Supersymmetry: Motivation, Models and Signatures

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Outline

- Introduction:

  Motivation for Physics Beyond the Standard Model (BSM)

- Supersymmetry Basics:

  Why SUSY ?

  * The hierarchy problem * Gauge Coupling unification

  * Radiative EWSB * Dark Matter * Baryogenesis

  SUSY generators and Lagrangian

  The Minimal Supersymmetric extension of the Standard Model

  Soft Supersymmetry Breaking

  Higgs and Super-particles Spectra

- Phenomenology:

  SUSY signals at Colliders

The Standard Model

A quantum theory that describes how all known fundamental particles interact via the strong, weak and electromagnetic forces

A gauge field theory with a symmetry group $SU(3)_c \times SU(2)_L \times U(1)_Y$

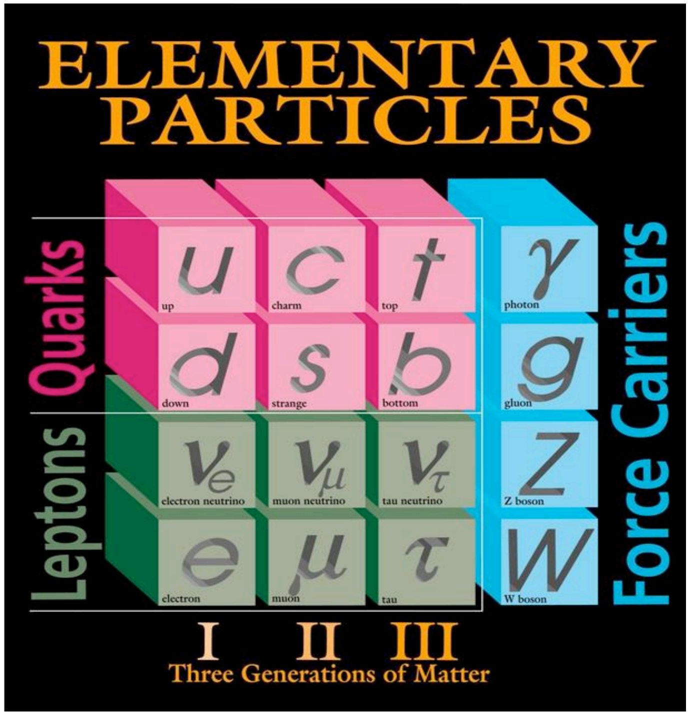
Force Carriers:

12 fundamental gauge fields:
8 gluons, 3 W_μ's and B_μ

and 3 gauge couplings: g_1, g_2, g_3

Matter fields :

3 families of quarks and leptons with the same quantum numbers under the gauge groups



SM particle masses and interactions have been tested at Collider experiments
==> incredibly successful description of nature up to energies of about 100 GeV

Matter Fields:

3 families of quarks and leptons have very different masses !

$$m_3/m_2 \text{ and } m_2/m_1 \cong \text{a few tens or hundreds}$$

$m_e \approx 0.5 \;\; 10^{-3}\, GeV$ $\quad m_\mu/m_e \approx 200$ $\quad m_\tau/m_\mu \approx 20$

Largest Hierarchies: $m_t \approx 175 \text{ GeV}$ $\quad m_t/m_e > 10^5$

neutrino masses as small as $10^{-10}\,\text{GeV}$

The Mystery of Mass

Crucial Problem in the SM:

The origin of mass of all fundamental particles

- A fermion mass term $L = m\,\overline{\psi}\psi = m\,(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$ is forbidden because it would mix left- and right-handed fermions which have different quantum numbers

• Is not possible to give mass to the gauge bosons respecting the gauge symmetry,

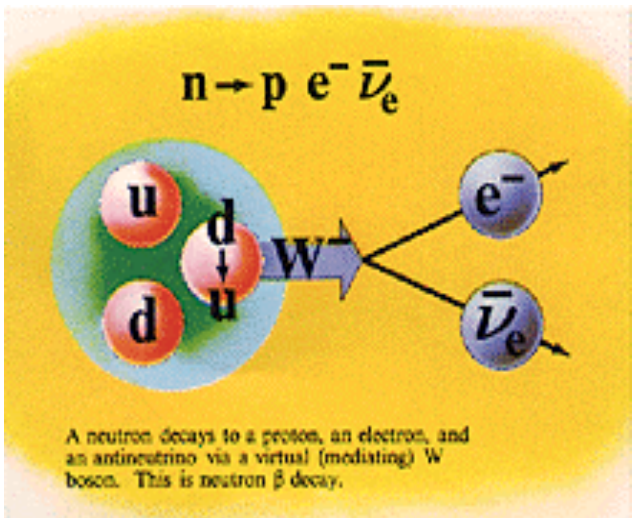
-- massless gauge bosons ==> imply long range forces --

How to give mass to the Z and W gauge bosons?

$$m_z = 91.1875 \pm 0.0017 GeV \qquad m_W = 80.449 \pm 0.034 GeV$$

W boson mass determines the strengthof the weak force $F_{weak} \propto \exp^{-M_W r}/r$

Weak Force



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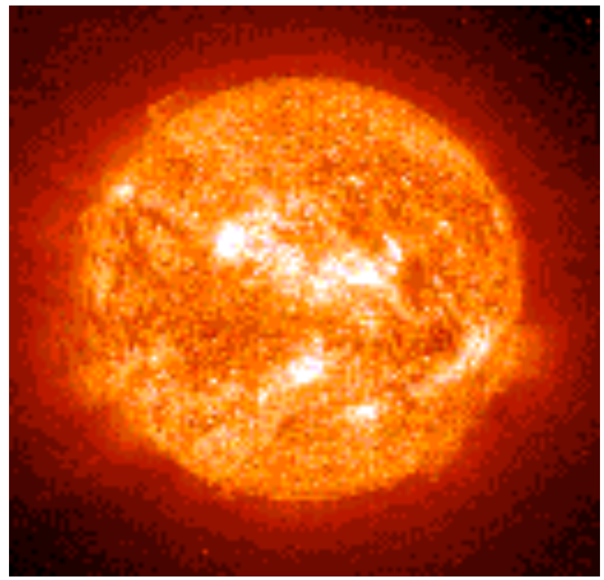
Nuclear Fusion in the Sun



The sun is still burning !

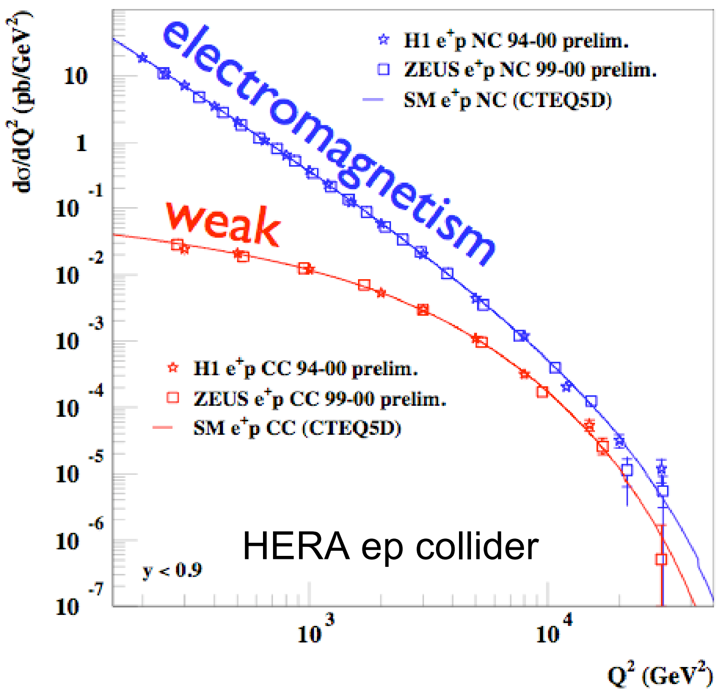
<u>The gauge symmetries of the model do not allow to generate mass at all!</u>

•What is the origin of Mass of the Fundamental Particles ?

or

the source of Electroweak Symmetry Breakdown (EWSB)

- There is a Field that fills all the Universe
  - -- it does not disturb gravity and electromagnetism but it renders the weak force short-ranged
  - -- it slows down the fundamental particles from the speed of light



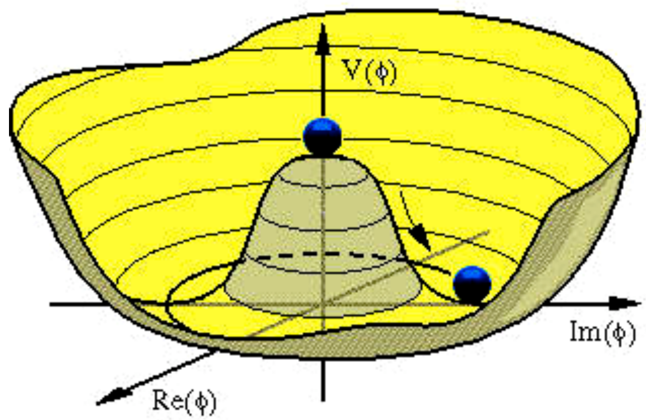
The electromagnetic and weak forces are unified
==> electroweak theory

what breaks the symmetry
==> the mysterious Field

EWSB occurs at the electroweak scale
New phenomena should lie in
the TeV range or below
within LHC/ILC reach

The origin of mass: The Higgs Mechanism

A self interacting complex scalar doublet with no trivial quantum numbers under $SU(2)_L$ x $U(1)_Y$



The Higgs field acquires non-zero value to minimize its energy

$$V(\Phi) = \mu^2 \Phi^+ \Phi + \frac{\lambda}{2}\left(\Phi^+ \Phi\right)^2 \qquad \mu^2 < 0$$

Higgs vacuum condensate v ==> scale of EWSB

- Spontaneous breakdown of the symmetry generates 3 massless Goldstone bosons which are absorbed to give mass to W and Z gauge bosons

- Higgs neutral under strong and electromagnetic interactions exact symmetry $SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ ==> $SU(3)_C$ x $U(1)_{em}$

$$\boxed{m_\gamma = 0 \quad m_g = 0}$$

- Masses of fermions and gauge bosons proportional to their couplings to the Higgs

$$\boxed{M_V^2 = g_{\phi VV}\, \mathrm{v}/2} \qquad \boxed{m_f = \mathrm{h_f}\ \mathrm{v}}$$

- One extra physical state -- Higgs Boson -- left in the spectrum

$$\boxed{m_{H_{SM}}^2 = 2\lambda\ \mathrm{v}^2}$$

The Hierarchy Problem of the SM Higgs Sector

- SM is an effective theory $\Longrightarrow$ low energy quantities (masses, couplings) expected to be given as a function of parameters of the fundamental theory valid at Q> $\Lambda_{eff.}$

✦ **low energy dimensionless couplings: receive quantum corrections prop. to log ($\Lambda_{eff.}$)**

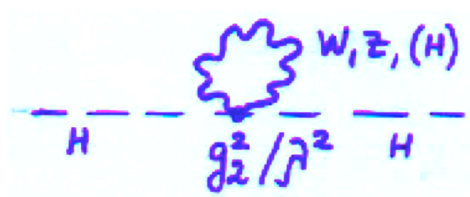
✦ **what about the Higgs potential mass parameter μ?** $v^2 = |\mu|^2 / 2\lambda$

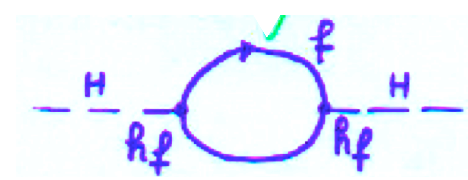
Quantum corrections to μ^2 are quadratically divergent

$$\mu^2 = \mu^2(\Lambda_{eff.}) + \Delta\mu^2 \longrightarrow \Delta\mu^2 \approx \frac{n_W g_{hWW}^2 + n_h \lambda^2 - n_f g_{hf\bar{f}}^2}{16\pi^2} \Lambda^2_{eff.}$$

to explain v $\approx O(m_W)$

either $\Lambda_{eff.} \leq$ 1 TeV or extreme fine tuning to give cancellation



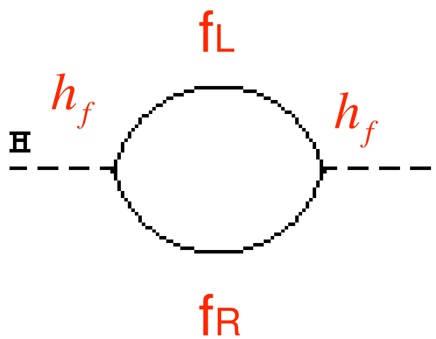


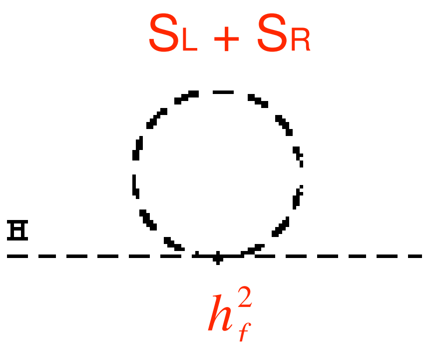
Quantum Corrections to the Higgs Mass Parameter

Quadratic Divergent contributions:

One loop corrections to the Higgs mass parameter cancel if the couplings of bosons and fermions are equal to each other

$$\delta m_H^2 = \frac{N_C h_f^2}{16\pi^2}\left[-2\Lambda^2 + 3m_f^2 \log\left(\frac{\Lambda^2}{m_f^2}\right) + 2\Lambda^2 - 2m_s^2 \log\left(\frac{\Lambda^2}{m_f^2}\right)\right]$$





If the mass proceed from a v.e.v of H, the cancellation of the log terms is ensured by the presence of an additional diagram induced by trilinear Higgs couplings. The fermion and scalar masses are the same in this case: $m_f = m_s = h_f v$

Supersymmetry is a symmetry between bosons and fermions that ensures the equality of couplings and masses

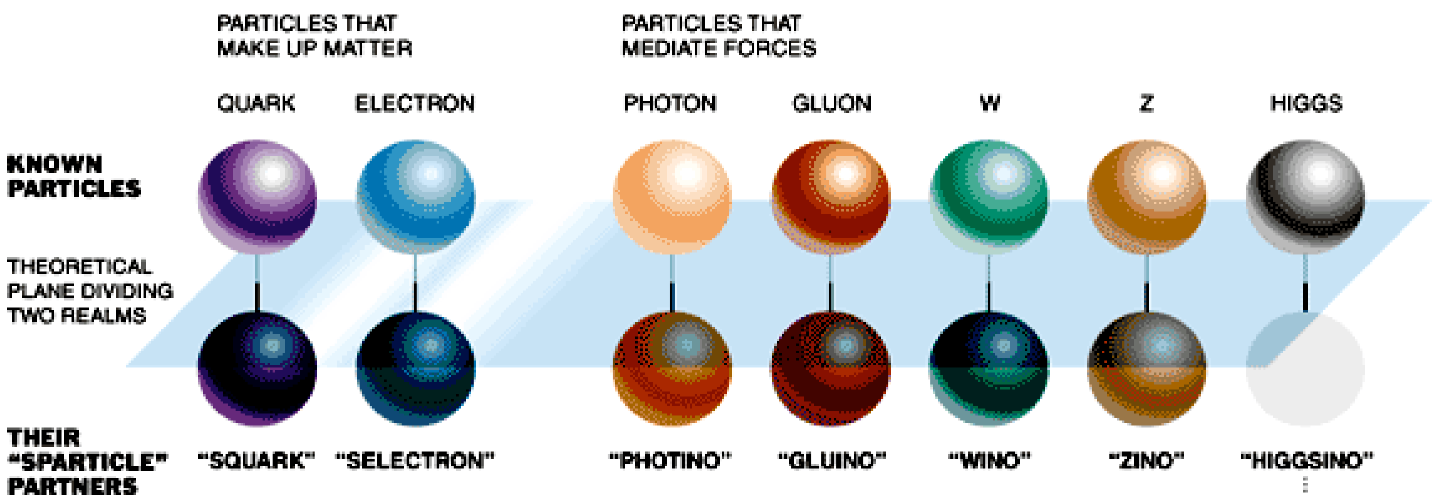
Automatic cancellation of loop corrections to the Higgs mass parameter

Supersymmetry

<u>lesson from history</u>: electron self energy ⟶ fluctuations of em fields generate a quadratic divergence but existence of electron antiparticle cancels it

Will history repeat itself? Take SM and double particle spectrum

New Fermion-Boson Symmetry: SUPERSYMMETRY (SUSY)



No new dimensionless couplings

Couplings of SUSY particles equal to couplings of SM particles

For every fermion there is a boson of equal mass and couplings

Why Supersymmetry?

