken

One might hope that the $U(1)_Y$ of the MSSM could get the D term v.e.v to break SUSY. Unfortunately MSSM squarks and sleptons do not hace Superpotential masses, so they will just get v.e.v's to make $D_Y=0$.

This would break $SU(3)_c$ and $U(1)_{em}$ but leave SUSY unbroken !!!

More generally, D -term breaking for any $U(1)$ turns out to have great difficulty in giving acceptably large masses to gauginos.

Appendix B

F -term breaking: the O'Raifeartaigh Model

The simplest example has $n = 3$ chiral supermultiplets, with $\ _1$ the required singlet, and:

$$W = -k\ _1 + m\ _2\ _3 + \frac{y}{2}\ _1\ _3^2$$

Then the auxiliary fields are:

$$F_1 = k - \frac{y}{2}\ _3^2, \qquad F_2 = -m\ _3, \qquad F_3 = -m\ _2 - y\ _1\ _3.$$

The reason SUSY must be broken is that $F_1 = 0$ and $F_2 = 0$ are not compatible. The minimum of this potential is at $\ _2 = \ _3 = 0$, with $\ _1$ not determined (classically). Quantum corrections fix the true minimum to be at $\ _1 = 0$. At the minimum:

$$F_1 = k, \qquad V = k^2 > 0.$$

F-term breaking (continued)

If you assume $m^2 > yk$ and expand the scalar fields around the minimum at ${}_1 = {}_2 = {}_3 = 0$, you will find 6 real scalars with tree-level squared masses:

$$0,\ 0,\ m^2,\ m^2,\ m^2 - yk,\ m^2 + yk.$$

Meanwhile, there are 3 Weyl fermions with squared masses

$$0,\ m^2,\ m^2.$$

The fact that the fermions and scalars aren't degenerate is a clear sign that SUSY has indeed been spontaneously broken.

The 0 mass^2 eigenvalues belong to the complex scalar ${}_1$ and its superpartner ${}_1$. The masslessness of ${}_1$ corresponds to the flat direction of the classical potential. It is lifted by quantum corrections at one loop, resulting in:

$$m^2_{\ 1} = \frac{y^4 k^2}{48\ {}^2 m^2}.$$

However, ${}_1$ remains **exactly** massless, even including loop effects. **Why?**

The Goldstino ($\tilde{G}$)

In general, the spontaneous breaking of a global symmetry gives rise to a massless Nambu-Goldstone mode with the same quantum numbers as the broken symmetry generator. Here, the broken generator is the fermionic charge Q , so the Nambu-Goldstone particle must be a massless, neutral, Weyl fermion, called the **Goldstino**. It is always the fermion that lives in the same supermultiplet with the auxiliary field that got a VEV to break SUSY.

The Goldstino is a consequence of spontaneously breaking **global** SUSY. Including gravity, SUSY becomes a local symmetry. The spinor used to define the SUSY transformations is no longer constant.

The resulting locally supersymmetric theory is **supergravity**. In unbroken supergravity, the graviton has a massless spin-$\frac{3}{2}$ partner (with only helicities $\pm\frac{3}{2}$) called the **gravitino**, with odd R-parity ($P_R = -1$).

When local SUSY is spontaneously broken, the gravitino absorbs the would-be massless Goldstino as its helicity $\pm \frac{1}{2}$ components, and acquires a mass:

$$m_{3/2} \qquad \frac{F}{M_{Planck}}$$

This follows by dimensional analysis, since $m_{3/2}$ must vanish if SUSY-breaking is turned off $(F \qquad 0)$ or gravity is turned off $(M_{Planck} \qquad)$. The gravitino inherits the couplings of the Goldstino it has eaten.

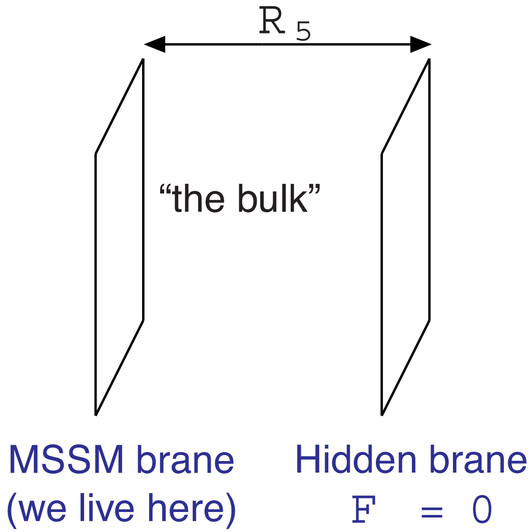
F-term Breaking directly coupled to the MSSM sector does not work

- There is no gauge-singlet chiral supermultiplet in the MSSM that could get a non-zero F -term VEV.

Even if there were such an F, there is another general obstacle. Gaugino masses cannot arise in a renormalizable SUSY theory at tree-level. This is because SUSY does not contain any (gaugino)-(gaugino)-(scalar) coupling that could turn into a gaugino mass term when the scalar gets a VEV.

Other Ideas: Extra dimensional mediated SUSY breaking

The Idea: Make the separation between hidden sector and visible sector a physical distance, for example along a hidden 5th dimension. The MSSM field theory is confined to a 4d "brane", and SUSY is spontaneously broken on another, parallel, 4d brane.



- Only gravity propagates in the bulk (Anomaly-Mediated SUSY Breaking)

  One can show that the resulting soft terms are given in terms of the renormalization group quantities (beta functions and anomalous dimensions) as:

$$M_a = ({}_{g_a} / g_a) m_{3/2} \qquad \text{(gaugino masses)}$$

$$(m^2)_i^j = -\frac{1}{2} \frac{d \; {}_i^j}{d(\ln Q)} m_{3/2}^2 \qquad \text{(scalar masses)}$$

Problem: Slepton are predicted to have negative squared masses