- Helps stabilize the weak scale-Planck scale hierarchy

- SUSY algebra contains the generator of space translations

  $\longrightarrow$ necessary ingredient of theory of quantum gravity

- Allows for Gauge Coupling Unification at a scale ~ 10^{16} GeV

- Starting from positive Higgs mass parameters at high energies, induces electroweak symmetry breaking radiatively.

- Provides a good Dark matter candidate:
  The Lightest SUSY Particle (LSP)

- Provides a solution to the baryon asymmetry of the universe.

Supersymmetry Generators

Supersymmetric transformations relate bosonic to fermionic degrees of freedom

the operator Q that generates that transformation acts, schematically

$$Q|B>=|F> \quad Q|F>=|B> \qquad Q^\dagger|B>=|F> \quad Q^\dagger|F>=|B>$$

The SUSY generators, Q and $Q^\dagger$, are two-component anti-commuting spinors satisfying:

$$\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = 2\sigma^\mu_{\alpha\dot\alpha} P_\mu \qquad \{Q_\alpha, Q_\beta\} = \{Q^\dagger_{\dot\alpha}, Q^\dagger_{\dot\beta}\} = 0$$

$$[Q_\alpha, P^\mu] = [Q^\dagger_{\dot\alpha}, P^\mu] = 0$$

where $\sigma^\mu = (I, \vec\sigma)$, $\bar\sigma^\mu = (I, -\vec\sigma)$, and σ^i are Pauli Matrices

$P^\mu = (H, \vec p)$ is the generator of spacetime translations

: part of the SUSY algebra

Vacuum State Energy

Since there is a relation between the momentum operator and the SUSY generators, one can compute the energy operator:

$$P_0 = H = \frac{1}{4}\left(Q_1 Q_1^\dagger + Q_1^\dagger Q_1 + Q_2 Q_2^\dagger + Q_2^\dagger Q_2\right)$$

Hence, the Hamiltonian operator is semidefinite positive

$$< H >= E \geq 0$$

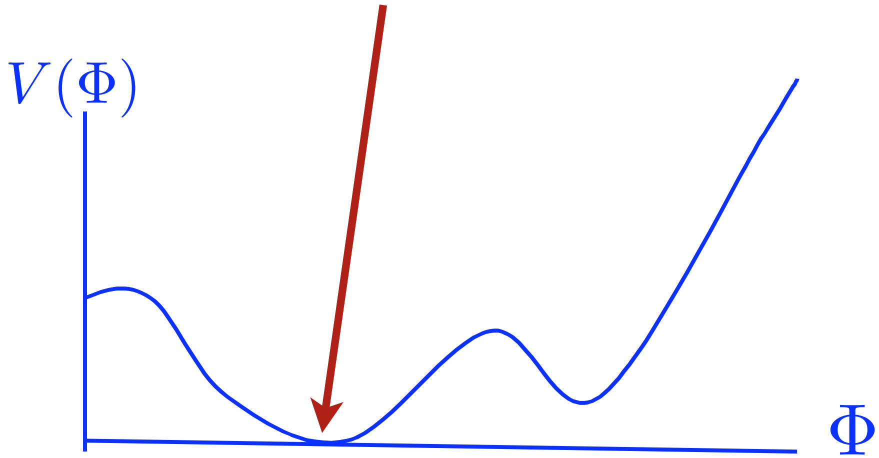
And, in a Supersymmetric theory, then the vacuum state is Supersymmetric and should be annihilated by Supersymmetric charges

$$Q_\alpha |0 >= 0, \;\; Q_\alpha^\dagger |0 >= 0 \quad \Rightarrow \quad < 0|H|0 >= 0$$

The vacuum state energy is zero!

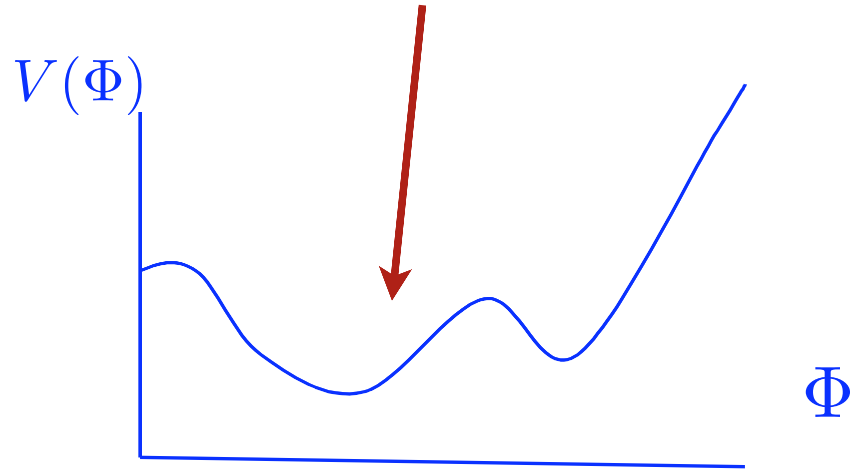
The vacuum energy is the order parameter for SUSY breaking.

Preservation of SUSY



A non-trivial Minimum could lead to the breakdown of gauge or global symmetries but SUSY is preserved, provided the value of the effective potential at the minimum is equal to zero

Spontaneous breakdown of SUSY



If V_{min} is non-zero, the vacuum state is non supersymmetric and breaks SUSY spontaneously.

A massless fermion, the Goldstino, appears in the spectrum of the theory.

In Supergravity (local SUSY), the Goldstino is the Gravitino longitudinal component.

SUSY Lagrangian

SM fermion superpartners + Higgs

SM fermions + Higgsinos

$$\mathcal{L}_{\mathrm{SUSY}} = (\mathcal{D}_\mu A_i)^\dagger \mathcal{D} A_i + \left(\frac{i}{2}\bar{\psi}_i \bar{\sigma}^\mu \mathcal{D}_\mu \psi_i + \mathrm{h.c.}\right)$$
$$- \frac{1}{4}\left(G^a_{\mu\nu}\right)^2 + \left(\frac{i}{2}\bar{\lambda}^a \bar{\sigma}^\mu \mathcal{D}_\mu \lambda^a + \mathrm{h.c.}\right)$$
$$- \left(\boxed{\frac{1}{2}\frac{\partial^2 P(A)}{\partial A_i \partial A_j}\psi_i\psi_j} - i\sqrt{2} g \underline{A_i^* T_a \psi_i \lambda^a} + h.c.\right) - V_{scalar}$$

Gauginos

Yukawa interactions

Novel gaugino-scalar-fermion interaction

Gauge bosons in covariant derivatives and in $G_{\mu\nu}$

$$V_{scalar} = \sum_i \left|\frac{\partial P(A)}{\partial A_i}\right|^2 + \frac{1}{2}\sum_a \left(g \sum_i A_i^* T^a A_i\right)^2$$

Quartic couplings governed by gauge couplings crucial for Higgs sector

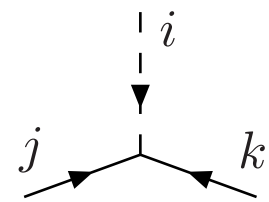
The Superpotential: $P(A) = \frac{m_{ij}}{2} A_i A_j + \frac{\lambda_{ijk}}{6} A_i A_j A_k$

Couplings

From the scalar part of the superpotential $P(A) = \frac{m_{ij}}{2} A_i A_j + \frac{\lambda_{ijk}}{6} A_i A_j A_k$

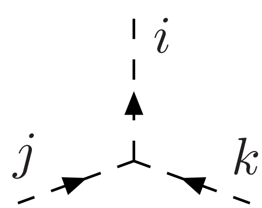
- The Yukawa couplings between scalar and fermion fields

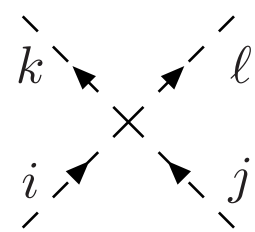
$$\frac{1}{2} \frac{\partial^2 P(A)}{\partial A_i \partial A_j} \psi_i \psi_j + h.c. \quad \longrightarrow \quad \lambda_{ijk} \; \psi_i \; \psi_j \; A_k$$



are governed by the same couplings as the scalar interactions coming from

$$\left(\frac{\partial P(A)}{\partial A_i} \right)^2 \longrightarrow m^*_{ml} \lambda_{mjk} \; A^*_i \; A_j A_k \text{ and } \lambda_{mjk} \; \lambda^*_{mil} A_j A_k A^*_i A^*_l$$





The superpotential parameters determine all non-gauge interactions

- Similarly, the gaugino-scalar-fermion interactions coming from

$$-i\sqrt{2}gA_i^*T_a\psi_i\lambda^a + h.c.$$

are governed by the gauge couplings

No new Couplings!

same couplings are obtained by replacing particles by their superpartners and changing the spinorial structure

Masses

The superpotential parameters determine the matter field masses

and give equal masses to fermions and scalars when the Higgs acquires a v.e.v

$$\boxed{m_f^2 = m_s^2 = \lambda_{ffh}^2 \, \mathrm{v}^2}$$

The Minimal SUSY extension of the Standard Model (MSSM)

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks ($\times 3$ families)	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
	U	$\widetilde{u}^*_R$	$(u^C)_L$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	D	$\widetilde{d}^*_R$	$(d^C)_L$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons ($\times 3$ families)	L	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
	E	$\widetilde{e}^*_R$	$(e^C)_L$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	?			

Matter Superfields

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\,\mathbf{8},\ \mathbf{1}\,,\ 0)$
winos, W bosons	$\widetilde{W}^{\pm}\ \ \widetilde{W}^0$	$W^{\pm}\ \ W^0$	$(\,\mathbf{1},\ \mathbf{3}\,,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\,\mathbf{1},\ \mathbf{1}\,,\ 0)$

Gauge Superfields

The winos and bino are not mass eigenstates, they mix with each other and with the Higgs superpartners, called higgsinos, of the same charge

The Higgs problem

- Problem: What to do with the Higgs field ?
- In the Standard Model masses for the up and down (and lepton) fields are obtained with Yukawa couplings involving H and $H^\dagger$ respectively.
- Impossible to recover this from the Yukawas derived from $P[\Phi]$, since no dependence on $\bar{\Phi}$ is admitted.
- Another problem: In the SM all anomalies cancel,

$$\begin{aligned} \sum_{quarks} Y_i &= 0; \qquad \sum_{left} Y_i = 0; \\ \sum_i Y_i^3 &= 0; \qquad \sum_i Y_i = 0 \end{aligned} \tag{38}$$

- In all these sums, whenever a right-handed field appear, its charge conjugate is considered.
- A Higgsino doublet spoils anomaly cancellation !

The Higgs Sector: two Higgs fields with opposite hypercharges

2 Higgs doublets necessary to give mass to both up and down quarks and leptons in a gauge/SUSY invariant way

2 Higgsino doublets necessary for anomaly cancellation

Names		spin 0	spin 1/2	$SU(3)_C,\, SU(2)_L,\, U(1)_Y$
Higgs, higgsinos	H_u	$(H_u^+ \quad H_u^0)$	$(\widetilde{H}_u^+ \quad \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_d^0 \quad H_d^-)$	$(\widetilde{H}_d^0 \quad \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

- Both Higgs fields acquire v.e.v. New parameter, $\tan\beta = v_2/v_1$.

Both Higgs fields contribute to the superpotential and give masses to up and down/lepton sectors, respectively

$$\boxed{\begin{array}{l} H_1 \equiv H_d \\ H_2 \equiv H_u \end{array}}$$

$$P[\phi] = h_u Q U H_2 + h_d Q D H_1 + h_l L E H_1$$

With two Higgs doublets, a mass term may be written $\delta P[\phi] = \mu H_1 H_2$

Interesting to observe:

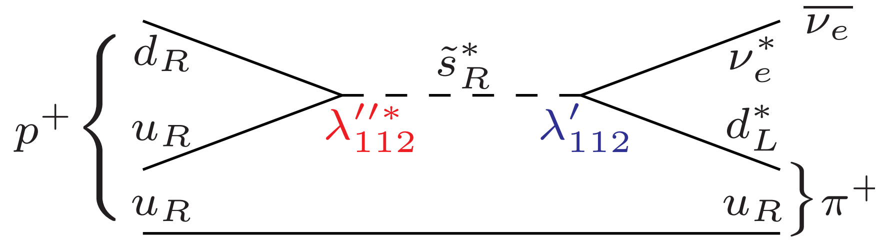
The quantum numbers of H_1 are the same as those of the lepton superfield L. One can add terms in the superpotential replacing H_1 by L

Dangerous Baryon and Lepton Number Violating Interactions

$$P[\Phi]_{new} \rightarrow \begin{array}{l} P_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \mu'_i L_i H_u \\ P_{\Delta B=1} = \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j D_k \end{array}$$

If both types of couplings were present, and of order 1, then the proton would decay in a tiny fraction of a second through diagrams like this:

Proton Decay



One cannot require B and L conservation since they are already known to be violated at the quantum level in the SM.

Instead, one postulates a new discrete symmetry called **R-parity.**

$$P_R = (-1)^{3(B-L)+2S}$$

All SM particles have $P_R = 1$

All Supersymmetric partners have $P_R = -1$

Important Consequences of R-Parity Conservation

Since SUSY partners are R-parity odd (have $P_R = -1$)

every interaction vertex must contain an even number of SUSY particles

- All Yukawa couplings induced by $P(\Phi)_{new}$ are forbidden (have and odd number of SUSY particles)

- The Lightest SUSY Particle (LSP) must be absolutely stable

If electrically neutral, interacts only weakly with ordinary matter

LSP is a good Dark Matter candidate

- In collider experiments SUSY particles can only be produced in even numbers (usually in pairs)

- Each sparticle eventually decays into a state that contains an LSP
==> Missing Energy Signal at colliders

Supersymmetry Breaking

If SUSY were an exact symmetry, the SM particles and their superpartners would have the exactly same masses

$m_{\tilde{e}_L} = m_{\tilde{e}_R} = m_e = 0.511$ MeV

$m_{\tilde{u}_L} = m_{\tilde{u}_R} = m_u$

$m_{\tilde{g}} = m_{\text{gluon}} = 0 +$ QCD-scale effects

etc.

- No supersymmetric particle have been seen: Supersymmetry is broken in nature
- Unless a specific mechanism of supersymmetry breaking is known, no information on the spectrum can be obtained.
- Cancellation of quadratic divergences:
  - Relies on equality of couplings and not on equality of the masses of particle and superpartners.
- Soft Supersymmetry Breaking: Give different masses to SM particles and their superpartners but preserves the structure of couplings of the theory.

does not change the dimensionless terms in the Lagrangian

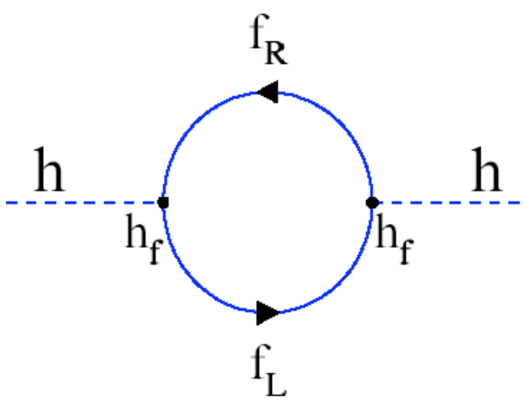
SUSY must be broken in nature

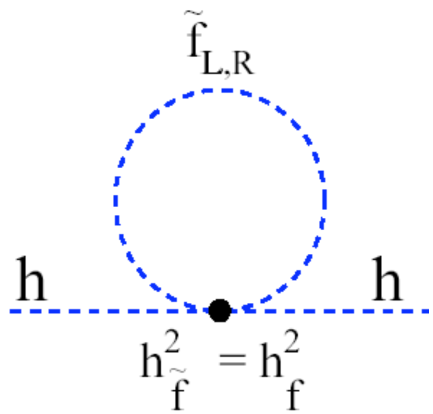
Back to SUSY corrections to the Higgs mass parameter:

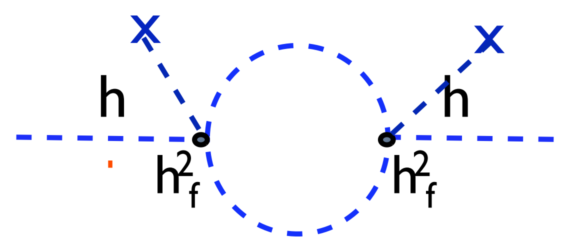
Cancellation of quadratic divergences in Higgs mass quantum corrections has to do with SUSY relation between couplings and bosonic and fermionic degrees of freedom

$$\Delta\mu^2 \approx g^2_{hf\bar{f}}[m_f^2 - m_{\tilde{f}}^2]\ln(\Lambda^2_{eff} / m_h^2)$$

not with the exact equality of fermion and scalar masses







In low energy SUSY: quadratic sensitivity to Λ_{eff} replaced by quadratic sensitivity to SUSY breaking scale

The scale of SUSY breaking must be of order 1 TeV, if SUSY is associated with the scale of electroweak symmetry breaking

Bookkeeping:

We started from the SUSY Lagrangian in terms of:

Standard fermions ψ_i and their superpartners, the scalar fields A_i
SM gauge bosons and gauginos λ^a, and the Higgs supermultiplets

We defined the interactions among fields in the MSSM: No new couplings!!
All interactions in terms of gauge couplings and parameters in the superpotential

We discuss the need for two Higgs doublets,
with the Higgsinos superpartners to cancel U(1) associated anomalies
and give mass to both, up-quarks and down-quarks/leptons.

We discussed advantages of imposing R-parity .

$\longrightarrow$ forbids Proton Decay

$\longrightarrow$ the LSP is stable and a good Dark Matter candidate

We showed that if SUSY is preserved up to energies of order a TeV,
the equality of fermion and boson couplings assures the
cancellation of quadratic divergences in the Higgs mass quantum corrections

The Soft SUSY-breaking Lagrangian for the MSSM

Gaugino masses, squark/slepton squared mass terms and trilinear/biliniar terms prop. to scalar superpotential do not spoil cancellation of quadratic divergences

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

Trilinear terms are proportional to the Yukawa couplings

induce L-R mixing in the sfermion sector once the Higgs acquire v.e.v.

$\rightarrow$ mixing proportional to fermion masses: relevant for 3rd generation

B $\longrightarrow$ SUSY breaking parameter to be determined from condition of proper EWSB

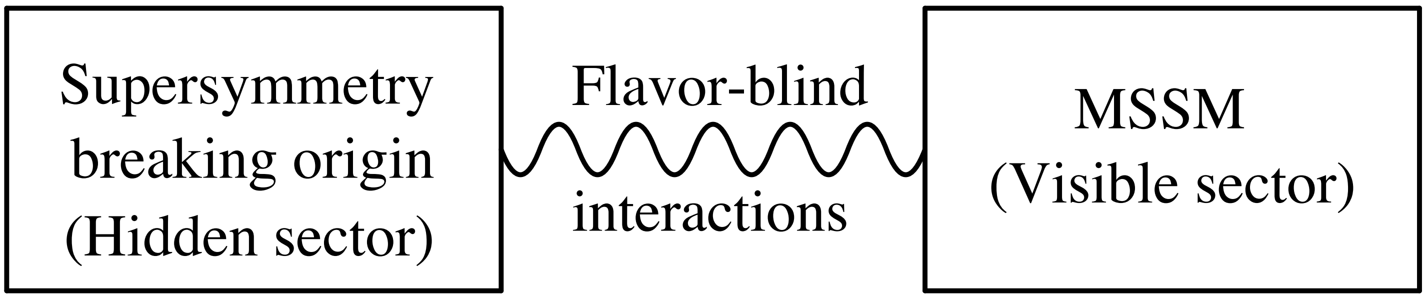
MSSM: 105 new parameters not present in the SM

Most of what we do not really know about SUSY is expressed by the question: "How is SUSY broken?"

Understanding the origins of Spontaneous SUSY breaking:

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 (gravity/ordinary gauge interactions), the MSSM soft SUSY breaking terms will also be flavor independent (favored experimentally)

Many alternatives: Gravity-type; Gauge; Extra Dimensional mediated, ...

$\Longrightarrow$ different boundary conditions at an specific SUSY breaking scale

The specific pattern of SUSY sparticle masses depend on the SUSY breaking scenario. The crucial question is how much can we learn about it from collider and astroparticle physics experiments

The SUSY Particles of the MSSM

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

Gaugino/Higgsino Mixing: similar to gauge boson mixing with Goldstone modes after spontaneous EWSB, gauginos mix with the Higgsinos of equal charge

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

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

- If μ is large, the lightest chargino is a Wino, with mass M_2, and its interactions to fermion and sfermions are governed by gauge couplings.
- If M_2 is large, the lightest chargino is a Higgsino, with mass μ, and the interactions are governed by Yukawa couplings.

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

- If the theory proceeds from a GUT, there is a relation between M_2 and M_1, $M_2 \simeq \alpha_2(M_Z)/\alpha_1(M_Z) M_1 \simeq 2M_1$.
- So, if μ is large, the lightest neutralino is a Bino (superpartner of the hypercharge gauge boson) and its interactions are governed by g_1.

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

The squark and slepton 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

Example: the Stop Sector

- Once the Higgs acquires a v.e.v., the mass matrix is

$$M_{\tilde{t}}^2 \simeq \begin{bmatrix} m_{Q_3}^2 + m_t^2 & m_t(A_t - \mu^*/\tan\beta) \\ m_t(A_t^* - \mu/\tan\beta) & m_{U_3}^2 + m_t^2 \end{bmatrix}$$

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

In the Sbottom/Stau sectors, the mixing is proportional to: $\mathbf{m_{b.\tau}(A_{b,\tau}} - \mu\tan\beta)$ and becomes relevant for large $\tan\beta$

Higgs Spectrum

- The two Higgs doublets carry eight real scalar degrees of freedom.
- Three of them are the charged and CP-odd Goldstone bosons that are absorbed in the longitudinal components of the W and the Z.
- Five Higgs bosons remain: Two CP-even, one CP-odd, neutral bosons, and a charged Higgs boson (two degrees of freedom).
- Generically, the electroweak breaking sector (Goldstones and real Higgs) is contained in the combination of doublets

$$\Phi = \cos\beta H_1 + \sin\beta i\tau_2 H_2^*, \qquad (18$$

$$\text{such that} < \phi > = \text{v}$$

while the orthogonal combination contains the other Higgs bosons

MSSM Higgs Sector

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

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

Soft SUSY breaking
Higgs mass parameters

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

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

Important corrections due to incomplete cancellation of particles and sparticles contributions. Mainly top and stops loops and also sbottom loops for tanb >10

Dependence on SUSY breaking parameters

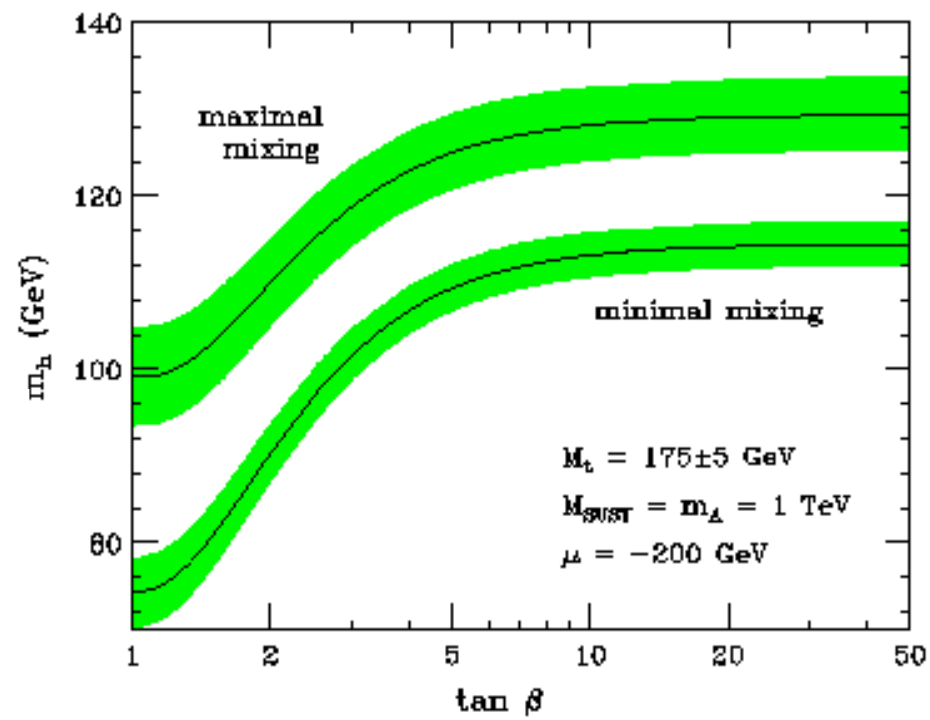
through the stop sector:

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

and $m_{H_i}^2$

Effect of Quantum Corrections on the Lightest Higgs Mass

- m_t^4 **enhancement**
- **log sensitivity to stop masses** M_S
- **depend. on stop mass mixing** X_t

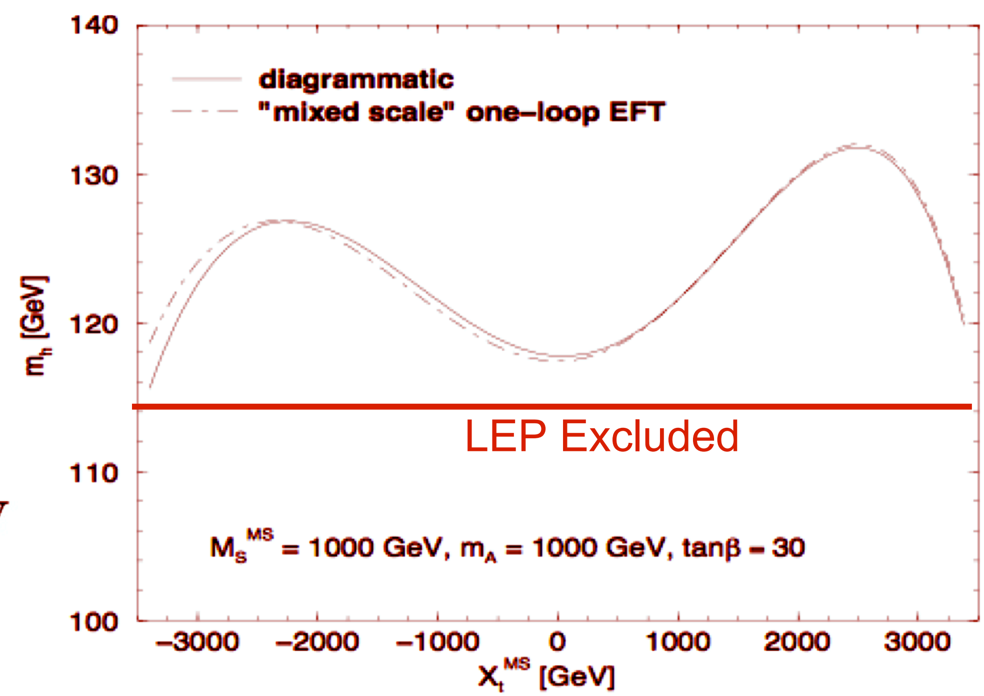


After 2 -loop corrections

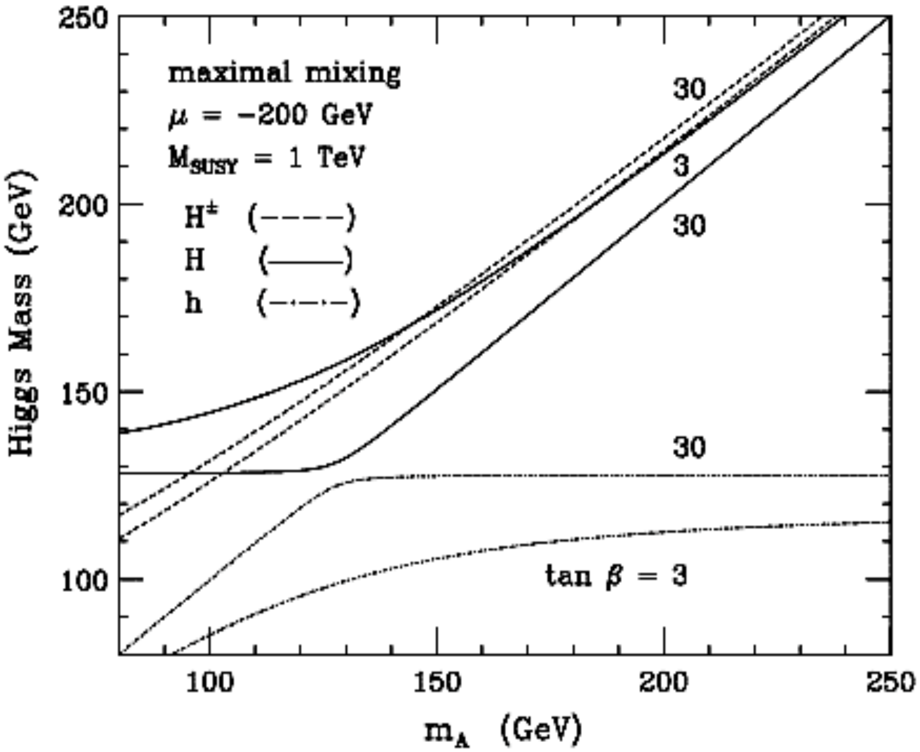
$$m_h \leq 135 \text{ GeV}$$

stringent test of the MSSM

$$M_S = 1 \to 2 \text{ TeV} \Longrightarrow \Delta m_h \simeq 2 - 5 \text{ GeV}$$
$$\Delta m_t = 1 \text{ GeV} \Longrightarrow \Delta m_h \sim 1 \text{ GeV}$$



MSSM Higgs Masses as a function of M_A



$$m_H^2 \cos^2(\beta-\alpha) + m_h^2 \sin^2(\beta-\alpha) = [m_h^{max}(\tan\beta)]^2$$

- $\cos^2(\beta-\alpha) \to 1$ for large $\tan\beta$, low m_A
  $\Longrightarrow$ H has SM-like couplings to W,Z
- $\sin^2(\beta-\alpha) \to 1$ for large m_A
  $\Longrightarrow$ h has SM-like couplings to W,Z

for large $\tan\beta$:
always one CP-even Higgs with SM-like couplings to W,Z
and mass below $m_h^{max} \leq 135$ GeV

$$\text{if } m_A > m_h^{max} \quad \to \quad m_h \simeq m_h^{max} \quad \text{and} \quad m_H \simeq m_A$$
$$\text{if } m_A < m_h^{max} \quad \to \quad m_h \simeq m_A \quad \text{and} \quad m_H \simeq m_h^{max}$$

m_A nearly degenerate with m_h or m_H

MSSM Higgs couplings to gauge bosons and fermions

At tree level: Higgs interactions are **flavor diagonal**

Higgs-Gauge Boson Couplings coming from $(\mathcal{D}_\mu H_i)^* \mathcal{D}^\mu H_i$

$$\text{hZZ, hWW, ZHA, WH}^\pm\text{H} \longrightarrow \sin(\beta - \alpha)$$
$$\text{HZZ, HWW, ZhA, WH}^\pm\text{h} \longrightarrow \cos(\beta - \alpha)$$

Normalized to SM couplings

Higgs-Fermion Couplings:

H_2 couples to $u\bar{u}$ and H_1 couples to $d\bar{d}$ and leptons

$$\text{(h,H,A)}\ u\bar{u} \longrightarrow \cos\alpha/\sin\beta,\ \ \sin\alpha/\sin\beta,\ \ 1/\tan\beta$$
$$\text{(h,H,A)}\ d\bar{d}/l^+l^- \longrightarrow -\sin\alpha/\cos\beta,\ \ \cos\alpha/\cos\beta,\ \ \tan\beta$$

$$H^- t\bar{b} \propto \left[m_t \cot\beta P_R + m_b \tan\beta P_L\right] \mathrm{V}_{tb} \qquad H^- \tau^+ \nu_\tau \propto m_\tau \tan\beta P_L$$

(tanb enhanced)

Normalized to SM couplings

MSSM Higgs couplings to gauge bosons and fermions

Quantum corrections to the couplings can be significant:

Vertex corrections to Higgs fermion Yukawa couplings through SUSY particle loops can induce **important flavor changing neutral and charged currents**

Depending on SUSY Spectrum, radiative corrections to Higgs couplings can change Higgs searches in a very crucial manner

Very important consequences for the interpretation of Higgs searches at the Tevatron and the LHC

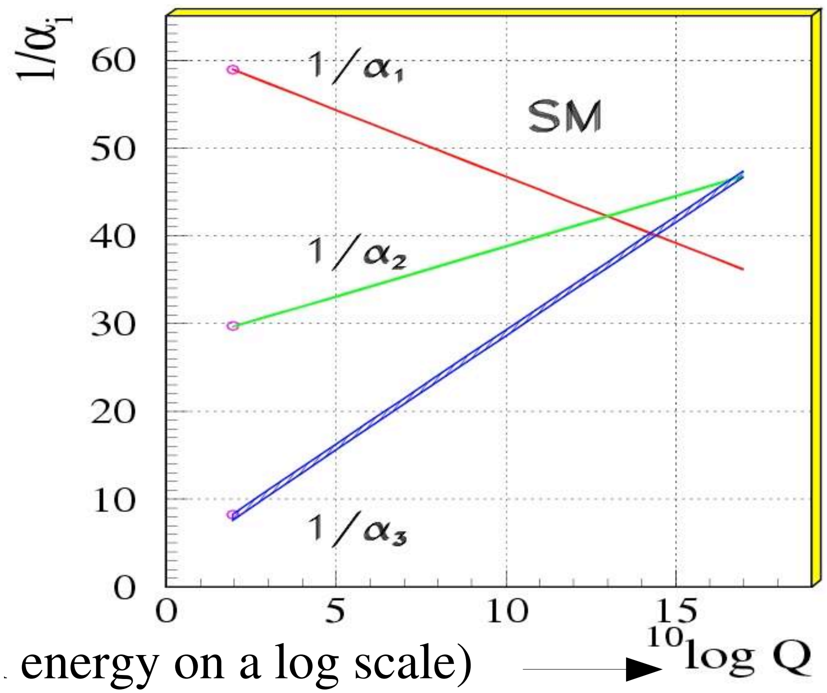
M.C. and Haber Higgs Review: Prog. in Particles and Nuclear Physics 50, 2003

Low Energy Supersymmetry

If SUSY exists, many of its most important motivations demand some SUSY particles at the TeV scale

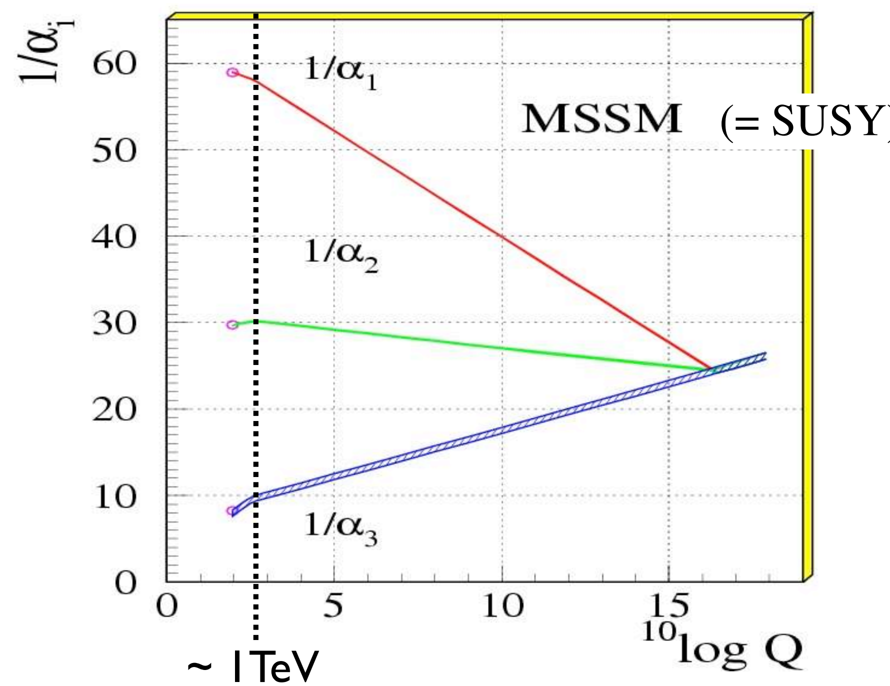
SUSY particles at the TeV scale allow Unification of Gauge Couplings

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!!

Electroweak Symmetry Breaking is generated radiatively

mSUGRA (CMSSM) example:

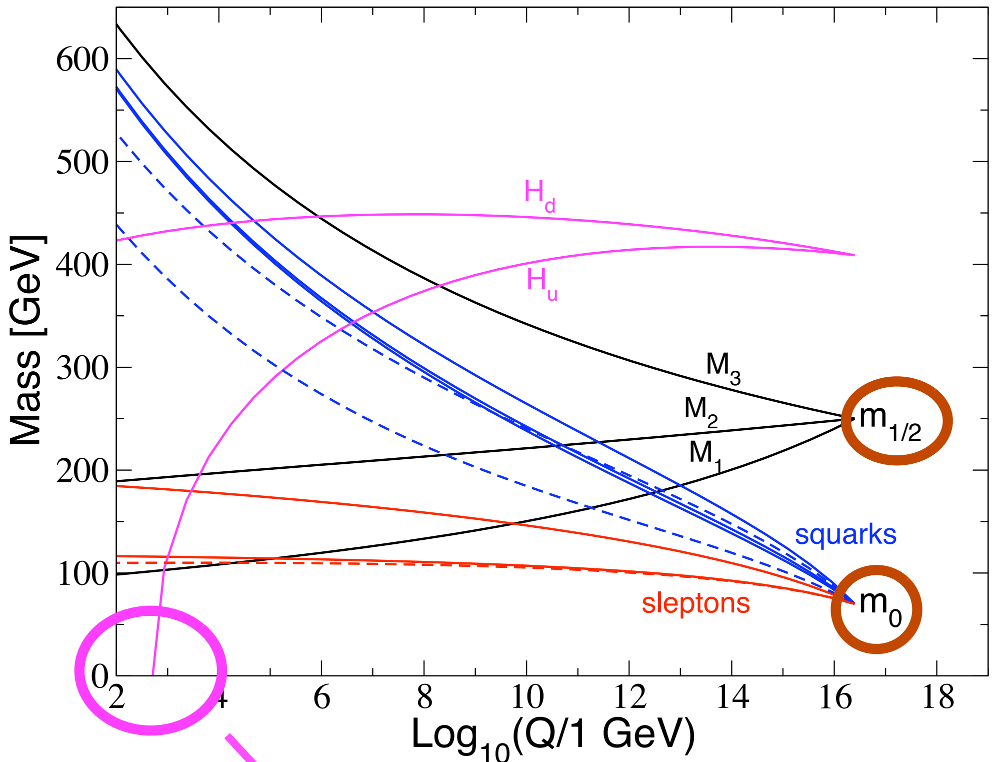
Renormalization group running of the soft SUSY breaking parameters starting with common values m_0 and $M_{1/2}$ for sfermion and guagino masses, respectively

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.

Low energy Supersymmetry

◈ SUSY is well motivated on purely particle physics grounds

- Stabilization of the electroweak scale
- Radiative breaking of the EW symmetry
- Unification of Gauge Couplings

◈ SUSY and Cosmology :

Dark Matter $\Rightarrow$

SUSY with R-parity discrete symmetry conserved $\longrightarrow$ $R_P = (-1)^{3B+L+2S}$

naturally provides a neutral stable DM candidate: LSP $\longrightarrow$ $\tilde{\chi}^0$

The LSP annihilation cross section is typically suppressed for most regions of SUSY spectrum $\longrightarrow$ too much relic density

Cosmology excludes many SUSY models!

Baryon Asymmetry $\Rightarrow$

- New CP violating Phases can arise when SUSY is softly broken
- Electroweak baryogenesis possible in Minimal SUSY SM extensions

Can SUSY explain both Mysteries of Matter?

Cosmology data ⟷ Dark Matter ⟷ New physics at the EW scale

Evolution of the Dark Matter Density

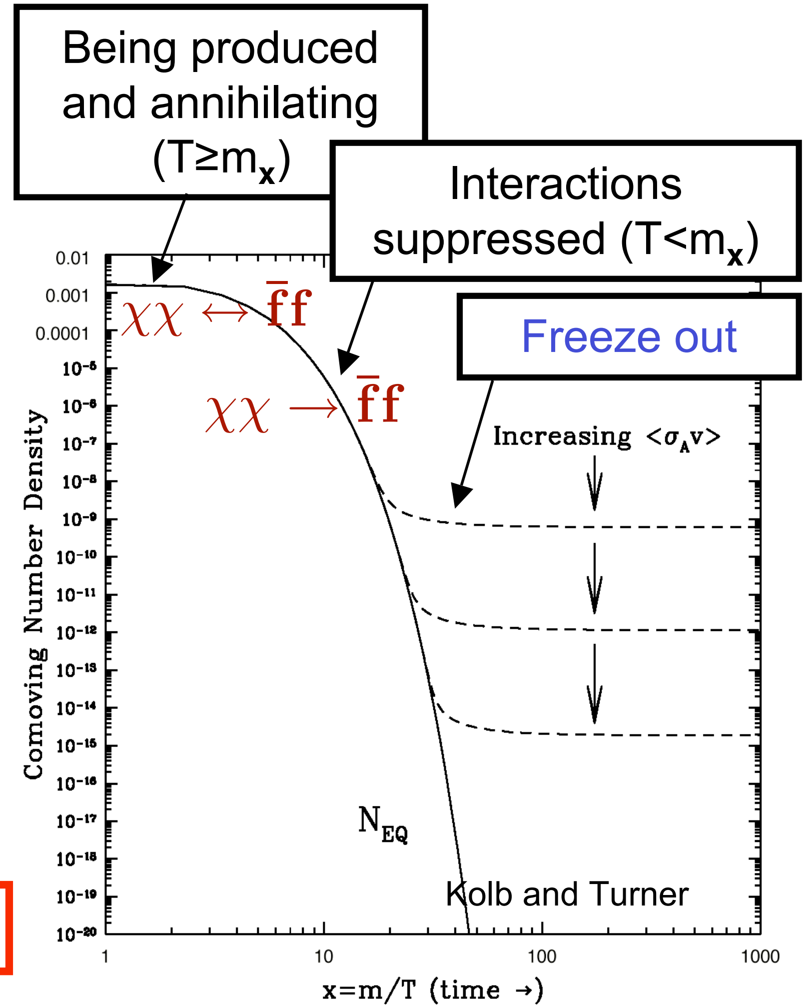
- Heavy particle initially in thermal equilibrium
- Annihilation stops when number density drops

$$H > \Gamma_A \approx n_\chi < \sigma_A v >$$

- i.e., annihilation too slow to keep up with Hubble expansion ("freeze out")

- Leaves a relic abundance:

$$\Omega_{DM} h^2 \approx \ <\sigma_A v>^{-1}$$



If m_x and σ_A determined by electroweak physics,

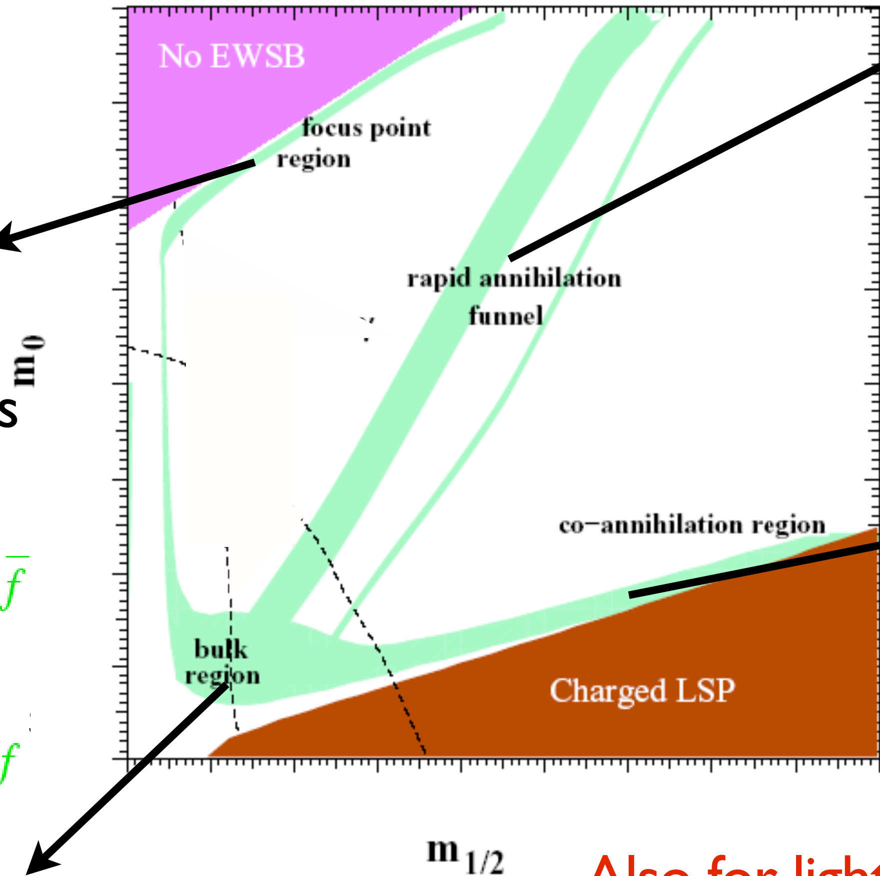
$\sigma_A \approx k\alpha_W^2 / m_X^2 \approx$ a few pb then Ω_{DM} h^2~0.1 for m_x~0.1-1 TeV

Remarkable agreement with WMAP-SDSS → $\Omega_{CDM} h^2 = 0.114 \pm 0.007$

Dark Matter density strongly restricts viable models:

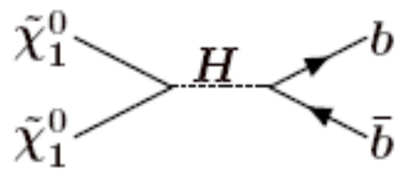
-- CMSSM example --

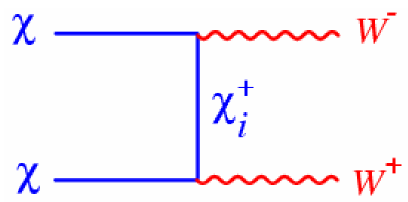
Only green regions allowed



Funnel region

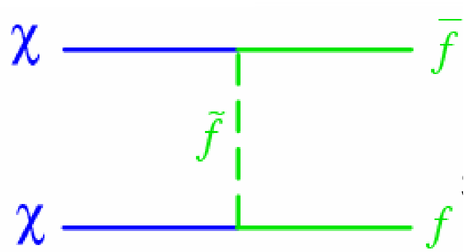
$m_H \approx 2m_\chi$





Focus point region

mixed neutralinos

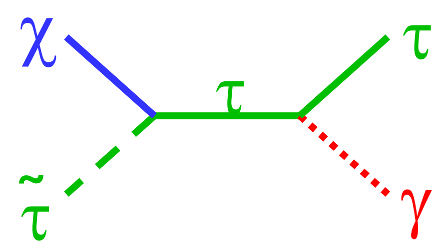


Bulk region

light sfermions

Co-annihilation region

degenerate LSP and stau



Also for light stops, $m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_{top}$

as necessary in EW Baryogenesis

EWBG facilitates agreement with DM relic density

The search for SUSY at Colliders

Depending on the mediation mechanism

and the associated scale of SUSY breaking :

Different initial conditions for the Soft SUSY breaking parameters

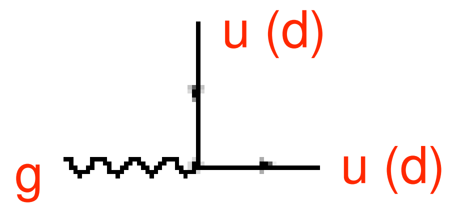
$\downarrow$

Different mass hierarchies among the SUSY particles

Concentrate in models with conserved R-parity: Neutralino LSP Dark Matter

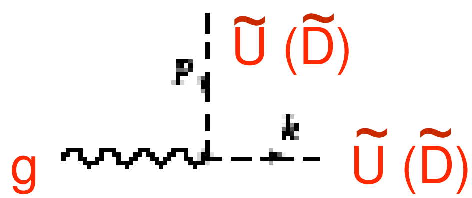
- The most important interactions for producing sparticles are gauge interactions, and interactions related to gauge interactions by SUSY. Their strength is known, up to mixing of sparticles.
- Two sparticles produced in each event, with opposite momenta.
- The LSPs are neutral and extremely weakly interacting, 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", $\not{E}_T$.

Interactions of Gauge and Matter fields



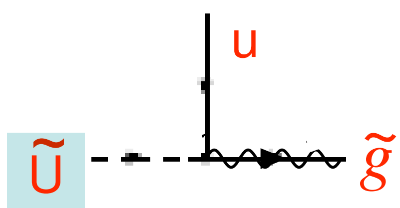
$$-ig_3 T^a \gamma^\mu$$

➔ Regular SM interactions

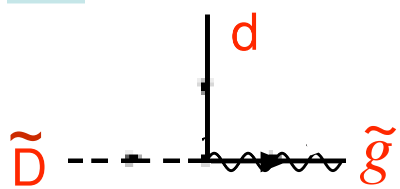


$$-ig_3 T^a (p+k)^\mu$$

➔ Sparticle-gauge interactions:
change fermions by scalars
(and gammas by momentum)



$$-ig_3 T^a (c_U P_L + s_U P_R)$$



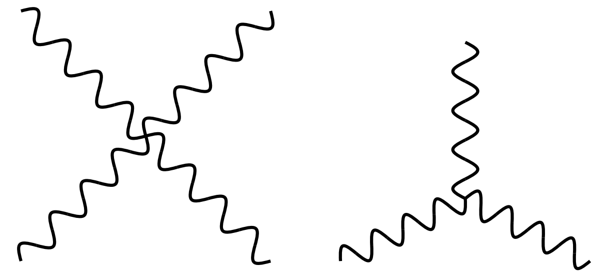
$$-ig_3 T^a (c_D P_L + s_D P_R)$$

➔ Sfermion-gaugino-fermion novel interactions
change gluon by gluino and one fermion by scalar

extra factors are mixing angles to project mass eigenstates into gauge eigenstates

Interactions of Gauge Supermultiplets

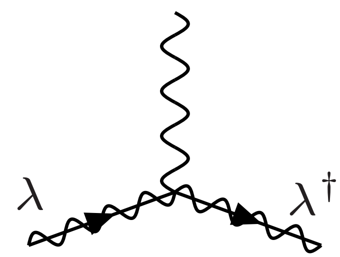
Usual 3 and 4 gauge bosons vertices
from kinetic term



Gaugino- gauge boson interactions

proportional to the gauge group structure constant

$$igf_{abc}\lambda^a\sigma^\mu\bar{\lambda}^b V^c_\mu$$

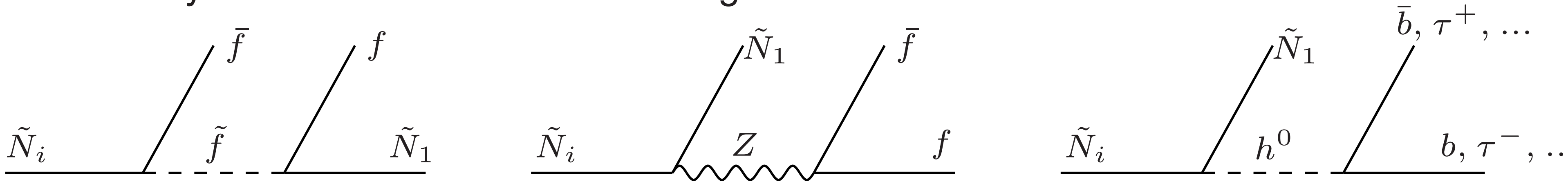


for gluon-gluinos ~ $g_3\ f_{abc}\ \gamma_\mu$

No interaction between U(1) gaugino and gauge field f_{abc} =0

Neutralino Decays: $\tilde{\chi}_i^0 \equiv \tilde{N}_i^0$

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 decay modes are

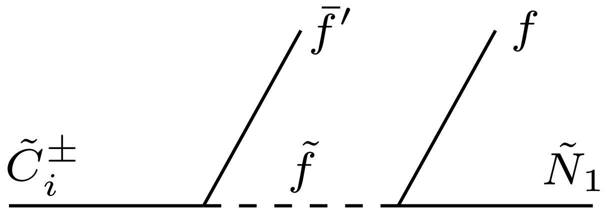
$$\tilde{N}_i \to q\bar{q}\tilde{N}_1 \qquad \text{(seen in detector as } jj + \not{E}\text{)}$$

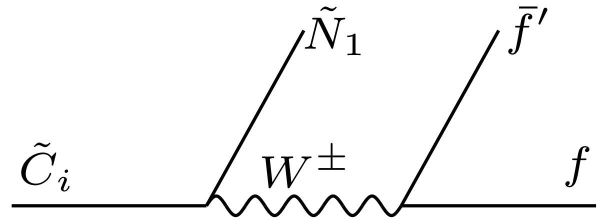
$$\tilde{N}_i \to \ell^+\ell^-\tilde{N}_1 \qquad \text{(seen in detector as } \ell^+\ell^- + \not{E}\text{)}$$

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.

Chargino Decays: $\tilde{\chi}_i^{\pm} \equiv \tilde{C}_i^{\pm}$

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





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

In general, the decay modes are

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

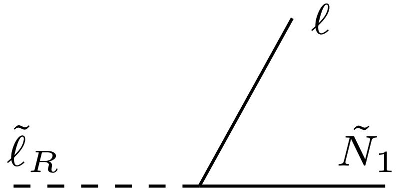
$$\tilde{C}_i^{\pm} \rightarrow \ell^{\pm}\nu\tilde{N}_1 \qquad \text{(seen in detector as } \ell^{\pm} + \not{E}\text{)}$$

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.

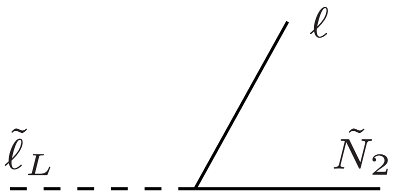
Slepton Decays:

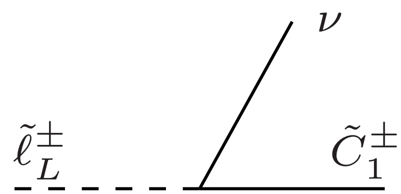
When $\tilde{N}_1$ is the LSP and has a large bino content, the sleptons $\tilde{e}_R$, $\tilde{\mu}_R$ (and often $\tilde{\tau}_1$ and $\tilde{\tau}_2$) prefer the direct two-body decays with strength proportional to g'^2:

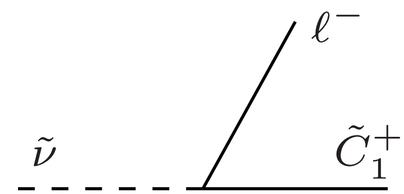


(seen in detector as $\ell^{\pm} + \not{E}$)

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:



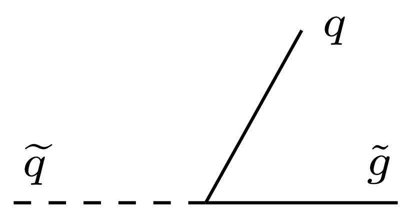




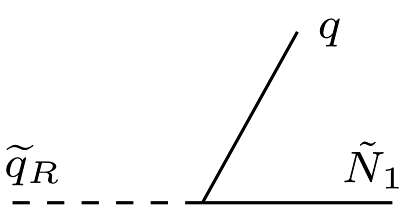
with $\tilde{N}_2$ and $\tilde{C}_1$ decaying as before.

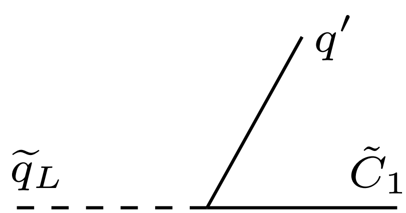
Squark Decays:

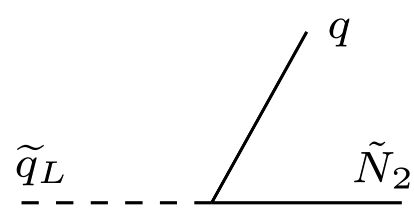
If the decay $\tilde{q} \to q\tilde{g}$ is kinematically allowed, it will always dominate, because the squark-quark-gluino vertex has QCD strength:



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 $\tilde{N}_2$:







Stop decays:

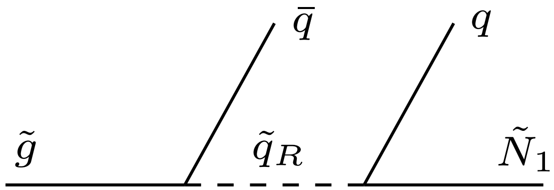
If a top squark is light, then the decays $\tilde{t}_1 \to t\tilde{g}$ and $\tilde{t}_1 \to t\tilde{N}_1$ may not be kinematically allowed, and it may decay only into charginos: $\tilde{t}_1 \to b\tilde{C}_1$. If even that is not allowed, it has only a suppressed flavor-changing decay: $\tilde{t}_1 \to c\tilde{N}_1$.

light stops

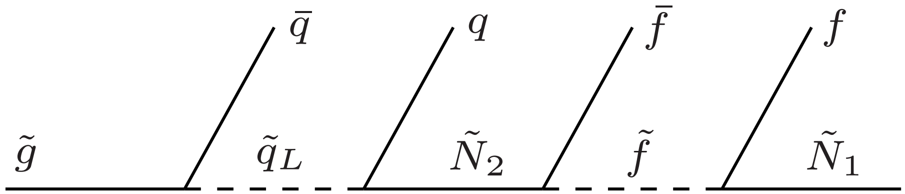
Gluino Decays:

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

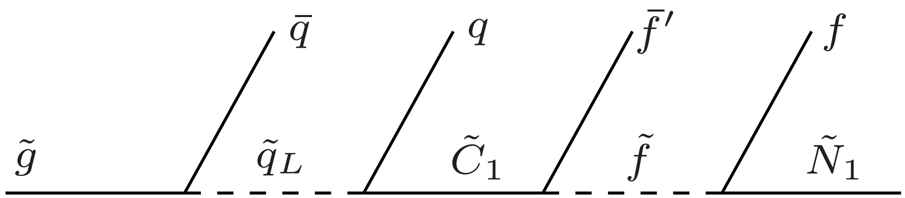
For example:



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



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

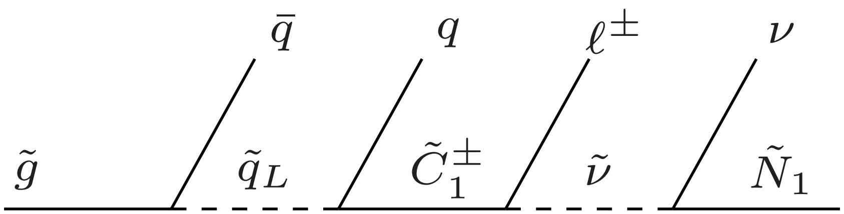


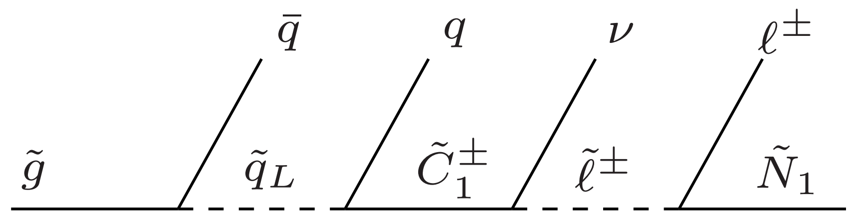
$jjjj + \not{E}$ or $t\bar{t}jj + \not{E}$ or
$jj\ell^\pm + \not{E}$

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

The possible signatures of gluinos and squarks are numerous and complicated
due to cascade decays

An important feature of gluino decays with one lepton:





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

Gluino pair production will have probability 0.5 to produce **same charge di-lepton signature**

This is important at hadron collider, where Standard Model backgrounds with same-charge leptons are much smaller.

$$\text{(SUSY)} \to \ell^+\ell'^+ + \text{ jets } + \not{E}_T$$

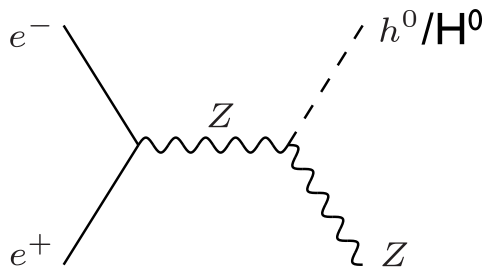
SUSY Limits from LEP2 e^+e^- collisions up to $\sqrt{s} = 208$ GeV

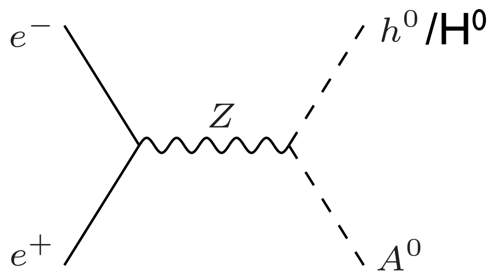
The CERN LEP2 collider had the capability of producing all sparticle-antisparticle pairs, except for the gluino:

$$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-,\ \tilde{C}_1^+\tilde{C}_1^-,\ \tilde{N}_1\tilde{N}_2,\ \tilde{N}_2\tilde{N}_2,\ \gamma\tilde{N}_1\tilde{N}_1,\ \tilde{q}\tilde{q}^*$$

Exclusions for charged sparticles are typically close to the kinematic limit.

LEP2 Searches for Higgs bosons





dominant decay modes to $b\bar{b}$ and $\tau^+\tau^-$

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

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

Hadron Colliders

Present:

Tevatron Signals for SUSY in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

Future:

LHC Signals for SUSY in pp collisions at $\sqrt{s} = 14$ TeV

The LHC is a gluon-gluon collider, to first approximation

One needs some distinctive signatures to overcome large QCD backgrounds

multi-leptons, same sign di-leptons, high E_T jets,

and large missing E_T

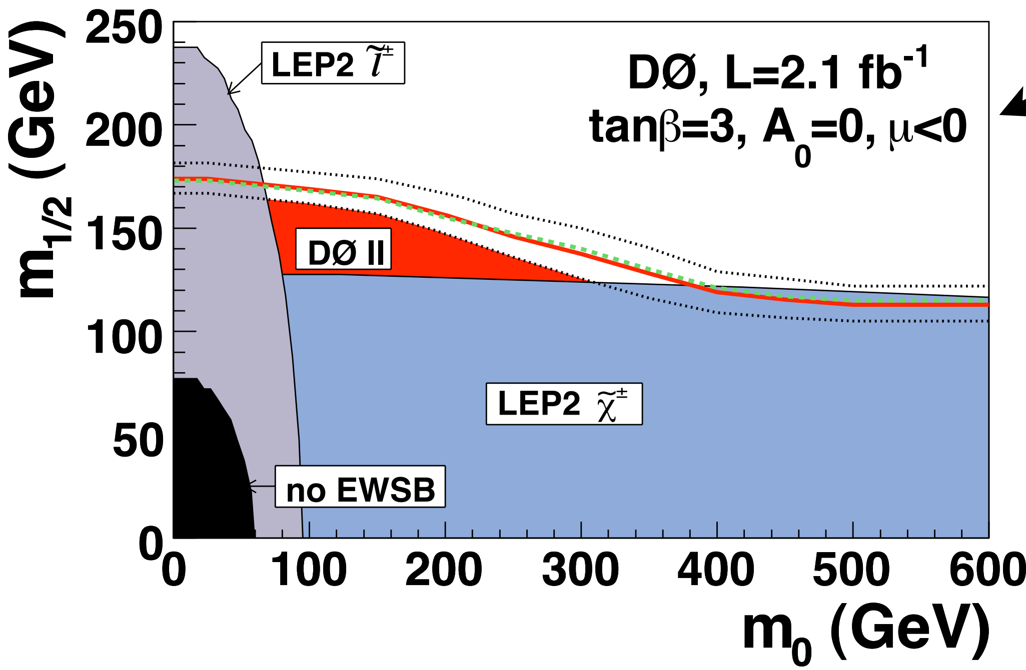
Squark and Gluino Searches

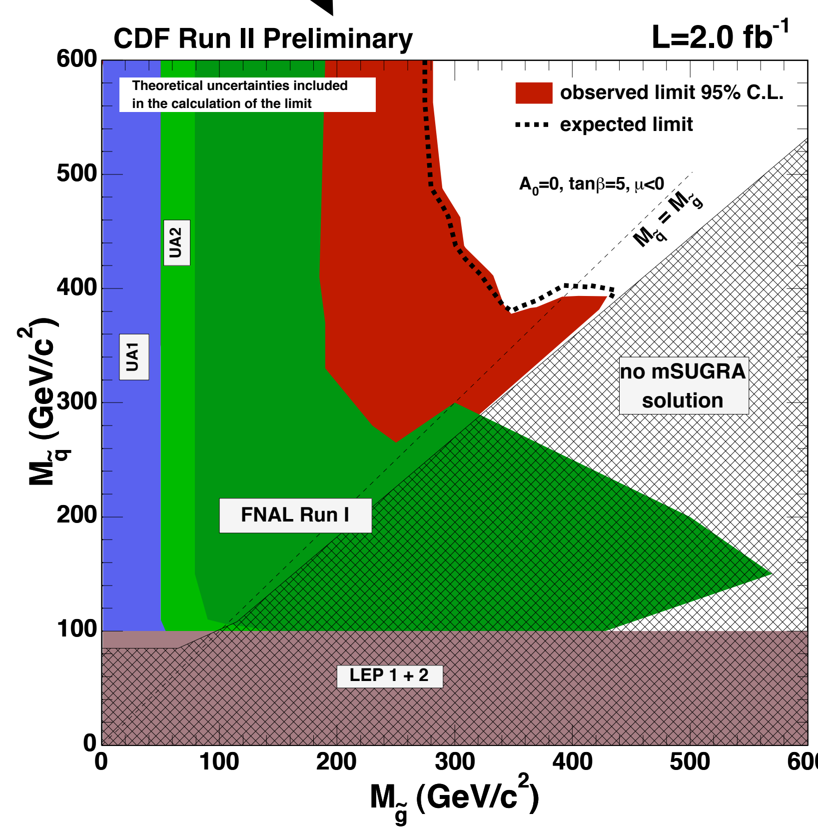
strong interacting particles are produced at large rates at hadorn colliders

- most likely types of signatures:
  - 'mSUGRA' type – high E_T jets and $\not{E}_T$ (maybe lepton

At the Tevatron

no evidence for squarks or gluinos up to masses of ~ 300-400 GeV



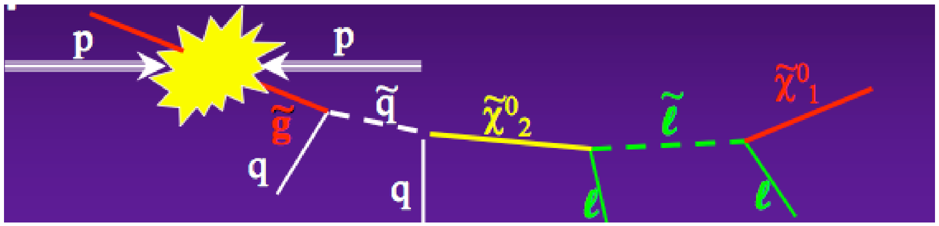


At low energy: $m_{\tilde{q}}^2 \simeq m_0^2 + 6M_{1/2}$

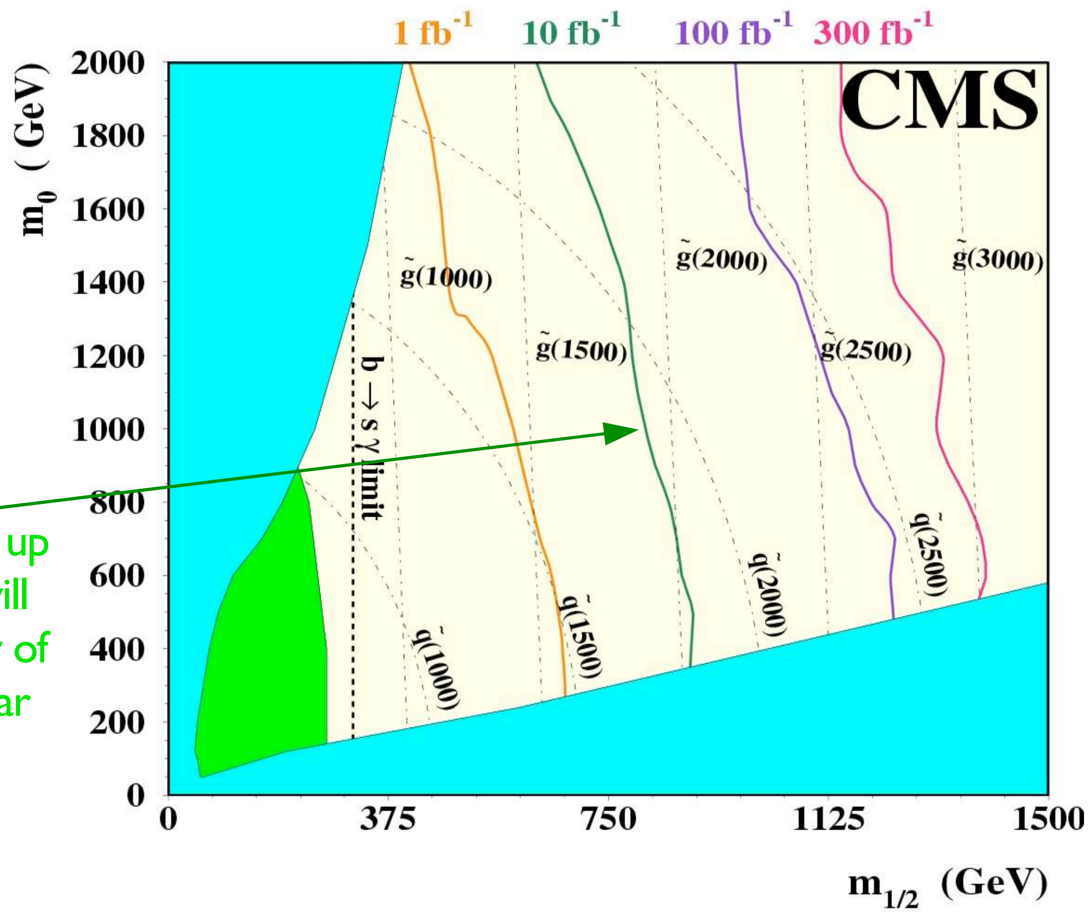
$$m_{\tilde{g}}^2 \simeq 2.5M_{1/2}$$

MET signals at the LHC

Typical SUSY event at LHC



Discovery signals can be classified by the number of leptons in the event.

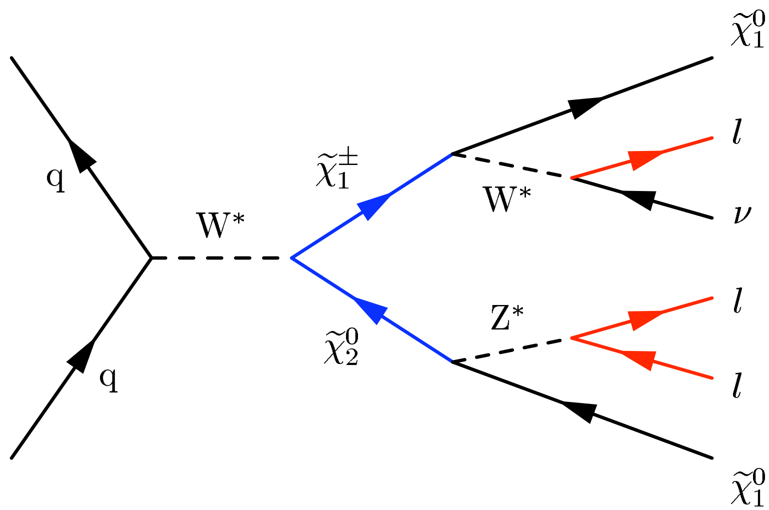


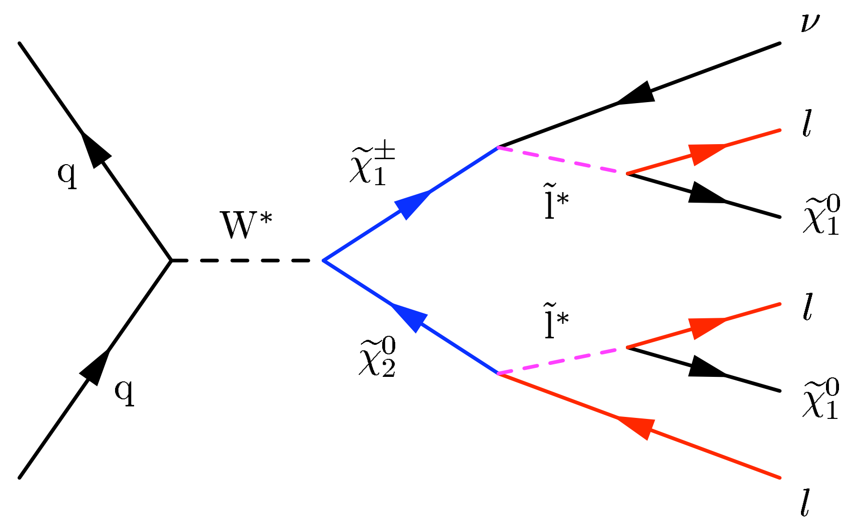
Once the LHC is up and running, it will deliver luminosity of 10 fb^{-1} in one year

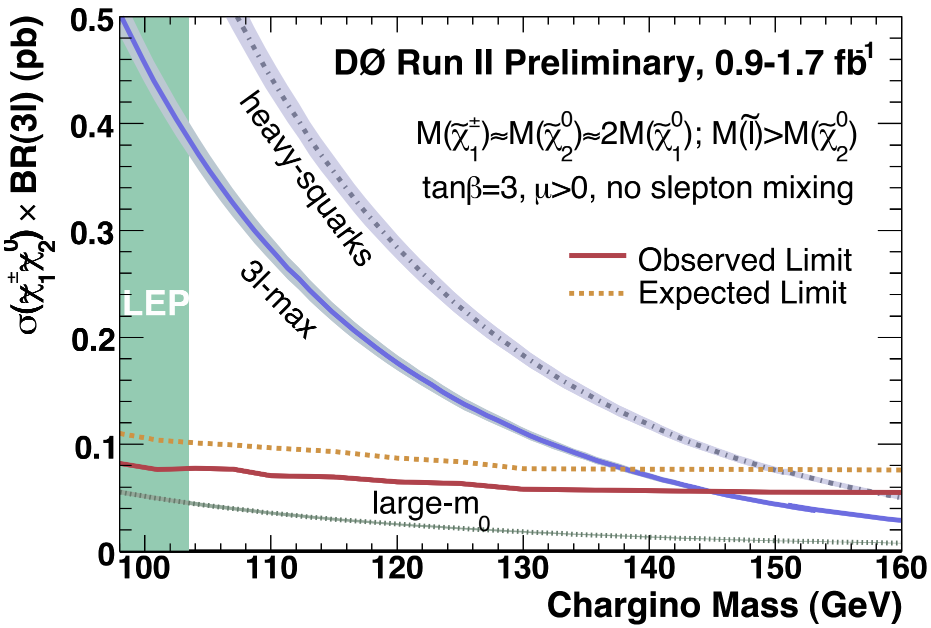
If low energy SUSY exists, we expect to see some of its signatures at LHC

reach: $M_{\tilde{q}}$ *and* $M_{\tilde{g}}$ *up to* ~ 2 *TeV with 10* fb^{-1}

Chargino/Neutralino Searches: Tri-lepton + lots of MET







No evidence at the Tevatron

At LHC, di-lepton and trilepton signatures can be very powerful.

We might be able to infer masses of SUSY particles or mass combinations using kinematic endpoints

mass determination with 10% accuracy

The search for a light Stop at Hadron Colliders

If a SM-like Higgs with mass below 125 GeV is found

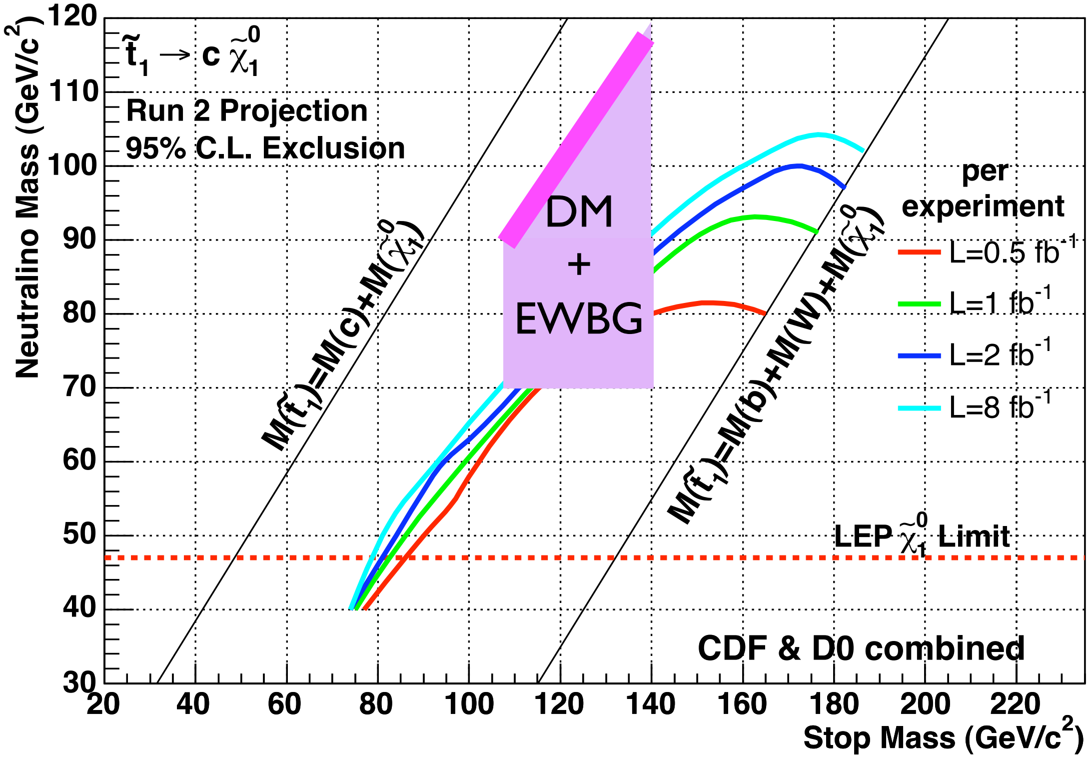
$\longrightarrow$ light stops will be the next probe of EWBG

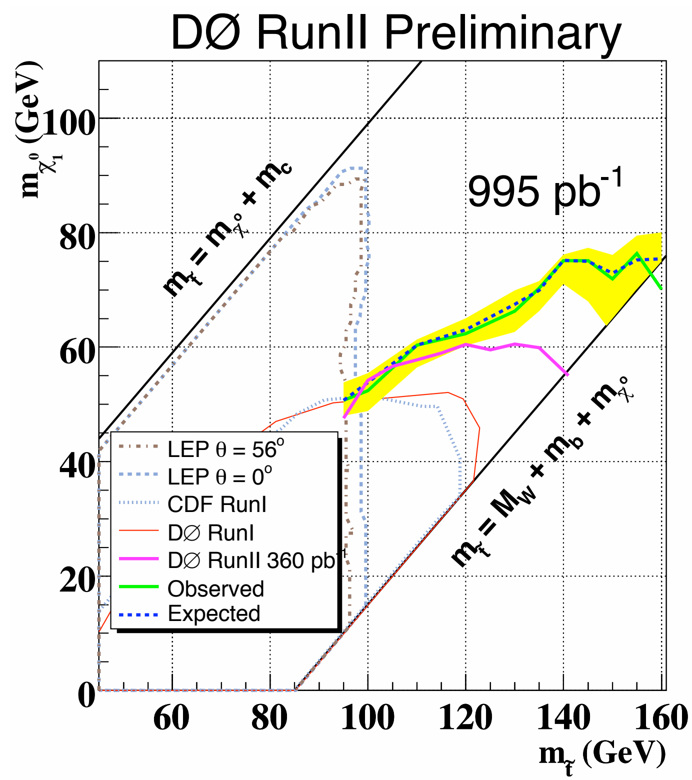
Light Stop models with Neutralino LSP Dark Matter $\longrightarrow$ $\not\!\!E_T$ signal

$\longrightarrow$ dominant decay $\boxed{\tilde{t}_1 \to c\,\tilde{\chi}_1^0}$

For small Stop-Neutralino mass difference: co-annihilation region $\Delta_{m_{\tilde{t}\tilde{\chi}}} < 30$ GeV

$\longrightarrow$ excellent agreement with WMAP data





Very Challenging for Hadron colliders

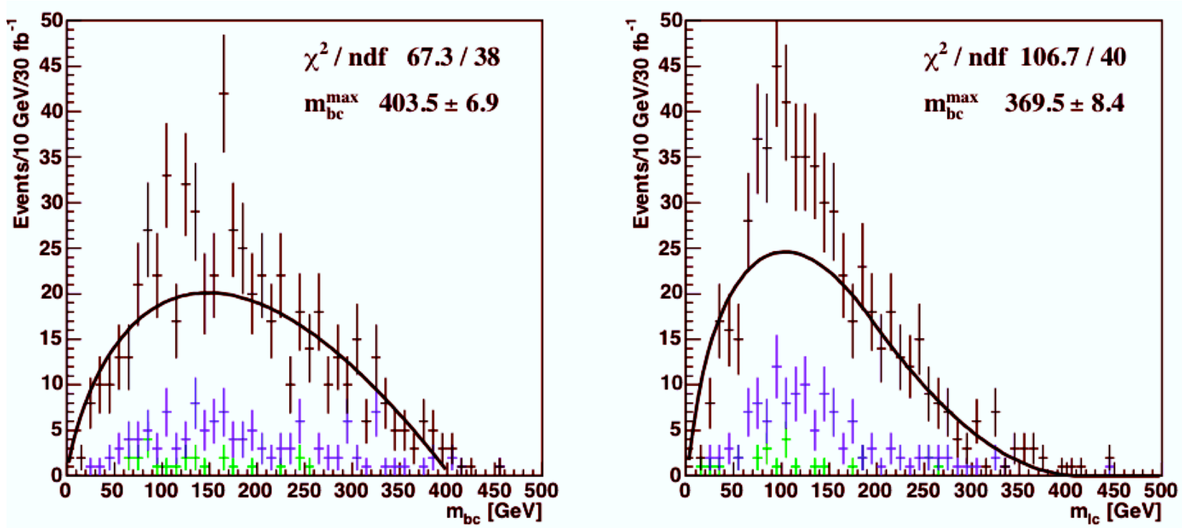
Light Stop Searches at the LHC

Same sign tops in gluino decays:

$$pp \to \tilde{g}\tilde{g} \to \mathrm{tt}\ \tilde{\mathrm{t}}_1^*\tilde{\mathrm{t}}_1^*, \qquad \mathrm{t} \to \mathrm{bl}^+\ \overline{\nu}_1 \qquad \tilde{\mathrm{t}}_1^* \to c\tilde{\chi}_1^0$$

Signal: 2 SS leptons, 2 SS bottoms, jets plus Missing Energy

Mass measurements from distributions, but not enough independent distributions to get absolute mass



Analysis valid for gluino masses up to ~ 900 GeV

Caveat: Signal decreases 50% if squarks out of the LHC reach, still may be possible to see the stops (under study)

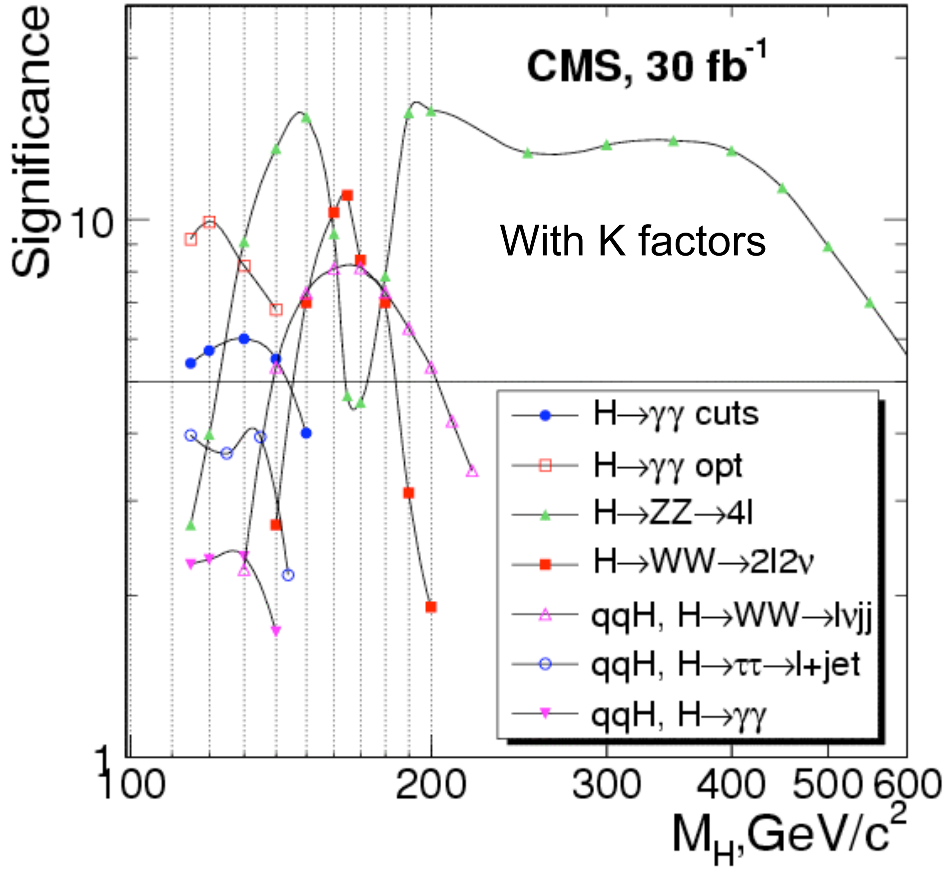
MSSM Higgs Boson Searches at colliders

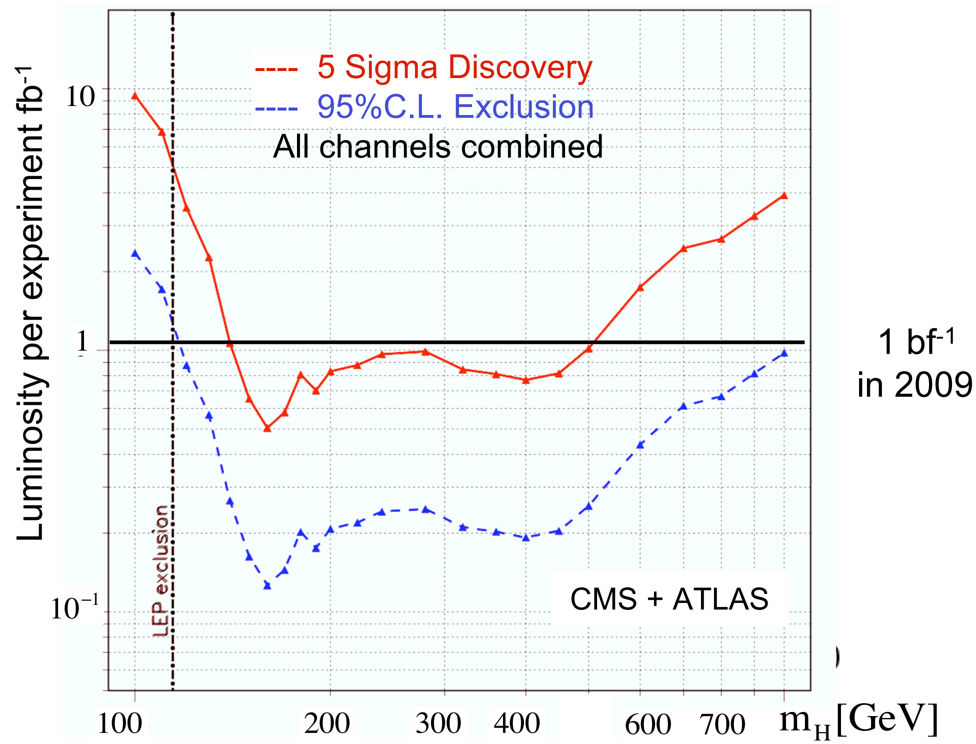
1) Search for a SM-like Higgs responsible for EWSB
must have SM-like couplings to W-Z gauge bosons
and most probably SM-like couplings to the top-quark

Results as expected for a SM-like Higgs of mass below ~ 135 GeV
hence in the $q\bar{q}H \to \tau^+\tau^-$ and $H \to \gamma\gamma$ channels $\longrightarrow$

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

LHC Discovery Potential of a SM Higgs





- **Low mass range** m_{HSM} < 200 GeV

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

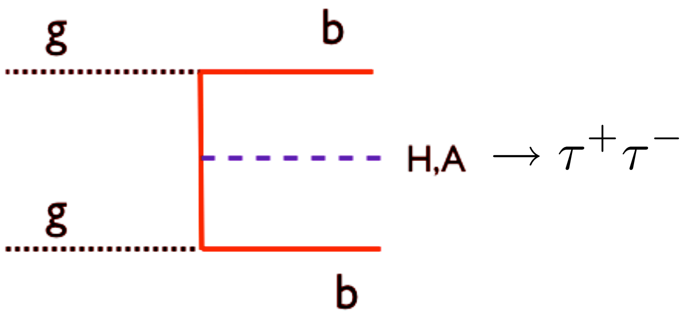
- **High mass range** m_{HSM} > 200 GeV

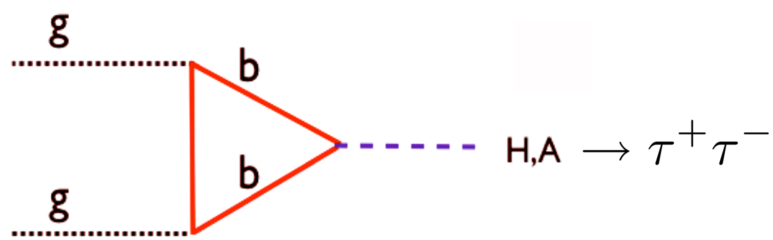
$$H \rightarrow WW,\ ZZ$$

A SM Higgs cannot escape detection at the LHC

See Yongsheng Gao's talk

Non-Standard MSSM Higgs searches in inclusive $\tau^+\tau^-$ decays





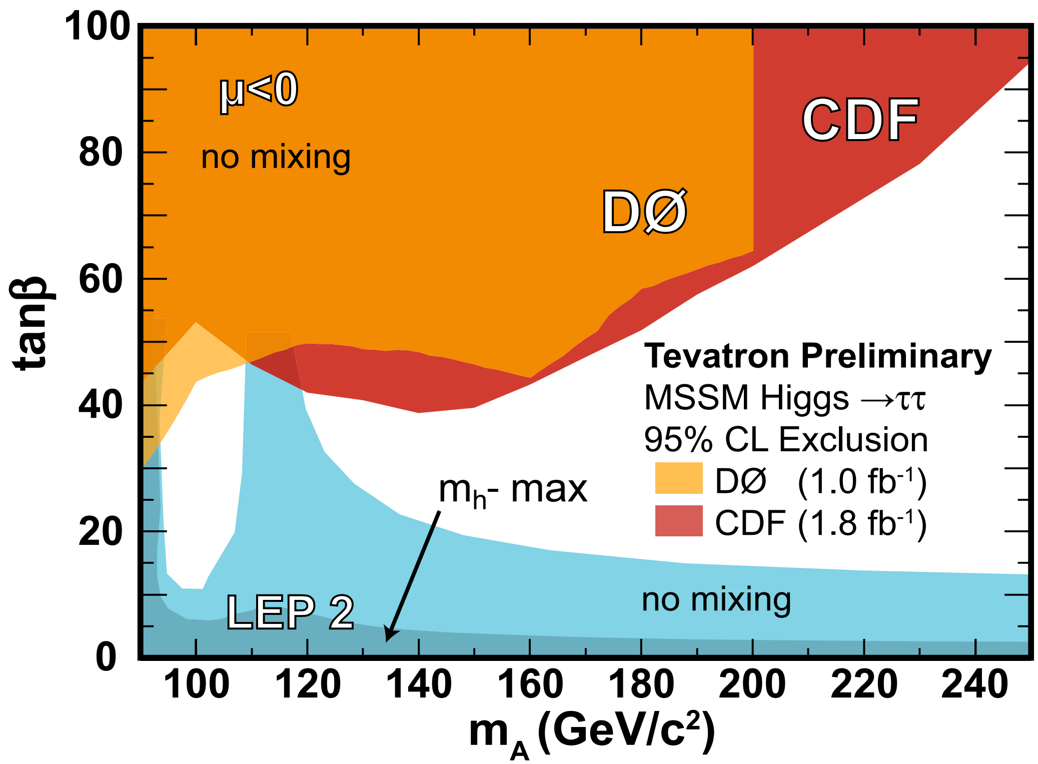
M. C., Heinemeyer, Wagner,Weiglein '05

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

- Important reach for large tanb, small m_A
- Weaker dependence on SUSY parameters via radiative corrections

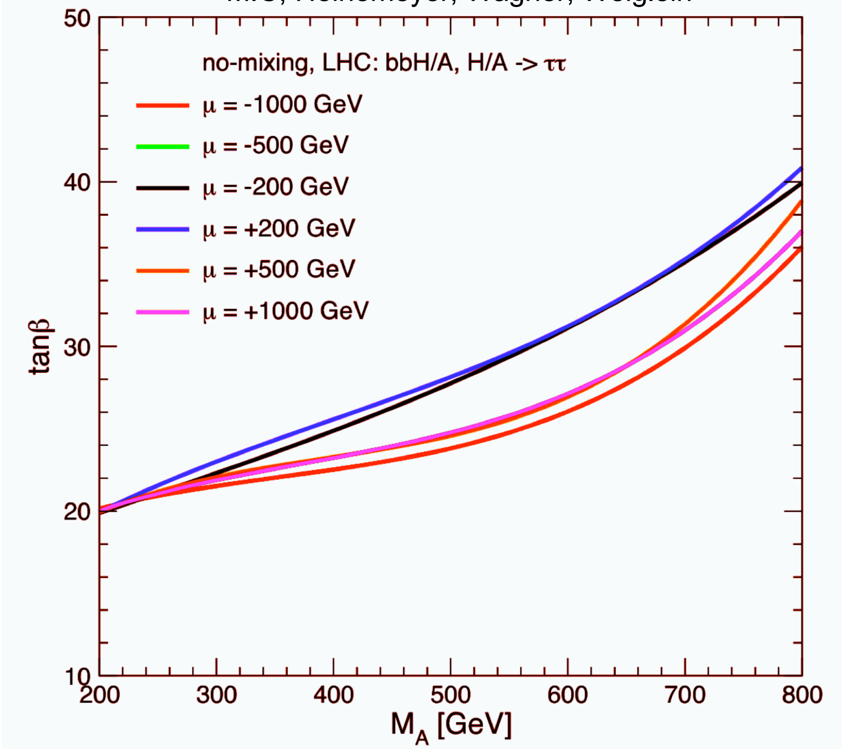
Also possible to look for bbA/H with A/H decays to bb ==> 4 b's final state BUT, strong dependence SUSY spectrum via radiative corrections and less sensitivity (at the Tevatron)

A/H Higgs searches at the Tevatron: The state of the art



Searches for Non-Standard Neutral Higgs bosons at the LHC

$pp \to A/H\,X,\;\; A/H \to \tau^+\tau^-,$ rescaling CMS prospects for 30 fb^{-1} (similar for ATLAS)



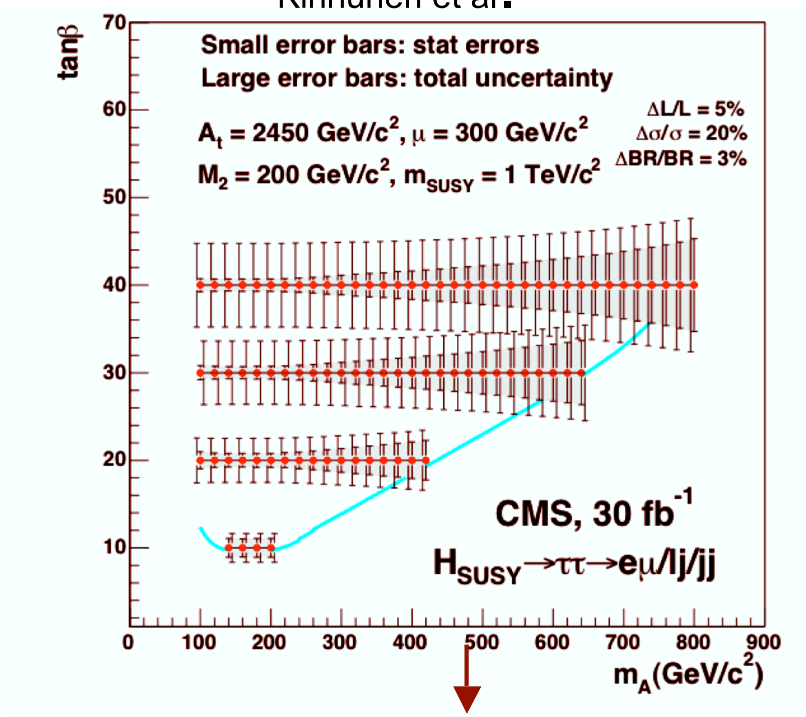
- Enhancement of Hbb and Abb couplings by factor $\tan\beta$ compared with SM Higgs.

  ==> large production cross section

  ==> decay dominated by $A/H \to \tau^+\tau^-$

  (with different decay modes of tau leptons)

Kinnunen et al.

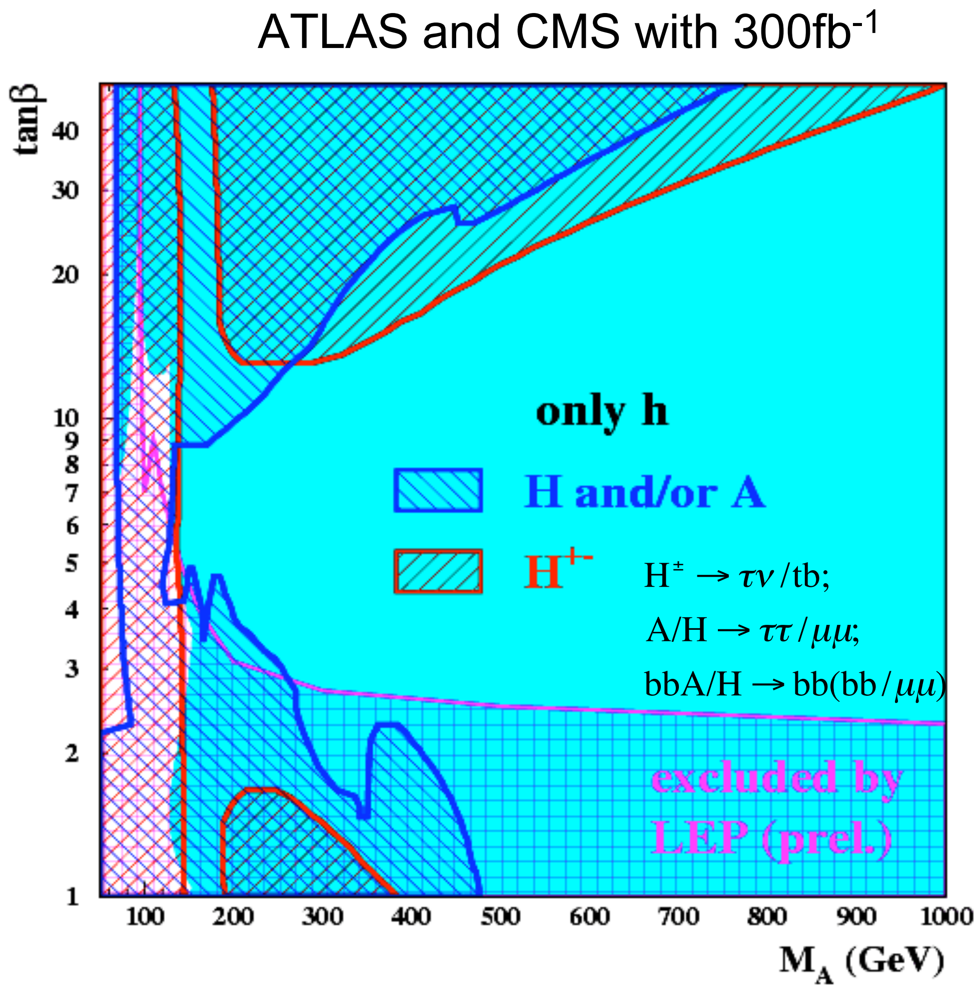


Cancellation of Δ_b effects ==> projections stable under variations of SUSY space ==> $\boxed{\Delta \tan\beta \approx 8}$

main variation ==> $A/H \to \tilde{\chi}_i^0 \tilde{\chi}_j^0,\;\; \tilde{\chi}_k^{\pm} \tilde{\chi}_l^{\mp}$

Robustness of results under variations of SUSY space ==>handle on tan beta

Many Higgs production and decay processes accesible with full LHC potential



Still regions where only a SM-like Higgs is visible

Outlook

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

Supersymmetry is a leading candidate

which may offer elegant solutions to many of the SM unsolved mysteries :

The hierarchy problem

Radiative Generation of EWSB

Unification of couplings

Predicts the existence of DM and can explain Baryogenesis at the EW scale

To provide such solutions at least some SUSY particles must be at LHC reach

and

A SM-like Higgs boson below 200 GeV must appear in most SUSY extensions

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